Status of the Expanding Photosphere Method for Distances

Luc Dessart

(Laboratoire d'Astrophysique de Marseille, France)

D. John Hillier

(University of Pittsburgh, USA)

Non-LTE (time-dependent) radiative transfer of SN ejecta

Outline of the Talk

- Methods for distance determinations with Type II SNe
- The Expanding Photosphere Method (EPM) of Kirshner & Kwan (1974)
- Type I versus Type II SNe for EPM distances
- Towards accurate EPM distances with Type II-P SNe (ξ, A_V, V_{phot} etc)
- Internal and external consistency checks
- EPM: Improvements/uncertainties.
- Summary and outlook

Distance Determinations with Type II-P SNe: EPM and Variants

- Expanding Photosphere Method *Kirshner & Kwan (1974), Branch (1987), Eastman & Kirshner (1989), Schmutz et al. (1990), Schmidt et al. (1992,1994), Eastman et al. (1996), Hamuy et al. (2001), Leonard et al. (2002ab), Elmhamdi et al. (2003), Vinko et al. (2004), Takats & Vinko (2006), Dessart & Hillier (2006), Dessart et al. (2008), Jones et al (2009), Jones & Hamuy (2009)*

- Theoretical insights on EPM: Wagoner (1981), *Eastman & Kirshner (1989), Schmutz et al. (1990), Eastman et al. (1996), Dessart & Hillier (2005)*

- Spectral-fitting Expanding Atmosphere Method (SEAM): *Mitchell et al. (2002), Baron et al. (2004,2007).* **Analogous to EPM**

- Standard-Candle Method (SCM): *Hamuy & Pinto (2002); Nugent et al. (2006),* Poznanski et al. (2009). **Invokes external calibration ($L \propto V_{phot}$)**

- Key Objects studied: Type II-pec (87A), Type II-P (99em, 99gi, 05cs, 06bp), Type Ic (94I, 02ap)

- Applications to cosmology, e.g. $\mathbf{H_0}$: Wagoner (1977,1979), Wagoner & Montes (1993), Schmidt et al. (1994; H_0 = 73 km/s/Mpc!)…

The Expanding Photosphere Method (EPM) of Kirshner & Kwan (1974)

- From Baade (1926) method for distances to pulsating stars
- Approximate light as continuum characterized by $B_\nu(T)$ and observed flux f_ν => $\theta^2 = (R/D)^2 = (f_\nu / \pi B_\nu(T))$
- Assume $V(m) = \text{const}$. (prompt acceleration to $V_{\text{asymptotic}}$) and neglect initial radius R_0 => $R = V\,(t-t_0)$ => $\theta/V = (t-t_0)/D$
- T obtained from photometry (colors), V from spectroscopy
- Fit the distribution of θ/V at multiple epochs with a line whose slope is 1/D
- Applied to 2 Type IIP SNe in NGC 1058 and M101 yielding 12±3 (10.6) and 6±3 (7.4) Mpc
- In principle, method applies to **all** SN types

Refinements since KK74:

1) **Better and larger dataset**
2) Use **Radiative transfer Techniques** to model the observed flux
3) Use knowledge of SN ejecta/physics to ***understand*** and ***reduce*** "errors" (i.e. flux mismatch)

=> Accuracy of the method set by our ability to fit observations

Type I versus Type II SNe for EPM distances

Type I SNe

- Low-mass chemically-stratified ejecta
- Local/global ejecta asymmetry
- Large μ => small κ (cm^2/g)
- Abundant IME/Metals => Dominance of line opacity, weak pure-continuum processes
- Dominance of lines => No true continuum
- Abundant IME/Metals => Issues with treatment of lines, rates (non-LTE), absorption/scattering character, accuracy of atomic data
- Nucleosynthetic yields at the photosphere
- Photospheric conditions directly affected by complexity of explosion physics

Type II SNe

- Massive homogeneous H-rich envelope (RSG)
- Quasi-spherical outer SN ejecta
- H domination => big κ
- H domination => Efficient thermalization by bf/ff processes
- H domination => True continuum windows
- IME/Metals subdominant ($\sim Z_{sun}$). Weaker effects of line blanketing. Non-LTE treatment doable. Very accurate atomic data for H and He.

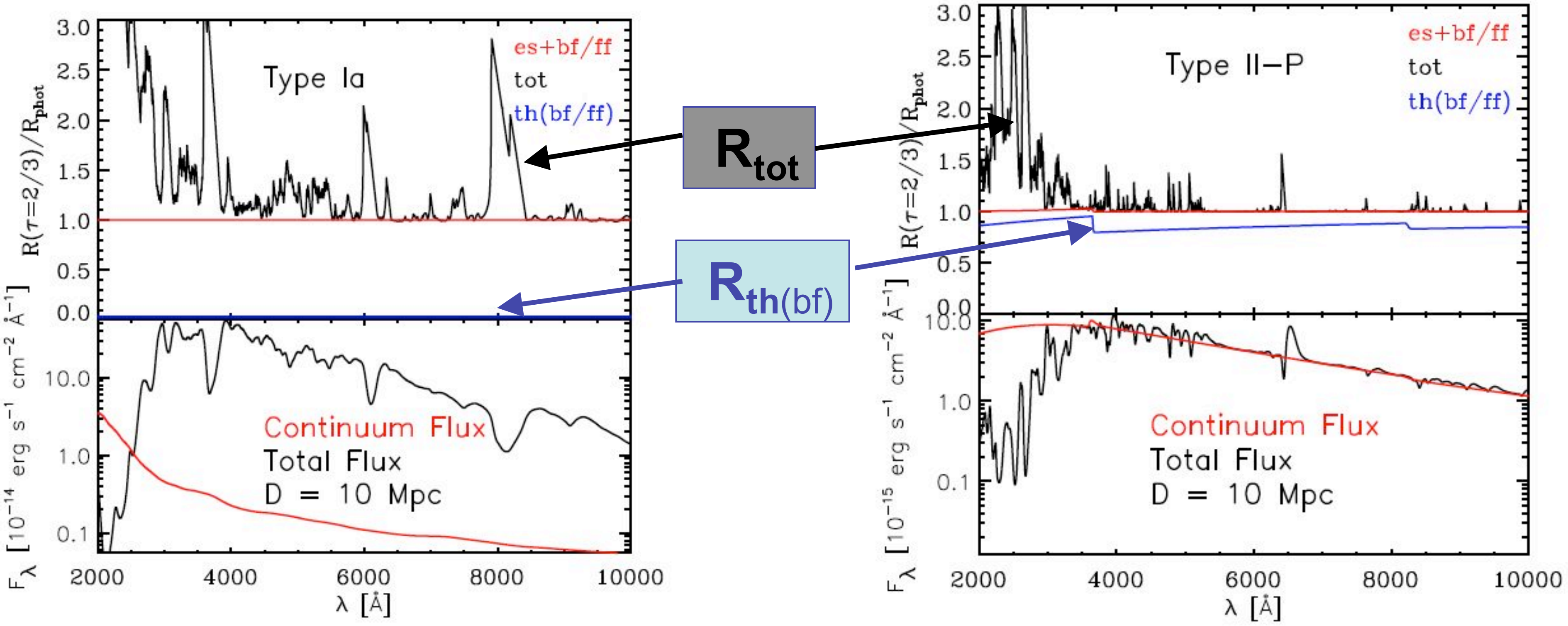
- None during 2/3 of plateau phase
- “Clean” properties of shock-heated envelope

EPM-distance accuracy ultimately set by agreement between synthetic and observed flux.
Tough to achieve with Type I (abc) SNe, easier with Type II SNe.
Diversity/heterogeneity of Explosion/ejecta/progenitor is less of an issue for Type II SNe.

Illustrations of the contrast between Type I and Type II-P SN Radiative Transfer Modeling

Nature of Thermalization processes

- **Type Ia**: thermalization done by **lines**
- **Type II-P**: thermalization done by **bf/ff of HI**

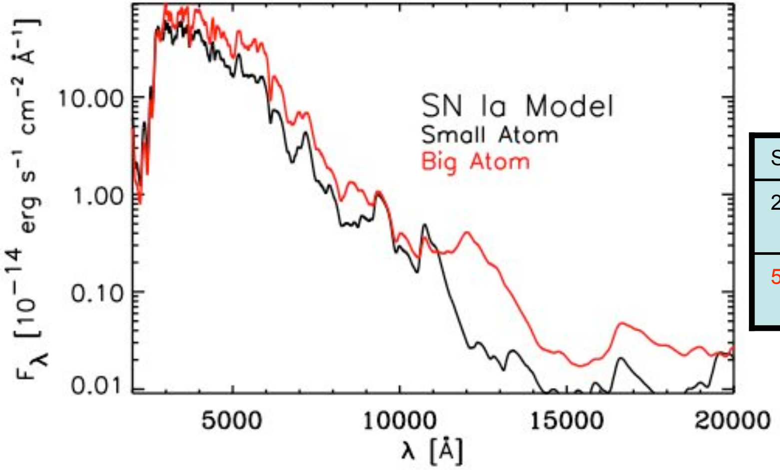


R_{tot}

$R_{th(bf)}$

Impact of Model Atom on Synthetic Flux

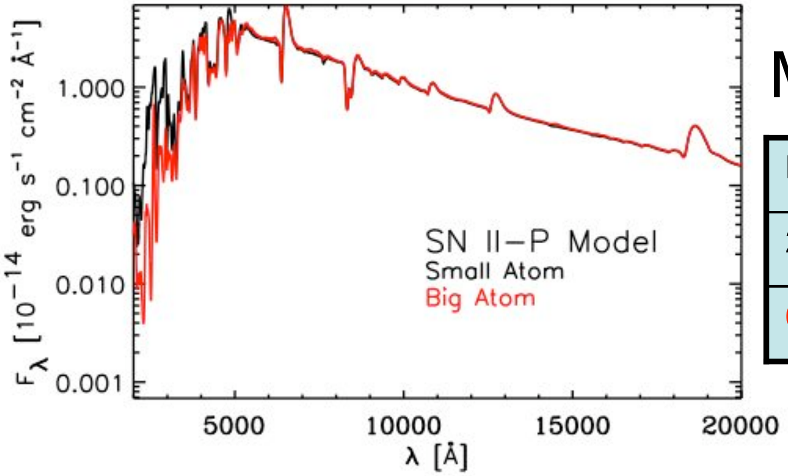
SN Ia



Model Atom (C,O, Ca, Ar fixed)

