A Shell Model for the High-Velocity Features (HVF) of SN Ia

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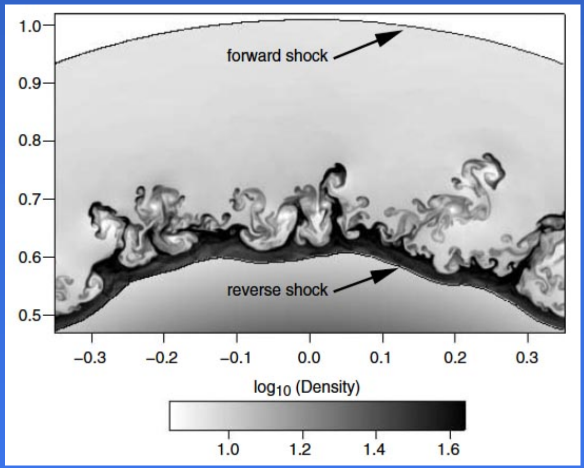
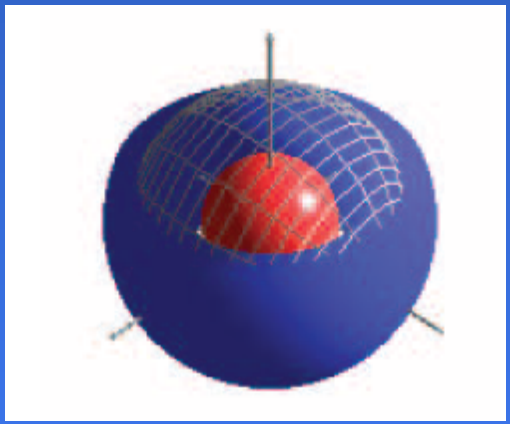




Carnegie SN Ia Progenitor Workshop, August 4, 2015

Brian Mulligan

With thanks to collaborators in the Texas cabal:
Howie Marion, Jeff Silverman, Jozsef Vinko

High-Velocity Features (HVF)

Most prominent in CaII IR triplet (CaIR3), but also seen in Si, Fe, other lines.

Common before maximum, but not universal (~91%; Marion+13, McGuire+14, Childress+14, Silverman+15).

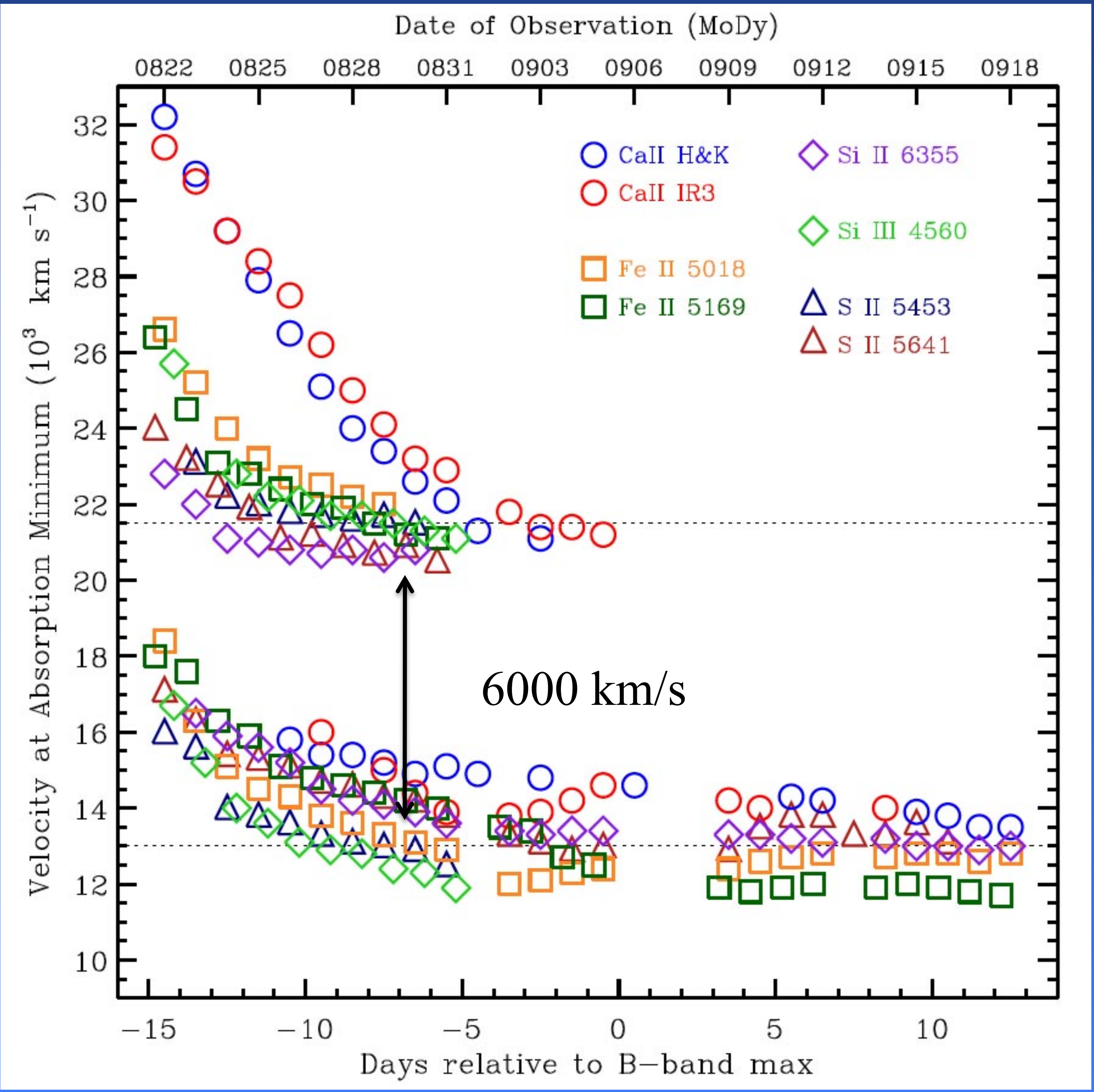
Distinctly separate from the photospheric velocity features (PVF) by ~ 6000 - 8000 km s^{-1}, kinematically detached.

HVF appear early, disappear with time, but never decrease to PVF.

Si appears more often in Wang+13 "High Velocity" events ($v_{Si} > 12{,}000$ km s^{-1}) (Silverman+15).

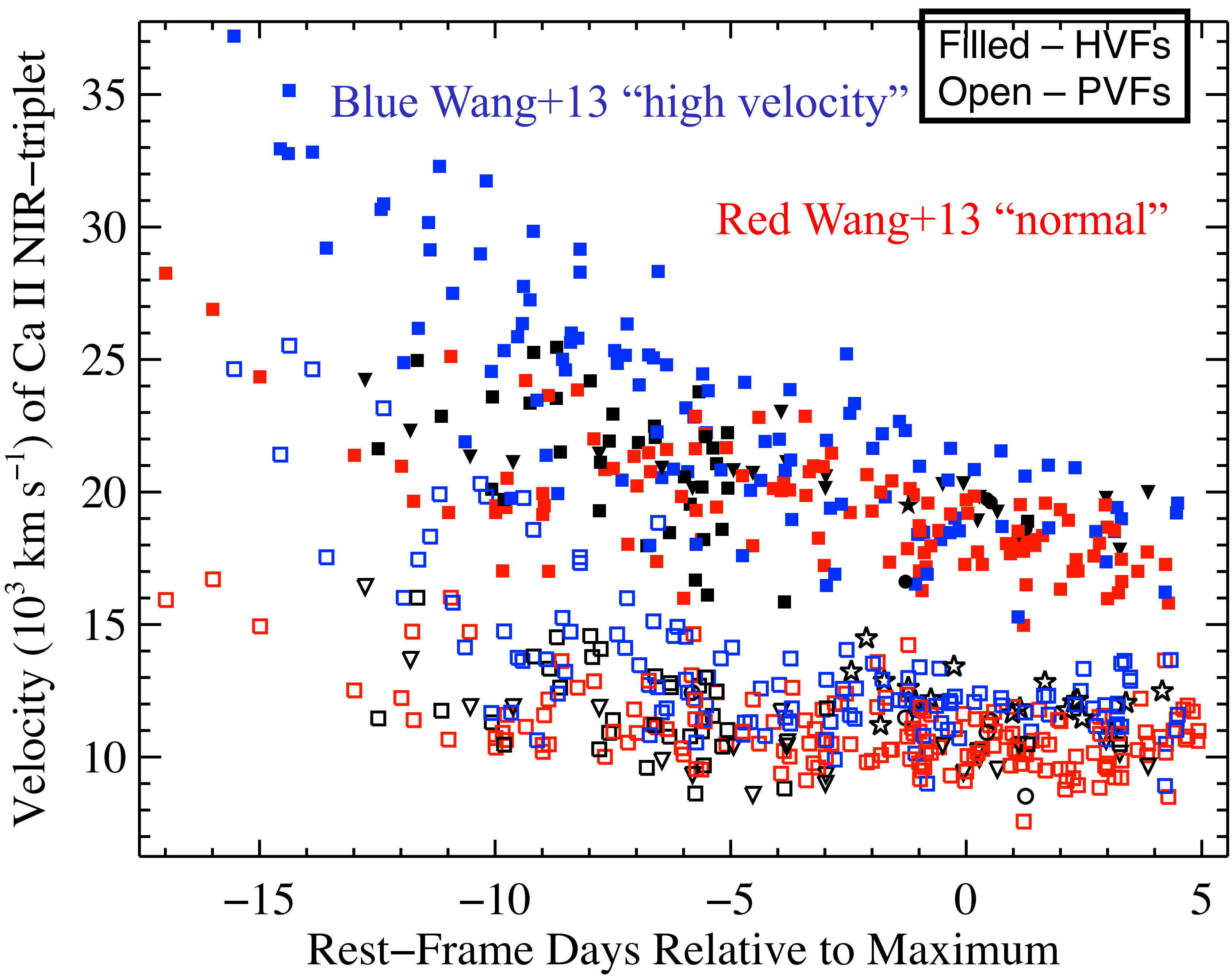
Not seen in 91bg-like (Silverman+15).

