Musings about Type Ia SN

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Special thanks: Atomic data community

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References

Website: http://www.pitt.edu/~hillier

Hillier & Dessart (2012, MNRAS, 424, 252 [astroph: 1204.0527])

Li, Hillier, and Dessart (2012, MNRAS, 426, 1671)

Hillier (2003, Stellar Atmosphere Modelling, ASP Conf. Ser., Vol. 288, 199)

Hillier & Miller (1998, ApJ, 496, 407)

Hillier (1990, A&A, 231, 116)

Atomic Data

Opacity Project:
    Seaton 1987; Hummer et al. 1993

Bob Kurucz
    Bell and Kurucz (1995)
    http://kurucz.harvard.edu

Keith Butler (Munich)

Sultana Nahar / Anil Pradhan
    http://www.astronomy.ohio-state.edu/~nahar/nahar_radiativeatomicdata/index.html

NIST
    http://www.nist.gov/pml/data/asd.cfm (Energy levels, f values, bib)
    http://www.nist.gov/pml/pubs/atspec/index.cfm (Introduction to Atomic Spectroscopy)

CLOUDY (Ferland/Verner)
    Charge exchange rates
    Ground state photoionization cross-sections

+ many others

Needed

Energy levels/wavelengths
Oscillator strengths
Photoionization cross sections
Collisional cross sections
Autoionization rates
Non-thermal cross sections

Spectral Modeling

Monte Carlo

Trace photon packets through ejecta

Treats absorption, scattering, and emission

3D is not much more complex than 1D (but very computational)

Full-non LTE possible, but many codes are pseudo non-LTE.

Exceptions -- codes of Anders Jerkstrand, Mattias Ergon

Solve Radiative Transfer Equation (ray-tracing)

Fully non-LTE

Not subject to statistical errors (but discretation errors).

3D is much more expensive than 1D (by factor of 10^5!)

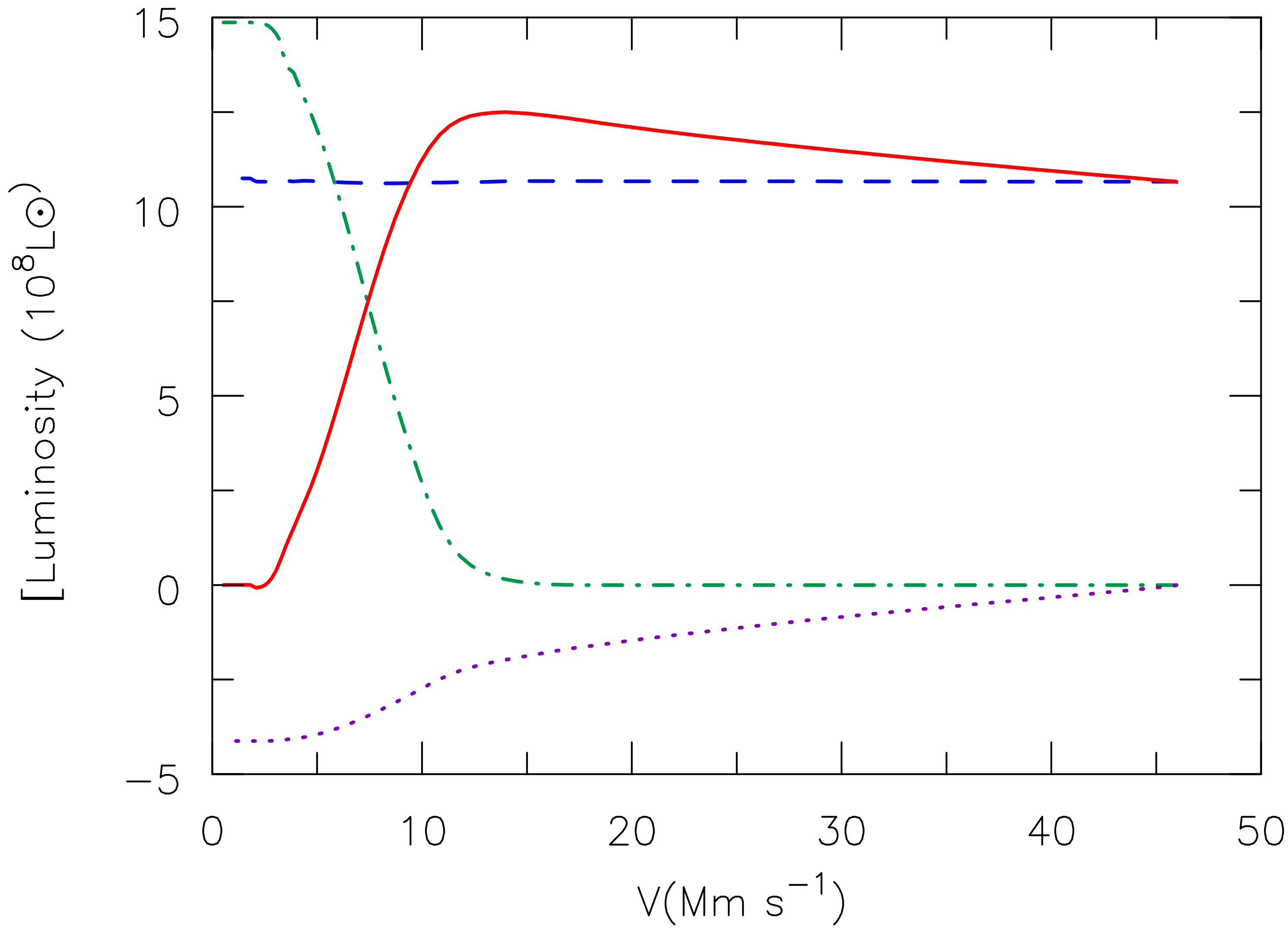
CMFGEN: 1D time dependent radiative transfer code.

e.g., Hillier & Miller (1998), Hillier & Dessart (2012)

(cf. codes of Peter Hoeflich; PHOENIX – Peter Hauschildt).

Energy Conservation

$$r_{\max}^2 H(r_{\max}) = r^2 H(r) + \int_r^{r_{\max}} \frac{r^2}{4\pi} \left(\dot{e}_{\text{decay}} - \rho \frac{De}{Dt} + \frac{P}{\rho} \frac{D\rho}{Dt} \right) - \frac{1}{cr^2} \frac{D(r^4 J)}{Dt} \; dr$$



Modeling SNe

1. Choose hydrodynamical model

    Put in required format

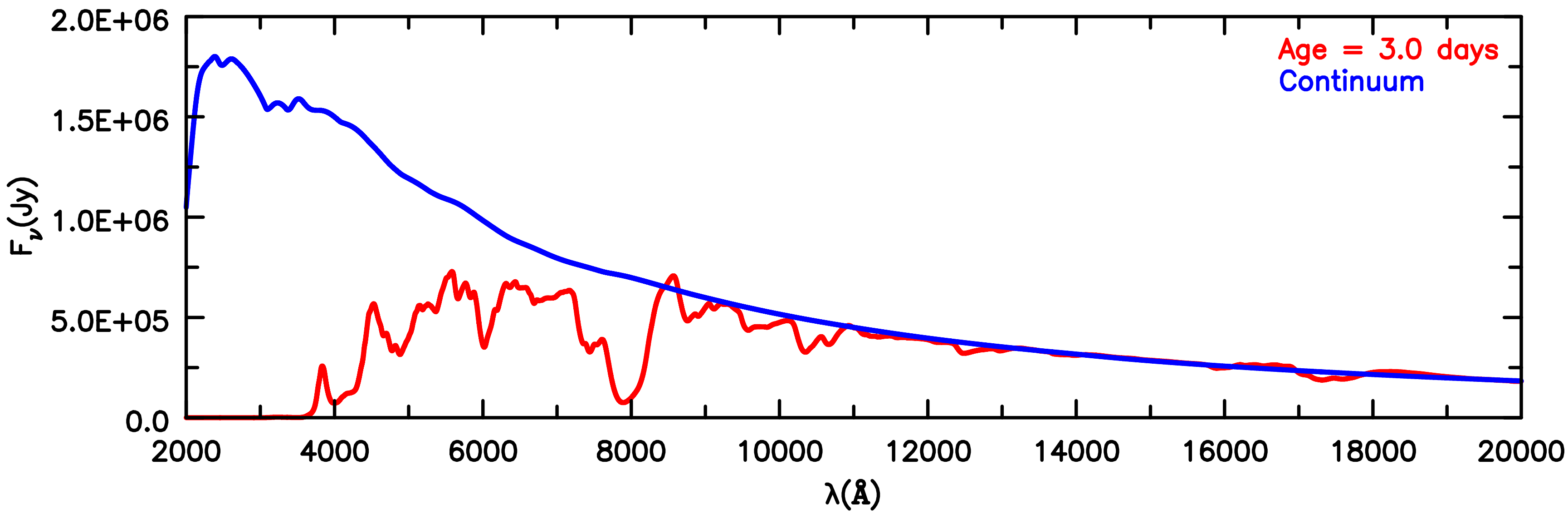
    No free parameters (almost) !

        Amount of mixing

2. Create initial CMFGEN model using temperature, density & composition from hydro model. Converge!

3. Run time sequence. Only changes in model are now dictated by the physics.

4. If comparing model model grid, select model and observation that agree -- not necessarily much freedom.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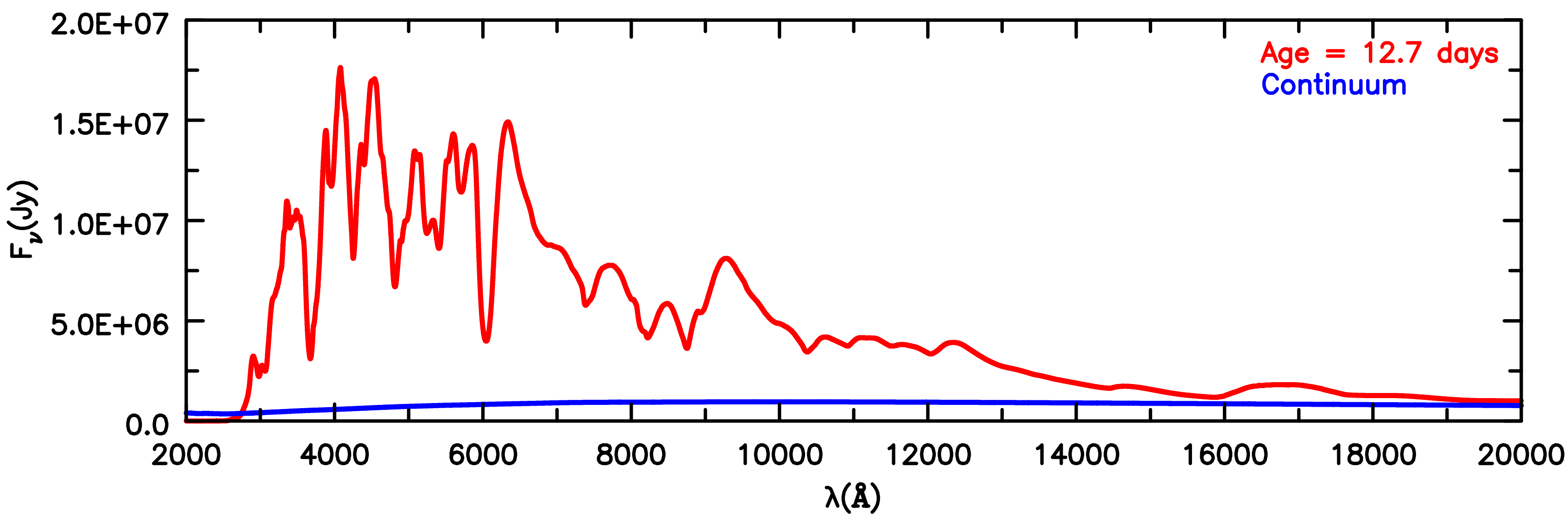
Continuum
F_ν(Jy)
2.0E+06
1.5E+06
1.0E+06
5.0E+05
0.0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
λ(Å)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F_ν(Jy)
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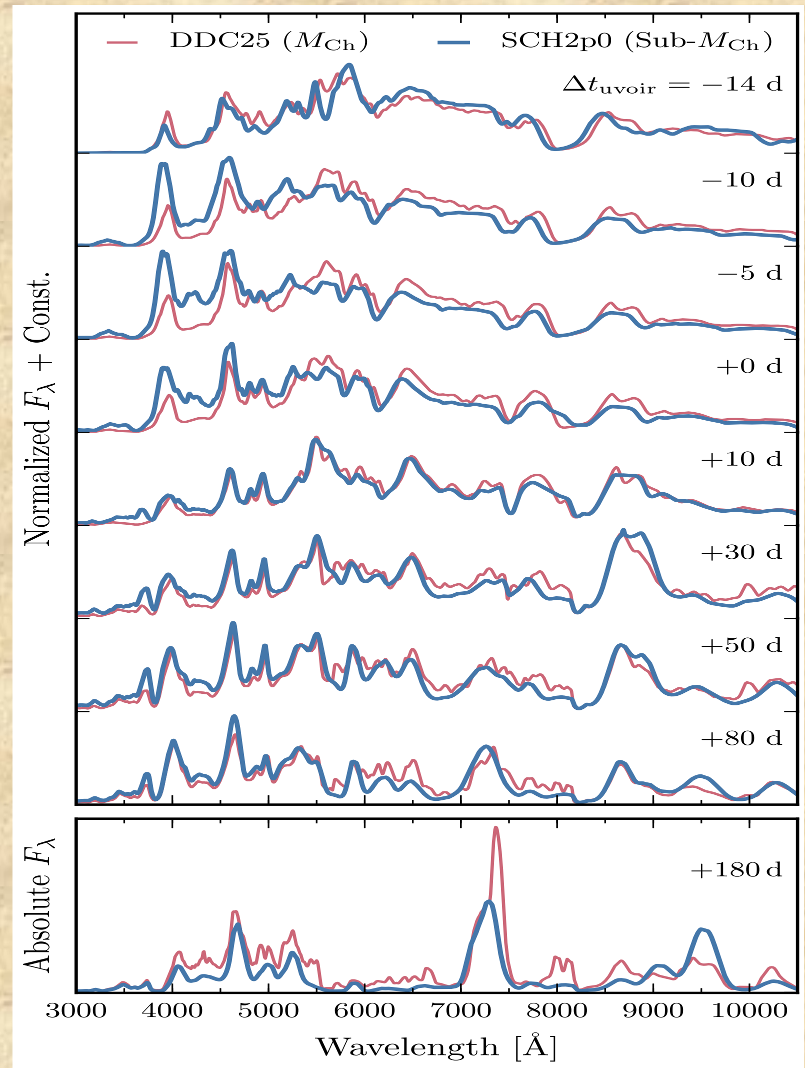
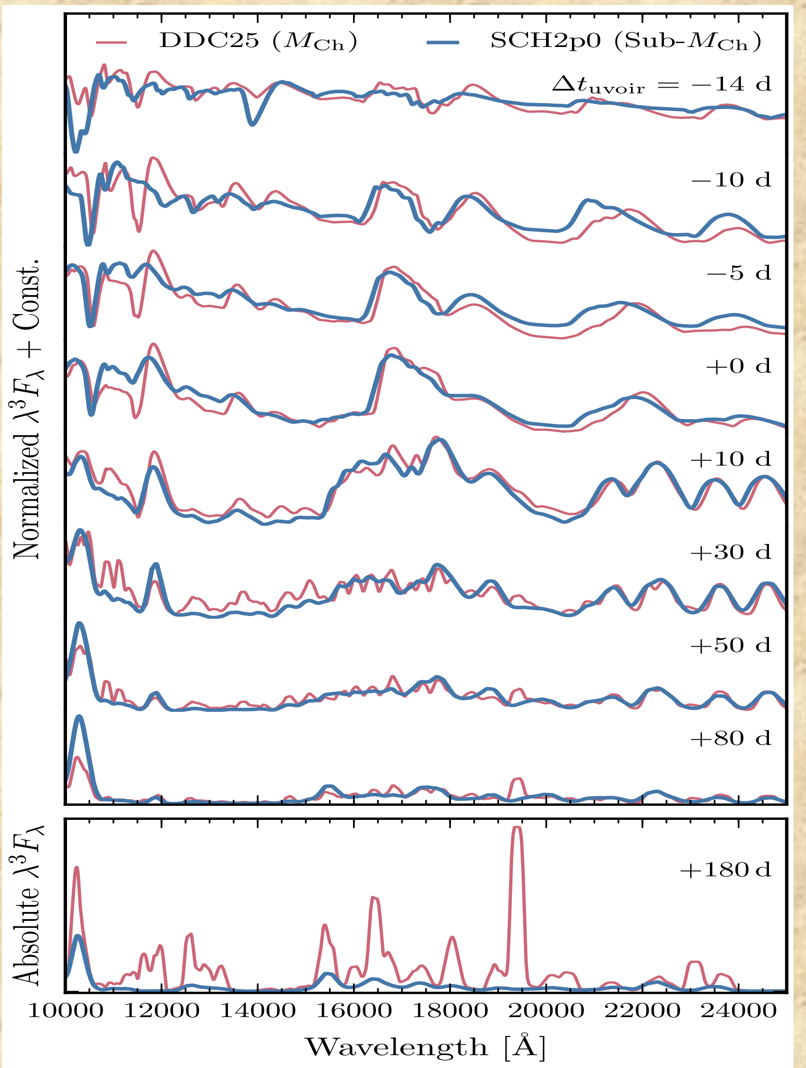
1.5E+07
1.0E+07
5.0E+06
0.0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
λ(Å)