SiII	SiIII	SII	SIII	FeII	FeIII	FeIV	CoII	CoIII	CoIV	NiII	NiIII	NiIV
24	28	83	44	207	314	336	253	331	342	426	420	436
59	61	324	98	827	607	1000	1000	1000	1000	1000	1000	1000

SN II-P



Model Atom (H, He, CNO, Na, Co, Ni untouched)

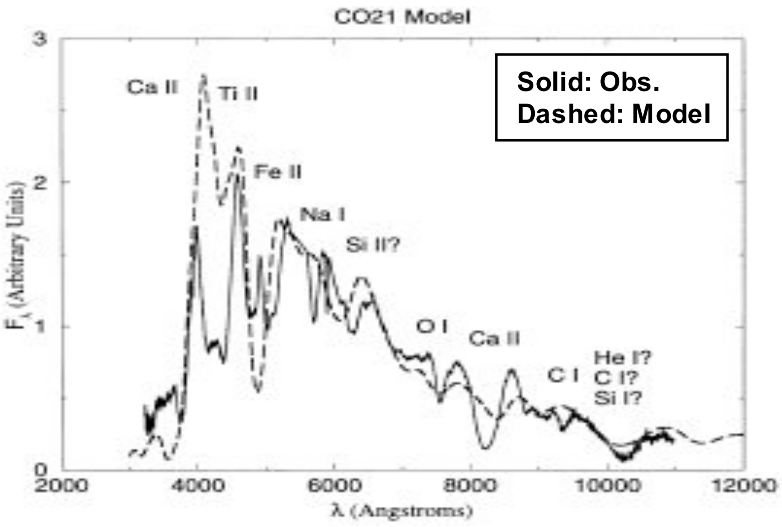
MgII	CaII	SiII	SiIII	FeII	FeIII	FeIV	TiII	TiIII
20	32	24	28	35	101	101	63	84
65	77	59	61	115	477	294	152	206

Radiative Transfer problem better defined in Photospheric phase Type IIP

Type Ib/c: Presence/absence of H/He/CNO etc? Asphericity etc.
SED shape strongly affected by lines

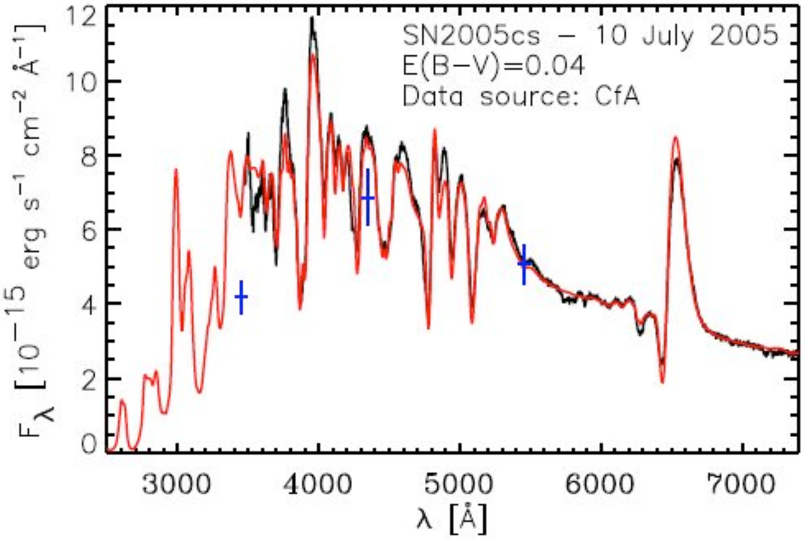
Type II-P spectral evolution: Ionization Effect in a spatially-confined homogeneous photosphere

SN Ic (1994I)



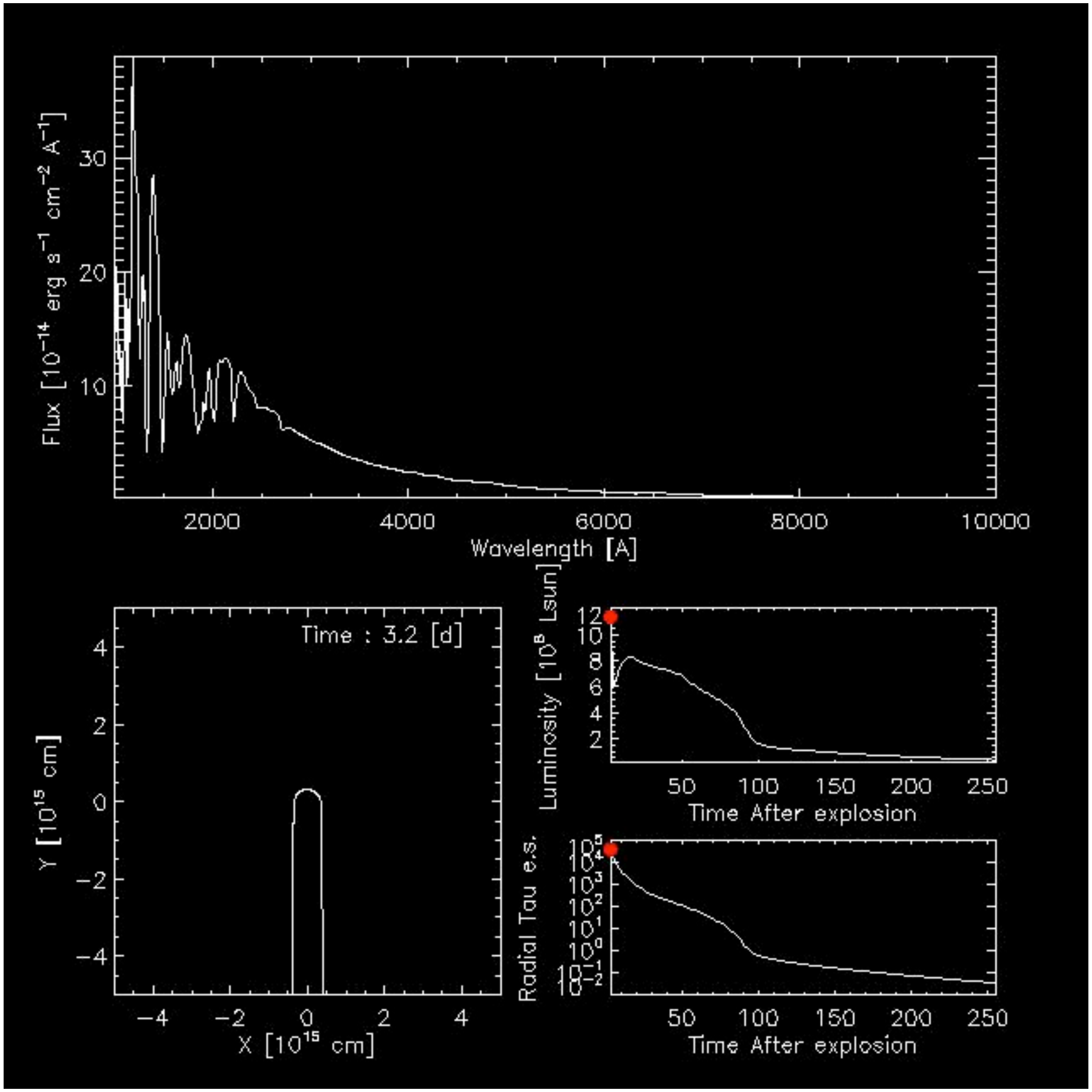
Baron et al. (1999)

SN II-P (2005cs)



Dessart et al. (2008)

Insight from Time-dependent non-LTE Radiative Transfer Modeling of a Type II-P SN

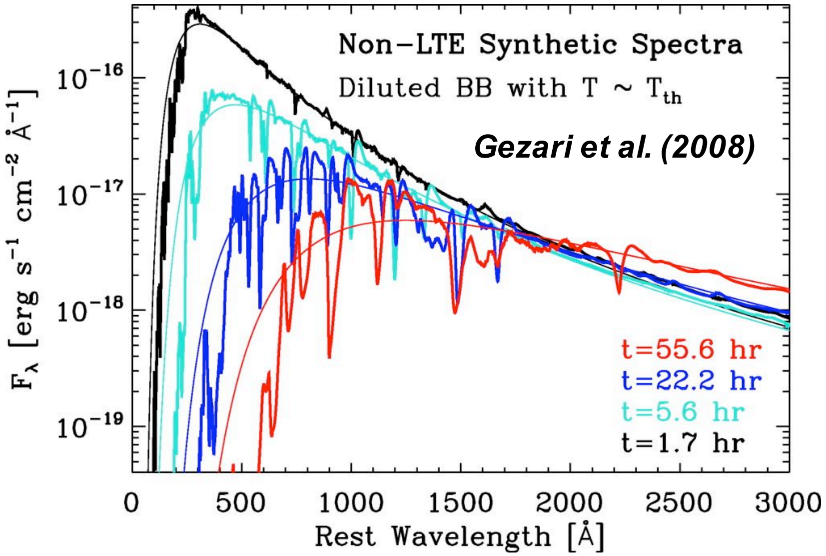


Focus on early times (< 50d)

