Comparative Studies of SN Ia Spectra — with Help from SYNOW

David Branch

KITP March 2007

SYNOW

- a parameterized resonance–scattering code
- download from http://nhn.ou.edu/∼parrent

Comparative Direct Analysis of SN Ia Spectra

- **I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.**
- II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.
- III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.
- IV. Postmaximum (underway)
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

Comparative Direct Analysis of SN Ia Spectra

- **I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.**
- **II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.**
- III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.
- IV. Postmaximum (underway)
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

Comparative Direct Analysis of SN Ia Spectra

- **I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.**
- **II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.**
- **III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.**
- IV. Postmaximum (underway)
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

Comparative Direct Analysis of SN Ia Spectra

- **I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.**
- **II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.**
- **III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.**
- **IV. Postmaximum (underway)**
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

Comparative Direct Analysis of SN Ia Spectra

- I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.
- II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.
- III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.
- IV. Postmaximum (underway)
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

Comparative Direct Analysis of SN Ia Spectra

- I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.
- II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.
- III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.
- IV. Postmaximum (underway)
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

Comparative Direct Analysis of SN Ia Spectra

- I. SN 1994D (Branch et al. 2005, PASP): 26 spectra, from day -12 to day $+115$.
- II. Maximum Light (Branch et al. 2006, PASP): near–max spectra of 24 SNe Ia.
- III. Premaximum (Branch et al. 2007, soon to be submitted to PASP): 29 premax spectra of 21 SNe Ia.
- IV. Postmaximum (underway)
  - Leann Chau Dang (Whitman College), Nicholas Hall, Joshua Harrison, Wesley Ketchum, Mercy Melakayil, Miriam Musco (Indiana University), Jerod Parrent, Michael Troxel
  - Darrin Casebeer
  - Eddie Baron, Kazuhito Hatano, David Jeffery

WHY?

- Line Identifications
- Internally Consistent Quantification of Spectroscopic Evolution and Diversity, via SYNOW
- Explore Relationships Among SNe Ia, e.g., Discrete Subgroups or Continuous Distribution of Properties?
- Explore How Various Manifestations of Diversity Are Related to their Physical Causes

WHY?

- **Line Identifications**
- Internally Consistent Quantification of Spectroscopic Evolution and Diversity, via SYNOW
- Explore Relationships Among SNe Ia, e.g., Discrete Subgroups or Continuous Distribution of Properties?
- Explore How Various Manifestations of Diversity Are Related to their Physical Causes

WHY?

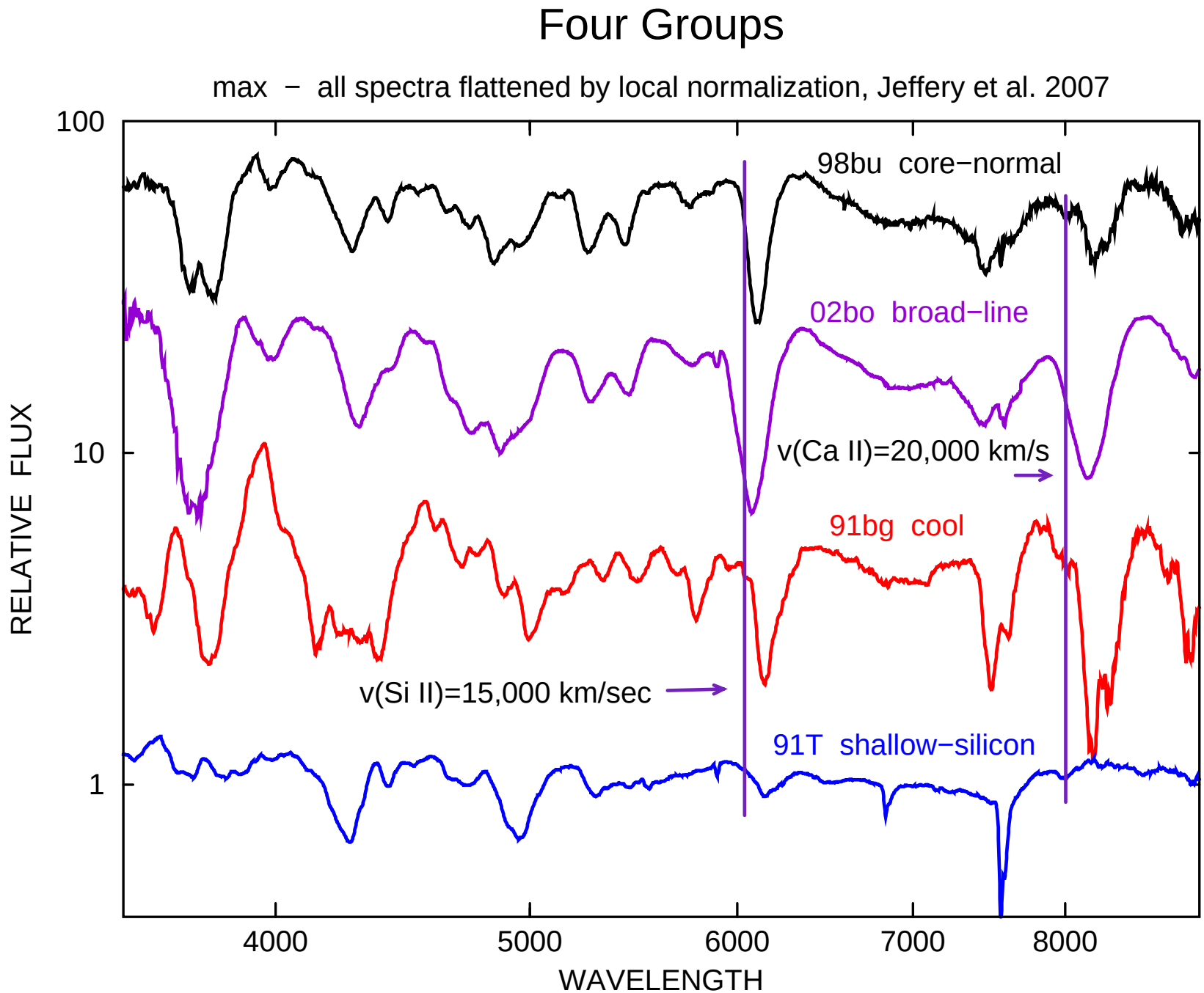
- **Line Identifications**
- **Internally Consistent Quantification of Spectroscopic Evolution and Diversity, via SYNOW**
- **Explore Relationships Among SNe Ia, e.g., Discrete Subgroups or Continuous Distribution of Properties?**
- **Explore How Various Manifestations of Diversity Are Related to their Physical Causes**

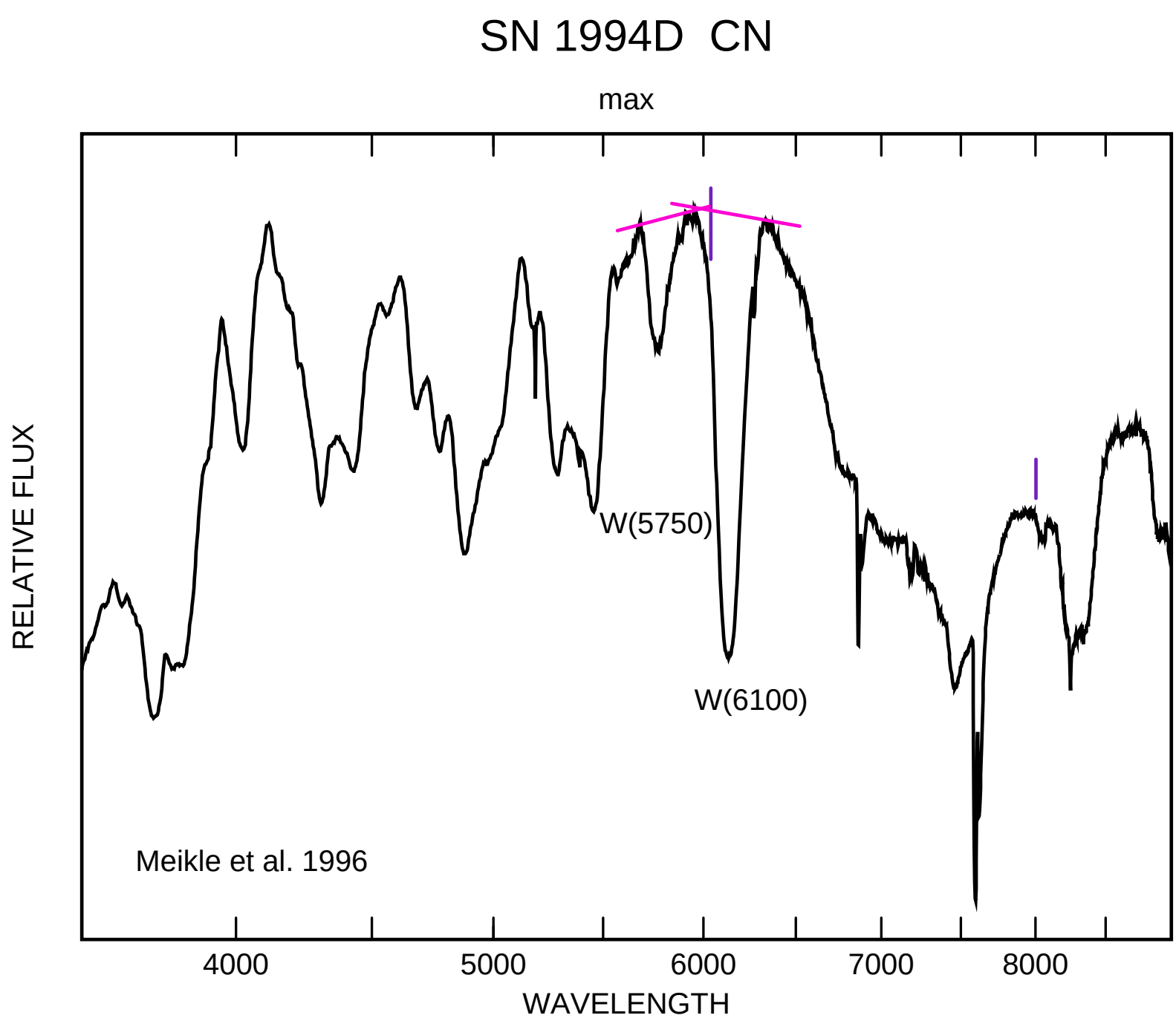
WHY?

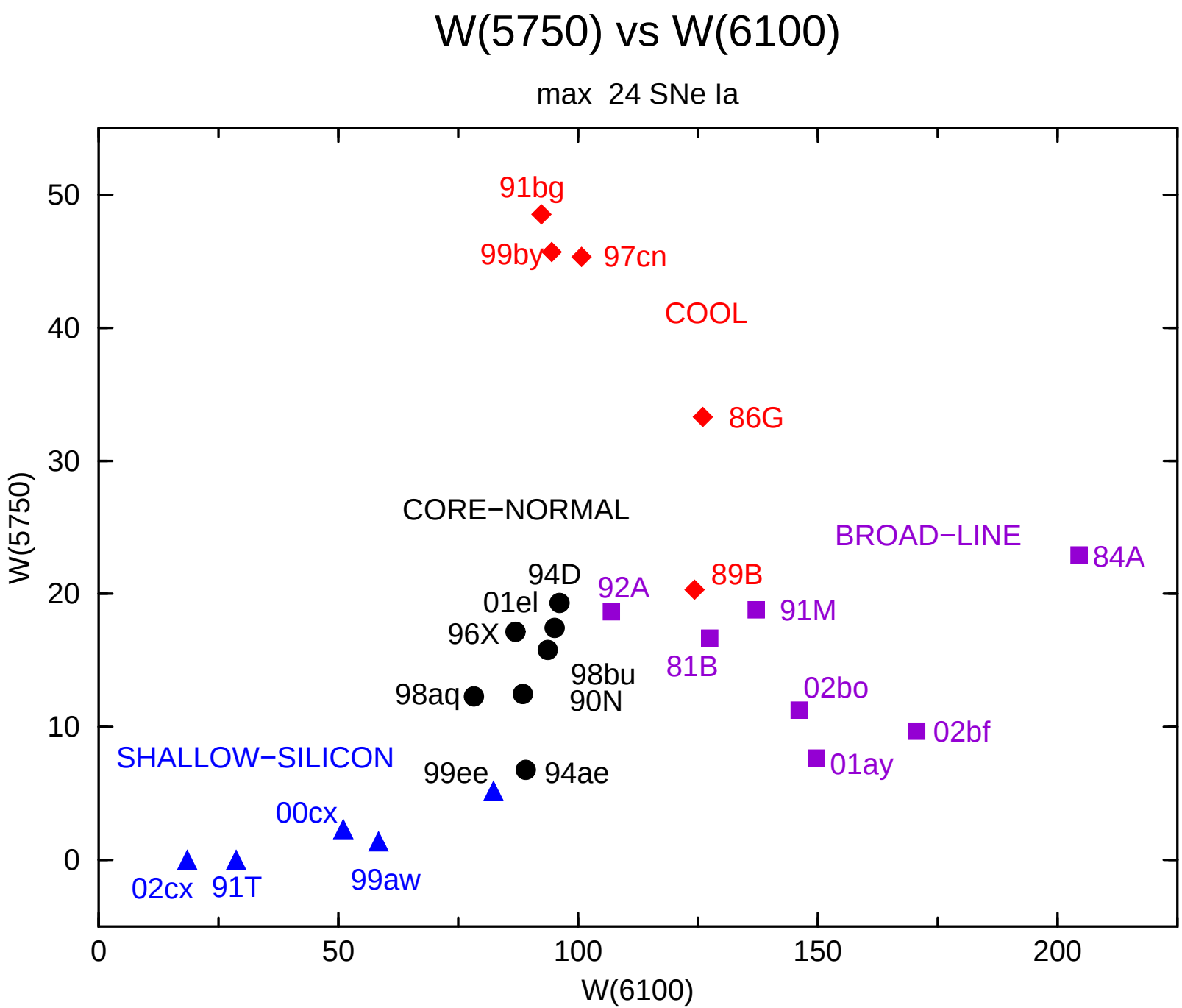
- **Line Identifications**
- **Internally Consistent Quantification of Spectroscopic Evolution and Diversity, via SYNOW**
- **Explore Relationships Among SNe Ia, e.g., Discrete Subgroups or Continuous Distribution of Properties?**
- **Explore How Various Manifestations of Diversity Are Related to their Physical Causes**