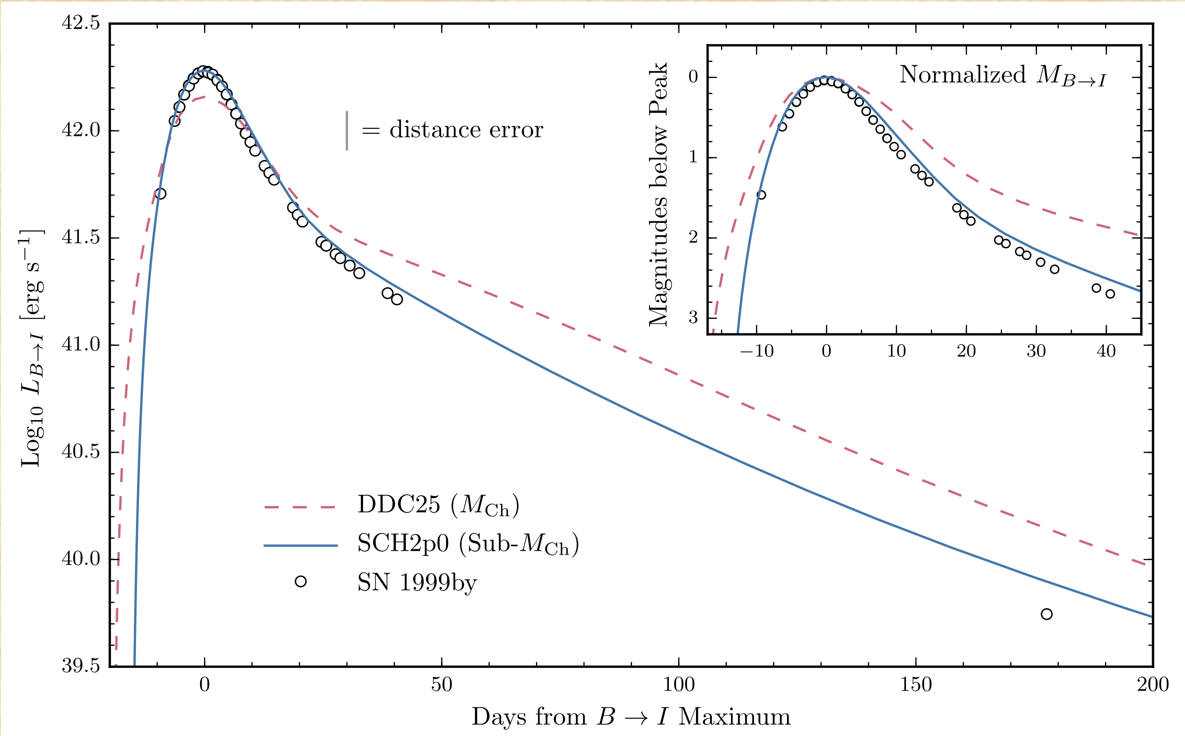
SN 1999by: Explosion of a sub-Chandrasekhar-mass white dwarf

Blondin et al. (2018, MNRAS, 474,3931)

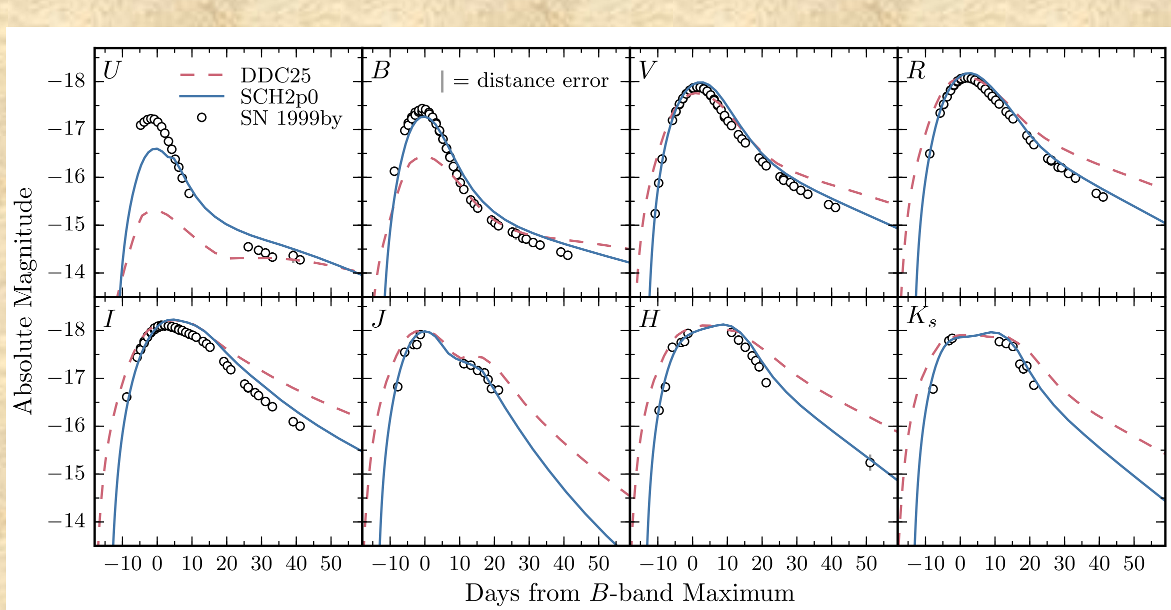
M_{sub}=0.9 $M_\odot$, M(^{56}Ni)=0.117$M_\odot$ M_{Cha}=1.4 $M_\odot$, M(^{56}Ni)=0.116$M_\odot$



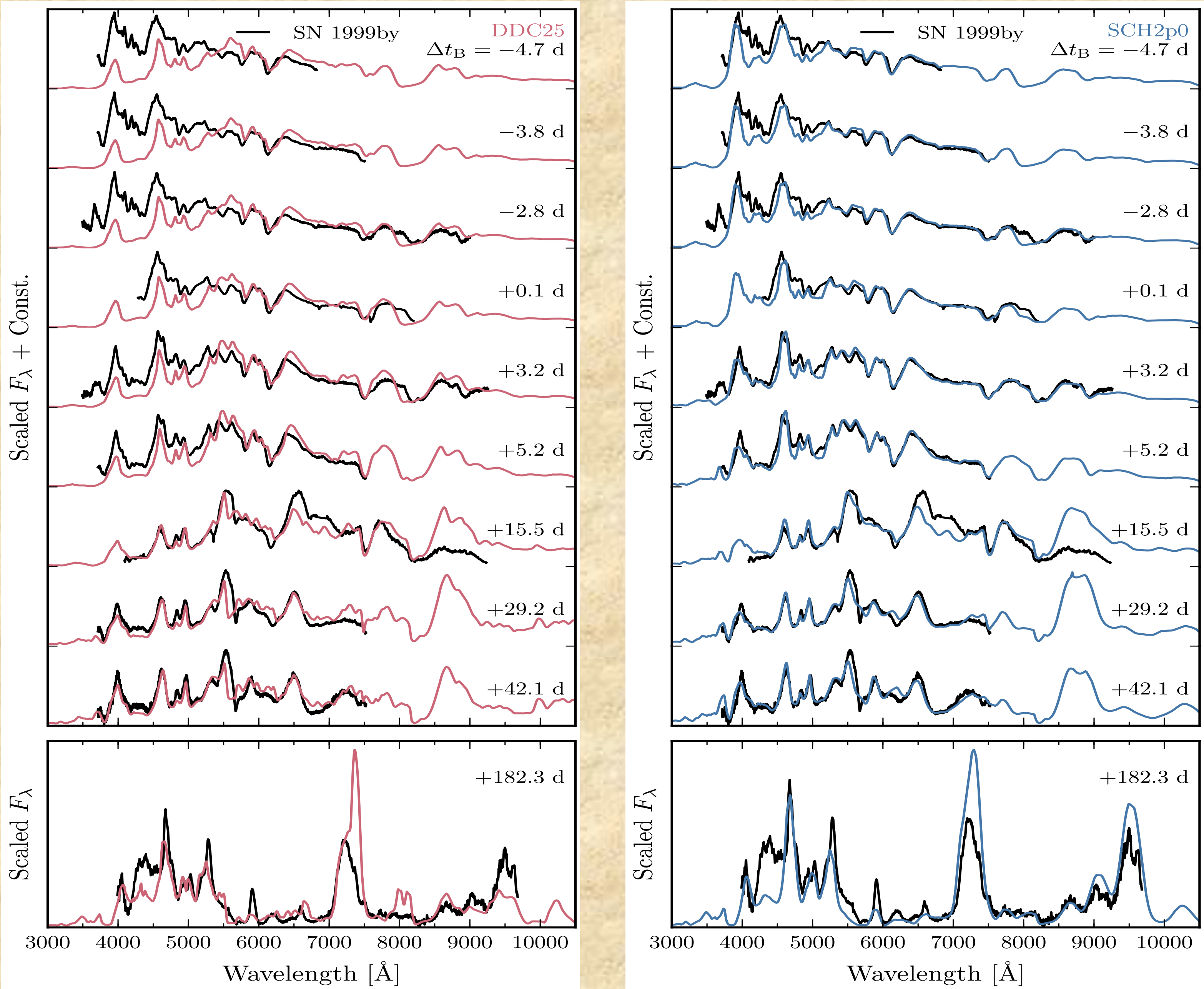




Normalized $M_{B\to I}$
Magnitudes below Peak
= distance error
DDC25 ($M_{\rm Ch}$)
SCH2p0 (Sub-$M_{\rm Ch}$)
SN 1999by
Log$_{10}$ $L_{B\to I}$ [erg s^{-1}]
Days from $B \to I$ Maximum



DDC25
SCH2p0
SN 1999by
= distance error
U
B
V
R
I
J
H
K_s
Absolute Magnitude
Days from B-band Maximum



SN 1999by
DDC25
$\Delta t_{\rm B} = -4.7$ d
−3.8 d
−2.8 d
+0.1 d
+3.2 d
+5.2 d
+15.5 d
+29.2 d
+42.1 d
+182.3 d
Scaled F_λ + Const.
Scaled F_λ
Wavelength [Å]
SCH2p0

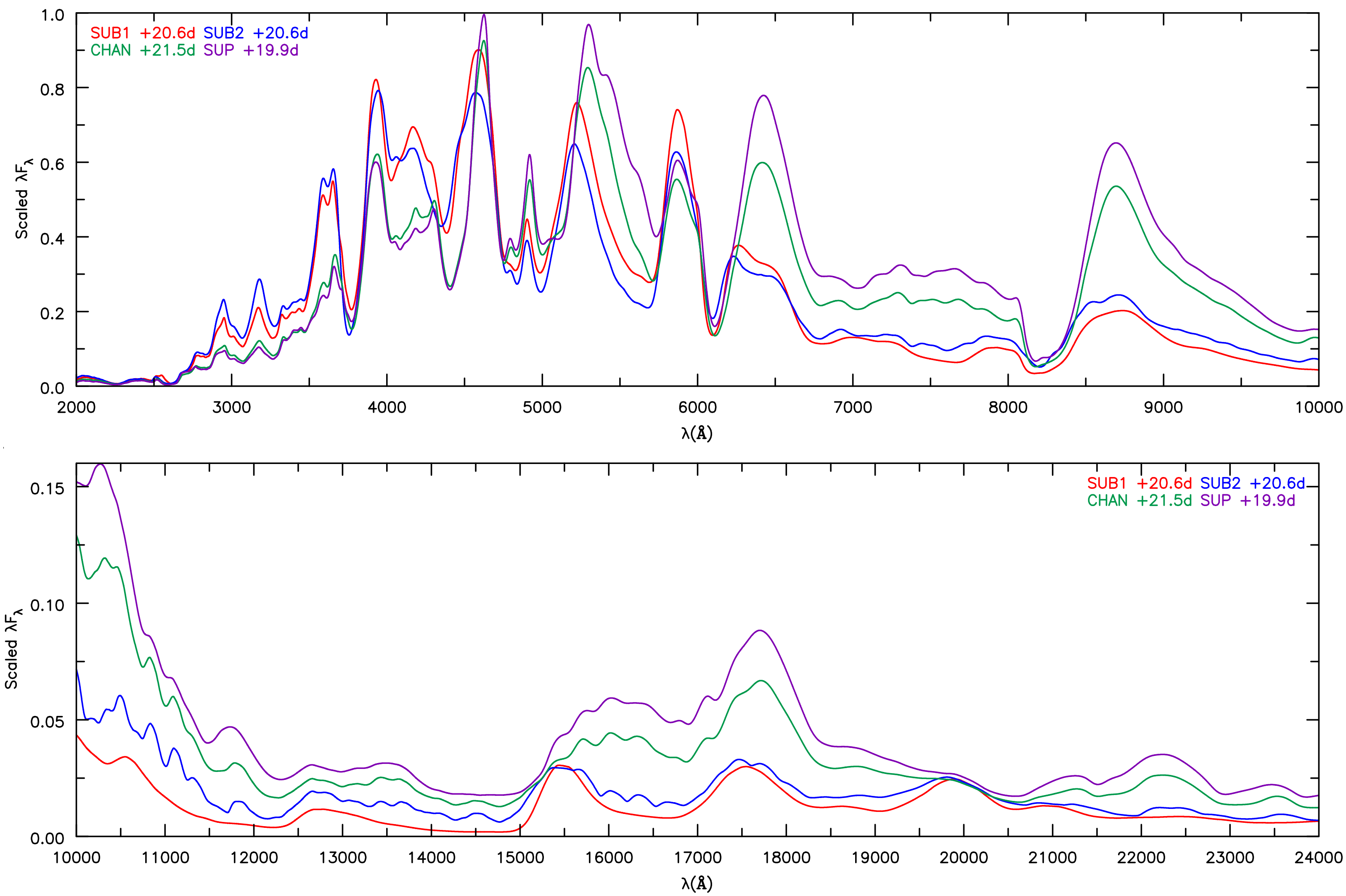
Ia Modelling

Wilk et al., 2018. 474, 3187

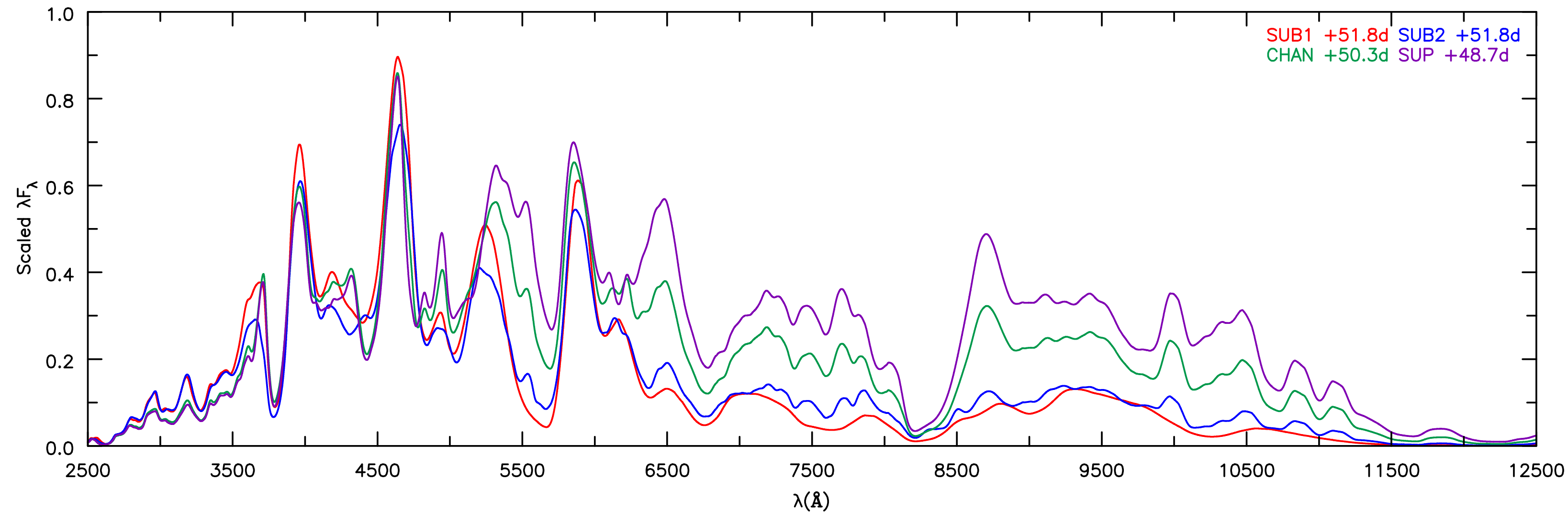
Model	Mass ($M_{\odot}$)	E_{Kin} 10^{51}erg	O ($M_{\odot}$)	Si ($M_{\odot}$)	S ($M_{\odot}$)	Ca ($M_{\odot}$)	Ar ($M_{\odot}$)	^{58,60}Ni ($M_{\odot}$)	^{56} Ni ($M_{\odot}$)
SUB1	1.04	1.22	0.052	0.15	0.10	0.024	0.022	0.011	0.57
SUB2	1.02	1.17	0.039	0.12	0.075	0.018	0.017	0.026	0.57
CHAN	1.40	1.51	0.096	0.26	0.17	0.041	0.037	0.025	0.57
SUP	1.70	1.81	0.13	0.38	0.24	0.056	0.052	0.030	0.57