Polarized.



Evolution of High-Velocity Features and Photospheric Features in SN2009ig (Marion+13).

Silverman+15



Origin of HVF?

Some structure in intrinsic explosion dynamics?

Ionization effect (Blondin+13; Mazzali)

Collision with circumstellar shell (Gerardy+04, Quimby+06)
(Not thin accretion disk, HVF too common).

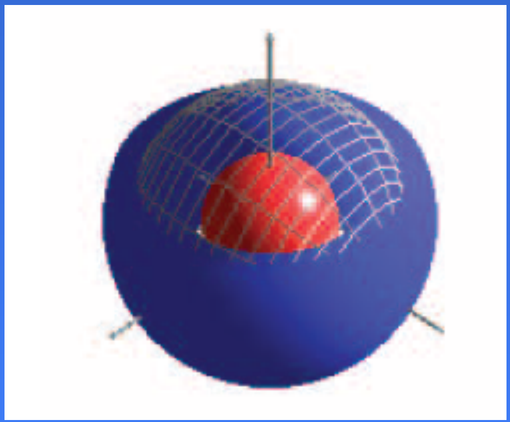
Important constraint: not just some material at high velocity, but must reproduce the observed velocity evolution; HVF must remain distinct from PVF.

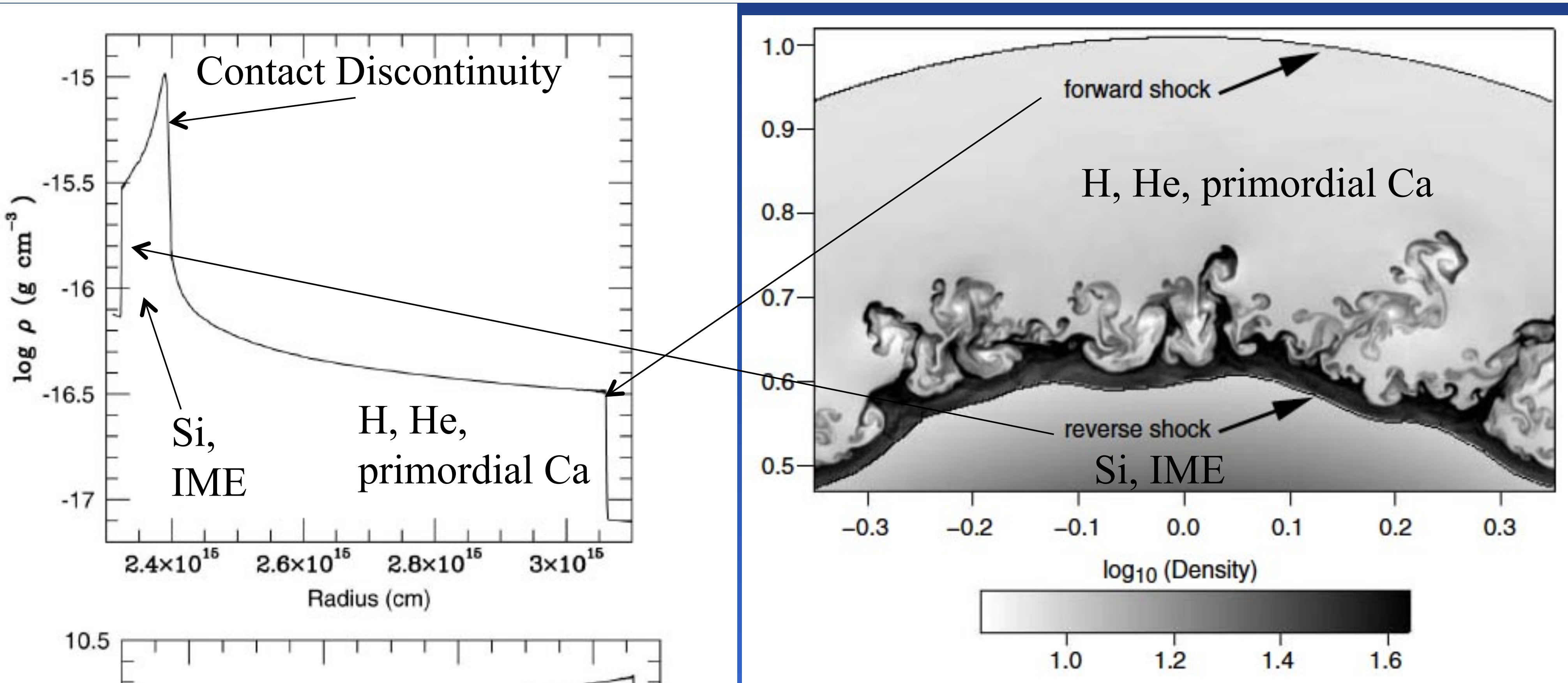
CSM Shell Model

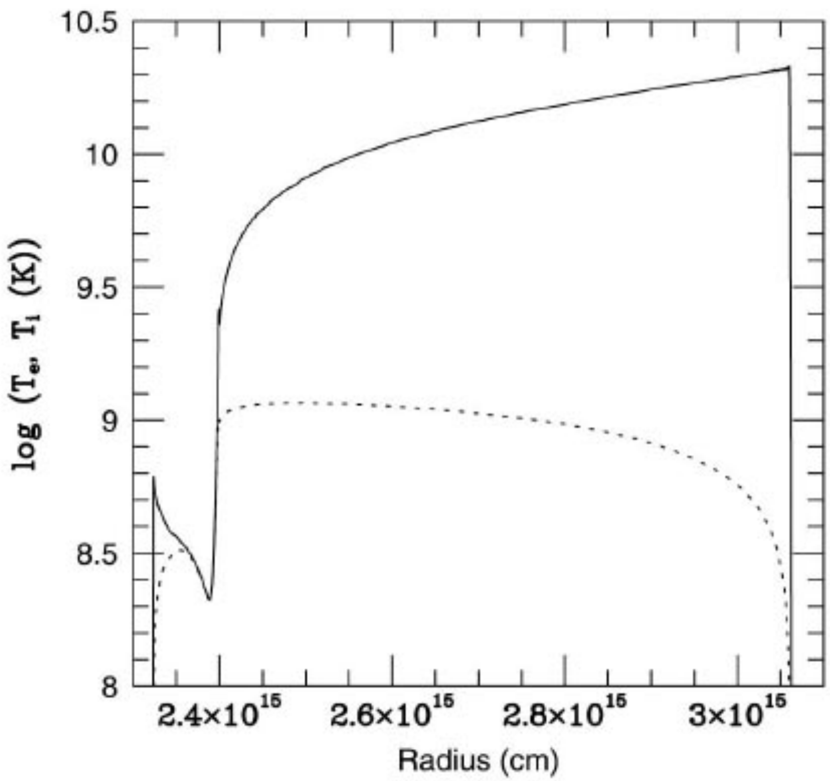
Impact of SN ejecta on CSM shell, m ~ few 0.01 $M_\odot$, with primordial Ca gives a reasonable representation of the asymptotic velocity of the HVF (Gerardy+04).

If CSM shell, must lie at << 10^{15} cm to avoid contamination of early light curve, must have large covering factor to be so common, but sufficiently asymmetric to account for polarization.

Tanaka+06







Chevalier – forward, reverse shocks, RT unstable contact discontinuity

CSM Shell Model

Aspirations to do full 3D model (Gamezo+03).

Proof of principle, azimuthally averaged to produce spherical model.

Explode model with FLASH into shells of variety of mass, 0.001 to 0.1 $M_{\odot}$, variety of density profiles, Gaussian, top hat, wedge inward (|\ ) , wedge outward (/|) .

Shape makes a difference; wedge inward and Gaussian, similar, OK; top hat and wedge outward fail.

Mass makes difference, ~ 0.005 $M_{\odot}$ for SN 2011fe.

Shell radius ~ 10^{10} cm (bigger than WD, small enough not to contaminate early light curve).

CSM Shell Model

After interaction, ~ 50 seconds, expand homologously, scale density profile to given post-explosion epoch.

Collision blended with breakout (before dark time).

Radio, X-ray limits okay.

CSM Shell Model

With various reasonable assumptions concerning ionization, excitation temperature, density profile from FLASH calculations, compute model spectra with SYN++, iterate to fit observed spectra.

Compare to early spectra, evolution of SN 2011fe.