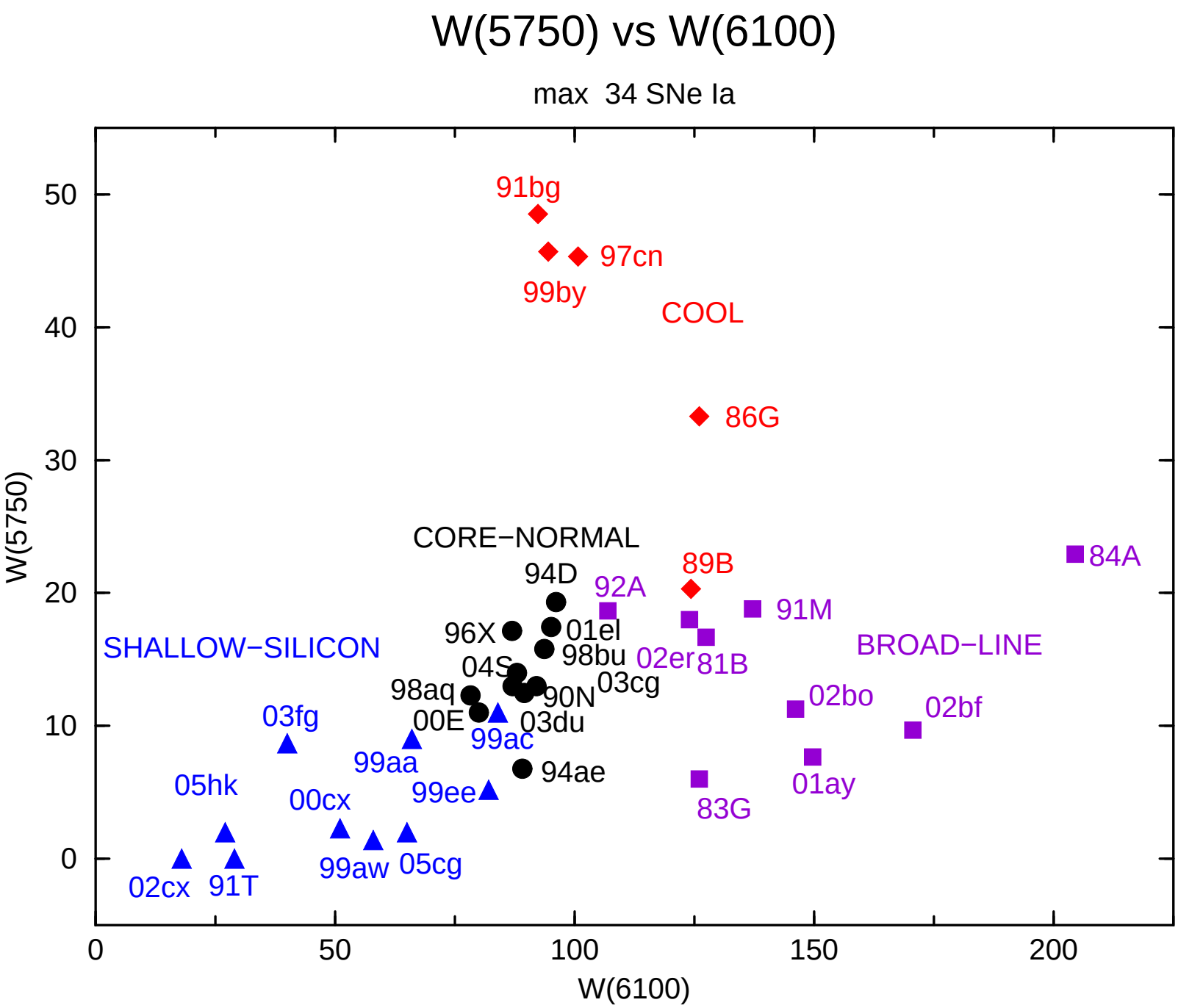
WHY?

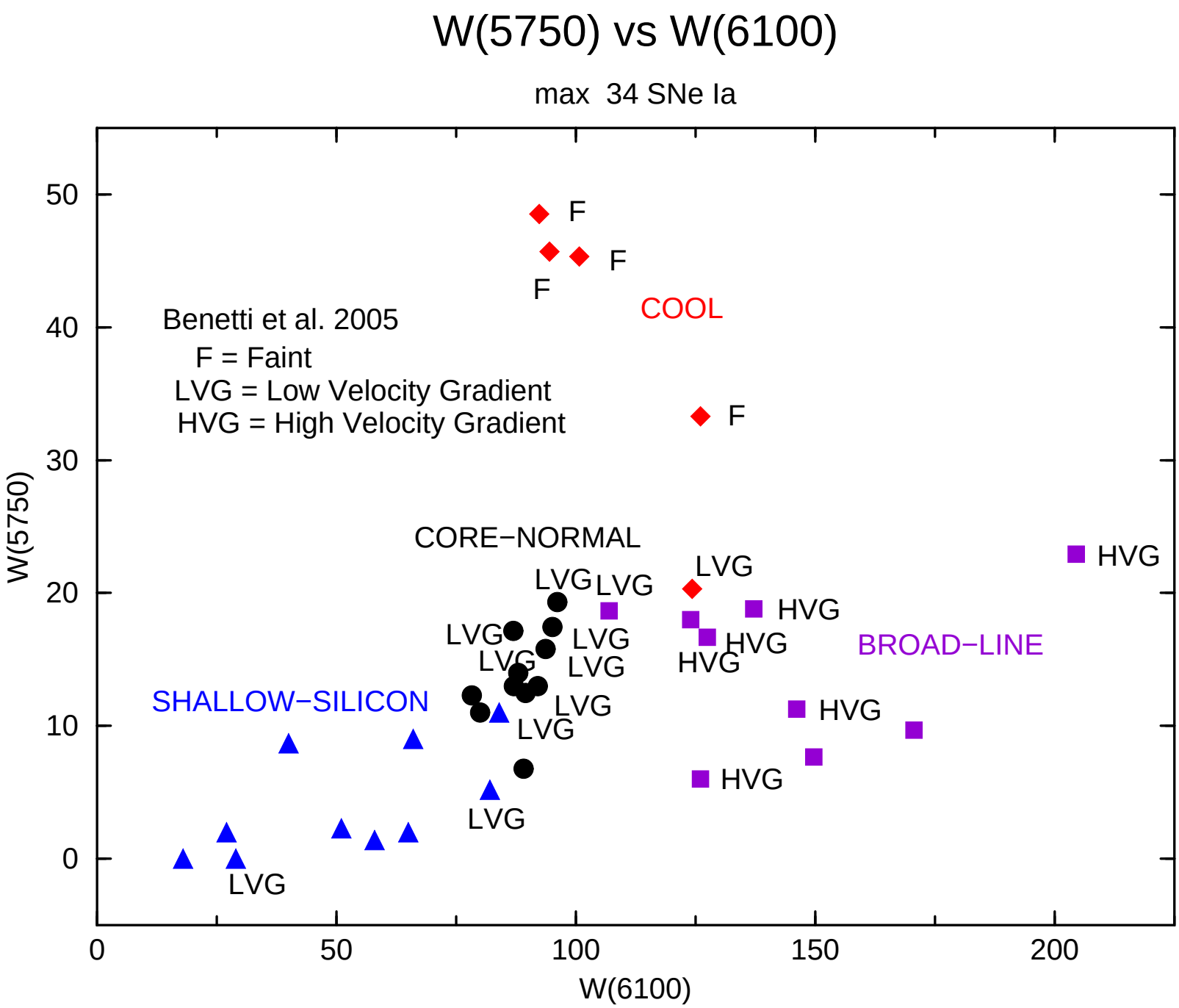
- **Line Identifications**
- **Internally Consistent Quantification of Spectroscopic Evolution and Diversity, via SYNOW**
- **Explore Relationships Among SNe Ia, e.g., Discrete Subgroups or Continuous Distribution of Properties?**
- **Explore How Various Manifestations of Diversity Are Related to their Physical Causes**

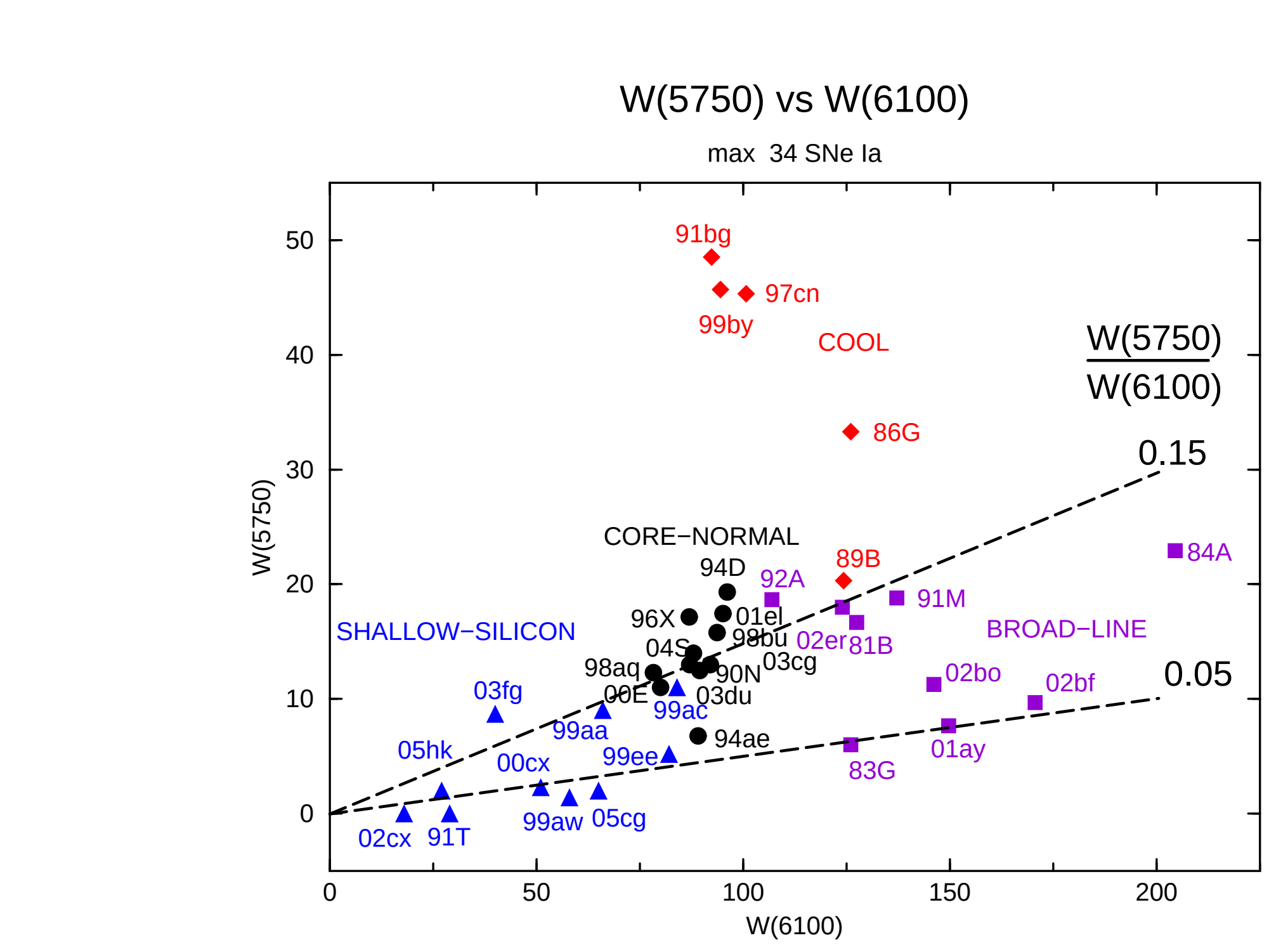

Four Groups
max − all spectra flattened by local normalization, Jeffery et al. 2007
100
10
1
RELATIVE FLUX
98bu core−normal
02bo broad−line
v(Ca II)=20,000 km/s
91bg cool
v(Si II)=15,000 km/sec
91T shallow−silicon
4000
5000
6000
7000
8000
WAVELENGTH

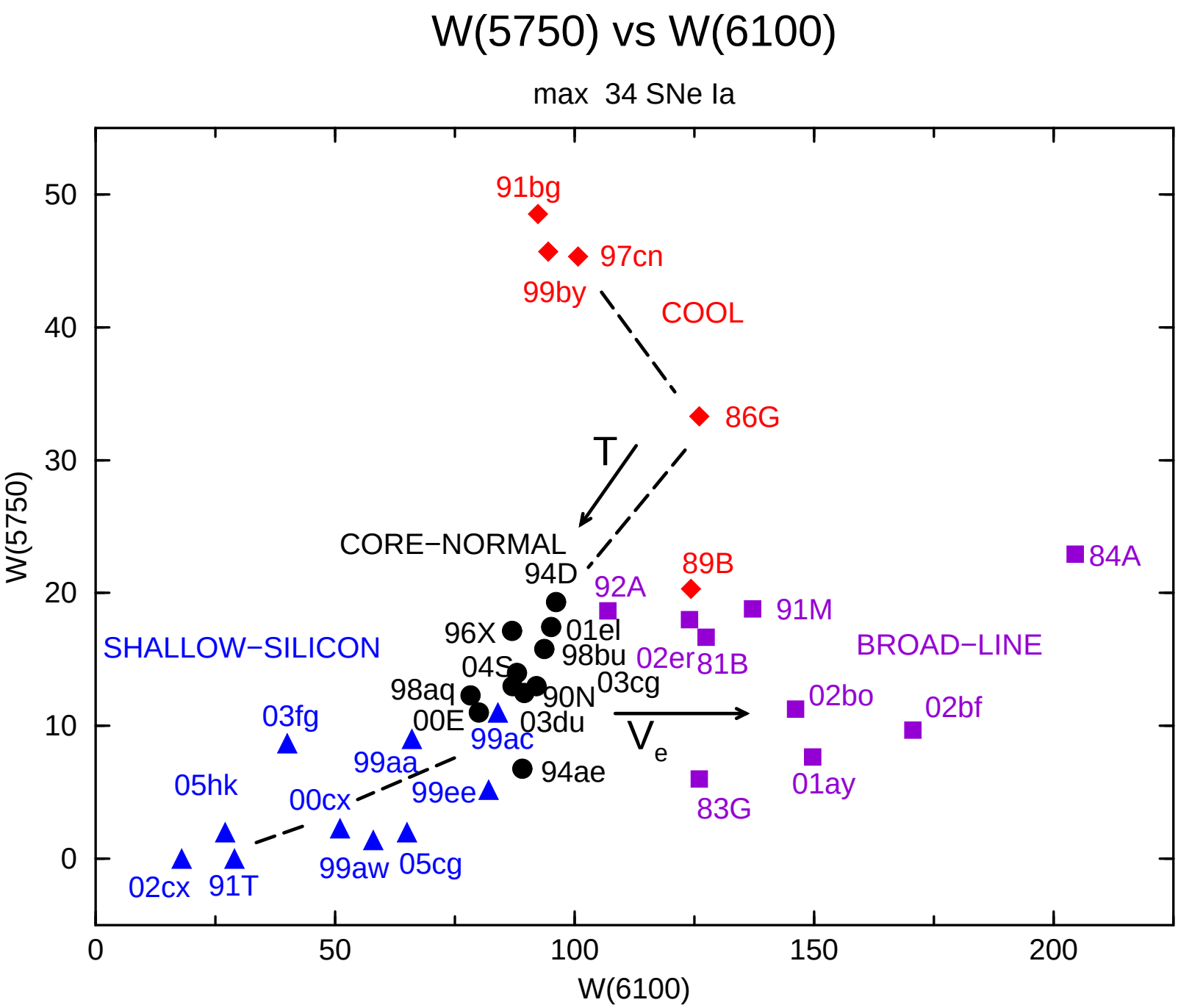

SN 1994D CN
max
W(5750)
W(6100)
Meikle et al. 1996
RELATIVE FLUX
4000
5000
6000
7000
8000
WAVELENGTH

