Probing the Progenitors and Diversity of Type Ia of Thermonuclear Supernovae

(P. Hoeflich et al., Florida State University)

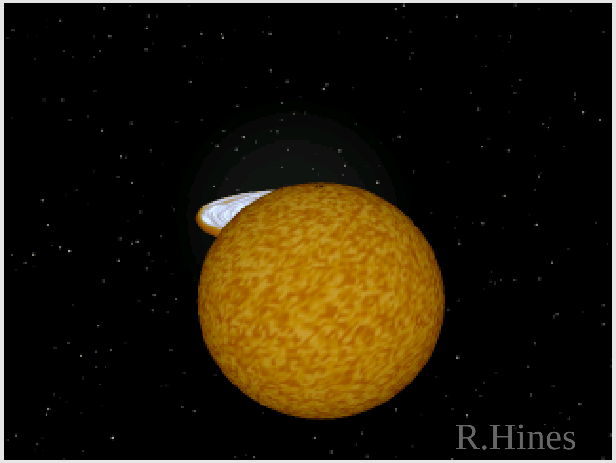
New signatures:

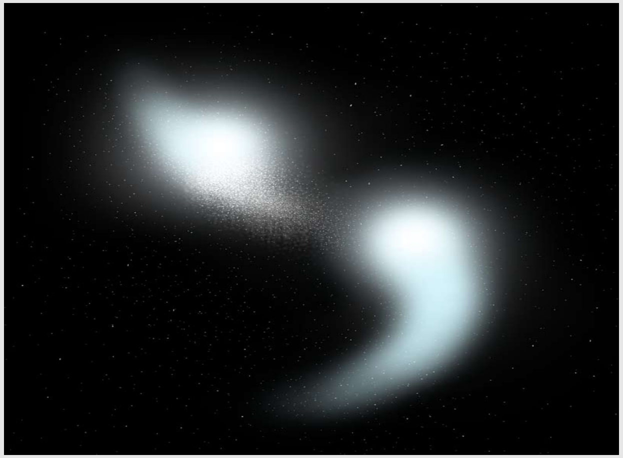
- Very-early time observations

or probing the outer $10^{-5\ldots-3}$ Mo

- Late time observations: (SN2014J & SN2016hnk)

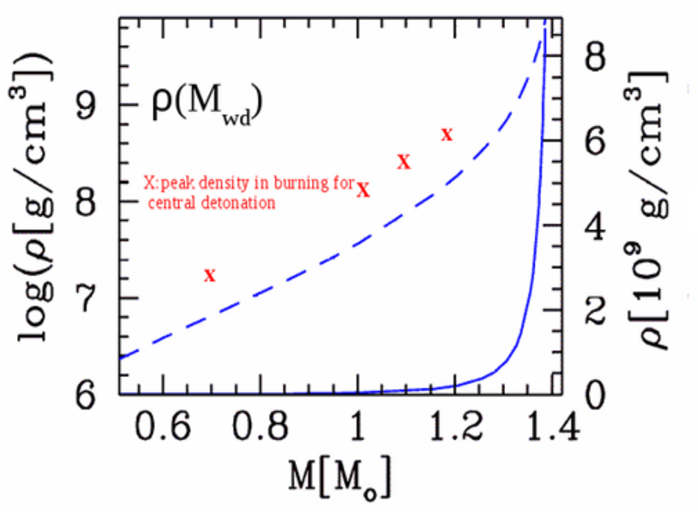
or probing the electron capture elements

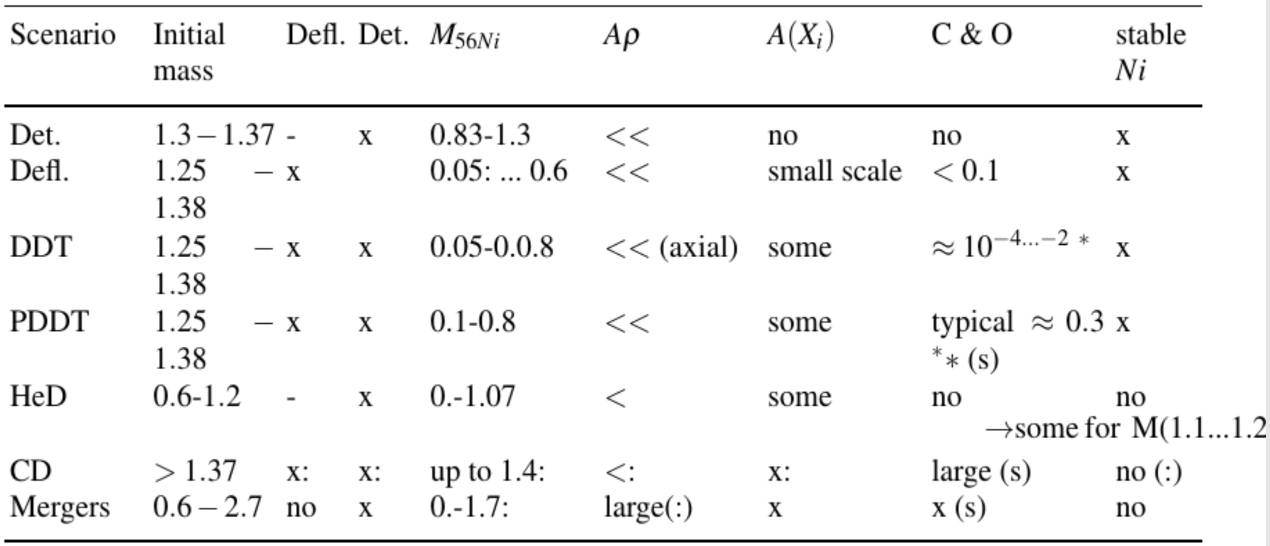




Nidia's Party, Nov. 05th, 2018

The Zoo: Explosion Scenarios of White Dwarfs





Scenario	Initial mass	Defl.	Det.	M_{56Ni}	$A\rho$	$A(X_i)$	C & O	stable Ni
Det.	$1.3-1.37$	-	x	0.83-1.3	$<<$	no	no	x
Defl.	$1.25 - 1.38$	x		0.05: ... 0.6	$<<$	small scale	< 0.1	x
DDT	$1.25 - 1.38$	x	x	0.05-0.0.8	$<<$ (axial)	some	$\approx 10^{-4...-2}$ $*$	x
PDDT	$1.25 - 1.38$	x	x	0.1-0.8	$<<$	some	typical ≈ 0.3 $^{*}*$ (s)	x
HeD	0.6-1.2	-	x	0.-1.07	$<$	some	no	no →some for M(1.1...1.2
CD	> 1.37	x:	x:	up to 1.4:	$<$:	x:	large (s)	no (:)
Mergers	$0.6-2.7$	no	x	0.-1.7:	large(:)	x	x (s)	no

Remark: To first order, a high mass M(HeD) and a M(DD,PDD) look similar

Currently favored models (depending on 'community')

- Delayed-detonations: 1.25 … 1.38 Mo
- HeD (Double-detonations): 0.6 ... 1.2 Mo

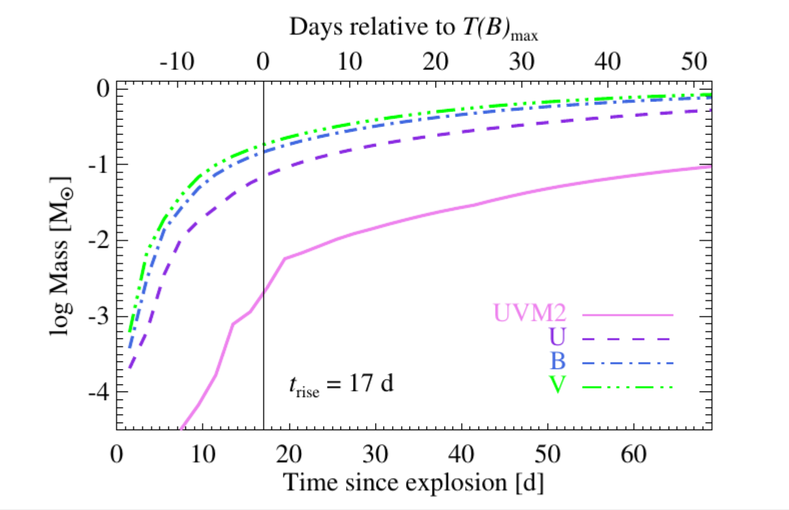
Differences:

very outer layers → Advances in time-domain (He vs. C/O, donor star ...)
inner layers → Late-time nebular spectra (electron capture elements)

Note: 22Ne/20Ne gravitational settling on Ye (see e.g. Deloye & Bildsten, 2002; H.etal 1998)

When do we see the outer layers ?

Example for 1.35Mo: Layer exposed as f(time)



HeD: He and products of He-burning

(Nomoto et al. 1983, H. et al. 1996, Bilsten et al., Pakmor et. al. 2015,...)

Death-nail for old models: 0.05 (1.2Mo) and 0.1 (0.8) of He for HeD

Now (with mixing of He and C): 5.E-3 to 2.E-2 corresponding
Trick: t(burn, 3 α→ C(He,γ))= 1 → 1E-2 sec (Nomoto & his group, 2016)
TS: 6-9 d (in LC colors)

DDT-models: C/O (HK96, …) including HIV Ca by interaction
(Gerardy et al. 2004, Quimby et al. 2006, ...).
Surface burning of accreted material (H.&Schaefer, 2008)
TS: 2...5 d (LC-colors)

In DD, outer layers as probe of accretion material (progenitor channel):

(e.g. Sigimoto et al. 1978, H.et al. 2006, …, Piersanti et al. 2014, ...)