Focus first on CaIR3

Shell of mass 0.005 $M_{\odot}$

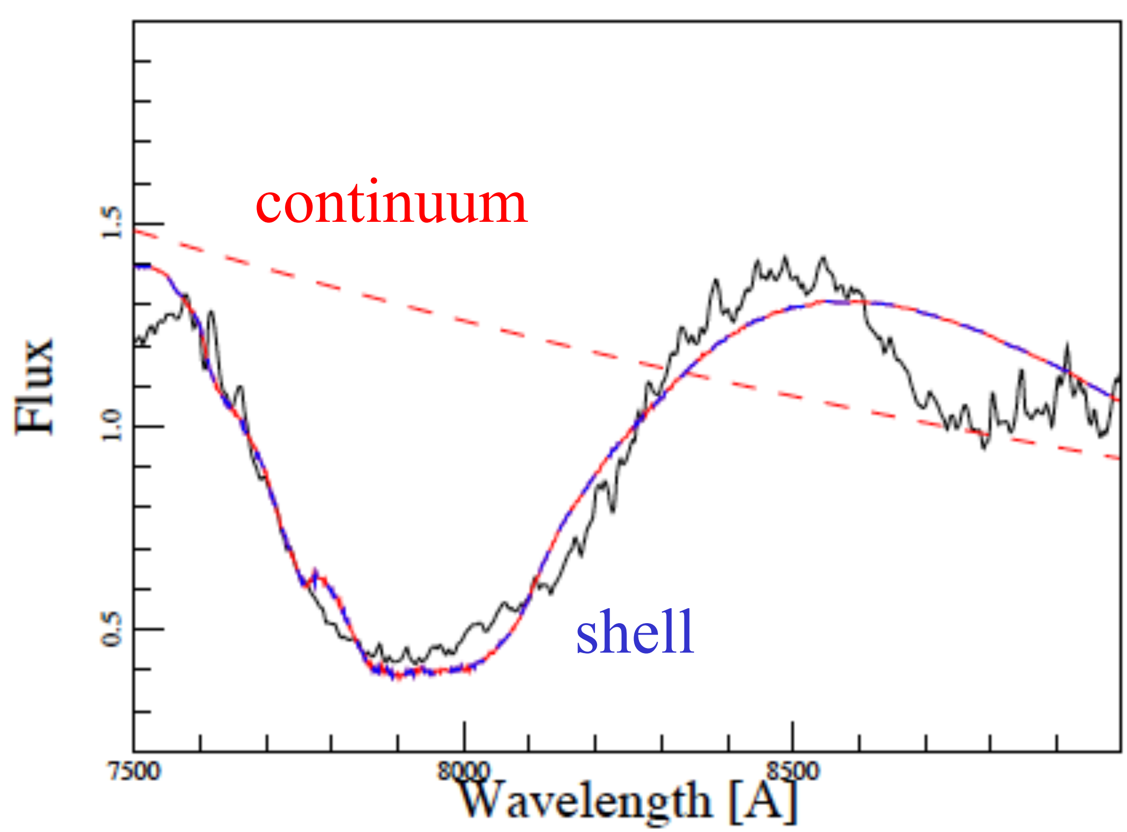
Solar abundance by mass of Ca

First models "substrate" unconstrained: H? He? C/O?

Agnostic on single or double degenerate, Chandra, Sub-Chandra

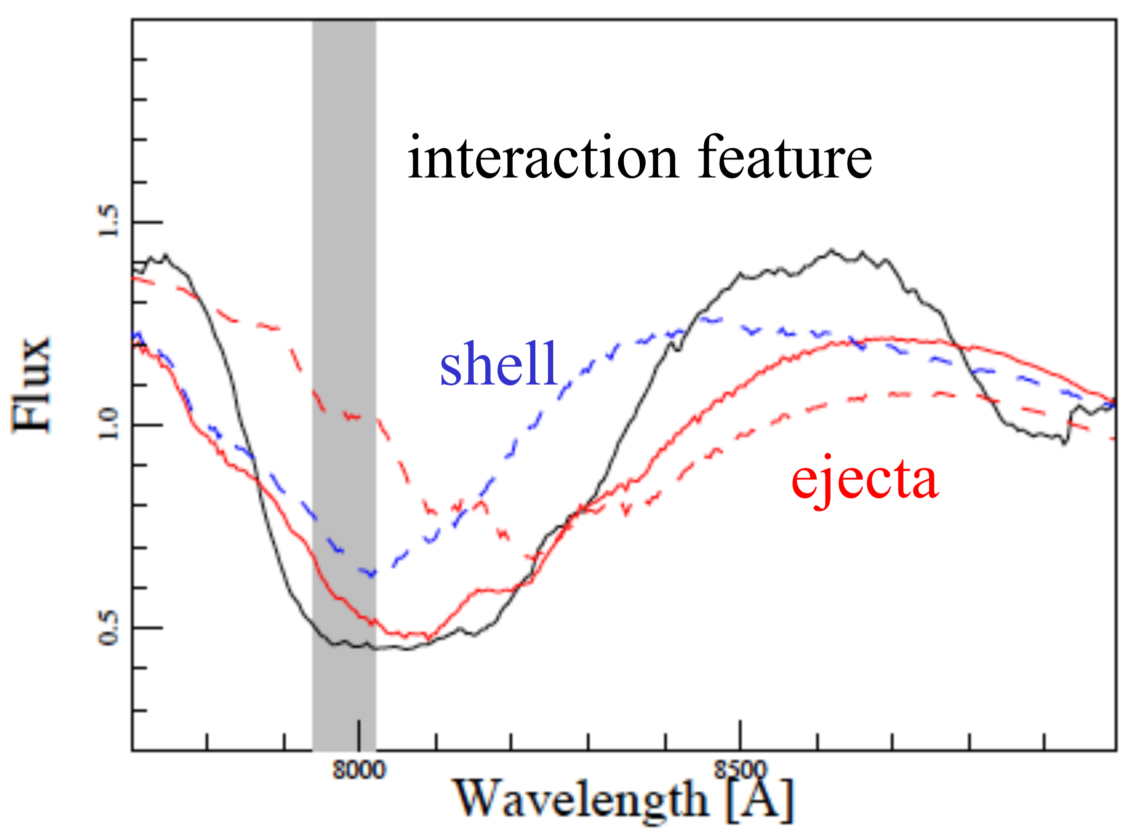
In the earliest models, the photosphere is entirely in the shell.
The ejecta are not seen.

The absorption profile is not Gaussian: caution in fitting PVF/HVF



(a) −16.54 d

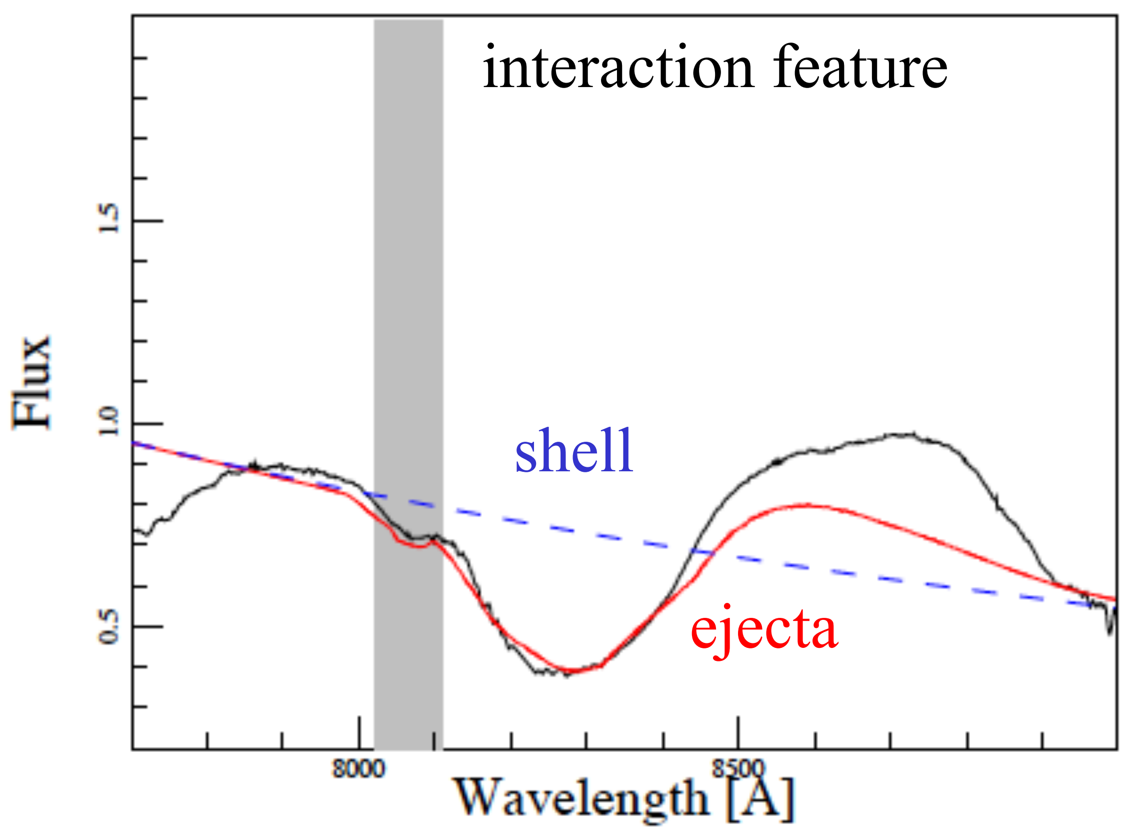
A few days later, the shell turns optically thin in the continuum. Both the shell and ejecta contribute to the CaIR3 feature