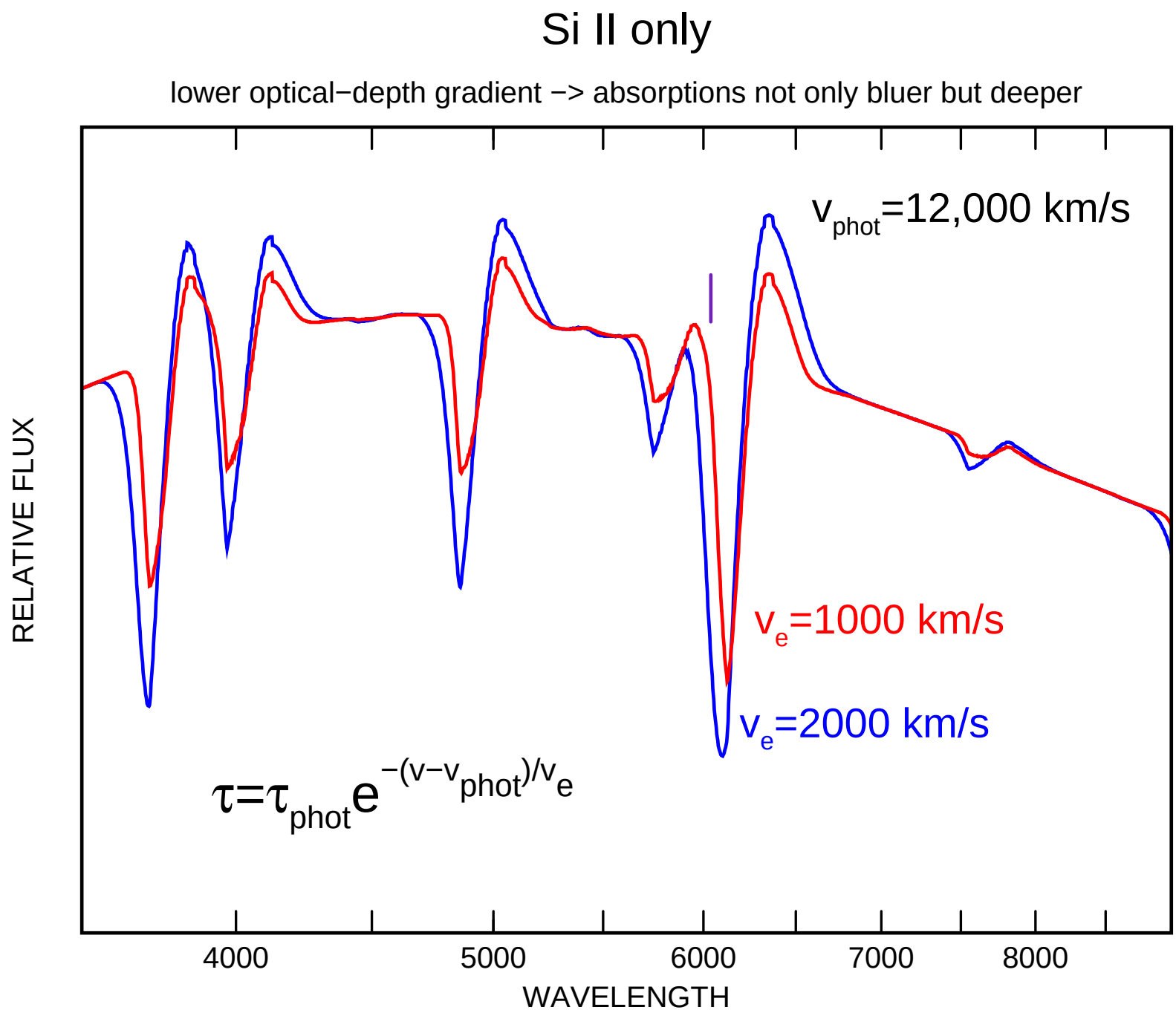

W(5750) vs W(6100)
max 24 SNe Ia
W(5750)
W(6100)
0
10
20
30
40
50
0
50
100
150
200
91bg
99by
97cn
COOL
86G
CORE−NORMAL
BROAD−LINE
84A
94D
92A
89B
01el
91M
96X
81B
98bu
98aq
90N
02bo
02bf
SHALLOW−SILICON
99ee
94ae
01ay
00cx
02cx
91T
99aw

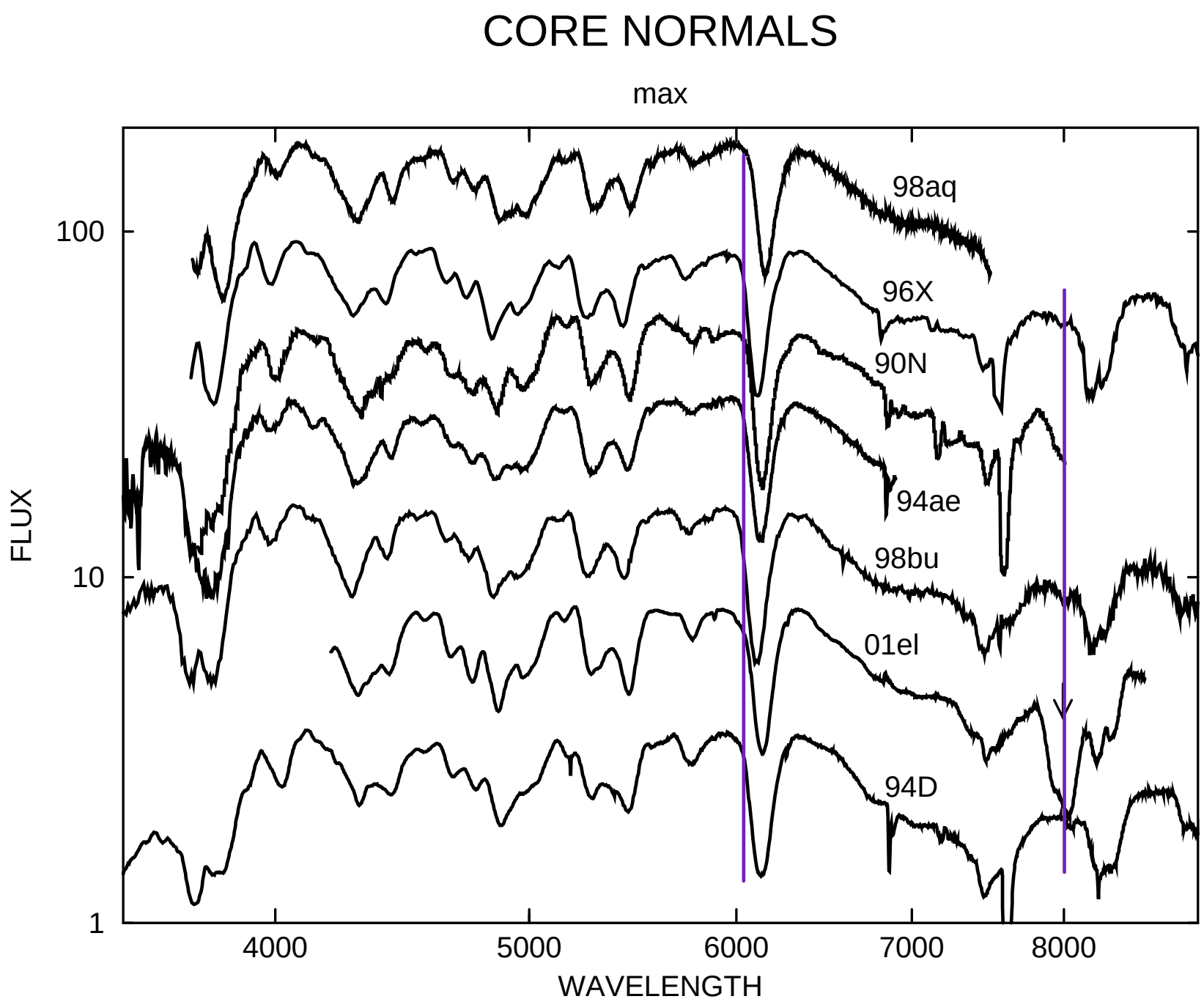

W(5750) vs W(6100)
max 34 SNe Ia
W(5750)
W(6100)
0
10
20
30
40
50
0
50
100
150
200
91bg
97cn
99by
COOL
86G
CORE−NORMAL
94D
89B
92A
84A
91M
96X
01el
98bu
02er
81B
BROAD−LINE
SHALLOW−SILICON
04S
03cg
98aq
90N
02bo
02bf
03fg
00E
03du
99ac
99aa
94ae
01ay
05hk
99ee
00cx
83G
99aw
05cg
02cx
91T

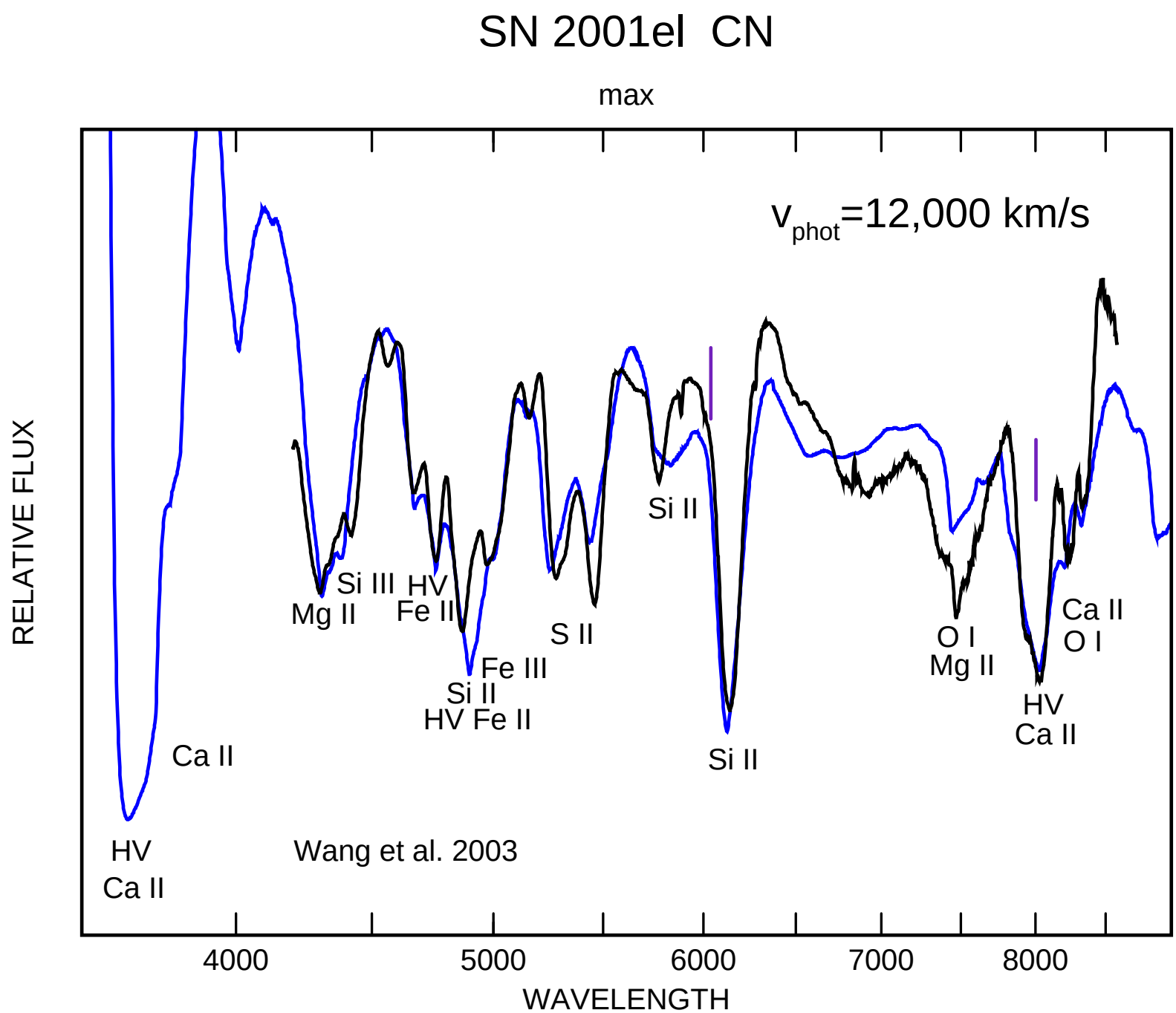

W(5750) vs W(6100)
max 34 SNe Ia
Benetti et al. 2005
F = Faint
LVG = Low Velocity Gradient
HVG = High Velocity Gradient
COOL
CORE−NORMAL
BROAD−LINE
SHALLOW−SILICON
F
LVG
HVG
W(5750)
W(6100)
0
10
20
30
40
50
0
50
100
150
200