- $\tau_{cont} > 30$
- Low polarization
- Weak line-blanketing
- Continuum windows
- Thermalized radiation at depth
- $R_{phot} \neq f(\lambda)$ in optical
- Large/sustained L_{bol}

1) Key Improvement of EPM since KK74: Use of a “correction” for the BB assumption

- Scattering-dominated atmosphere => $\kappa << \sigma \Rightarrow \lambda = \kappa / (\kappa + \sigma) << 1$
- Eddington Approximation and $dB/d\tau$ =const. => Flux $\propto 2\sqrt{\lambda}\ B(\tau = 1/\sqrt{3\lambda})$
  - -> $\tau = 1/\sqrt{3\lambda}$: thermalization depth
  - -> $2\sqrt{\lambda}$: Factor of “dilution” (<<1)
- Introduce ξ in KK74: $F_{obs} = \xi^2 \theta^2 \pi B_\nu(T_C)$; ($R_{phot} \rightarrow \xi R_{phot}$)
- In practice, ξ corrects for **ANY** deviation from a blackbody distribution => Provided the model fits the observations, the corresponding ξ will lead to the observed flux **EXACTLY**

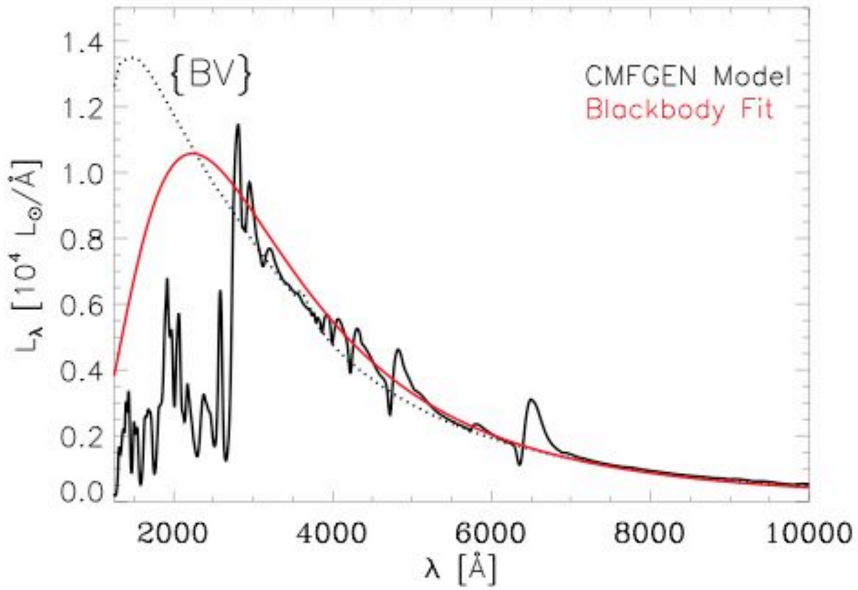


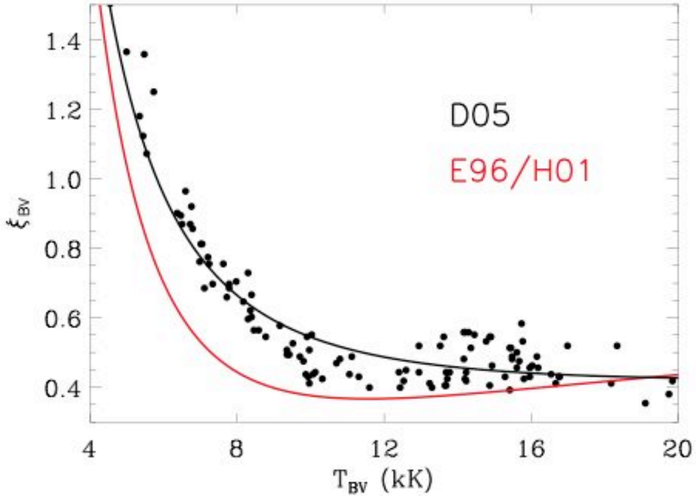
Gezari et al. (2008)

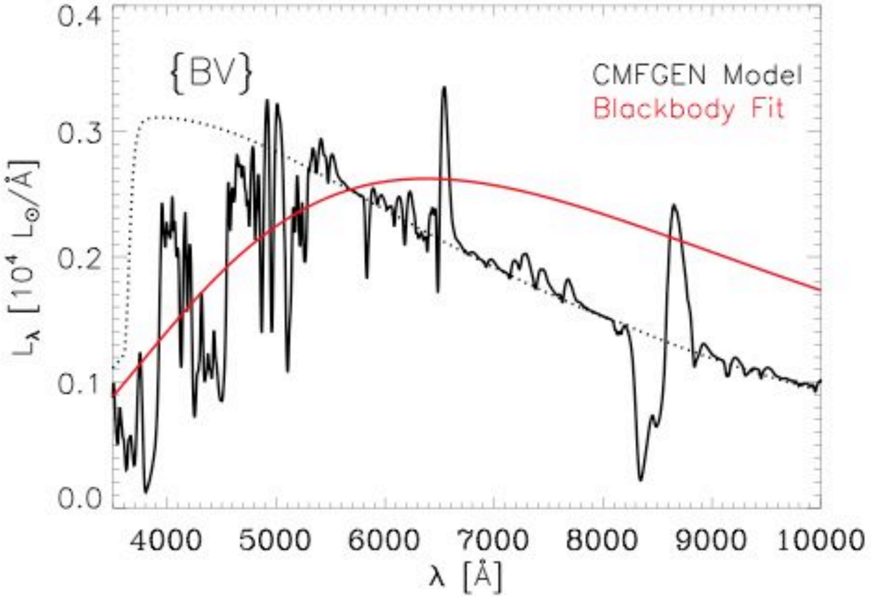
Example with early post-breakout models: SEDs fitted with $B(T_{th})$ and ξ~0.6

Properties of Correction Factors

- Two sources of correction factors: E96, D05
- ξ(T) computed with large set of theoretical models
- ξ ~ 0.4-0.6 in “hot” models: Strong dilution due to electron scattering
- ξ rises to ~1 in “cool” models: Weak dilution due to recombination (HI)
- ξ rises above 1 in “very cool” models. In theory, “dilution” **cannot** exceed 1. Instead, rise is due to **line blanketing**. Large **scatter** at small T
- Disagreement between D05 and E96/H01: ξ now greater by 10-20% => upward revision of distances







2) The Photospheric Velocity

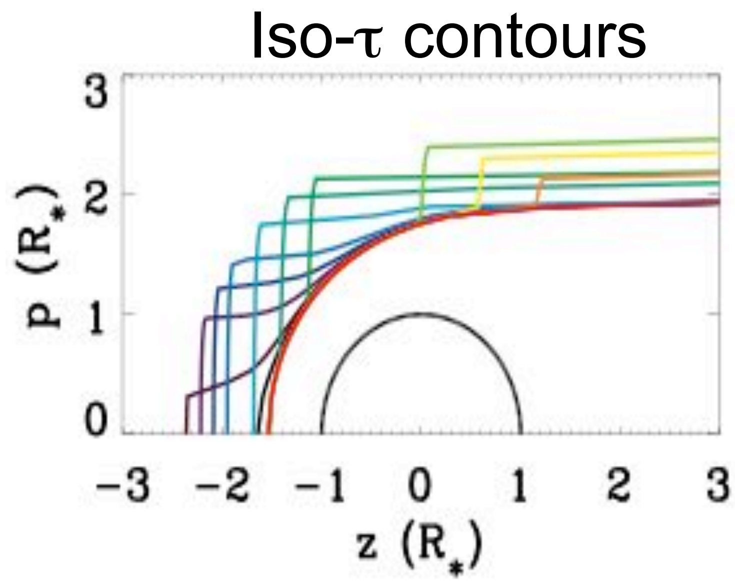
- Needed to determine $R_{phot}(t)$
- V ~ R => $\mathbf{V_{LOS} \sim Z}$ (depth along ray)
- Large velocities make things difficult:

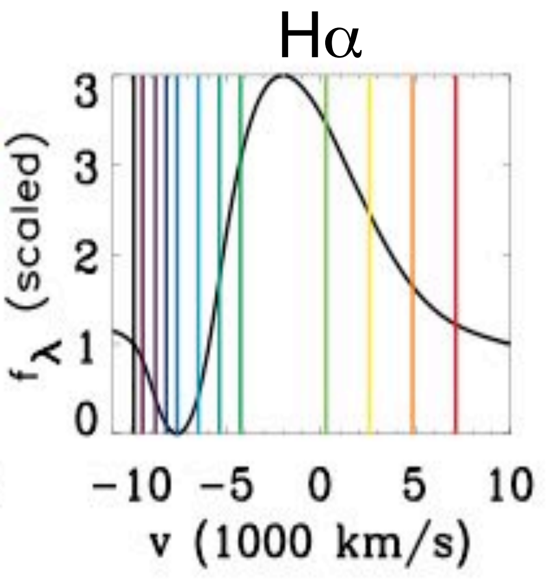
  Pb 1: peak blue-shifts + weak and broad lines at early times