(c) −13.21 d

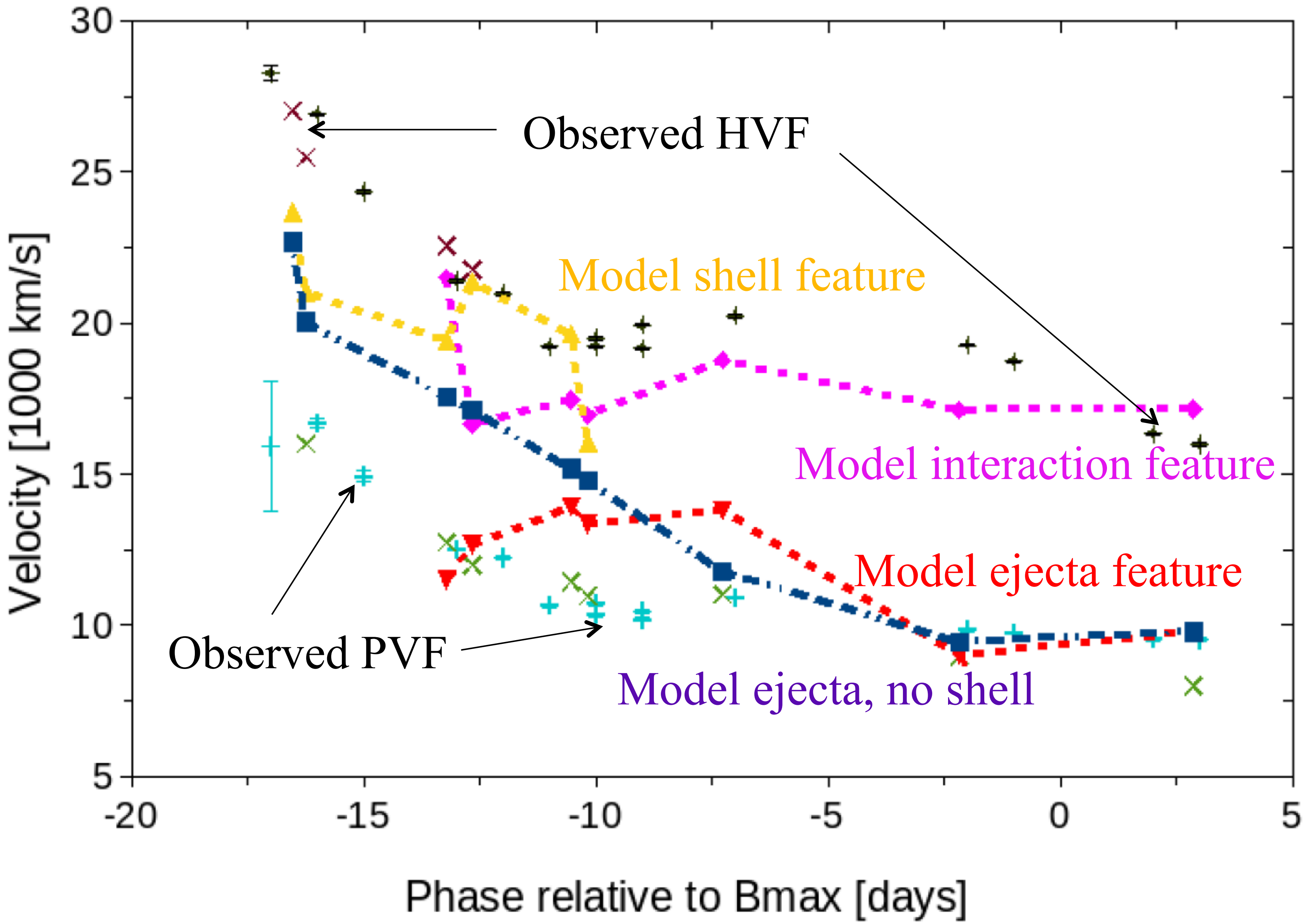
Somewhat before maximum in this particular model, the shell becomes optically thin in the CaIR3 line.

The CaIR3 line forms entirely in the ejecta. The “interaction feature” in the ejecta (not in model with no shell, not obviously associated with reverse shock) appears in the model and in the data, where it is identified as an HVF.



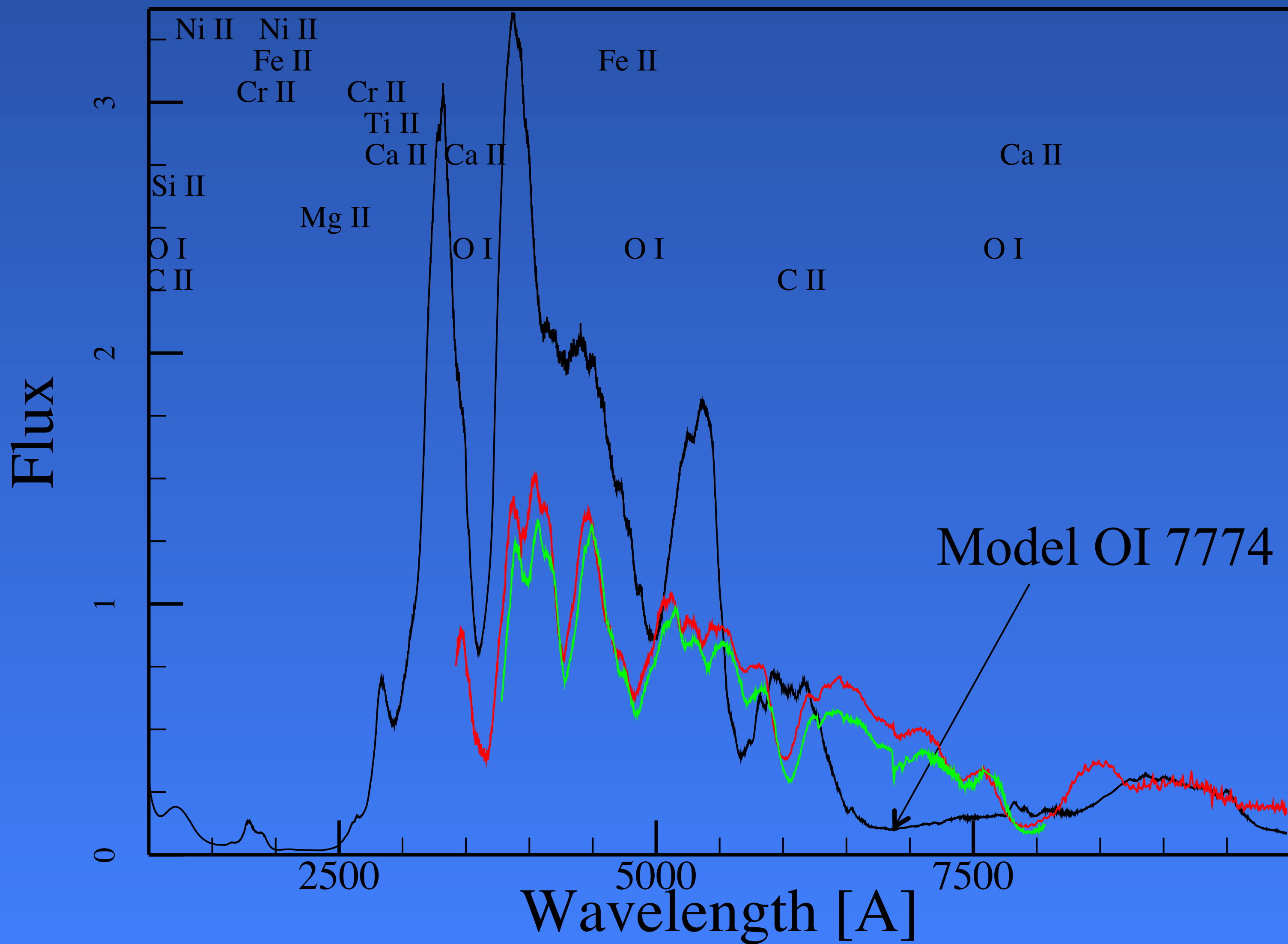
(i) +2.87 d

Model and Observed Velocity Evolution of CaIR3 in SN 2011fe



Preliminary model with other ions; C/O shell with solar Ca, -16 days.

OI 7774 is MUCH too strong: the shell (if it exists), is NOT composed of C/O.



Conclusions

Judiciously chosen nearby circumstellar shell might reproduce the line profiles and observed velocity evolution of CaIR3, PSF and HVF.

Caution must be exercised in identifying HVF using Gaussian fitting to potentially non-Gaussian absorption line profiles.

The "Interaction Feature" in our models that forms in the ejecta fits an observed feature in SN 2011fe (that does not necessarily appear in other SN Ia). The observed feature has been identified as an HVF near maximum, but may not be.

Need to compute more elaborate models, more lines to reduce parameter degeneracies and compare to other SN Ia.

If there is a shell, it is unlikely to be composed of C/O.