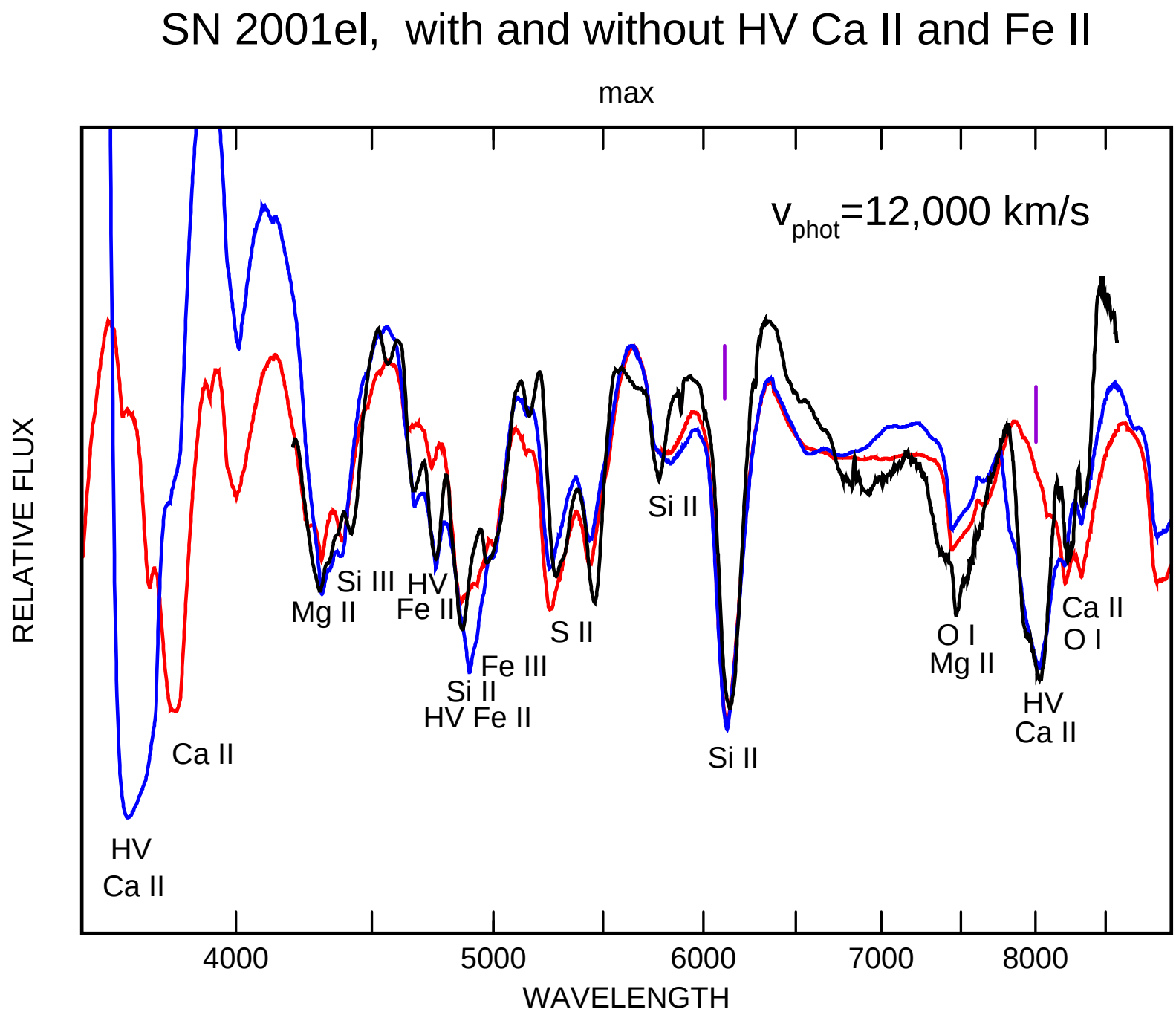

W(5750) vs W(6100)
max 34 SNe Ia
W(5750)
W(6100)
0
50
100
150
200
0
10
20
30
40
50
91bg
97cn
99by
COOL
86G
W(5750)
W(6100)
0.15
0.05
CORE−NORMAL
94D
92A
89B
84A
91M
96X
01el
98bu
02er
81B
BROAD−LINE
SHALLOW−SILICON
04S
03cg
98aq
90N
02bo
02bf
03fg
00E
03du
99ac
99aa
05hk
94ae
99ee
00cx
01ay
83G
02cx
91T
99aw
05cg


W(5750) vs W(6100)
max 34 SNe Ia
W(5750)
W(6100)
0
50
100
150
200
0
10
20
30
40
50
91bg
97cn
99by
COOL
86G
T
CORE−NORMAL
94D
89B
92A
91M
84A
96X
01el
98bu
02er
81B
BROAD−LINE
SHALLOW−SILICON
04S
03cg
98aq
90N
02bo
02bf
03fg
00E
03du
99ac
V_e
99aa
94ae
01ay
05hk
99ee
83G
00cx
02cx
91T
99aw
05cg


Si II only
lower optical−depth gradient −> absorptions not only bluer but deeper
v_phot=12,000 km/s
v_e=1000 km/s
v_e=2000 km/s
τ=τ_phot e^−(v−v_phot)/v_e
RELATIVE FLUX
4000
5000
6000
7000
8000
WAVELENGTH


CORE NORMALS
max
98aq
96X
90N
94ae
98bu
01el
94D
100
10
1
FLUX
4000
5000
6000
7000
8000
WAVELENGTH


SN 2001el CN
max
v_{phot}=12,000 km/s
RELATIVE FLUX
HV
Ca II
Ca II
Mg II
Si III
HV
Fe II
Fe III
Si II
HV Fe II
S II
Si II
Si II
O I
Mg II
HV
Ca II
Ca II
O I
Wang et al. 2003
4000
5000
6000
7000
8000
WAVELENGTH


SN 2001el, with and without HV Ca II and Fe II
max
v_{phot}=12,000 km/s
RELATIVE FLUX
HV
Ca II
Ca II
Mg II
Si III
HV
Fe II
Si II
HV Fe II
Fe III
S II
Si II
Si II
O I
Mg II
HV
Ca II
Ca II
O I
4000
5000
6000
7000
8000
WAVELENGTH

SNe Ia at Maximum Light

- **Core–normals — highly homogeneous. (How?)**
- Broad–lines — higher density at high velocities. (Why?)
- Cools — lower T.
- Shallow–silicons — higher T.
- We see continuity, rather than discrete subgroups — except for SN 02cx–likes (and possibly the cools).
- HV features are not clearly correlated with PV features.

SNe Ia at Maximum Light

- **Core–normals — highly homogeneous. (How?)**
- **Broad–lines — higher density at high velocities. (Why?)**
- Cools — lower T.
- Shallow–silicons — higher T.
- We see continuity, rather than discrete subgroups — except for SN 02cx–likes (and possibly the cools).
- HV features are not clearly correlated with PV features.

SNe Ia at Maximum Light

- **Core–normals — highly homogeneous. (How?)**
- **Broad–lines — higher density at high velocities. (Why?)**
- **Cools — lower T.**
- **Shallow–silicons — higher T.**
- **We see continuity, rather than discrete subgroups — except for SN 02cx–likes (and possibly the cools).**
- **HV features are not clearly correlated with PV features.**

SNe Ia at Maximum Light

- **Core–normals — highly homogeneous. (How?)**
- **Broad–lines — higher density at high velocities. (Why?)**
- **Cools — lower T.**
- **Shallow–silicons — higher T.**
- **We see continuity, rather than discrete subgroups — except for SN 02cx–likes (and possibly the cools).**
- **HV features are not clearly correlated with PV features.**

SNe Ia at Maximum Light

- **Core–normals — highly homogeneous. (How?)**
- **Broad–lines — higher density at high velocities. (Why?)**
- **Cools — lower T.**
- **Shallow–silicons — higher T.**
- **We see continuity, rather than discrete subgroups — except for SN 02cx–likes (and possibly the cools).**
- **HV features are not clearly correlated with PV features.**

SNe Ia at Maximum Light

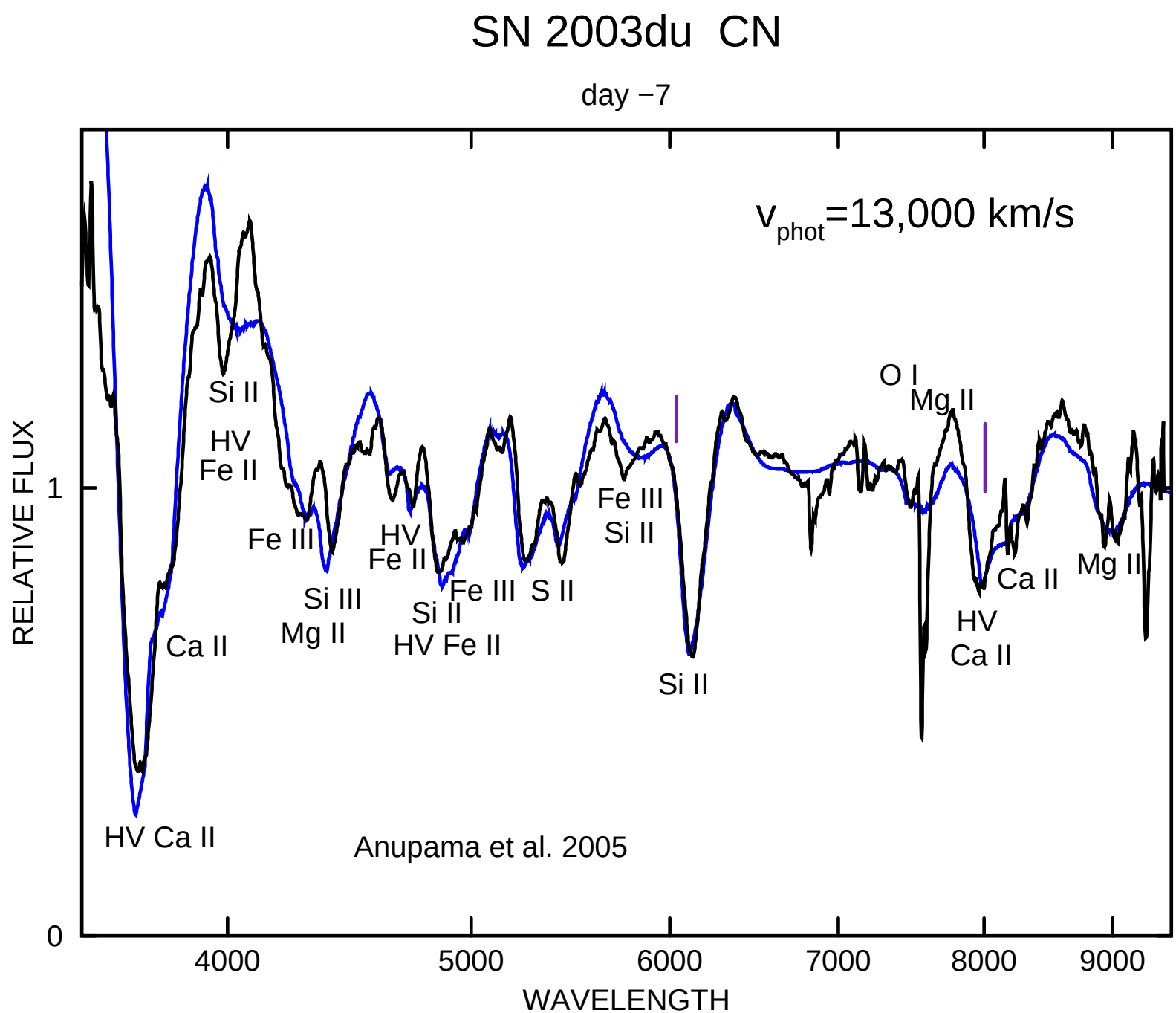
- **Core–normals — highly homogeneous. (How?)**
- **Broad–lines — higher density at high velocities. (Why?)**
- **Cools — lower T.**
- **Shallow–silicons — higher T.**
- **We see continuity, rather than discrete subgroups — except for SN 02cx–likes (and possibly the cools).**
- **HV features are not clearly correlated with PV features.**

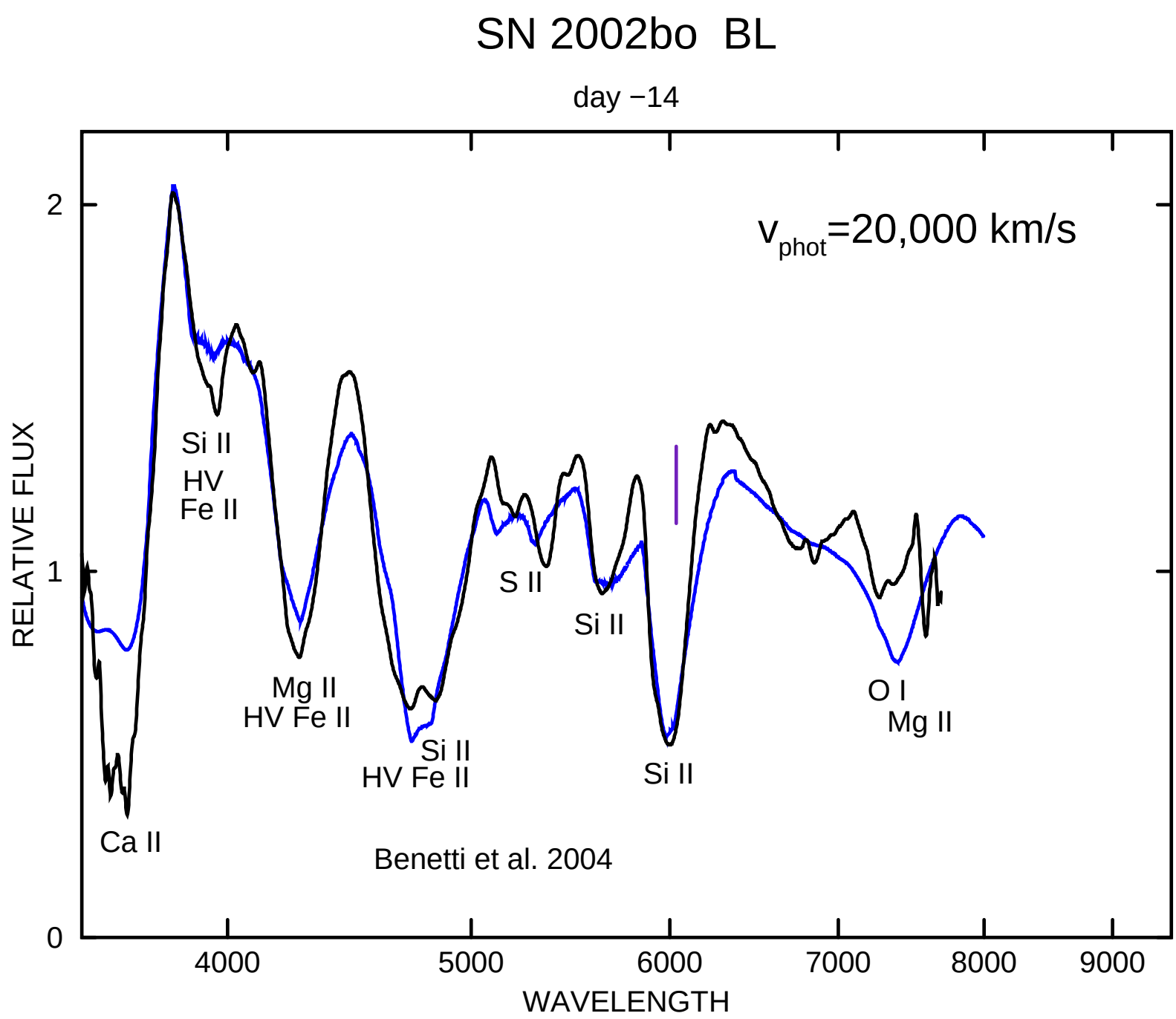
The Premax Sample:
21 “One Week Premax”, 8 “Early”