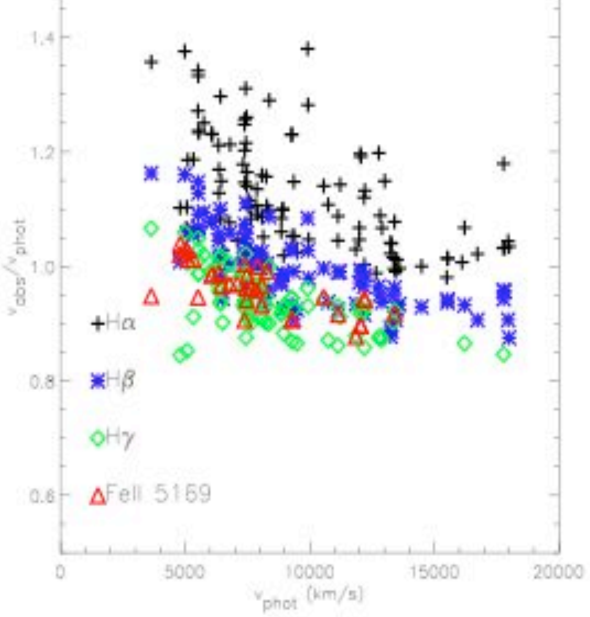
  Pb 2: Different lines have different optical depths => Different v_{abs}

  Pb 3: $\tau_{line} >> \tau_{cont}$ => $R_{phot}(\lambda)$

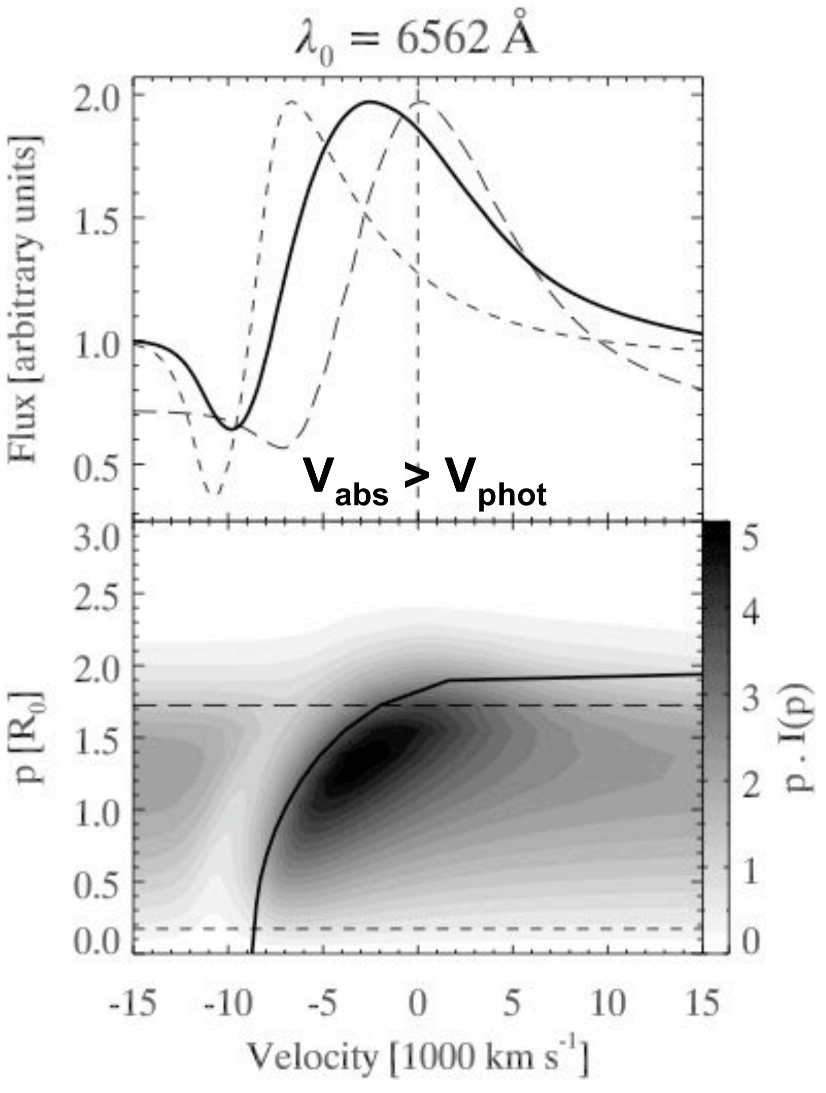
  Pb 4: Strong line-overlap at late times
- KK74 used Balmer lines (assumed as pure-scattering) => Use Model Atmosphere or measurement from **FeII 5169A** (when present!)



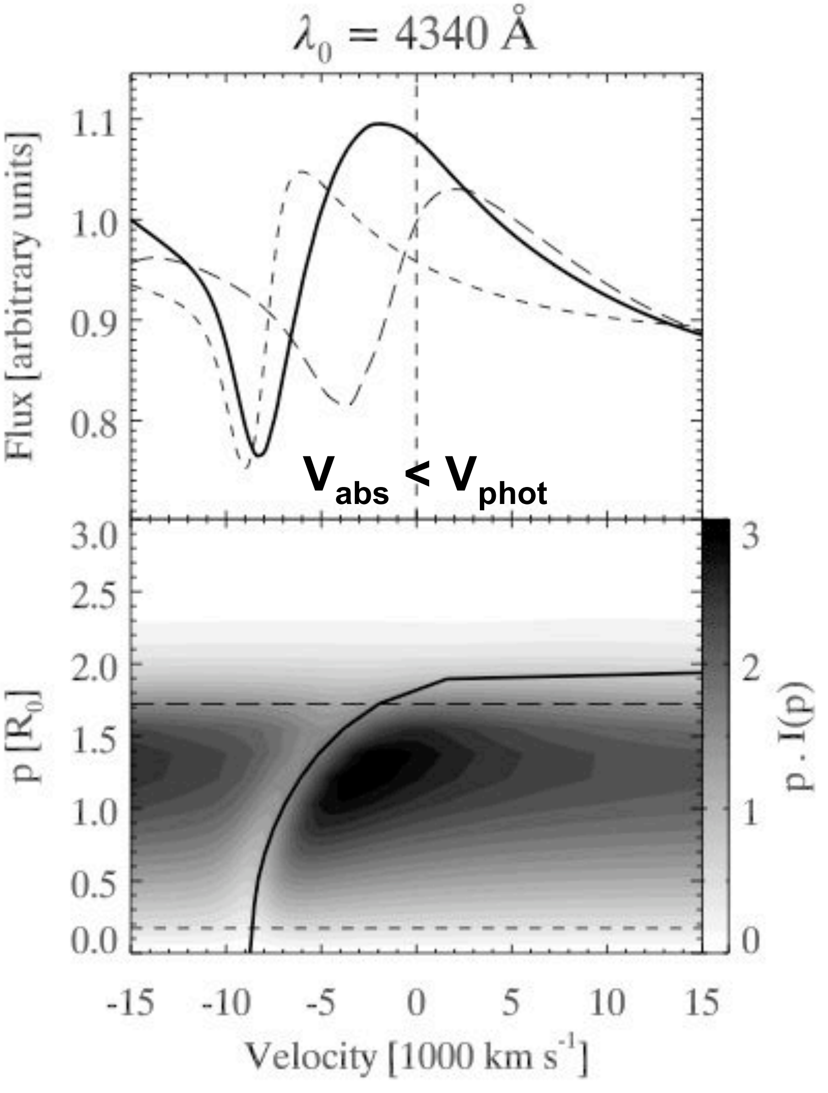




Note: v_{abs} > or < v_{phot} => Potential under- or over-estimate!



