Signatures of Type Ia of Thermonuclear Supernovae

New Prospects in the Age of JWST & Co & early time-domain observations

(P. Hoeflich, Florida State University)

Punch line:

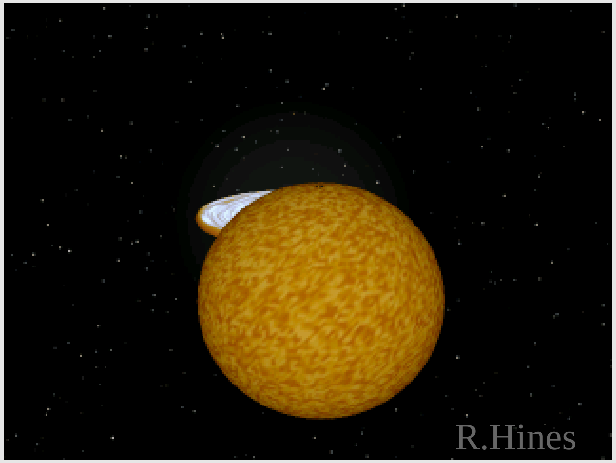
- Direct detection of ‘rare isotopes’ rather than using solar abundances as yardstick

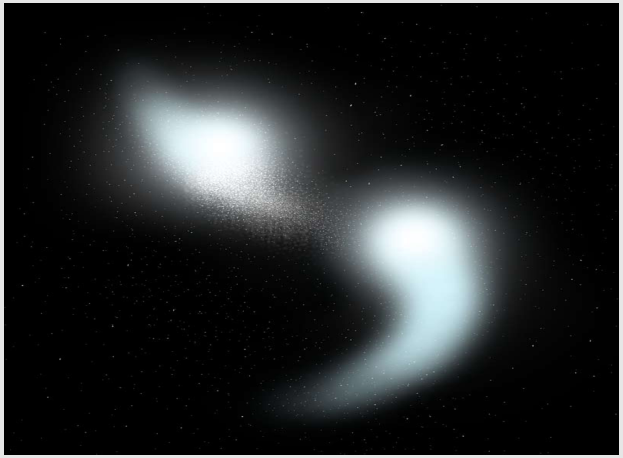
- Observations within hours allow to probe the outer layers the outer $10^{(-3...-6)}$ M_o

- 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/distributions

- Higher sensitivity → diversity of SNe Ia

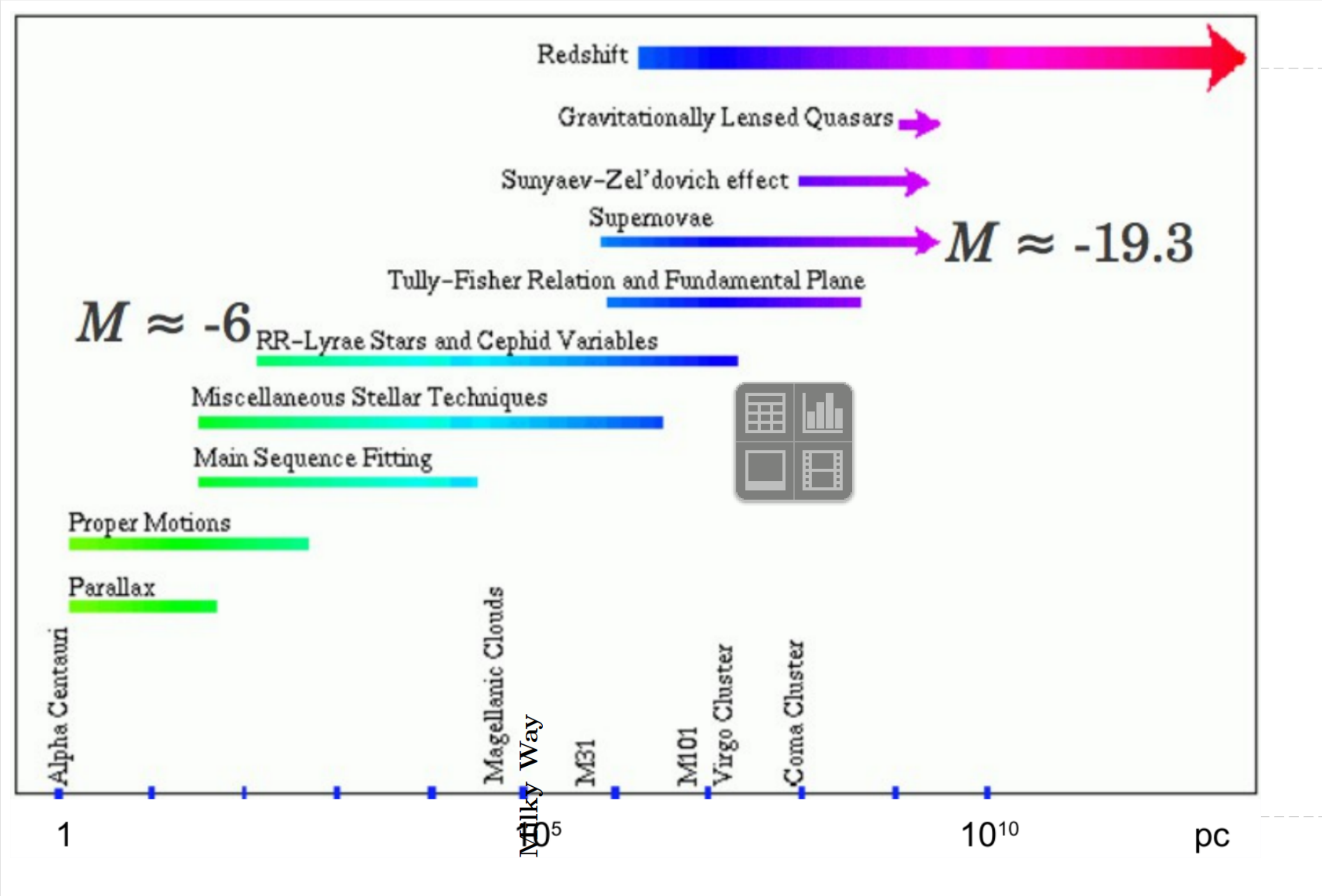




NIC June 2018

Cosmology, Distance Ladder & Big Bang Nucleosynthesis

H_o [km/s/Mpc] = 73.24 ±1.74 (SNIa, z(SN)<1.6 & local δ-Cepheii , Riess et al., 2016),
= 73.2 ±2.3 (SNIa, local SN(CSP), Burns et al. 2018)
= 66.93 ± 0.62 (MWB, assumptions: flat & 3 neutrino flavors, Planck-Collaboration et al. 2016)
= 69.3 ± 0.7 (MWB, " , WMAP+ACT+SPT+BAO, Bennet et al. 2013)



=> e.g. Δ H(^{7}Li/H) = 7- 30 %

Potential of BBN + SNe

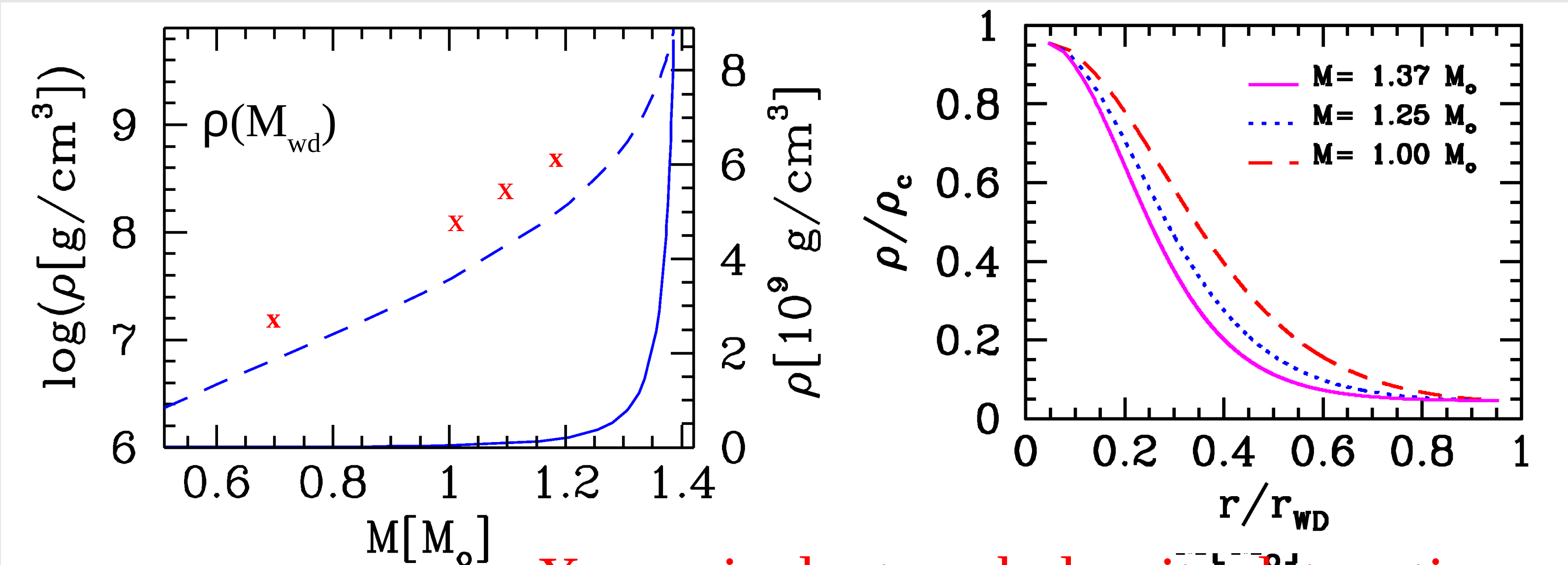
- confirm current physics*
- cosmology (e.g. flatness?)
- Dark matter (early black holes?)
- new physics beyond HEP-standard model

1st future improvement: Gaya

Remark: SN(models & SN-observations) = 68 ± 4 [km/s/Mpc] (Hoeflich & Khokhlov, 1996, H. et al. 2017)
→ ***Models identify*** systematics but *do not improve absolute calibration* !!!

* see Ingo Wiedenhoever's talk, or astrophysical abundances.

Initial WD Structure ^ Diversity for all Scenarios



X : equivalent peak density detonations

Remark

M(Ch) → sub-M(Ch)

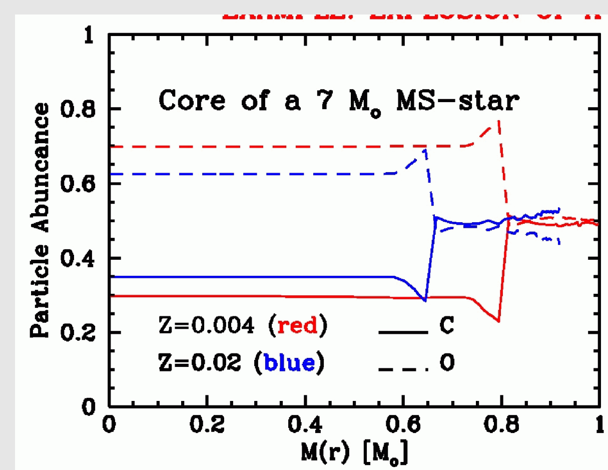
Part. relativistic -> non-relativistic EOS

I) Problem: Overall similar structure

M_{Ch} > 1.3 Mo (start as deflagration)

Sub-M_{Ch} < 1.2 Mo (" " detonation)

II) M(MS) & Z changes within all scenarios → diversity and systematics



Dominguez et al. 2001
H. etal 1998, 2001

Thumbnail Sketch of Thermonuclear Supernovae

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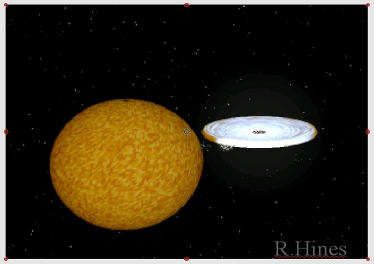
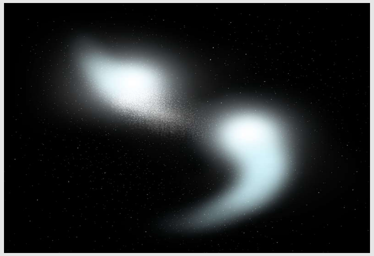
SNe Ia are **thermonuclear** explosions of White Dwarfs (C/O core of a star with less than 8 M_o)

SNe Ia are homogeneous because **nuclear physics** determines the WD structure & explosion
The total energy production is given by the total amount of burning
The light curves are determined by the amount of radioactive **^{56}Ni**





Classes of Progenitor Systems

Accreting WD (MS, RG, He-star, C-star) (SD-systems)

(e.g.Nomoto et al. 1984, Wang &Han, 2013), …)

Two merging WDs (DD-systems)

Common Causes Diversity:

