Explosive/Eruptive LBV-like mass loss and

Superluminous Supernovae (especially Type IIn)

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In Tucson
(not ASU in Tempe)

Chandra/HST

OVERVIEW

$E_{rad} \approx 10^{51}$ ergs

OVERVIEW	SLSN IIn	SLSN Ic
Examples:	2006gy, 2006tf, 2008fz, 2008am 2003ma, 2010jl, etc. (2002ic, 2005gj, etc.)	2005ap, SC06F6, PTF09atu, PTF09cnd, 2009jh, 2010gx, etc. (2007bi, 1999as, PTF10nmn)
Diversity:	Very diverse	Not so diverse
Line widths:	100-4000 km/s	10,000 km/s
Duration:	100-1000 days	Faster decline (not ^{56}Co)
Temperature:	Usually 6000-7000 K X-rays often self-absorbed	>12,000 K Peak in UV
Engine(s):	cc + CSM int. SN Ia + CSM int. PISN/Magnetar + CSM int.	cc + opaque CSM int. cc + Magnetar (^{56}Ni – PISN)
Progenitors:	Massive eruptive star (LBV-like, pulsational PI) or Ia	Massive WC/WO-like star (very massive if p-PI or PISN)
Hosts:	Dwarfs, $Z \leq Z_{\odot}$	Dwarfs, $Z << Z_{\odot}$
Rates:	10^{-4} to 10^{-3} ccSN	10^{-4} ccSN

2008es (?)

DIVERSITY

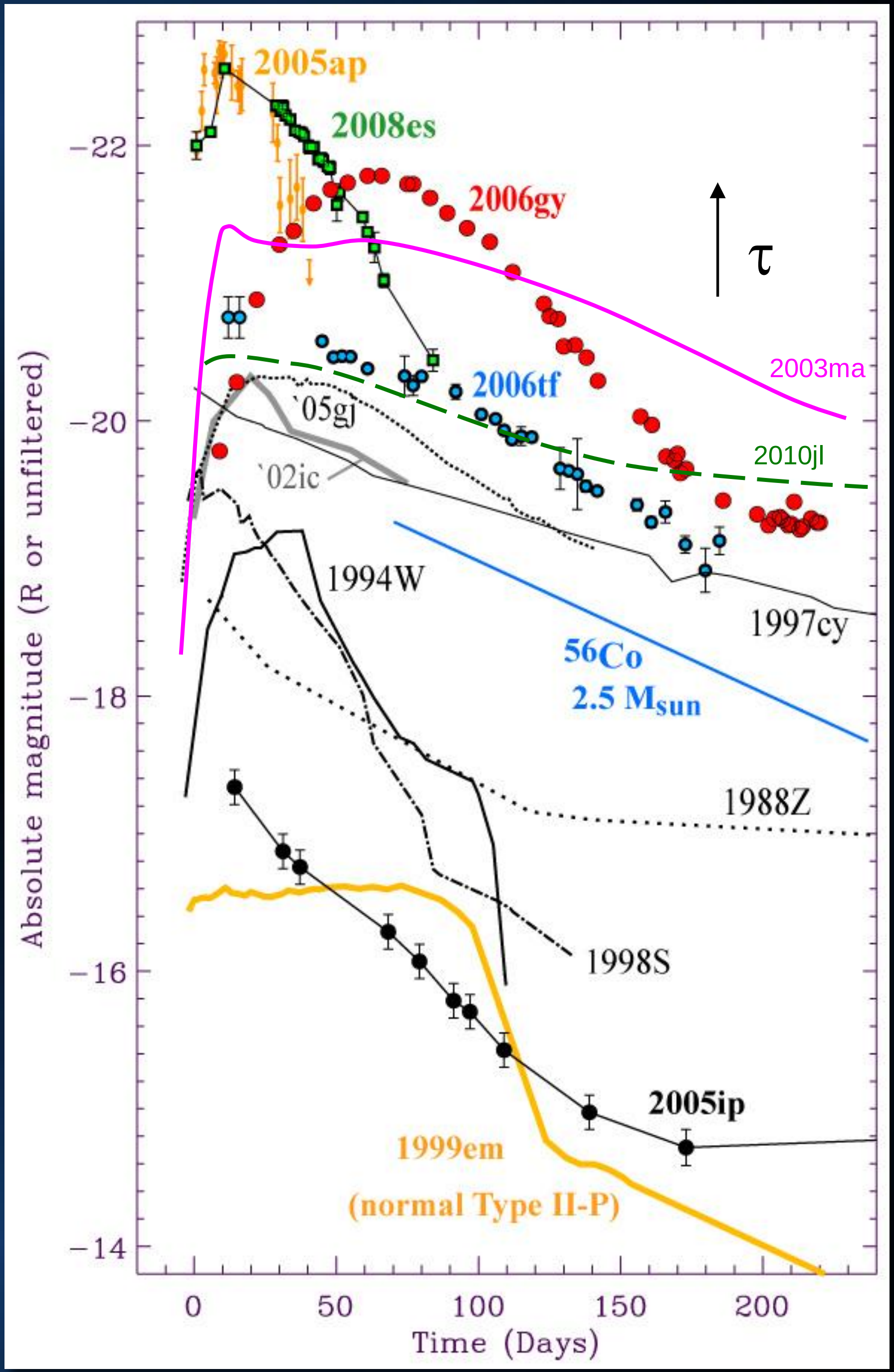
Type IIn supernovae:
Luminosity range ➔ CSM diversity

SN 2006gy Smith+07,08,10; Ofek+07; Woosley+07…
SN 2006tf Smith et al. 2008
SN 2003ma Rest et al. 2011
SN 2008am Chatzopoulos et al. 2011
SN 2008fz Drake et al. 2010
SN 2010jl Smith+11, 12; Andrews+11; Stoll+11; Zhang+12

SN 2002ic many many papers
SN 2005gj Aldering+06; Prieto+??

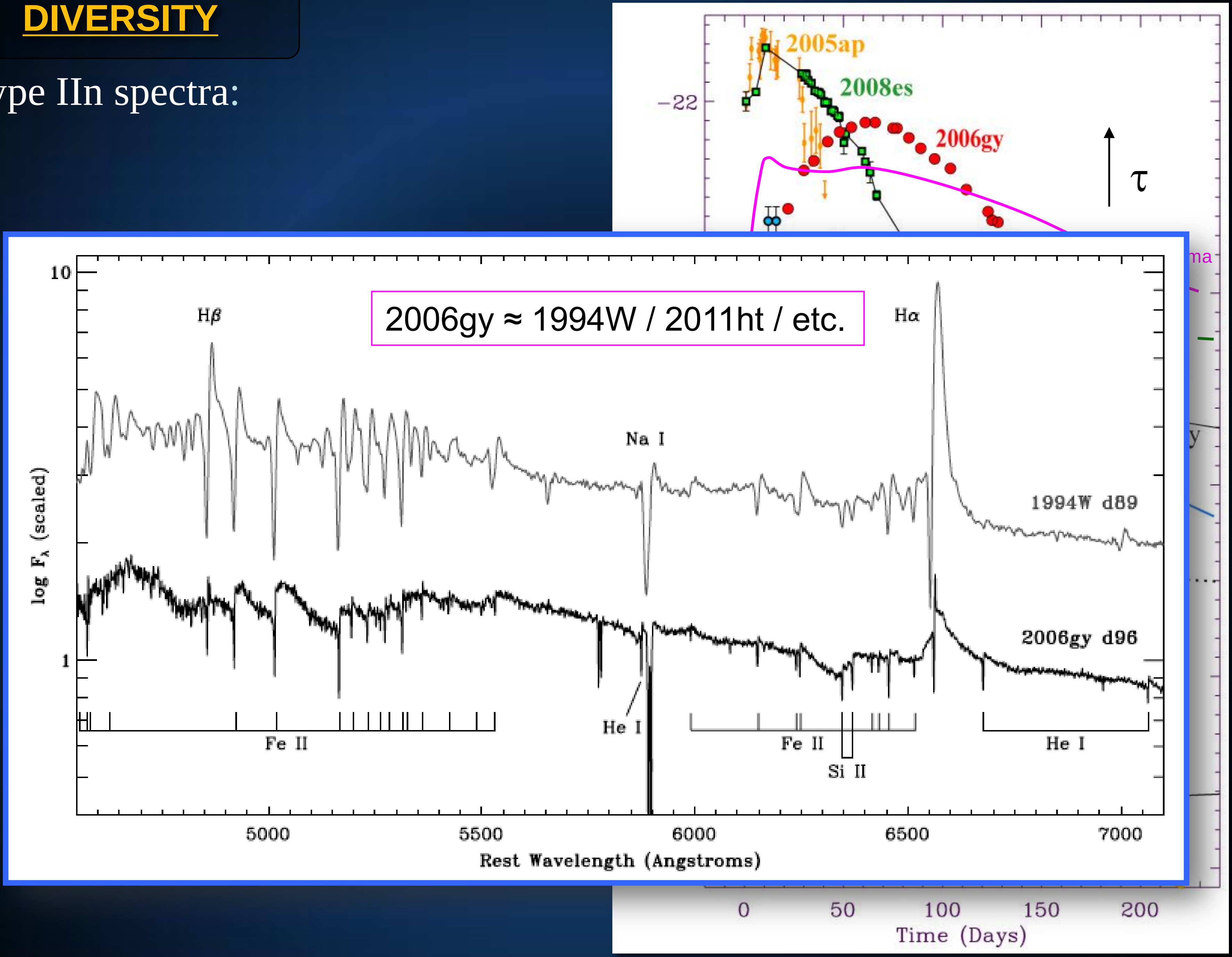
SN 2008es Miller+09; Gezari+09 (NOT a IIn)

Diversity of CSM for SNe IIn results from a range of CSM mass and distribution (more later)



DIVERSITY

Type IIn spectra:



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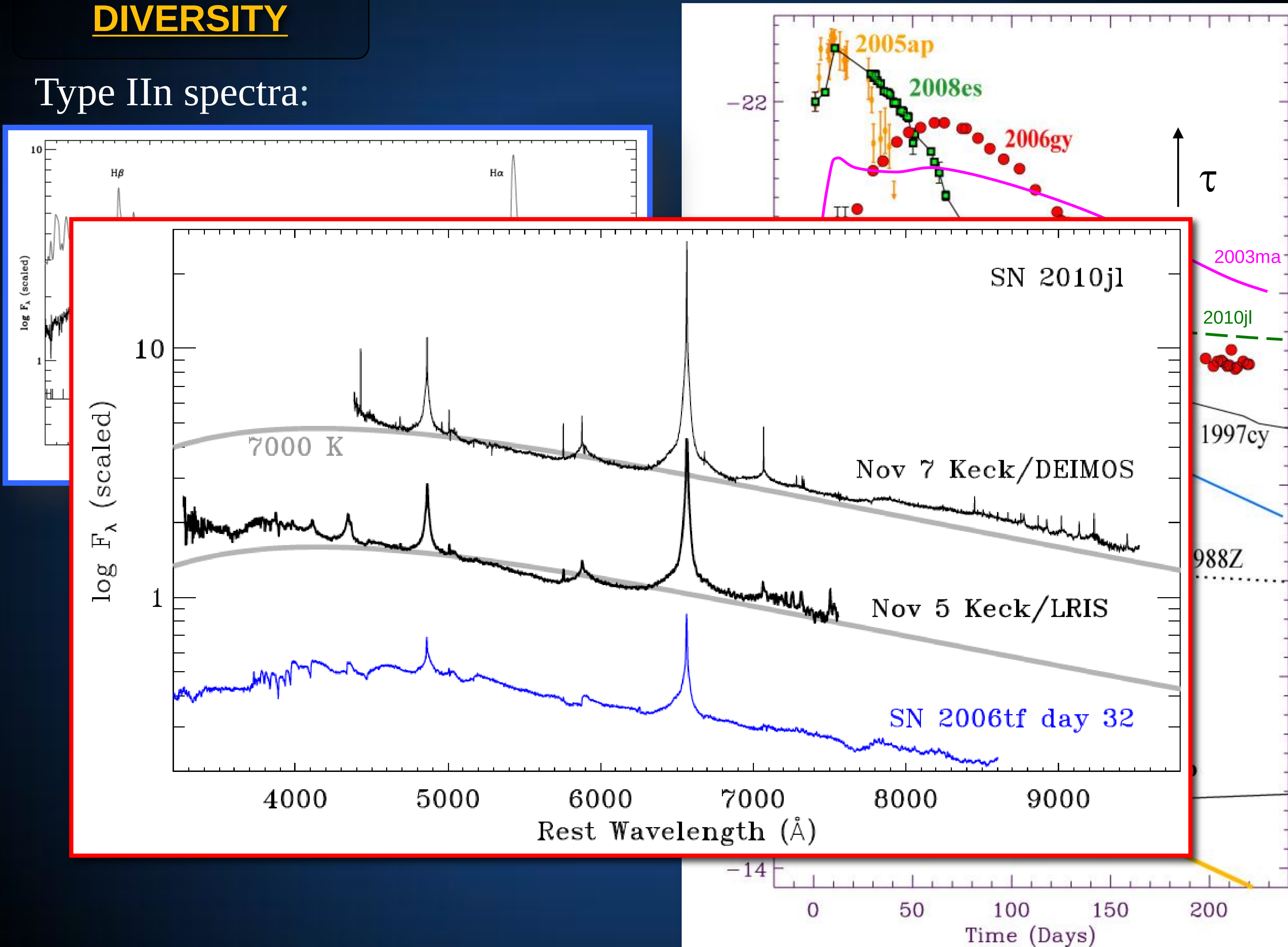

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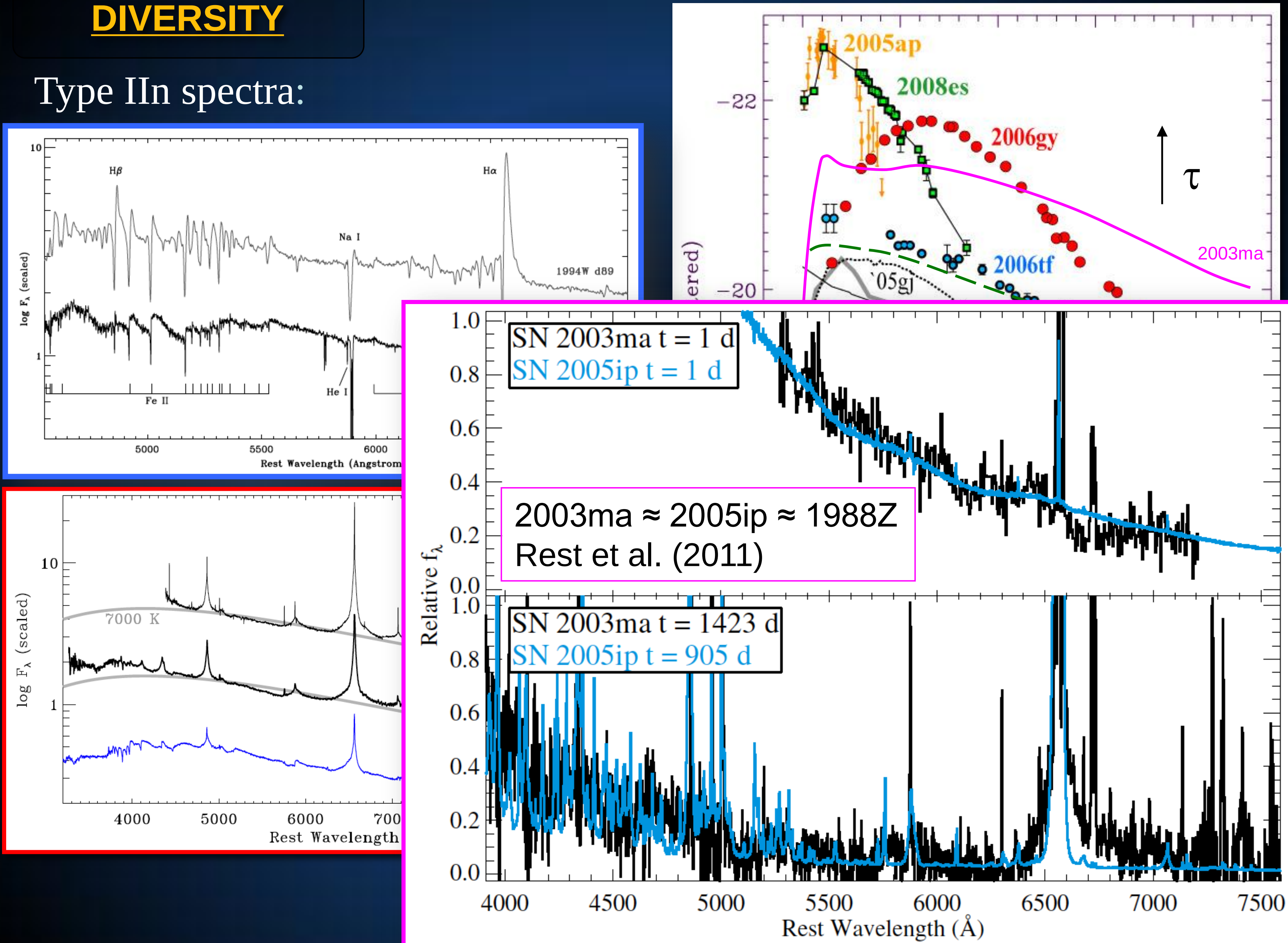
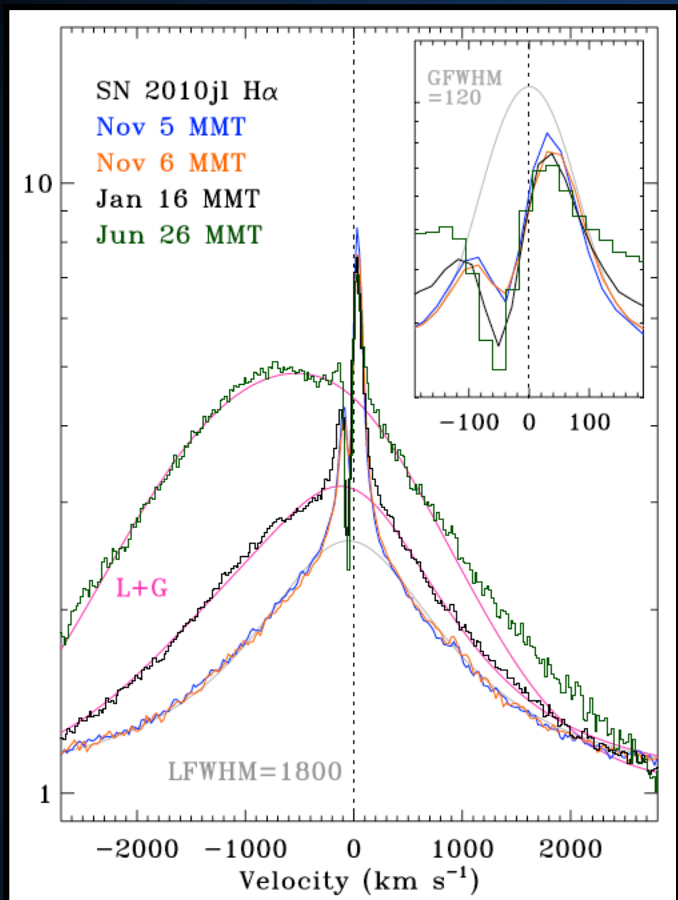
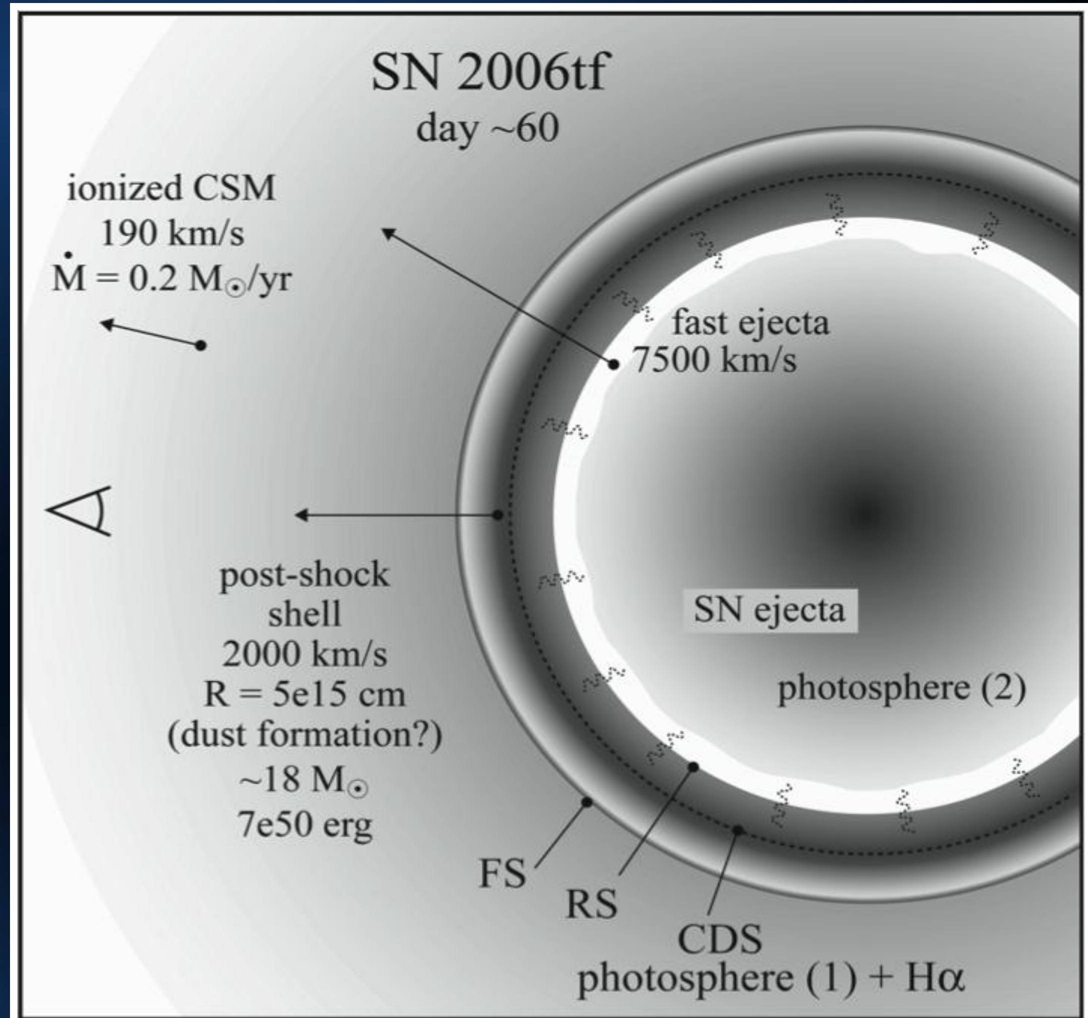


CSM Interaction





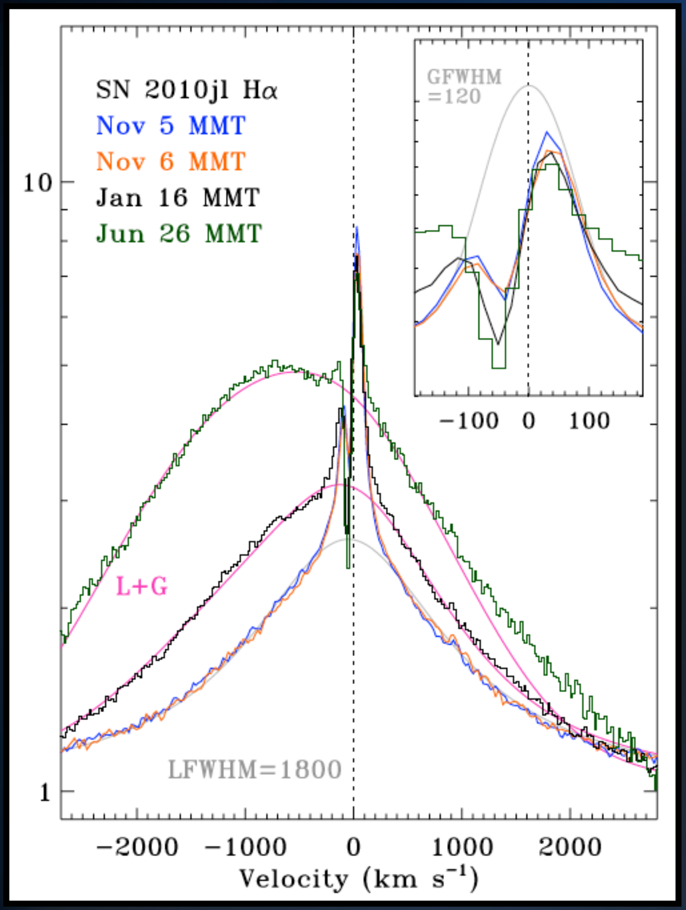
$$L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2} \dot{M} \frac{V_{SN}^3}{V_w}$$

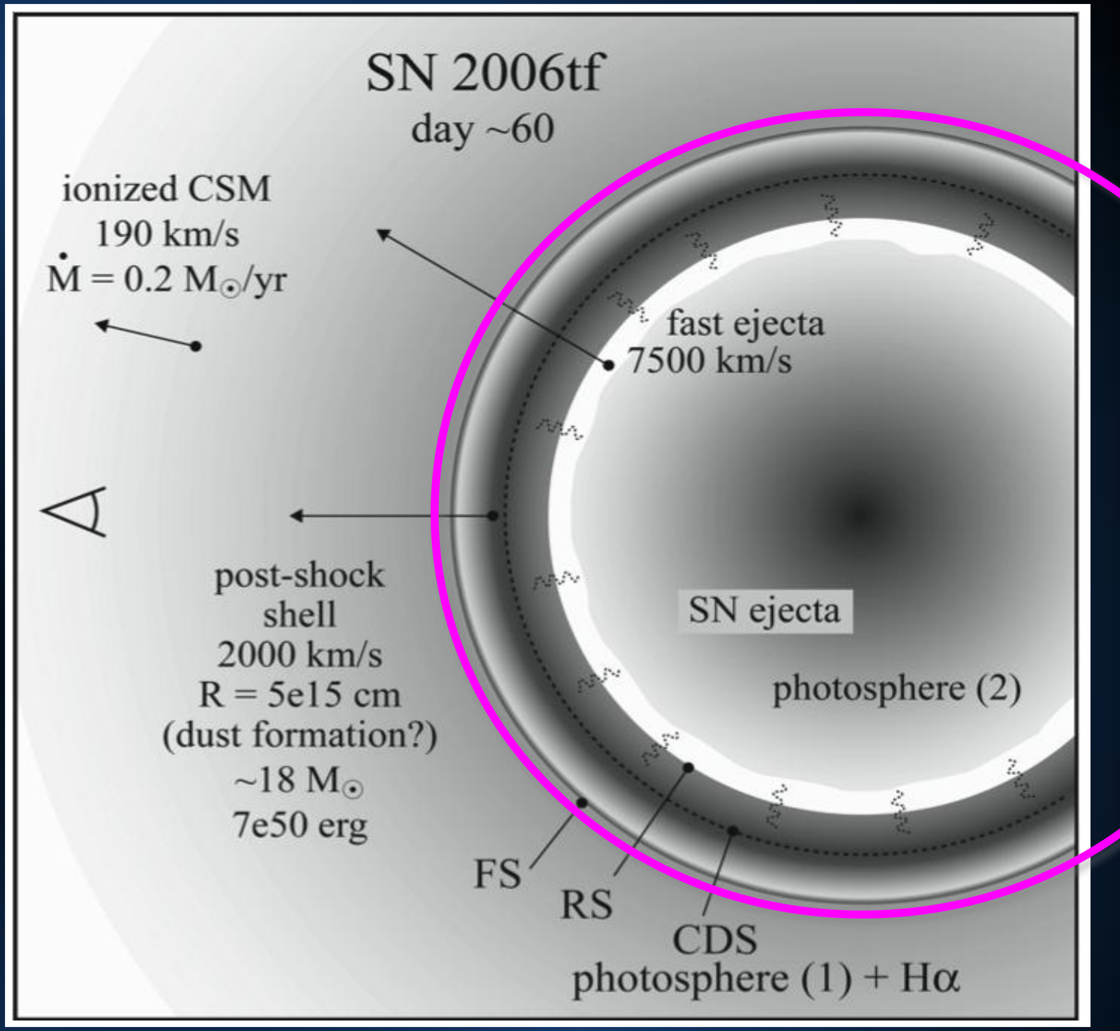
Efficient conversion of KE ⟹ Light

We can observe V_{SN}, V_w and L, and thus constrain CSM mass.