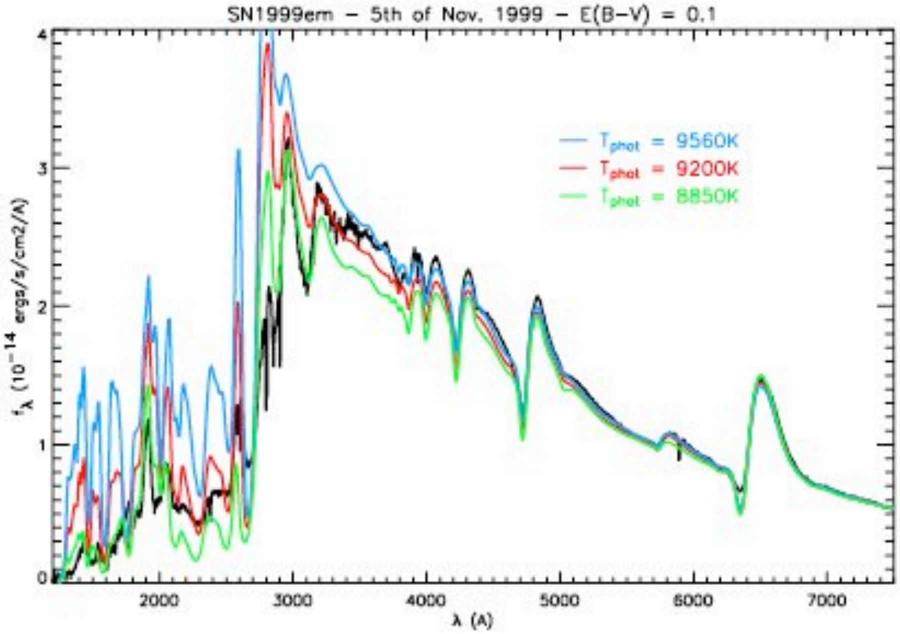
V_{abs} > V_{phot}

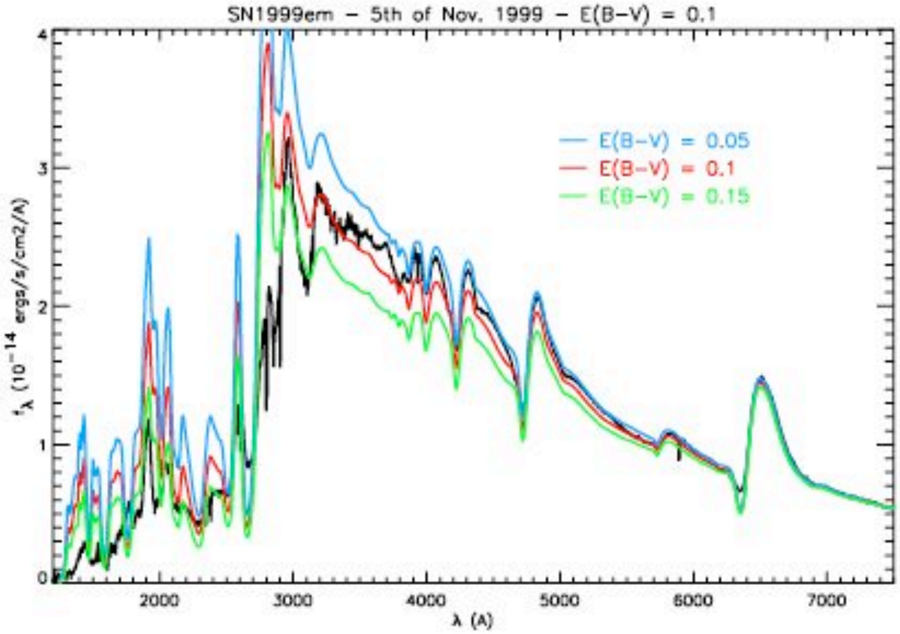


V_{abs} < V_{phot}

3) Use Model Atmosphere Calculations to Determine the Reddening

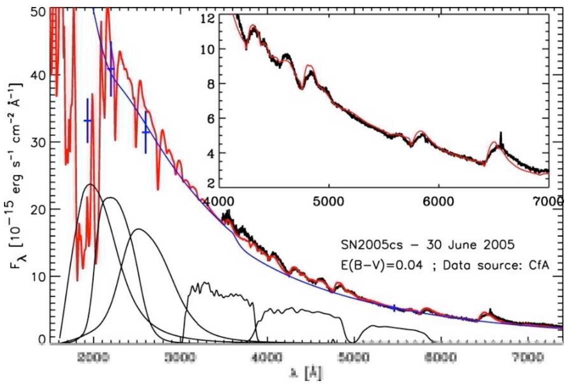
- Ionization constrained from lines
- Reddening constrained from SED slope using early-time observations (true continuum windows)
- Need spectral observations in UV or U/B bands
- Need accurate relative flux calibration

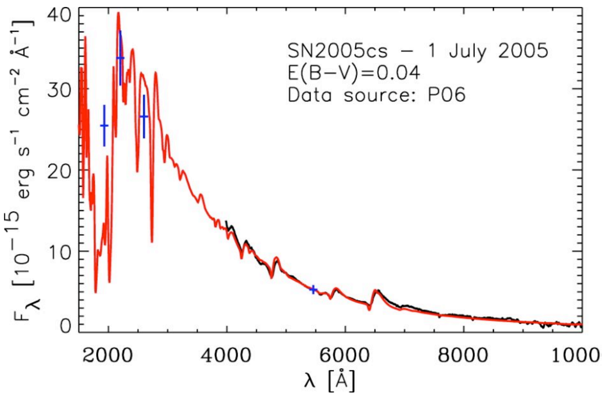


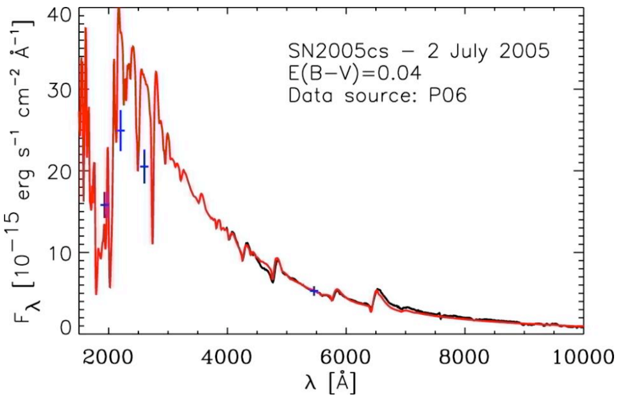


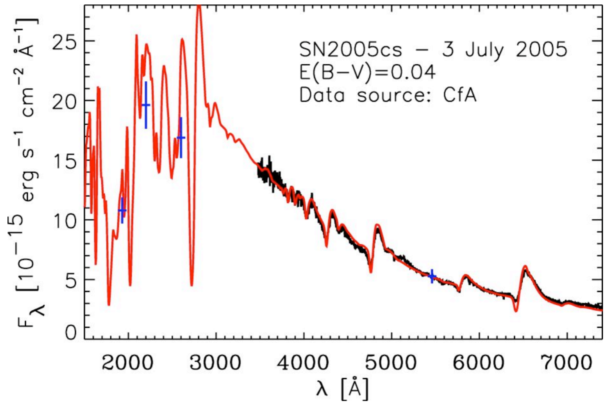
Non-LTE Radiative Transfer Modeling

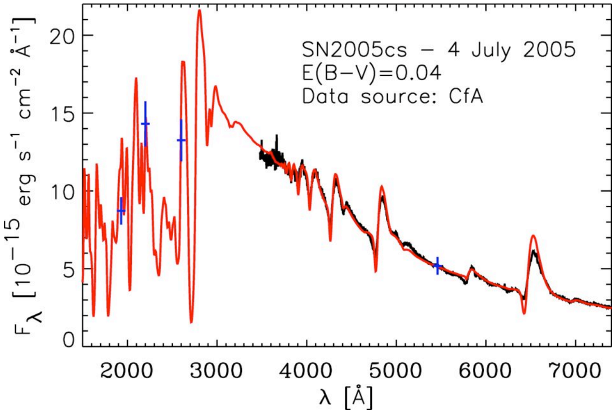
The case of the Type II-P SN 2005cs in NGC 5194 *(Dessart et al. 2008)*