Example: He-star donor

WD-Structure (Wang, Podsiadlowski, Han, 2017)

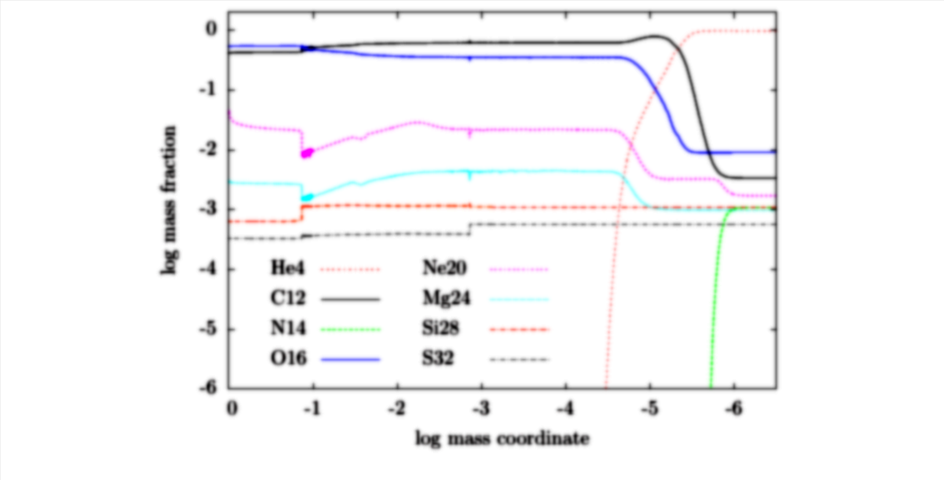
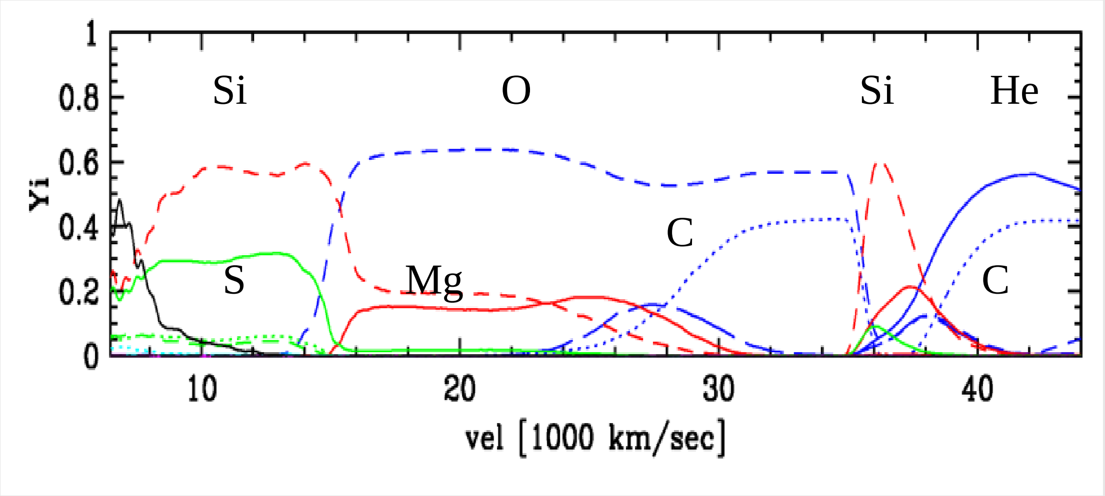


Figure 5. Chemical abundance profile at the point of explosive carbon ignition.

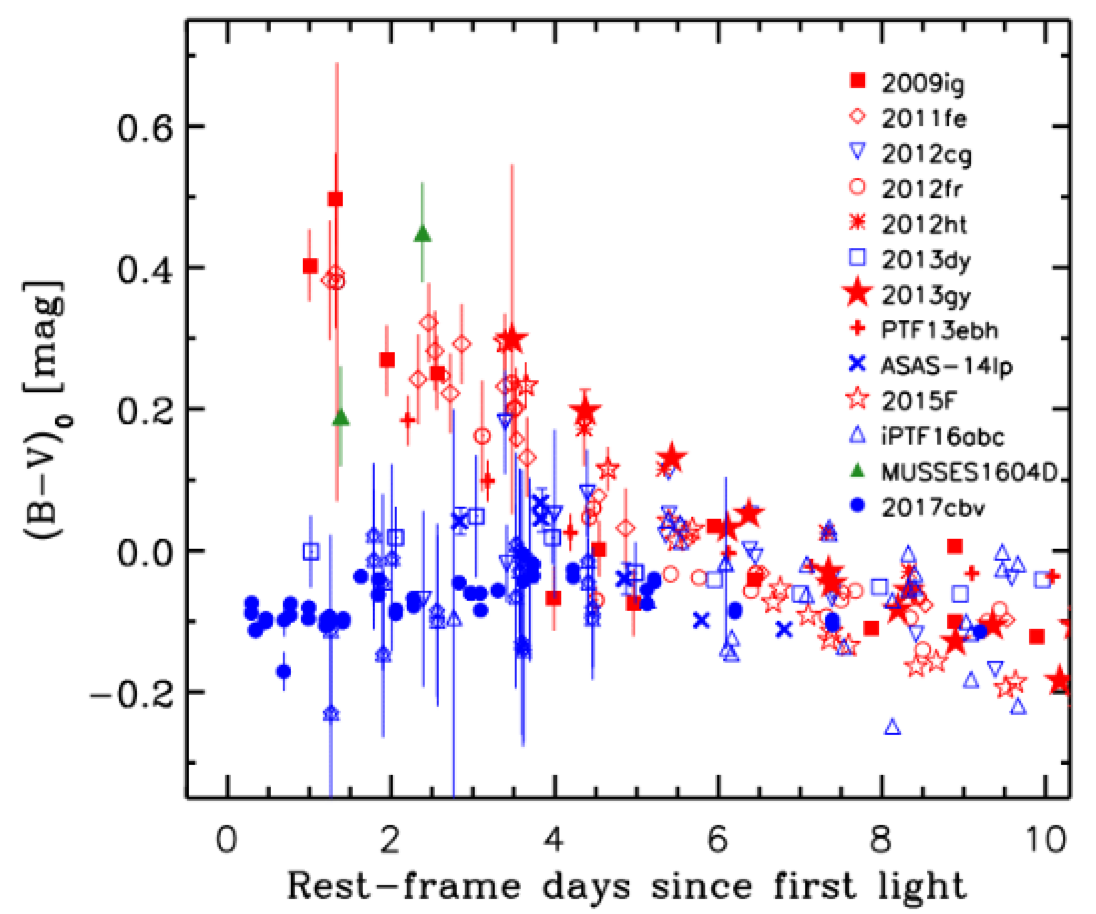
DD **after** explosion w. C/He mixing (H. et al., 2018, in prep.)
(res.=1.E-7 Mo, mix 2E-5Mo, MS=5Mo, solar/10, rho(WD,c)=1E9 g/ccm



Time domain: NEW/Some observational evidence B-V

(from Stritzinger et al. 2018)

Colors of SNe caught right after explosion.



Rem. Lower B-V means hotter
Region about 3-4E14cm

Suggestion:

- 2 groups ?

Possible reasons:

- different accreters
 (H vs. He, this talk)

- different models
 PDDs vs. DD s (HK 96, Hetal2017, Gall et al. 2018)
 HeDs (Ni heating, e.g. Diehl et al. 2015 ?)

- Interaction in the vicinity
 of progenitor system
(Gerardy et al. 2007, Dragulin & Hoeflich 2015)

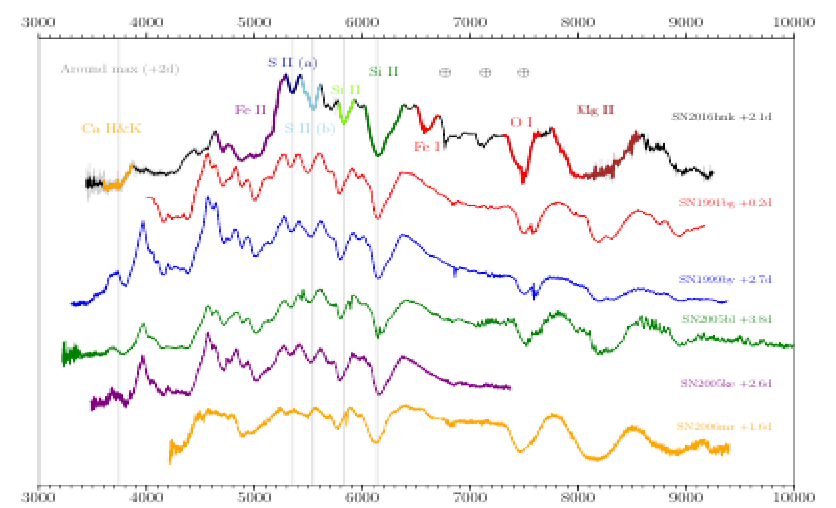
Late-time spectra of SN2016hnk in MCG-01-06-070