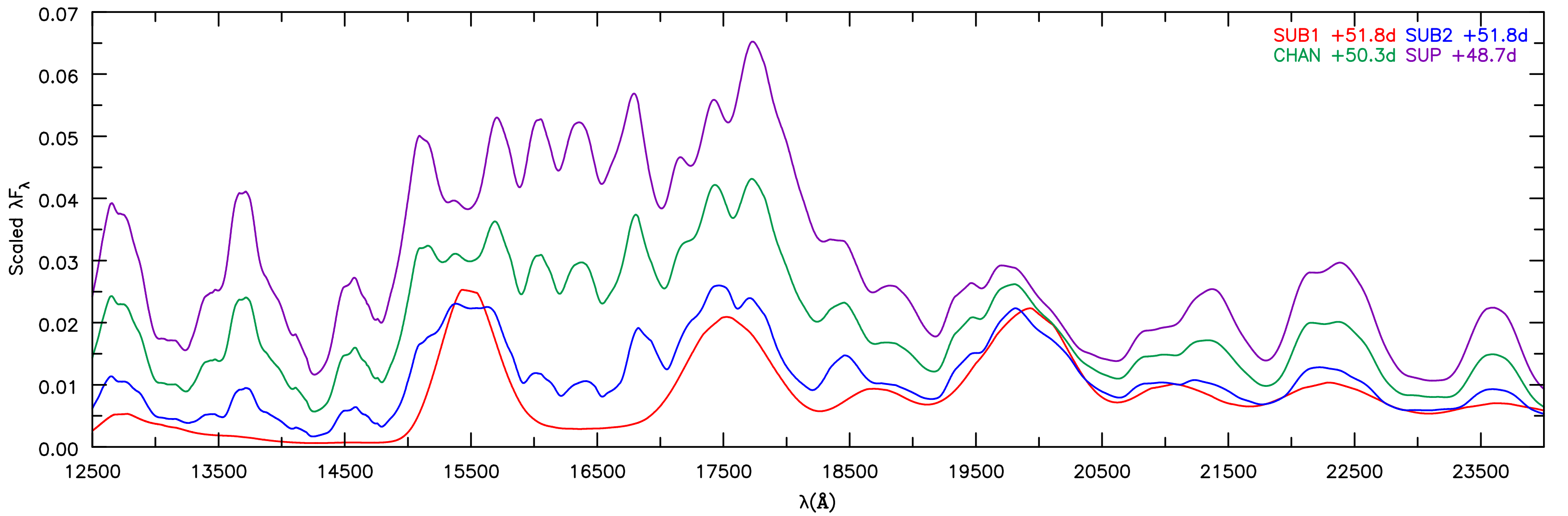
Model	M_U (mag)	$t(U_{\max})$ (d)	$\Delta M_{15}(U)$ (mag)	M_B (mag)	$t(B_{\max})$ (d)	$\Delta M_{15}(B)$ (mag)	M_V (mag)	$t(V_{\max})$ (d)	$\Delta M_{15}(V)$ (mag)
SUB1	−19.89	14.13	1.07	−19.39	16.97	0.95	−19.36	17.99	0.88
SUB2	−19.96	13.35	1.08	−19.41	15.64	0.94	−19.36	16.48	0.96
CHAN	−19.78	14.90	1.06	−19.31	18.54	0.94	−19.31	19.91	0.68
SUP	−19.67	15.92	1.03	−19.25	19.86	0.99	−19.31	21.89	0.60

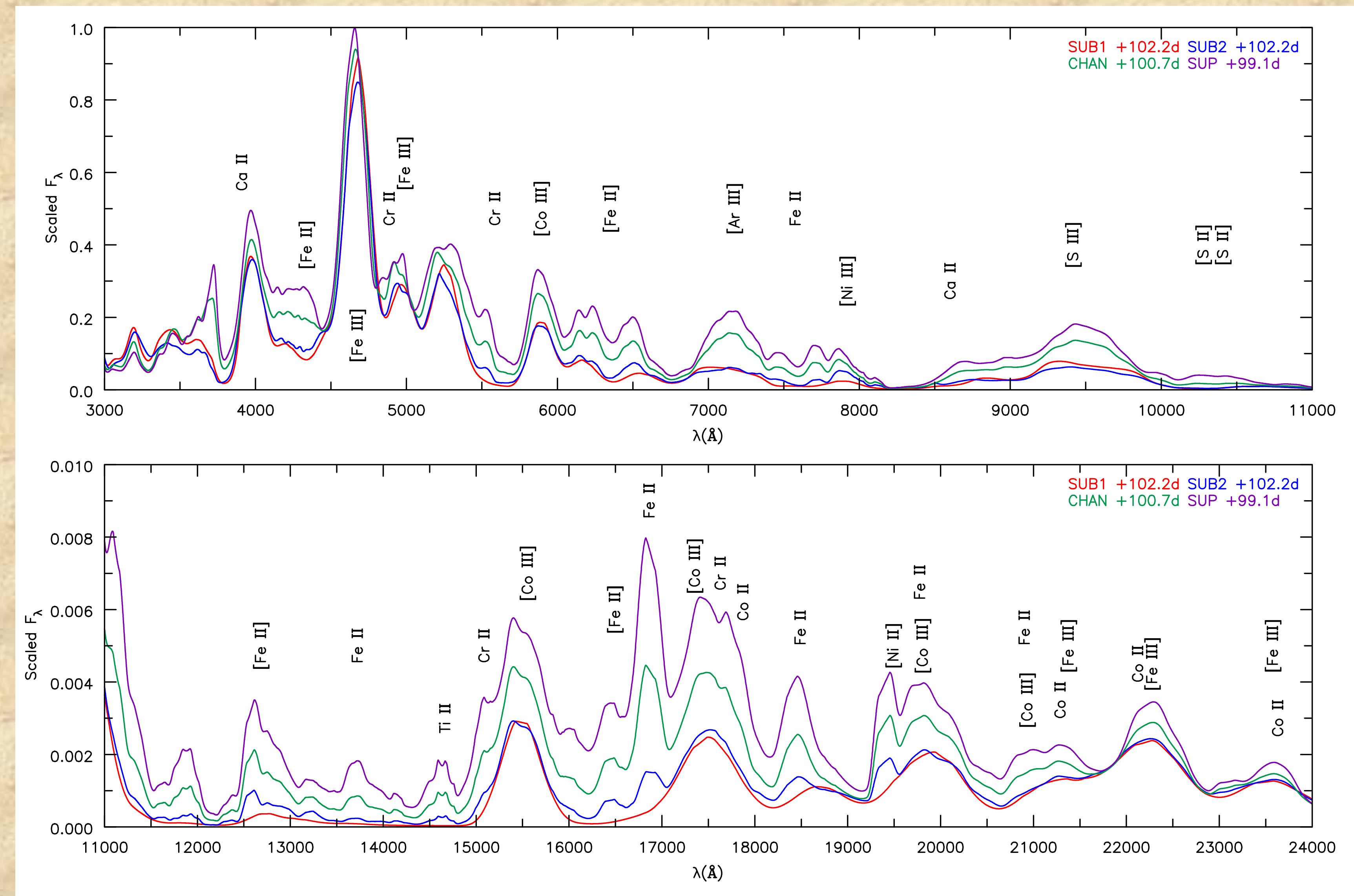
	M_I (mag)	$t(I_{\max})$ (d)	$\Delta M_{15}(I)$ (mag)	M_J (mag)	$t(J_{\max})$ (d)	$\Delta M_{15}(J)$ (mag)	M_H (mag)	$t(H_{\max})$ (d)	$\Delta M_{15}(H)$ (mag)
SUB1	−18.68	12.86	0.70	−18.24	9.60	1.54	−17.87	8.76	0.29
SUB2	−18.60	13.76	0.64	−18.06	8.39	1.03	−17.70	7.81	0.09
CHAN	−18.87	16.41	0.44	−18.48	12.73	1.26	−18.08	10.73	0.10
SUP	−18.99	19.01	0.27	−18.67	15.29	1.17	−18.30	12.91	0.02



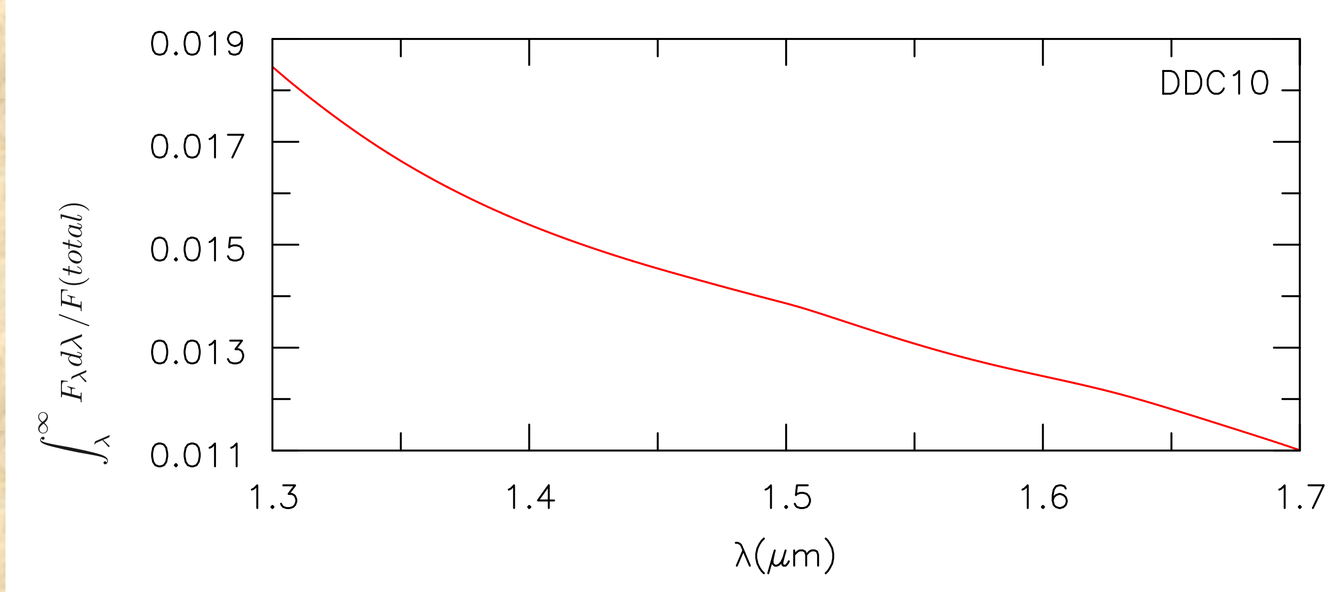
SUB1 +20.6d SUB2 +20.6d
CHAN +21.5d SUP +19.9d
Scaled λF$_\lambda$
λ(Å)
SUB1 +20.6d SUB2 +20.6d
CHAN +21.5d SUP +19.9d
Scaled λF$_\lambda$
λ(Å)


SUB1 +51.8d SUB2 +51.8d
CHAN +50.3d SUP +48.7d
Scaled λF_λ
λ(Å)
0.0
0.2
0.4
0.6
0.8
1.0
2500
3500
4500
5500
6500
7500
8500
9500
10500
11500
12500

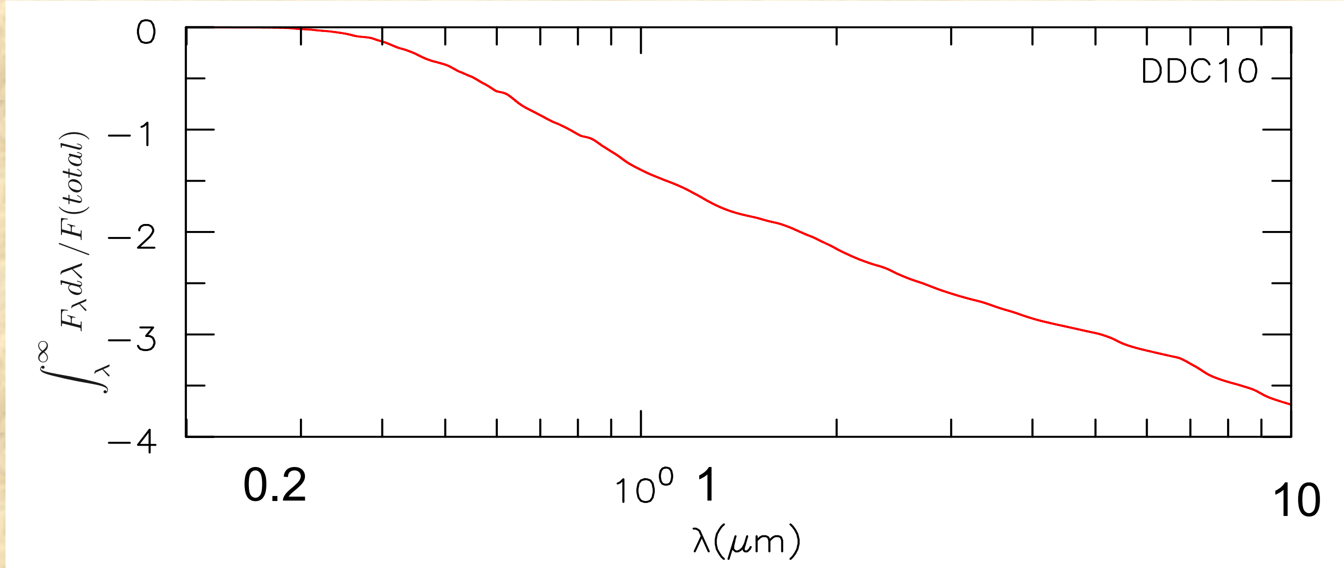

SUB1 +51.8d SUB2 +51.8d
CHAN +50.3d SUP +48.7d
Scaled λF_λ
λ(Å)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
12500
13500
14500
15500
16500
17500
18500
19500
20500
21500
22500
23500


SUB1 +102.2d SUB2 +102.2d
CHAN +100.7d SUP +99.1d
Scaled Fλ
λ(Å)
Ca II
[Fe II]
[Fe III]
Cr II
[Fe III]
Cr II
[Co III]
[Fe II]
[Ar III]
Fe II
[Ni III]
Ca II
[S III]
[S II]
[S II]
[Fe II]
Fe II
Ti II
Cr II
[Co III]
[Fe II]
Fe II
[Co III]
Cr II
Co II
Fe II
[Ni II]
[Co III]
Fe II
[Co III]
Fe II
Co II
[Fe III]
Co II
[Fe III]
[Fe III]
Co II