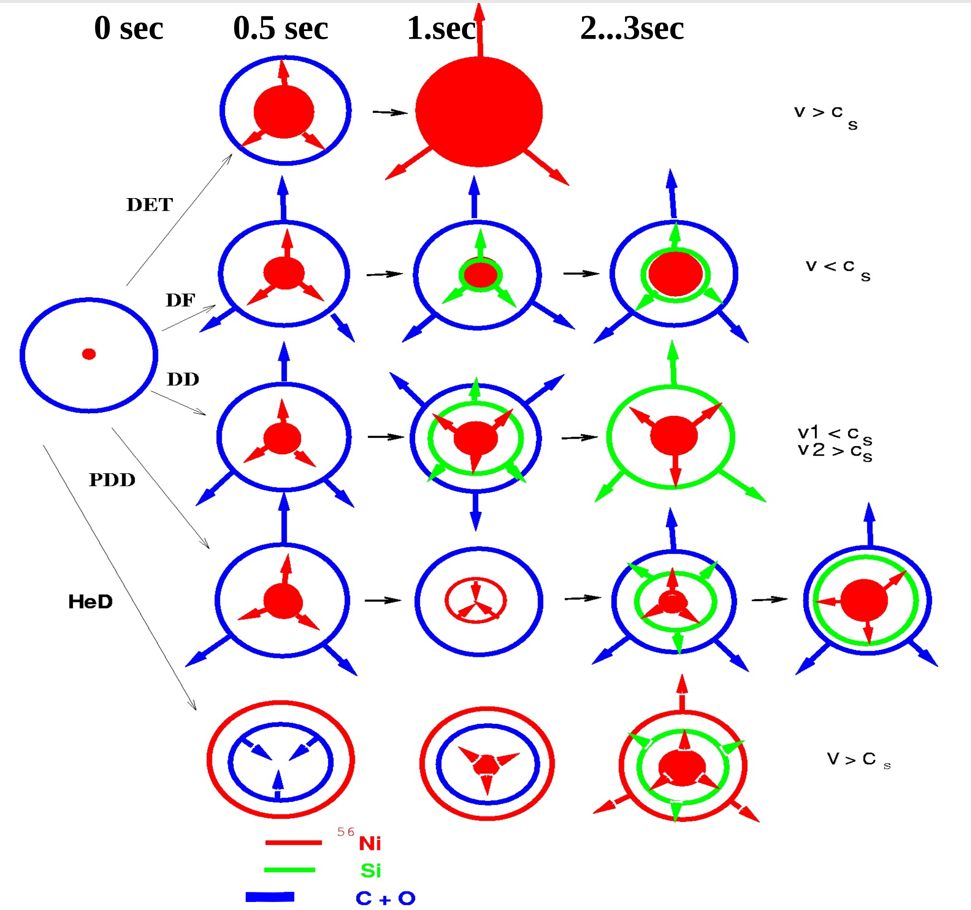
- Main Sequence mass M(MS) → Explosion energy E(nuc)
- Mass of progenitor → central density
- Metallicity Z → E(nuc) and 56Ni
- Magnetic fields → Hydro & Spectra
- Environment → Interaction, 'ISM'

Classes for Explosions

M(Ch) mass WDs: Ignition by compressional heat (originates from either SD or DD, CD)

Heat release during dynamic process (dynamical mergers, violent mergers, He-detonations)

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

Currently favored models

(depending on 'community')

- Delayed-detonations: 1.25 … 1.38 Mo

- HeD (Double-detonations): 0.6 ... 1.2 Mo

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

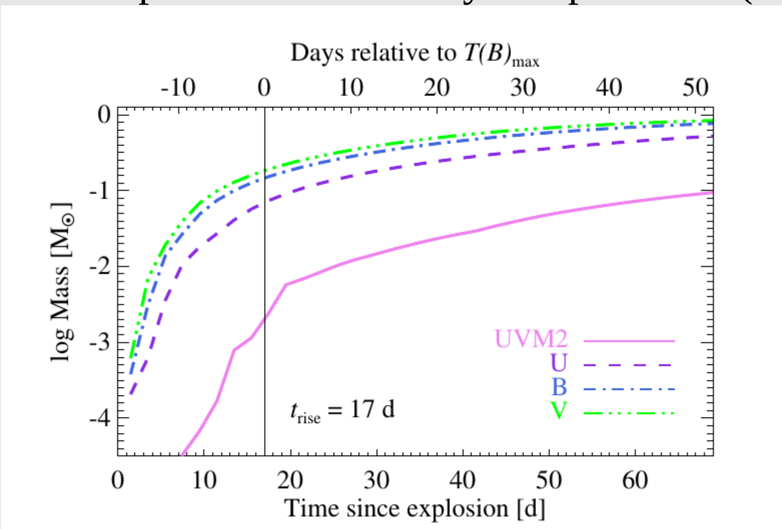
Main difference:

very outer layers → Advances in time-domain (He vs. C/O, ...)

Inner layers → Late-time nebular spectra (electron capture elements)

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 1.E-2 corresponding.
Trick: t(burn, 3 α→ C(He,γ))= 1 → 1E-2 sec (Nomoto and his group, 2016)

DD-models: C/O (HK96, …) including HIV Ca by interaction
(Gerardy et al. 2004, Quimby et al. 2006, ...).

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

Example: He-star donor

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

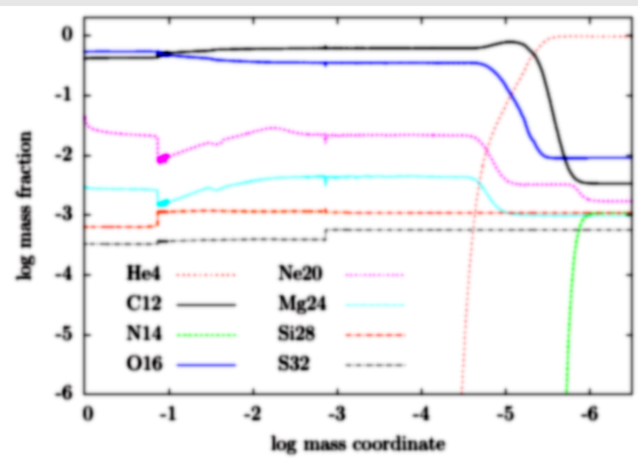
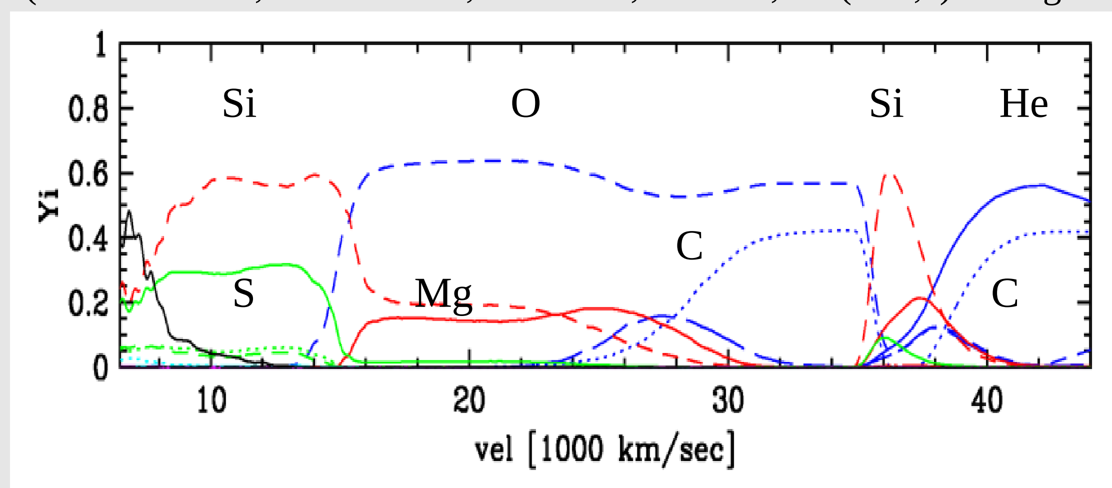


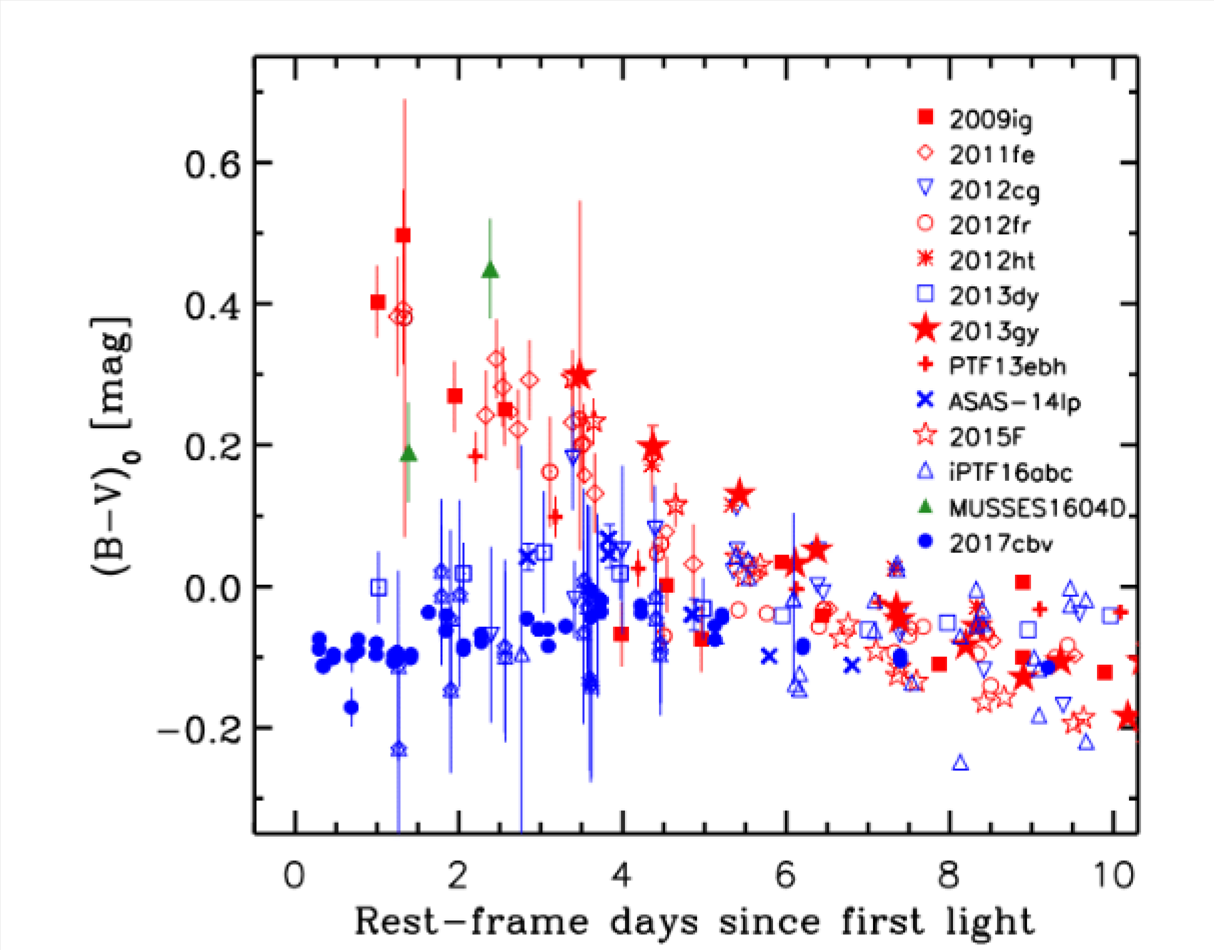
Figure 5. Chemical abundance profile at the point of explosive carbon ignition.

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



New/Some observational evidence B-V

(Stritzinger et al. 2018, in preparation)



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

Suggestion:

- 2 groups ?