Other models for HVF need to address the issue of line evolution and do at least as well as this model.

Question 1

All viable SN Ia models rely on detonations.

We do not fundamentally understand when and how detonations start in Chandra models, sub-Chandra models, helium-shell detonation, DD mergers, violent mergers, gravitationally-confined detonation models.

Is it consistent to assume that a Chandra mass C/O white dwarf does NOT detonate in the center because we think it would violate observations (hence the delayed-detonation models), but assume that other conditions MUST detonate because they would not agree with observations if they did not?

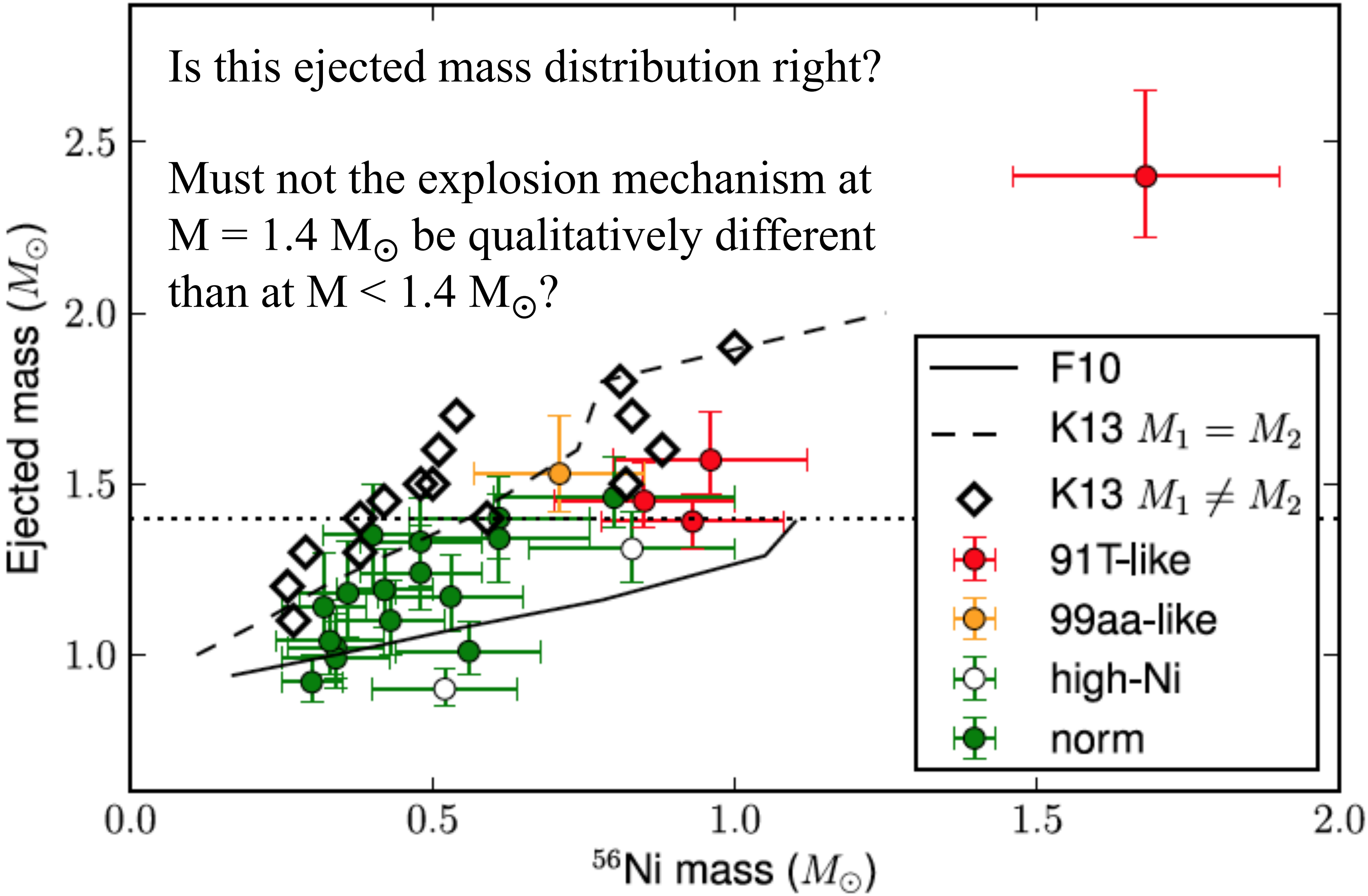
Dynamical burning doth not (necessarily) a detonation make.

Question 2

Scalzo+14

Is this ejected mass distribution right?

Must not the explosion mechanism at M = 1.4 $M_\odot$ be qualitatively different than at M < 1.4 $M_\odot$?

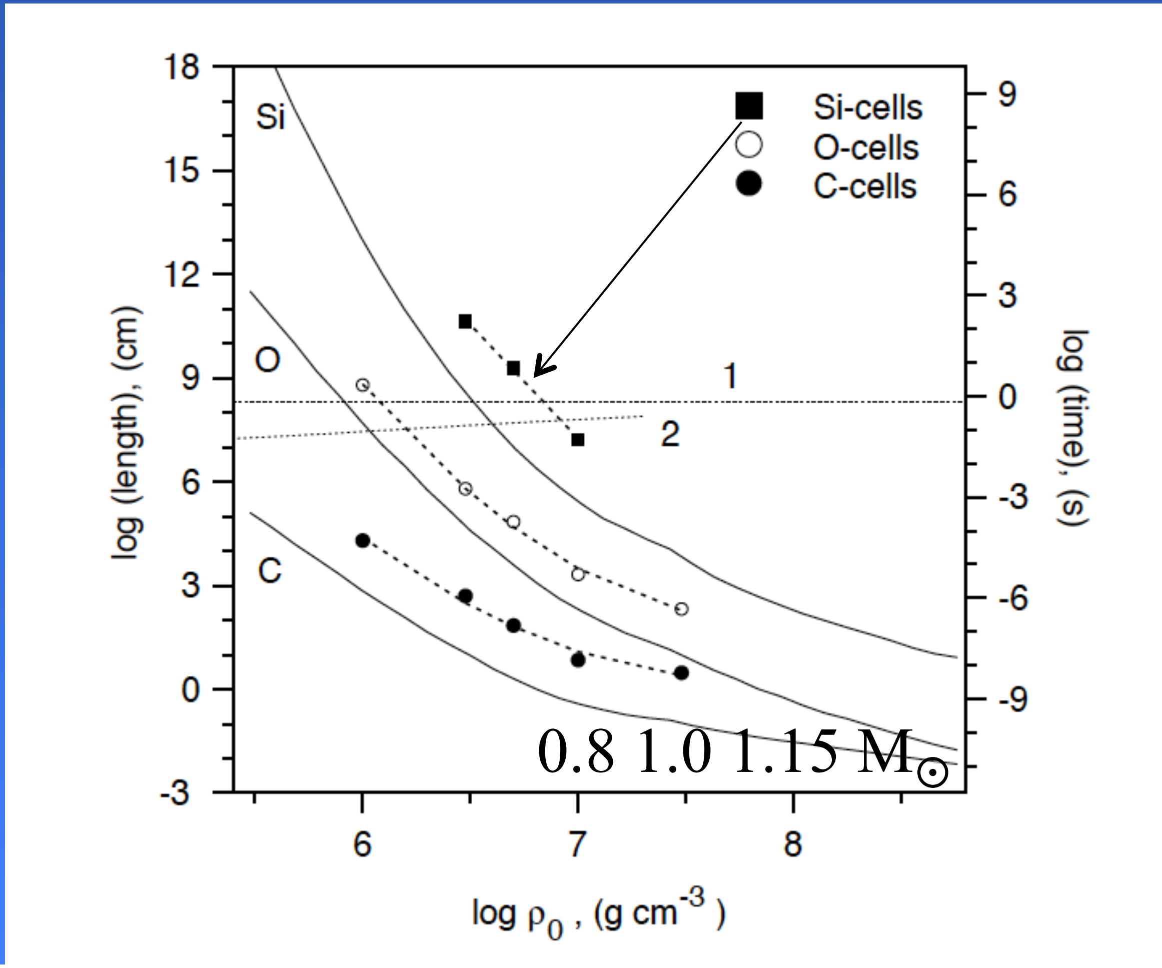


Question 3

Detonations must form a 3D "cell" structure to propagate in a steady state.

Silicon detonation cells get comparable to a white dwarf scale height at a density < few x 10^7 g cm^{-3}: can sub-Chandrasekhar mass models make ^{56}Ni in those circumstances?