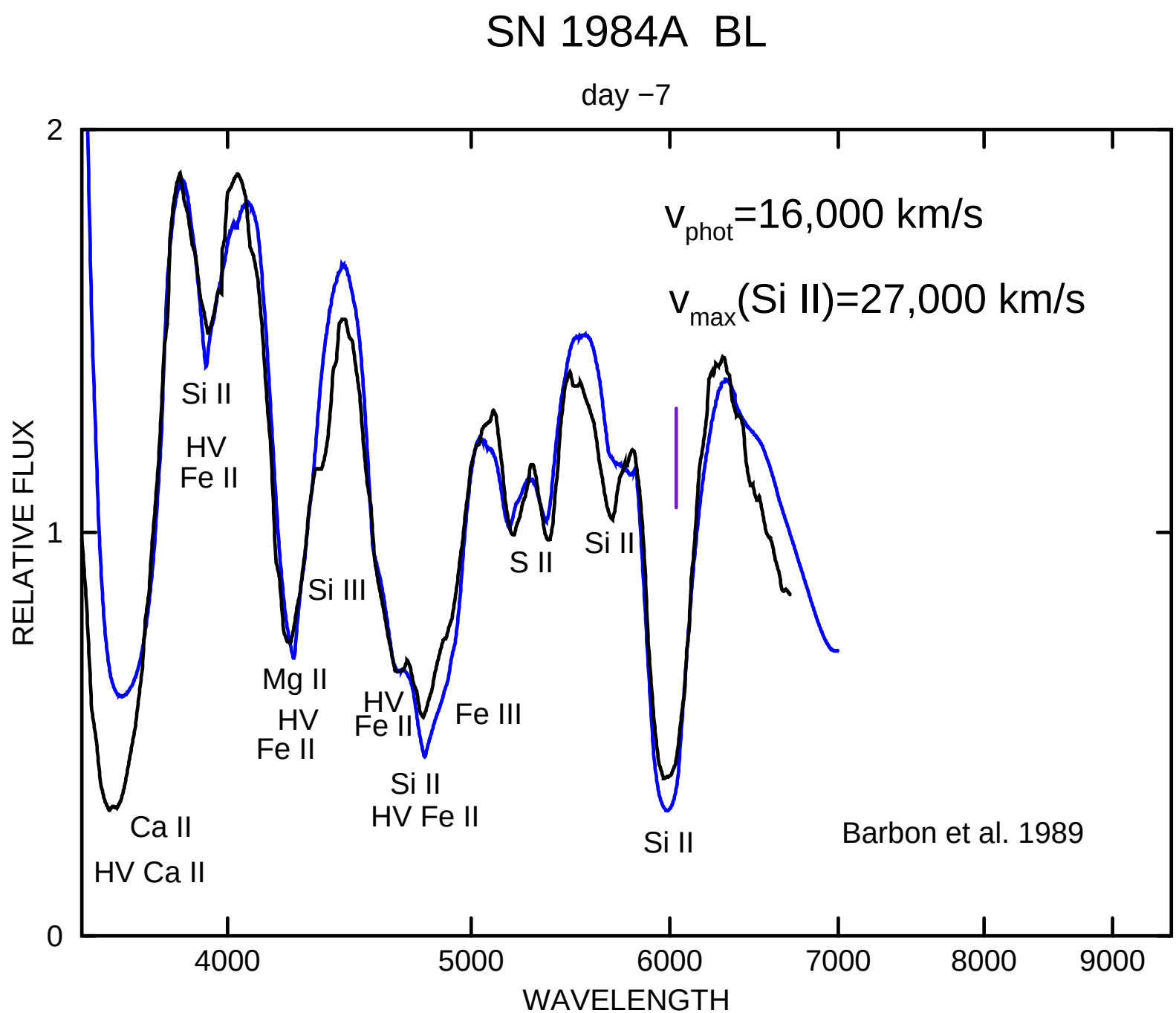
- **1984A BL −7** Barbon et al. (1989)
- **1986G CL −6** Cristiani et al. (1992)
- **1989B CL −7** Wells et al. (1994)
- **1990N CN −8, −14** Leibundut et al. (1991)
- **1991T SS −7, −11** Phillips et al. (1992)
- **1992A BL −6** P. Challis, unpublished
- **1994D CN −8, −12** Meikle et al. (1996)
- **1997br SS −7** Li et al. (1999)
- **1998aq CN −8** Branch et al. (2003)
- **1998bu CN −6** Hernandez et al. (2000)
- **1999aa SS −7, −12** Garavini et al. 2004)
- **1999ac SS −9, −15** Garavini et al. 2005)
- **1999by CL −5** Garnavich et al. (2004)
- **1999ee SS −7** Hamuy et al. (2002)

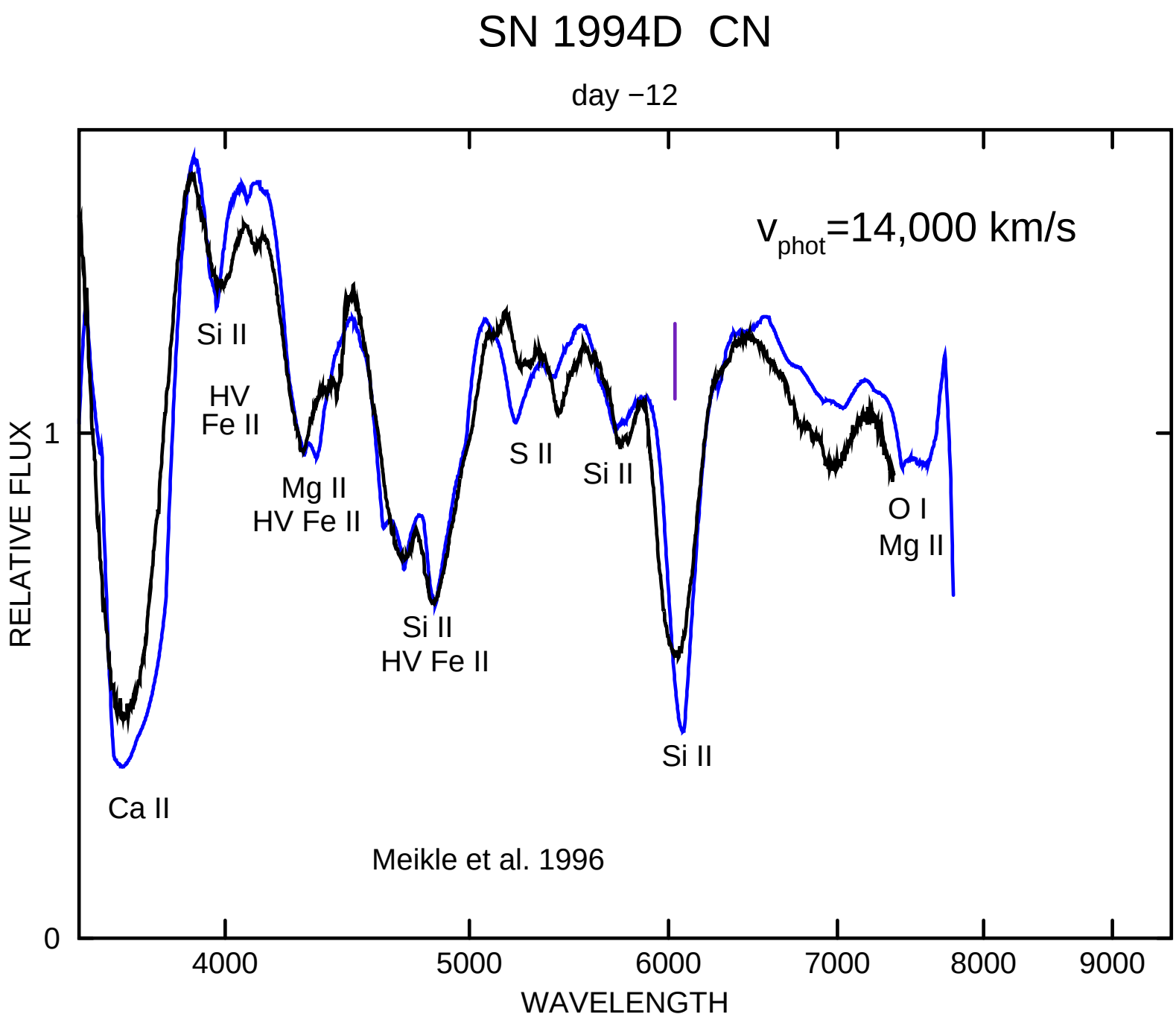
The Premax Sample (continued)

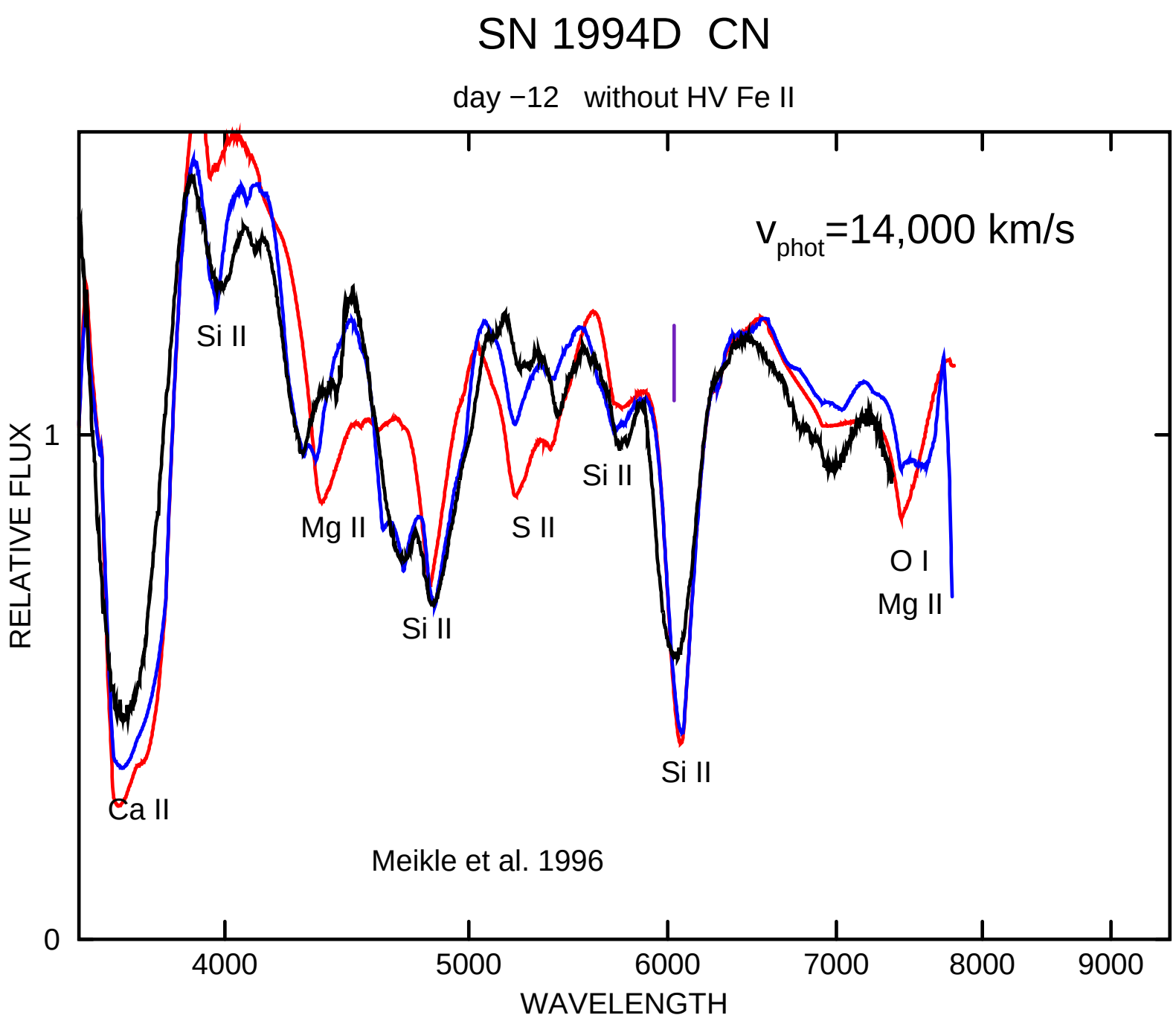
- **2001el CN -8 Mattila et al. (2005)**
- **2002bo BL -6, -14 Benetti et al. (2004)**
- **2002er BL -7, -11 Kotak et al. (2006)**
- **2003cg CN -7 Elias–Rosa et al. (2006)**
- **2003du CN -7, -11 Anupama et al. (2005), Stanishev et al. (2007)**
- **2005cg SS -9 Quimby et al. (2006)**
- **2005hk SS -5 Chornock et al. (2006)**

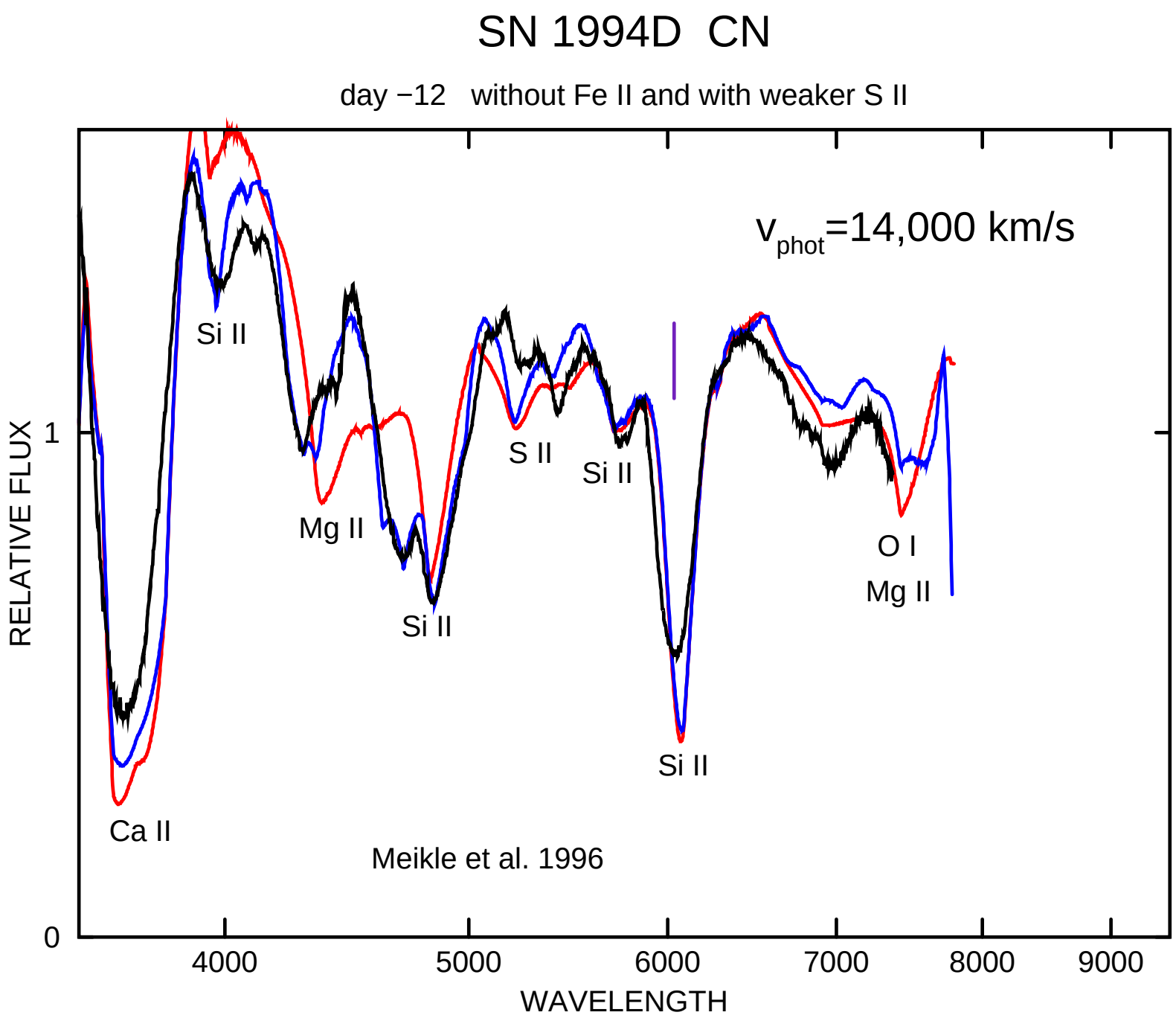

SN 2003du CN
day −7
v_{phot}=13,000 km/s
RELATIVE FLUX
1
0
Si II
HV
Fe II
Fe III
Si III
Mg II
HV
Fe II
Si II
HV Fe II
Fe III
S II
Fe III
Si II
Si II
O I
Mg II
HV
Ca II
Ca II
Mg II
Ca II
HV Ca II
Anupama et al. 2005
4000
5000
6000
7000
8000
9000
WAVELENGTH