Flux in IR

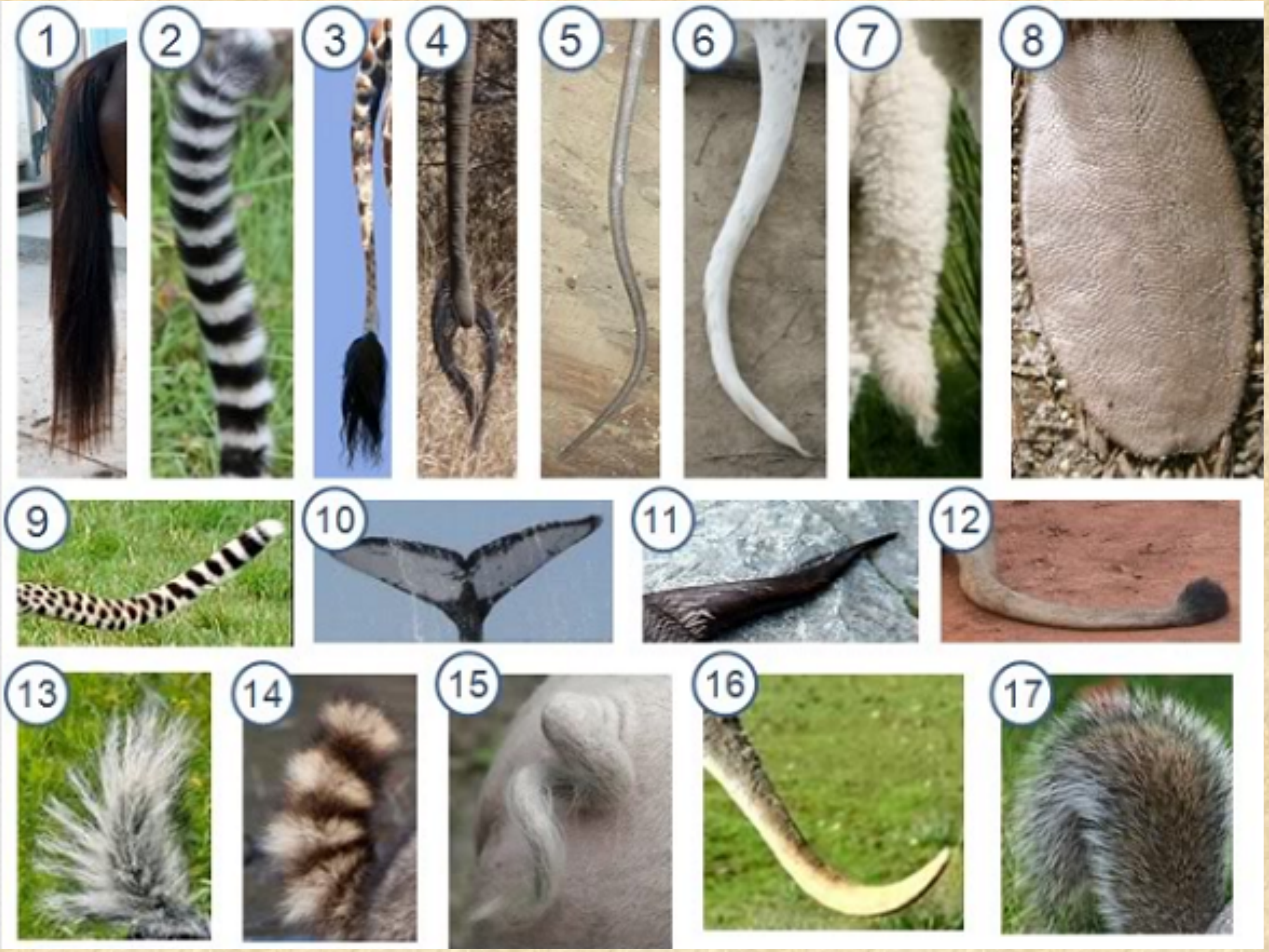


0.019
0.017
0.015
0.013
0.011
DDC10
$\int_\lambda^\infty F_\lambda d\lambda / F(total)$
1.3
1.4
1.5
1.6
1.7
λ(μm)



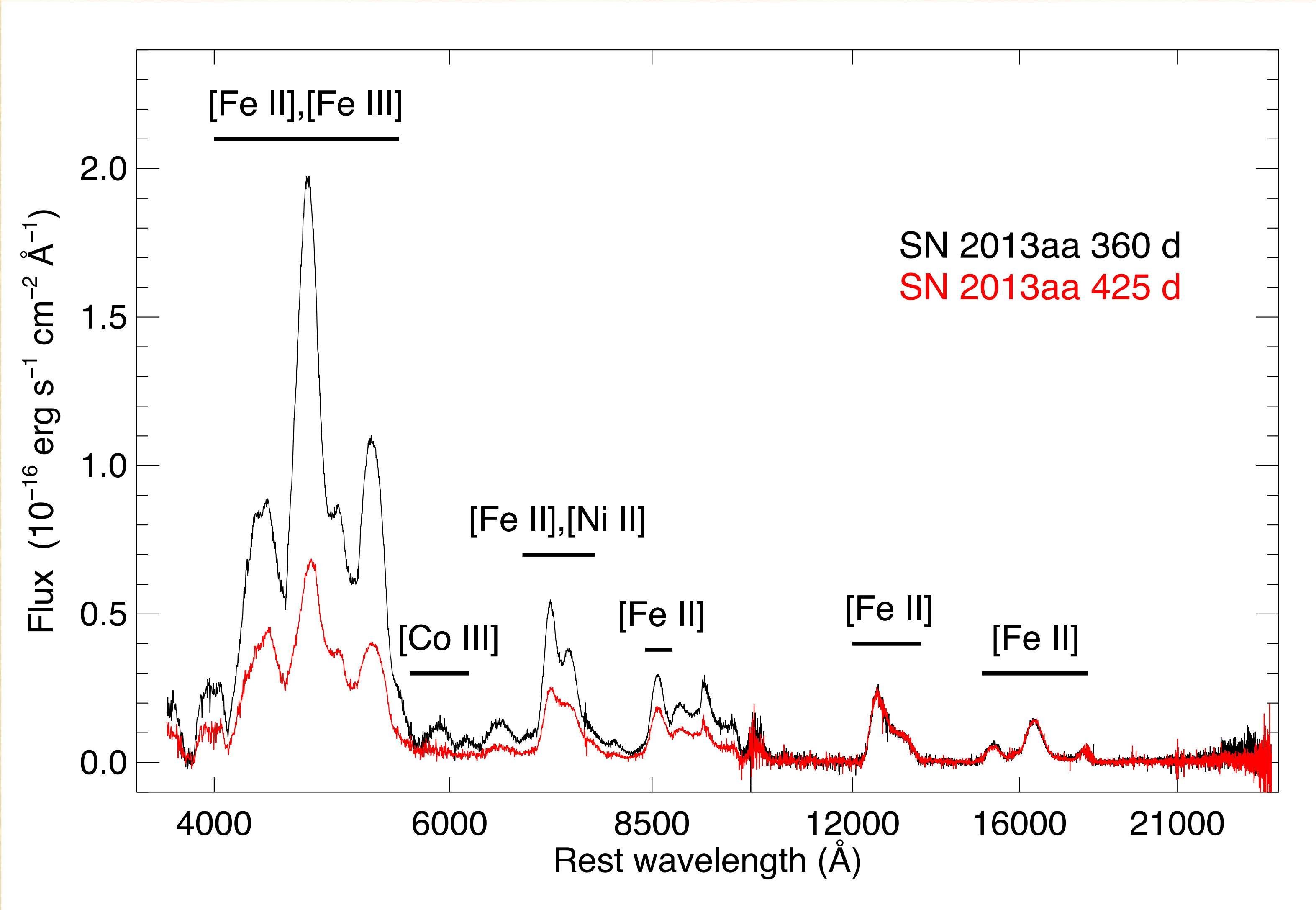
0
−1
−2
−3
−4
DDC10
$\int_\lambda^\infty F_\lambda d\lambda / F(total)$
0.2
10^0
1
10
λ(μm)

H – band : The Tail of the flux distribution.



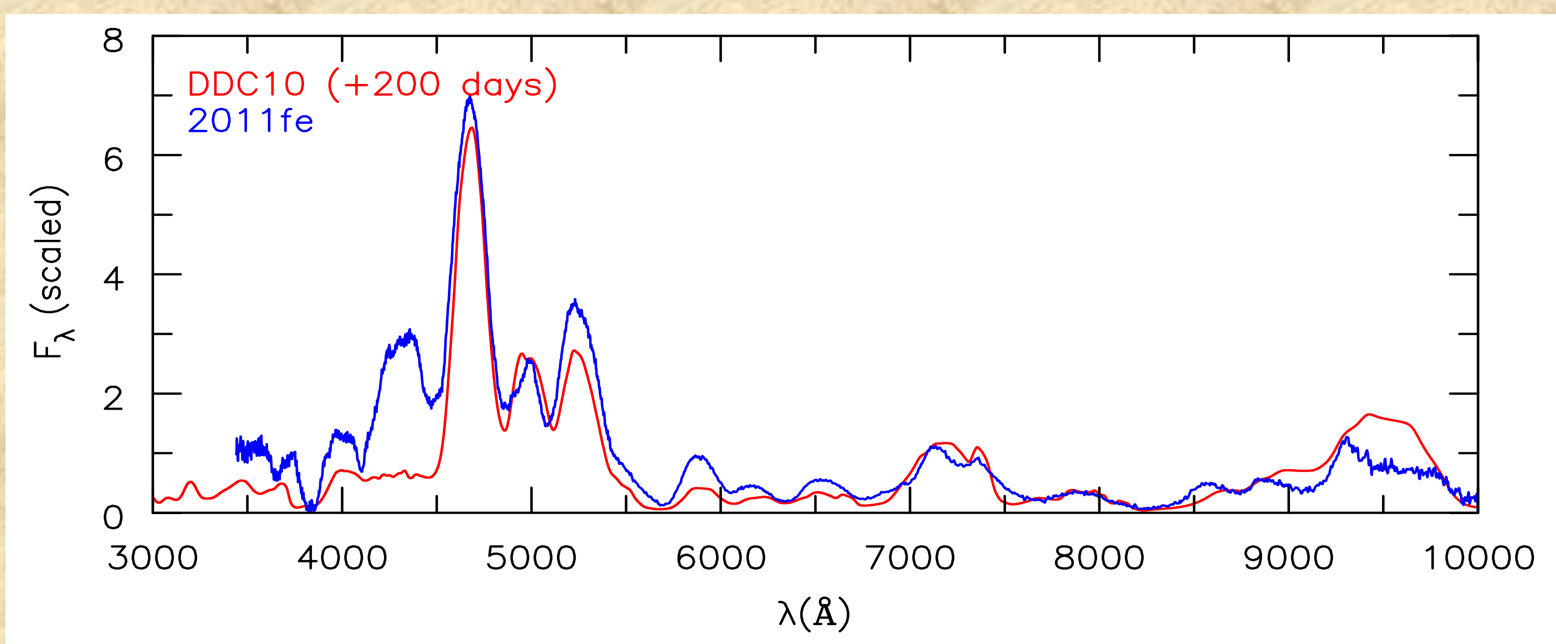
From PLAYBUZ.

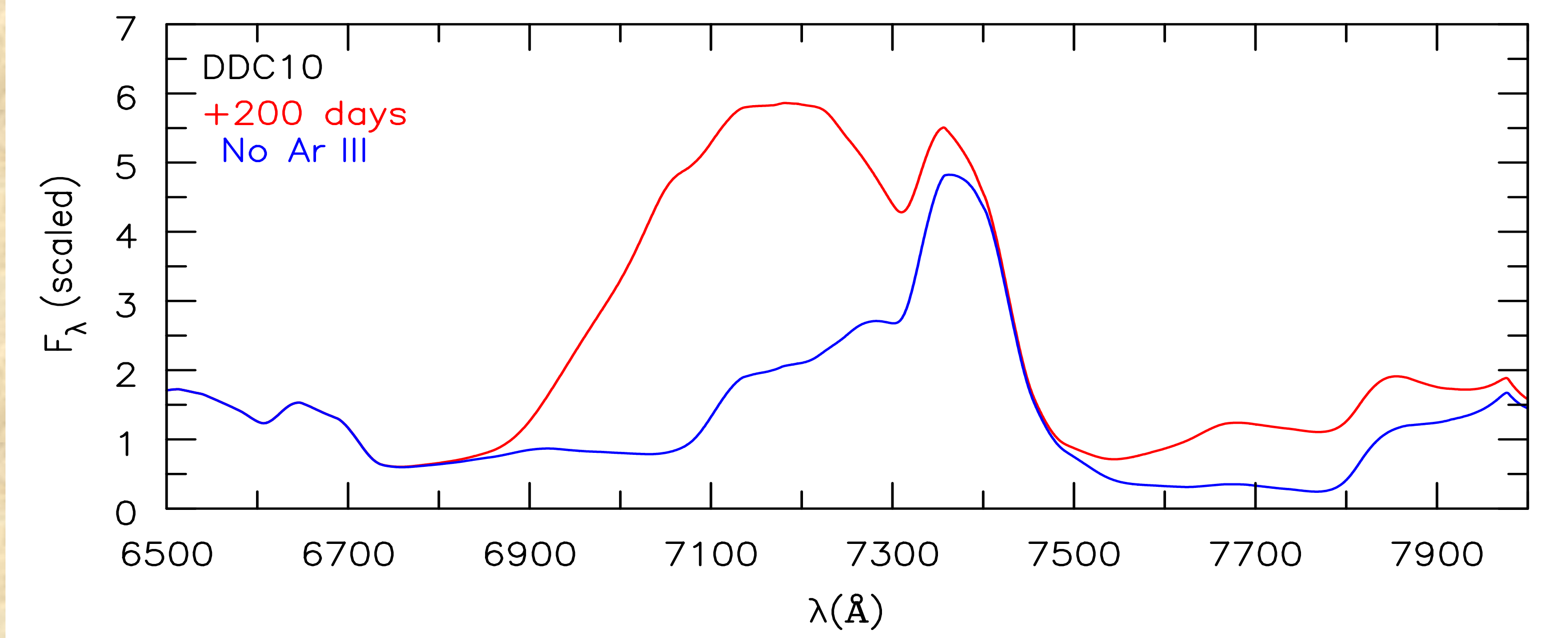
Where are the lines due to IMEs?