Gamezo+99



Synthetic spectra

SYN++: synthetic spectra tool for supernovae

-Modified to allow arbitrary optical depth profile

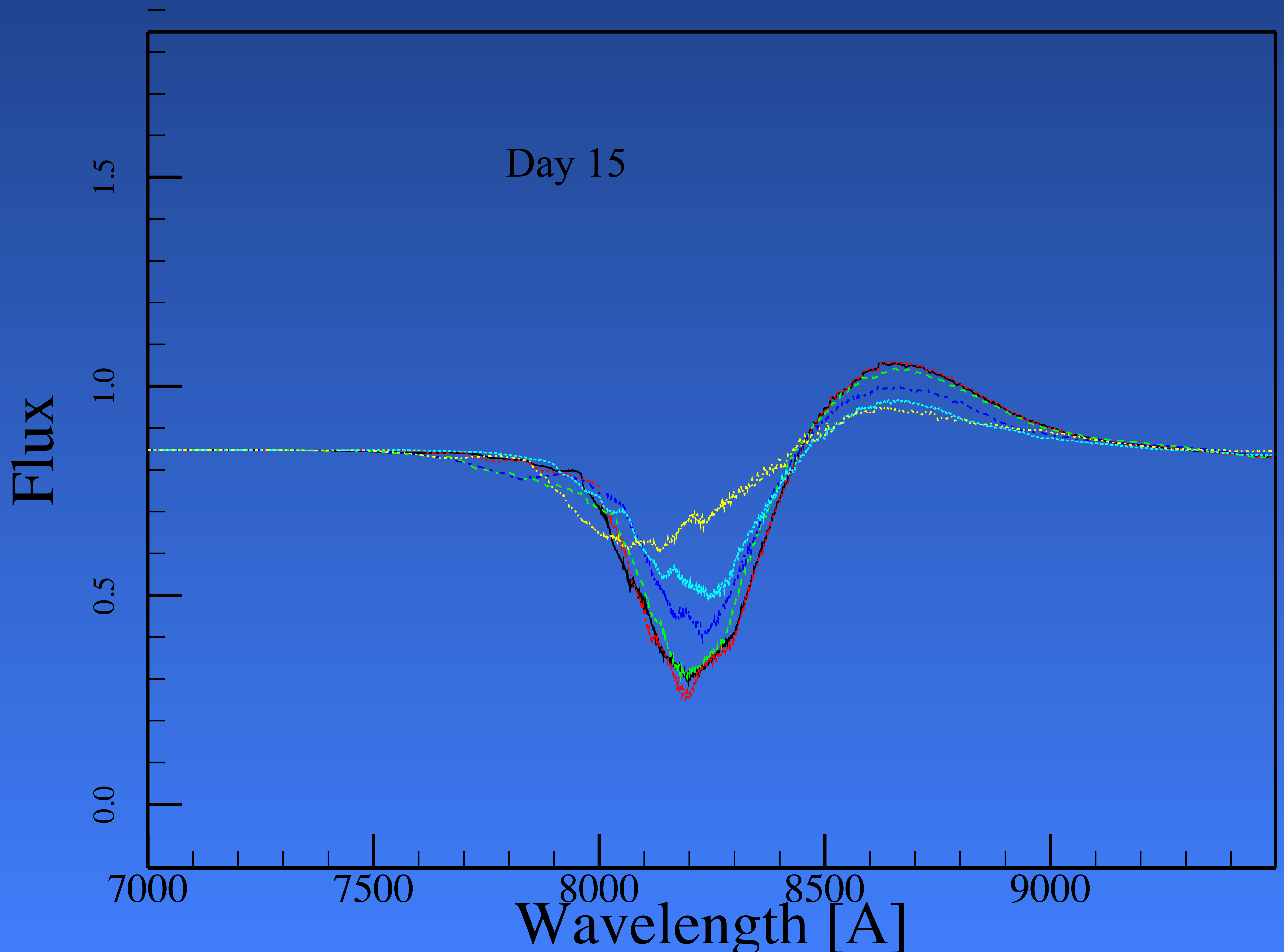
Free parameters

-# of days after explosion
-photospheric velocity – sets minimum velocity for ion
-photospheric temp – continuum temp
-Ejecta ionization * Ca/Si abundance
-HVF ionization * Ca abundance

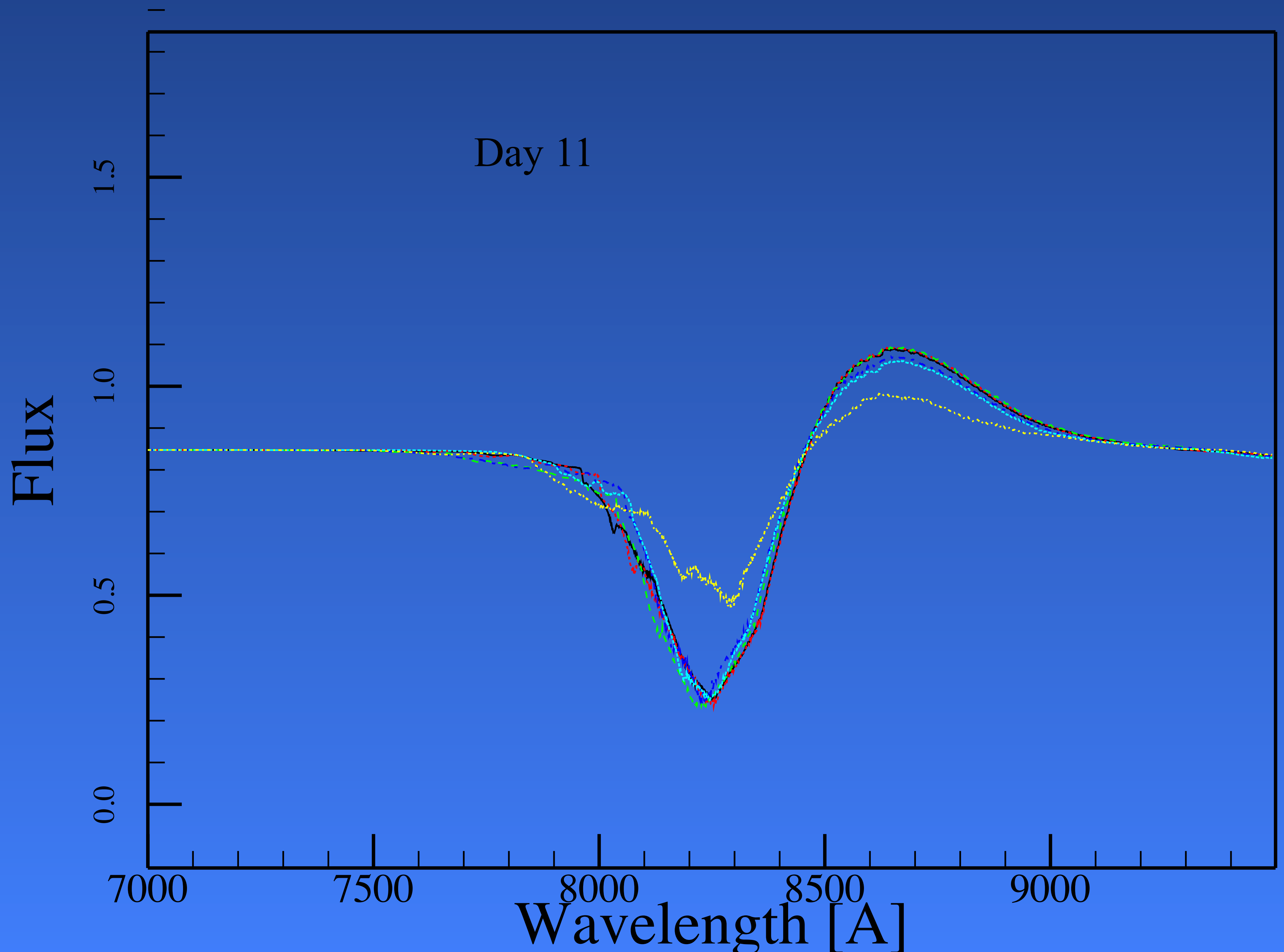
Excitation temperature = 10,000 K

The effects of the excitation temperature, ion mass fraction, composition and time after explosion are degenerate.