(Galgany, Ashall, Hoeflich et al. 2018, in prep)

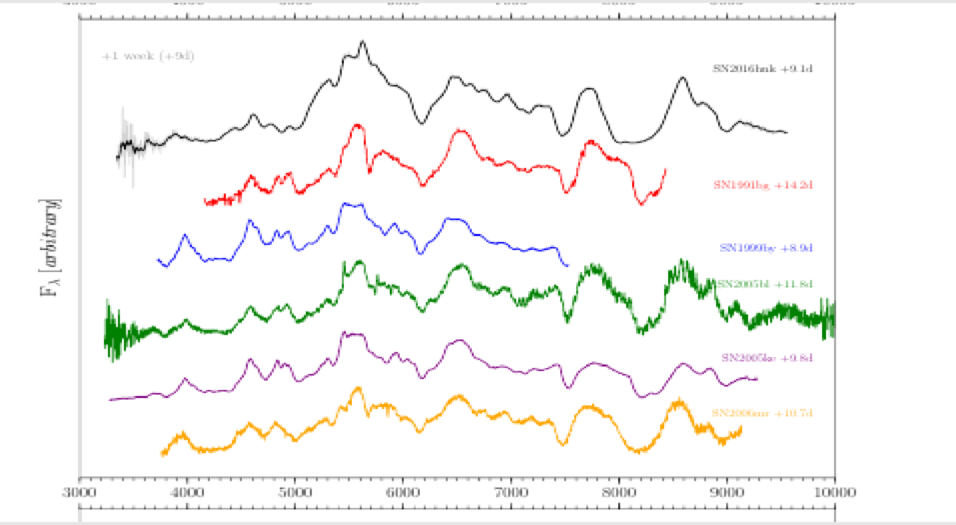
General properties of early Spectra and LCs:

dm(15,s) = 1.80 +- 0.20 mag => ballpark of SN1991by and SN1999by.
E(B-V) = 0.45 with R(V)= 2.1

Maximum



\+ 10 days



=> Spectra and LCs look similar to SN1991bg and SN1999by

Tomography (Chris Ashall) suggests chemical structure similar to models used for SN1999by (Hoeflich et al. 2001)

Life would be good but …

X-Shooter Spectrum at day 350 after maximum (X-shooter)

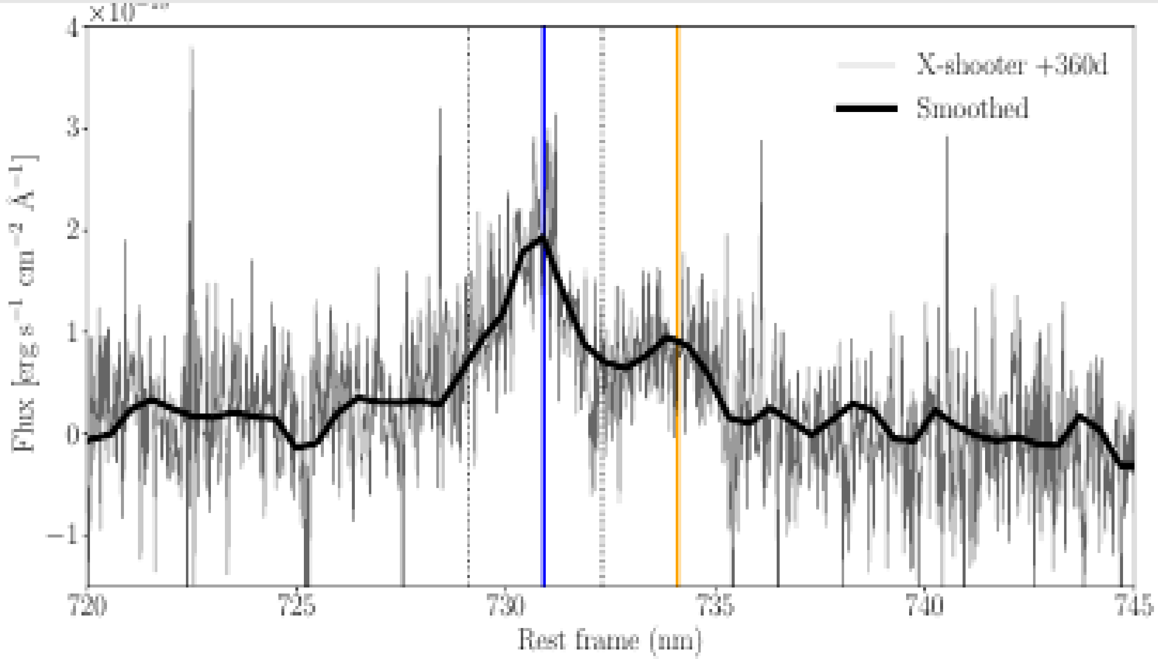


Figure 16. Zoom-in to the composed X-shooter optical spectrum showing the only two features detected in the whole UV+optical+NIR wavelength range.

Problem: One strong,feature at 7300 A of 1000 km/sec,
and no obvious iron-group elements as usual (hard to do by hydro)

Ansatz: Modify the DD model for SN1999by & nuclear phys. to the rescue of M(ch).
[Games played by Brachwitz et al. 2000, Hoeflich et al. 2006, Thielemann et al., 2014
But too the extreme]

Modify DDT model for SN1999by

(with Hydra: RT,gamma & positrons, full non-LTE)

Ansatz: Increase central density from 2E9g/cm^3 to close AIC & start with slow deflagration

=> EC down to 0.438 in the center.

Density, velocity structure & tau(350d) and Isotopes as a function of v

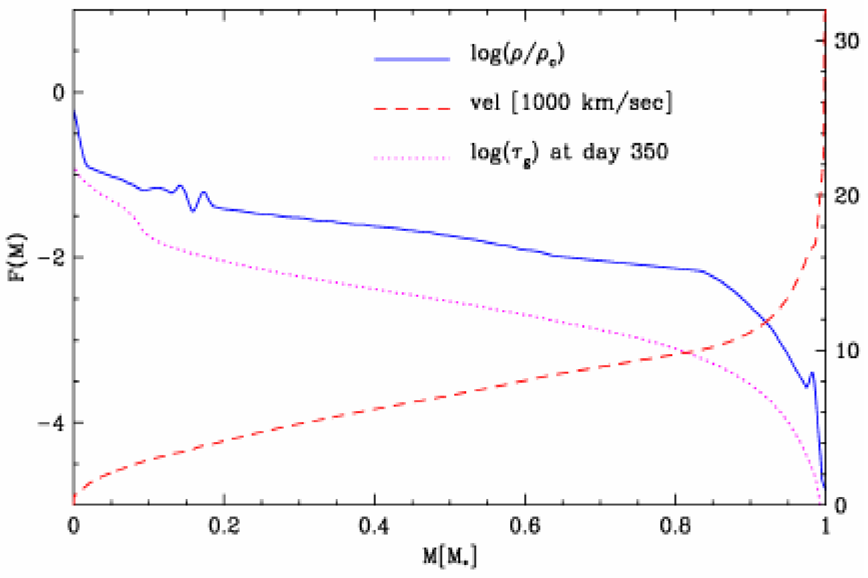


Figure 20. Structure during the phase of homologeous expansion as a function of the mass coordinate for our subluminous model with high central density. We give the normalized density as $log(\rho/rho_c)$ (left scale), velocity (right scale) and the mean optical depth $log(\tau_\gamma)$ (right scale) in γ-rays at day 350.

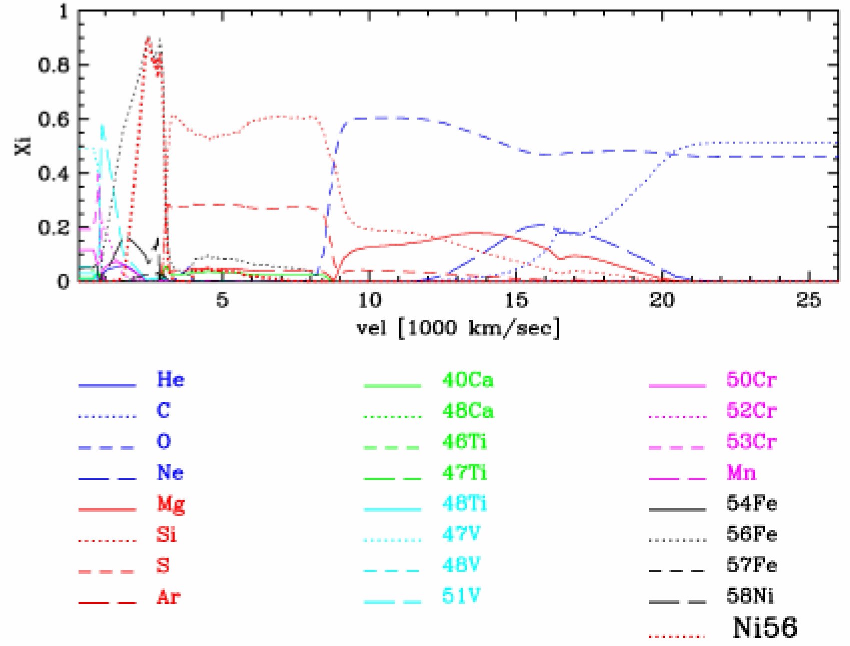


Figure 21. Same as Fig. 20 but we show the overall abundance structure as a function of mass (top) and expansion velocity (below). It is very similar to the subluminous model for SN1999by and consistent with the chemical structure based on out abundance tomography given in Table 3.