SLSN IIn require 10-30 $M_\odot$ of CSM ejected a few to 1000 yr before core collapse.

CSM Interaction



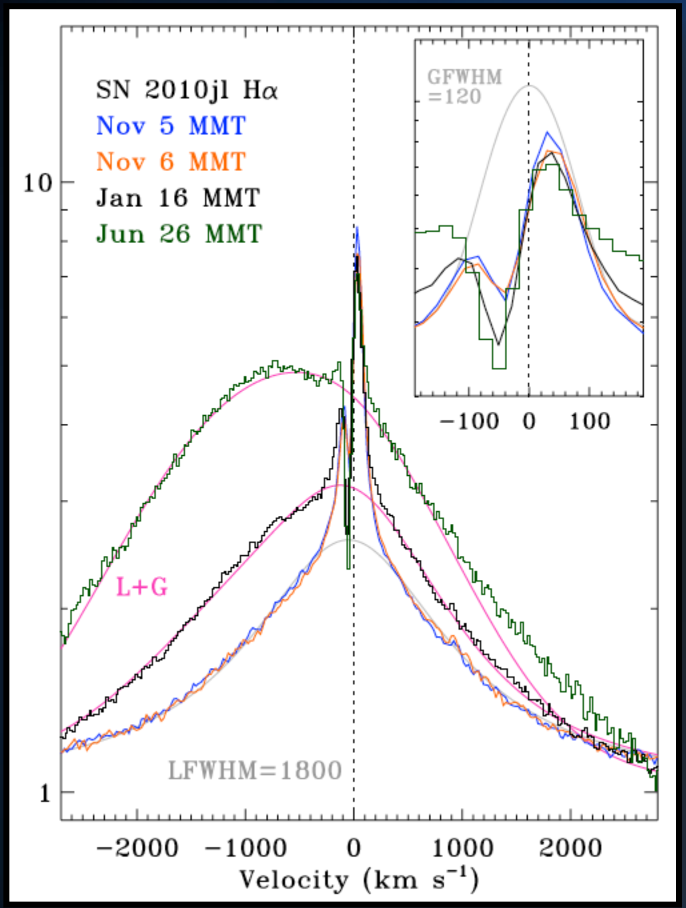


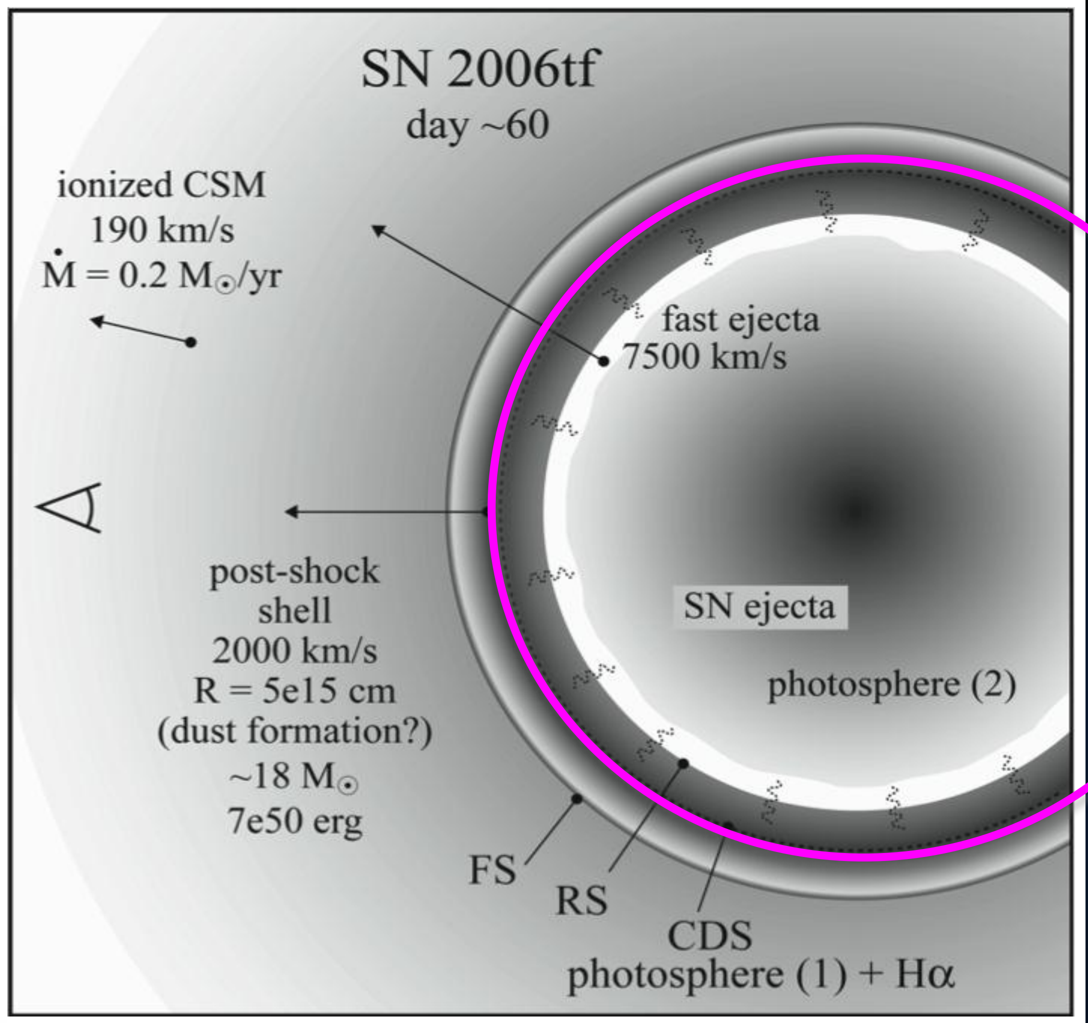
Where is the photosphere?

Early times = ahead of shock in dense CSM

Later = into CDS and beyond

CSM Interaction





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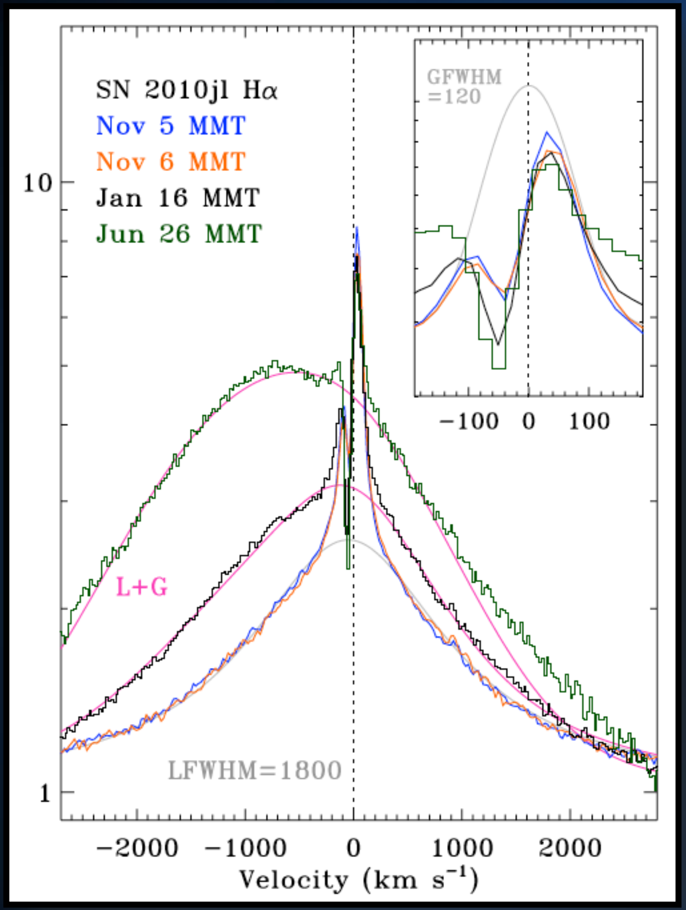

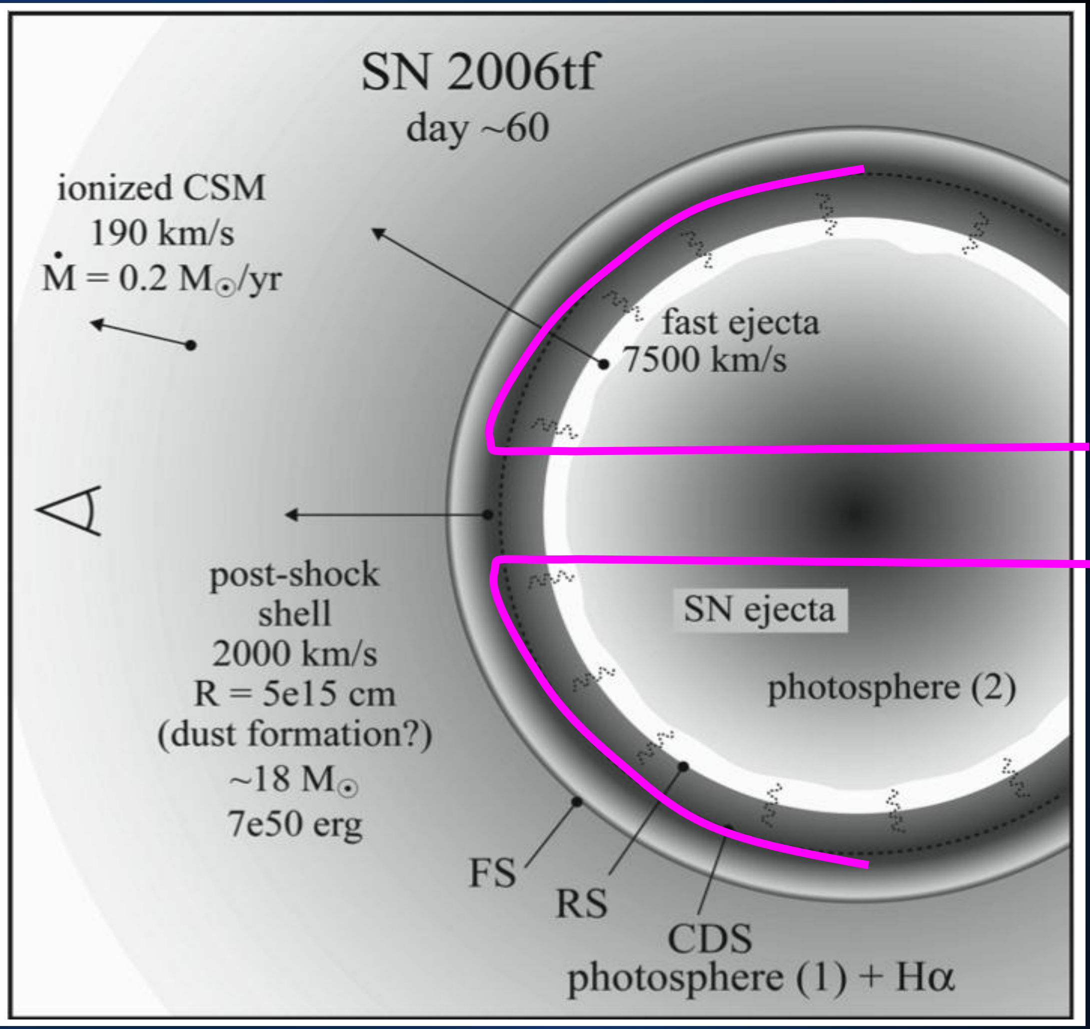

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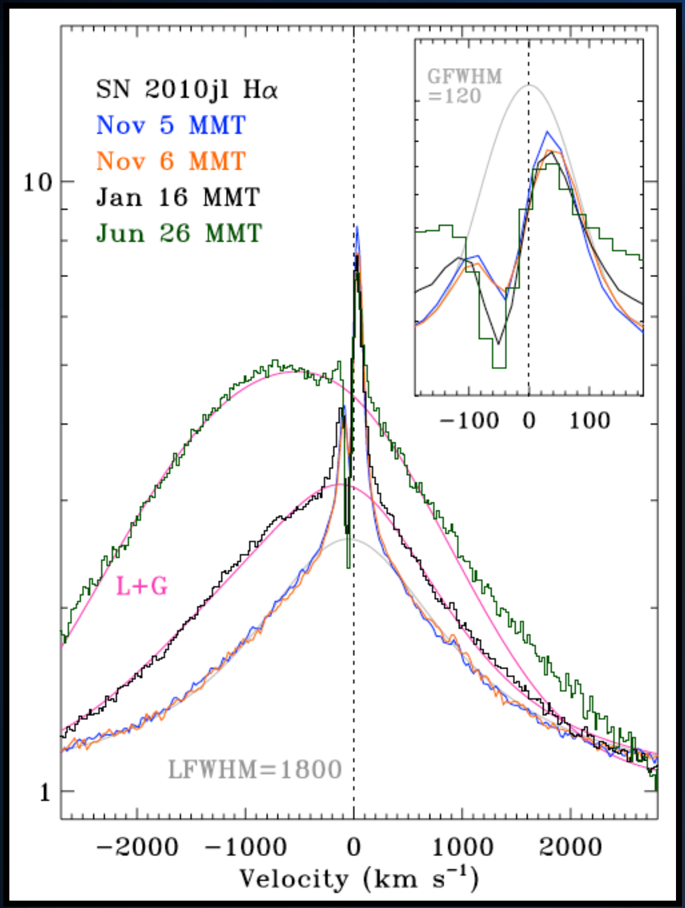

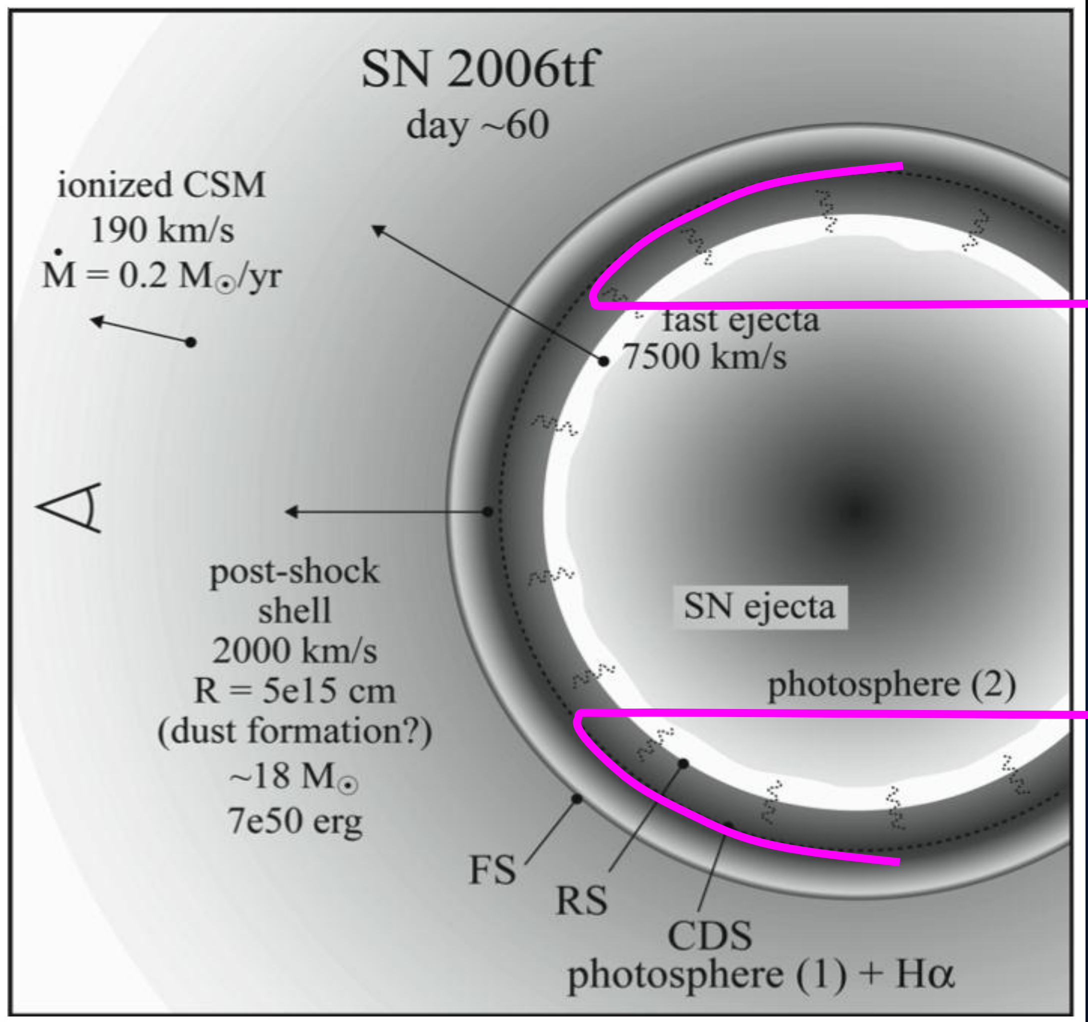

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CSM Interaction

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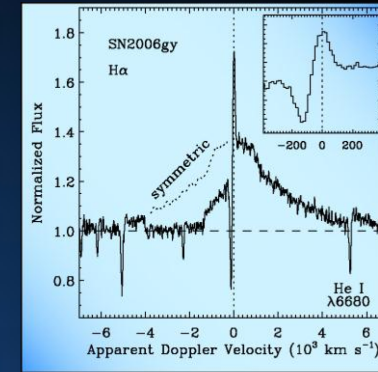
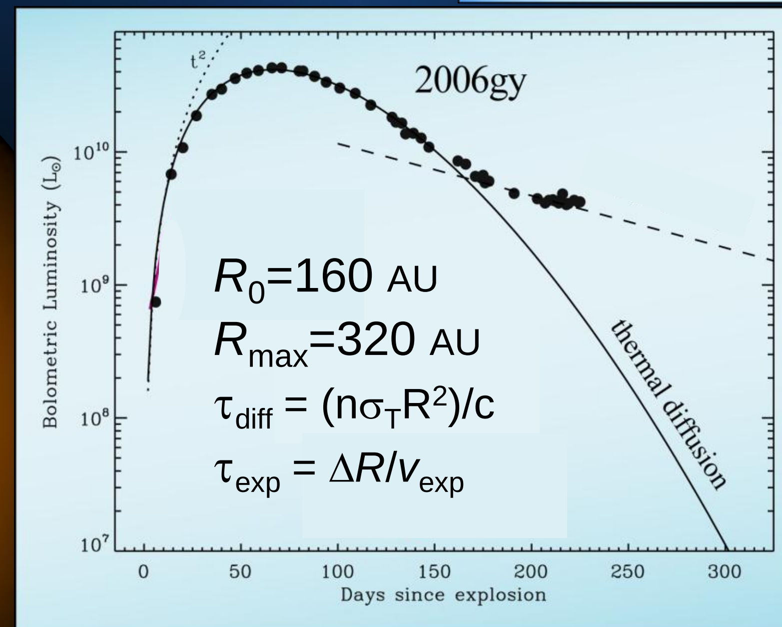


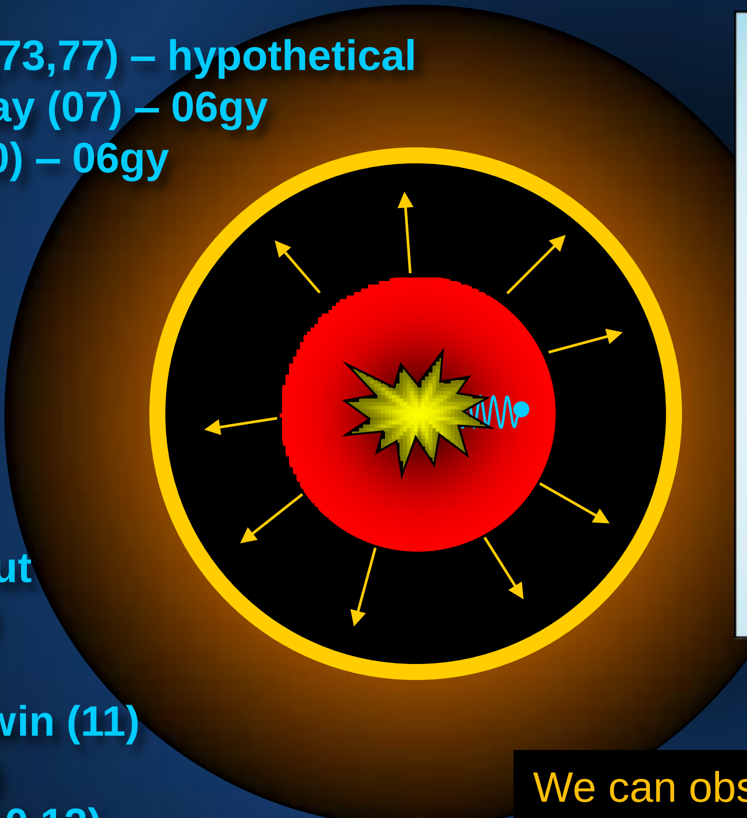
Subsequent CSM interaction at lower level ➔ Ha

DIFFUSION AT HIGH OPTICAL DEPTH

Weak H-alpha
X-rays thermalized

Falk & Arnett (73,77) – hypothetical
Smith & McCray (07) – 06gy
Smith et al. (10) – 06gy





$\tau_{diff} = \tau_{exp}$ **=70 days** (see Falk & Arnett 1973)

Shock Breakout
In Dense wind

Chevalier & Irwin (11)
Ofek et al. (10)
Moriya et al. (10,12)
Chatzopoulos et al. (12)
Ginzburg & Balberg (12)

We can observe V_{SN} , V_w and L, and thus constrain CSM mass.