A multi-variable simplex fitting routine is used to minimize the variance

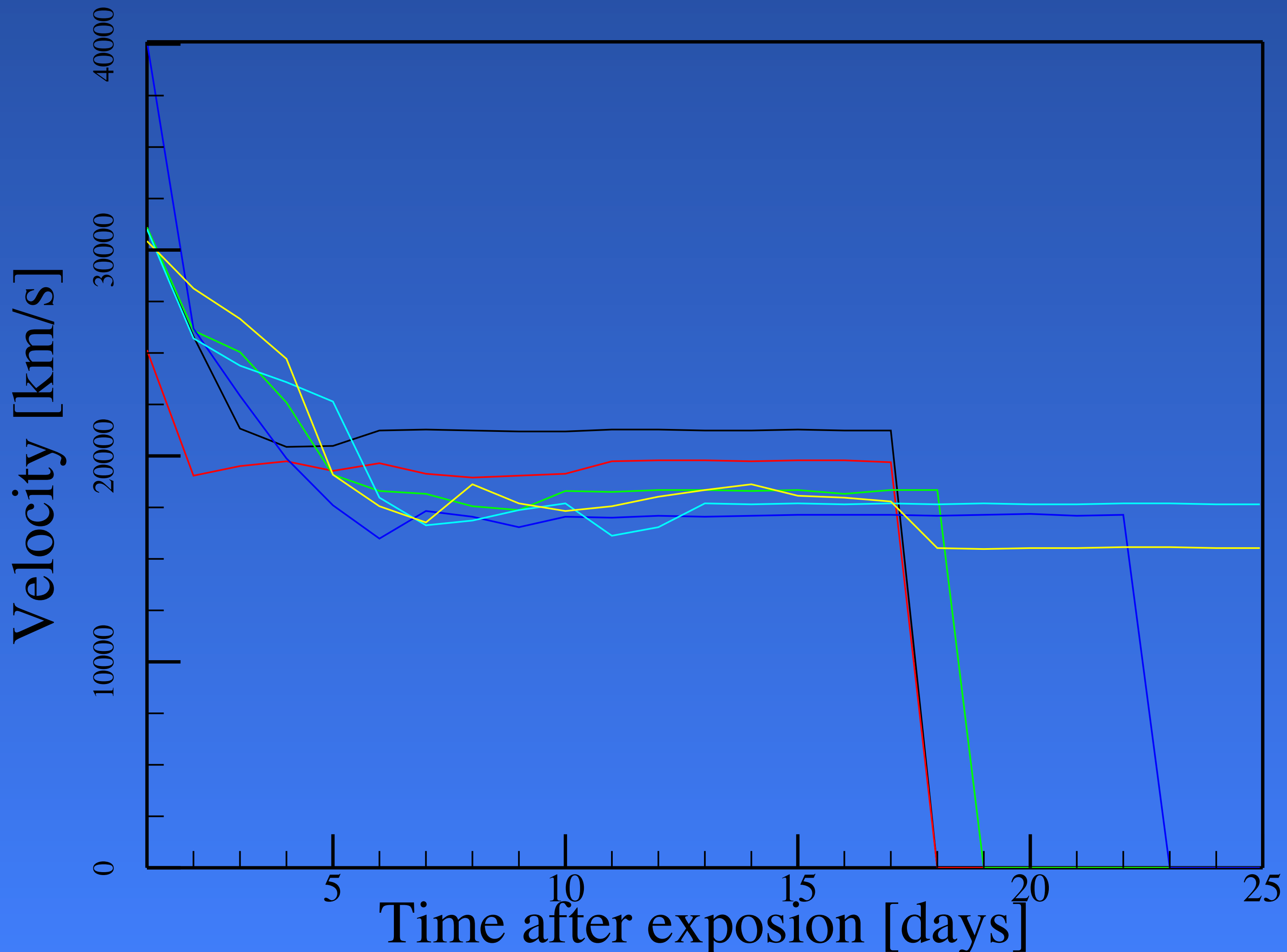


Day 15
Flux
0.0
0.5
1.0
1.5
7000
7500
8000
8500
9000
Wavelength [A]



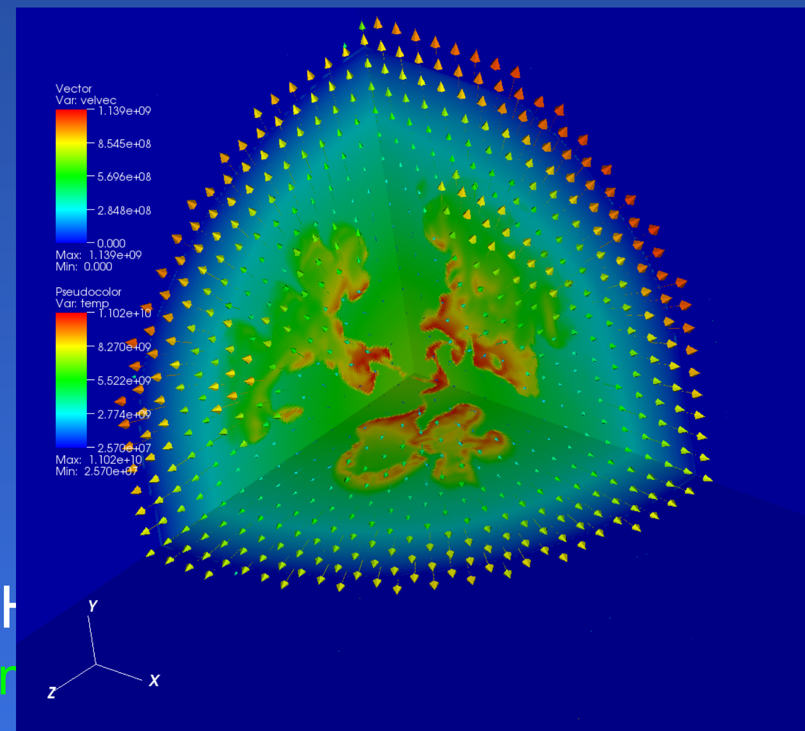
Day 11
Flux
1.5
1.0
0.5
0.0
7000
7500
8000
8500
9000
Wavelength [A]

Velocity evolution of CaIR3 HVF versus shell mass: 0.003 to 0.012 $M_\odot$



Simulation: Hydrodynamics

- FLASH 4.1
- Hydro only, split PPM
- AMR
- EOS: Helmholtz, Ideal (Gamma law)
- Multipole gravity
- Multispecies (H,He,α-elements up to Ni-56)
- 1-D (spherically averaged from model)
- t_{max} = 50s (Constrained by low density limit in H
  - Received extended helm table from Frank Timm