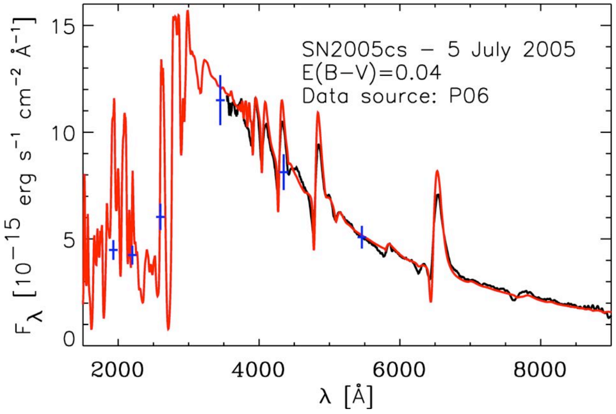


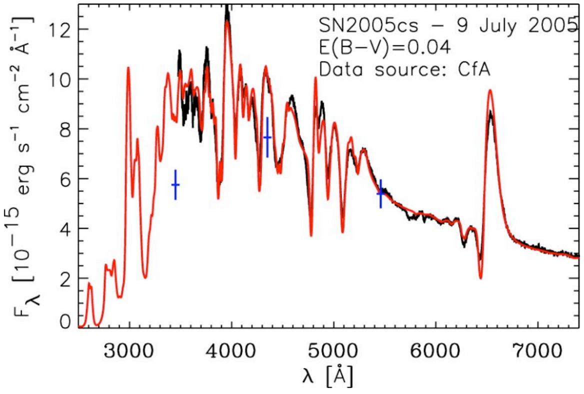


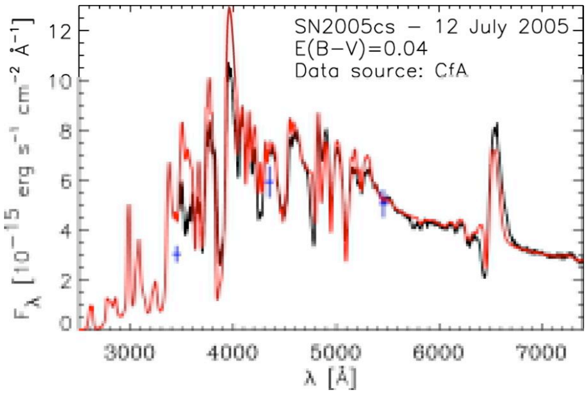


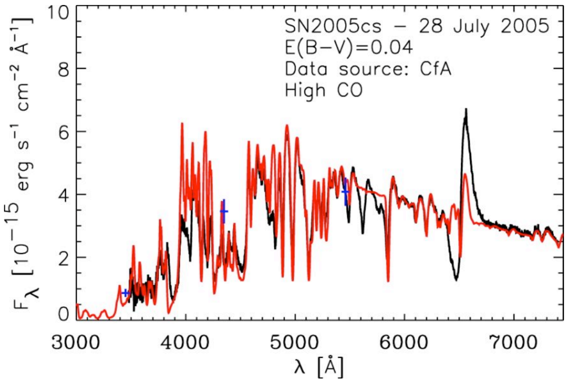












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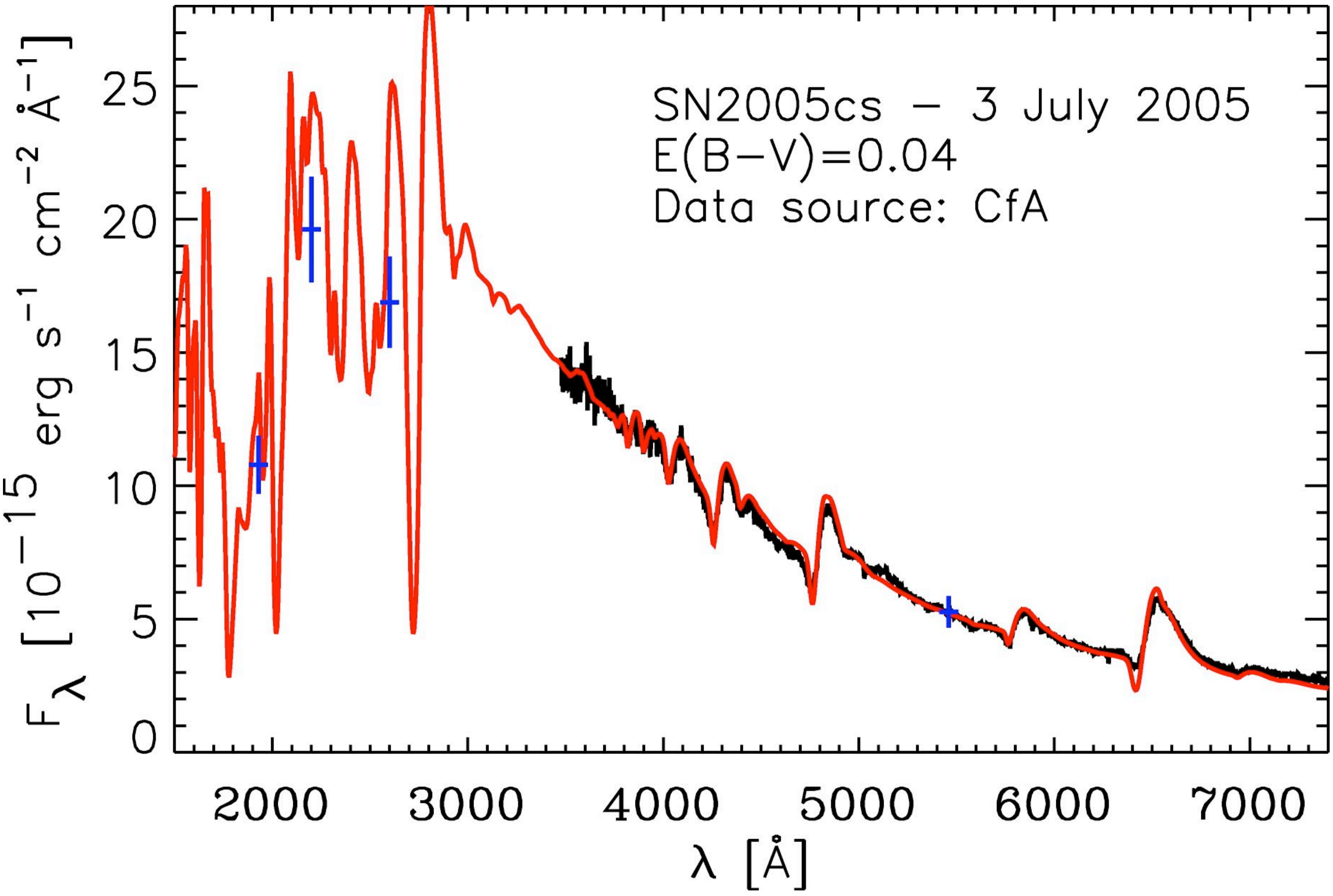
The case of the Type II-P SN 2005cs in NGC 5194 *(Dessart et al. 2008)*

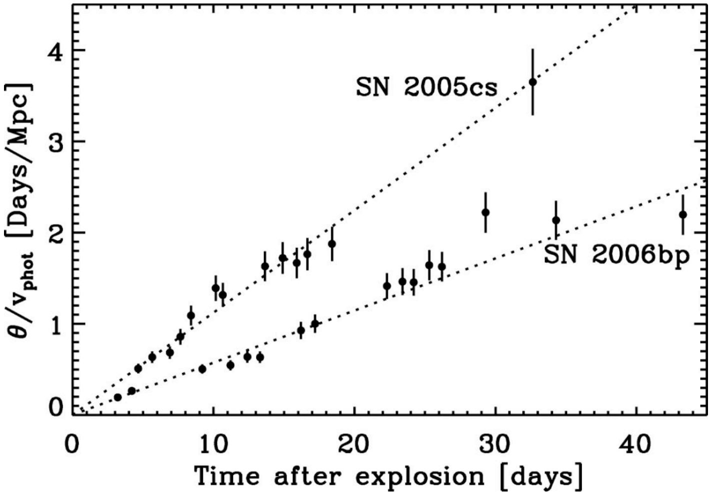


EPM Distance: Internal Consistency

SN 2005cs

JD (+2,453,000)	DAY	ANGULAR SIZE (10^8 km Mpc^{-1})			CORRECTION FACTOR			COLOR TEMPERATURE (K)		
		θ_{BV}	θ_{BVI}	θ_{VI}	ξ_{BV}	ξ_{BVI}	ξ_{VI}	T_{BV}	T_{BVI}	T_{VI}
552.25...............	2005 Jun 30	3.006	3.028	3.028	0.562	0.597	0.617	17835	16813	16122
553.25...............	2005 Jul 01	3.778	3.822	3.822	0.496	0.532	0.552	16272	15280	14649
554.50...............	2005 Jul 02	3.645	3.778	3.822	0.496	0.527	0.552	16242	15400	14619
555.25...............	2005 Jul 03	4.505	4.527	4.527	0.466	0.501	0.527	14438	13597	12935
556.00...............	2005 Jul 04	5.139	5.139	5.104	0.431	0.486	0.526	13498	12327	11456
557.75...............	2005 Jul 05	5.783	5.748	5.692	0.403	0.471	0.518	12792	11441	10525
558.25...............	2005 Jul 06	5.982	5.960	5.872	0.416	0.486	0.542	12184	10951	10020
561.25...............	2005 Jul 09	6.599	6.643	6.709	0.471	0.486	0.491	10200	9989	9899
562.50...............	2005 Jul 10	6.776	6.820	6.864	0.552	0.506	0.491	8997	9448	9689
563.50...............	2005 Jul 11	6.291	6.423	6.555	0.567	0.516	0.486	9118	9599	10080
564.25...............	2005 Jul 12	6.445	6.577	6.754	0.622	0.537	0.491	8547	9268	9929
566.00...............	2005 Jul 14	6.291	6.379	6.423	0.888	0.657	0.542	6923	7975	9178
580.25...............	2005 Jul 28	7.084	7.084	7.216	1.359	0.858	0.642	5240	6262	7525
D (Mpc)...........		9.0 + 0.5	8.9 + 0.5	8.7 + 0.5						
$t_{\mathrm{explosion}}$ (JD)......		2,453,547.6 ± 0.5	2,453,547.6 ± 0.5	2,453,547.7 ± 0.5						

Good agreement between filter sets
and number of epochs
=> **internal consistency**



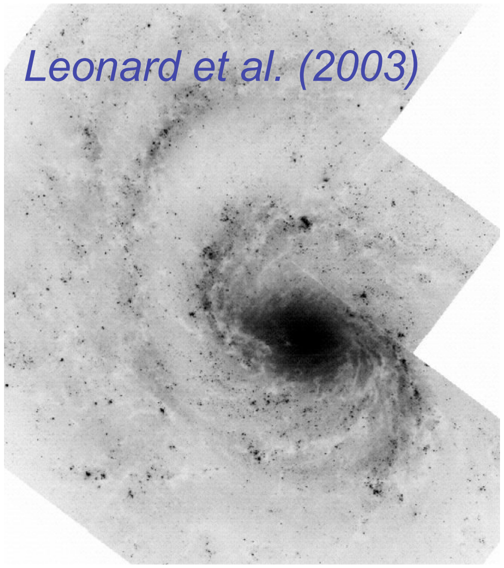
External Consistency: Comparison with the SEAM distance and other
Mitchell et al. (2001); Baron et al. (2004,2007)

- Based on non-LTE radiative transfer calculations (no blackbody assumption; no correction for “dilution”)
- Assume homologous expansion, i.e. $R \sim V t$
- Procedure: Minimize the scatter between epochs of the distance modulus $\mu_S(t, t_{exp}) = m_S(t) - M_S(t,t_{exp}) - A_S$, $S=\{B,V,I\}$, for a set of guesses on the explosion time t_{exp}

SN	EPM	SEAM	Other
1999em	11.5 ± 1.0 (D06)	12.2 ± 2.0 (D06)	11.7 ± 1.0 (Cepheid; L03)
2005cs	8.9 ± 0.5 (D08)	8.9 ± 0.7 (D08)	7.7 ± 1.0 (SBF; T01)
2006bp	17.5 ± 0.6 (D08)	17.1 ± 0.4 (D08)	17.0±? (TF; T88)

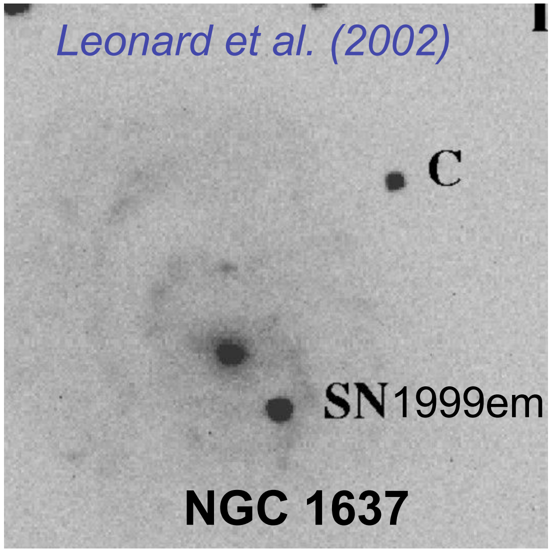
Good agreement between EPM and SEAM distance
=> **External consistency**