Maguire et al 2018, MNRAS, in press

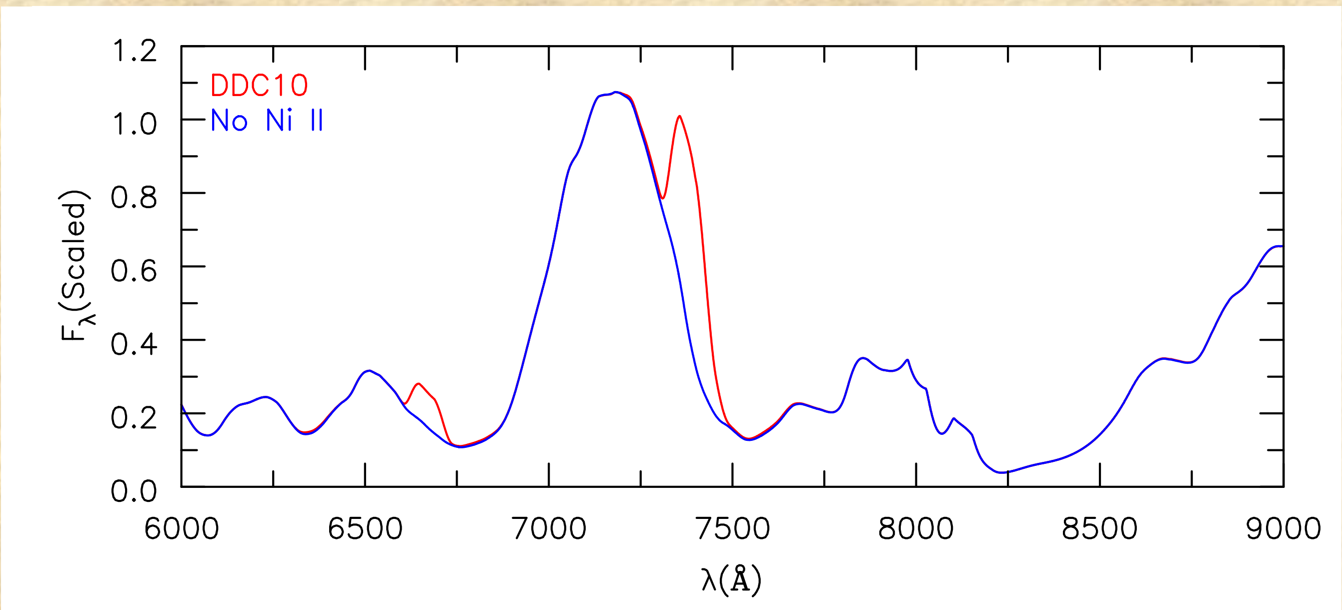
IMEs -- Argon


DDC10 (+200 days)
2011fe
F_λ (scaled)
0
2
4
6
8
3000
4000
5000
6000
7000
8000
9000
10000
λ(Å)

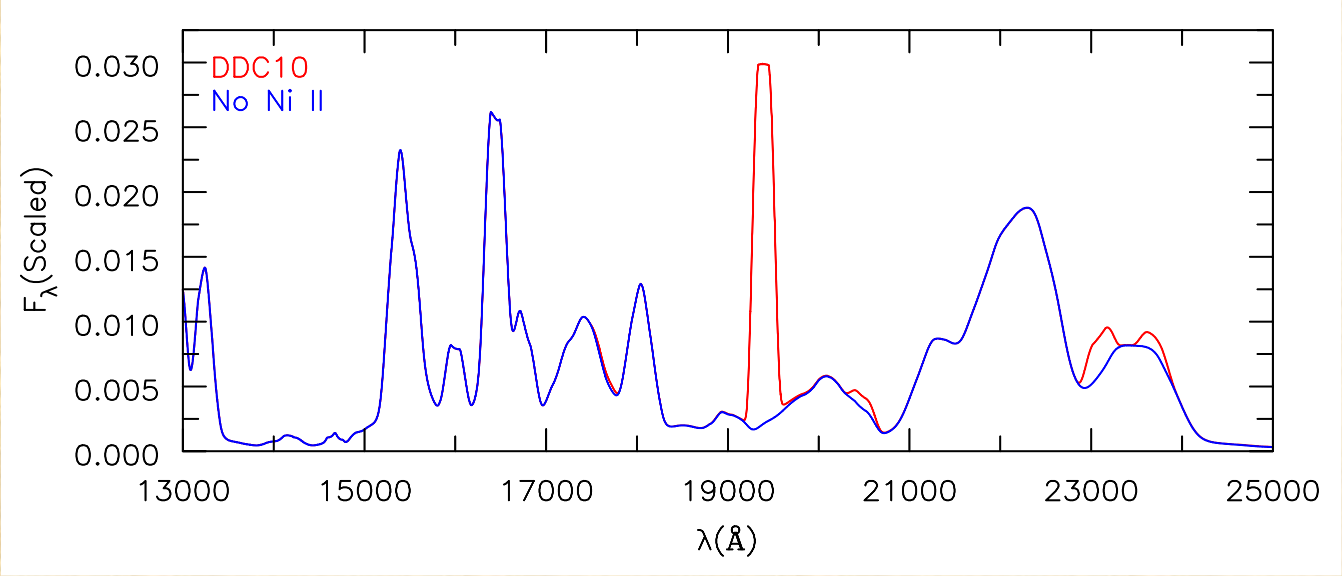

DDC10
+200 days
No Ar III
F_λ (scaled)
0
1
2
3
4
5
6
7
6500
6700
6900
7100
7300
7500
7700
7900
λ(Å)

Ni II lines
Optical and IR

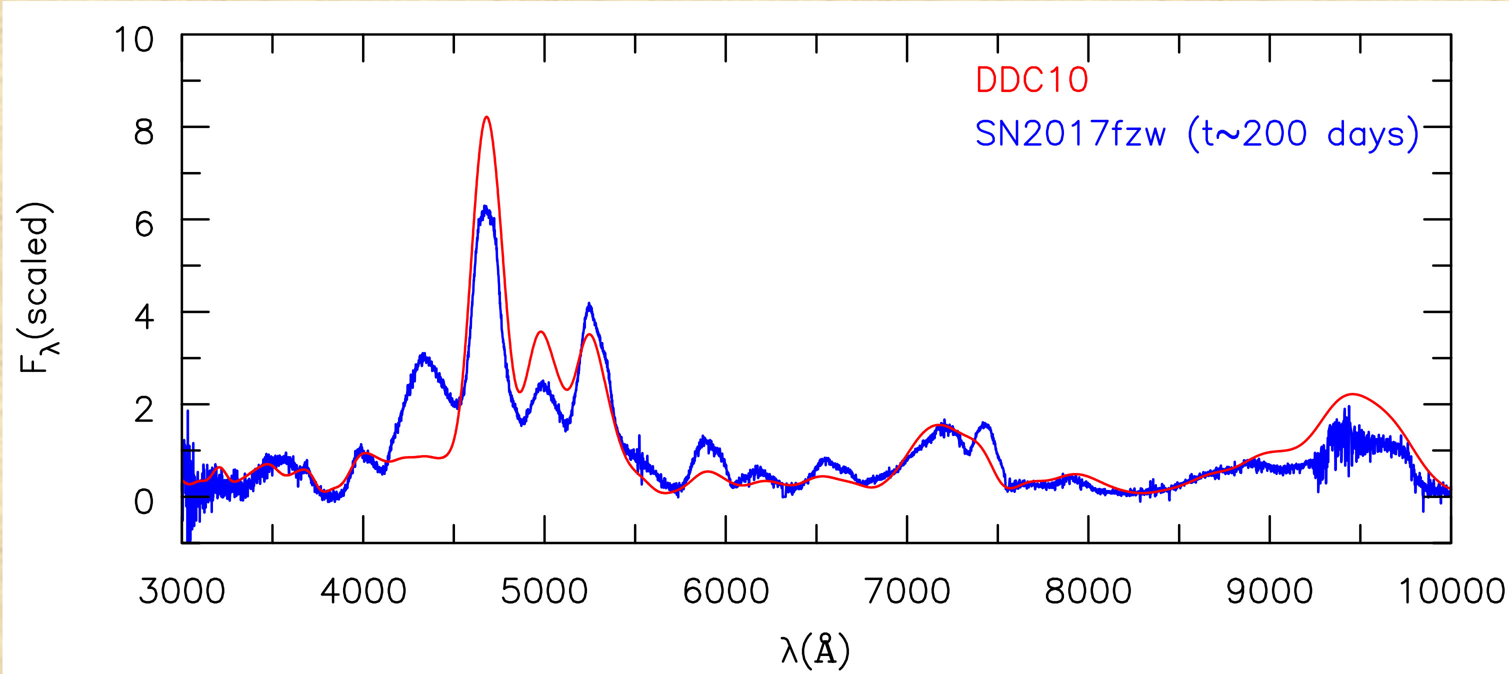
Lower	Upper	A(s^{-1})	λ(Å)	E(eV)
$3d^9\ ^2D_{5/2}$	$3d^8(^3F)4s\ ^4F_{7/2}$	0.200	7377.83	1.16
$3d^9\ ^2D_{3/2}$	$3d^8(^3F)4s\ ^2F_{5/2}$	0.162	7411.61	1.32
$3d^8(^3F)4s\ ^4F_{9/2}$	$3d^8(^3F)4s\ ^2F_{7/2}$	0.0925	19387.74	1.16
$3d^8(^3F)4s\ ^4F_{5/2}$	$3d^8(^1D)4s\ ^2D_{3/2}$	0.401	7307.65	2.95
$3d^8(^3F)4s\ ^4F_{5/2}$	$3d^8(^1D)4s\ ^2P_{3/2}$	0.149	6813.57	3.07

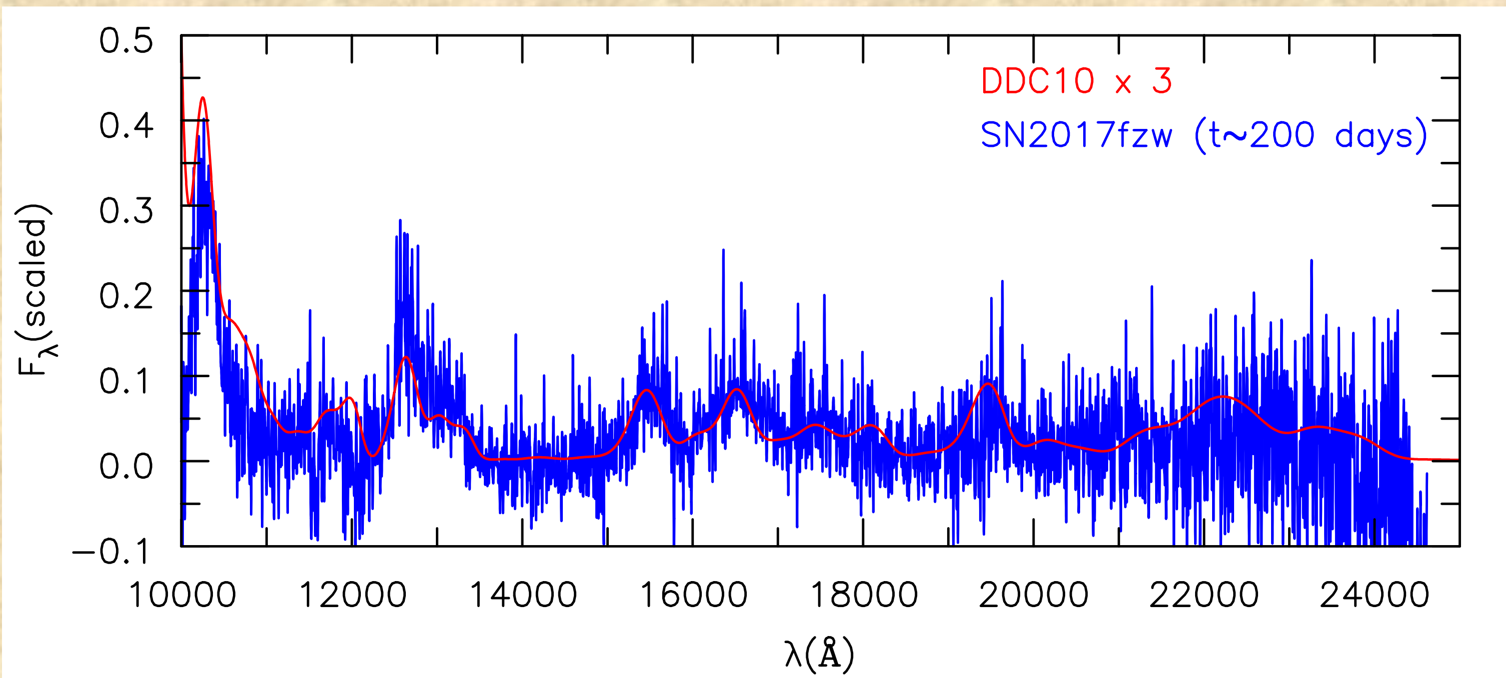


DDC10
No Ni II
1.2
1.0
0.8
0.6
0.4
0.2
0.0
F_λ(Scaled)
6000
6500
7000
7500
8000
8500
9000
λ(Å)

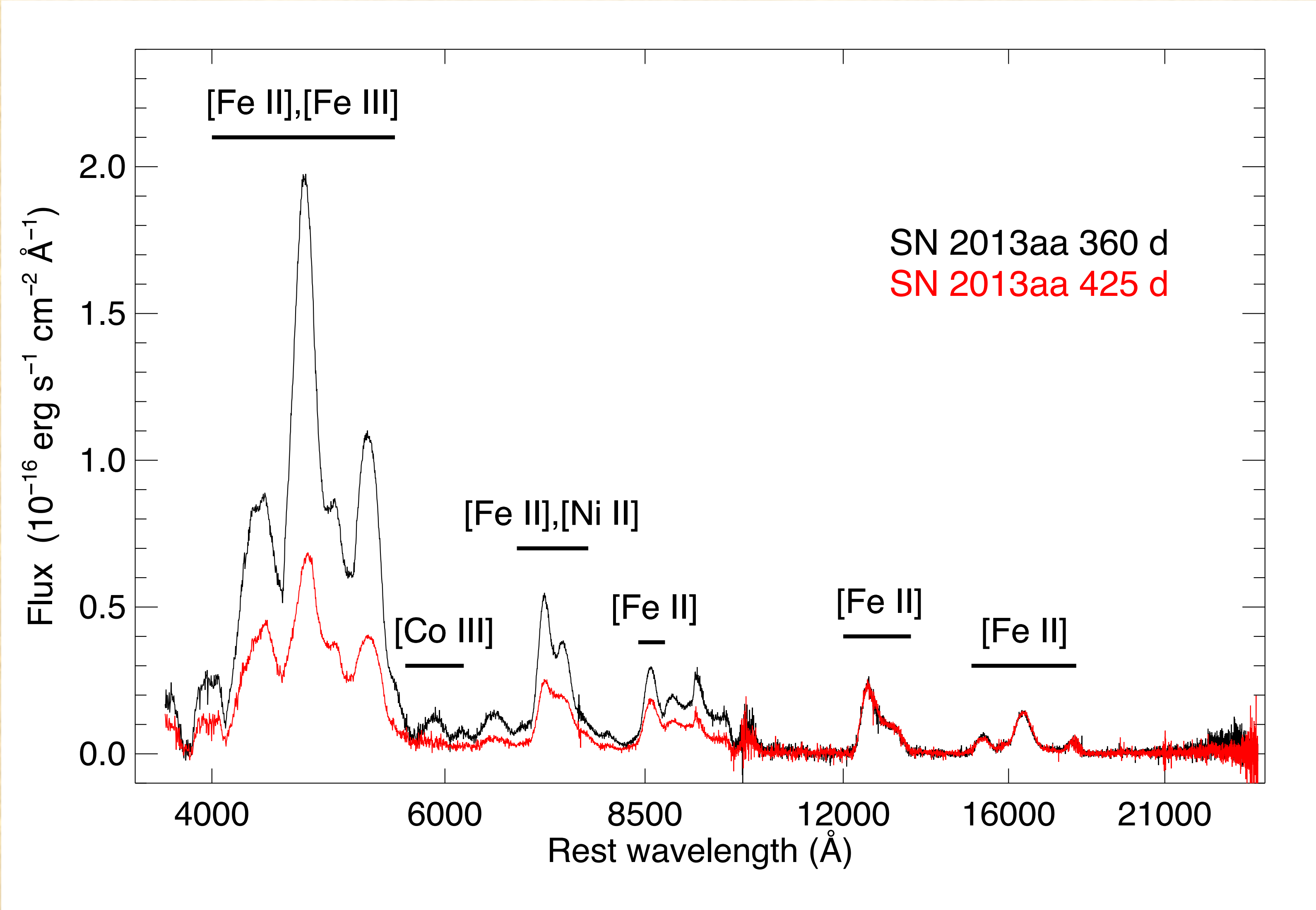


DDC10
No Ni II
0.030
0.025
0.020
0.015
0.010
0.005
0.000
F_λ(Scaled)
13000
15000
17000
19000
21000
23000
25000
λ(Å)


DDC10
SN2017fzw (t~200 days)
F_λ(scaled)
λ(Å)

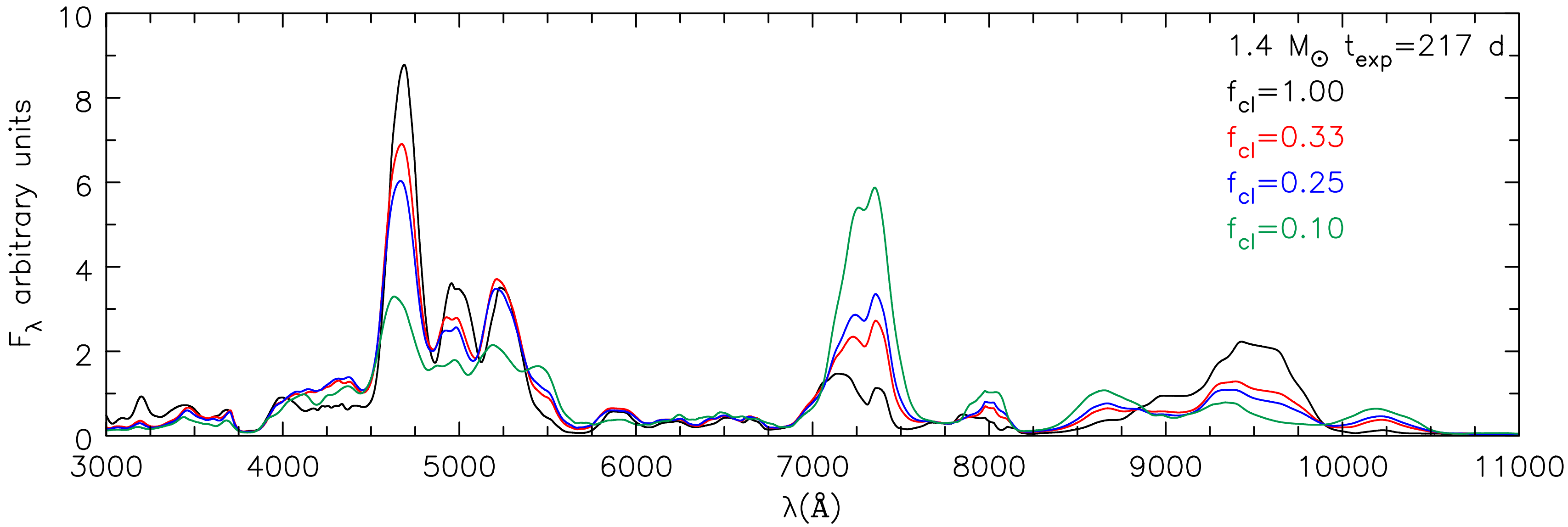

DDC10 x 3
SN2017fzw (t~200 days)
F_λ(scaled)
λ(Å)

Where is the IR Ni II line at 1.94 μm?