Possible reasons:

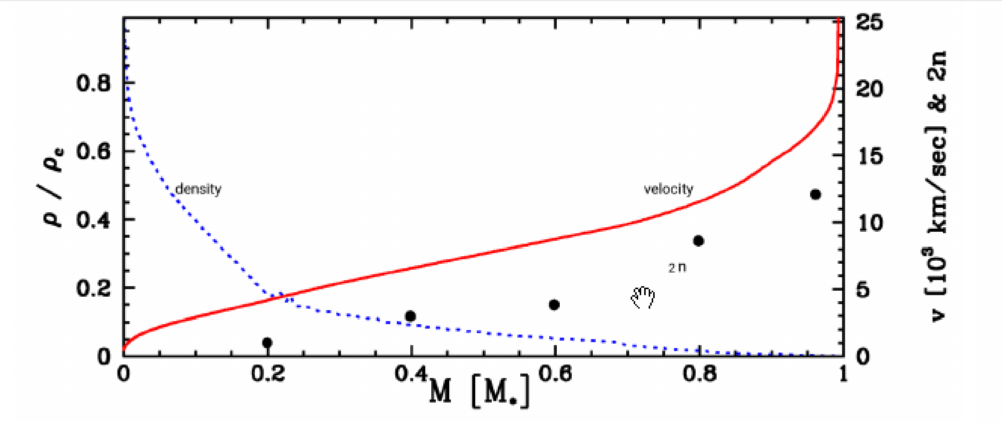
- different accreters (H vs. He, this talk)

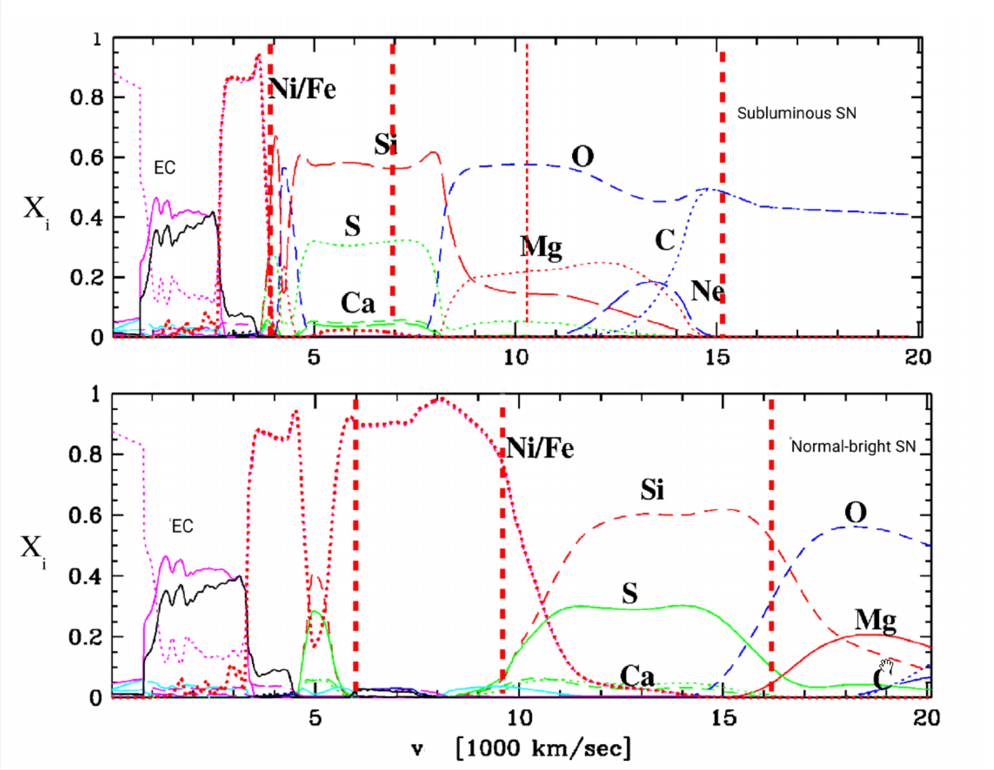
- different models
 PDDs vs. DD s (HK 96, Hetal2017, Gall et al. 2018)
 HeDs (Ni heating, e.g. Diehl et al. 2015 ?)

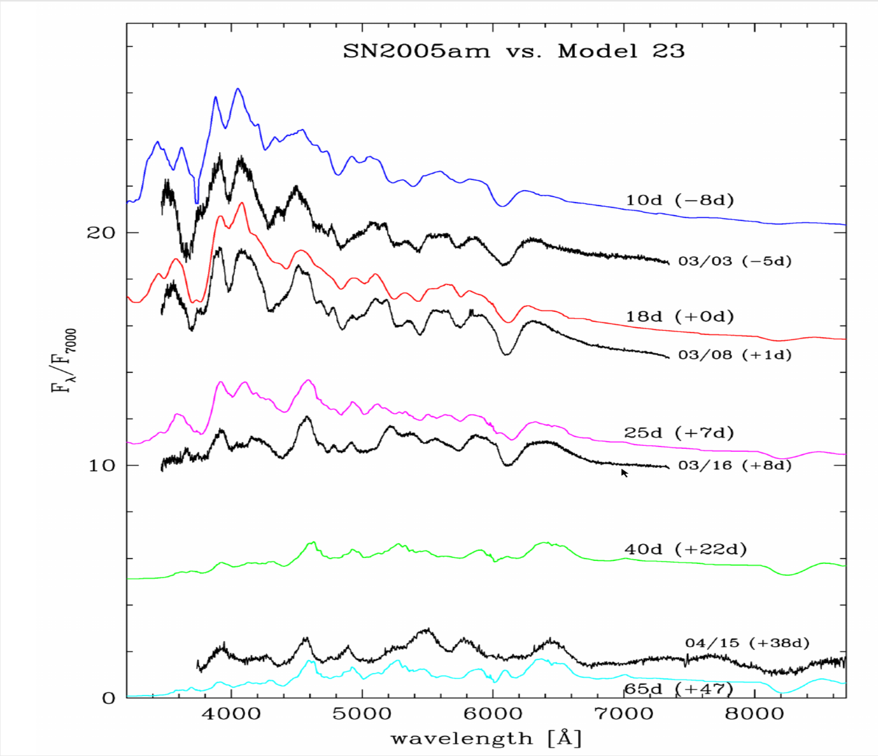
- Interaction in the vicinity of progenitor system
(Gerardy et al. 2007, Dragulin & Hoeflich 2015)

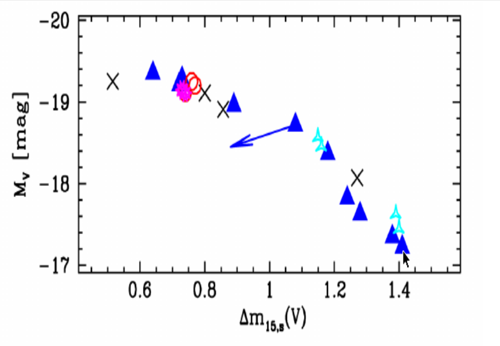
Example: Delayed detonation models for various transition densities rho(tr)

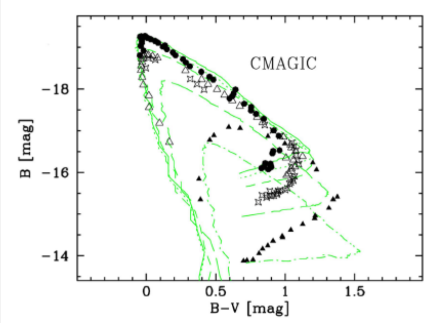
[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(c)= 2E9 g/ccm with rho(tr)=8, 16, 25 g/ccm]







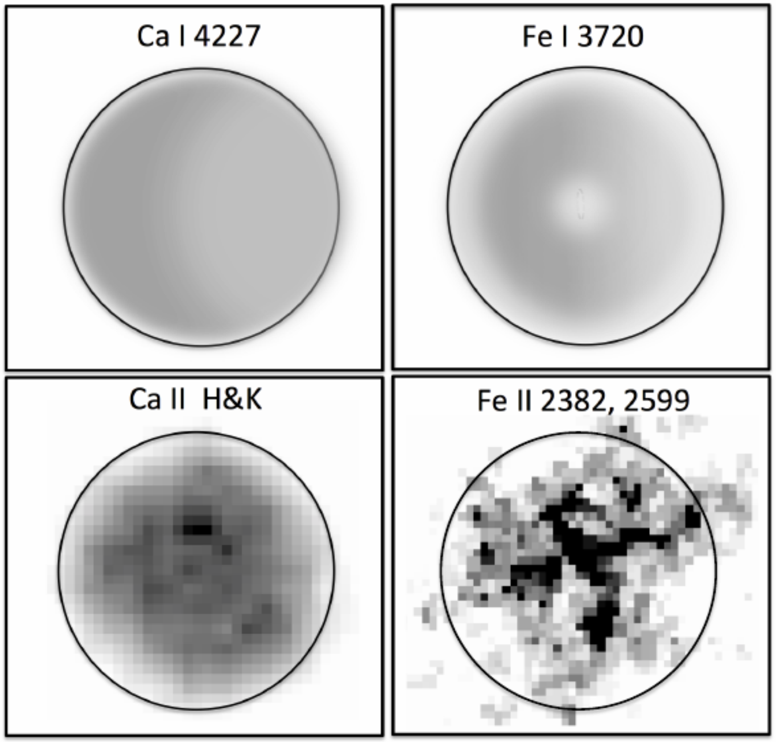


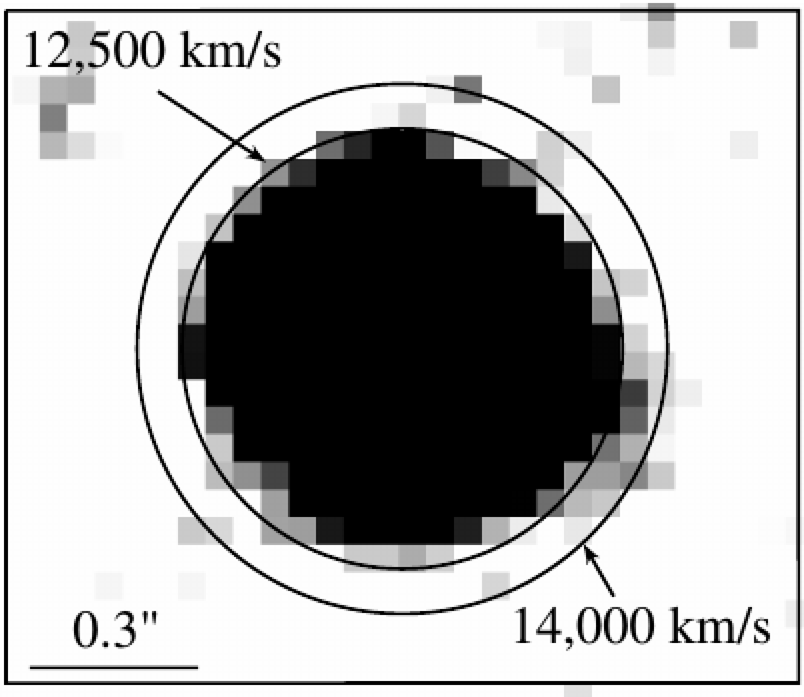


Qualitative difference between spherical scenarios:

& Multi-Dimensional:

Example: SN1885 with HST (Fesen et al. 2005,15,17)





- Signature of deflagration fronts with reduced mixing

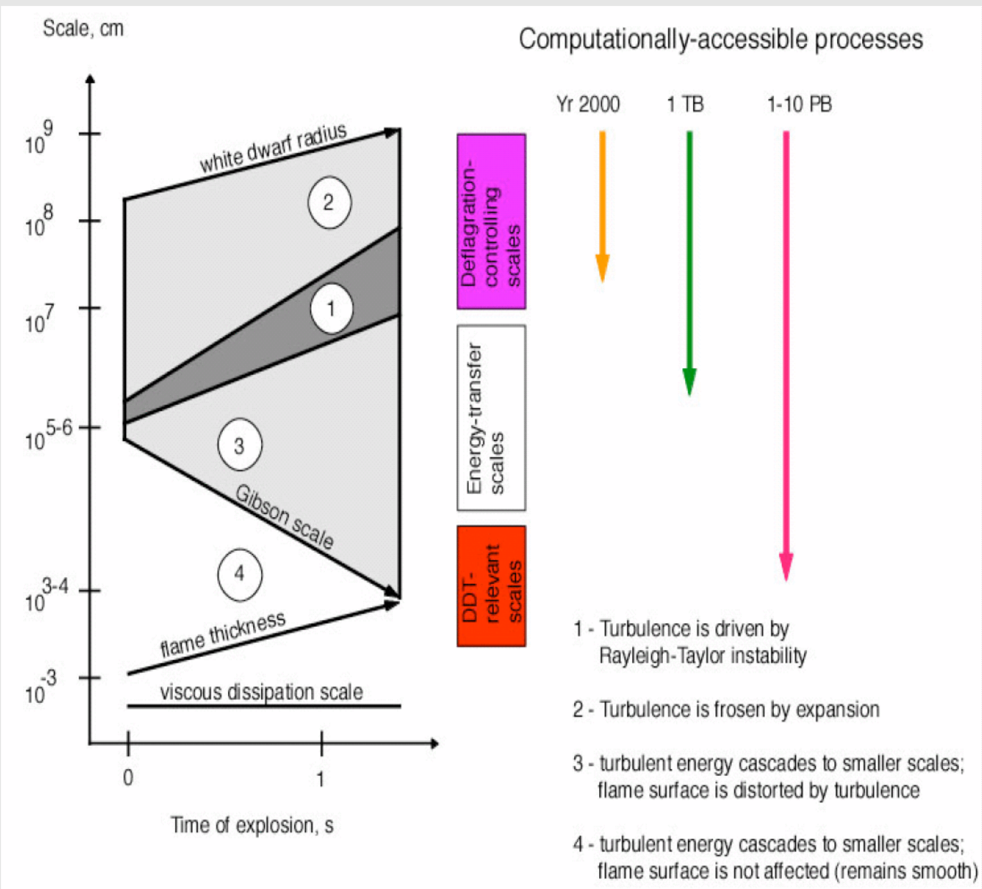
(Lucky case but hardly repeatable)