Zoom-in and spectra

Ansatz: Increase central density from 2E9g/cm^3 to close AIC & start with slow deflagration

=> EC down to 0.438 in the center.

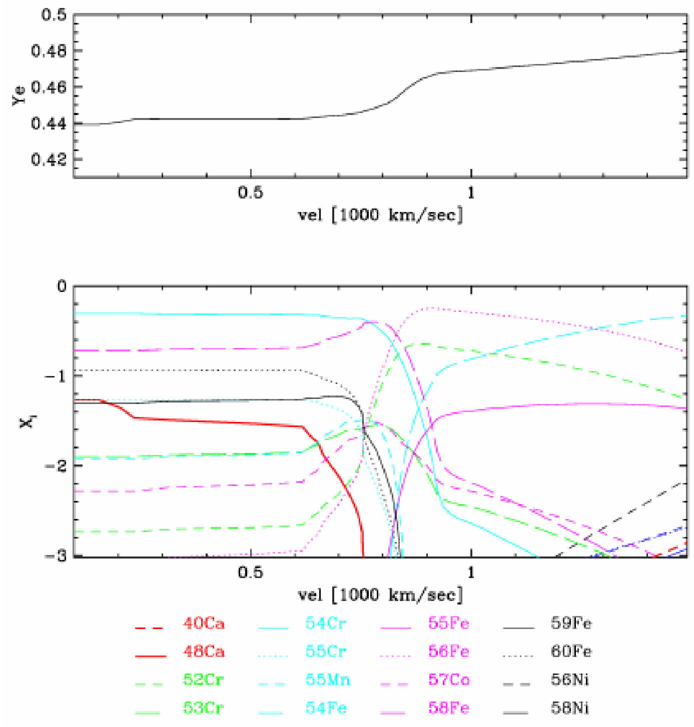


Figure 22. Distribution of most abundant isotopes and Ye as a function of velocity for the central region are dominated by neutron-rich isotopes several minutes after the explosion. Subsequently, radioactive isotopes decay on time scales given in bracket, namely $^{55}Cr(3.5m) \rightarrow^{55} Mn$; $^{55}Fe(1001d) \rightarrow^{55} Mn$; $^{56}Ni(6d) \rightarrow^{56} Co(88d) \rightarrow^{56} Fe(88d)$; $^{57}Co(271d) \rightarrow^{57} Fe$.

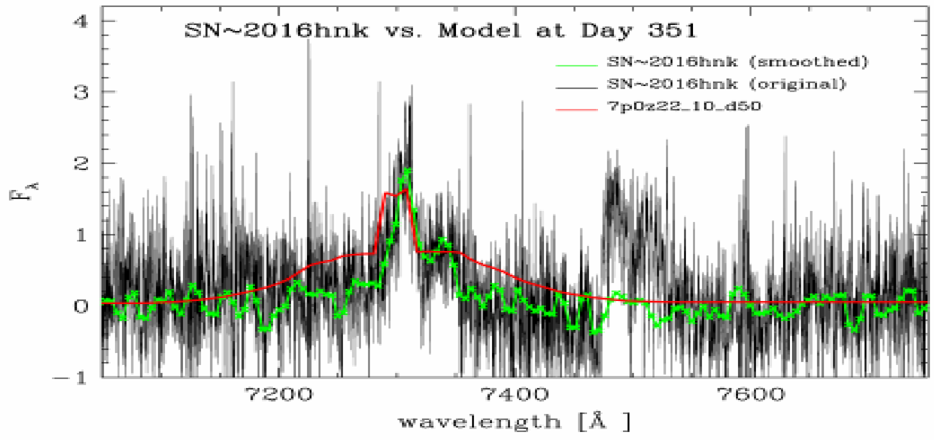


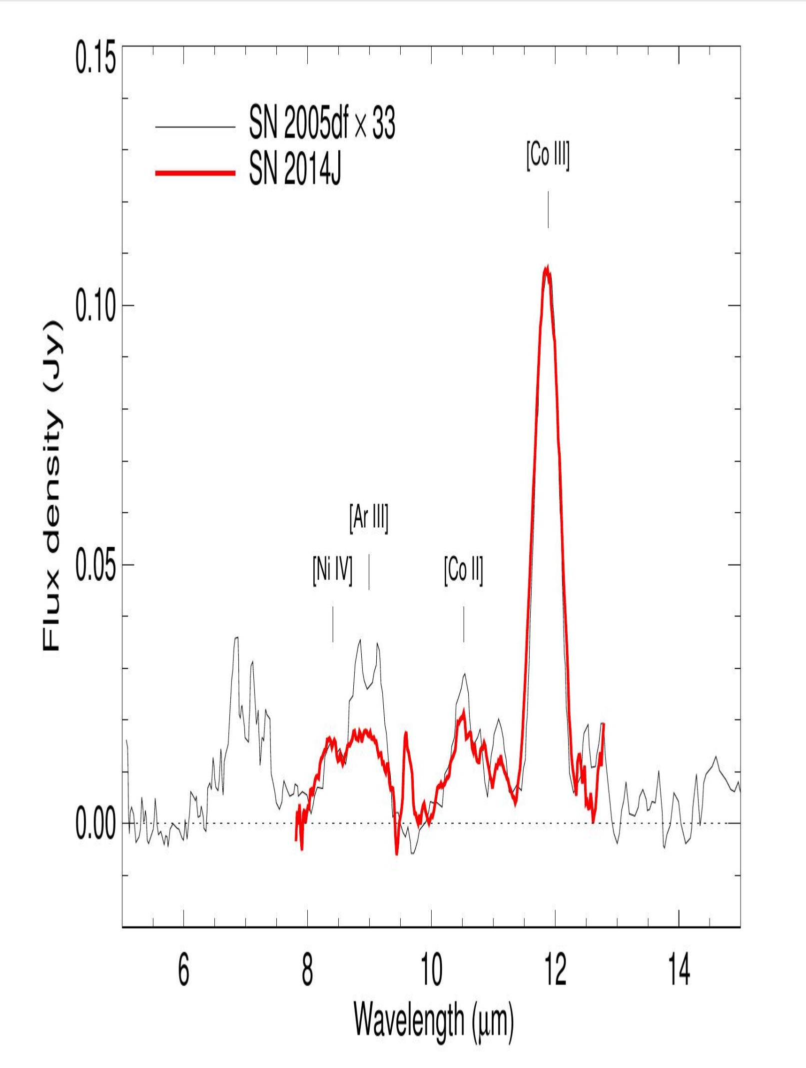
Figure 23. Comparison of the nebular spectrum of SN 2016hnk with our high-density DDT model between in the rest frame assuming a redshift of $z = 0.01610$ (see Fig. 16). The flux is in $10{-}18erg/sec/cm^2$ on the same scale as Fig. ?. The theoretical spectrum is dominated by a narrow, forbidden [Ca II] duplet at 7293.48 and 7325.91 above a quasi-continuum at about the 3 % level formed by many transitions of mostly heavier elements including Fe,Co,Ni,Cr etc.

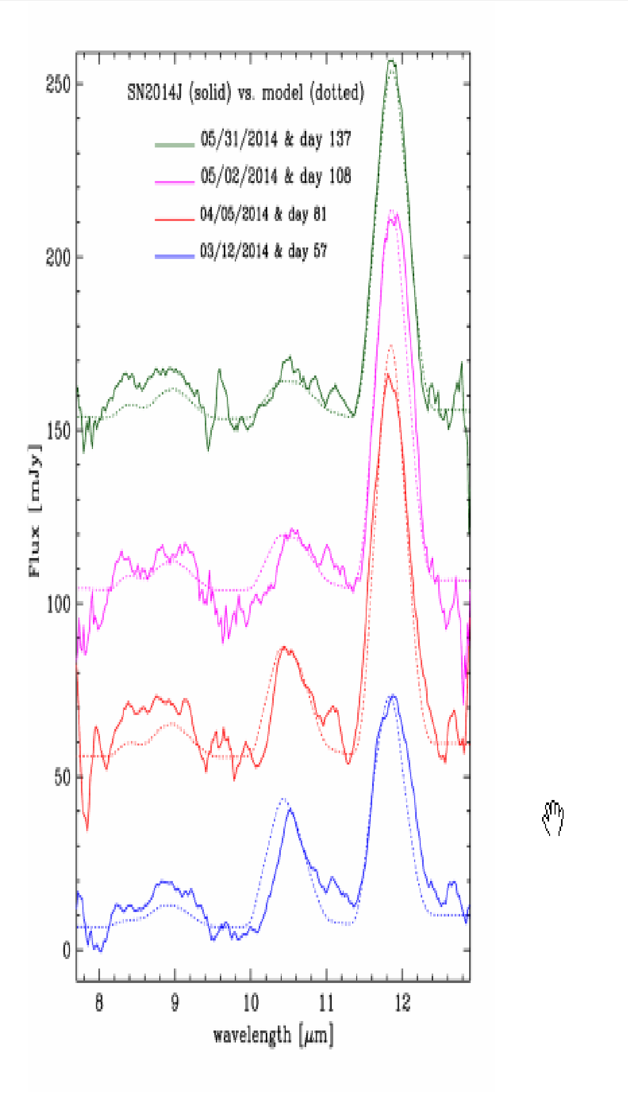
Suggested punch-line:

- feature is the [Ca II]-duplet (ground state)
- sticks out because it is narrow and to ground state
- Fe lines form a ‘quasi-continuum’ and are smeared out by velocity from UV-MIR (few % level of Ca).