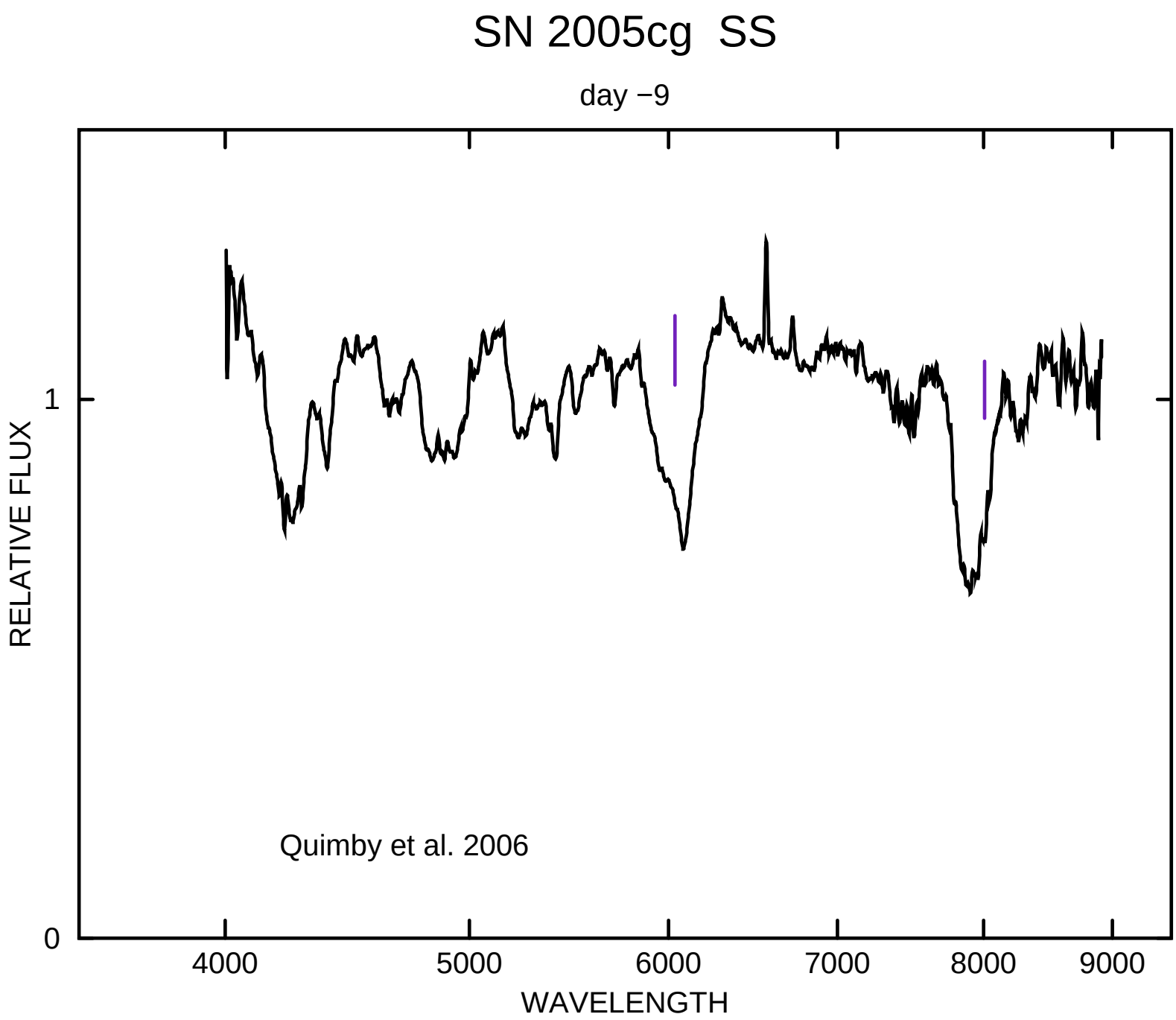

SN 2002bo BL
day −14
v_{phot}=20,000 km/s
RELATIVE FLUX
WAVELENGTH
0
1
2
4000
5000
6000
7000
8000
9000
Ca II
Si II
HV
Fe II
Mg II
HV Fe II
Si II
HV Fe II
S II
Si II
Si II
O I
Mg II
Benetti et al. 2004

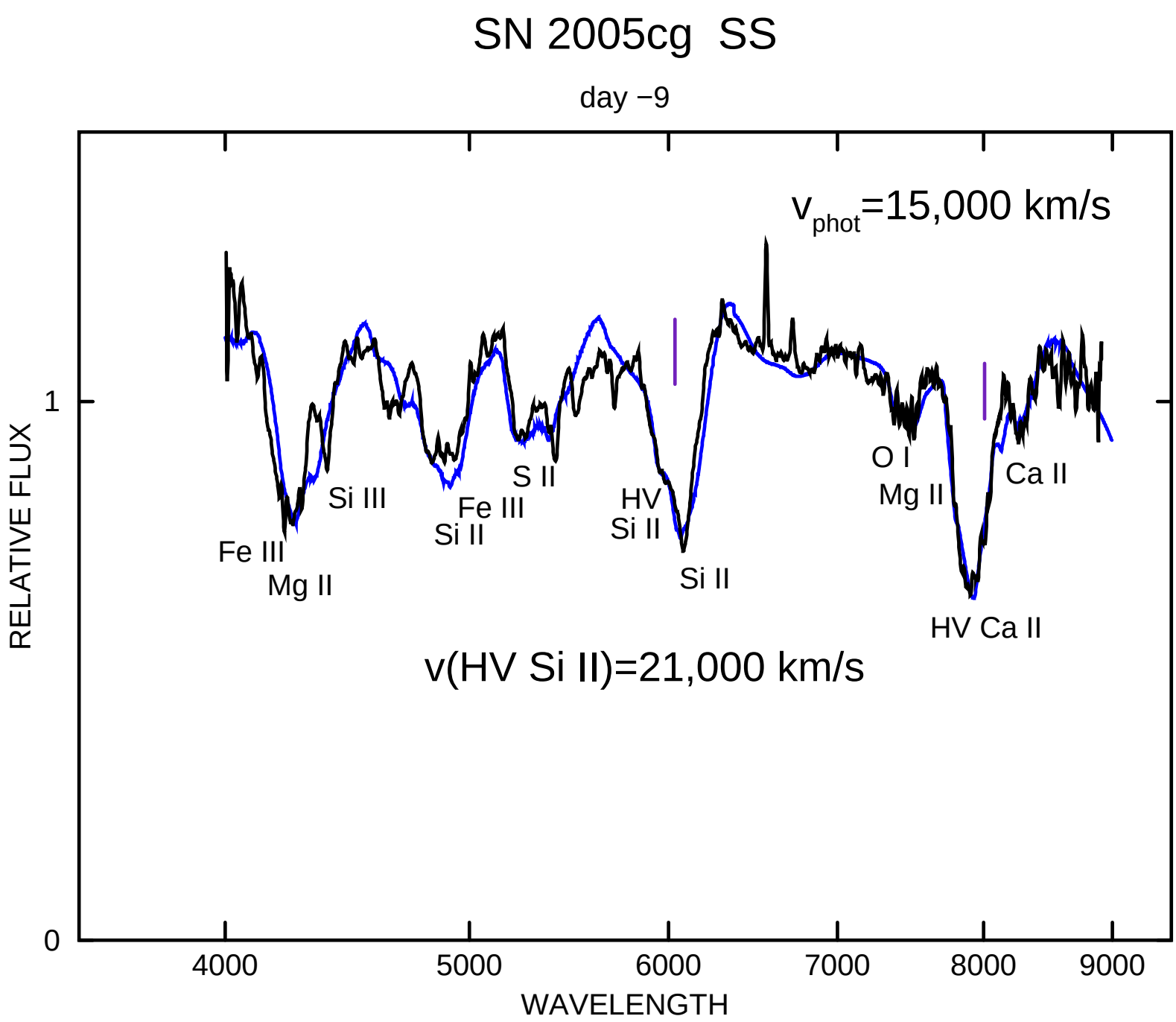

SN 1984A BL
day −7
v_{phot}=16,000 km/s
v_{max}(Si II)=27,000 km/s
Si II
HV
Fe II
Si III
Mg II
HV
Fe II
HV
Fe II
Si II
HV Fe II
Fe III
S II
Si II
Ca II
HV Ca II
Si II
Barbon et al. 1989
RELATIVE FLUX
WAVELENGTH
0
1
2
4000
5000
6000
7000
8000
9000

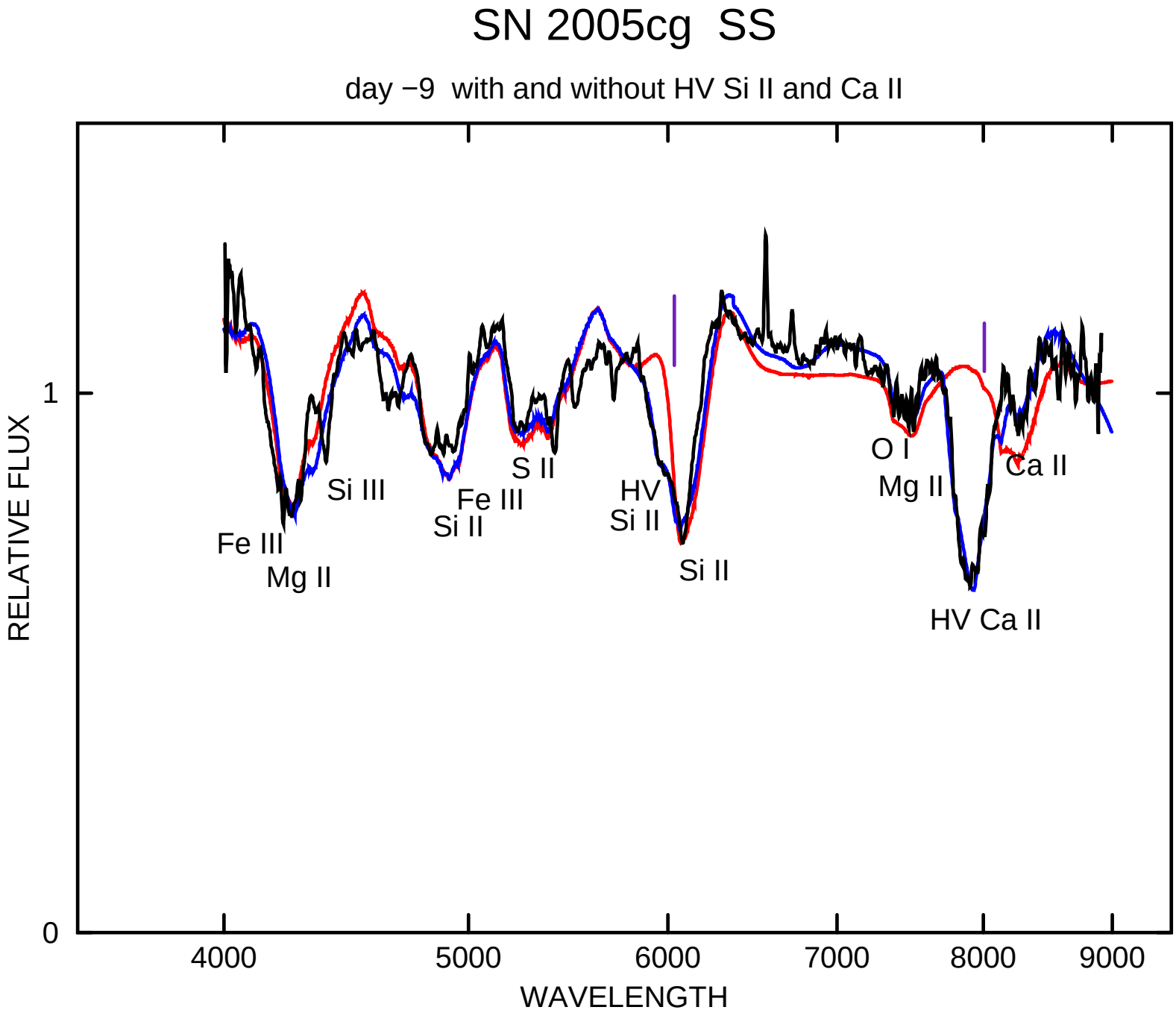

SN 1994D CN
day −12
v_{phot}=14,000 km/s
Si II
HV
Fe II
Mg II
HV Fe II
Si II
HV Fe II
S II
Si II
Si II
O I
Mg II
Ca II
Meikle et al. 1996
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH