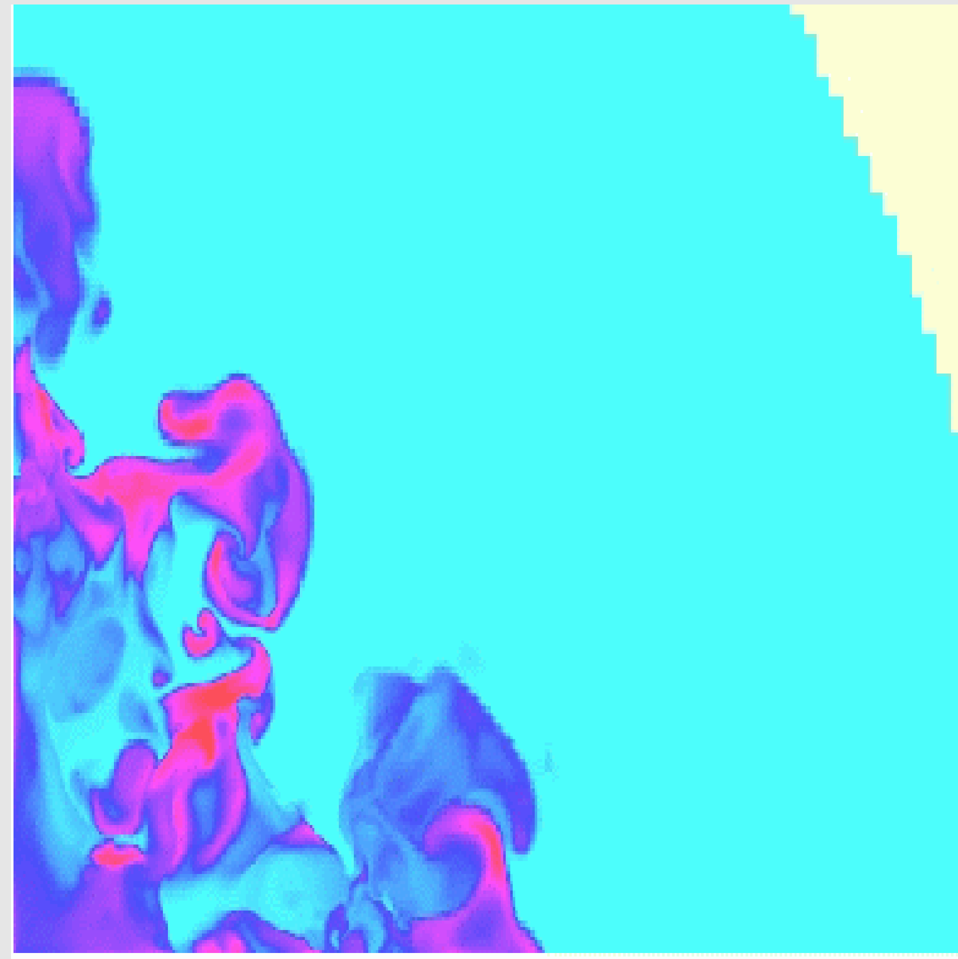
How can we get this information otherwise?

General Rule: Never look to close

Hydrodynamics of Nuclear Burning Fronts (Gamezo et al. 2003)

see also (Khokhlov et al. 2001,Niemeyer et al. 2002,Gamezo et al. 2004,Livne et al. 2003,Roepke et al. 2003,Hoeflich et al., 2004, Roepke et al. 2006/7,Fesen et al. 2007, …,Seitenzahl et al. 2013)

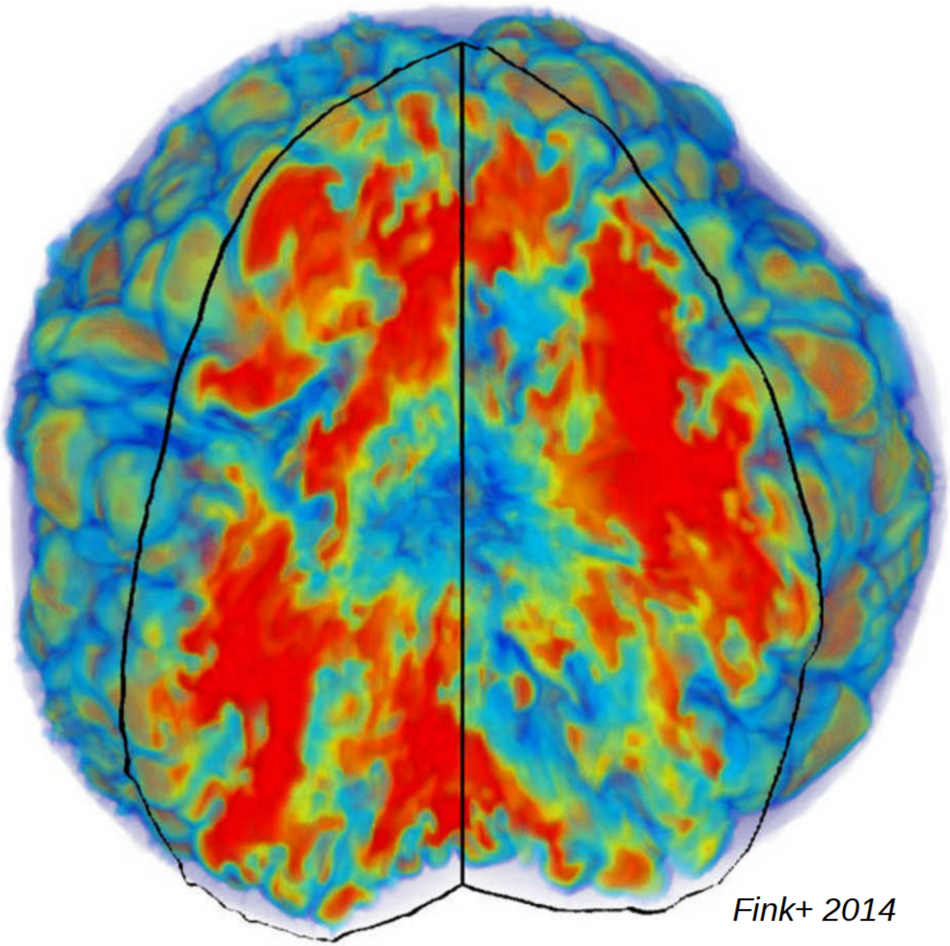




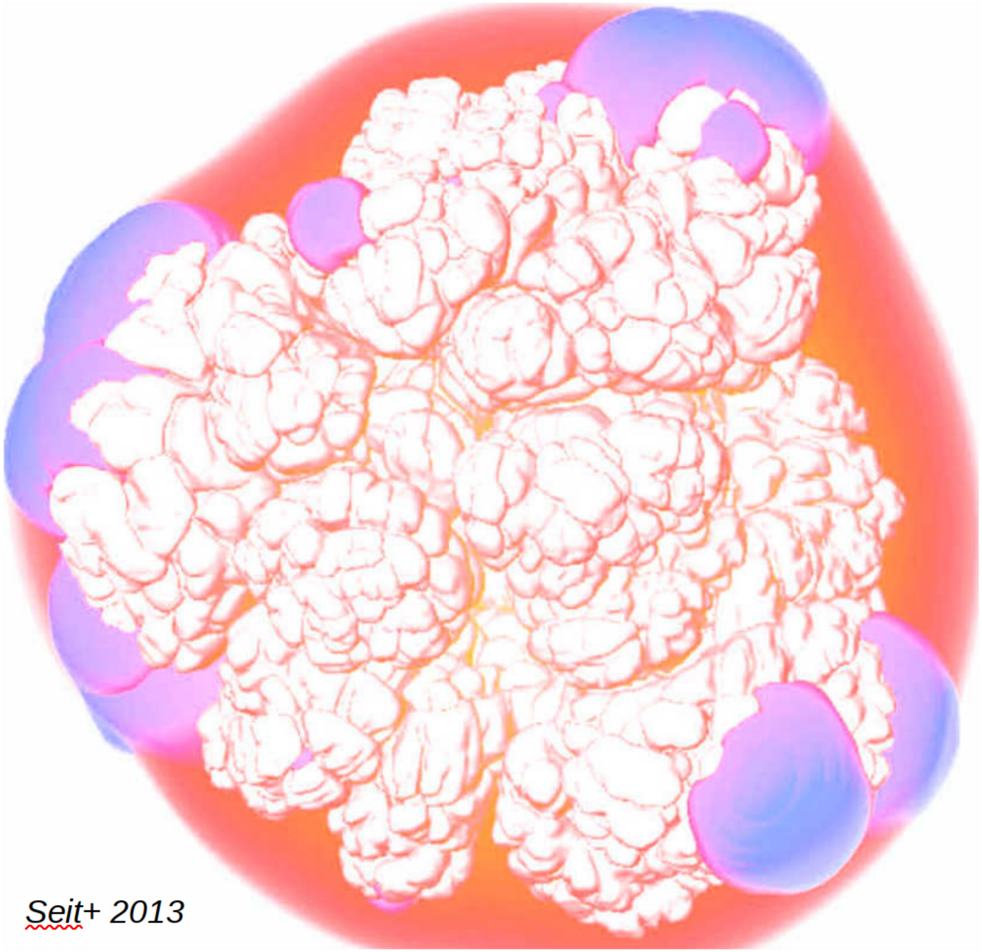
Problem: We do not see this kind of mixing !!!

Question: Shall we give up on M(Ch) ?

General Rule: Never look to close



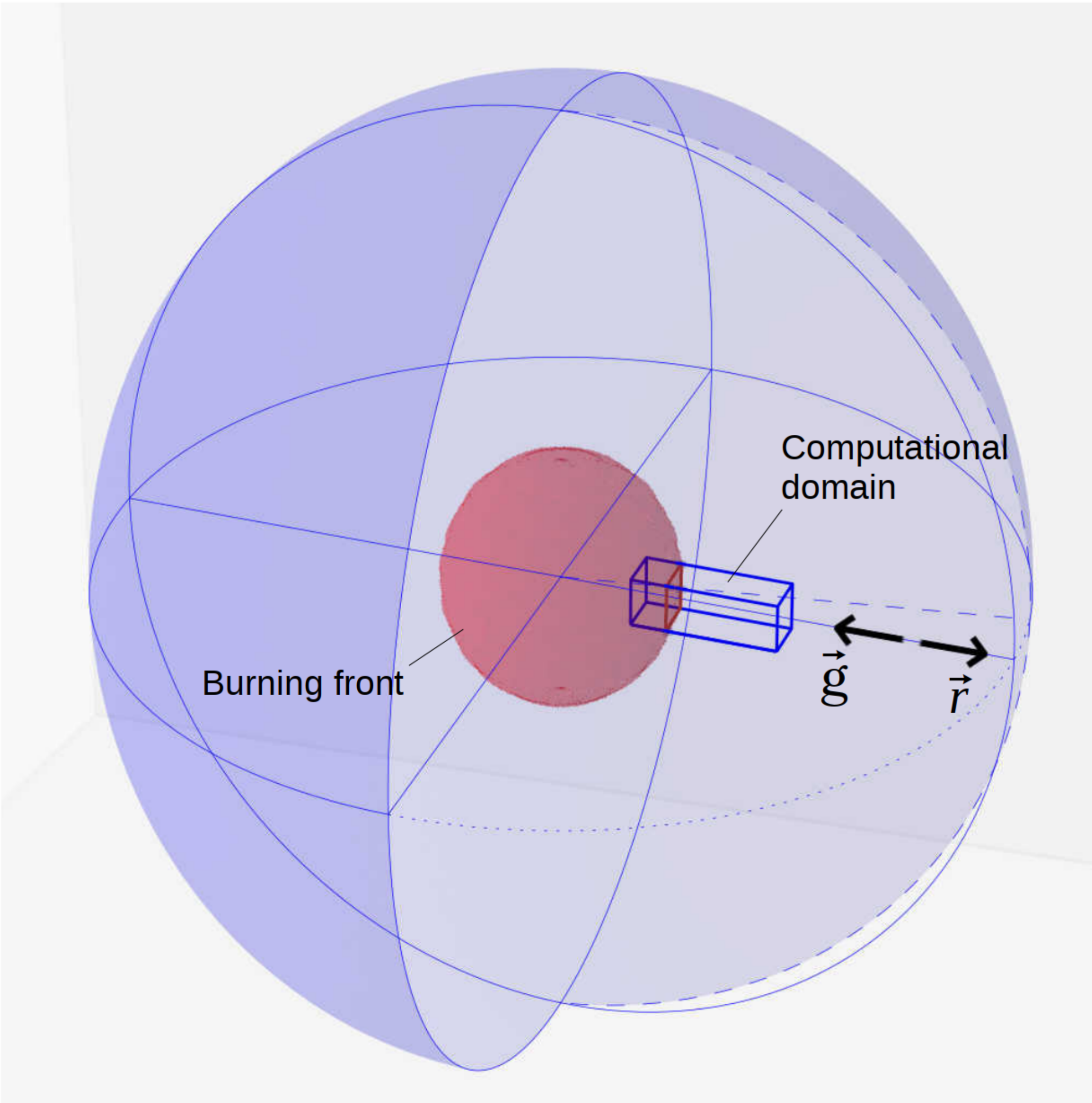
Fink+ 2014



Seit+ 2013

Possible role of Magnetic Fields

(Hristov et al. 2018)