SN2014J: Why do we need Mid-IR spectra (Spitzer, CanariCam & JWS

SN 2014J and SN2005df have the same M(V), dm15, [Co III]
but differ in the Ar distribution and, definitely, no Chromium.
(Gerardy et al. 2007, Telesco et al., 2015)





Others:

- Direct measure of photon redistribution
- [Co III] @ 11.8 mu as new standard candle ?
- magnetic fields
- mixing …

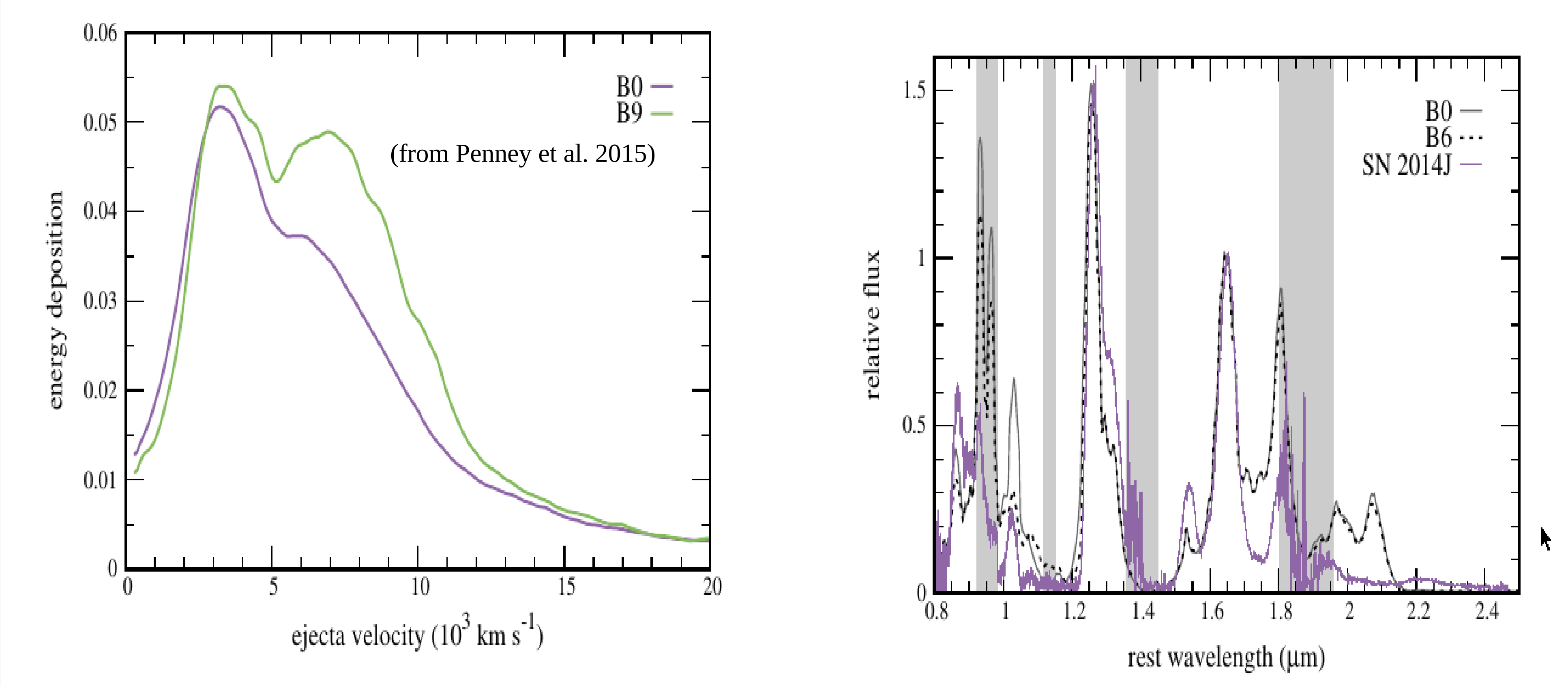
Diamond et al. 2017

How can we get
57Co in all the mess

Probing mixing and positron transport effects in the NIR ?

The S II 1.05 mu feature at 466 days in SN2014J (Diamond et al. 2018)

Energy deposition by positron



(from Penney et al. 2015)

- Non-local excitation of SII by positron transport

Electron capture as probe of the burning conditions ?

(e.g. Brachwitz et al., 2001, …, & see talk by FKT)