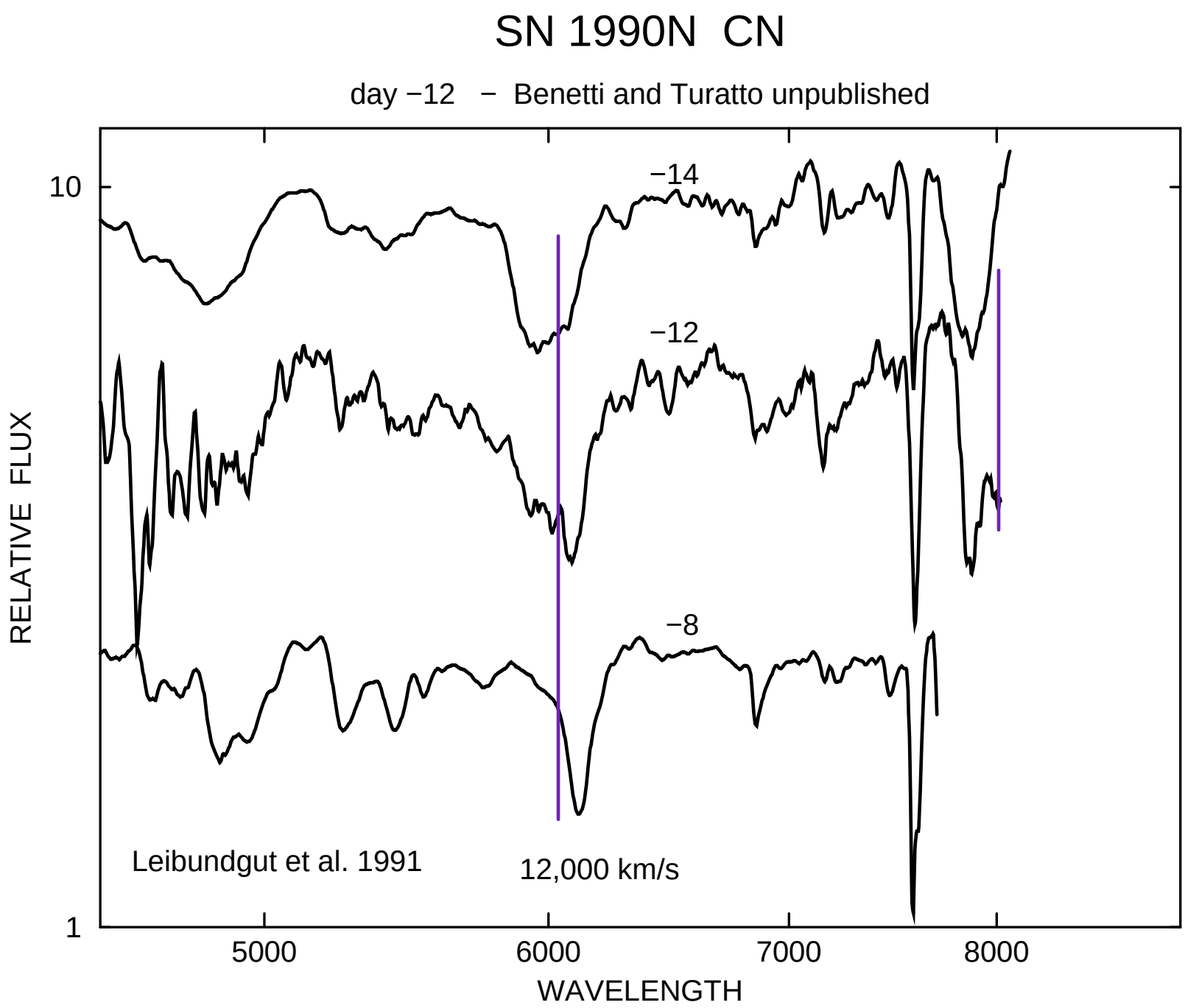

SN 1994D CN
day −12 without HV Fe II
v_{phot}=14,000 km/s
Si II
Mg II
Si II
S II
Si II
Si II
O I
Mg II
Ca II
Meikle et al. 1996
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH

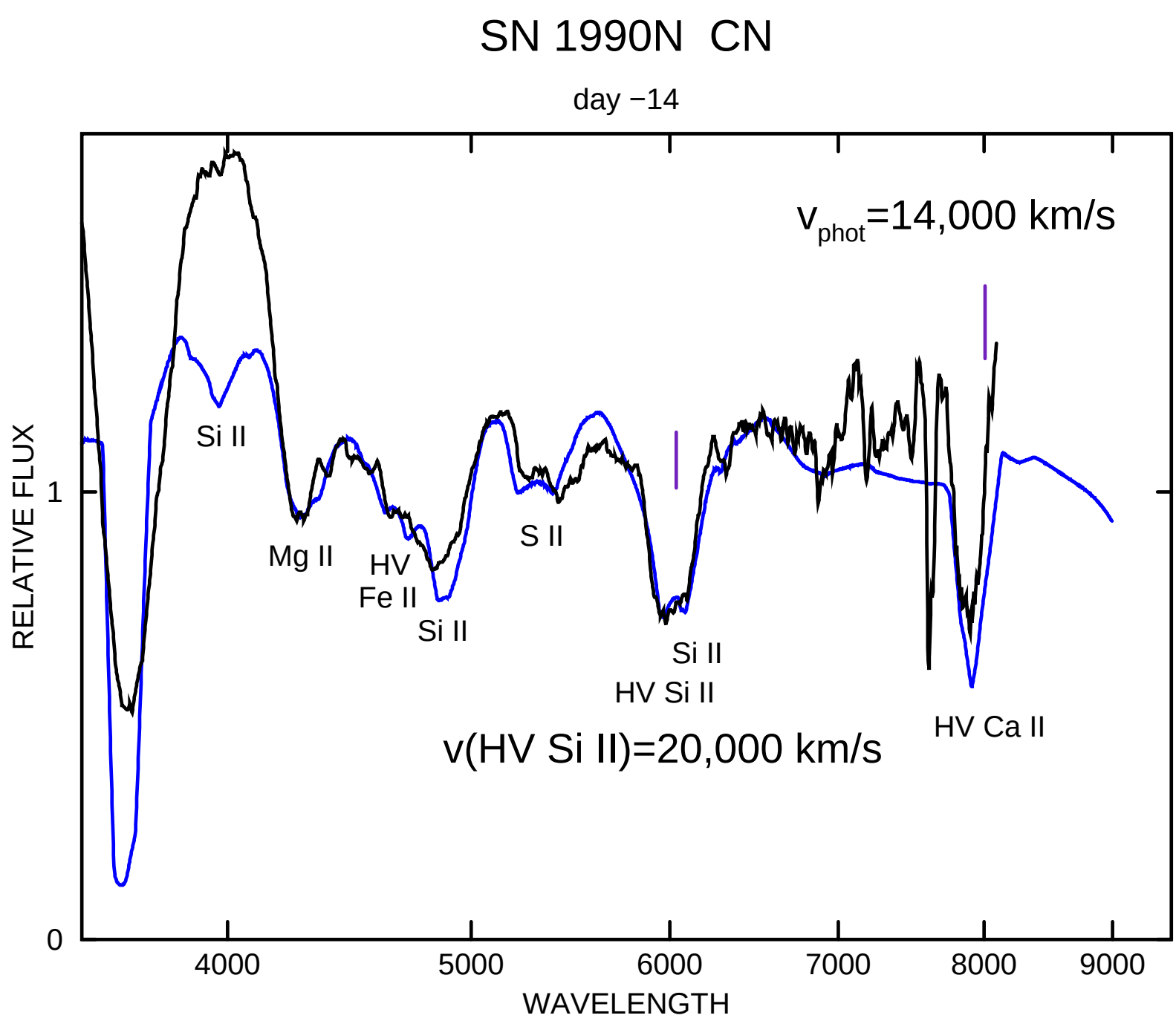

SN 1994D CN
day −12 without Fe II and with weaker S II
v_{phot}=14,000 km/s
Si II
Mg II
Si II
S II
Si II
Si II
O I
Mg II
Ca II
Meikle et al. 1996
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH

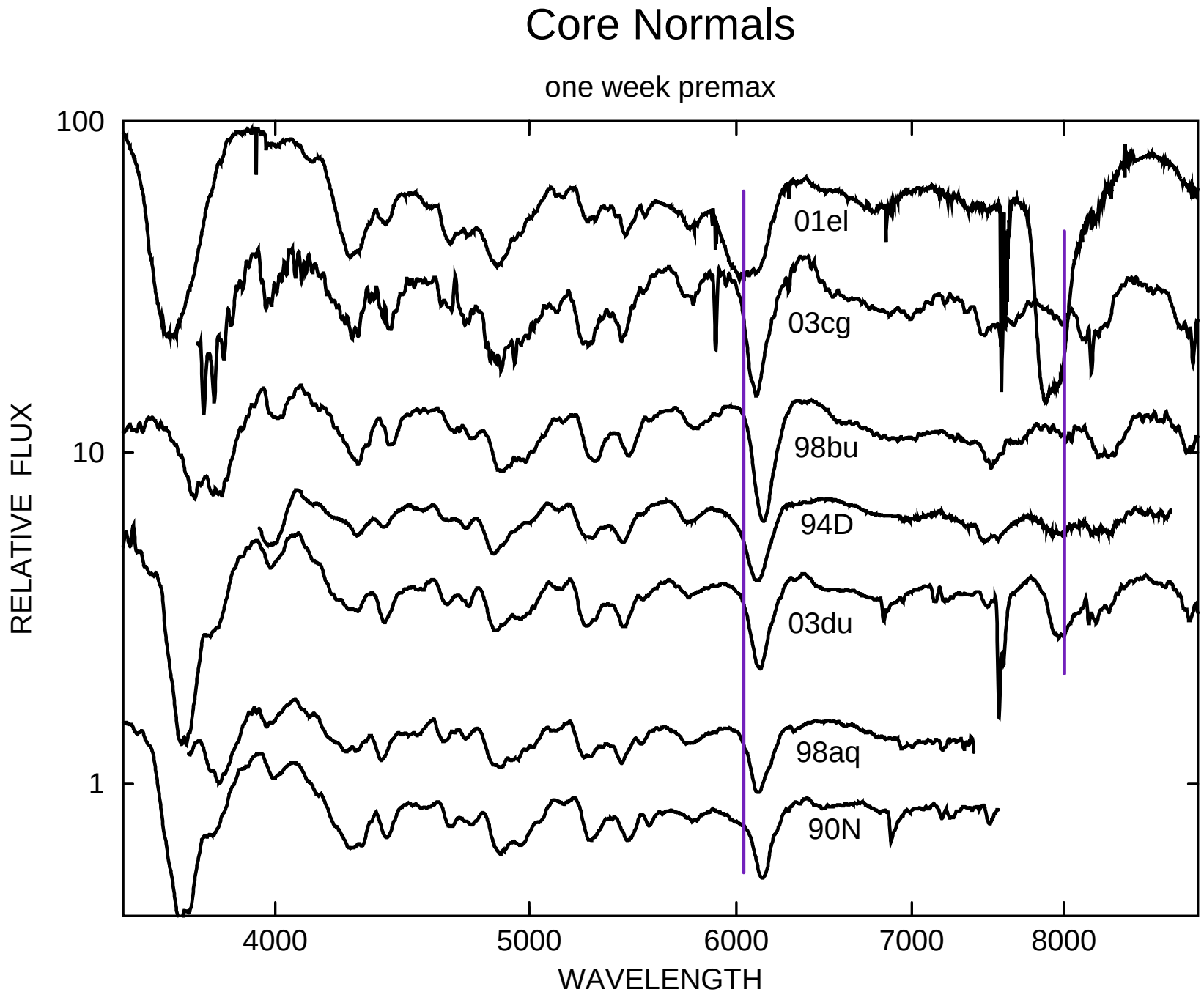

SN 2005cg SS
day −9
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH
Quimby et al. 2006

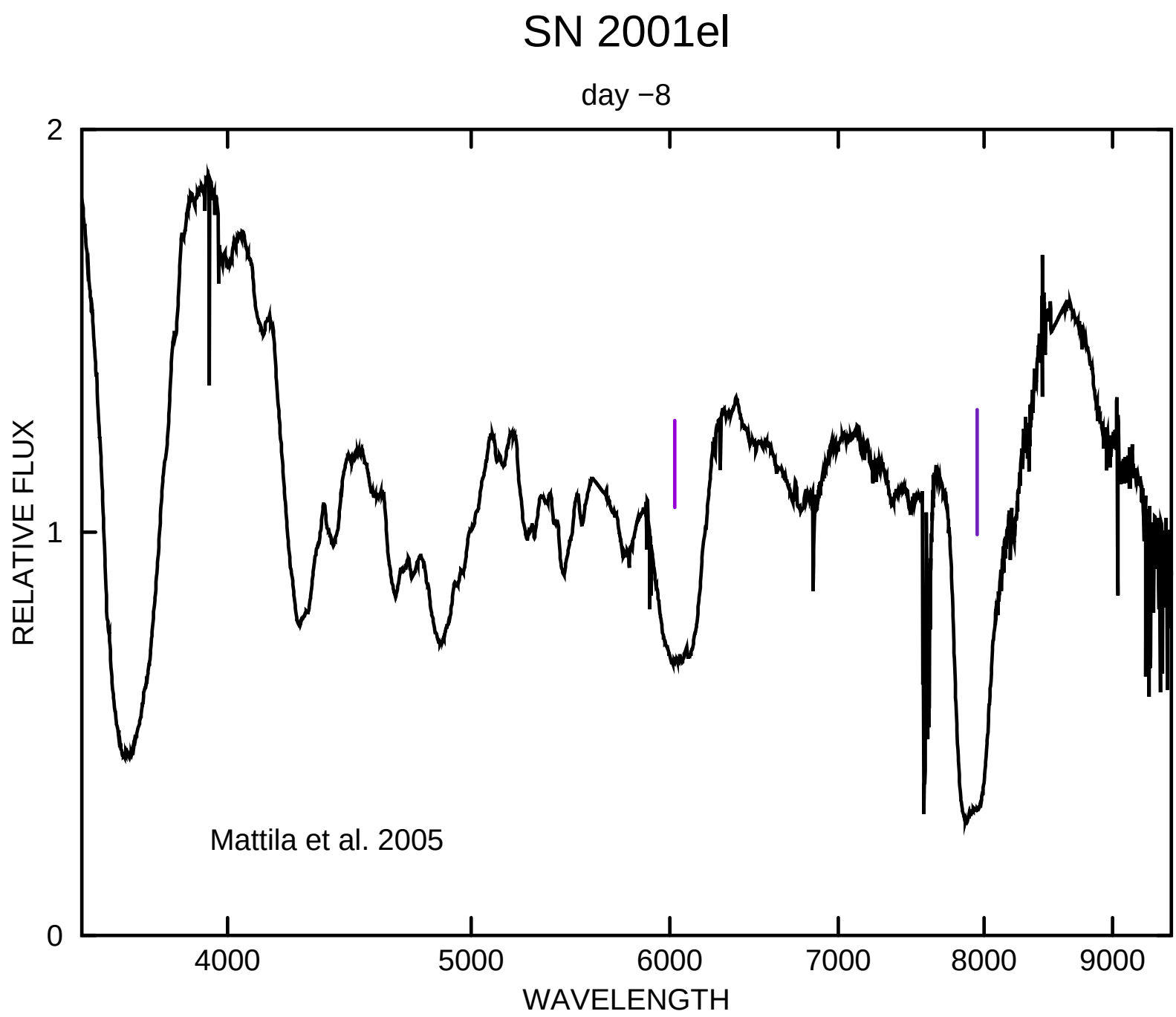

SN 2005cg SS
day −9
v_phot=15,000 km/s
v(HV Si II)=21,000 km/s
Fe III
Mg II
Si III
Si II
Fe III
S II
HV
Si II
Si II
O I
Mg II
HV Ca II
Ca II
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH