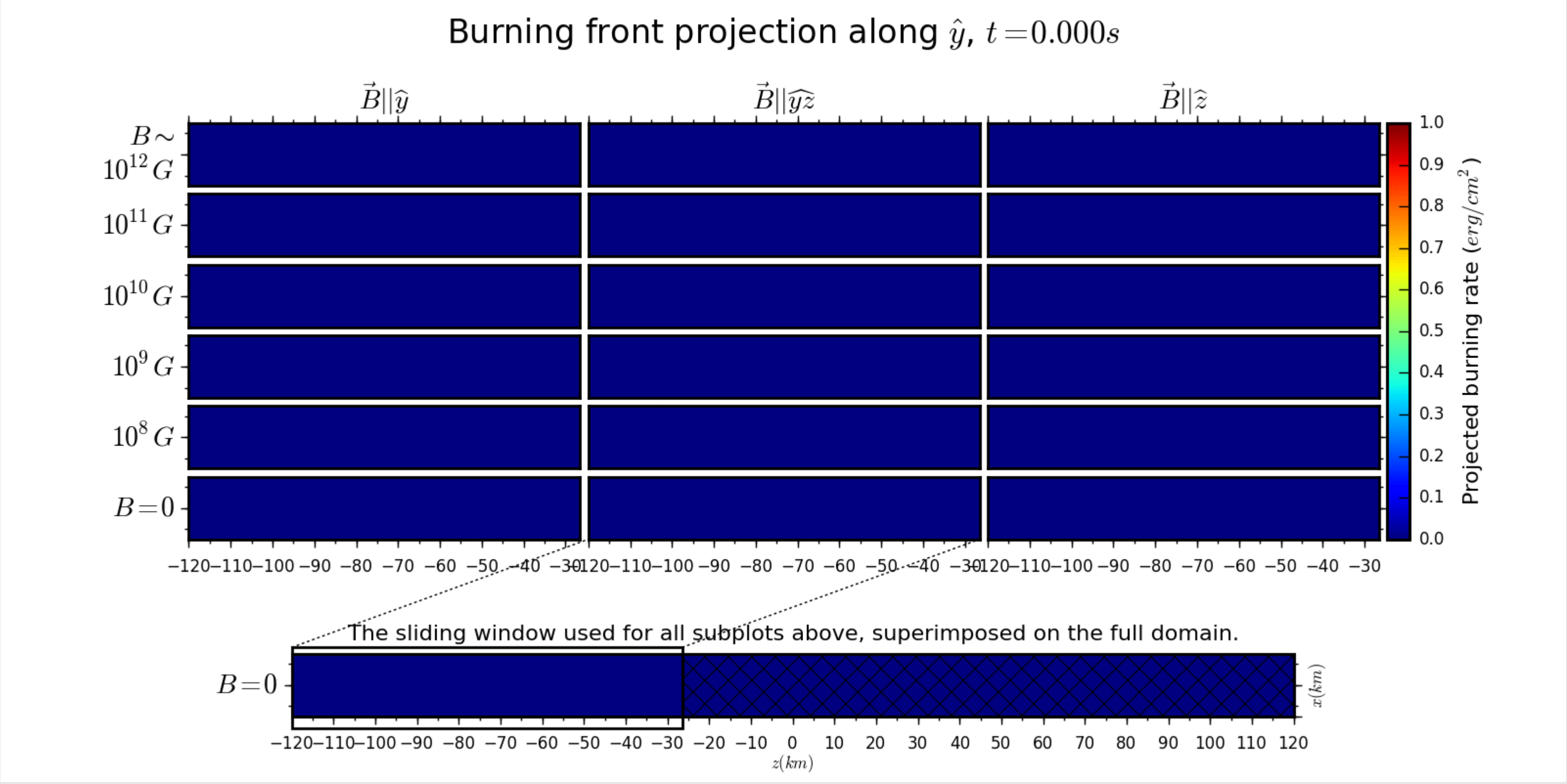
Initial $\vec{B}$ orientation, $\sphericalangle(\vec{B},\vec{r})$	
90°,	$\vec{B} \perp \vec{r}$
45°,	
0°,	$\vec{B} \parallel \vec{r}$

Initial $\lg_{10}(B/1G)$ magnitudes
12 G
11 G
10 G
9 G
8 G
0 G, no field

Influence of the B field no nulcear burning under WD conditions with ENZO

(B. Hriskov, D. Collins, P. Hoeflich, 2015/16/17, see also Remming & Khokhlov, 2015)

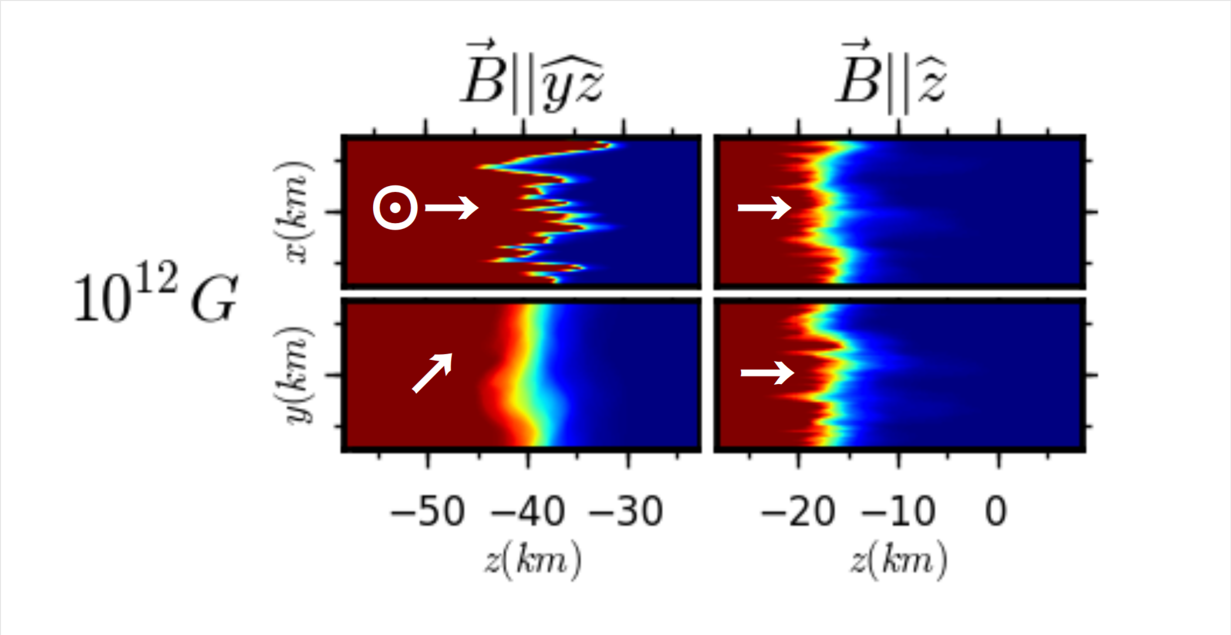
rho(1E8g/ccm), C/O=1, gamma=1.35, dE/dt)

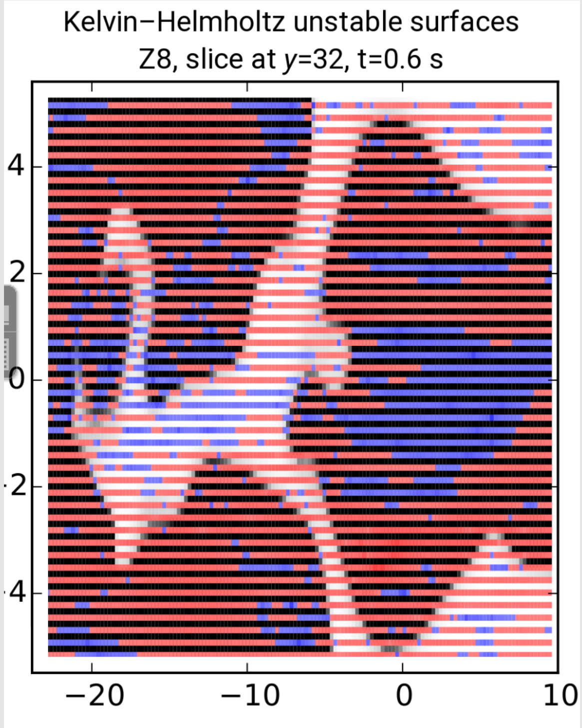


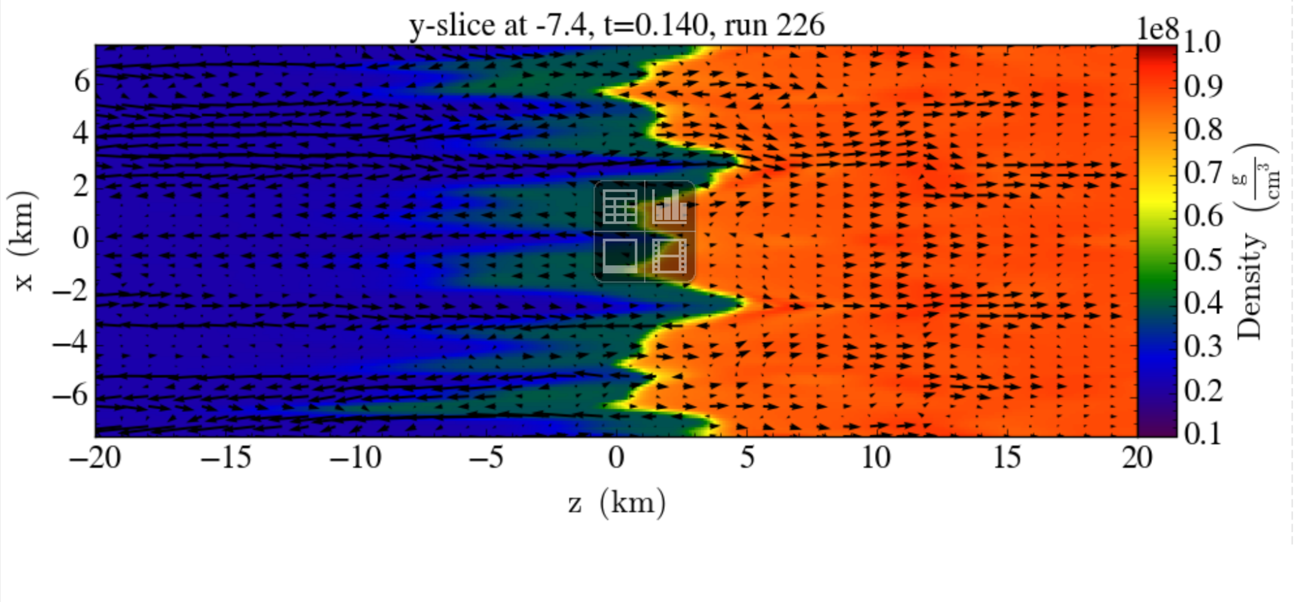
- High B fields slow down the burning front
- RT-instabilities are suppressed
- Coam-instabilities are created for high B.

Question: Does this cure the RT in SN models and create DDT ?

New B-induced Instability in non-distributed regime ?





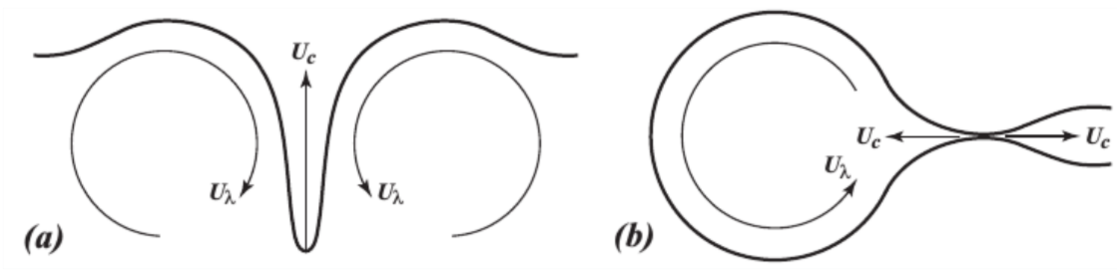


- **Possible Origin:**
 Smoldering phase prior to runaway (add citations)

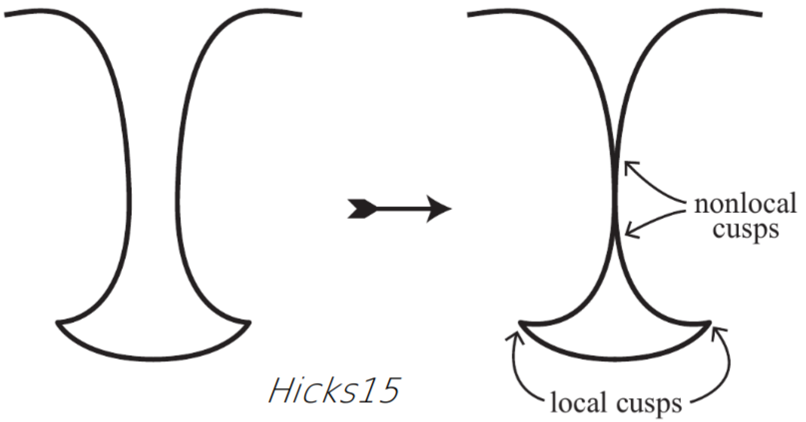
- Possible DDT (non-Zeldovich)