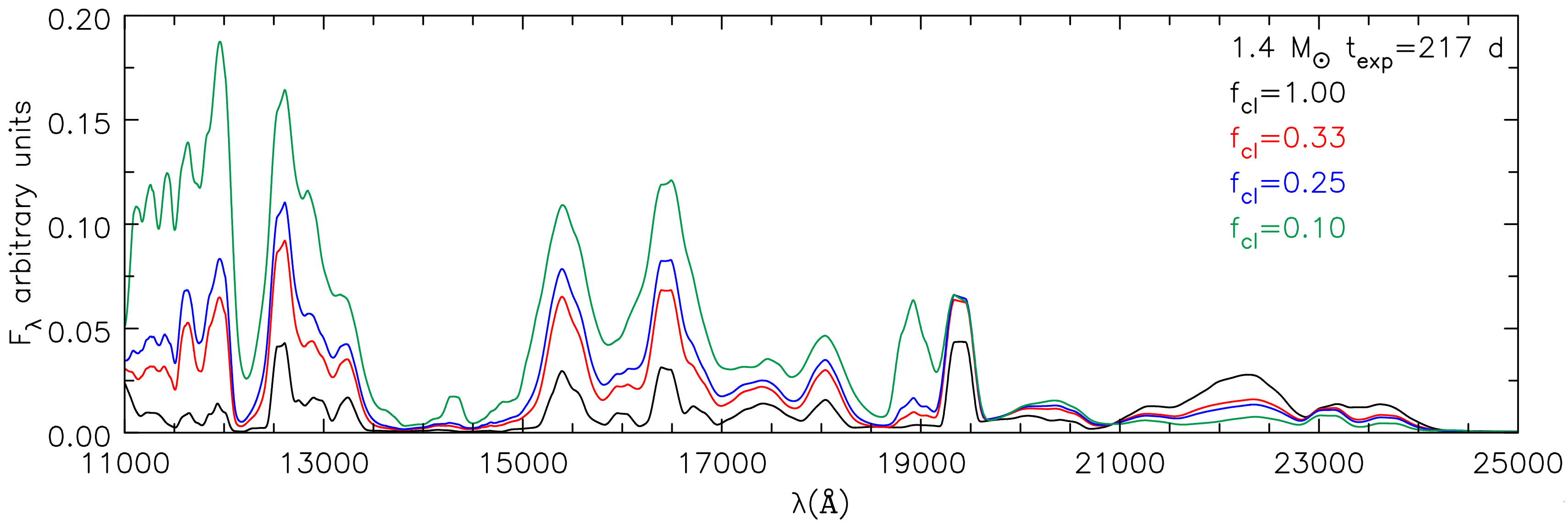


Maguire et al 2018, MNRAS, in press

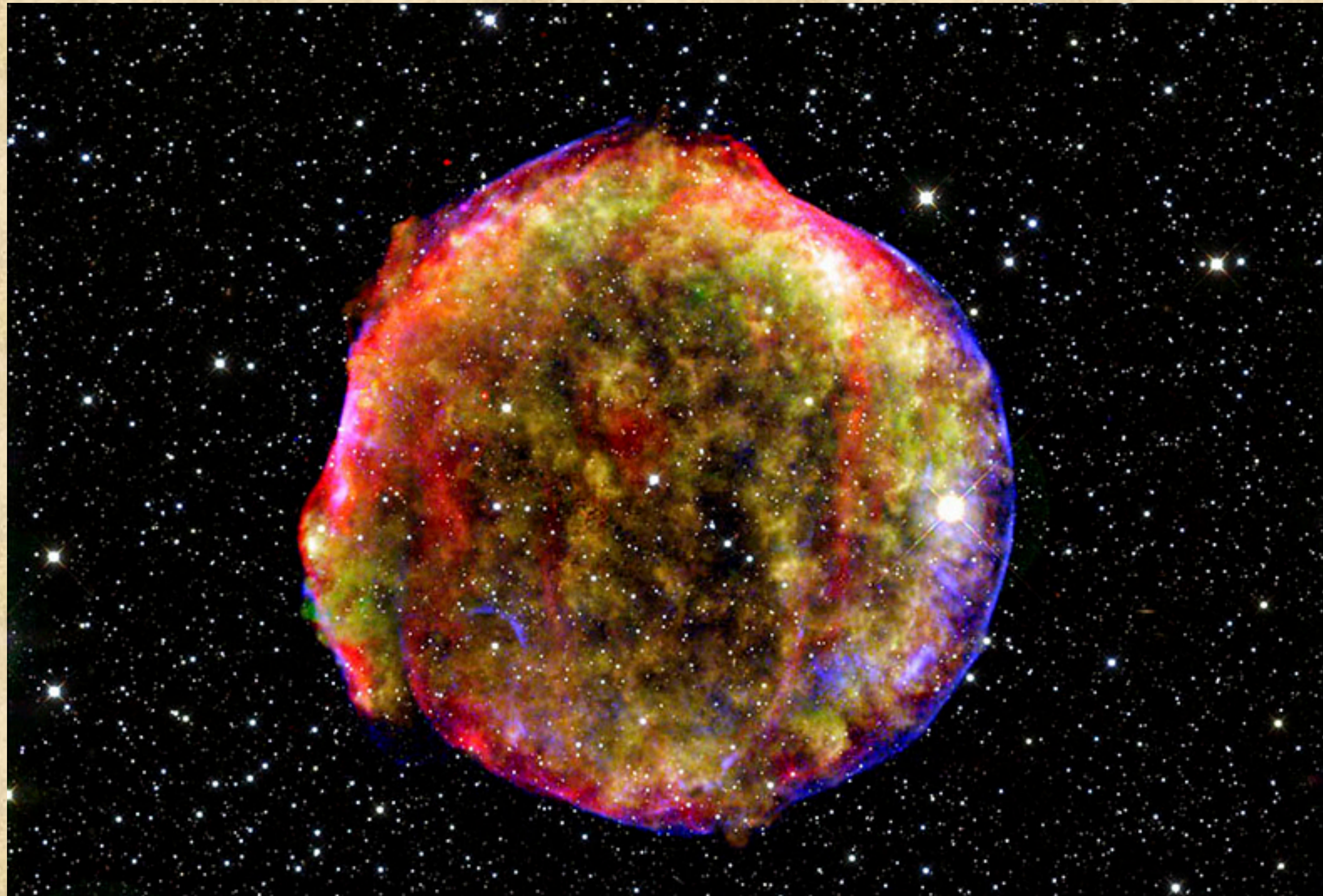
Clumping



1.4 $M_\odot$ t_{exp}=217 d
f_{cl}=1.00
f_{cl}=0.33
f_{cl}=0.25
f_{cl}=0.10
F_λ arbitrary units
λ(Å)

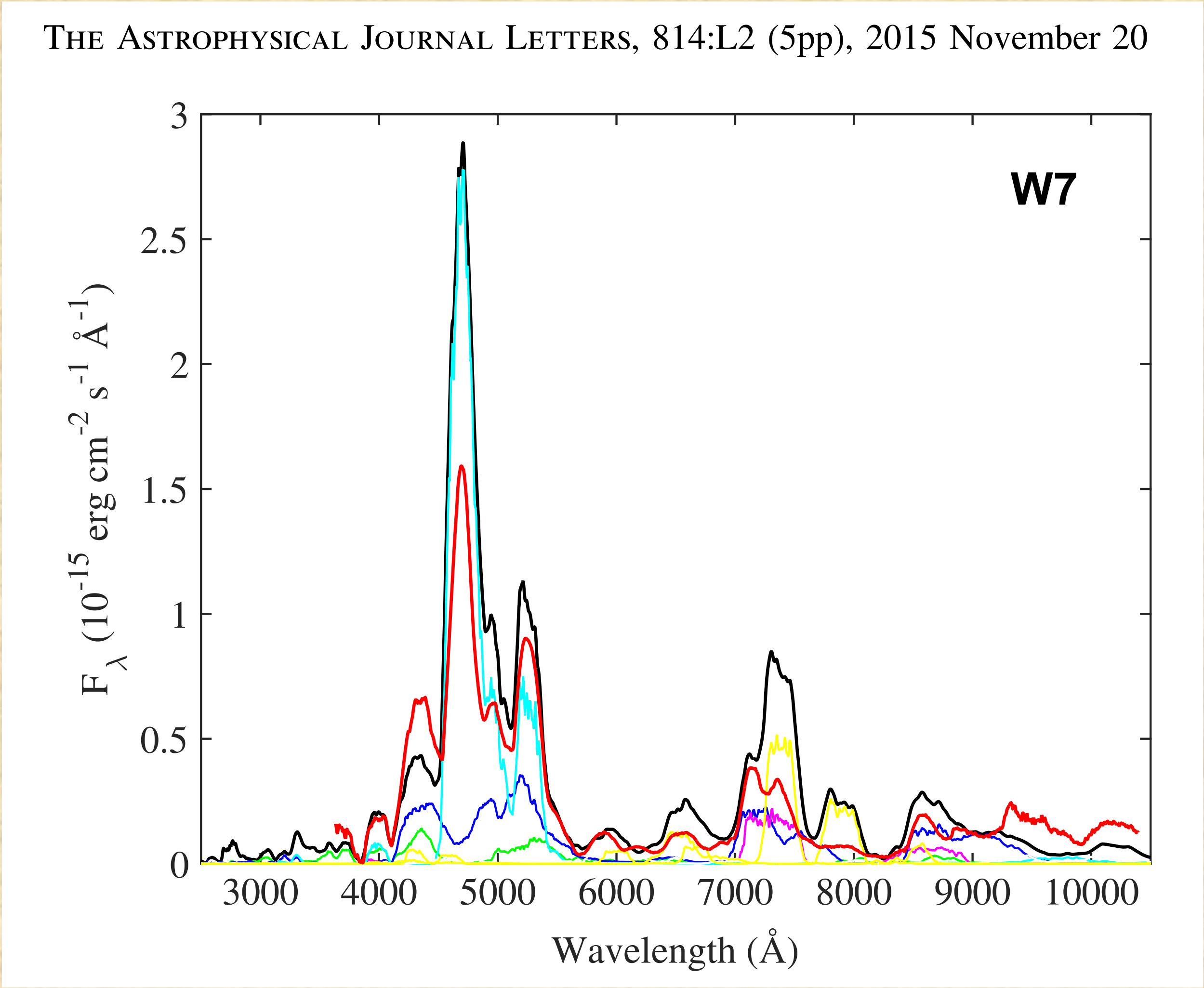


1.4 $M_\odot$ t_{exp}=217 d
f_{cl}=1.00
f_{cl}=0.33
f_{cl}=0.25
f_{cl}=0.10
F_λ arbitrary units
λ(Å)



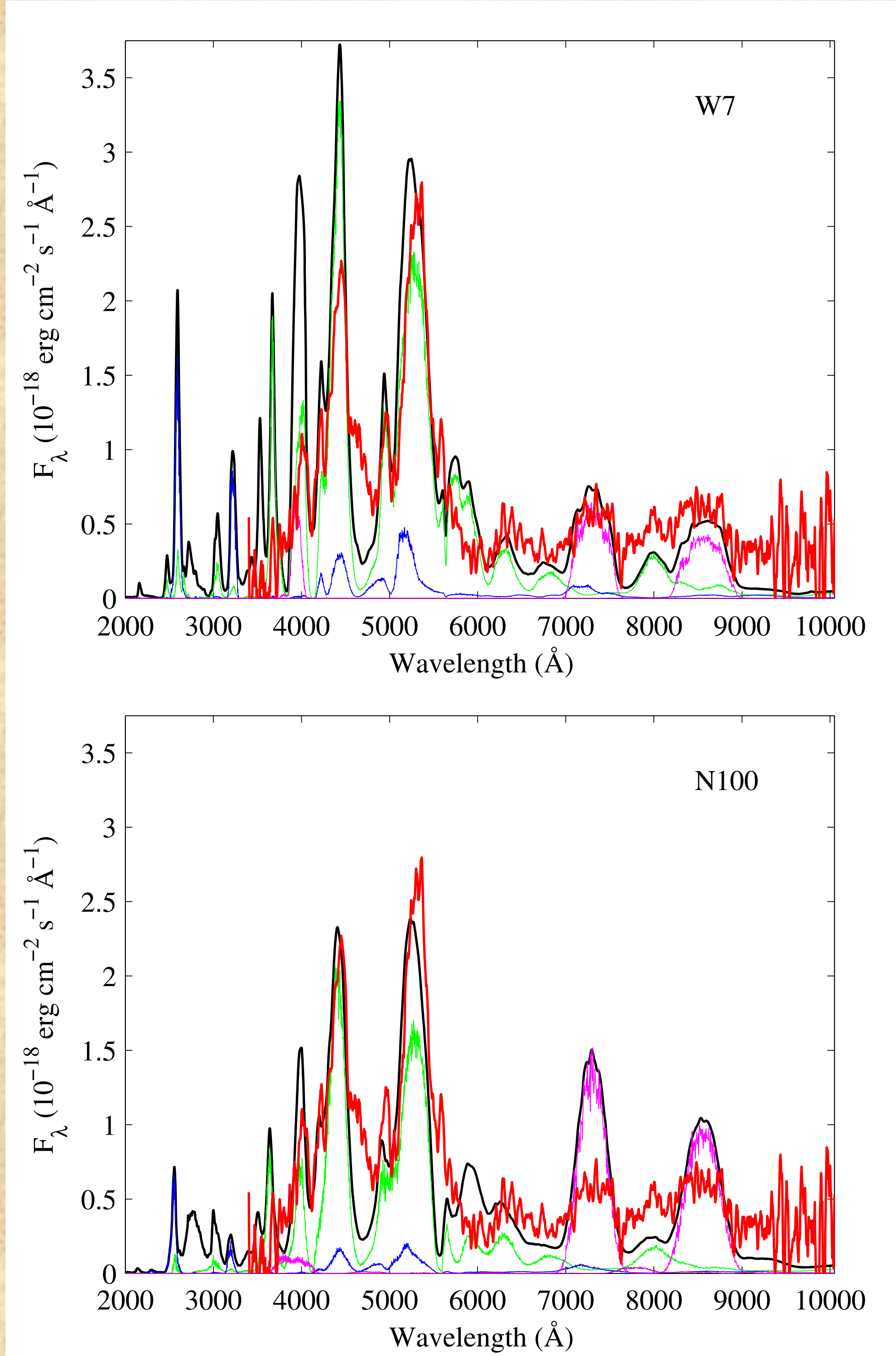
Credit: *X-ray:* NASA/CXC/SAO; *Infrared:* NASA/JPL-Caltech;
Optical: MPIA, Calar Alto, O. Krause et al.