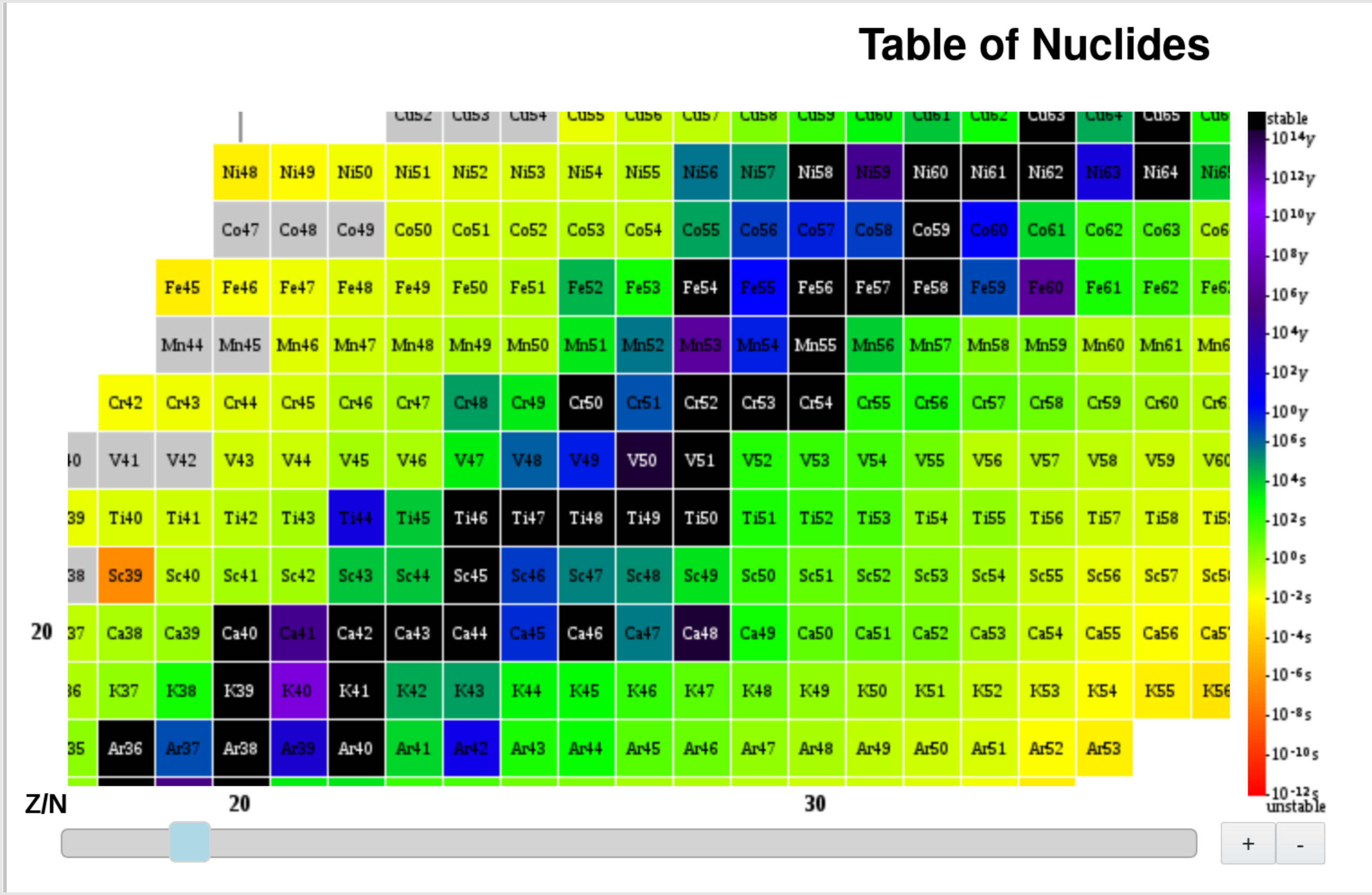


Table of Nuclides

							Cu52	Cu53	Cu54	Cu55	Cu56	Cu57	Cu58	Cu59	Cu60	Cu61	Cu62	Cu63	Cu64	Cu65	Cu6
				Ni48	Ni49	Ni50	Ni51	Ni52	Ni53	Ni54	Ni55	Ni56	Ni57	Ni58	Ni59	Ni60	Ni61	Ni62	Ni63	Ni64	Ni6
				Co47	Co48	Co49	Co50	Co51	Co52	Co53	Co54	Co55	Co56	Co57	Co58	Co59	Co60	Co61	Co62	Co63	Co6
			Fe45	Fe46	Fe47	Fe48	Fe49	Fe50	Fe51	Fe52	Fe53	Fe54	Fe55	Fe56	Fe57	Fe58	Fe59	Fe60	Fe61	Fe62	Fe6
			Mn44	Mn45	Mn46	Mn47	Mn48	Mn49	Mn50	Mn51	Mn52	Mn53	Mn54	Mn55	Mn56	Mn57	Mn58	Mn59	Mn60	Mn61	Mn6
		Cr42	Cr43	Cr44	Cr45	Cr46	Cr47	Cr48	Cr49	Cr50	Cr51	Cr52	Cr53	Cr54	Cr55	Cr56	Cr57	Cr58	Cr59	Cr60	Cr6
	40	V41	V42	V43	V44	V45	V46	V47	V48	V49	V50	V51	V52	V53	V54	V55	V56	V57	V58	V59	V60
	39	Ti40	Ti41	Ti42	Ti43	Ti44	Ti45	Ti46	Ti47	Ti48	Ti49	Ti50	Ti51	Ti52	Ti53	Ti54	Ti55	Ti56	Ti57	Ti58	Ti5
	38	Sc39	Sc40	Sc41	Sc42	Sc43	Sc44	Sc45	Sc46	Sc47	Sc48	Sc49	Sc50	Sc51	Sc52	Sc53	Sc54	Sc55	Sc56	Sc57	Sc5
20	37	Ca38	Ca39	Ca40	Ca41	Ca42	Ca43	Ca44	Ca45	Ca46	Ca47	Ca48	Ca49	Ca50	Ca51	Ca52	Ca53	Ca54	Ca55	Ca56	Ca5
	36	K37	K38	K39	K40	K41	K42	K43	K44	K45	K46	K47	K48	K49	K50	K51	K52	K53	K54	K55	K56
	35	Ar36	Ar37	Ar38	Ar39	Ar40	Ar41	Ar42	Ar43	Ar44	Ar45	Ar46	Ar47	Ar48	Ar49	Ar50	Ar51	Ar52	Ar53		
Z/N				20										30							

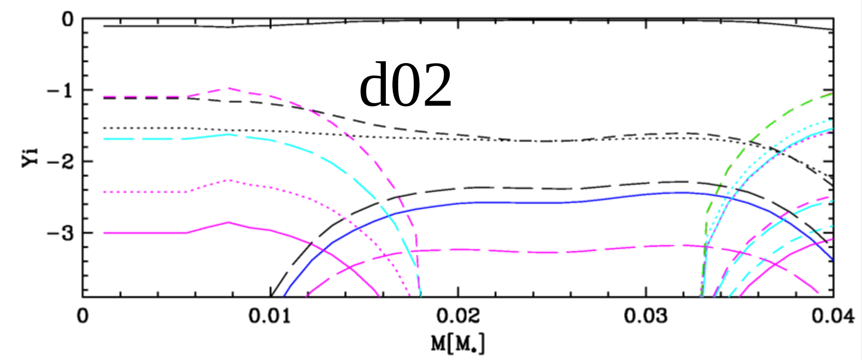
Decay times

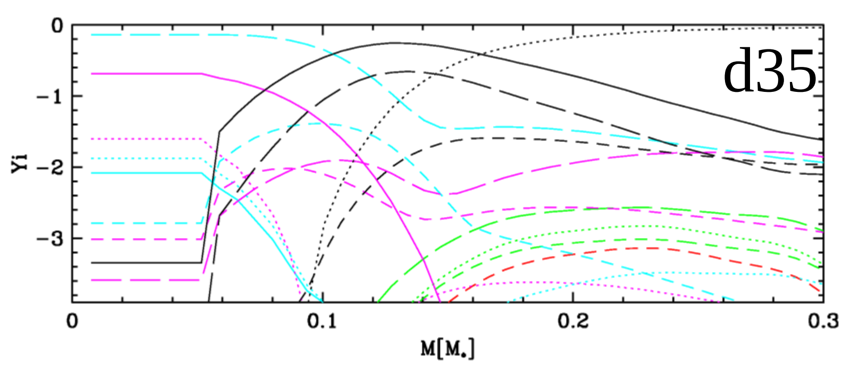
49V =330d
55Fe =2.7 yr
57Co=271d

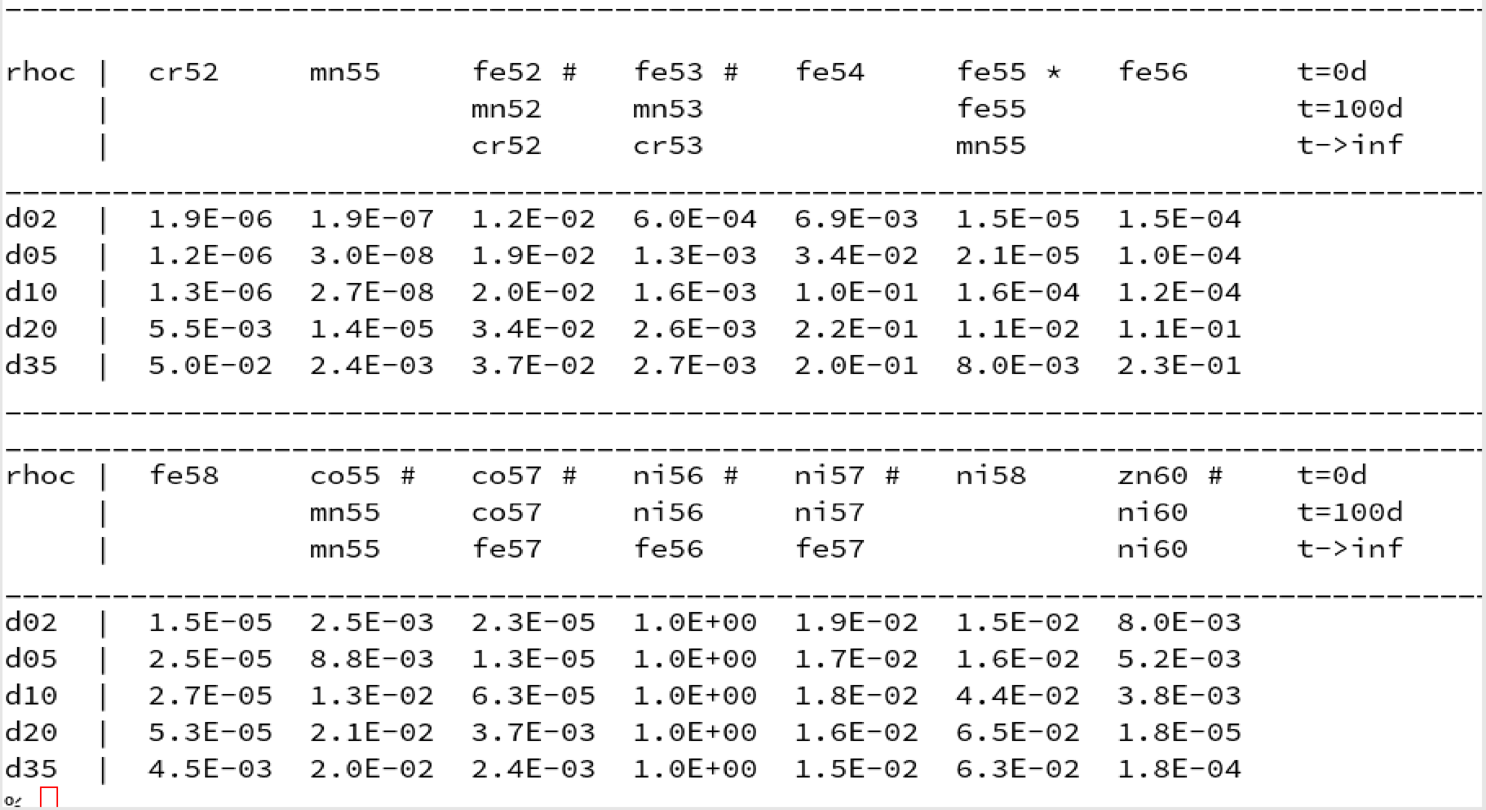
Electron capture as probe of the central density d [1E8g/cm3]

(e.g. Brachwitz et al., 2001, …, & see talk by FKT)

Example DD-models (5p0Z4T25-series: M(56Ni)=0.52...0.61Mo,E(kin)=1.2foe)







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----------------------------------------------------------------------------------------

rhoc |  cr52      mn55      fe52 #    fe53 #    fe54      fe55 *    fe56       t=0d
     |                      mn52      mn53                fe55                 t=100d
     |                      cr52      cr53                mn55                 t->inf