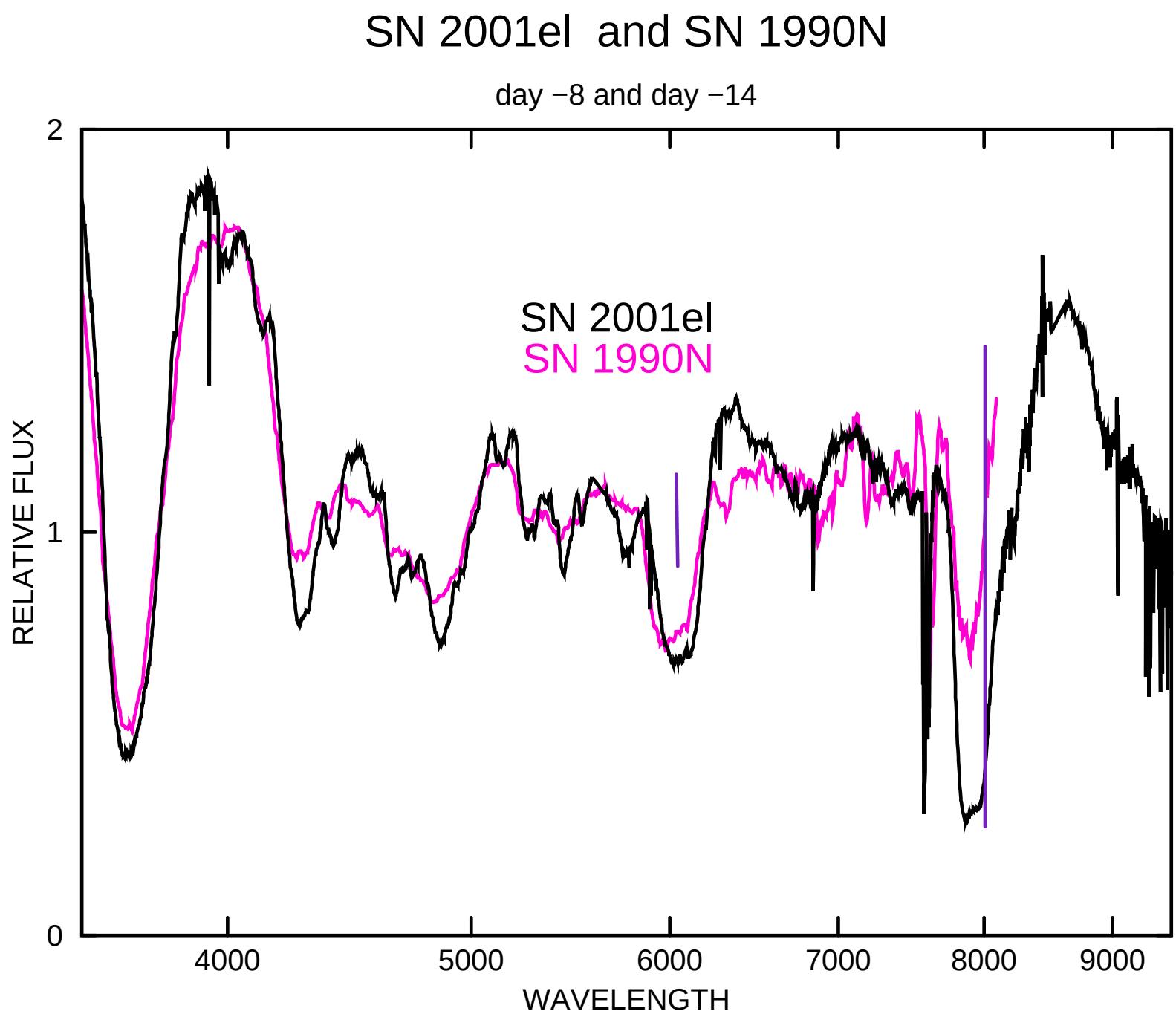

SN 2005cg SS
day −9 with and without HV Si II and Ca II
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH
Fe III
Mg II
Si III
Si II
Fe III
S II
HV
Si II
Si II
O I
Mg II
Ca II
HV Ca II

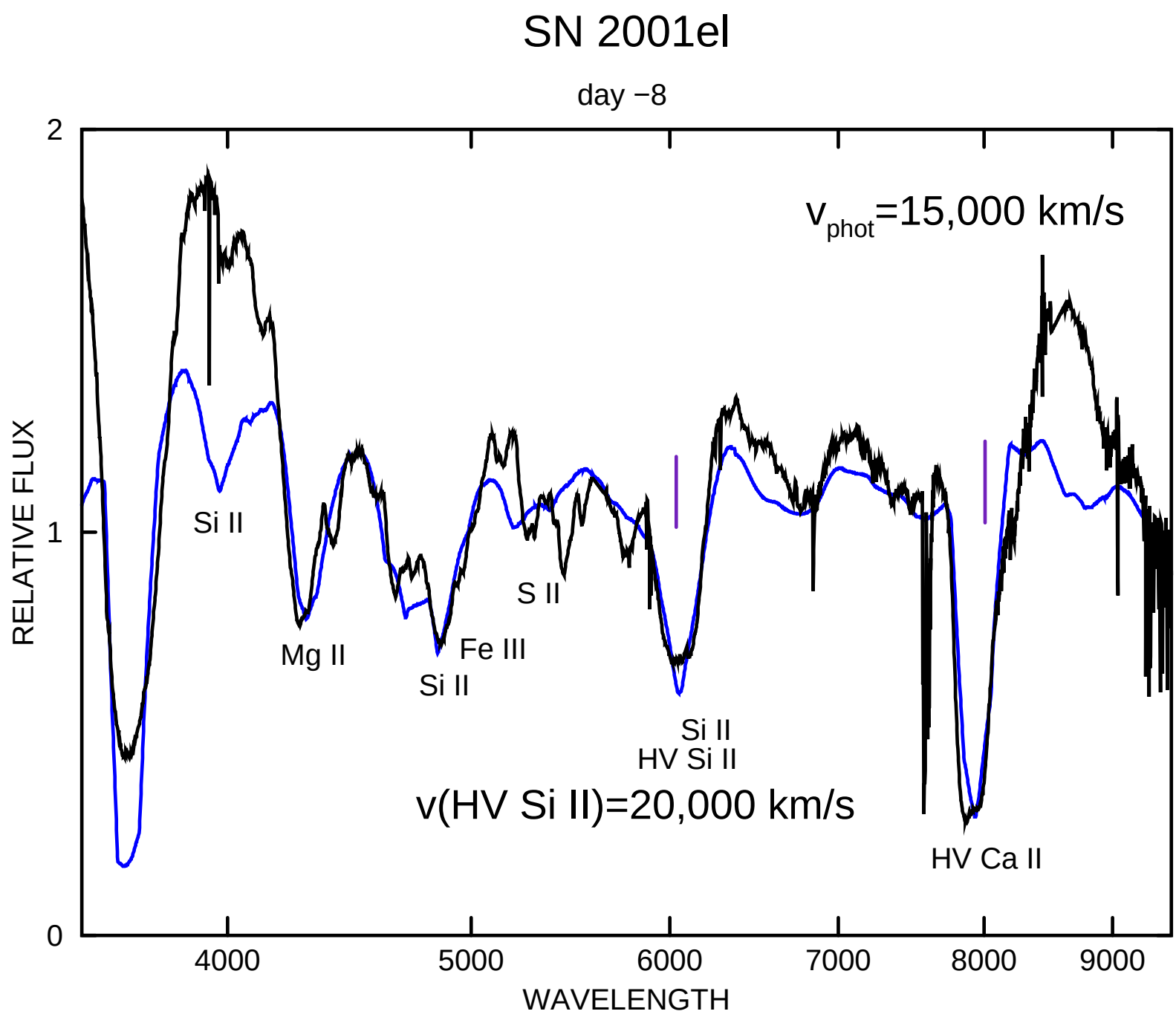

SN 1990N CN
day −12 − Benetti and Turatto unpublished
−14
−12
−8
10
1
RELATIVE FLUX
5000
6000
7000
8000
WAVELENGTH
Leibundgut et al. 1991
12,000 km/s


SN 1990N CN
day −14
v_{phot}=14,000 km/s
Si II
Mg II
HV
Fe II
Si II
S II
Si II
HV Si II
HV Ca II
v(HV Si II)=20,000 km/s
RELATIVE FLUX
1
0
4000
5000
6000
7000
8000
9000
WAVELENGTH


Core Normals
one week premax
100
10
1
RELATIVE FLUX
01el
03cg
98bu
94D
03du
98aq
90N
4000
5000
6000
7000
8000
WAVELENGTH


SN 2001el
day −8
2
1
0
RELATIVE FLUX
4000
5000
6000
7000
8000
9000
WAVELENGTH
Mattila et al. 2005


SN 2001el and SN 1990N
day −8 and day −14
SN 2001el
SN 1990N
RELATIVE FLUX
WAVELENGTH
0
1
2
4000
5000
6000
7000
8000
9000


SN 2001el
day −8
v_{phot}=15,000 km/s
v(HV Si II)=20,000 km/s
Si II
Mg II
Si II
Fe III
S II
Si II
HV Si II
HV Ca II
RELATIVE FLUX
WAVELENGTH
0
1
2
4000
5000
6000
7000
8000
9000

Premaximum SNe Ia

- **SYNOW fits are about as good as at maximum; most line identifications seem clear.**
- Synthesized silicon is generally present up to 15,000 km s^{-1}, sometimes above 20,000 km s^{-1}, and to 27,000 km s^{-1} in SN 1984A at day -7.

  Ca II IR3 is generally present up to 25,000 km s^{-1}, and to 34,000 km s^{-1} in SN 2001el at day -8.
- HV Ca II and HV Fe II (?) are ubiquitous; HV Si II is not uncommon at early times; HV features usually are at 20,000 km s^{-1} and above.
- Even at premaximum, C II is elusive, but it is seen in at least six SNe Ia. Carbon clumps not in front of the photosphere would not be seen, so the ubiquitous presence of carbon clumps at v $\sim$ 15,000 km s^{-1} is not excluded. See Thomas et al. (2007) on SN 2006D.

Premaximum SNe Ia

- **SYNOW fits are about as good as at maximum; most line identifications seem clear.**
- **Synthesized silicon is generally present up to 15,000 km s^{-1}, sometimes above 20,000 km s^{-1}, and to 27,000 km s^{-1} in SN 1984A at day -7.**

  Ca II IR3 is generally present up to 25,000 km s^{-1}, and to 34,000 km s^{-1} in SN 2001el at day -8.
- HV Ca II and HV Fe II (?) are ubiquitous; HV Si II is not uncommon at early times; HV features usually are at 20,000 km s^{-1} and above.
- Even at premaximum, C II is elusive, but it is seen in at least six SNe Ia. Carbon clumps not in front of the photosphere would not be seen, so the ubiquitous presence of carbon clumps at v $\sim$ 15,000 km s^{-1} is not excluded. See Thomas et al. (2007) on SN 2006D.

Premaximum SNe Ia

- **SYNOW fits are about as good as at maximum; most line identifications seem clear.**
- **Synthesized silicon is generally present up to 15,000 km s^{-1}, sometimes above 20,000 km s^{-1}, and to 27,000 km s^{-1} in SN 1984A at day -7.**

  Ca II IR3 is generally present up to 25,000 km s^{-1}, and to 34,000 km s^{-1} in SN 2001el at day -8.
- **HV Ca II and HV Fe II (?) are ubiquitous; HV Si II is not uncommon at early times; HV features usually are at 20,000 km s^{-1} and above.**
- **Even at premaximum, C II is elusive, but it is seen in at least six SNe Ia. Carbon clumps not in front of the photosphere would not be seen, so the ubiquitous presence of carbon clumps at v $\sim$ 15,000 km s^{-1} is not excluded. See Thomas et al. (2007) on SN 2006D.**

Premaximum SNe Ia

- SYNOW fits are about as good as at maximum; most line identifications seem clear.
- Synthesized silicon is generally present up to 15,000 km s^{-1}, sometimes above 20,000 km s^{-1}, and to 27,000 km s^{-1} in SN 1984A at day -7.

  Ca II IR3 is generally present up to 25,000 km s^{-1}, and to 34,000 km s^{-1} in SN 2001el at day -8.
- HV Ca II and HV Fe II (?) are ubiquitous; HV Si II is not uncommon at early times; HV features usually are at 20,000 km s^{-1} and above.
- Even at premaximum, C II is elusive, but it is seen in at least six SNe Ia. Carbon clumps not in front of the photosphere would not be seen, so the ubiquitous presence of carbon clumps at v $\sim$ 15,000 km s^{-1} is not excluded. See Thomas et al. (2007) on SN 2006D.

Premaximum SNe Ia

- SYNOW fits are about as good as at maximum; most line identifications seem clear.
- Synthesized silicon is generally present up to 15,000 km s^{-1}, sometimes above 20,000 km s^{-1}, and to 27,000 km s^{-1} in SN 1984A at day -7.

  Ca II IR3 is generally present up to 25,000 km s^{-1}, and to 34,000 km s^{-1} in SN 2001el at day -8.
- HV Ca II and HV Fe II (?) are ubiquitous; HV Si II is not uncommon at early times; HV features usually are at 20,000 km s^{-1} and above.
- Even at premaximum, C II is elusive, but it is seen in at least six SNe Ia. Carbon clumps not in front of the photosphere would not be seen, so the ubiquitous presence of carbon clumps at $v \sim 15{,}000$ km s^{-1} is not excluded. See Thomas et al. (2007) on SN 2006D.

SYNOW approximations

- spherical symmetry
- sharp photosphere
- velocity proportional to radius
- lines form by resonance scattering, treated in the Sobolev approximation
- relative strengths of lines of an ion are in LTE
- multiple scattering is taken into account

SYNOW input parameters

- velocity at the photosphere
- optical depth at the photosphere of one “reference line” per ion
- radial optical–depth profile, e.g., $\tau = \tau_{phot} e^{-(v - v_{phot})/v_e}$
- optional maximum and minimum (“detachment”) velocities for each ion
- excitation and temperature