→ Effect on nucleosynthesis

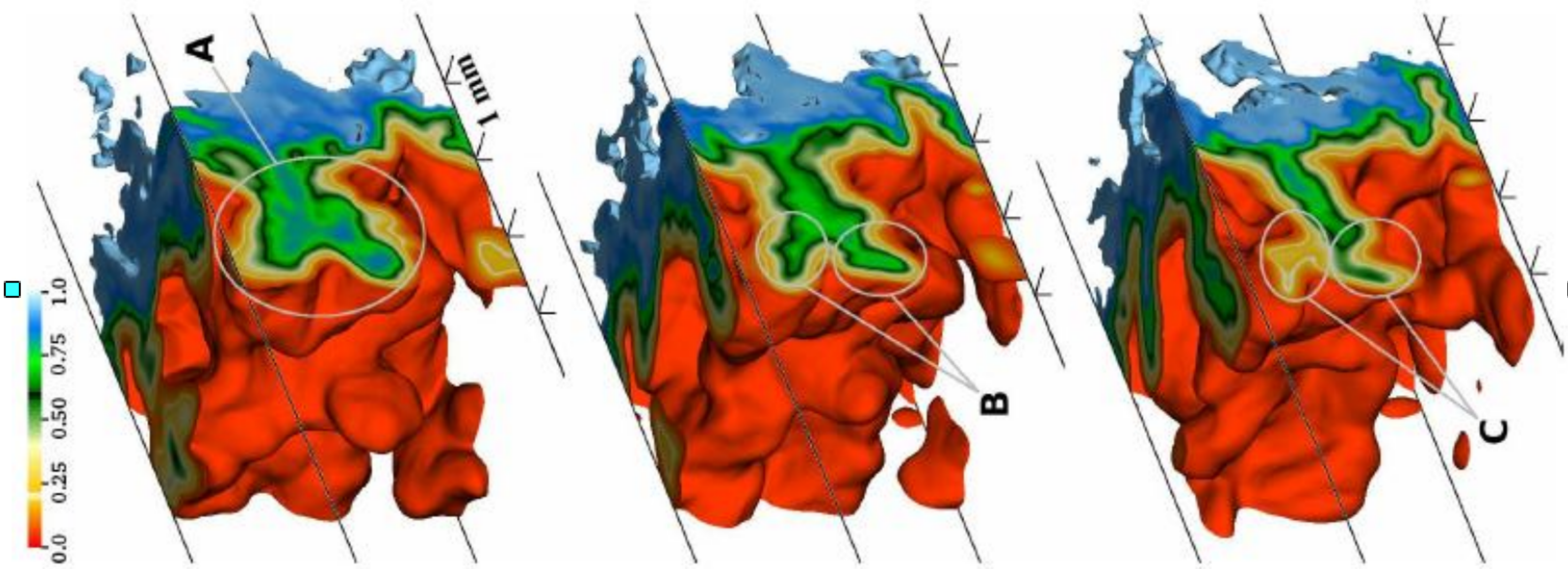
How does a detonation propagate ?



Poludnenko+Oran11



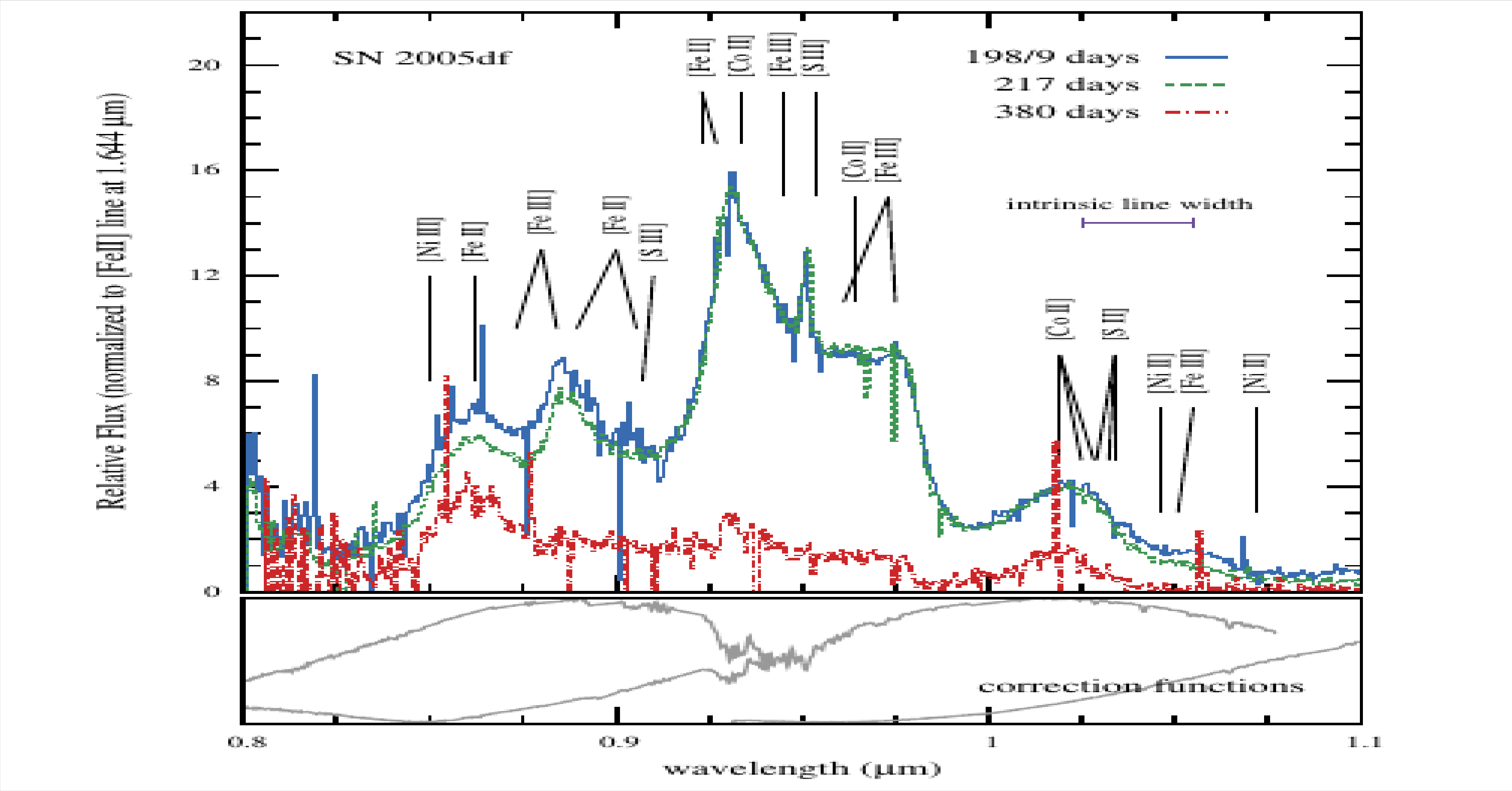
Hicks15



Poludnenko+Oran11

Electron Capture & Nebular NIR Spectra

Example: SN2005df at 10 Mpc (Diamond et al. 2015)

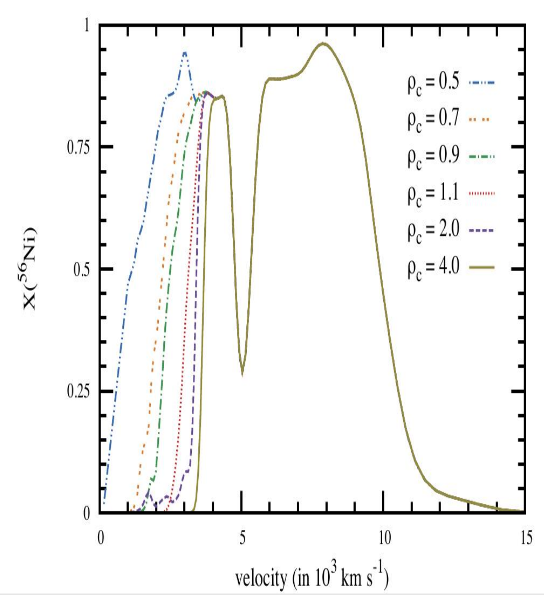


NIR are less blended than optical wavelength => Line profile

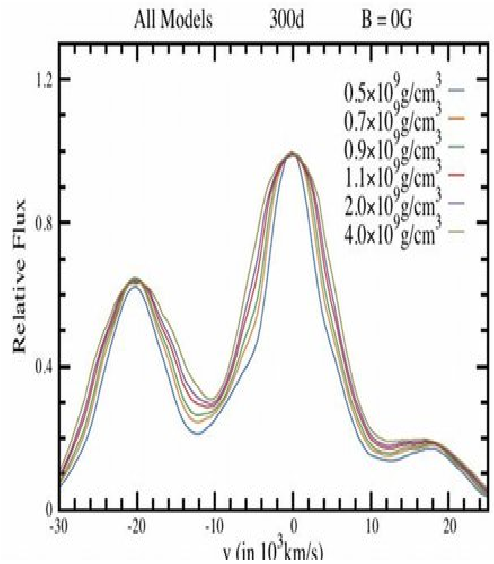
The [Fe II] line at 1.644 mu as “Swiss-Armee Knife” @ SN 2005df

(Diamond et al., 2015, 2018)

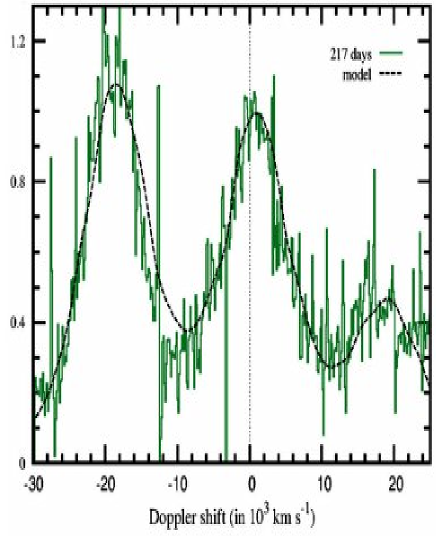
X(56Ni)= f(v)
for rho(c)



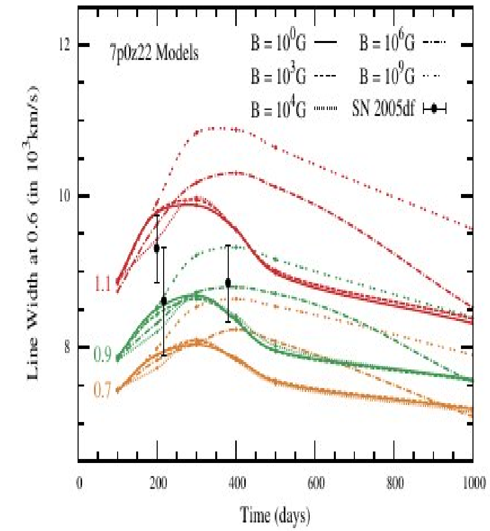
Theoretical Profiles
with Doppler-shift



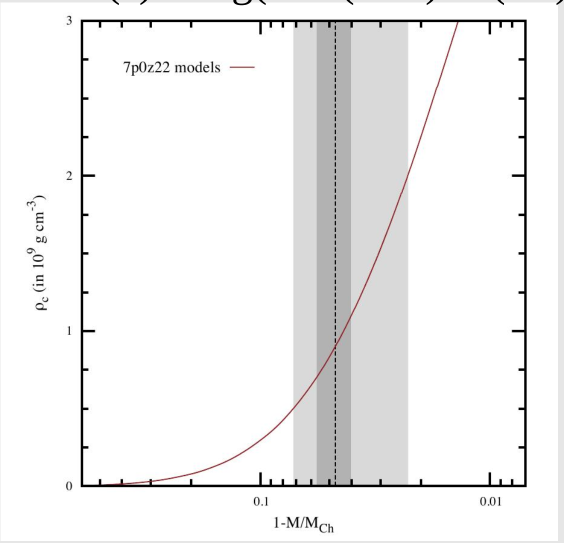
SN05df vs. Model
at day 200



Half width=f(t)
for B=0 ,1E4 & 1E9G



Rho(c) = log(1-M(WD)-M(Ch)