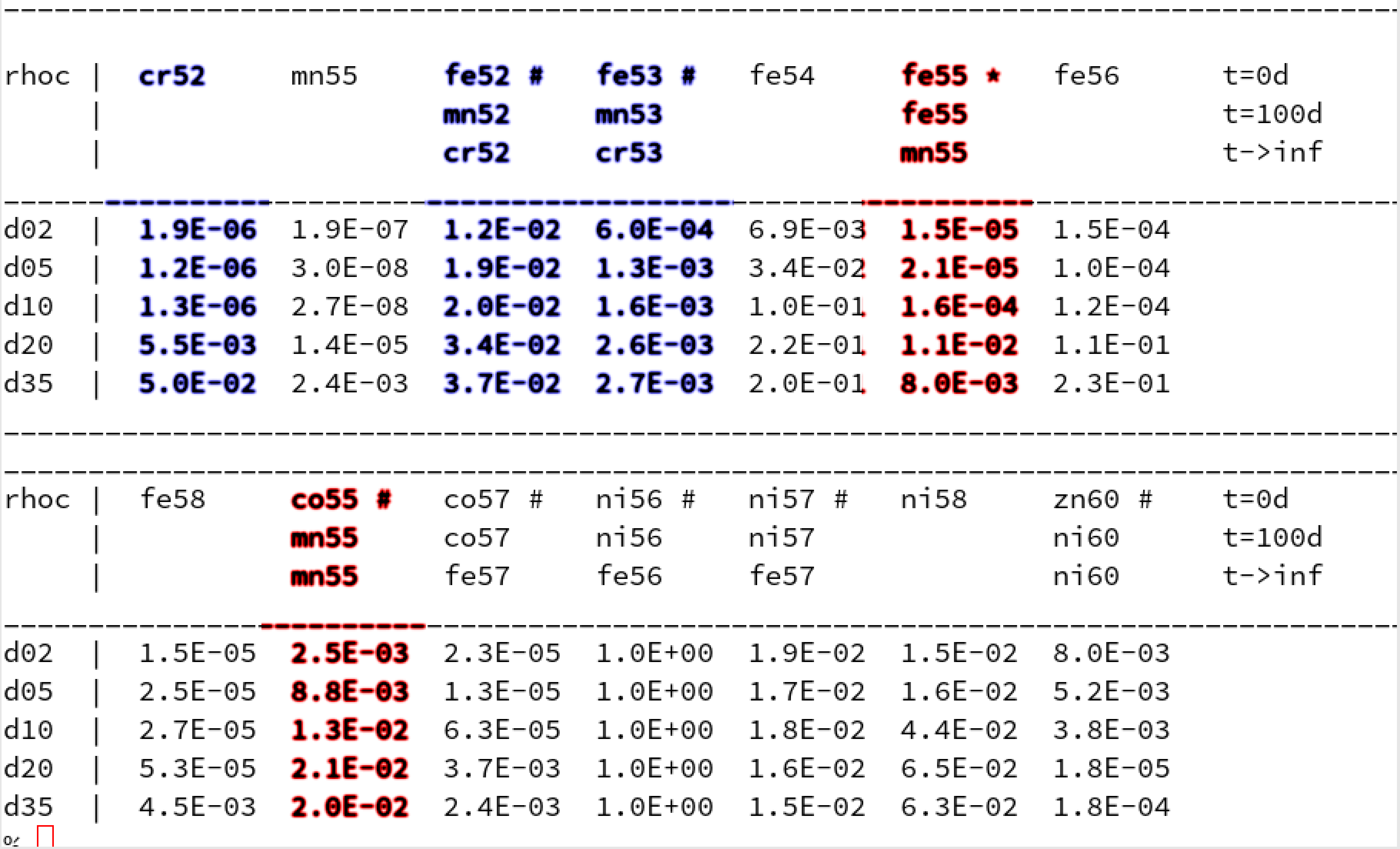
----------------------------------------------------------------------------------------
d02  |  1.9E-06   1.9E-07   1.2E-02   6.0E-04   6.9E-03   1.5E-05   1.5E-04
d05  |  1.2E-06   3.0E-08   1.9E-02   1.3E-03   3.4E-02   2.1E-05   1.0E-04
d10  |  1.3E-06   2.7E-08   2.0E-02   1.6E-03   1.0E-01   1.6E-04   1.2E-04
d20  |  5.5E-03   1.4E-05   3.4E-02   2.6E-03   2.2E-01   1.1E-02   1.1E-01
d35  |  5.0E-02   2.4E-03   3.7E-02   2.7E-03   2.0E-01   8.0E-03   2.3E-01

----------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------
rhoc |  fe58      co55 #    co57 #    ni56 #    ni57 #    ni58      zn60 #     t=0d
     |            mn55      co57      ni56      ni57                ni60       t=100d
     |            mn55      fe57      fe56      fe57                ni60       t->inf

----------------------------------------------------------------------------------------
d02  |  1.5E-05   2.5E-03   2.3E-05   1.0E+00   1.9E-02   1.5E-02   8.0E-03
d05  |  2.5E-05   8.8E-03   1.3E-05   1.0E+00   1.7E-02   1.6E-02   5.2E-03
d10  |  2.7E-05   1.3E-02   6.3E-05   1.0E+00   1.8E-02   4.4E-02   3.8E-03
d20  |  5.3E-05   2.1E-02   3.7E-03   1.0E+00   1.6E-02   6.5E-02   1.8E-05
d35  |  4.5E-03   2.0E-02   2.4E-03   1.0E+00   1.5E-02   6.3E-02   1.8E-04
%
```

Electron capture as probe of the central density d [1E8g/cm3]

Example: DD-models (5p0Z4T25-series: M(56Ni)=0.52...0.61Mo,E(kin)=1.2foe)



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---------------------------------------------------------------------------
rhoc |  cr52    mn55     fe52 #   fe53 #   fe54     fe55 *   fe56      t=0d
     |                   mn52     mn53              fe55               t=100d
     |                   cr52     cr53              mn55               t->inf
---------------------------------------------------------------------------
d02  |  1.9E-06 1.9E-07  1.2E-02  6.0E-04  6.9E-03  1.5E-05  1.5E-04
d05  |  1.2E-06 3.0E-08  1.9E-02  1.3E-03  3.4E-02  2.1E-05  1.0E-04
d10  |  1.3E-06 2.7E-08  2.0E-02  1.6E-03  1.0E-01  1.6E-04  1.2E-04
d20  |  5.5E-03 1.4E-05  3.4E-02  2.6E-03  2.2E-01  1.1E-02  1.1E-01
d35  |  5.0E-02 2.4E-03  3.7E-02  2.7E-03  2.0E-01  8.0E-03  2.3E-01
---------------------------------------------------------------------------

---------------------------------------------------------------------------
rhoc |  fe58    co55 #   co57 #   ni56 #   ni57 #   ni58     zn60 #    t=0d
     |          mn55     co57     ni56     ni57              ni60      t=100d
     |          mn55     fe57     fe56     fe57              ni60      t->inf
---------------------------------------------------------------------------
d02  |  1.5E-05 2.5E-03  2.3E-05  1.0E+00  1.9E-02  1.5E-02  8.0E-03
d05  |  2.5E-05 8.8E-03  1.3E-05  1.0E+00  1.7E-02  1.6E-02  5.2E-03
d10  |  2.7E-05 1.3E-02  6.3E-05  1.0E+00  1.8E-02  4.4E-02  3.8E-03
d20  |  5.3E-05 2.1E-02  3.7E-03  1.0E+00  1.6E-02  6.5E-02  1.8E-05
d35  |  4.5E-03 2.0E-02  2.4E-03  1.0E+00  1.5E-02  6.3E-02  1.8E-04
```
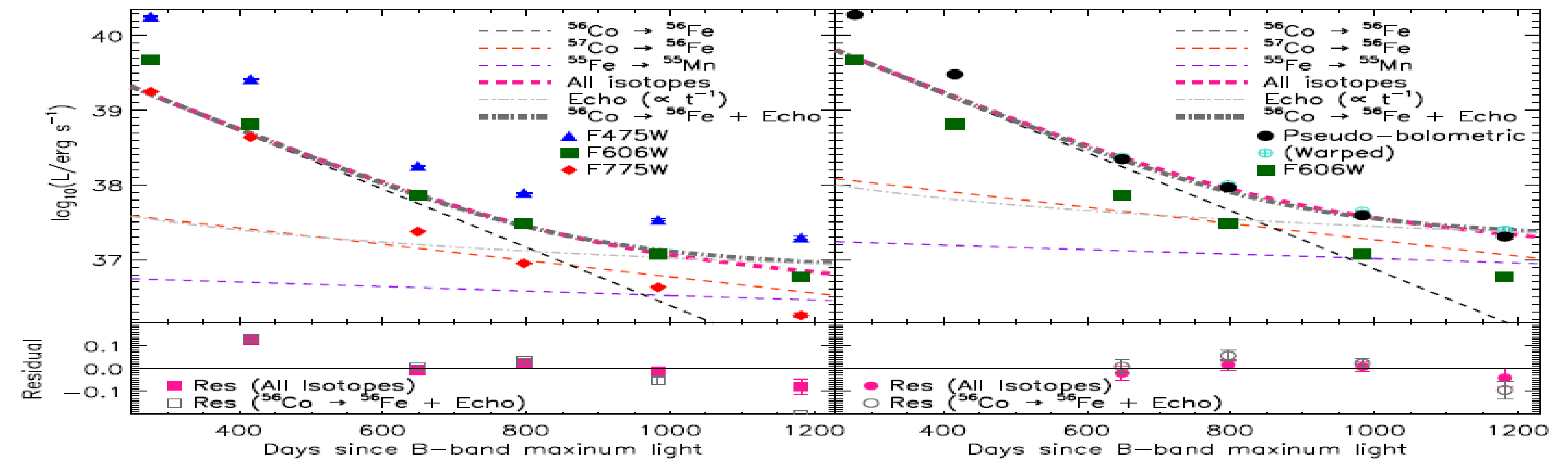

Cr *and* ***Mn*** *are excellent indicators for electron capture →* ***MIR (JWST)***