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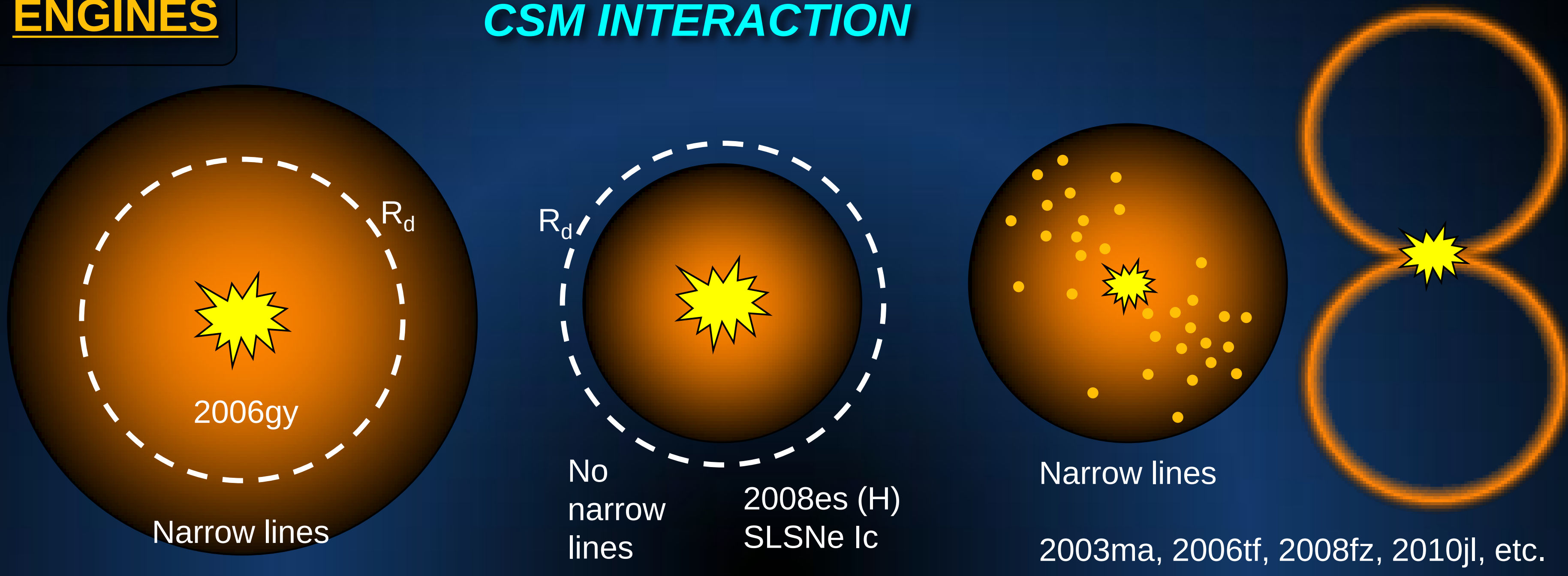
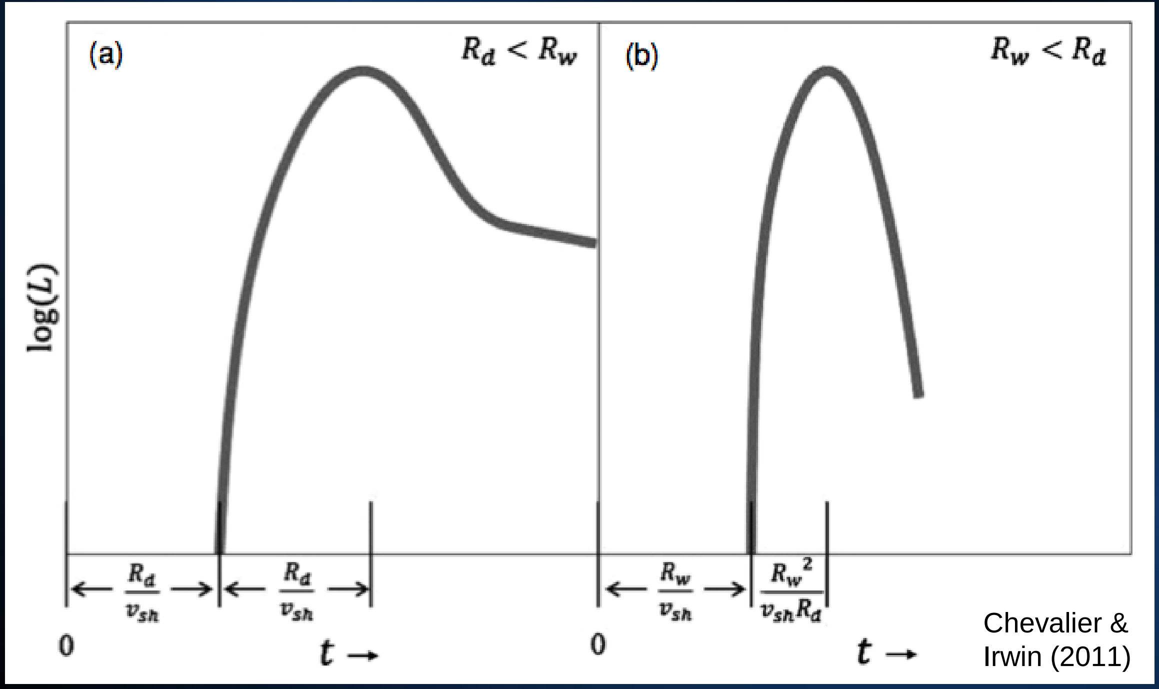
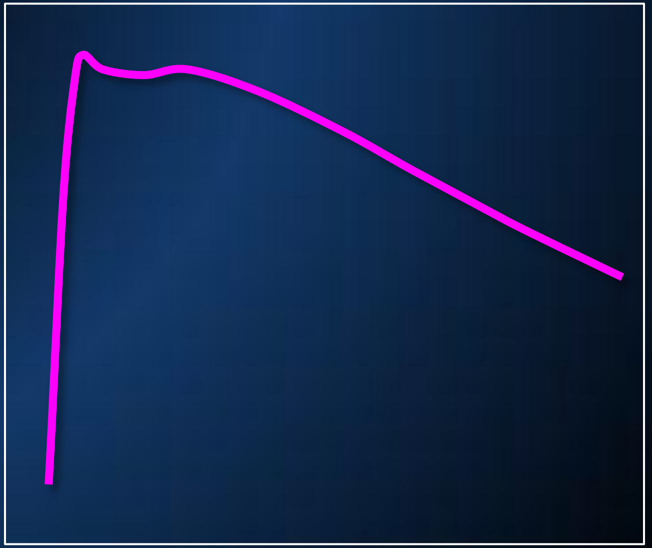
Efficient conversion of KE ➔ Light

ENGINES

CSM INTERACTION







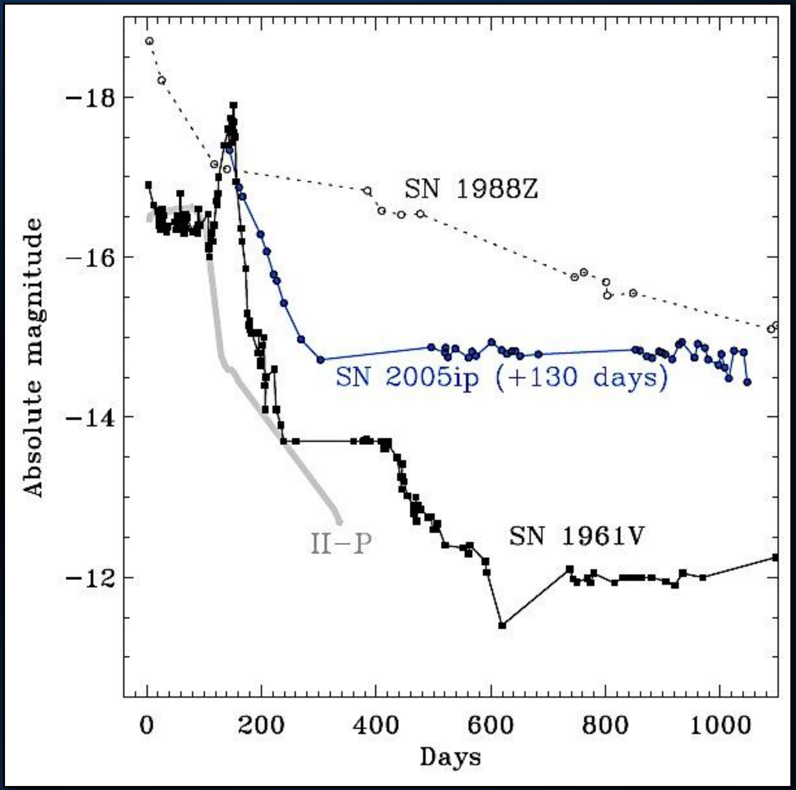
ENGINES

CSM INTERACTION

How extended is the CSM? How long before the SN was the star “active”?

Some SNe IIn are very long lived. SN 1988Z, 2003ma, SN 2005ip, etc.

- See talk this afternoon by Ori Fox
- Smith et al. (2009) – discussed possible RSG progenitors. Normal RSGs like Betelgeuse don’t cut the mustard. Must be extreme things like VY CMa.
- Mauerhan & Smith (2012). SN 1998S is still going strong. Consistent with 1000yr extreme RSG wind.
- Ask Yoon & Cantiello about it.



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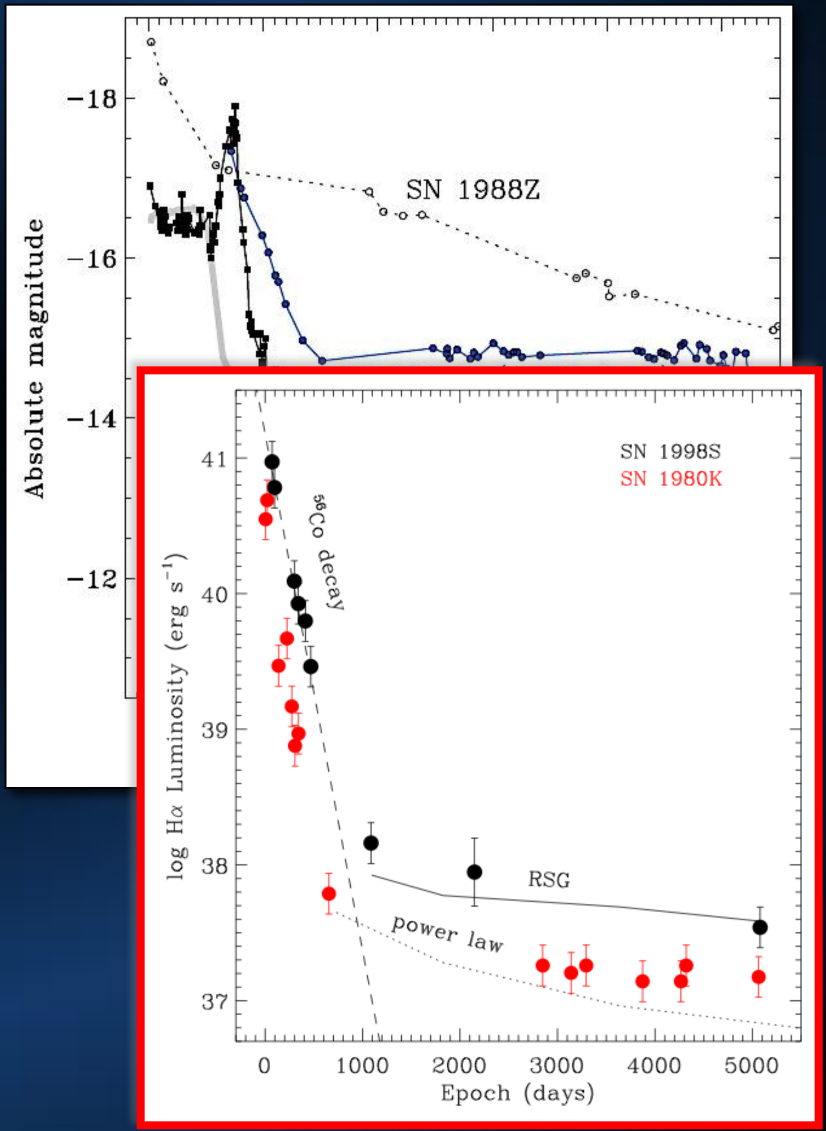


SUMMARY/QUESTIONS

- Diversity of SNe IIn can be understood with range of CSM mass and geometry.

Bright ones need 10-30 $M_\odot$ in few years, decades, or centuries before core collapse. Must have sudden LBV-like precursor eruptions.

Fainter SNe IIn can be extreme RSG winds for ~1000 yr before core-collapse.

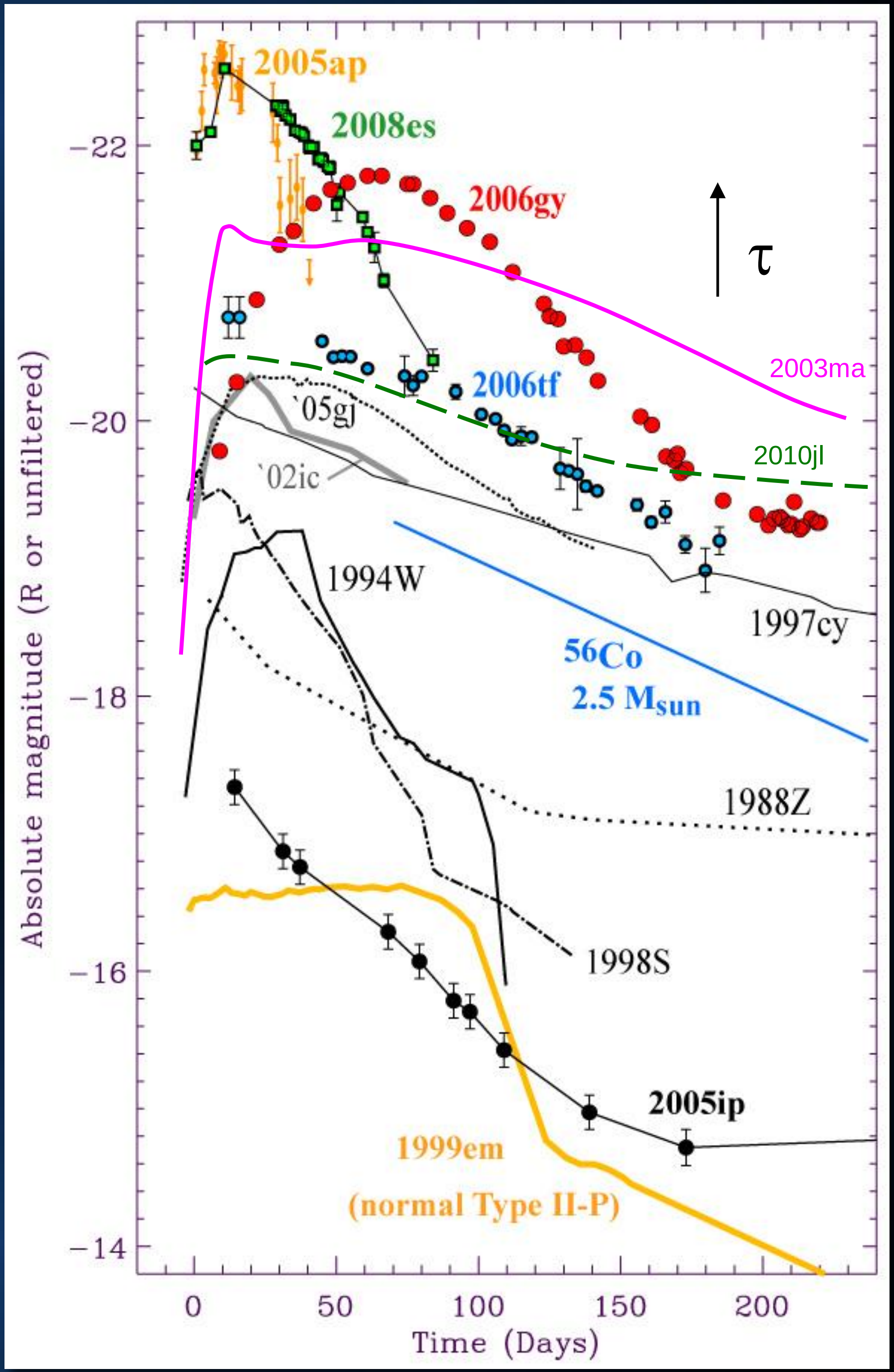
- Seems like M > 30 $M_\odot$ do indeed explode.

- What the hell is making these stars explode before they explode?

  Need mechanism working over few years, decades, centuries, or even 1000 yr.

- Are they all core collapse?

- What are the progenitor stars (really)?



PROGENITORS

SN 1961V

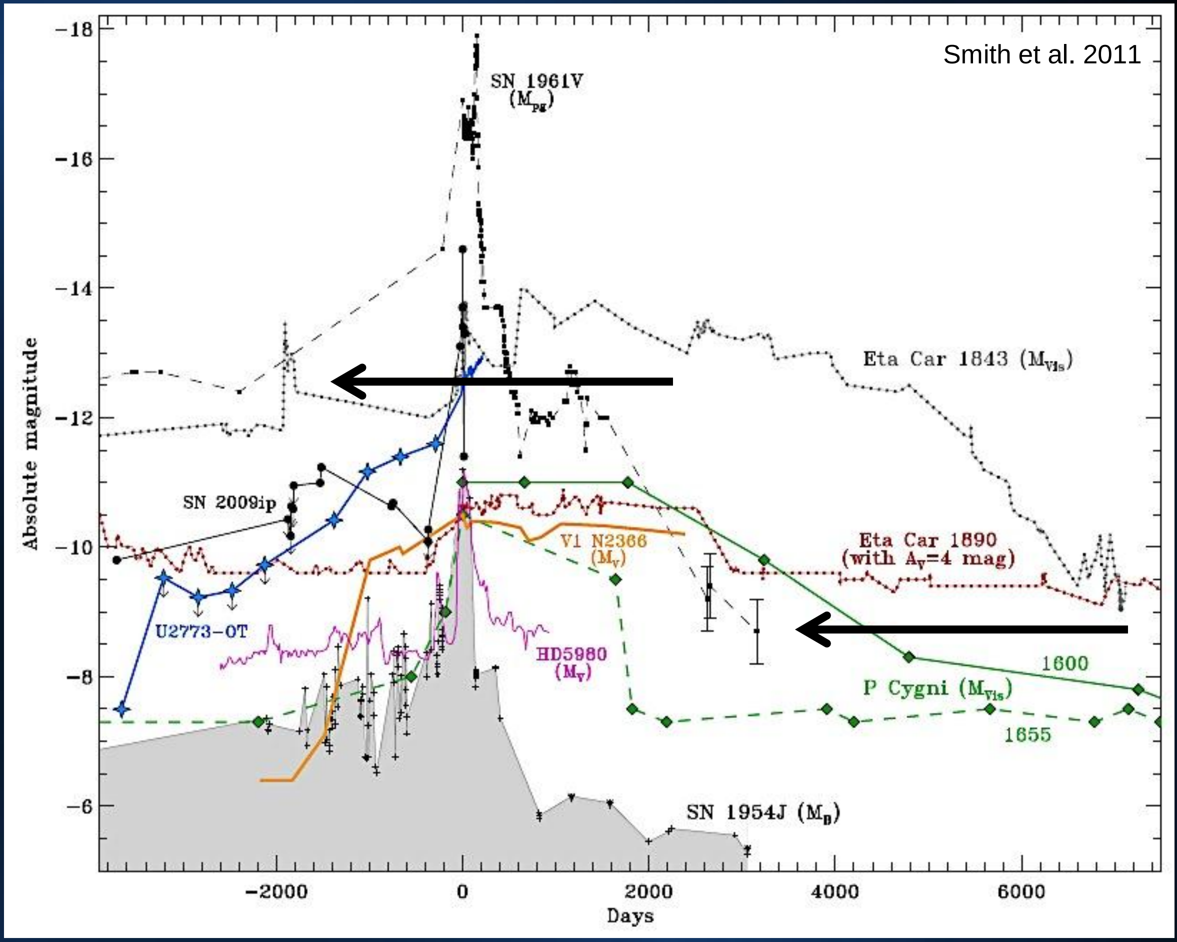
SN 1961V was probably a real core-collapse Type IIn.

Peak L was 40x brighter than Eta Car's eruption, and brighter than any other SN impostor, but in-line with other SNe IIn (Smith et al. 2011).

V band: by 1970 it was 4 mag fainter than progenitor. Today it is at least 5.5 mag fainter.

Spitzer upper limits to any present-day IR source suggest that the LBV star did not survive (Kochanek et al. 2011)

See however, Van Dyk & Matheson 2011.



If SN 1961V was a core collapse, then we have:

- a clear detection of the very massive (~100 $M_\odot$) LBV progenitor
- detection of a pre-SN eruption, and
- subsequent disappearance of the luminous source.

Present-day H-alpha source might be ongoing CSM interaction

Faded by 4 mag by +10 yrs

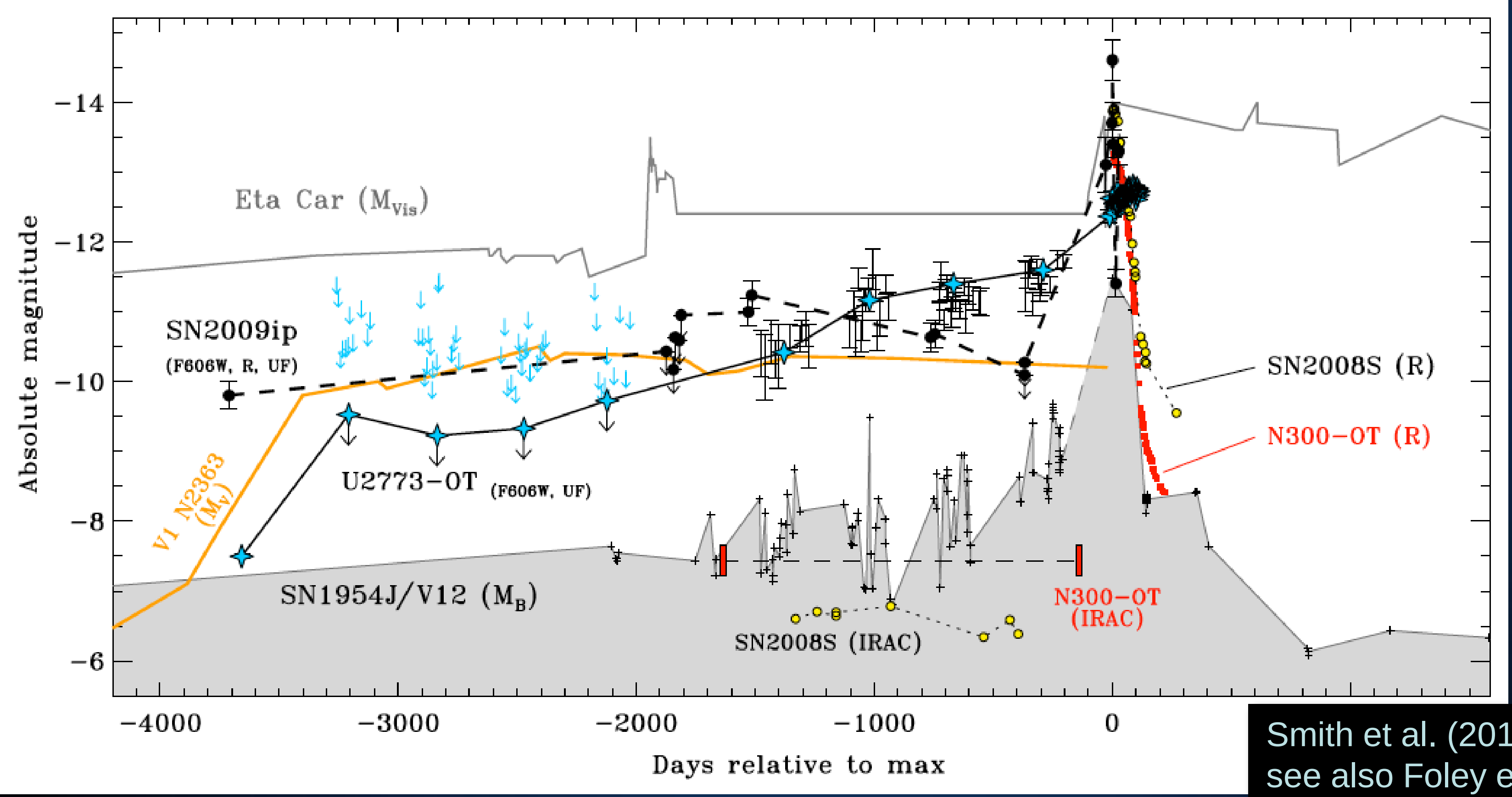
Now 5.5 mag fainter than progenitor

PROGENITORS

SN 2009ip

Luminous, [blue], variable progenitor star (S Dor-like eruption and brief blue eruptions lasting a few weeks)

Quiescent HST progenitor implies M_{ZAMS} = 50-80 $M_{\odot}$

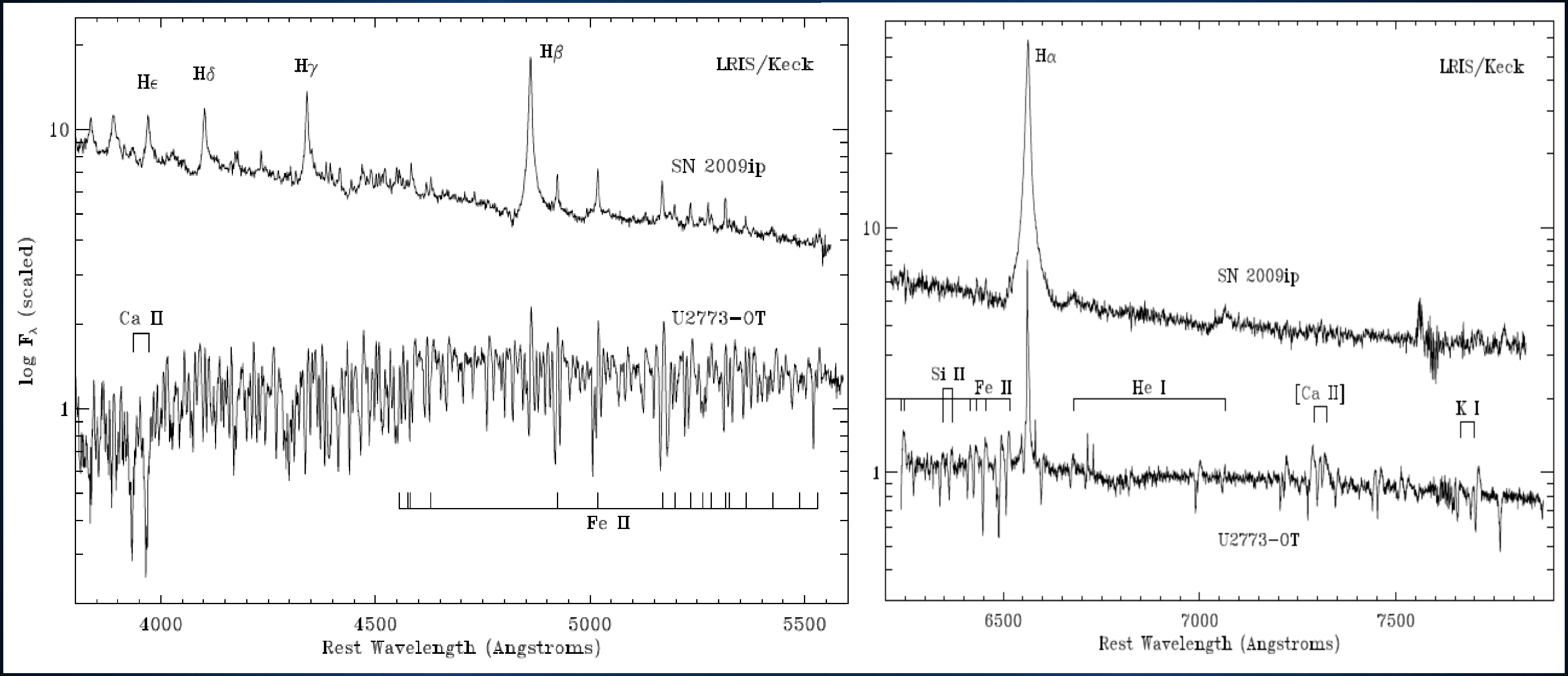


Smith et al. (2010)
see also Foley et al. (2011)