Fransson and Jerkstrand (2015)



Day 331: SN 2011fe

Fe I , Fe II, Fe III, Ca II, Ni II-III



Fransson
&
Jerkstrand (2015)

Day 331: SN 2011fe
Fe I , Fe II, Ca II

Understanding SN Ia behavior at early times

Standard DDC models do poor job at explaining early light curves and spectra.

Possible solutions:

- Wrong non-LTE calculations (atomic data / physics?).
- Mixing?
  - ^{56}Ni closer to the surface means that ^{56}Ni heating can warm SN "photosphere" earlier.
    Helps but may not sufficient.
- Different progenitor model?
  - Pulsationally delayed detonation model (PPDEL)
  - Binary merger / double degenerate models
  - Helium shell
- Departures from spherical geometry
  - Free-parameter heaven

The FLUFF is (potentially) important at early times.

Do SN Ia have a dark phase?

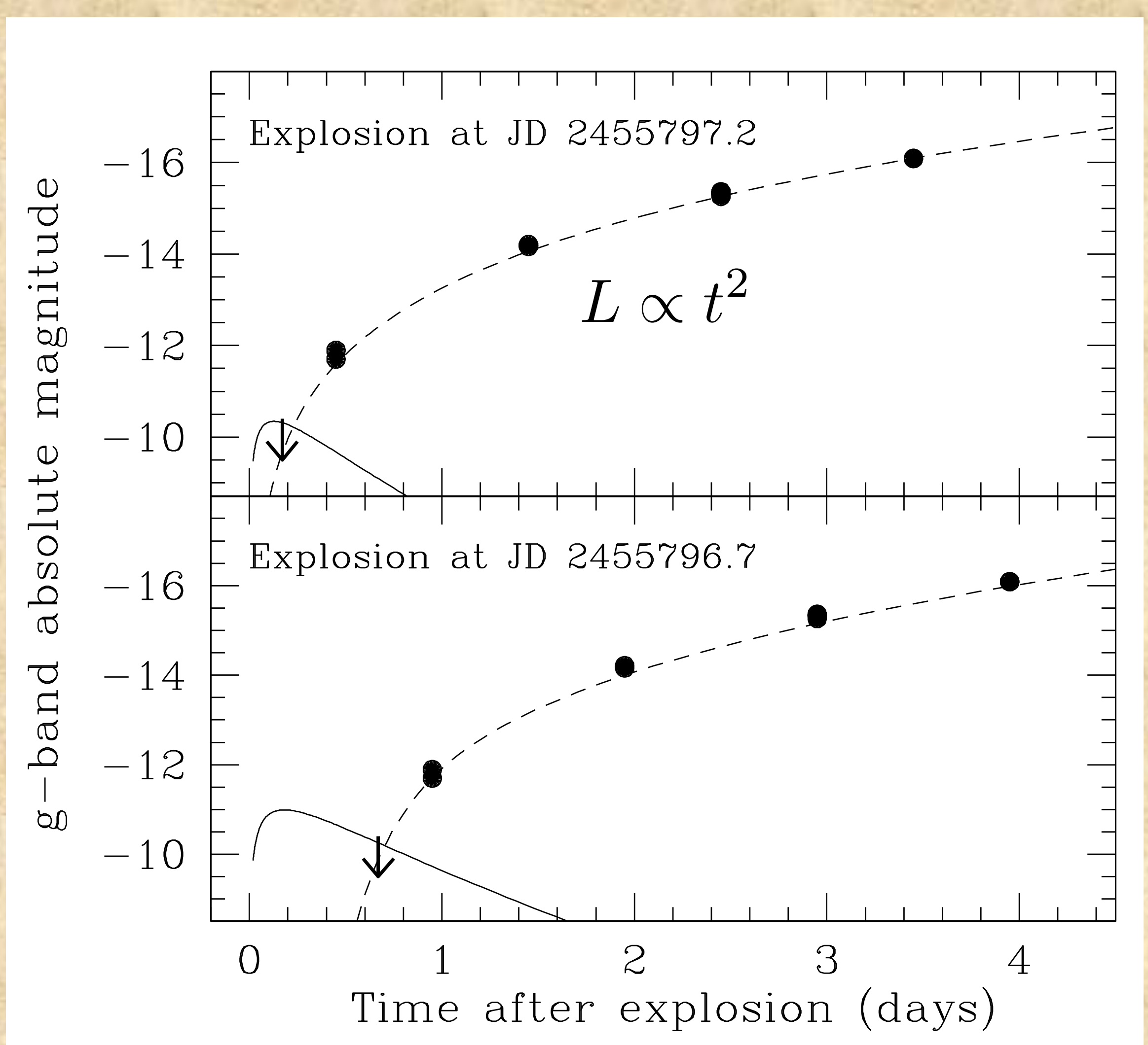
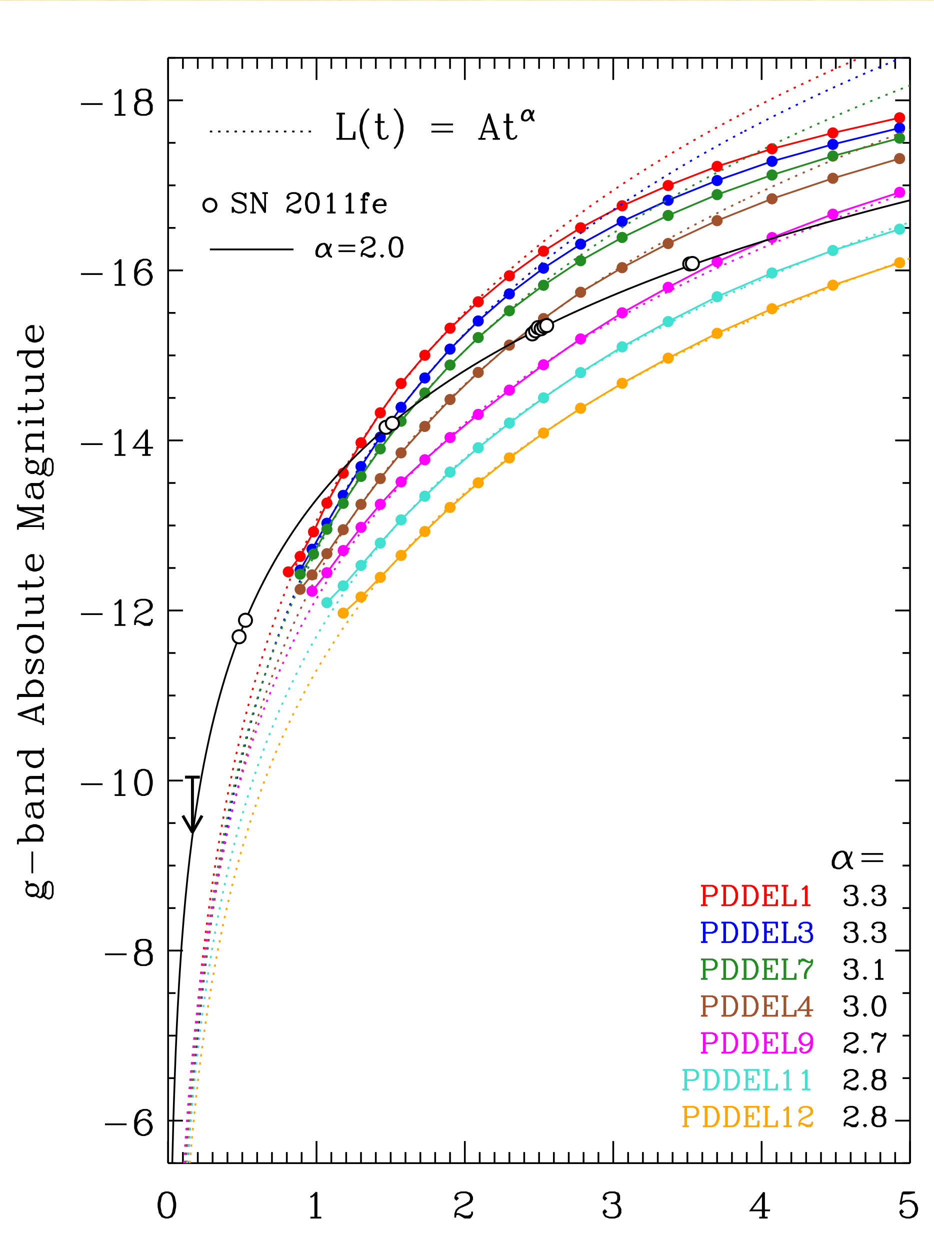
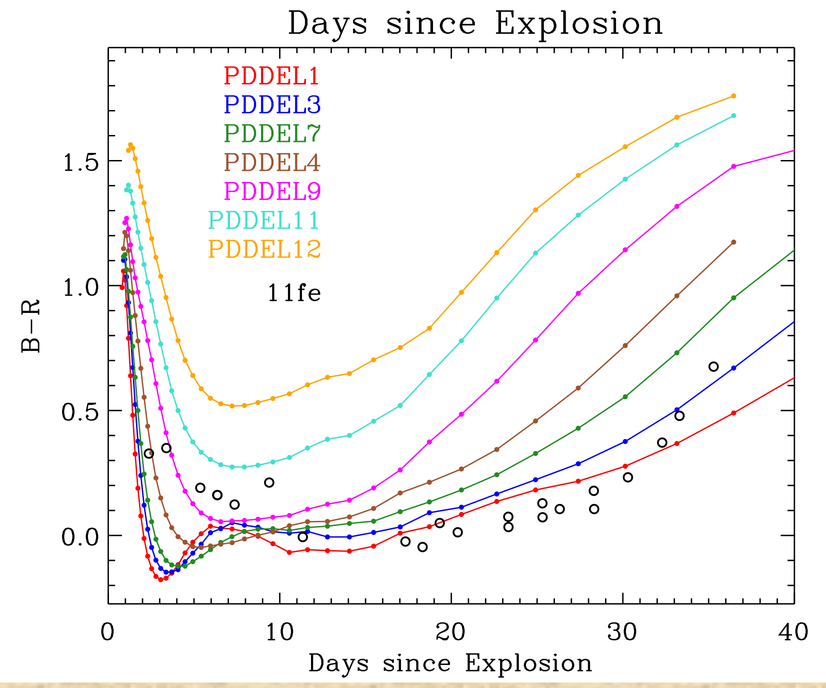


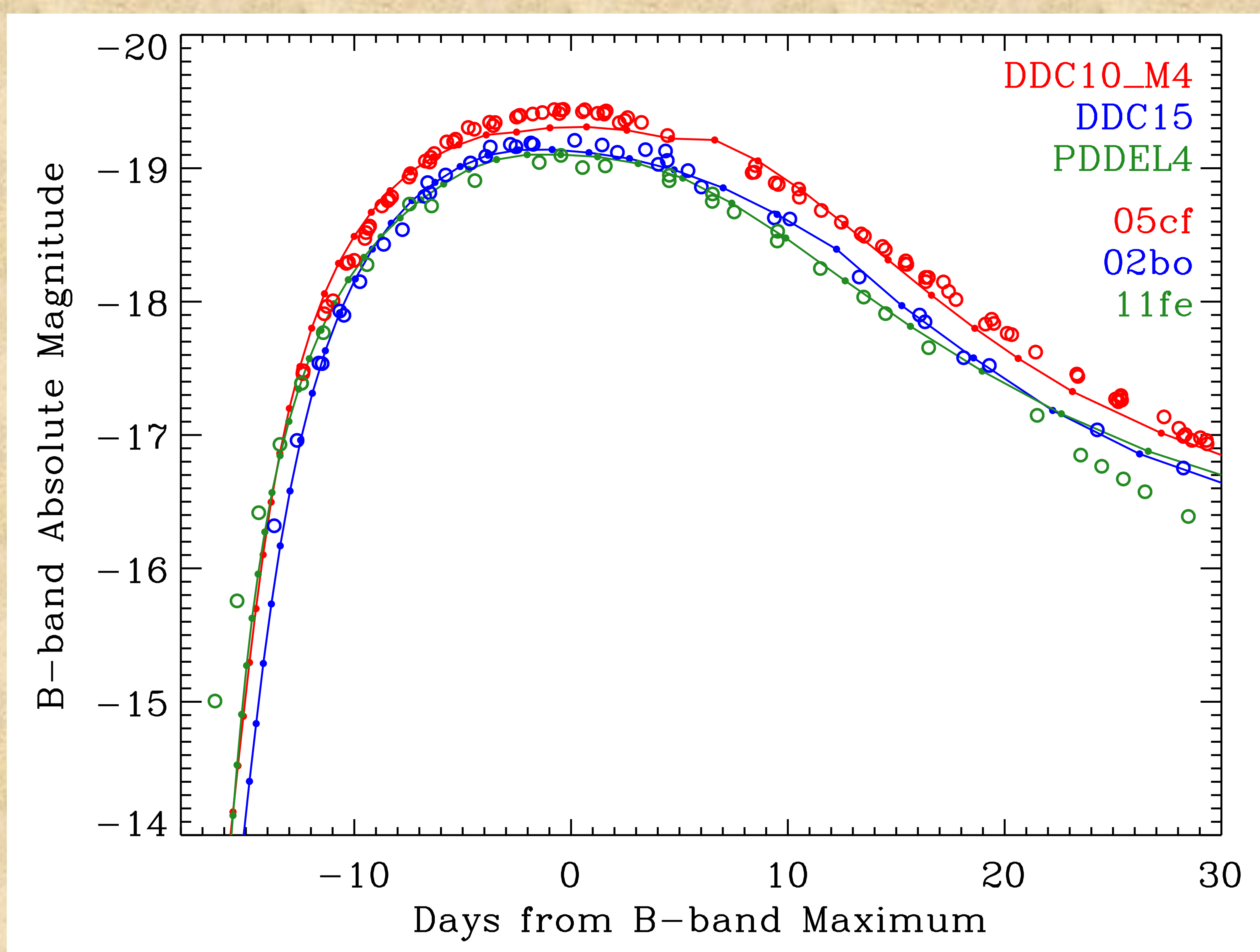
Figure from Piro and Nakar (2012)