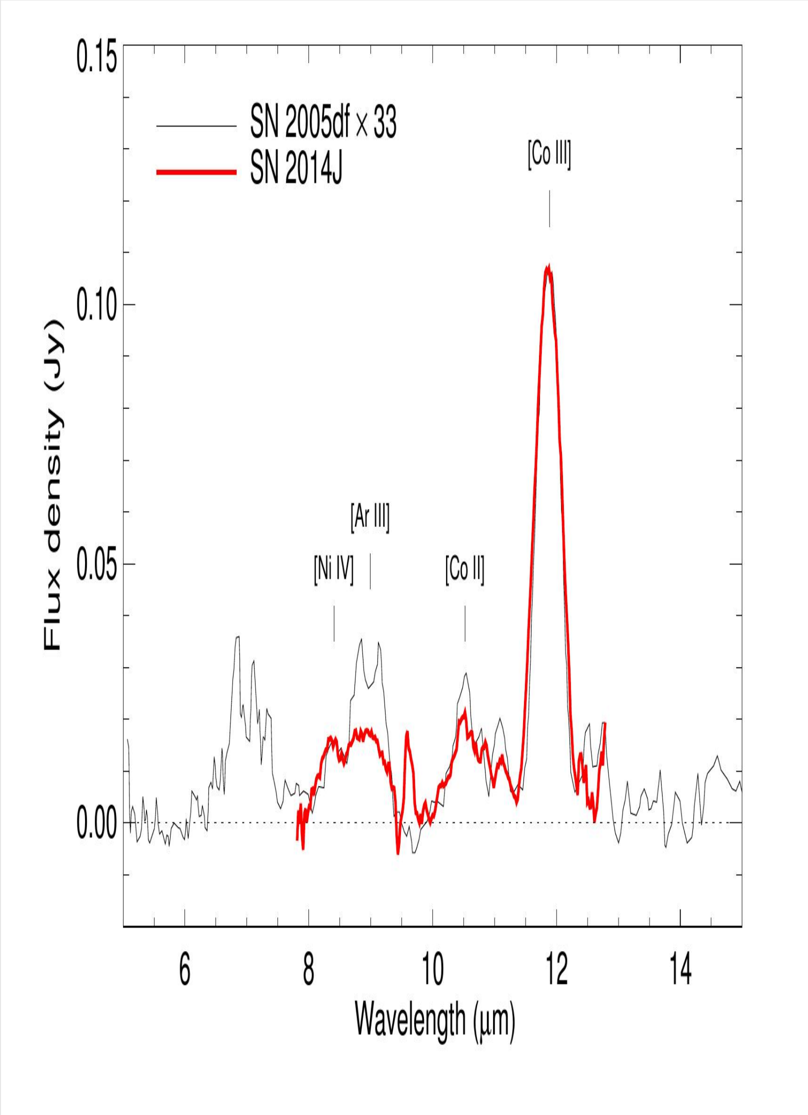
Results for SN 2005df

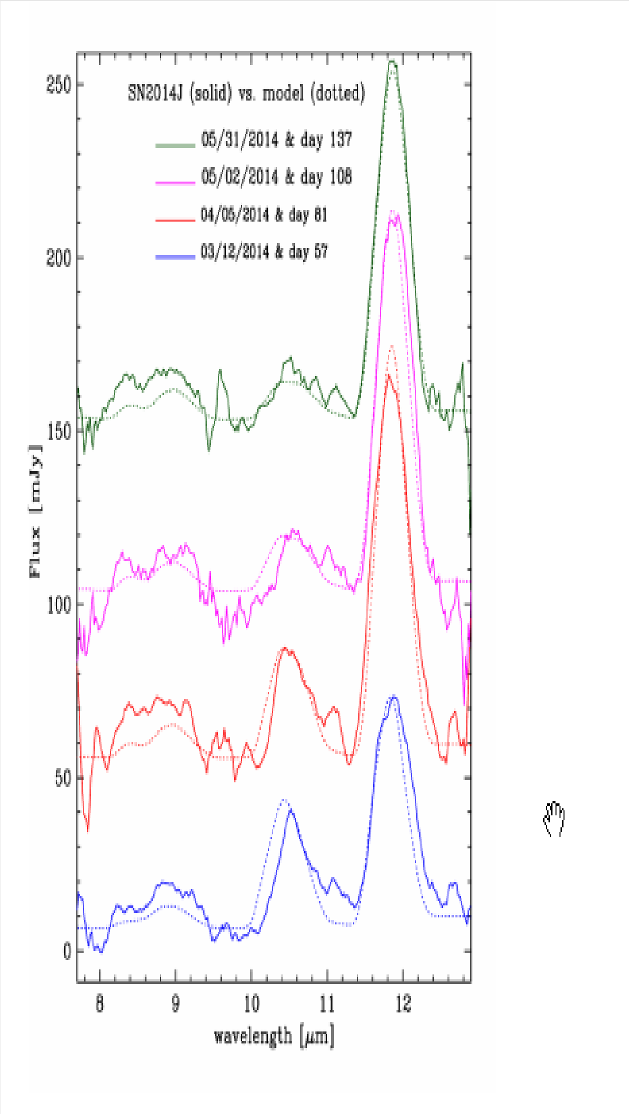
- M(Ch) explosion likely

- low density (almost too low for H accreter
  -> He or C (SD or DD progenitor system)

Why do we need Mid-IR spectra (Spitzer, CanariCam & JWST)?

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





Others:

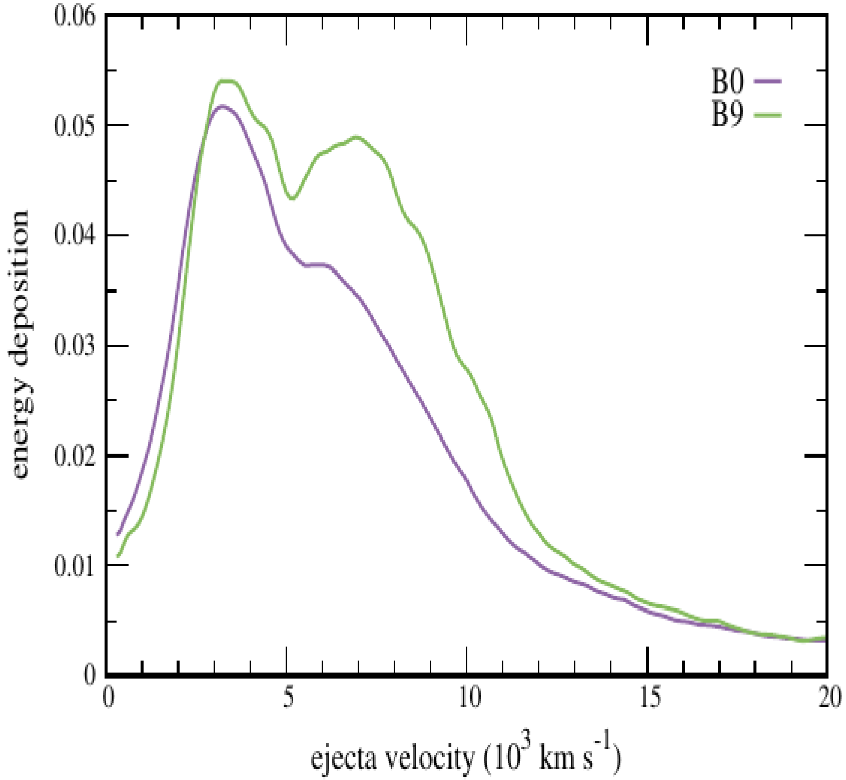
- Direct measure of photon redistribution
- [Co III] @ 11.8 mu as new standard candle ?
- magnetic fields
- mixing …

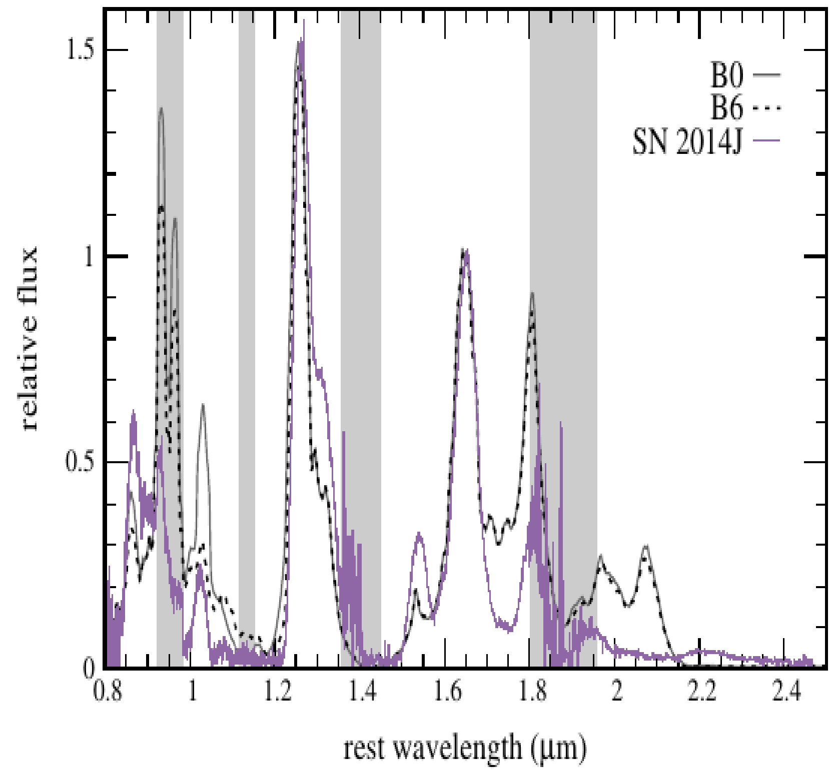
Diamond et al. 2017

How can we get 57Co in all the mess

Probing mixing and positron transport effects in the NIR ?

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

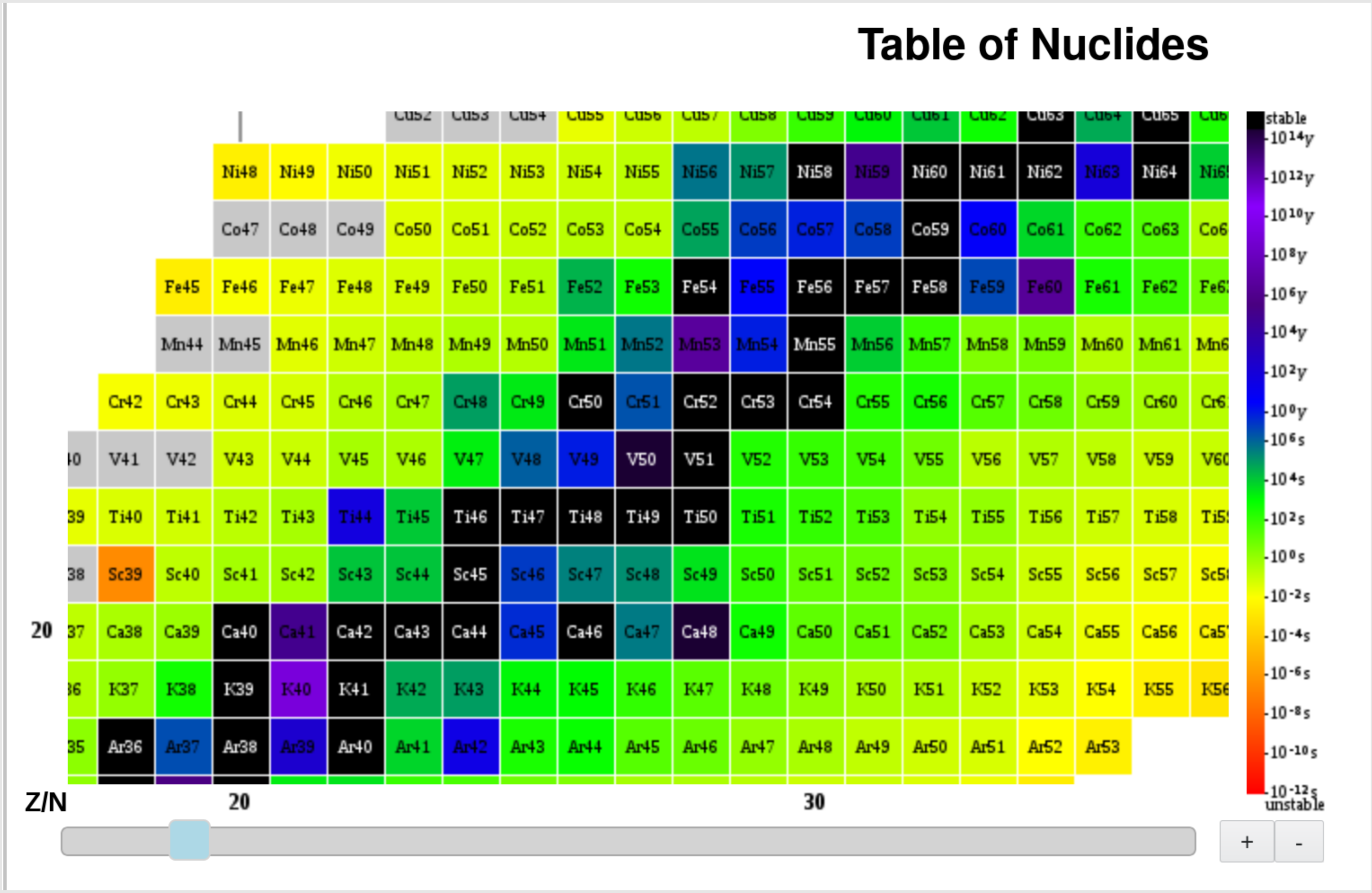




- Non-local excitation of SII by positron transport

Electron capture as probe of the burning conditions ?