SN 2009ip

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

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



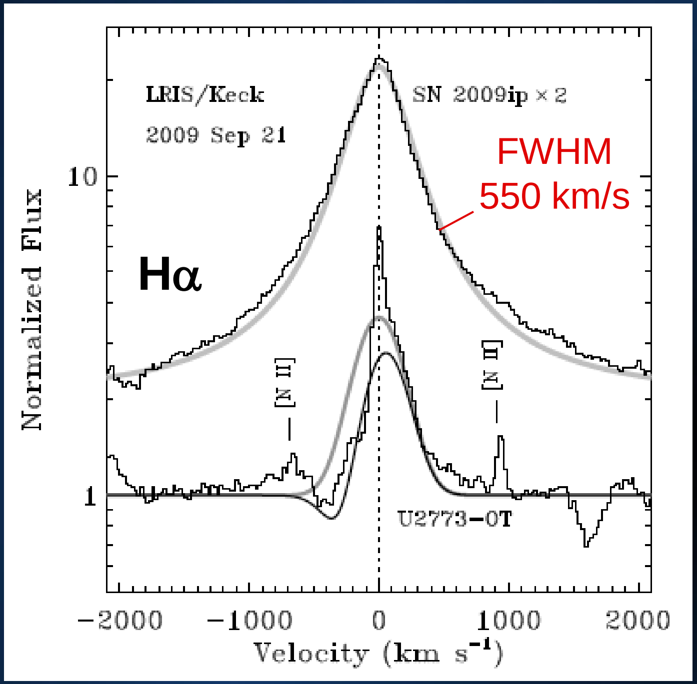
SN2009ip: looks like "Hot" LBV, Lorentzian profiles, weak P Cyg abs., weak He I lines
UGC 2773-OT: looks like "Cool" LBV, F-type supergiant, narrow absorption

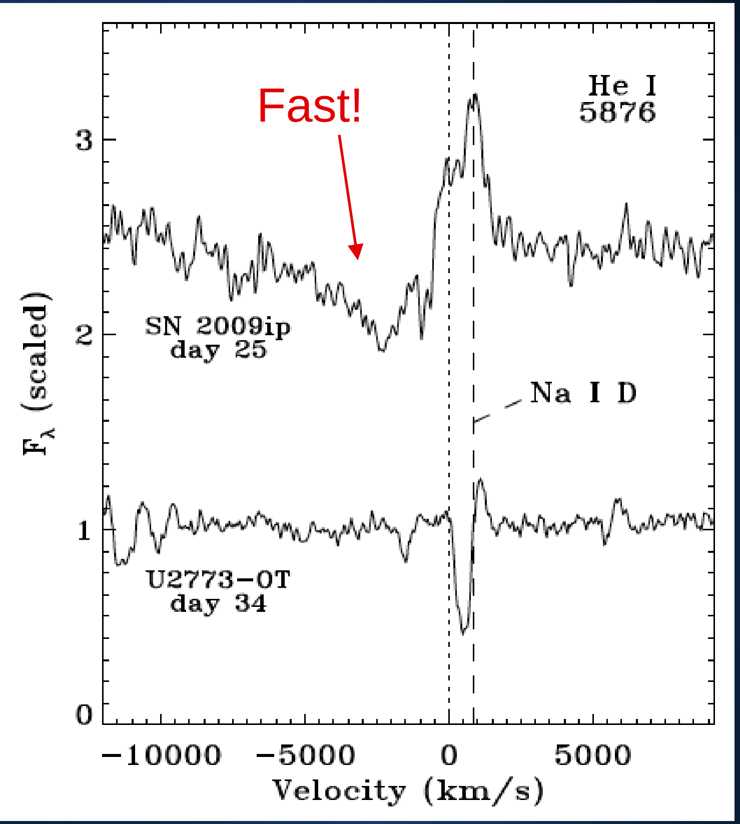
Reminiscent of spectra of LBVs in hot/cool states (but not exactly the same).

SN 2009ip

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

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





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

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

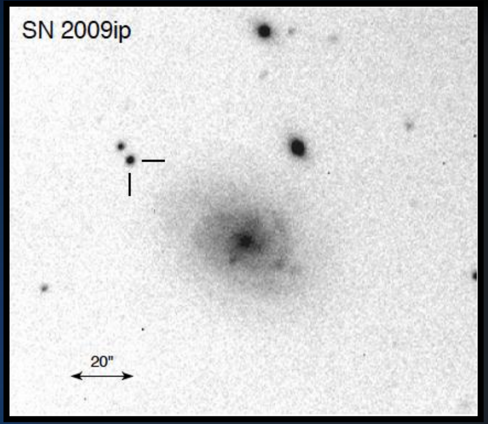
SN2009ip also shows evidence for some fast outflow speeds of 3,000-5,000 km/s like Eta Car (Smith 2008).

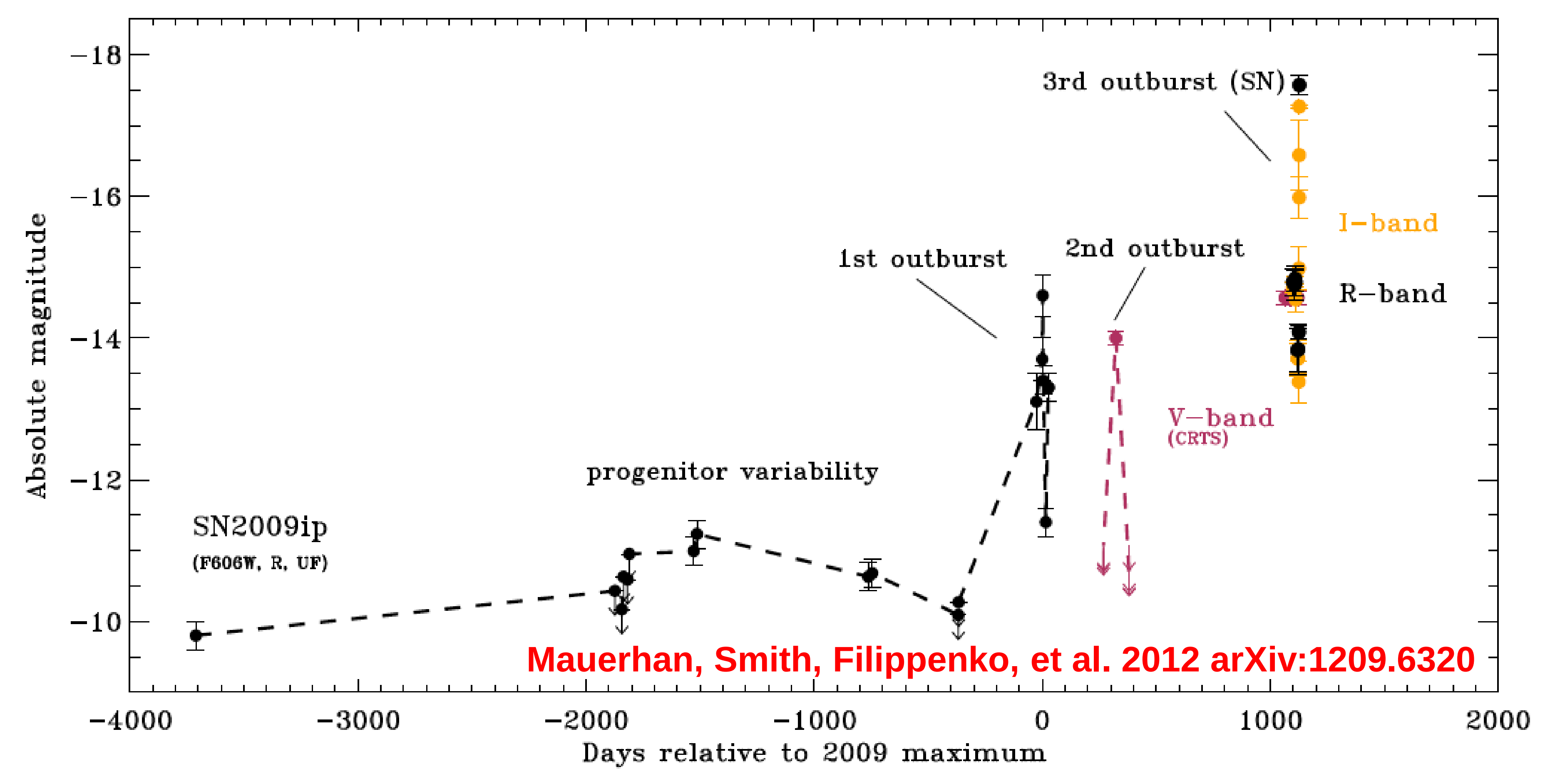
Very fast ejecta/shock wave…
Does CSM interaction make it hot?

SN 2009ip

its 2012 demise

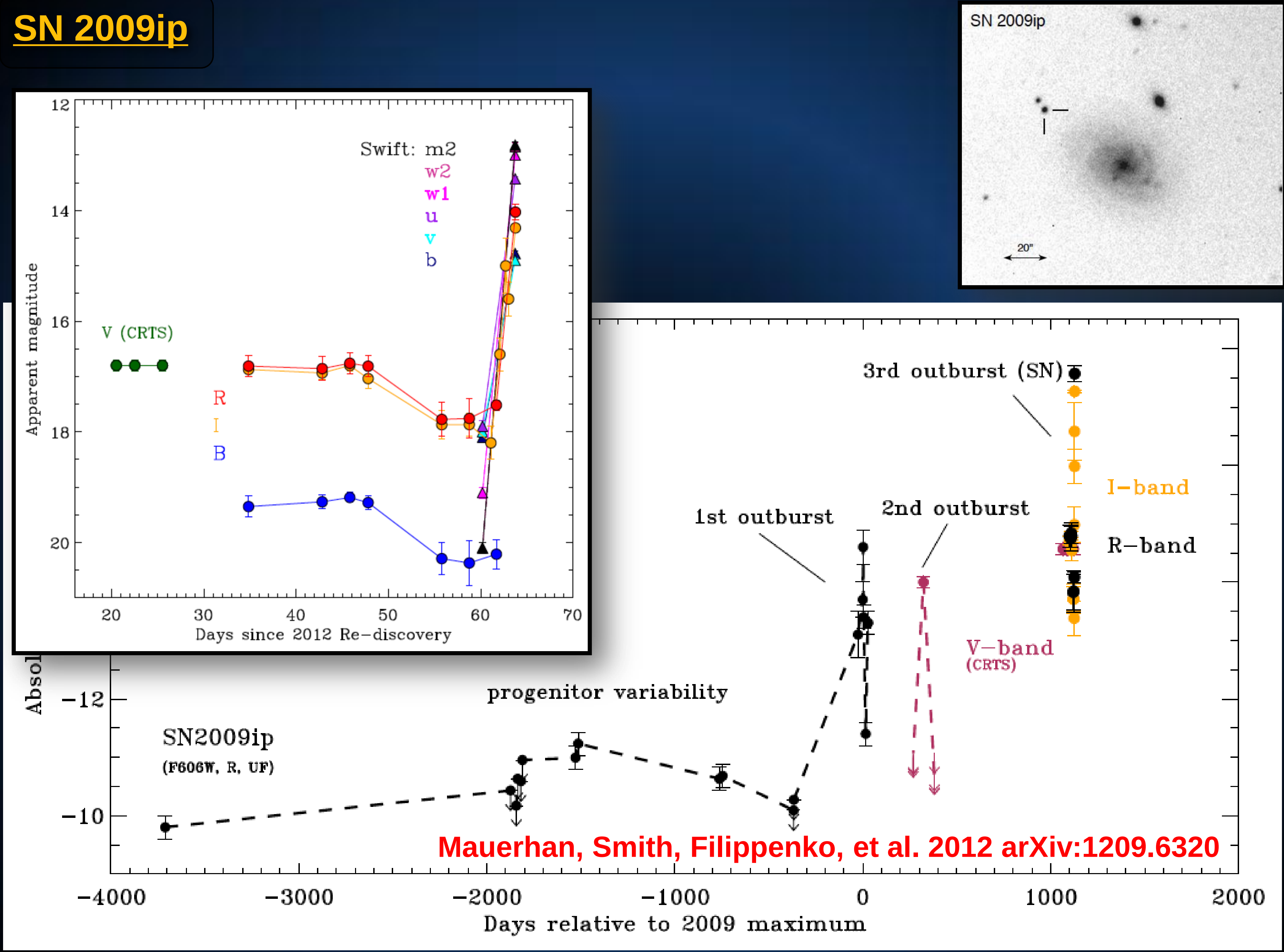
- First discovered In Aug 2009 (Maza et al. CBET 1928)
- Re-brightened in July 2010 (Drake et al. 2010, Atel 2897)
- Re-brightened in July 2012 (Drake et al. 2012, Atel 4334)





Mauerhan, Smith, Filippenko, et al. 2012 arXiv:1209.6320

SN 2009ip



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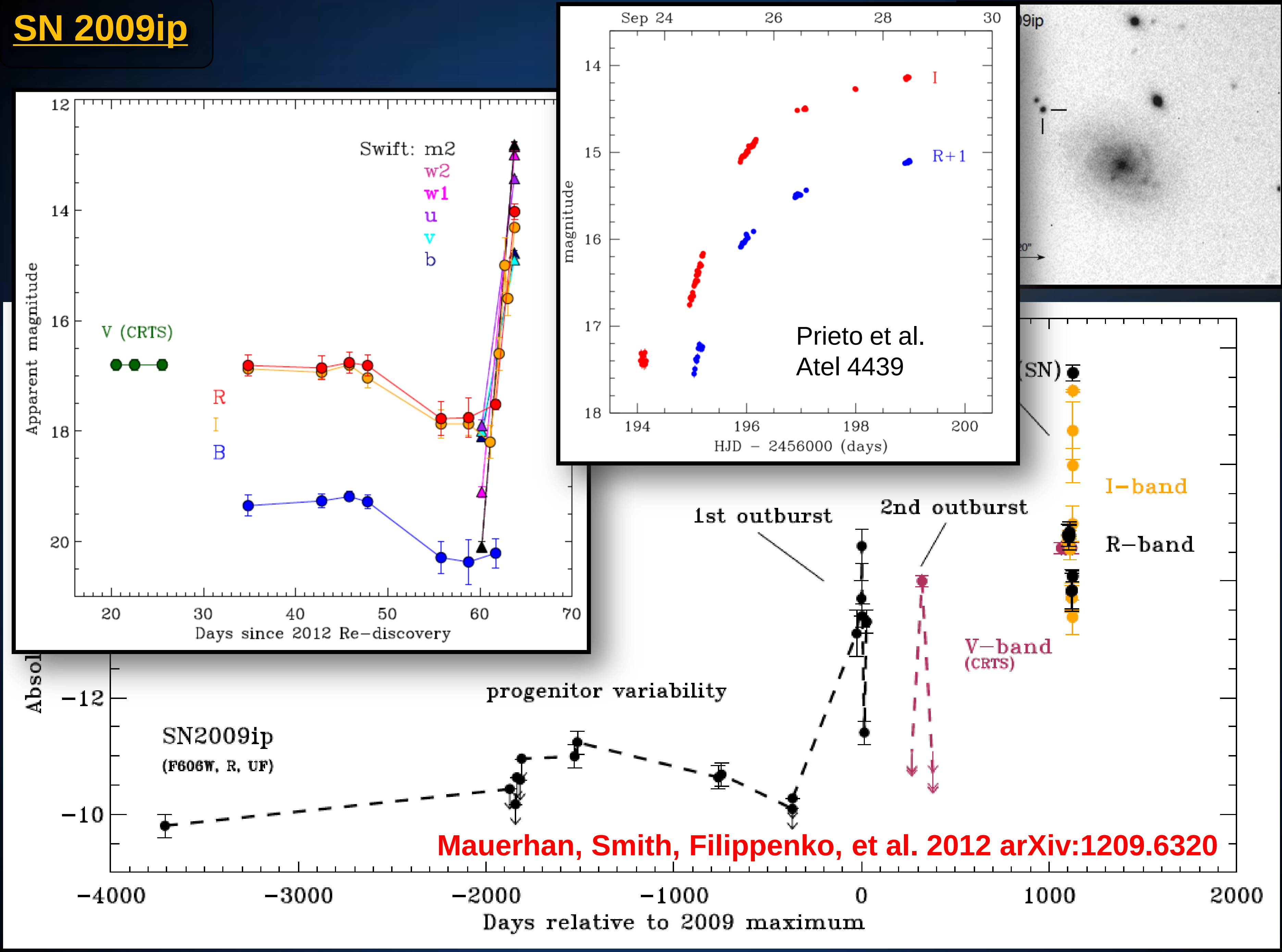

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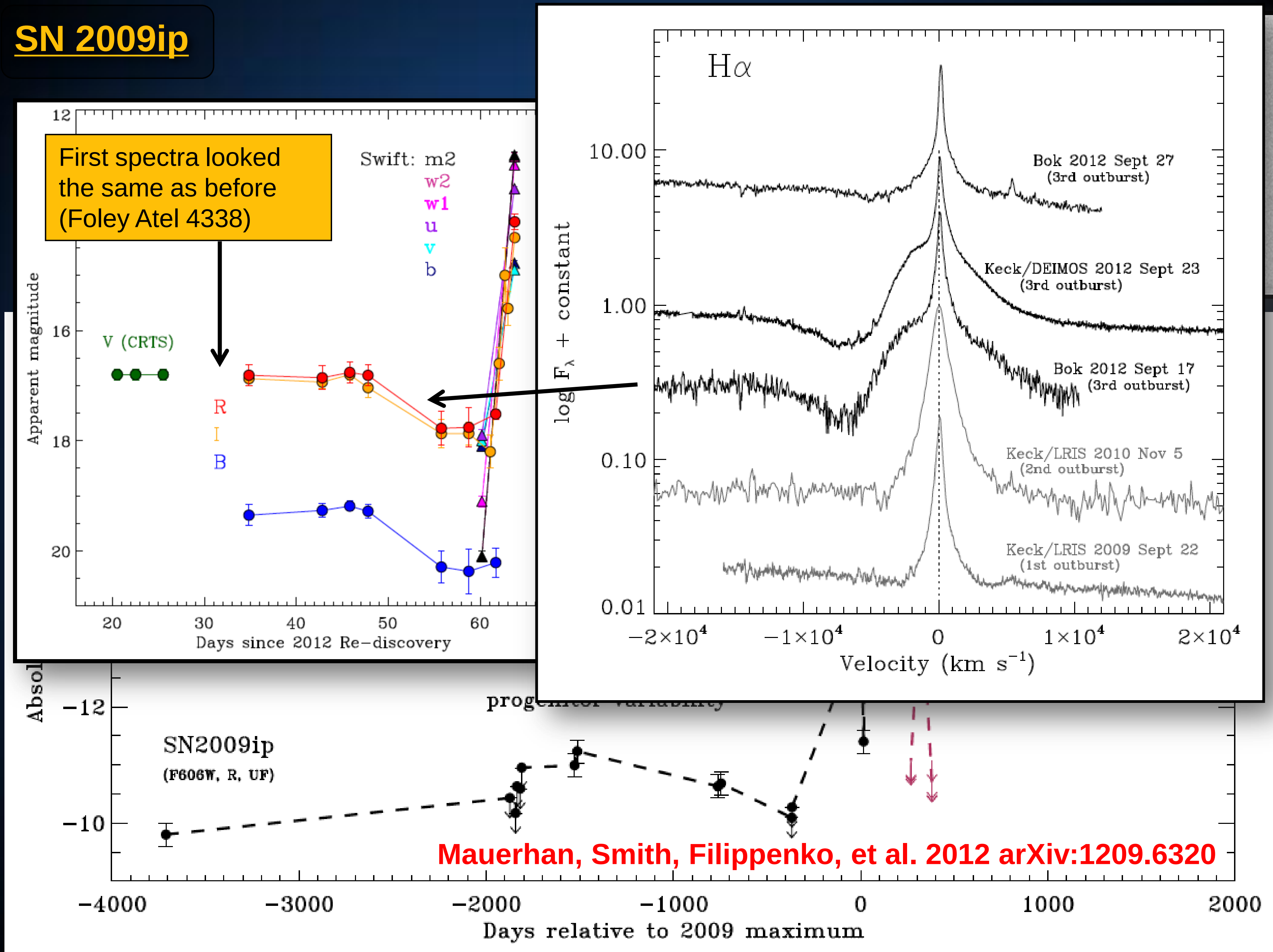

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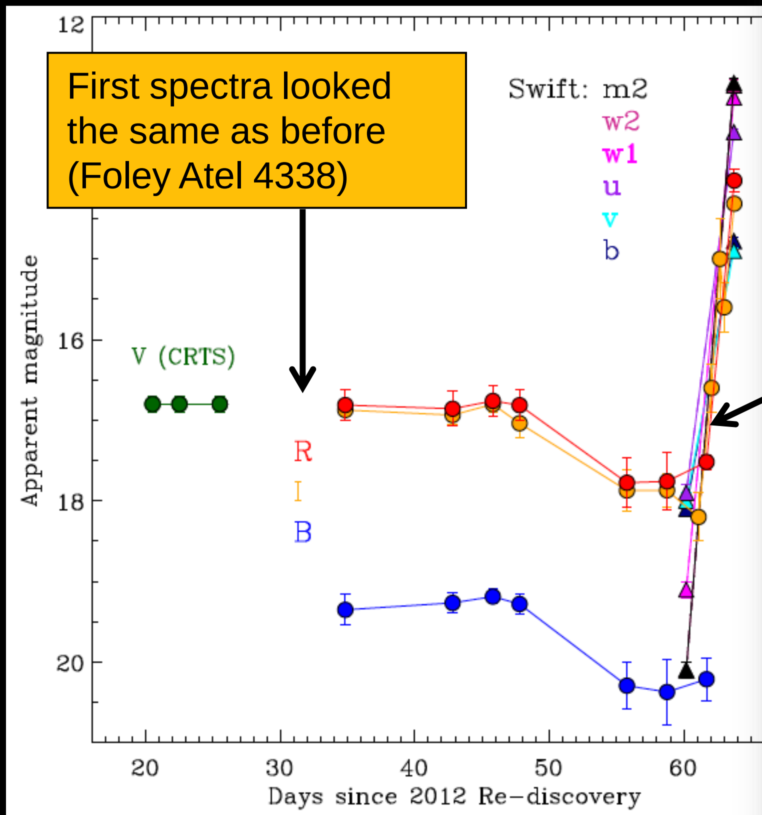