PDDEL models

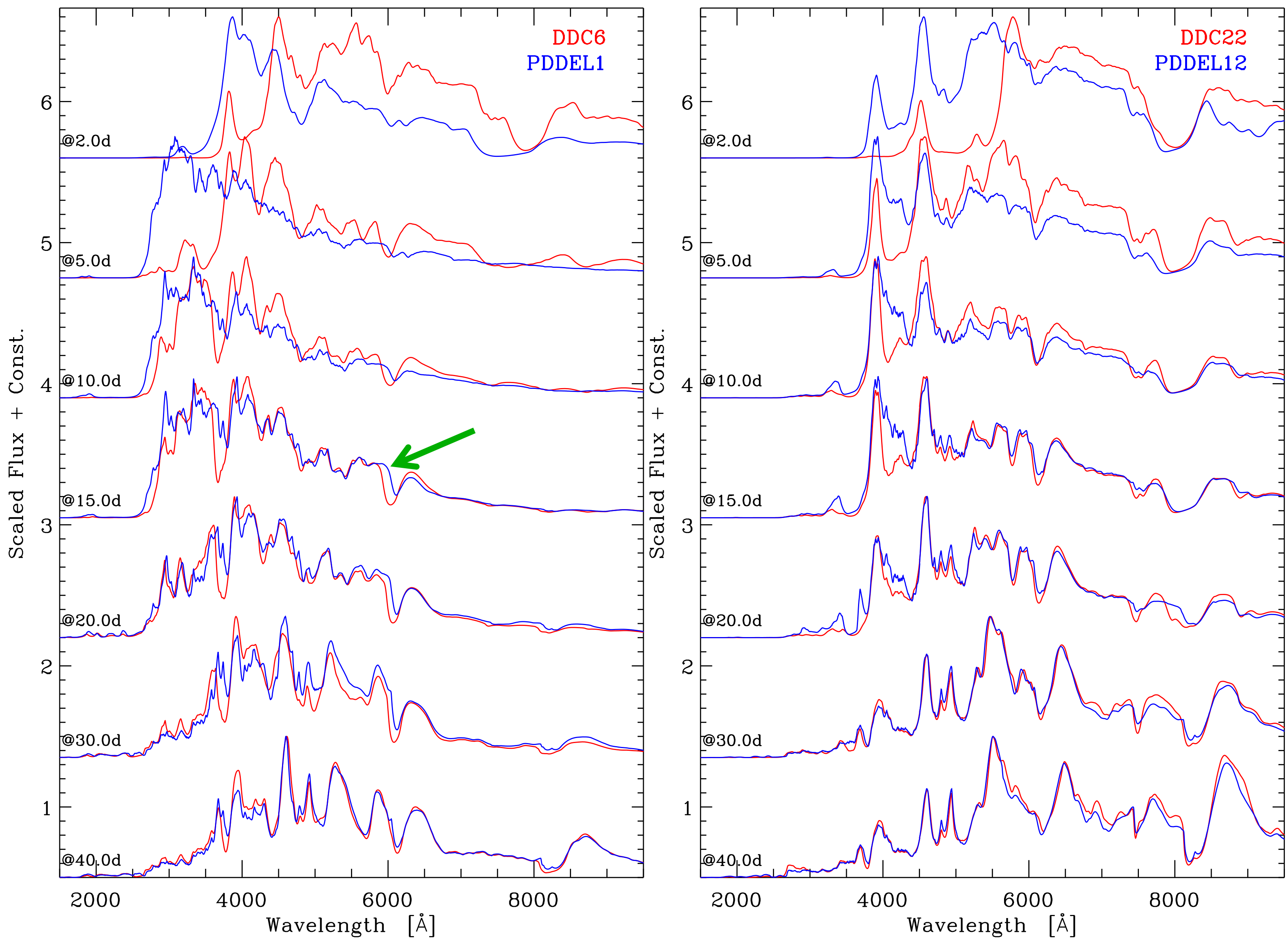


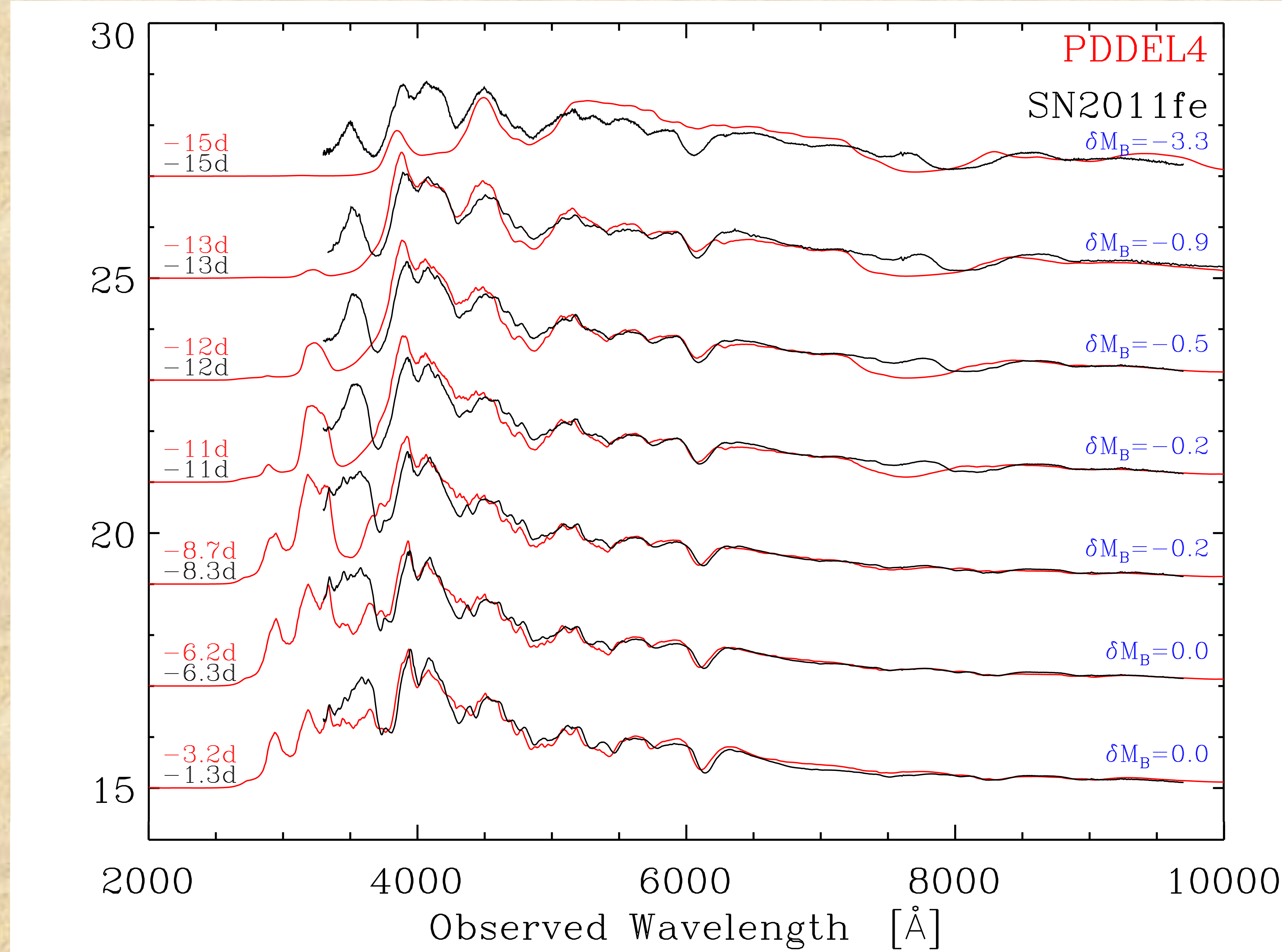
Models are bluer.




DDC10_M4
DDC15
PDDEL4
05cf
02bo
11fe
B-band Absolute Magnitude
Days from B-band Maximum
−20
−19
−18
−17
−16
−15
−14
−10
0
10
20
30

DDC & PDDEL models are similar after maximum

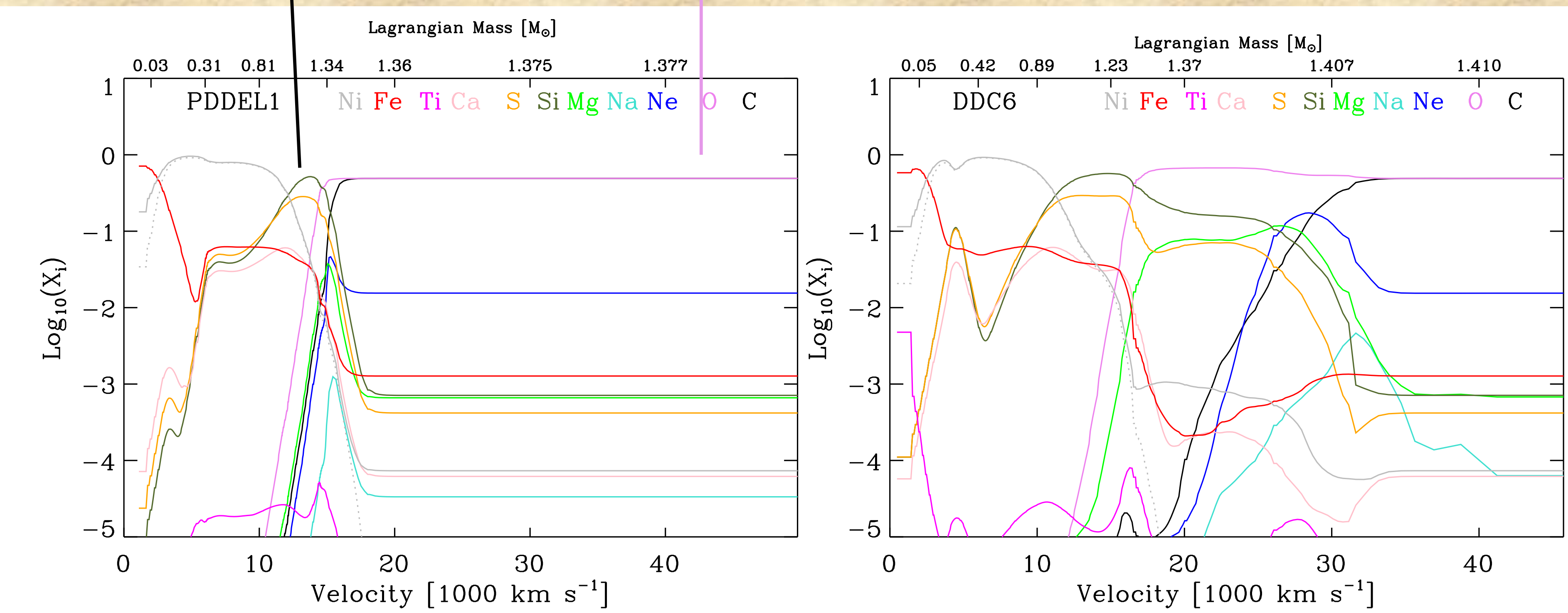




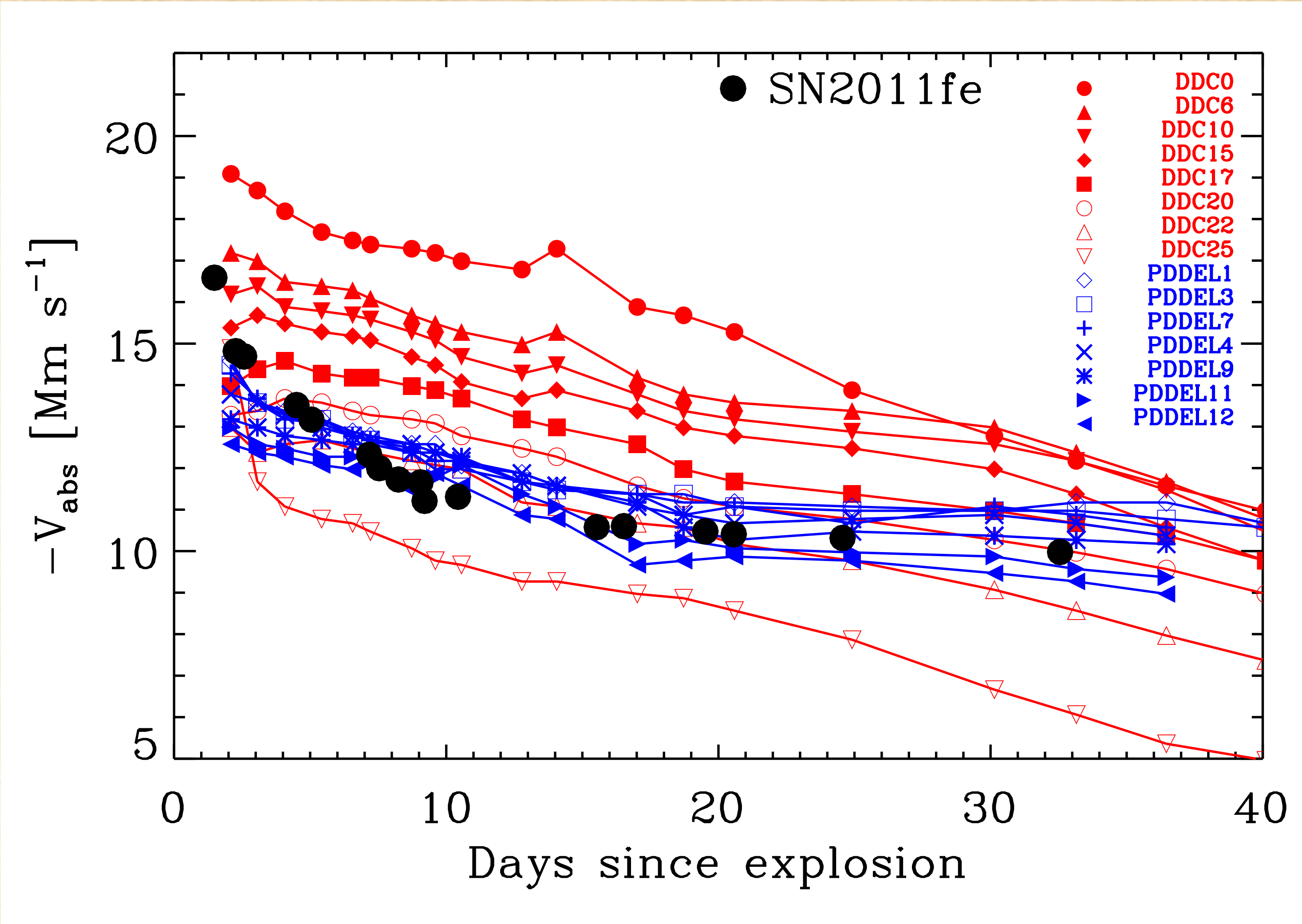
PDDEL4
SN2011fe
−15d
−15d
$\delta M_B=-3.3$
−13d
−13d
$\delta M_B=-0.9$
−12d
−12d
$\delta M_B=-0.5$
−11d
−11d
$\delta M_B=-0.2$
−8.7d
−8.3d
$\delta M_B=-0.2$
−6.2d
−6.3d
$\delta M_B=0.0$
−3.2d
−1.3d
$\delta M_B=0.0$
30
25
20
15
2000
4000
6000
8000
10000
Observed Wavelength [Å]

Si restricted to narrower velocity range.

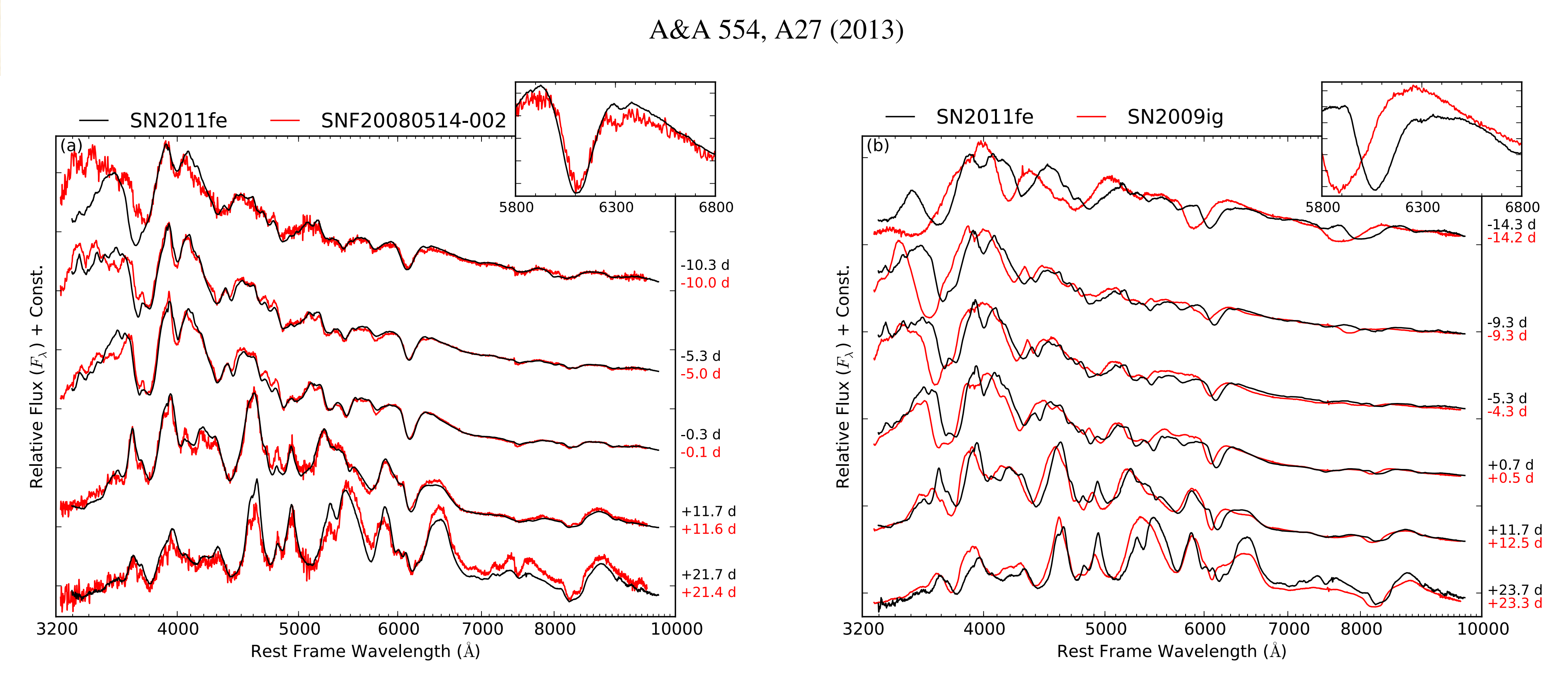
More unburnt C



Progenitor effects V(abs) of Si II 6355



Pereira et al (2013, A&A, 554, A27)
Nearby SN factory.



THE

END