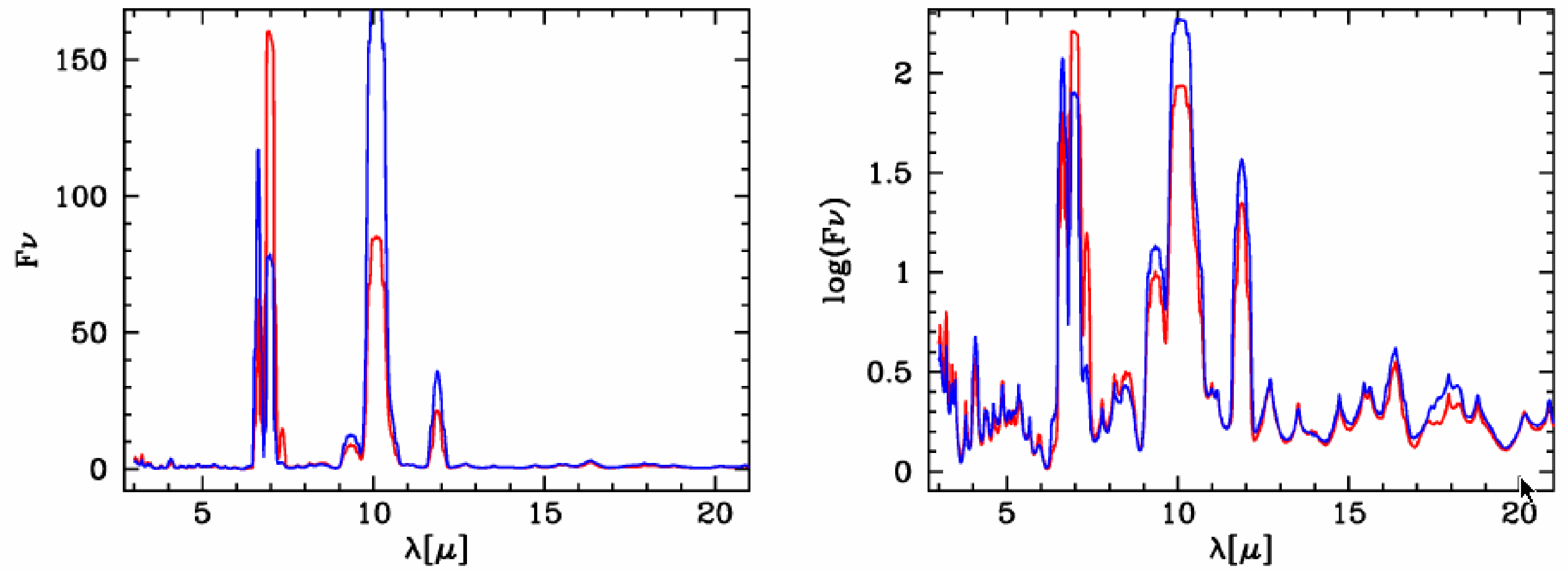
Remark: Because compression rather deflagration , a 1.2 Mo HeD → DD(d02)

How can we distinguish 57Co from 56Co, and get mixing and B ?

*Suggestion: SN2014J & u*ltra-late-time MIR spectra (Hoeflich & FSU, Wang & TAMU, JWST-P.)



Model for SN2014J at day 3000 for B=0 and 1E9 G



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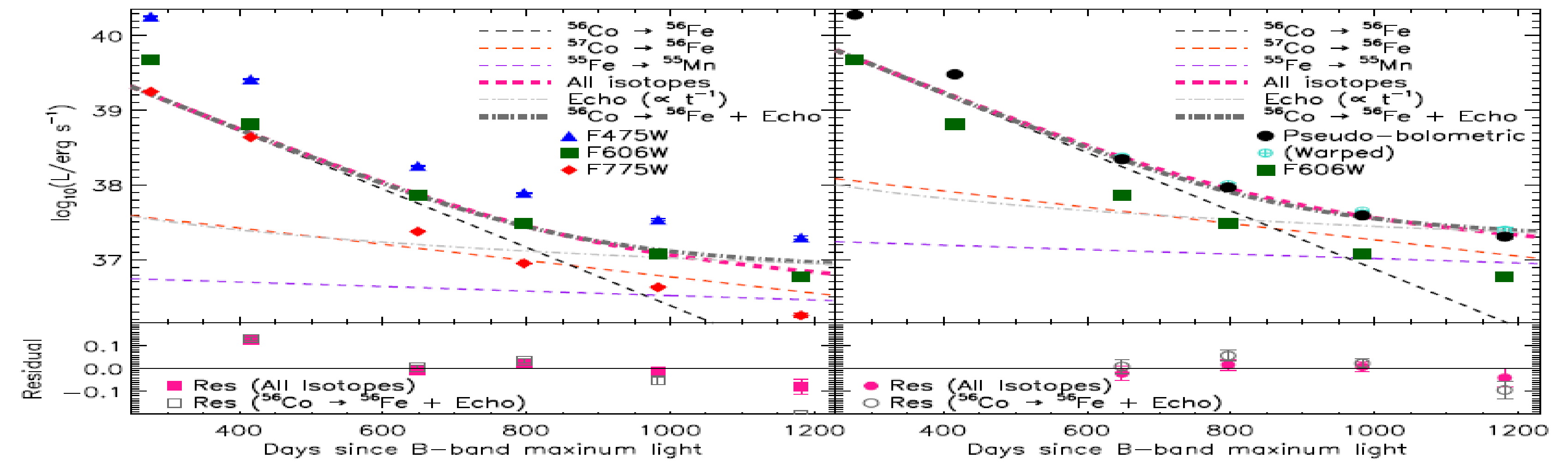
Suggestion: Ultra-late time NIR and MIR spectra (Hoeflich &FSU, Wang &TAMU)



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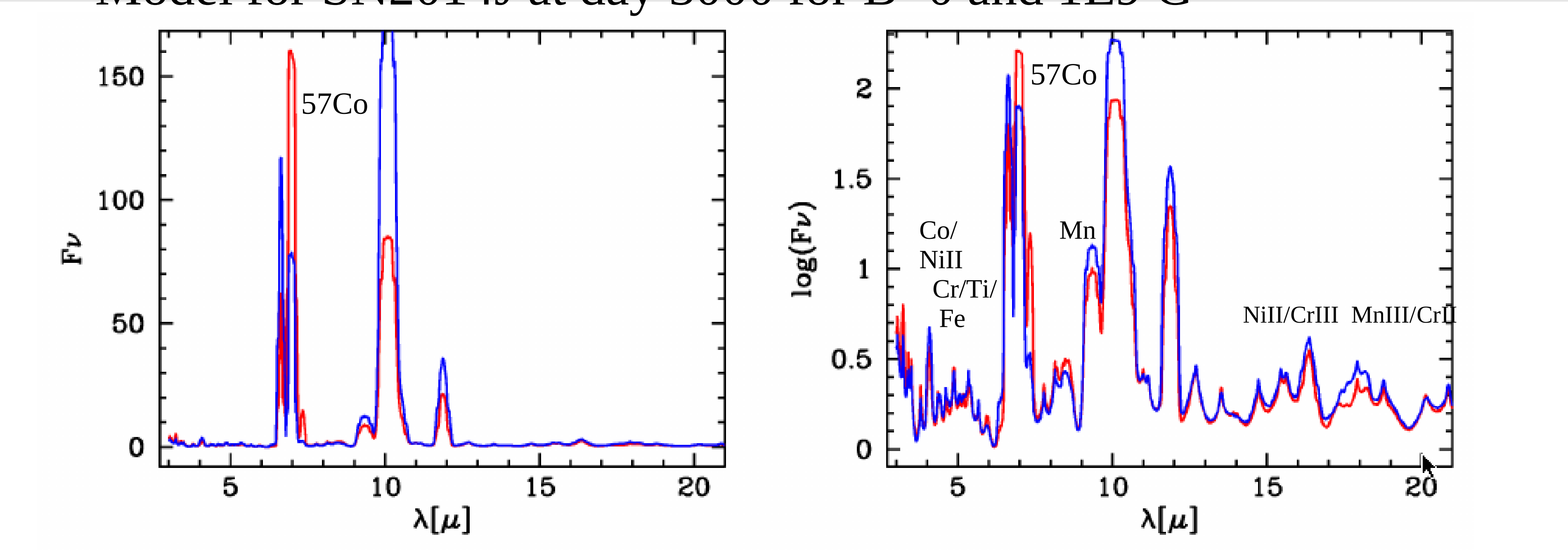

Σ , New Prospects & Preliminary Conclusions

- Time-domain observations and NIR and MIR are here and we see EC effects.

- We are starting to probe the outer 1E-3 to 1E-7 Mo
  (which are dominated by the progenitor configuration)
  & and have several theoretical interpretations

- Narrow feature in the SN2016hk can be understood in terms of high-density M(Ch).
  This density is well beyond the reach of sub-M(Ch) or DD s.

- Ultra-late times (1000-5000 days) in NIR and MIR
  Transition from probing by
  ^{56}Ni->^{56}Co->^{56}Fe
  => ^{57}Co, Ni/Mn/Cr lines and line-profiles

- Mixing during the burning must be partially suppressed
  (e.g. high B in M(ch) or, maybe, He-triggered detonations

- Probing of ‘New supernovae physics’ which relies on nuclear cross sections.