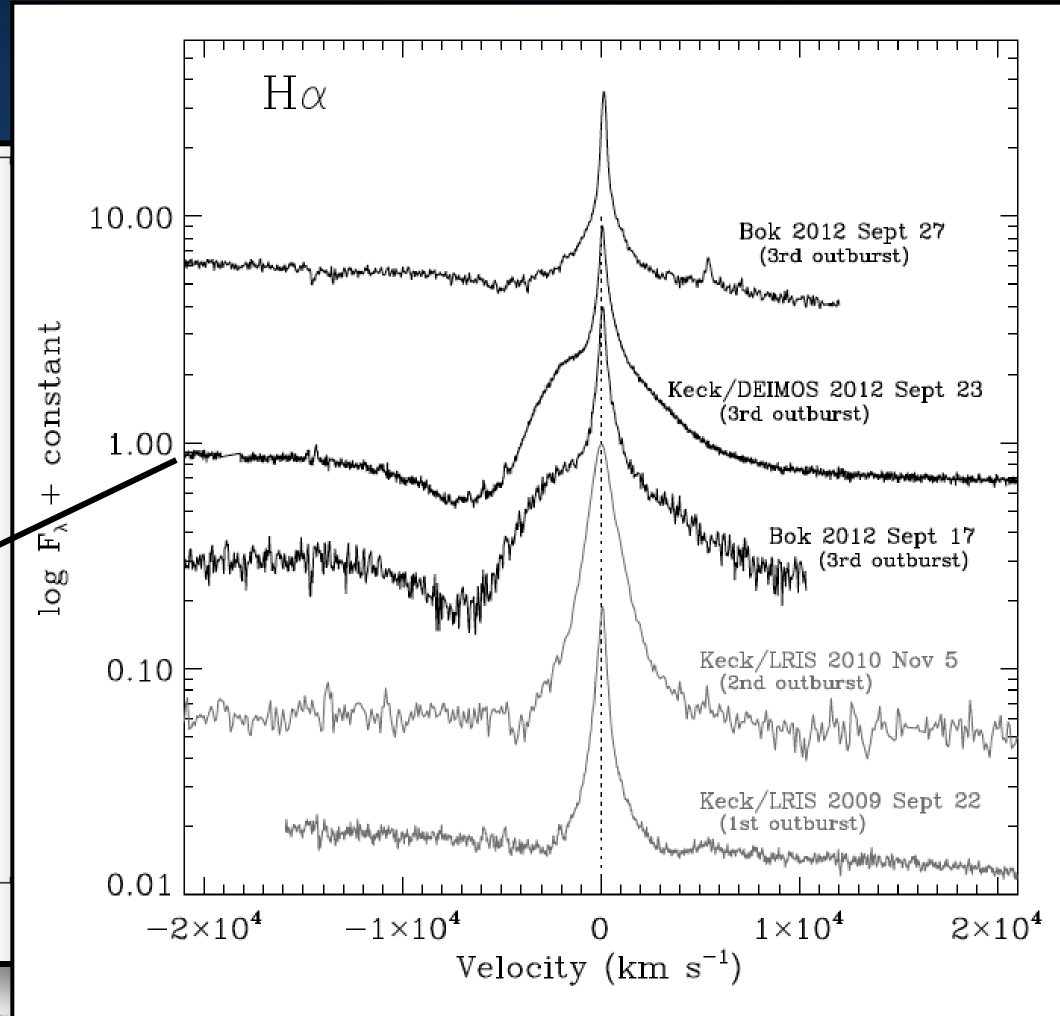

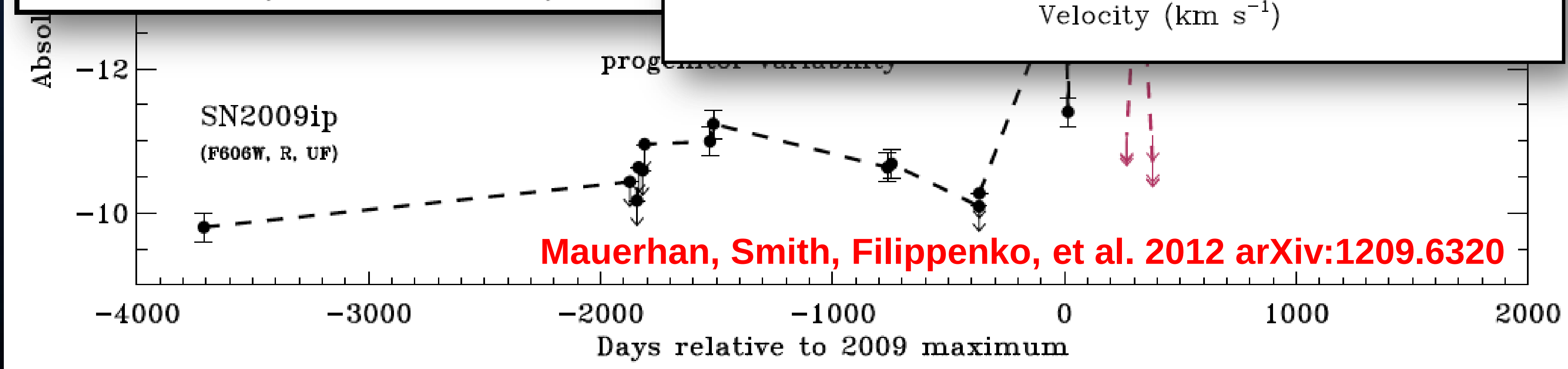

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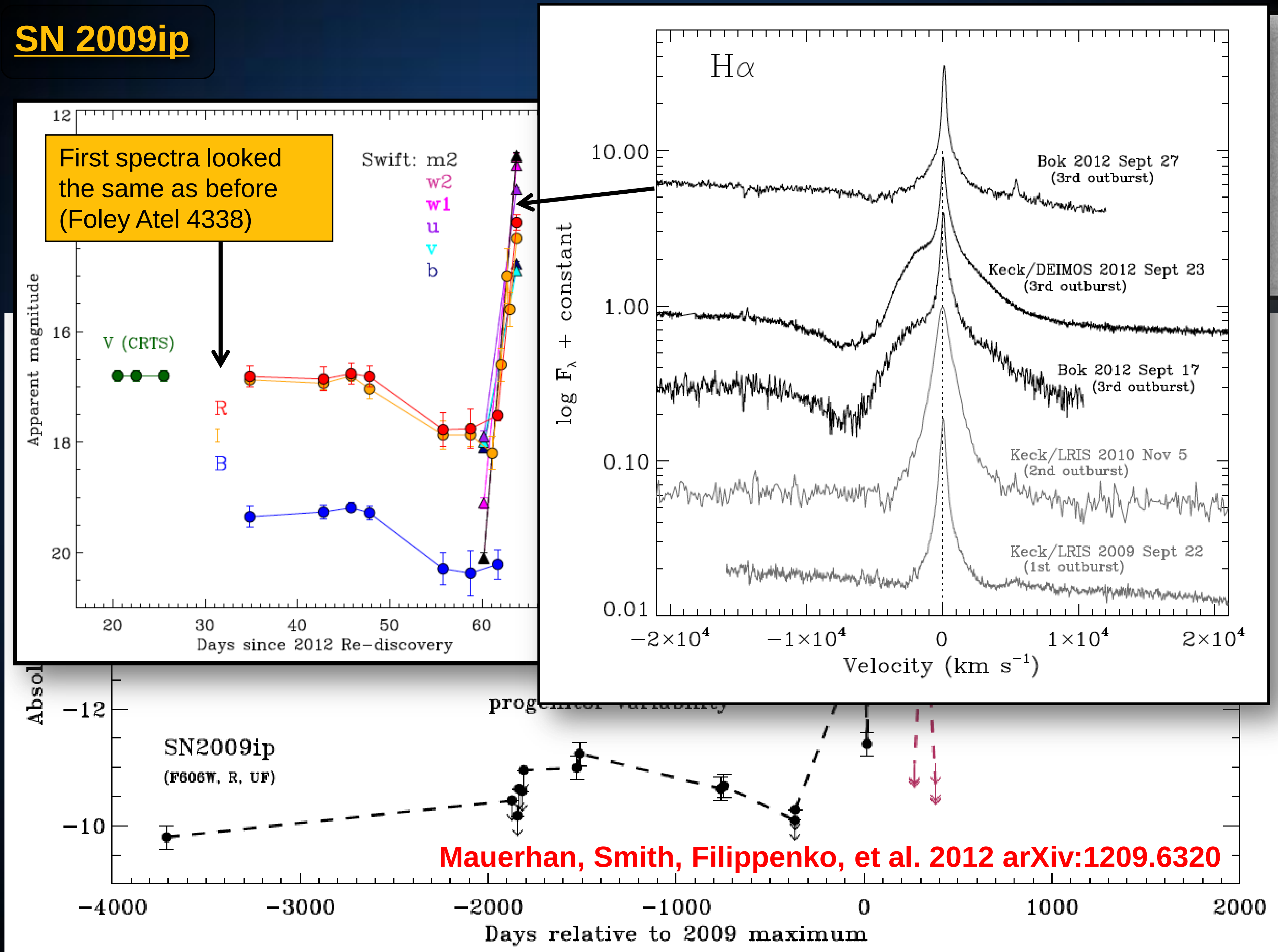

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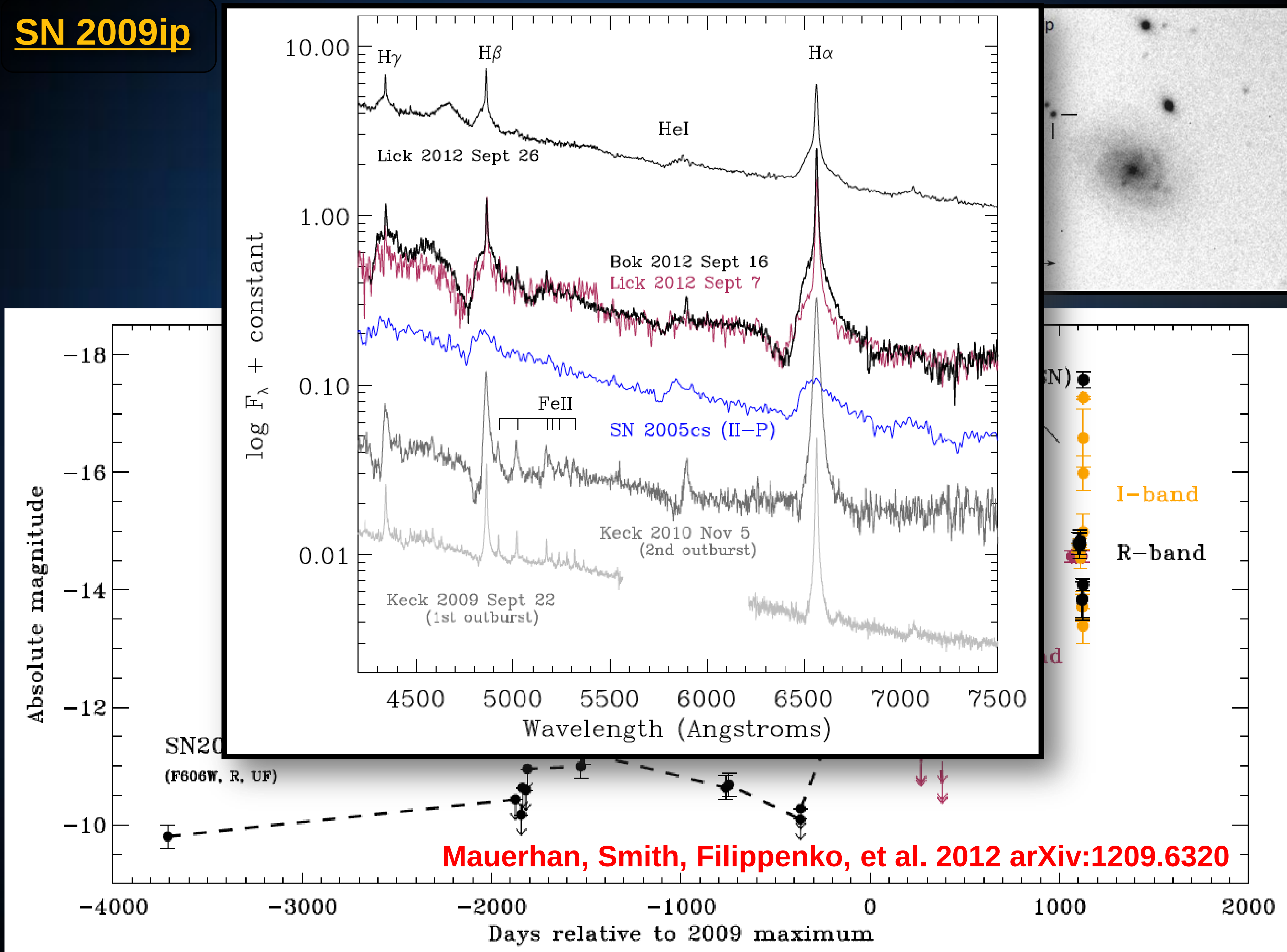

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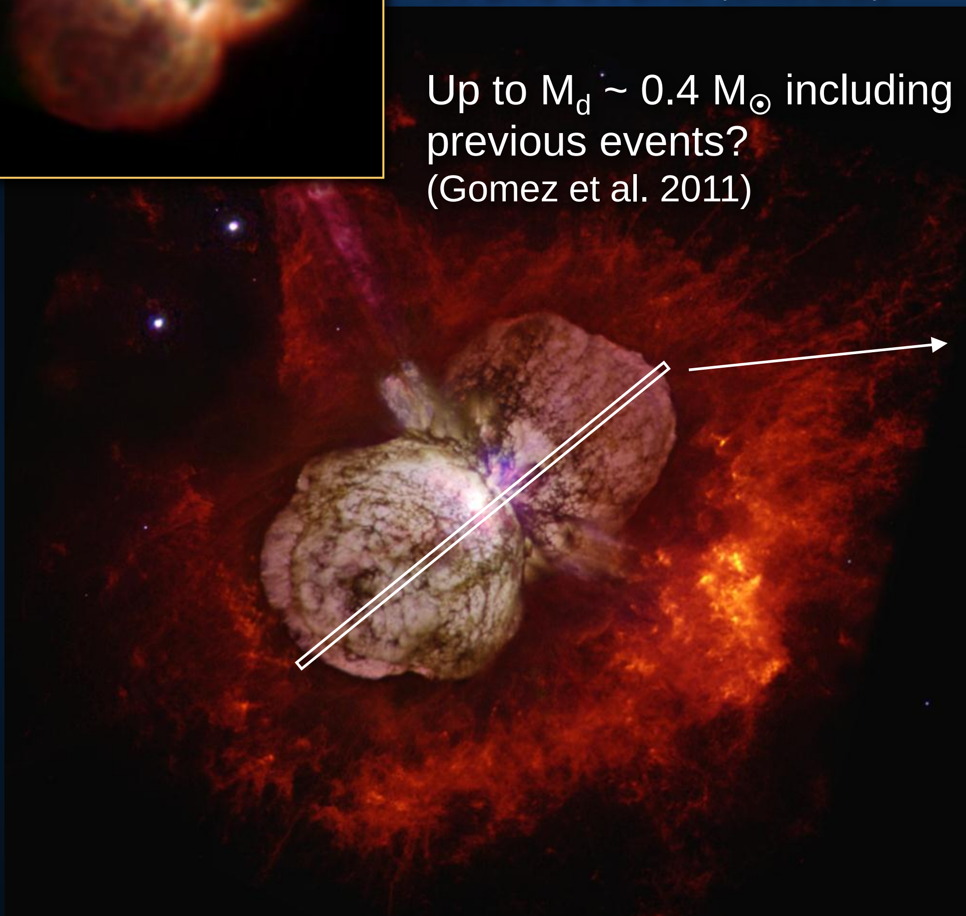
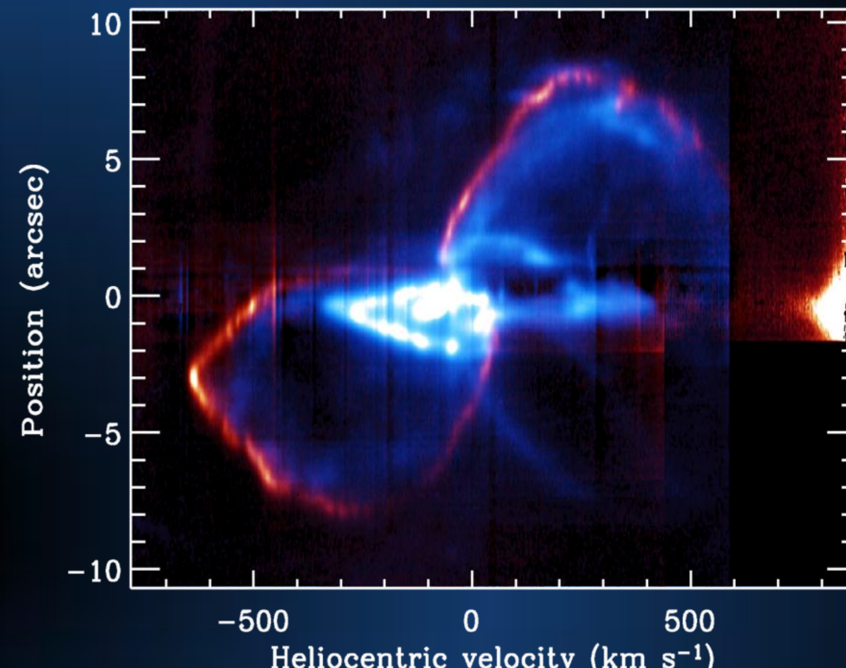
DUST MASS

$M_d \sim 0.1\text{-}0.15\ M_\odot$
in one event! (Smith et al.)



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

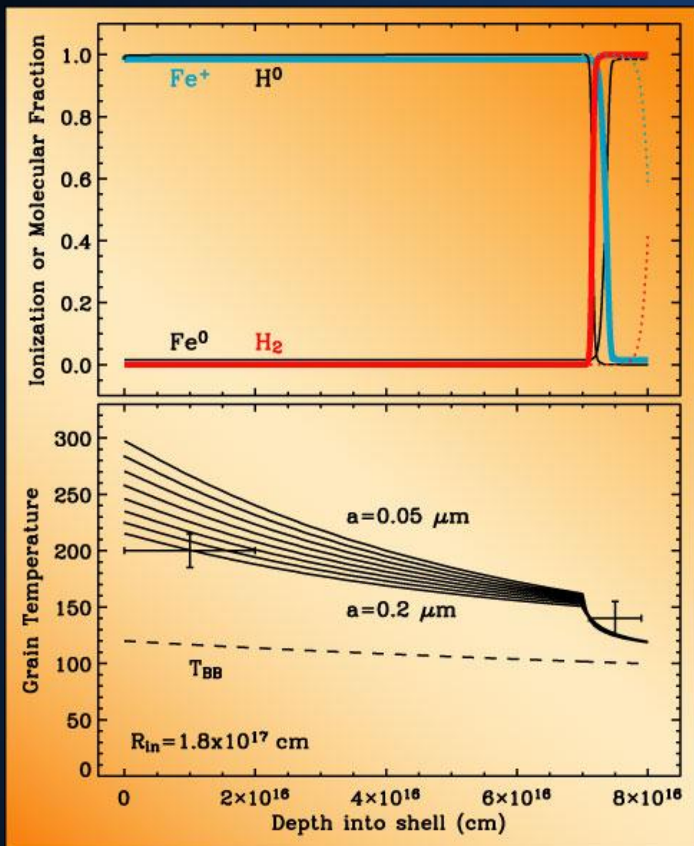
Eta Carinae’s
1843 eruption:

Ejected mass = $\sim 15\ M_\odot$
KE = 10^{50} erg
$E_{rad} = 10^{49.5}$ erg

← $KE/E_{rad} \approx 3$

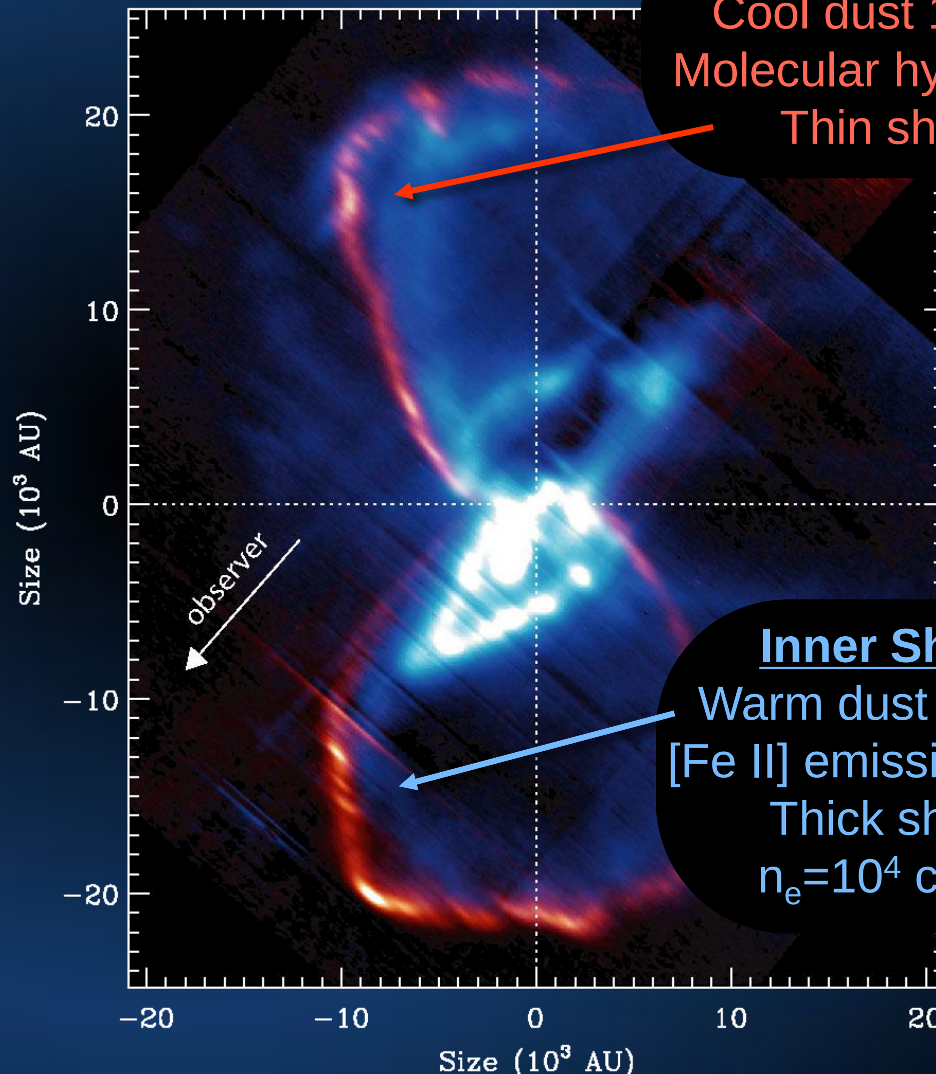
Wind or Explosion?

Massive Dusty Molecular Shell



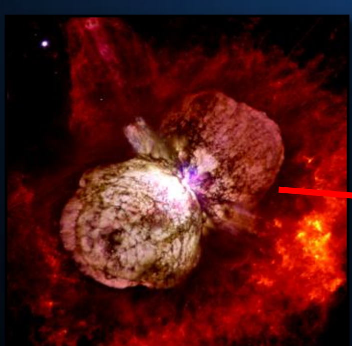
CLOUDY models: survival of H_2 requires a density of $n_H = 10^{6.7\text{-}7}$ cm^{-3} in the outer shell, implying a total gas mass of 17-35 $M_{\odot}$.

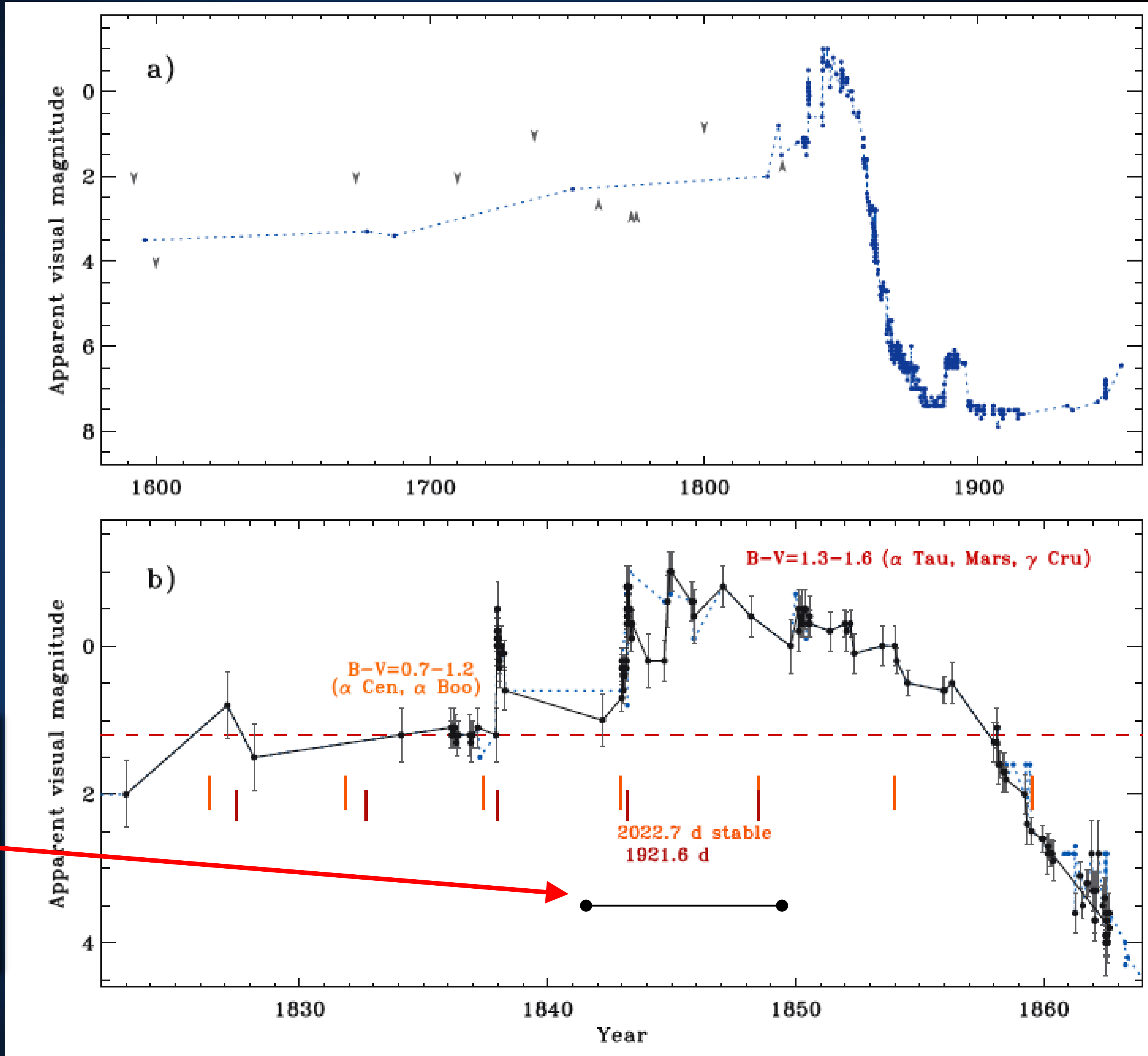
Smith & Ferland (2007, ApJ, 655, 911)



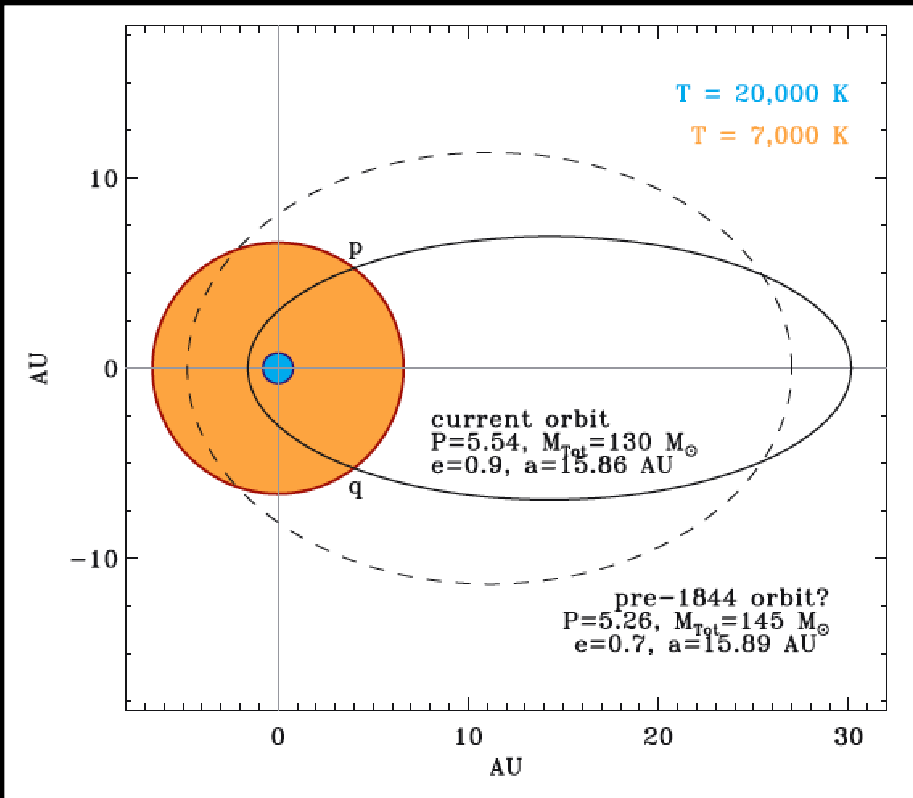
Outer shell
Cool dust 140 K
Molecular hydrogen
Thin shell