Former Discrepancy with the EPM:
the case of SN 1999em and Cepheids in the host NGC 1637



Leonard et al. (2003)

D_{cepheid}= **11.7 +/- 1.0** Mpc *(Leonard et al. 2003)*



Leonard et al. (2002)

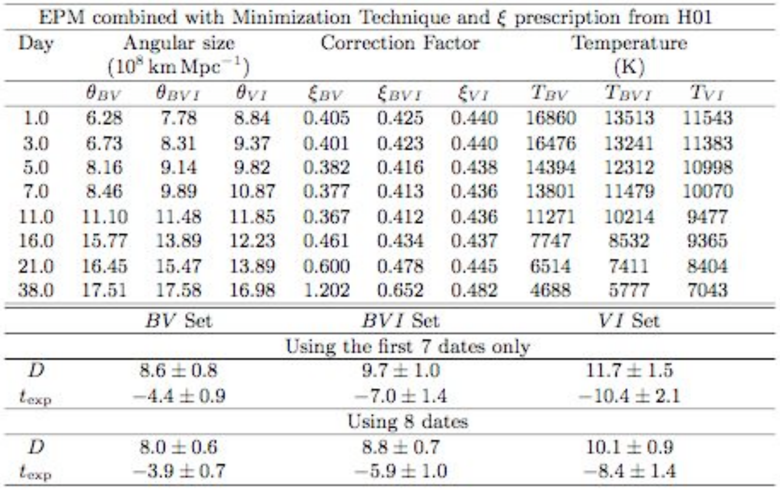
- EPM distance using **analytical** ξ of E96

  D_{SN1999em} = **7.9 +/- 0.5 Mpc** *(Hamuy et al. 2001, Leonard et al. 2002, Elmhamdi et al. 2003)*

- EPM/SEAM distance using tailored models

  D_{SN1999em} = 12.5 +/- 1.8 Mpc *(Baron et al. 2004)*
  D_{SN1999em} = 11.5 +/- 1.0 Mpc (Dessart & Hillier 2006)

Analytical versus Model correction factors



EPM combined with Minimization Technique and ξ prescription from H01

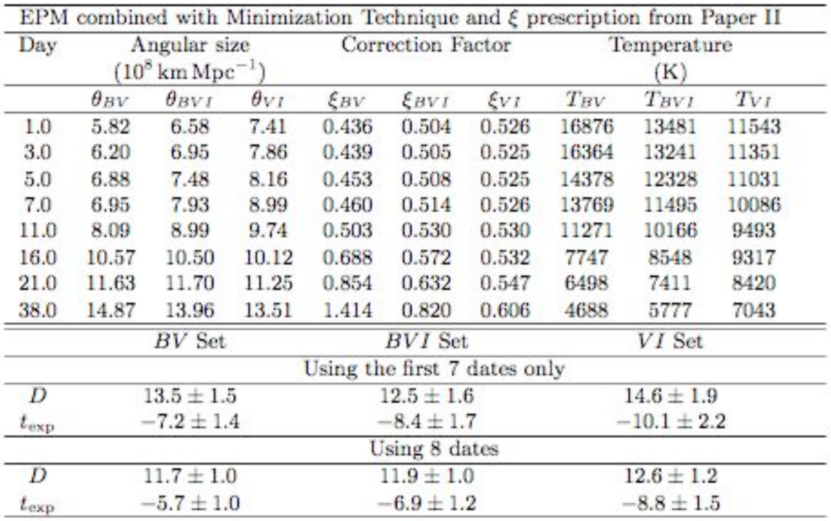
Day	Angular size (10^8 km Mpc^{-1})			Correction Factor			Temperature (K)		
	θ_{BV}	θ_{BVI}	θ_{VI}	ξ_{BV}	ξ_{BVI}	ξ_{VI}	T_{BV}	T_{BVI}	T_{VI}
1.0	6.28	7.78	8.84	0.405	0.425	0.440	16860	13513	11543
3.0	6.73	8.31	9.37	0.401	0.423	0.440	16476	13241	11383
5.0	8.16	9.14	9.82	0.382	0.416	0.438	14394	12312	10998
7.0	8.46	9.89	10.87	0.377	0.413	0.436	13801	11479	10070
11.0	11.10	11.48	11.85	0.367	0.412	0.436	11271	10214	9477
16.0	15.77	13.89	12.23	0.461	0.434	0.437	7747	8532	9365
21.0	16.45	15.47	13.89	0.600	0.478	0.445	6514	7411	8404
38.0	17.51	17.58	16.98	1.202	0.652	0.482	4688	5777	7043

	BV Set	BVI Set	VI Set
	Using the first 7 dates only		
D	8.6 ± 0.8	9.7 ± 1.0	11.7 ± 1.5
$t_{\rm exp}$	-4.4 ± 0.9	-7.0 ± 1.4	-10.4 ± 2.1
	Using 8 dates		
D	8.0 ± 0.6	8.8 ± 0.7	10.1 ± 0.9
$t_{\rm exp}$	-3.9 ± 0.7	-5.9 ± 1.0	-8.4 ± 1.4

Old prescription for analytical $\xi(T)$
=> **Lower D + scatter**

Cepheid Distance: 11.7 Mpc

New prescription for analytical $\xi(T)$
=> **Higher D + scatter**

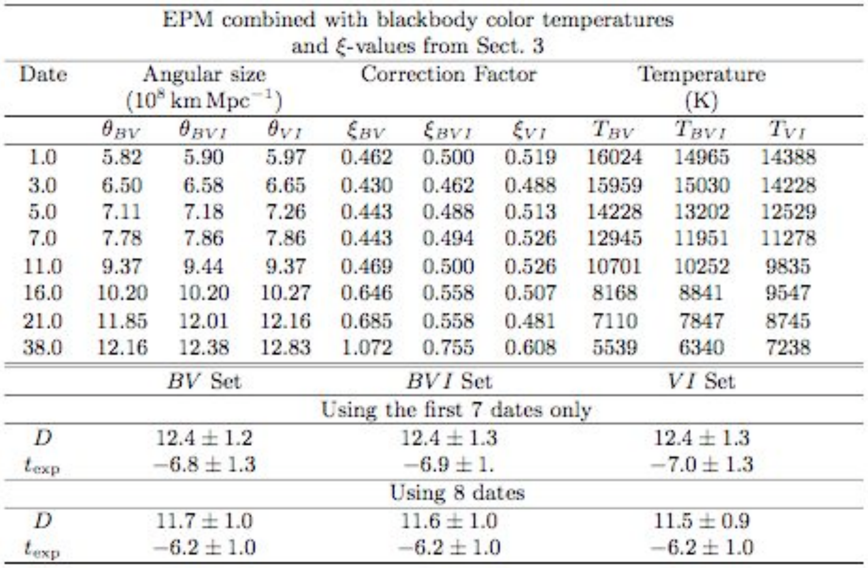


EPM combined with Minimization Technique and ξ prescription from Paper II

Day	Angular size (10^8 km Mpc^{-1})			Correction Factor			Temperature (K)		
	θ_{BV}	θ_{BVI}	θ_{VI}	ξ_{BV}	ξ_{BVI}	ξ_{VI}	T_{BV}	T_{BVI}	T_{VI}
1.0	5.82	6.58	7.41	0.436	0.504	0.526	16876	13481	11543
3.0	6.20	6.95	7.86	0.439	0.505	0.525	16364	13241	11351
5.0	6.88	7.48	8.16	0.453	0.508	0.525	14378	12328	11031
7.0	6.95	7.93	8.99	0.460	0.514	0.526	13769	11495	10086
11.0	8.09	8.99	9.74	0.503	0.530	0.530	11271	10166	9493
16.0	10.57	10.50	10.12	0.688	0.572	0.532	7747	8548	9317
21.0	11.63	11.70	11.25	0.854	0.632	0.547	6498	7411	8420
38.0	14.87	13.96	13.51	1.414	0.820	0.606	4688	5777	7043

	BV Set	BVI Set	VI Set
	Using the first 7 dates only		
D	13.5 ± 1.5	12.5 ± 1.6	14.6 ± 1.9
$t_{\rm exp}$	-7.2 ± 1.4	-8.4 ± 1.7	-10.1 ± 2.2
	Using 8 dates		
D	11.7 ± 1.0	11.9 ± 1.0	12.6 ± 1.2
$t_{\rm exp}$	-5.7 ± 1.0	-6.9 ± 1.2	-8.8 ± 1.5

ξ from Tailored Models
=> **Higher D + NO scatter**



EPM combined with blackbody color temperatures
and ξ-values from Sect. 3

Date	Angular size (10^8 km Mpc^{-1})			Correction Factor			Temperature (K)		
	θ_{BV}	θ_{BVI}	θ_{VI}	ξ_{BV}	ξ_{BVI}	ξ_{VI}	T_{BV}	T_{BVI}	T_{VI}
1.0	5.82	5.90	5.97	0.462	0.500	0.519	16024	14965	14388
3.0	6.50	6.58	6.65	0.430	0.462	0.488	15959	15030	14228
5.0	7.11	7.18	7.26	0.443	0.488	0.513	14228	13202	12529
7.0	7.78	7.86	7.86	0.443	0.494	0.526	12945	11951	11278
11.0	9.37	9.44	9.37	0.469	0.500	0.526	10701	10252	9835
16.0	10.20	10.20	10.27	0.646	0.558	0.507	8168	8841	9547
21.0	11.85	12.01	12.16	0.685	0.558	0.481	7110	7847	8745
38.0	12.16	12.38	12.83	1.072	0.755	0.608	5539	6340	7238