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



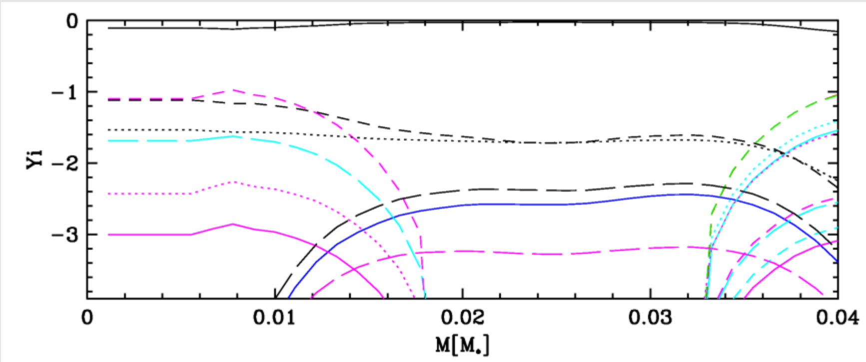
Decay times

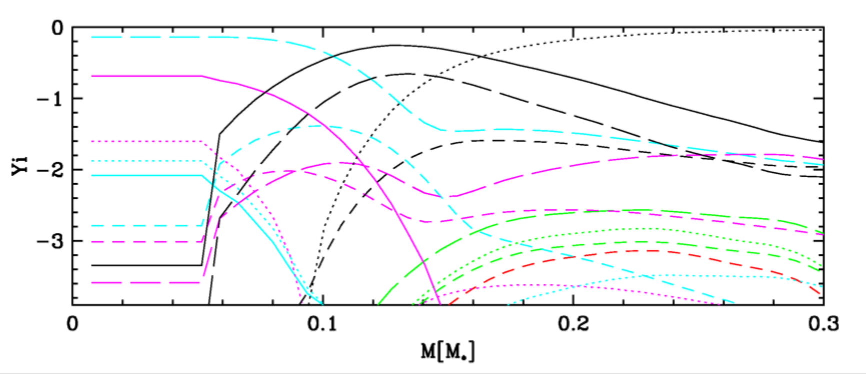
49V =330d
55Fe =2.7 yr
57Co=271d

Electron capture as probe of the burning conditions ?

(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)





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 burning conditions ?

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

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	

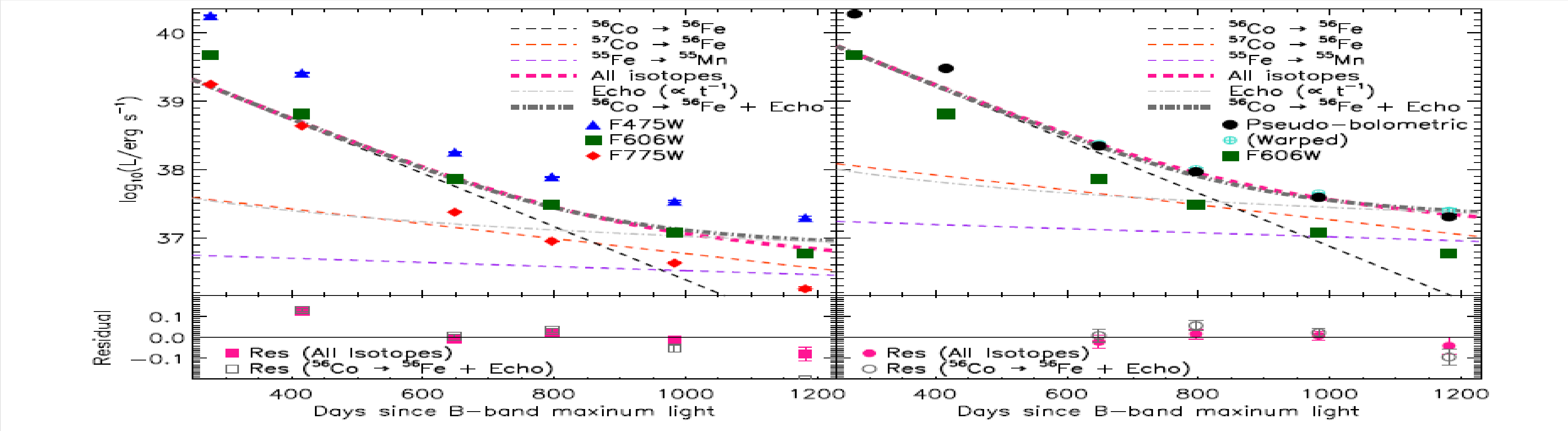
rhoc	fe58	**co55 #**	co57 #	ni56 #	ni57 #	ni58	zn60 #	t=0d
		mn55	co57	ni56	ni57		ni60	t=100d
		mn55	fe57	fe56	fe57		ni60	t->inf
d02	1.5E-05	**2.5E-03**	2.3E-05	1.0E+00	1.9E-02	1.5E-02	8.0E-03	
d05	2.5E-05	**8.8E-03**	1.3E-05	1.0E+00	1.7E-02	1.6E-02	5.2E-03	
d10	2.7E-05	**1.3E-02**	6.3E-05	1.0E+00	1.8E-02	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)***

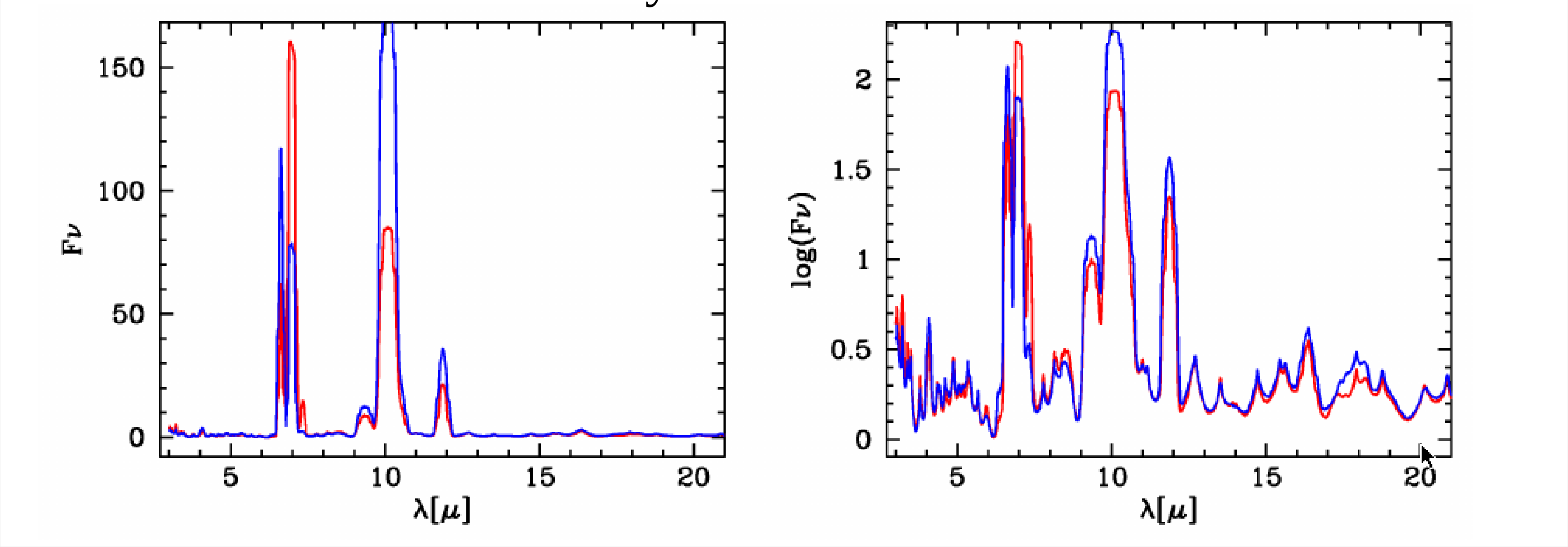
Remark: Because compression rather deflagration , a 1.2 Mo HeD → DD(d02)

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

*Suggestion: SN2014J & u*ltra-late time NIR and MIR spectra (Hoeflich &FSU, Wang &TAMU



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



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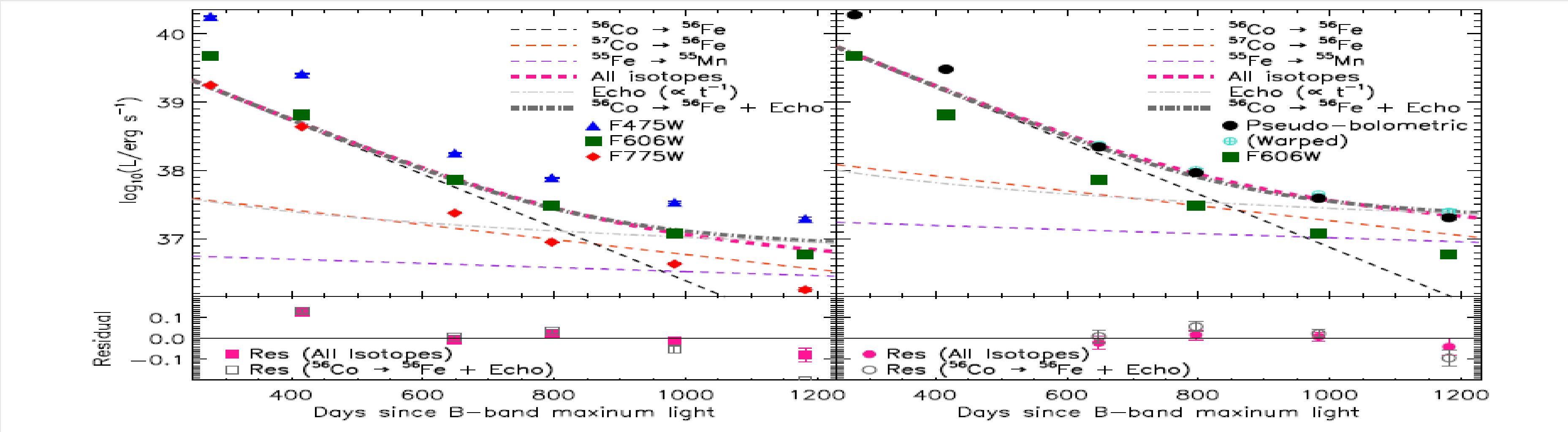
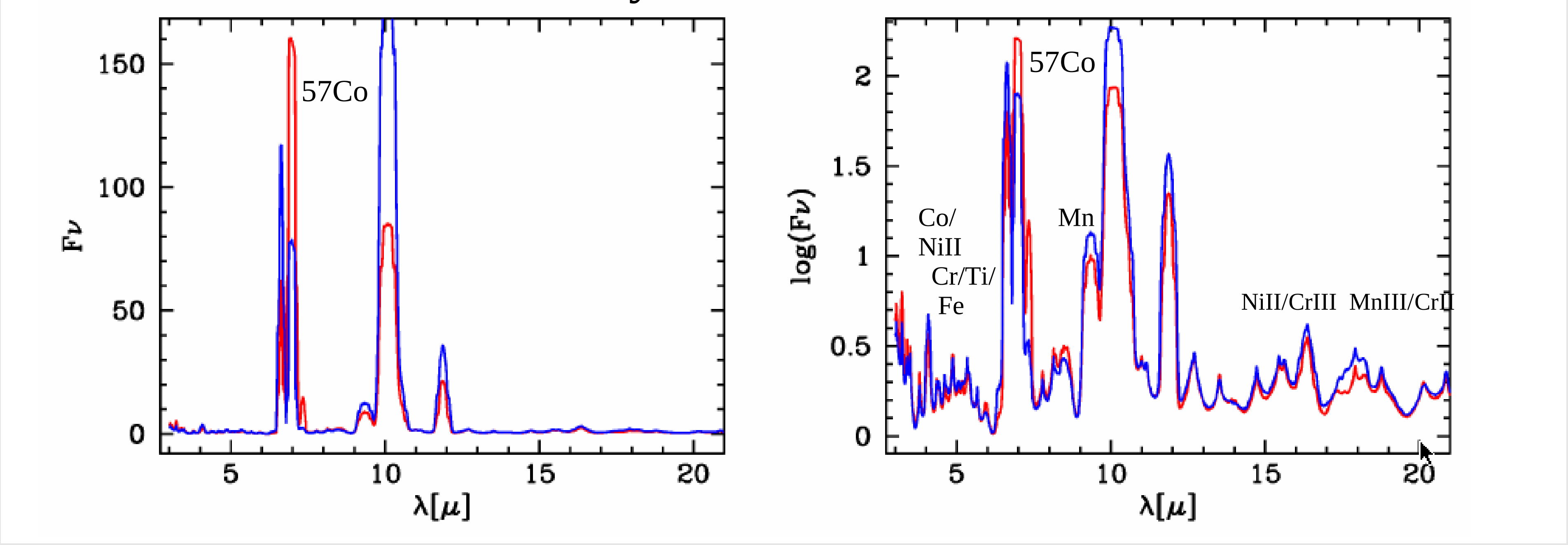


Model for SN2014J at day 3000 for B=0 and 1E9 G



Σ , New Prospects & Preliminary Conclusions

- Time-domain observations and NIR and MIR are here

- 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

- 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 section

- Higher sensitivity → diversity of SNe Ia
  Normal bright SNeIa are high masses (1.2 … 1.4 Mo) from SN-observations
  Low masses would lead to correspondingly high Ho

- SN are an important puzzle for BBN and Cosmology