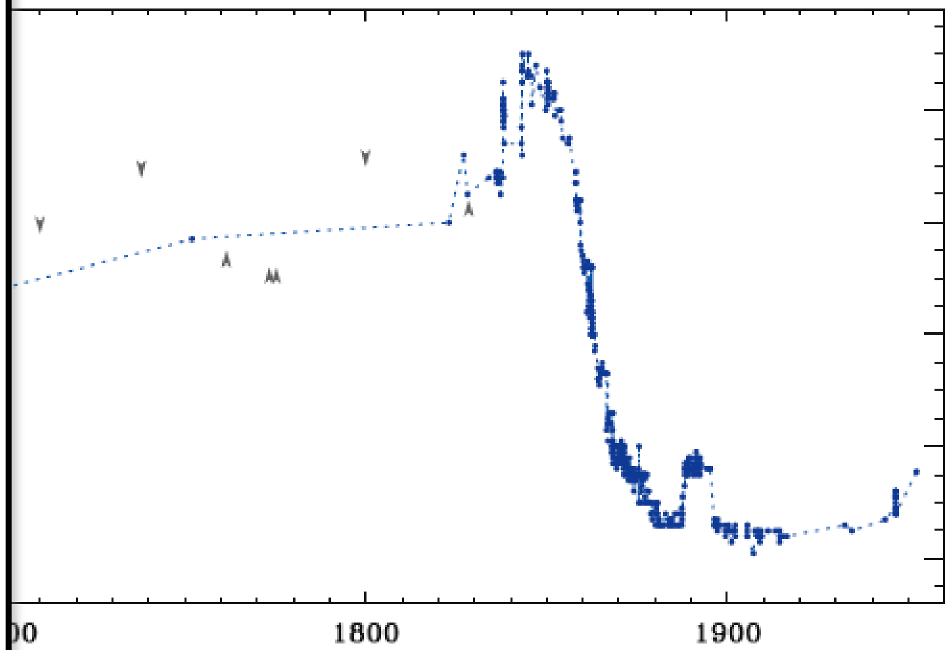
Inner Shell
Warm dust 200 K
[Fe II] emission, etc.
Thick shell
$n_e = 10^4$ cm^{-3}

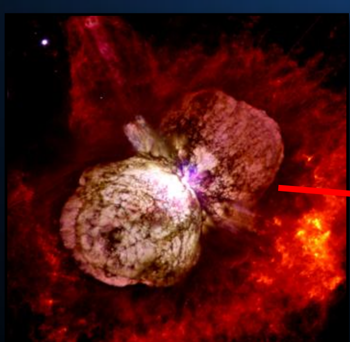


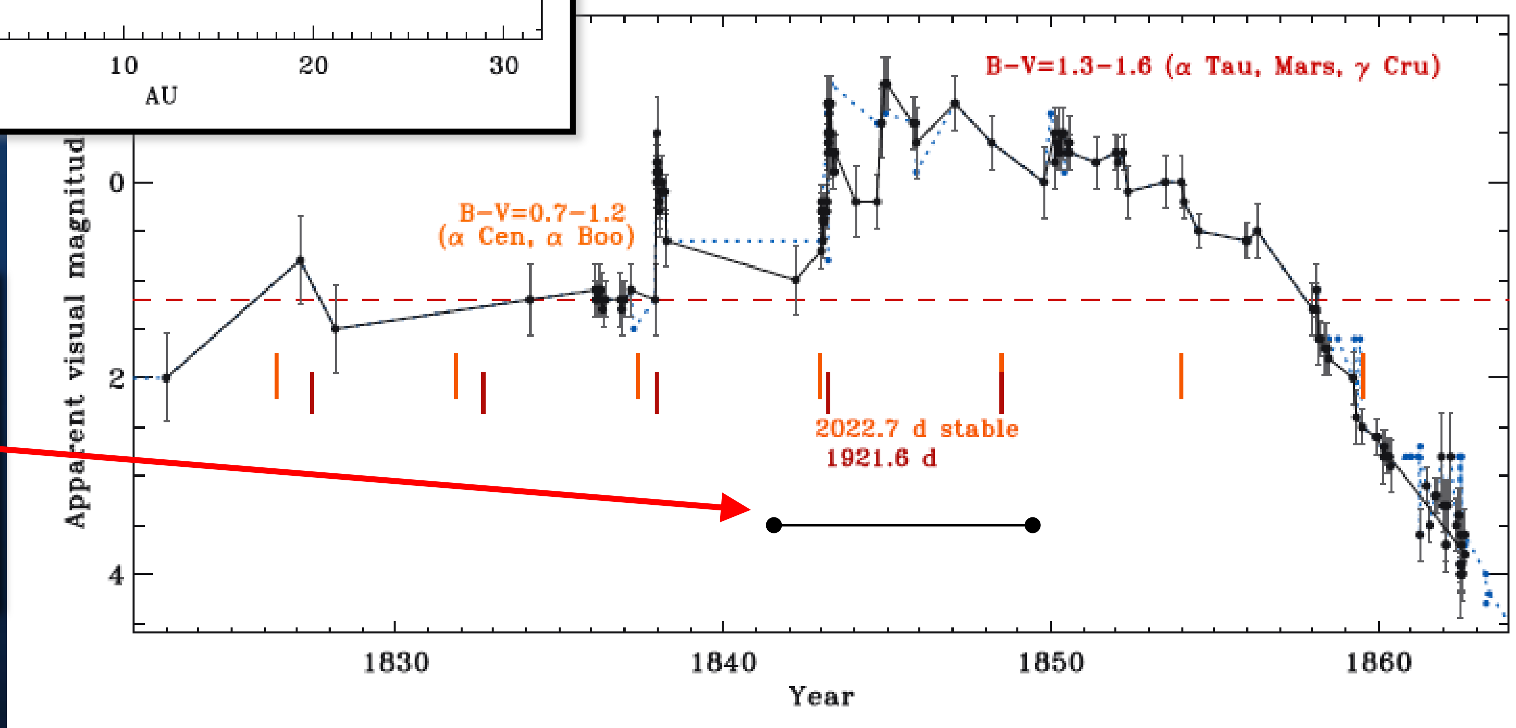


Smith & Frew (2010)









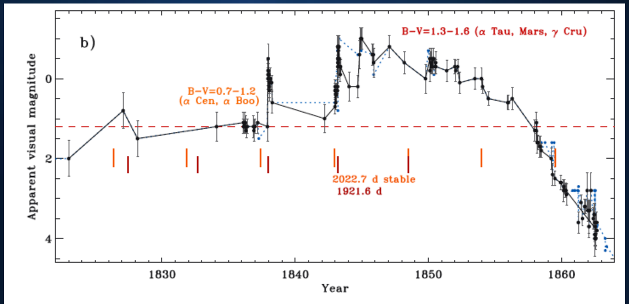
Smith & Frew (2010)

A Model for the 19th Century Eruption of Eta Carinae: CSM Interaction Like a Scaled-Down Type IIn Supernova

Last Friday - arXiv:1209.6155

Nathan Smith*
Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

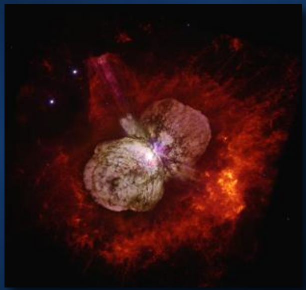
1. Can we power the 10-year Great Eruption luminosity with a 10^{50} erg explosion and CSM interaction, as in a Type IIn supernova?

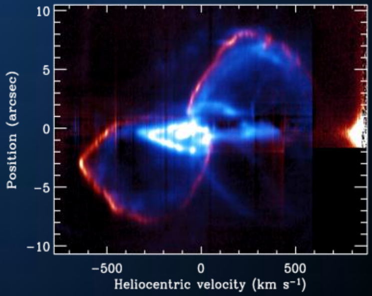


$$L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2} \dot{M} \frac{V_{SN}^3}{V_w}$$

- V_{SN} is now speed of Homunculus (assume 600 km/s)
- Observed luminosity of roughly L=2.5e7 $L_\odot$ requires w = 10^{18} g/cm

1. Is this consistent with everything else we see (Homunculus, etc)?

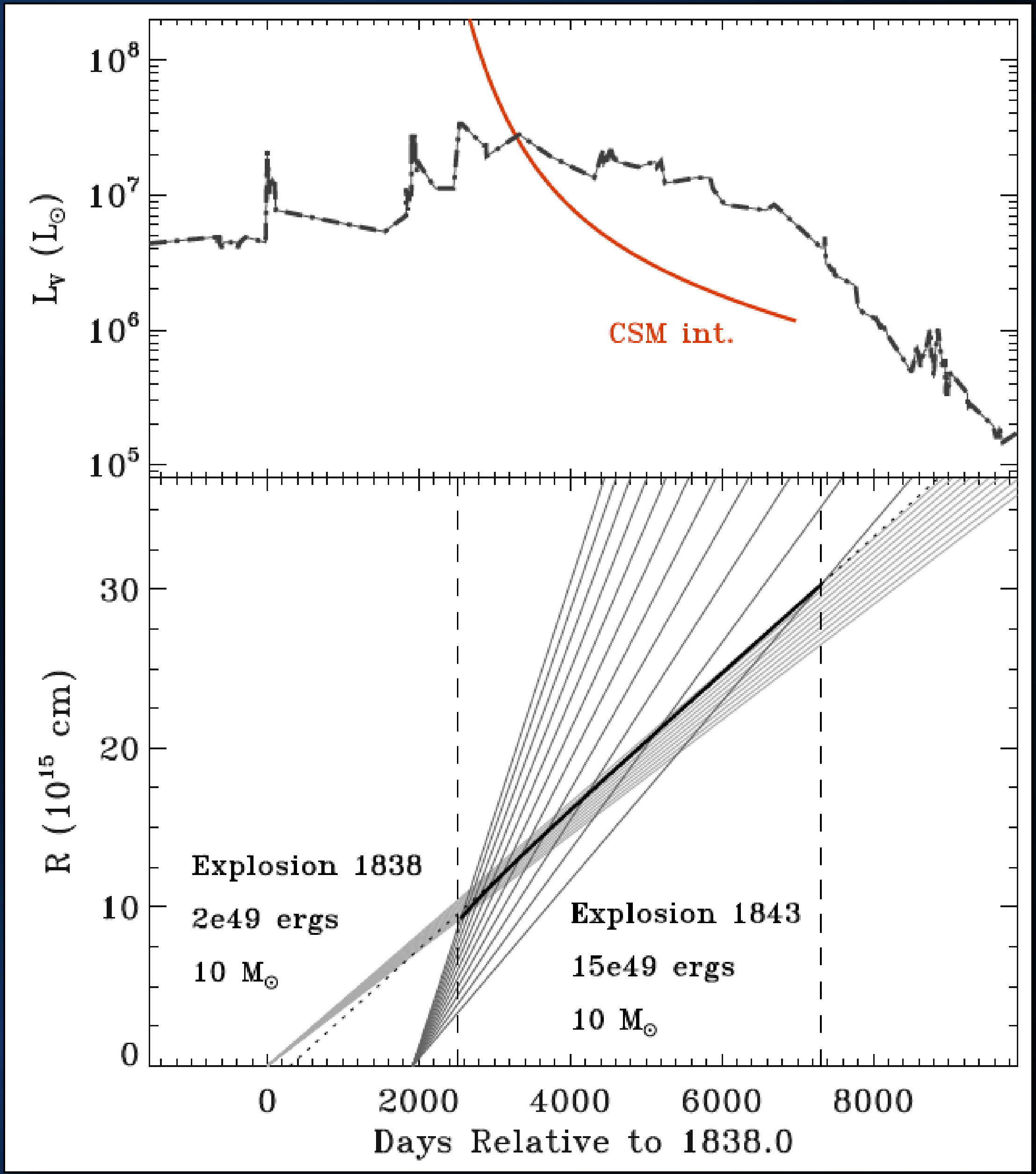




Attempt #1:

2 explosions
(at periastron passages)

Might work but needs to be finely tuned.



Attempt #2:

Explosion expands into slow dense wind of 200 km/s.

$$L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2} \dot{M} \frac{V_{SN}^3}{V_w}$$

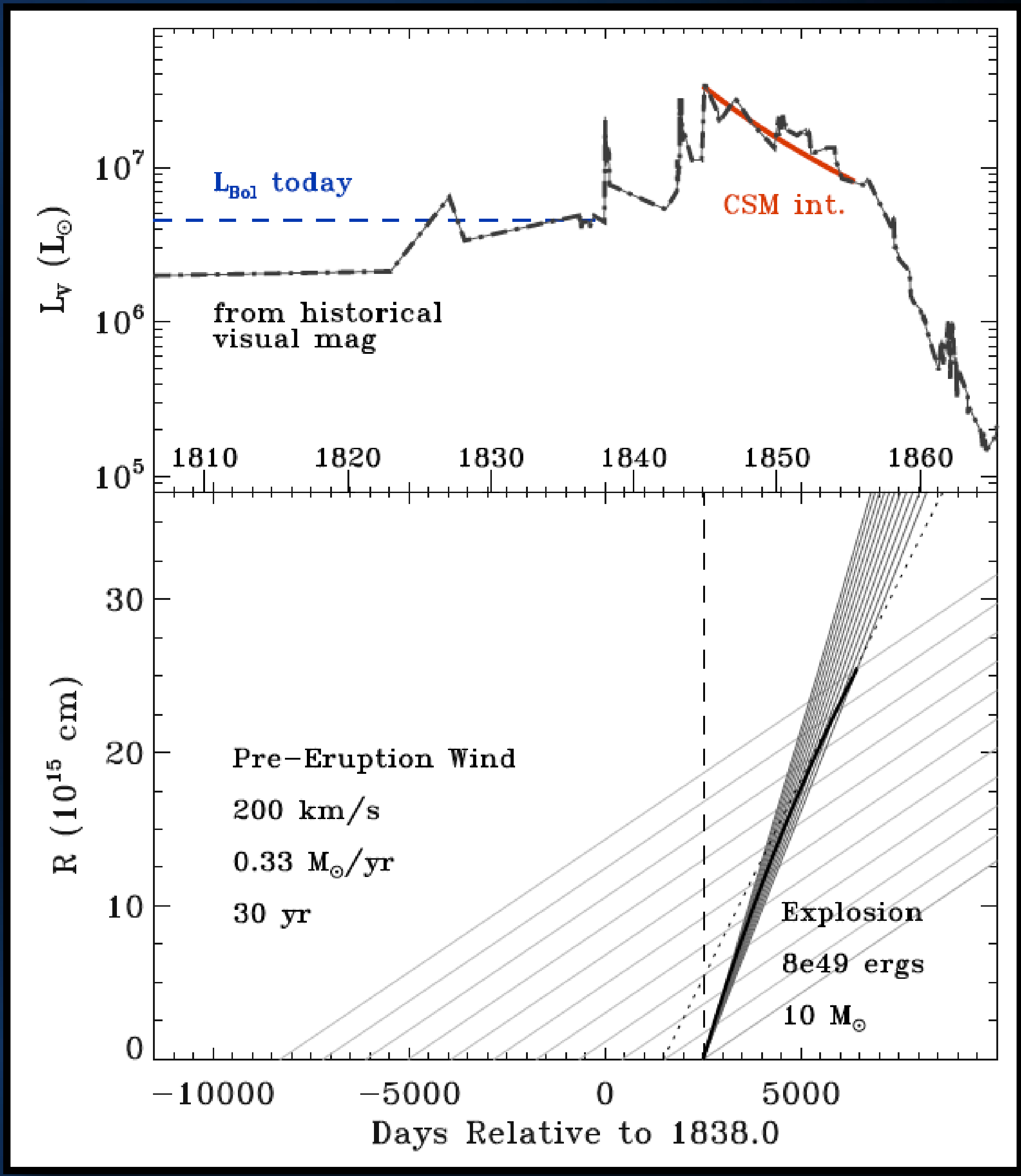
Slow wind has advantage.

Requires Mdot = 0.3 $M_\odot$/yr for a few decades.

Works easily… but can it explain everything else?

WHY 200 km/s?

200 km/s is roughly the escape speed for the radius in the 1830s, and 200 km/s was observed in 1890 eruption.



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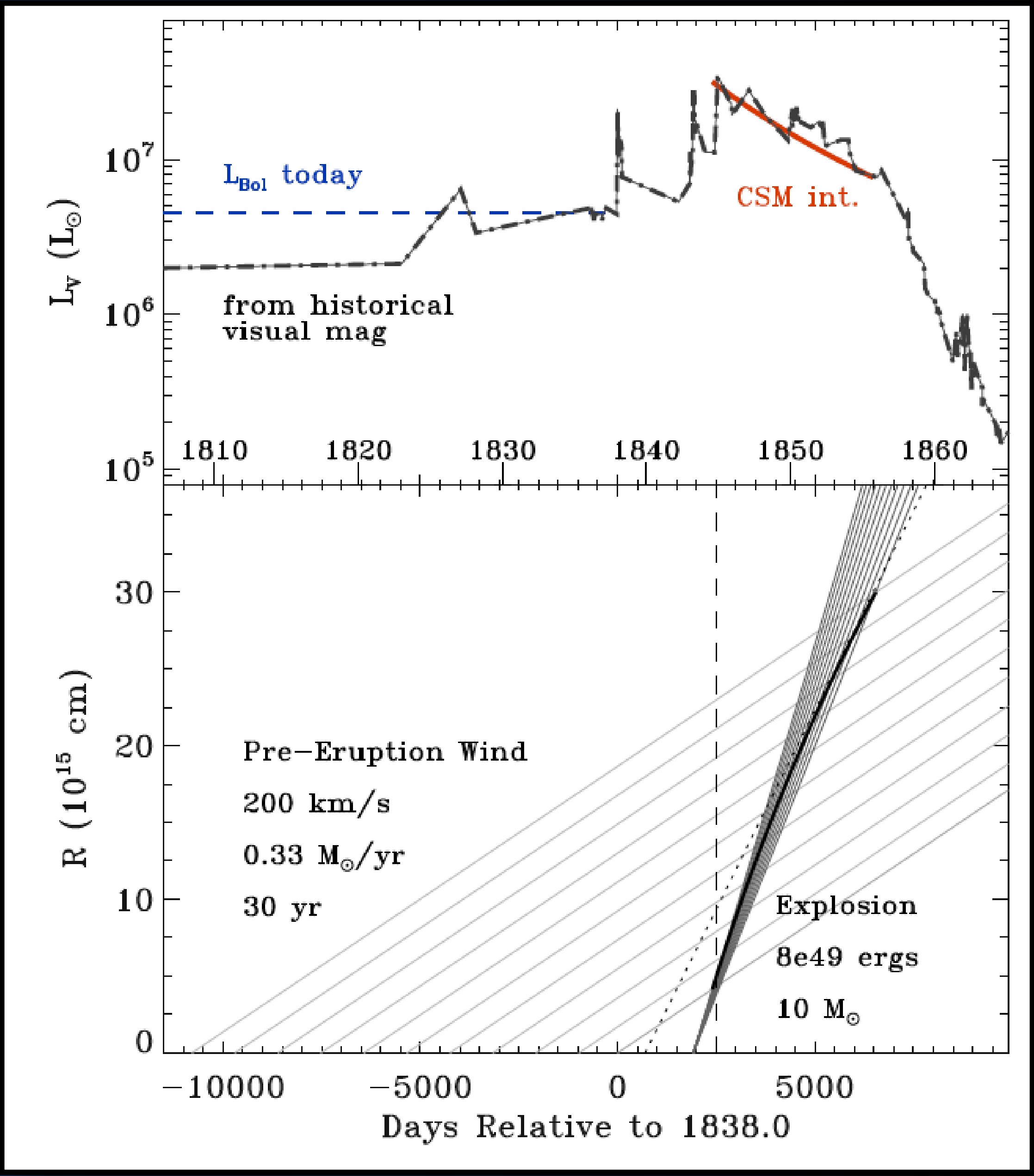
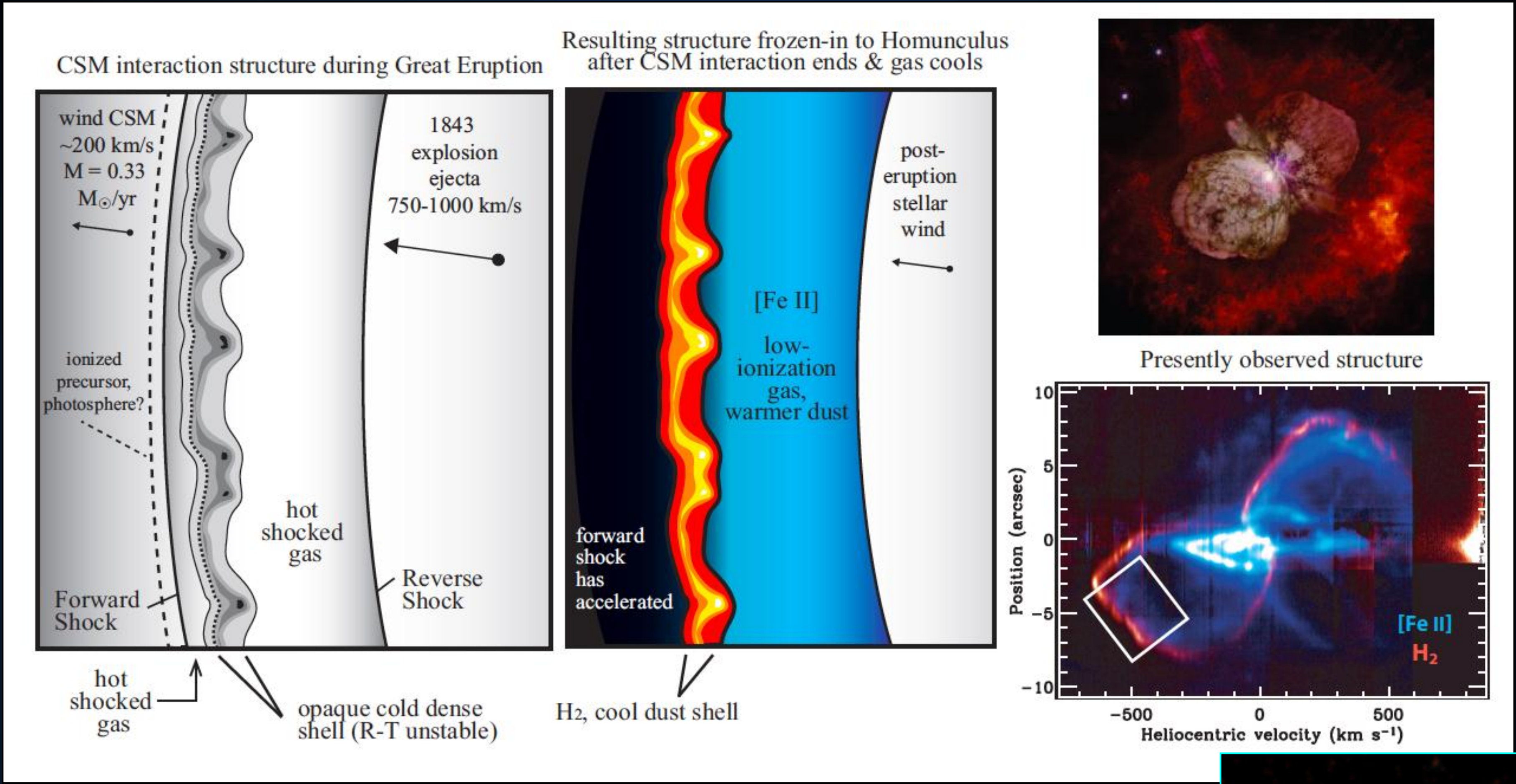
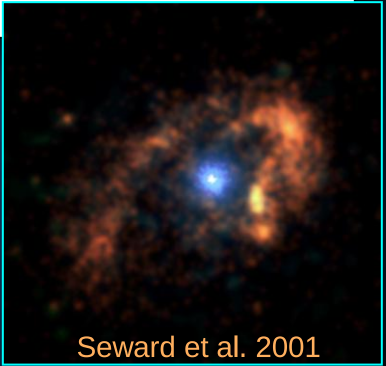
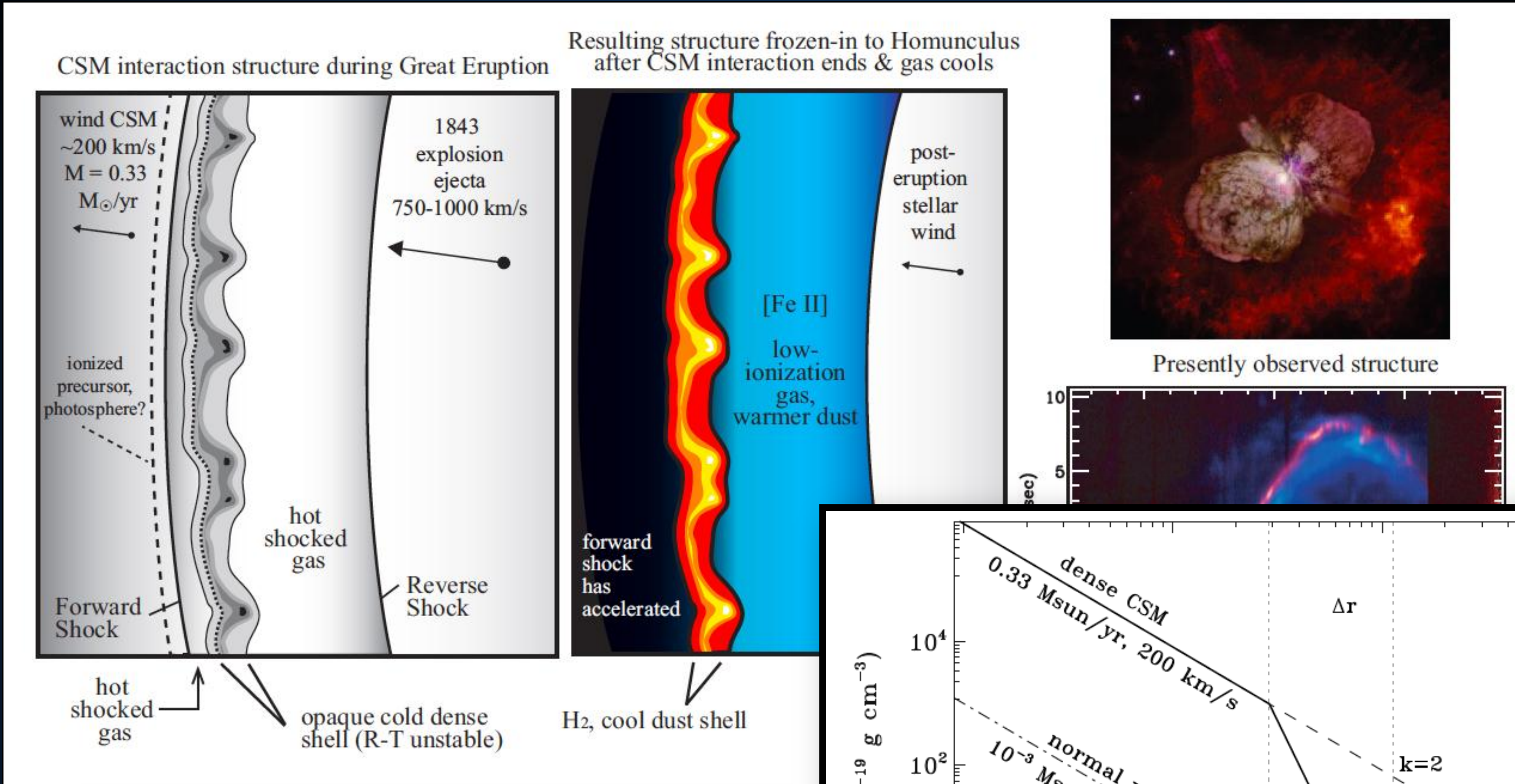
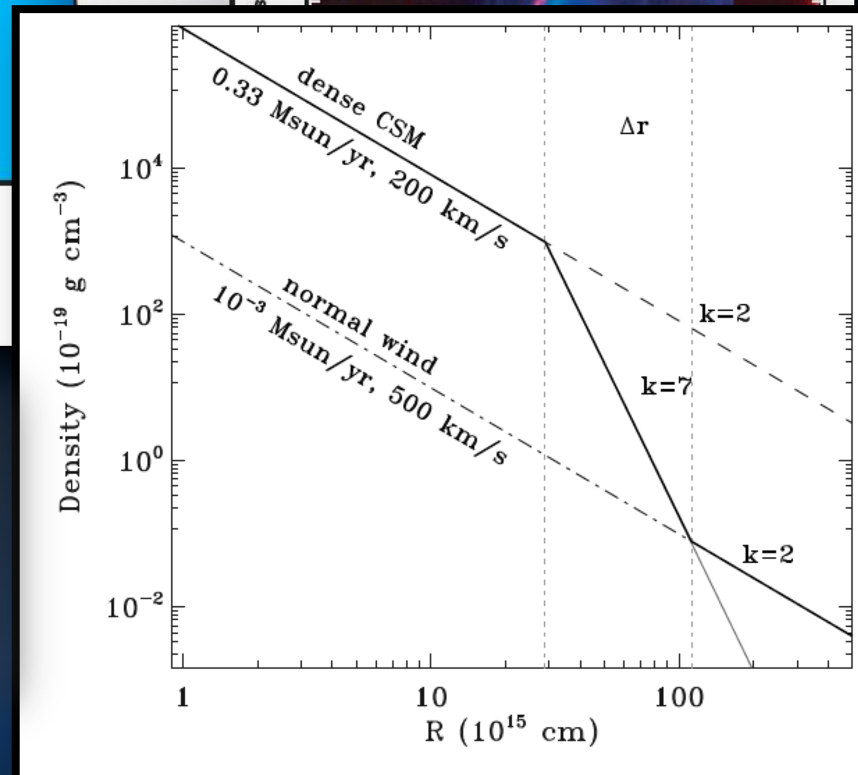