	BV Set	BVI Set	VI Set
	Using the first 7 dates only		
D	12.4 ± 1.2	12.4 ± 1.3	12.4 ± 1.3
$t_{\rm exp}$	-6.8 ± 1.3	$-6.9 \pm 1.$	-7.0 ± 1.3
	Using 8 dates		
D	11.7 ± 1.0	11.6 ± 1.0	11.5 ± 0.9
$t_{\rm exp}$	-6.2 ± 1.0	-6.2 ± 1.0	-6.2 ± 1.0

Tips for an accurate SN distance

- Status of the EPM: good to a few tens of % using analytical ξ and to ~10% using tailored models.
- Need non-LTE model atmospheres to grasp effects of scattering/thermalization
- Focus on early-time observations (weaker line blanketing and overlap, well-defined “continuum”, large τ, unique R_{phot})
- Use multiple epochs (Δt=4-5d over 30-50d)
- Extract v_{phot} from FeII 5169A or model atmosphere earlier on
- Use model atmosphere to avoid scatter in correction factors in EPM and determine reddening.
- Check internal consistency; Same distance for BV, BVI, VI, EPM or SEAM. Use alternate methods: SCM

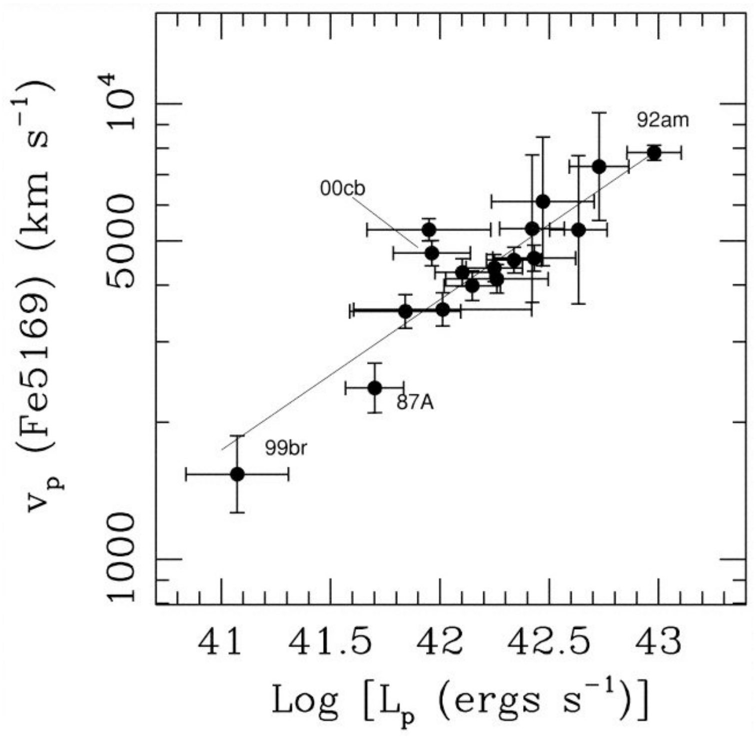
Future with the EPM and Type II SN distances

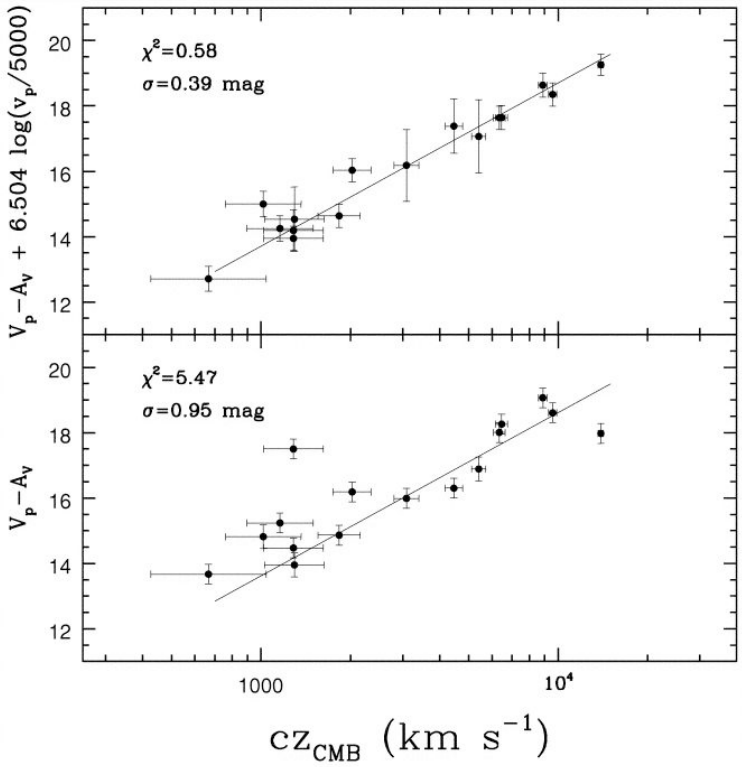
- Accurate use requires tailored radiative transfer models.
- Confront EPM to Cepheid distances: need to do this for SNe 2005cs (NGC 5194) and 2006bp (NGC 3953). Key for external check on EPM.
- Use shock-breakout detections with GALEX/Pan-STARRS to obtain t_{exp} => D is then the only unknown (1-2 follow-up observations would be enough).
- **Independent determination of the Hubble constant**
- Use SCM for high-redshift Type II-P SNe; Cosmology
- Note: The distance is a byproduct of the analysis, from which we learn on SN ejecta properties, explosion mechanisms, pre-SN evolution etc…

The Standard-Candle Method

Hamuy & Pinto (2002); Nugent et al. (2006)

- Based on empirical relation between luminosity and expansion velocity
- Original idea from Hamuy & Pinto (2002)
- Improvements by Nugent et al. (2006) for reddening and velocity determinations
- Fewer epochs needed => method can be applied to more distant SNe.





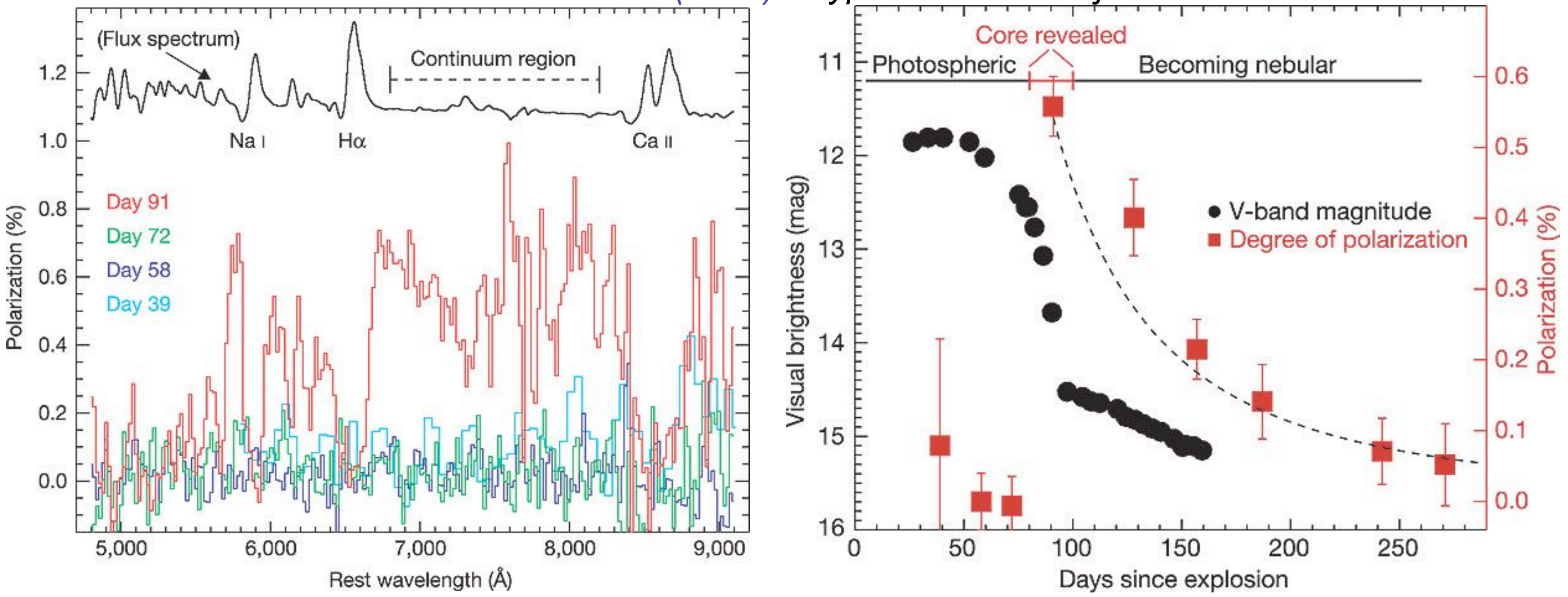
Departures from Spherical Symmetry

Low Polarization during Photosheric Phase

=> Small departure from sphericity during the photospheric phase

=> Little impact on distance

Leonard et al. (2006) - Type IIP SN2004dj



Time Dependent Effects

Utrobin & Chugai (2005); Dessart & Hillier (2008)

- $t_{rec} \sim t_{exp}$
- Optical depth effects can yield DDT effects even at early times
- Ionization freeze-out => increases N_e, depth of thermalization, and strength of “dilution” (lower ξ)
- Modifies τ_l and hence line width ad strength