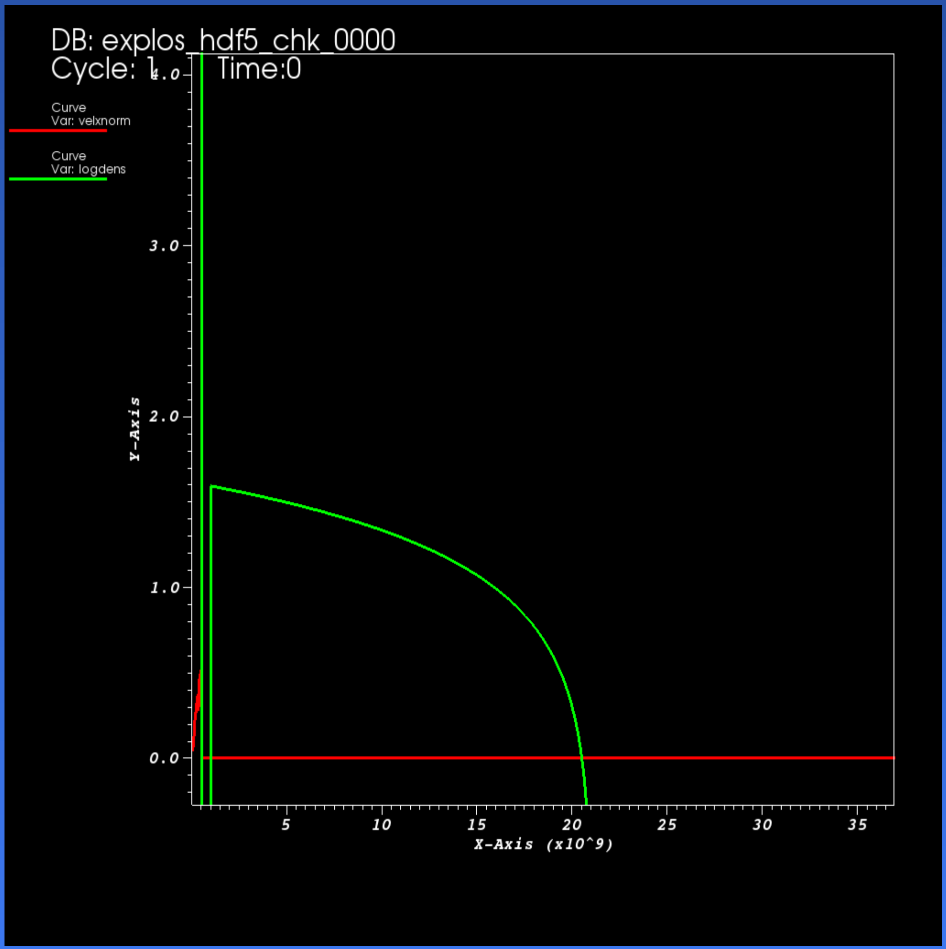


Circumstellar Shell and Medium

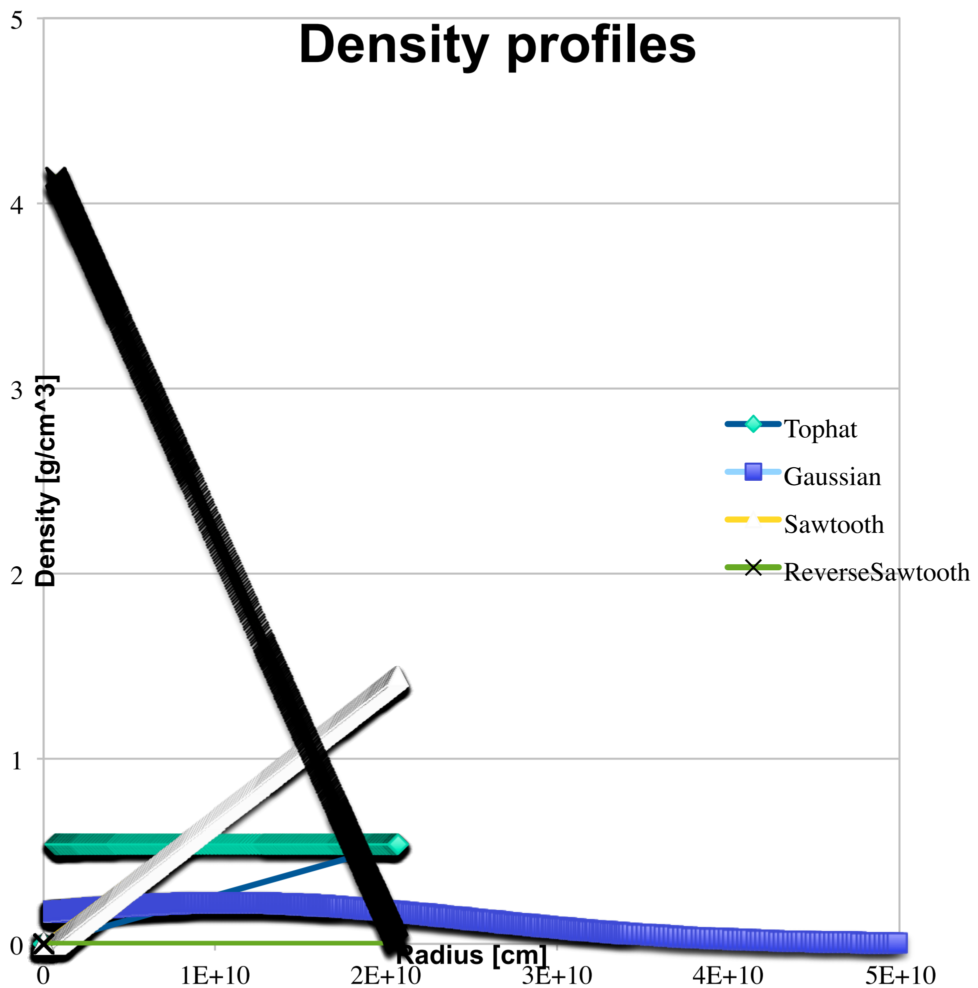
Spherically symmetric shell

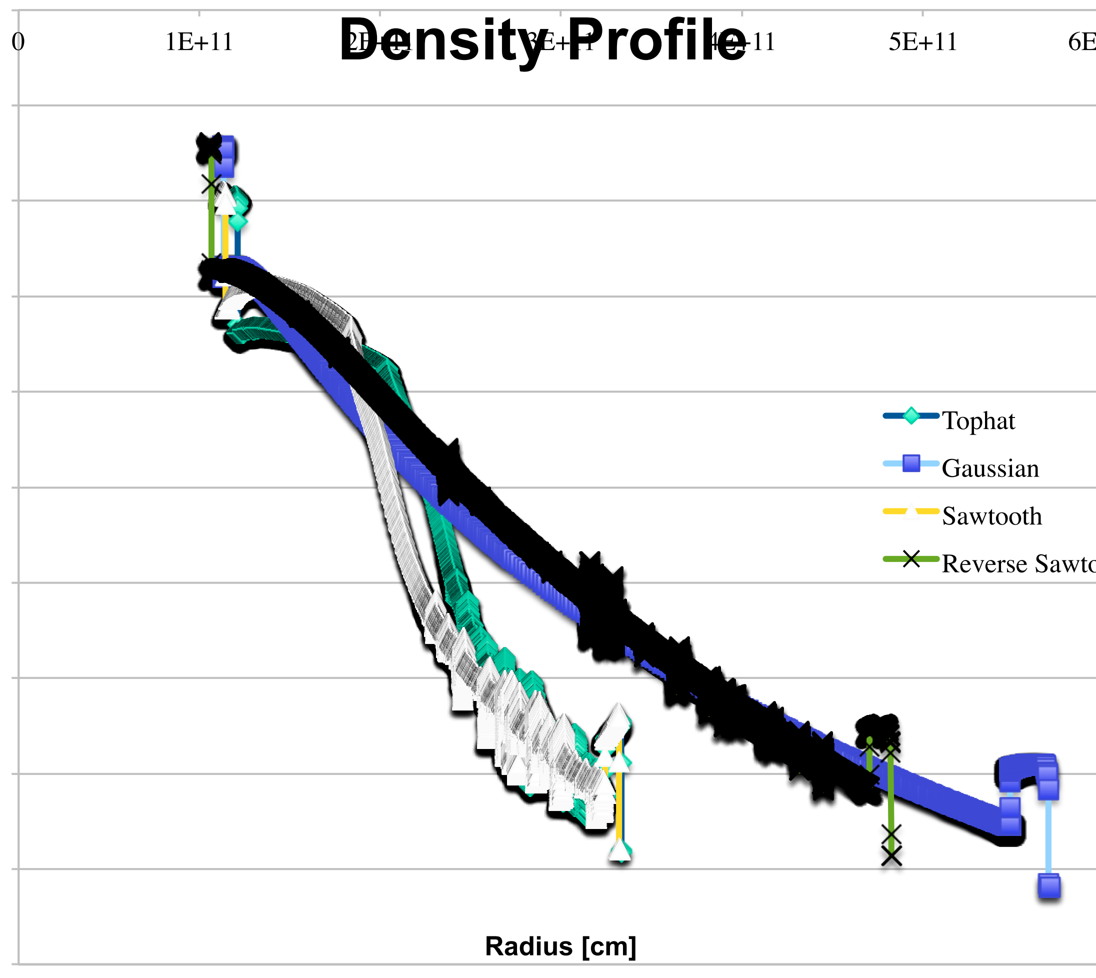
- Free parameters (shell):
  - Total shell mass
  - Density profile
  - Shell initial temperature
  - Distance from progenitor WD
  - Shell width
  - Abundance [solar]

- Free parameters (CSM):
  - Density
  - Temperature
  - Abundance [solar]

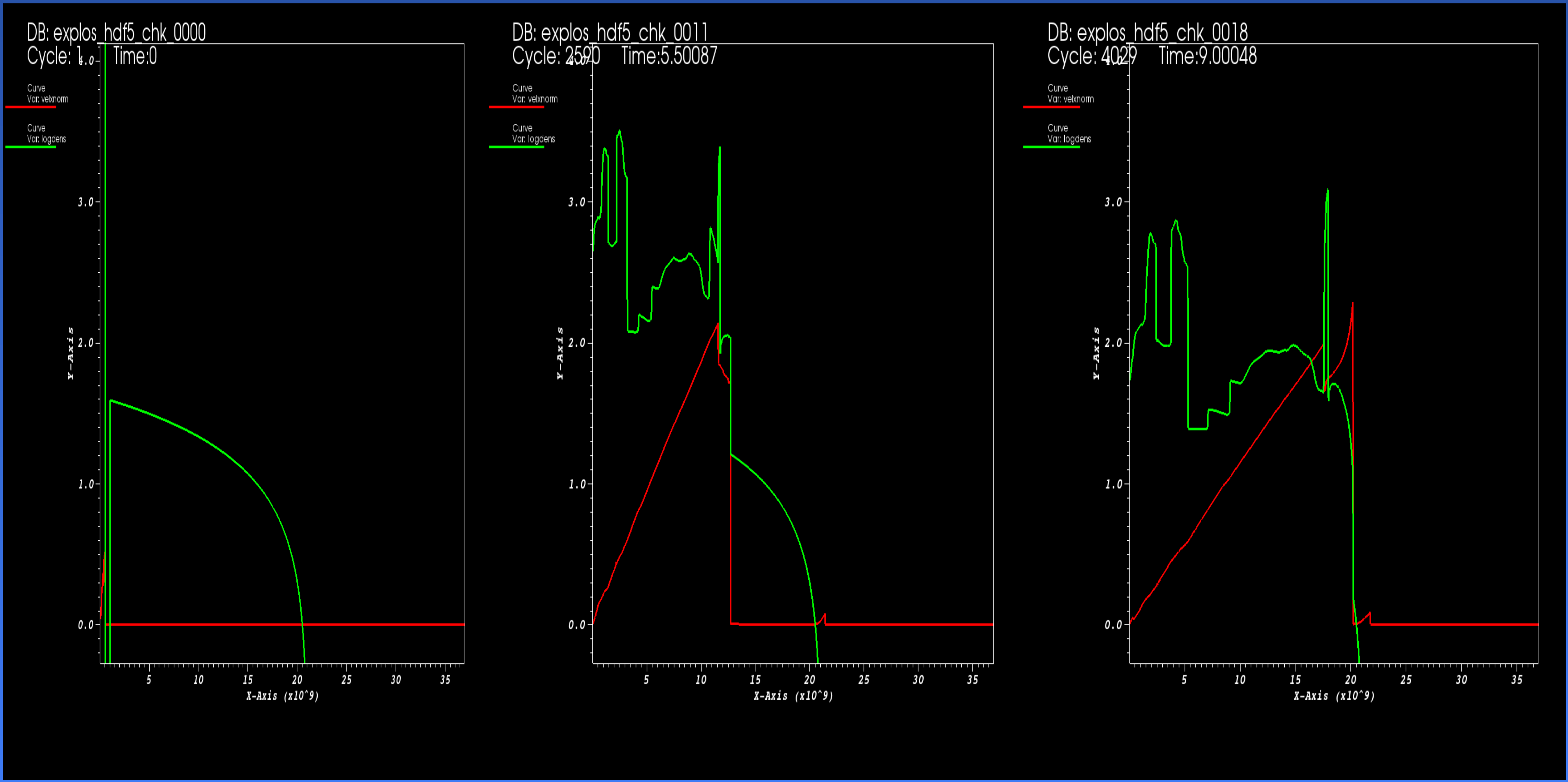


Shell Geometry





SN-shell interaction



SN-shell: breakout