Seward et al. 2001

- High ratio of KE to E_{rad}
- Double shells (thin outer shell, thicker inner shell) frozen in
- Single age (Hubble flow)
- Mottled structure in lobes (thin shell instabilities, frozen in)
- Efficient rapid post-shock dust formation (as seen in SNe IIn)
- Fast ejecta outside Homunculus (forward shock accelerates) – X-ray shell
- Bipolar shape (already explained – Frank et al., Dwarkadas & Balick, etc --- but different parameters…only 10 yr). Did torus come from periastron events?





For a blast wave propagating through a medium with a density gradient given by $\rho \propto R^{-k}$, the velocity of a blast wave is described by

$$V_{BW} \propto R^{\frac{-(3-k)}{2}} \quad (3)$$

(see Ostriker & McKee 1988). For steady winds with k=2,

PROGENITORS

SN 2005gl

Moderate Luminosity Type IIn supernova: Narrow H lines

Progenitor star was very Luminous: M_V = -10.3 or L = 1.1×10^6 $L_\odot$
Implies $M_{ZAMS} \geq 50\ M_\odot$

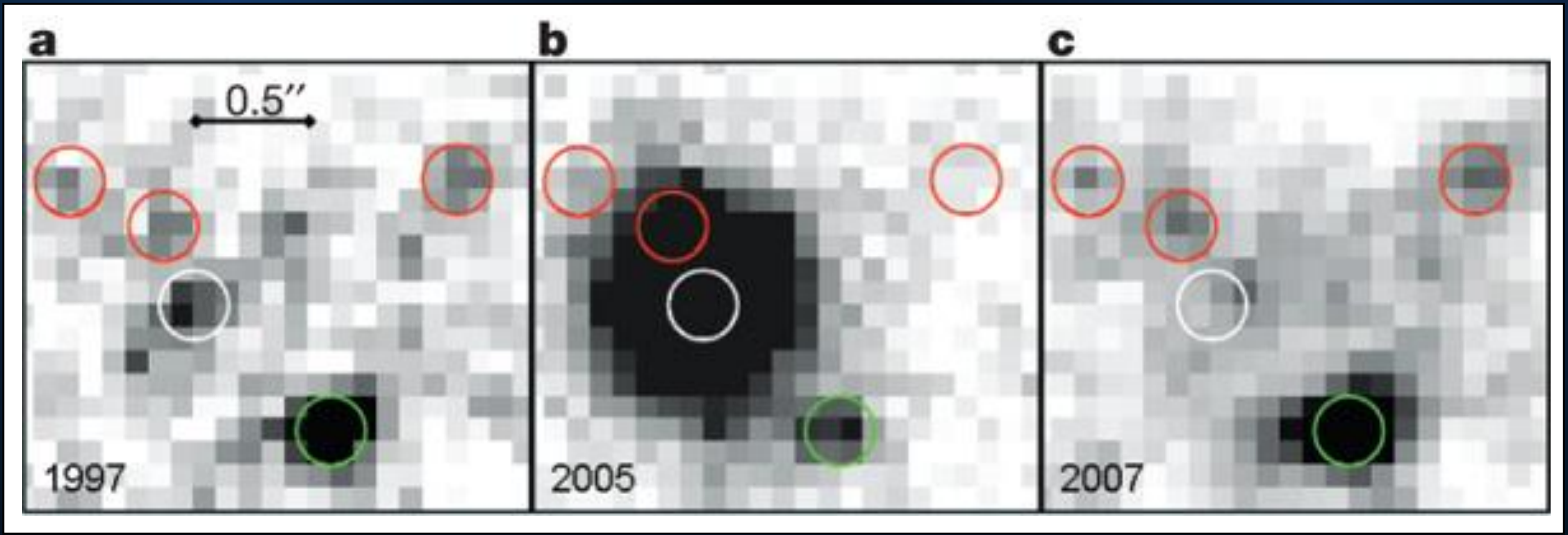
Progenitor mass-loss rate about 0.03 $M_\odot$/yr: like P Cyg in 1600 AD

The progenitor star of SN 2005gl faded after the supernova event.

Faded by >1.5 mag

LBV progenitor V=24.1 mag

No survivor V>25.6 mag



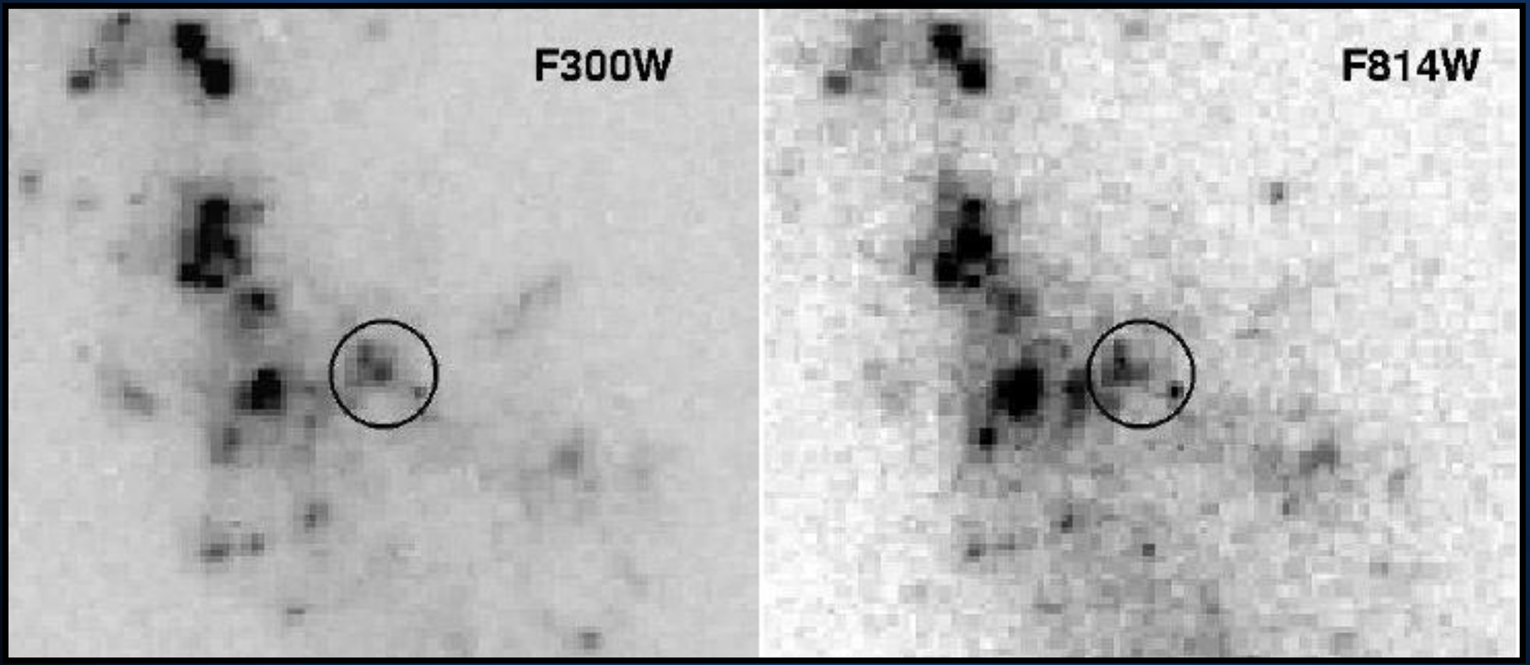
Gal-Yam & Leonard *Nature* (2009)

PROGENITORS

SN 2010jl

Very luminous Type IIn supernova (-20.something)
Bright blue source at SN position: $M_{F300W} = -12$
(either massive young cluster or very luminous progenitor star)

Implies $M_{ZAMS} \geq 30\ M_{\odot}$



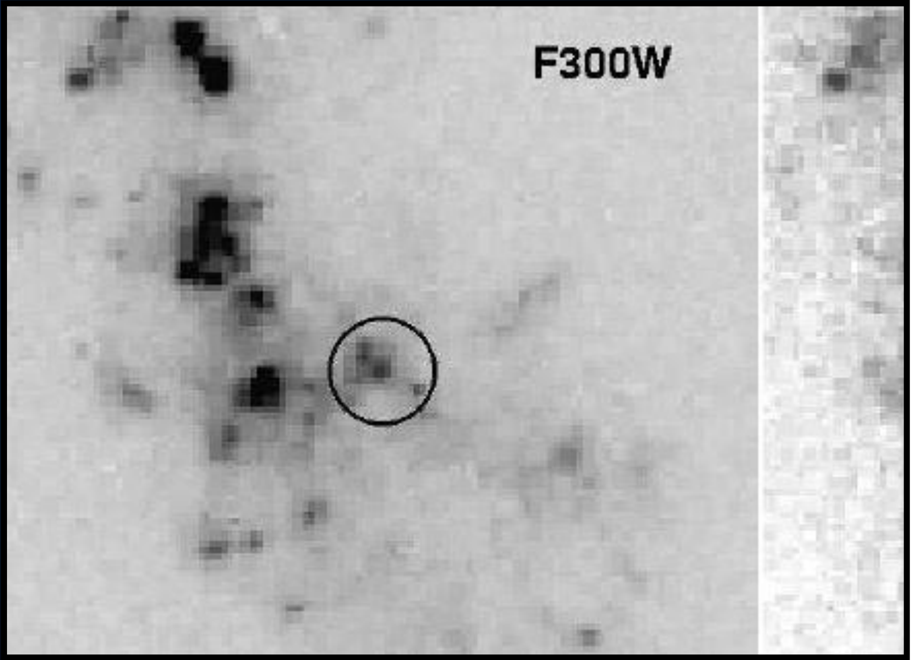
Smith et al. (2011)

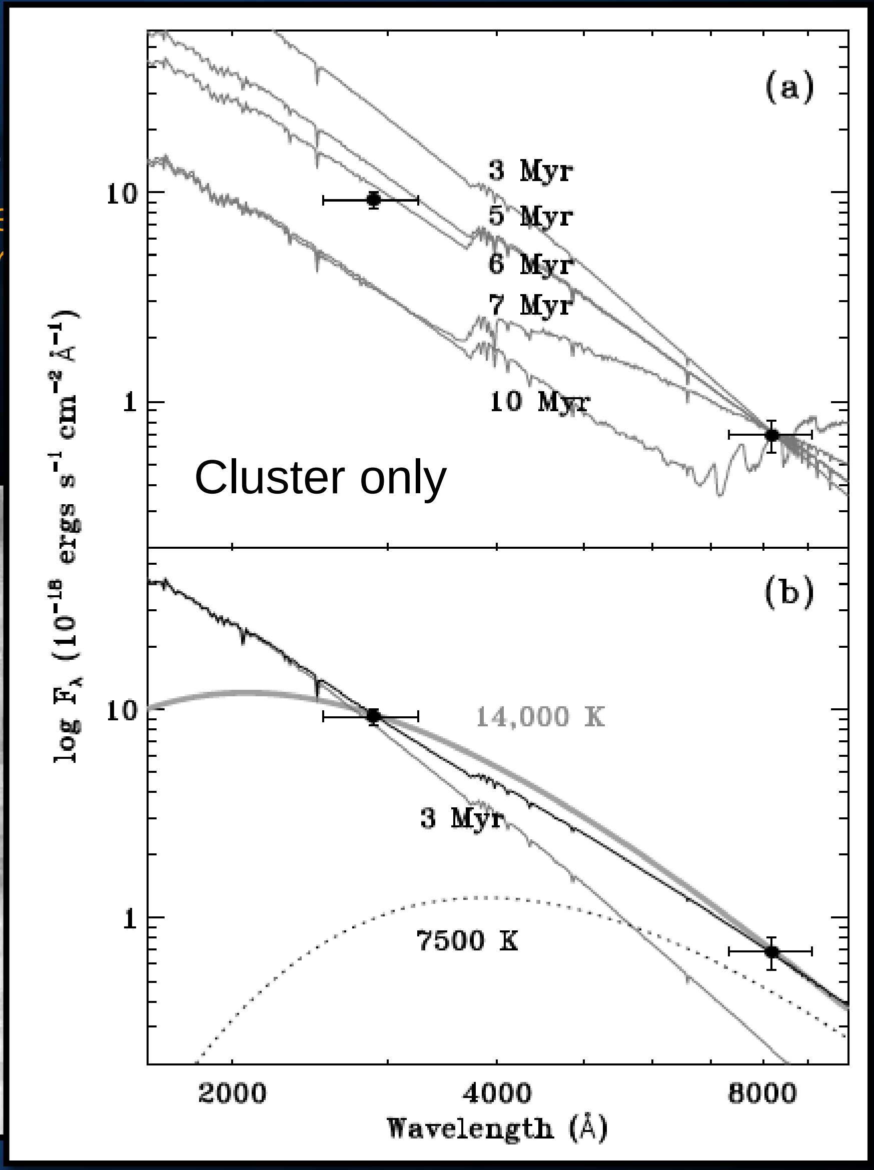
PROGENITORS

SN 2010jl

Very luminous Type IIn supernova (-2
Bright blue source at SN position: M_{F3}
(either massive young cluster or ver

Implies $M_{ZAMS} \geq 30\ M_{\odot}$





Smith et al. (2011)

PROGENITORS

SN 1961V

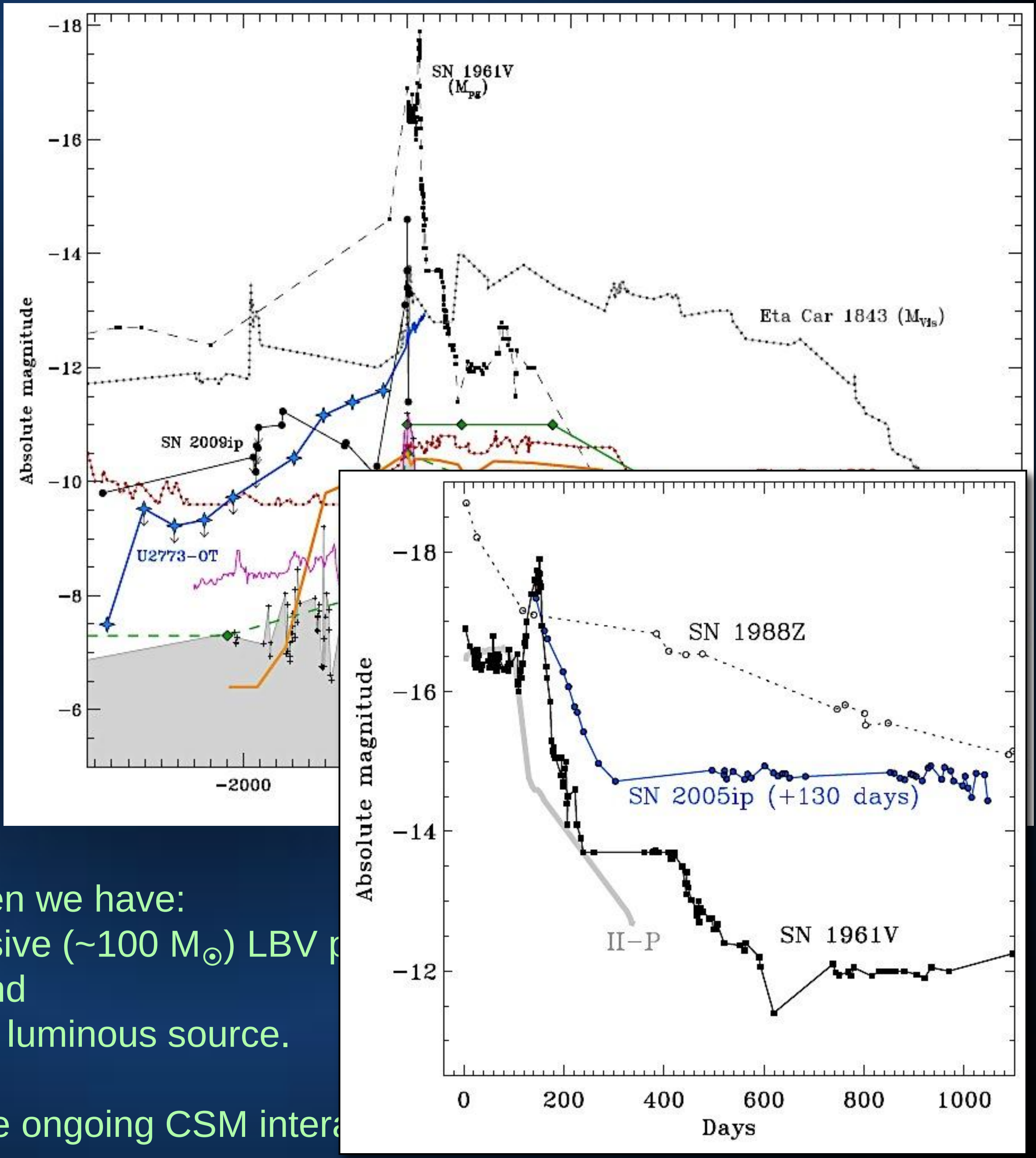
SN 1961V was probably a real core-collapse Type IIn.

Peak L was 40x brighter than Eta Car's eruption, and brighter than any other SN impostor, but in-line with other SNe IIn (Smith et al. 2011).

V band: by 1970 it was 4 mag fainter than progenitor. Today it is at least 5.5 mag fainter.

Spitzer upper limits to any present-day IR source suggest that the LBV star did not survive (Kochanek et al. 2011)

See however, Van Dyk & Matheson 2011.



If SN 1961V was a core collapse, then we have:

- a clear detection of the very massive (~100 $M_{\odot}$) LBV p
- detection of a pre-SN eruption, and
- subsequent disappearance of the luminous source.

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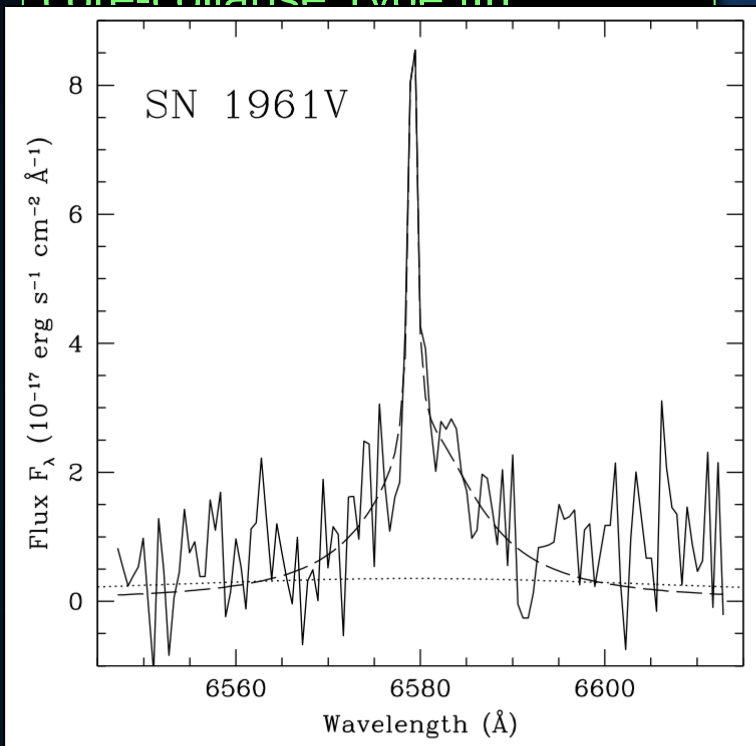

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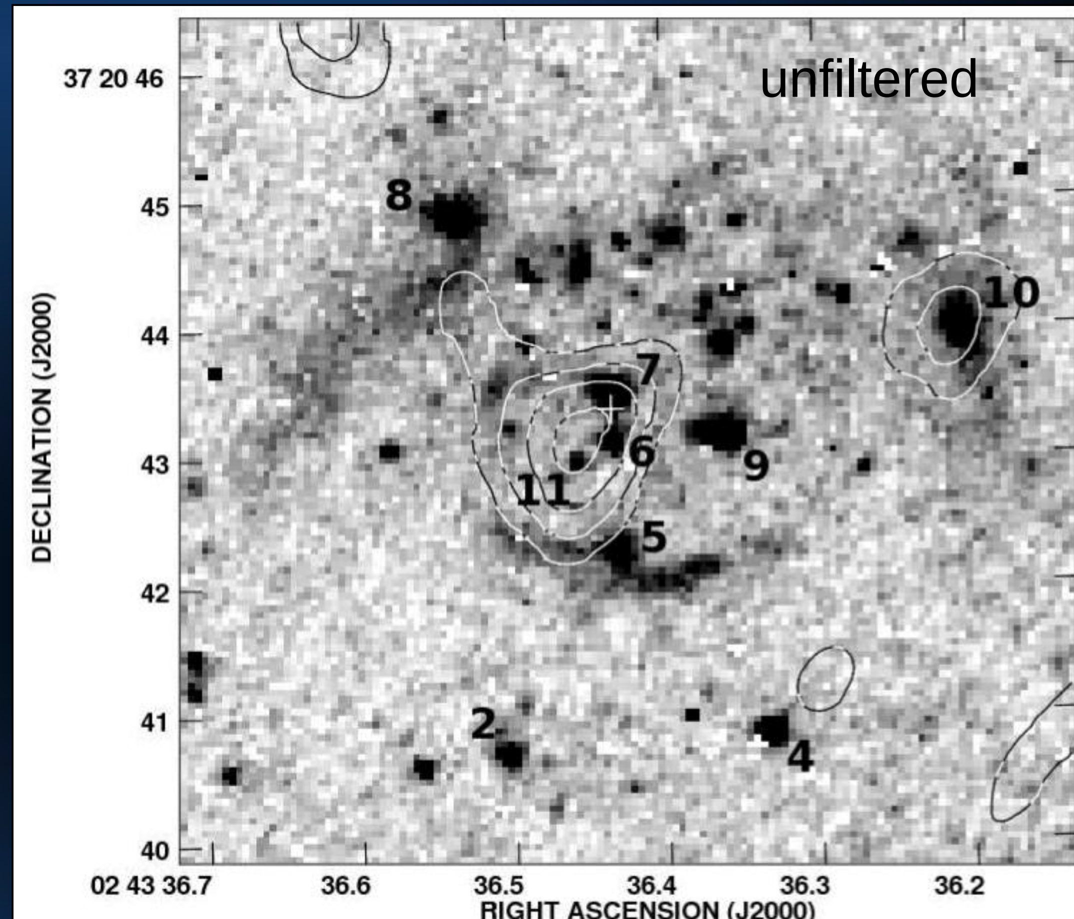

Van Dyk & Matheson 2011, Chu et al. 2004

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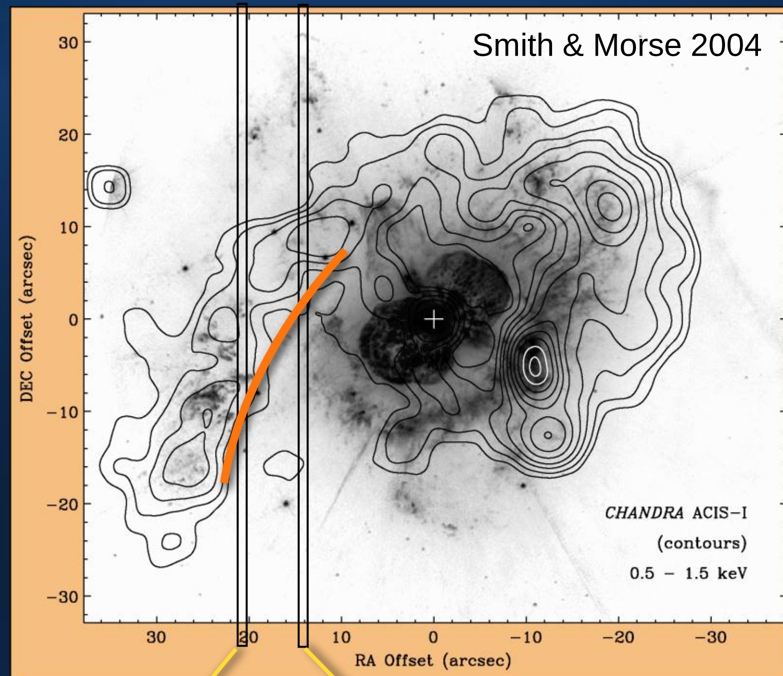
- detection of a pre-SN eruption, and
- subsequent disappearance of the luminous source.

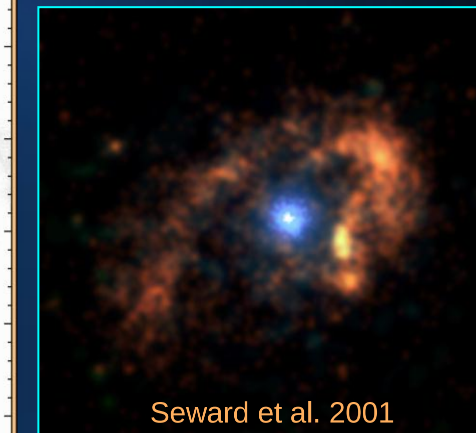
Present-day H-alpha source might be ongoing late-time CSM interaction

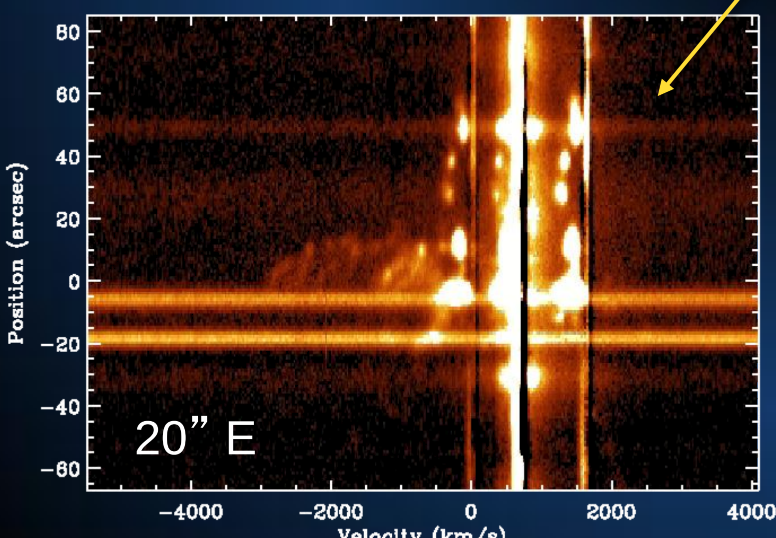
A BLAST WAVE FROM THE 1843 ERUPTION OF ETA CARINAE?

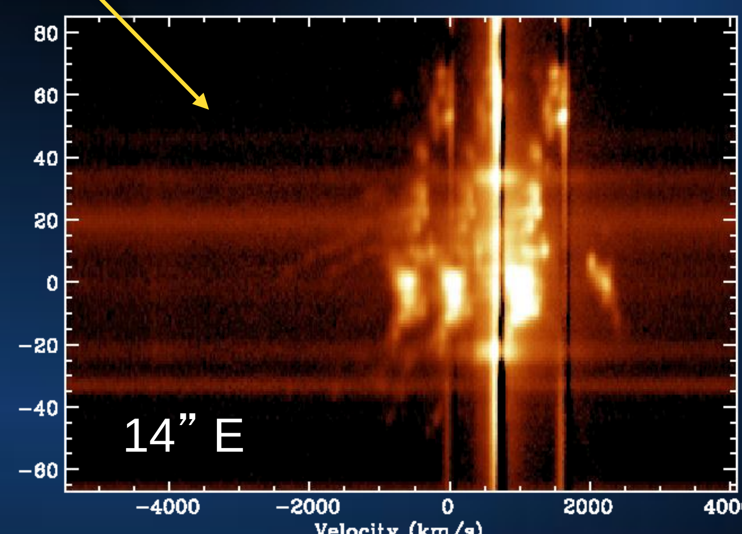
Spectra of [N II] reveal ***fast*** material with Doppler shifts up to ~3000 km/s.

True velocities of 5000 to 6000 km/s.



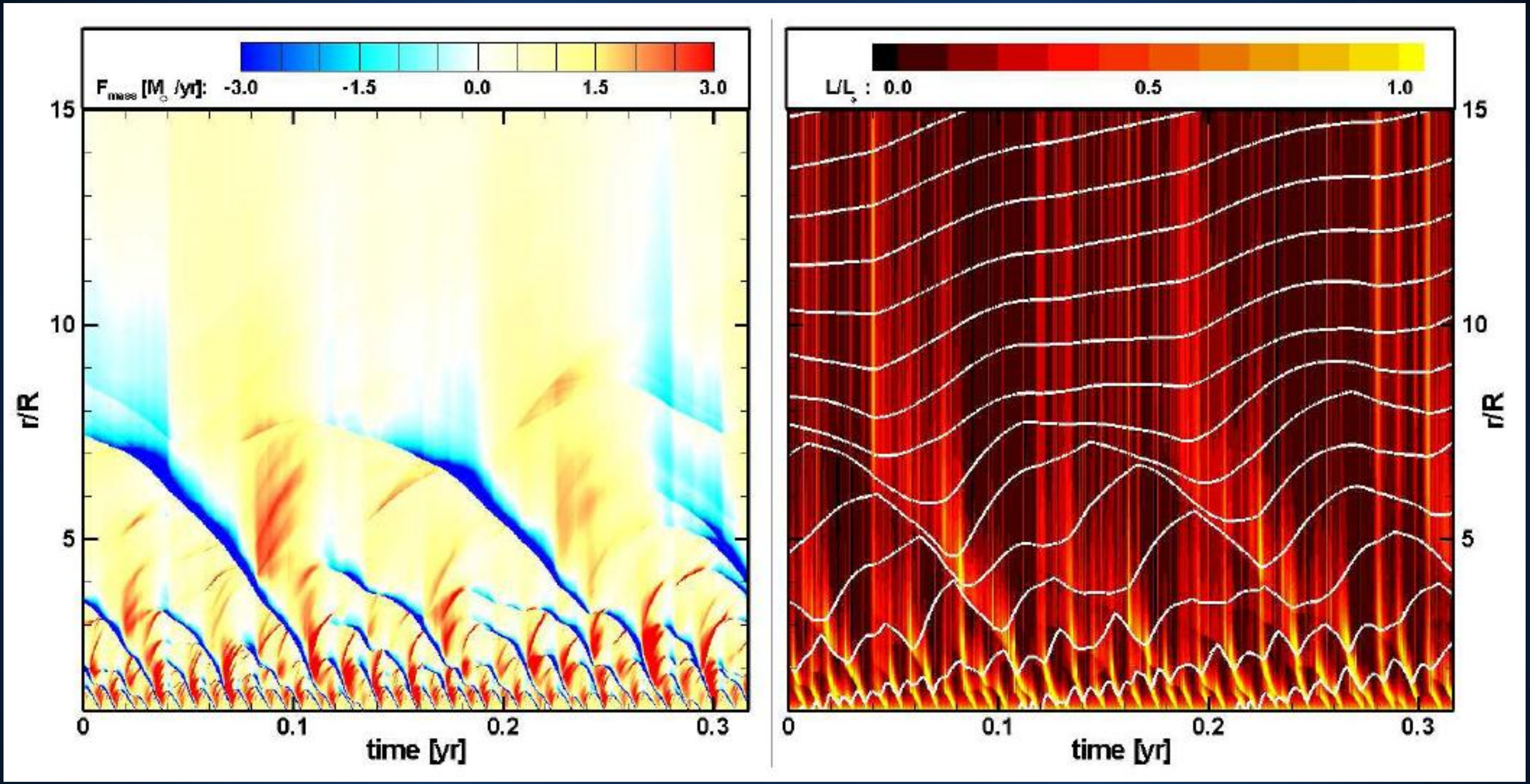

Seward et al. 2001





Smith (2008)
Nature, 455, 201

Numerical simulations of continuum-driven super-Eddington winds



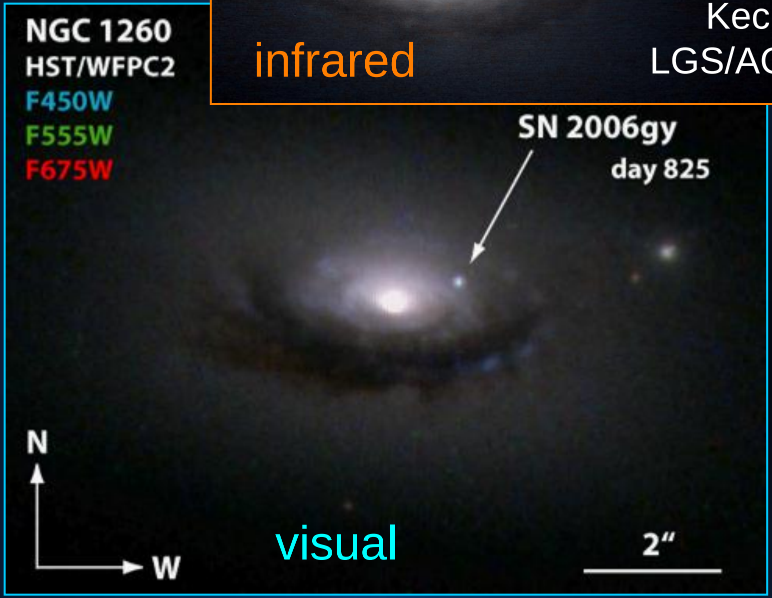
Van Marle, Owocki, & Shaviv 2009

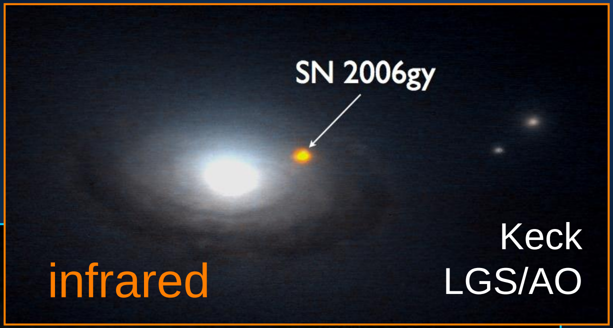
Photon tiring…

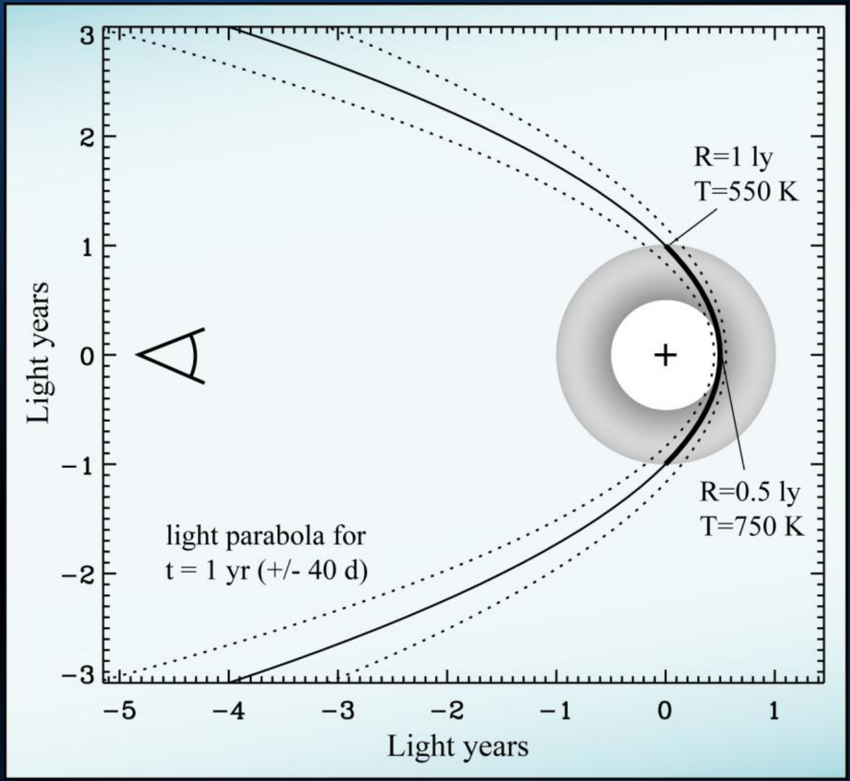
…wind stagnates.

G = 10

SLSNe IIn have IR echoes from circumstellar dust shells







IR/optical echo:
Massive dust shell at R=0.5-1 light year (ejected 1500 yr before SN).

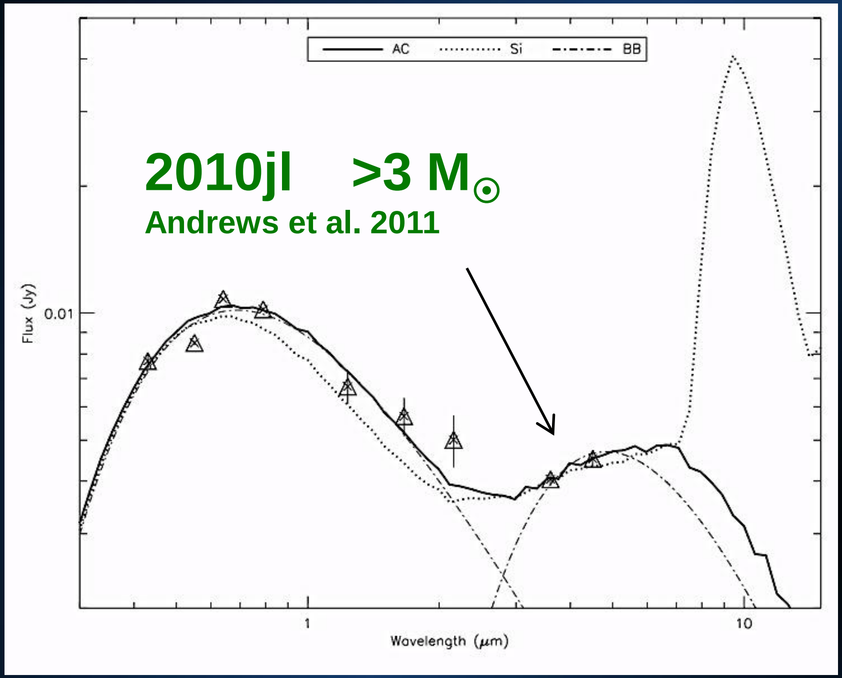
Smith et al. 2008, ApJ, 686, 485
Smith et al. 2010, ApJ, 709, 856
Miller et al. 2010, AJ, 139, 2218

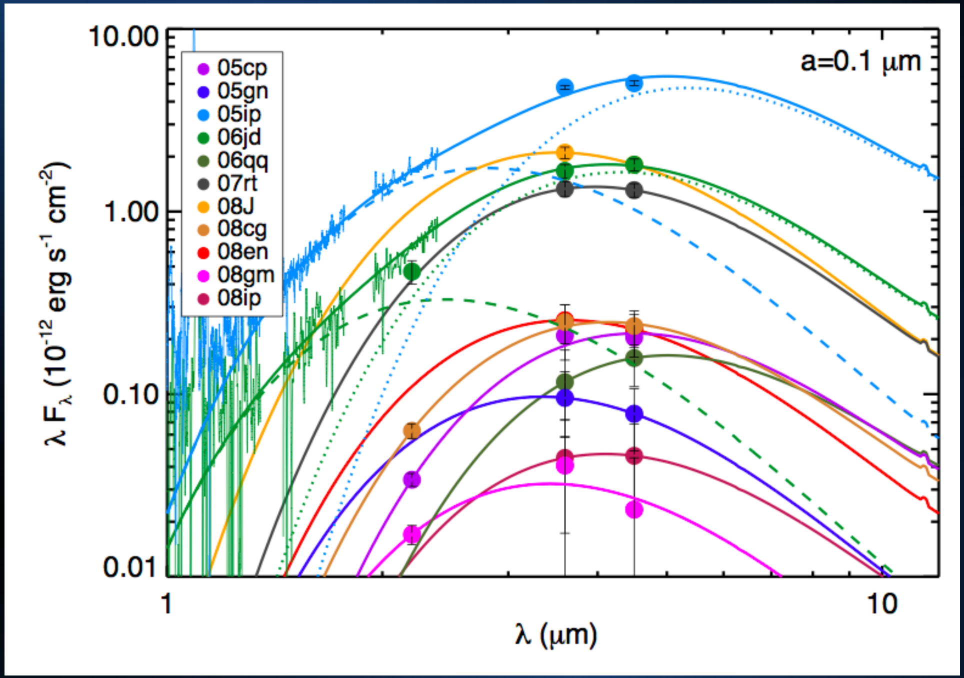
Requires 0.05-0.1 $M_\odot$ of dust (5-10 $M_\odot$ total mass).

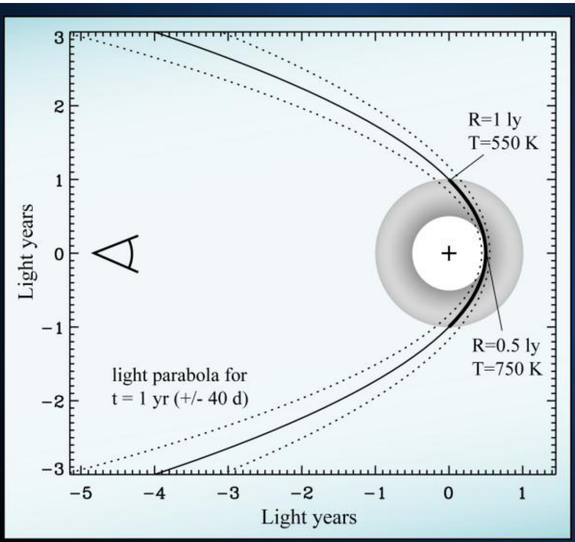
Multiple massive shell ejections, 8 yr before and ~1500 yr before.

DUST

SLSNe IIn have IR echoes from circumstellar dust shells





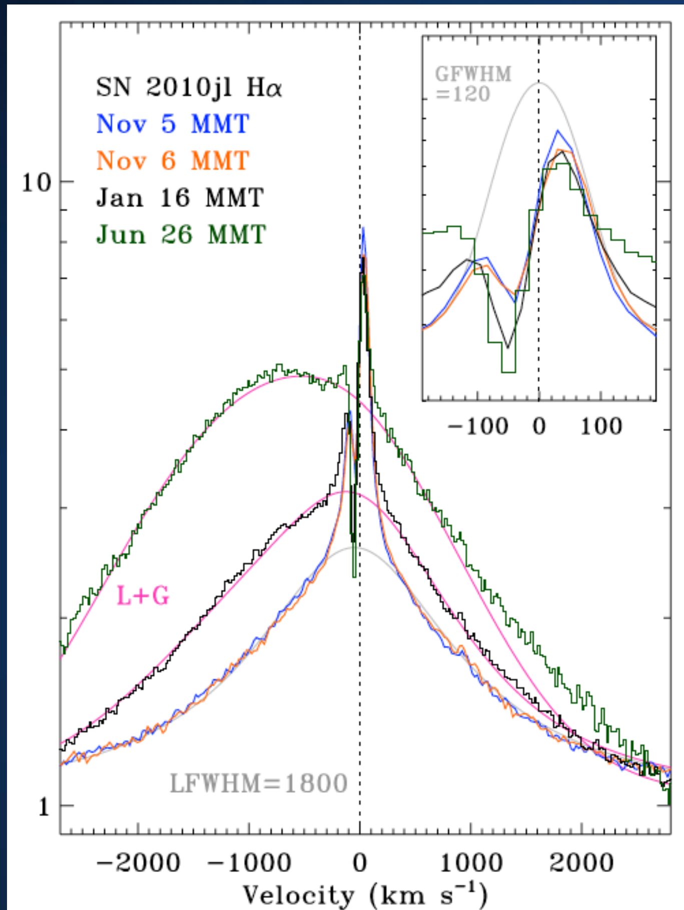


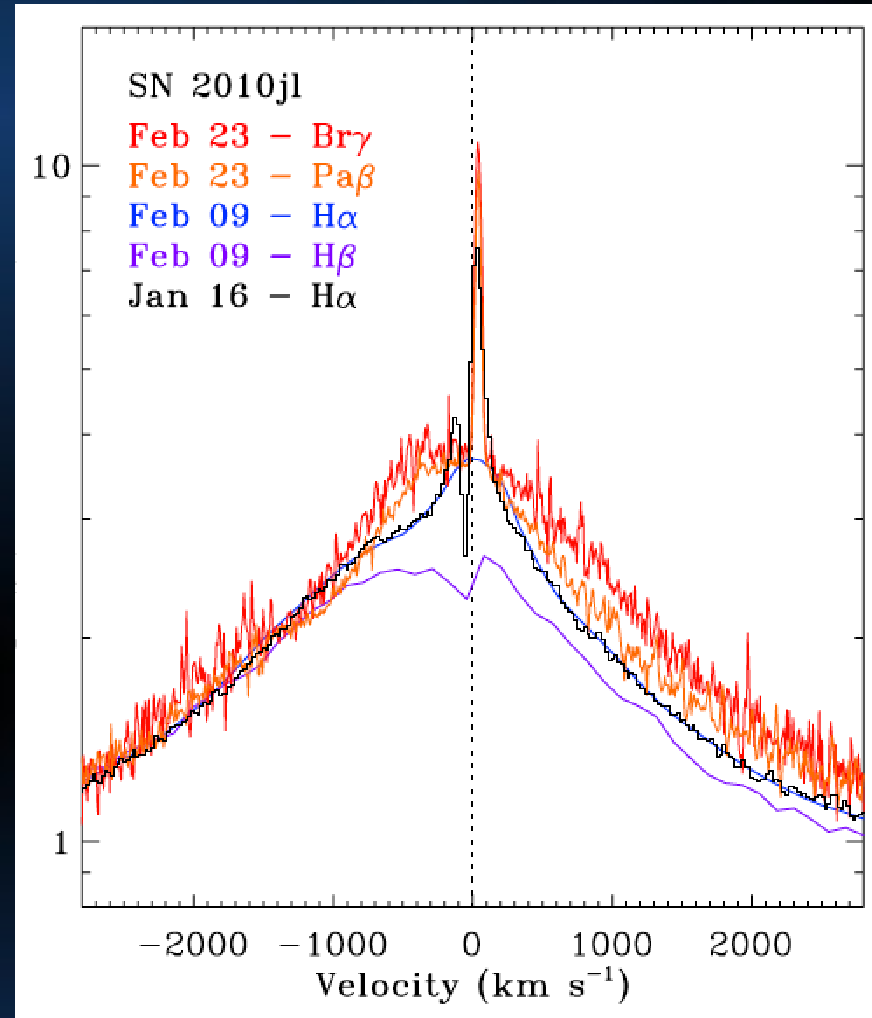
IR Echoes from normal SNe IIn (not SLSNe) are common too.

Fox et al. (2011)

DUST

SLSNe IIn also have dust formation





However, asymmetric line profiles also indicate ***new dust formation*** in post-shock gas.

Smith et al. (2012)