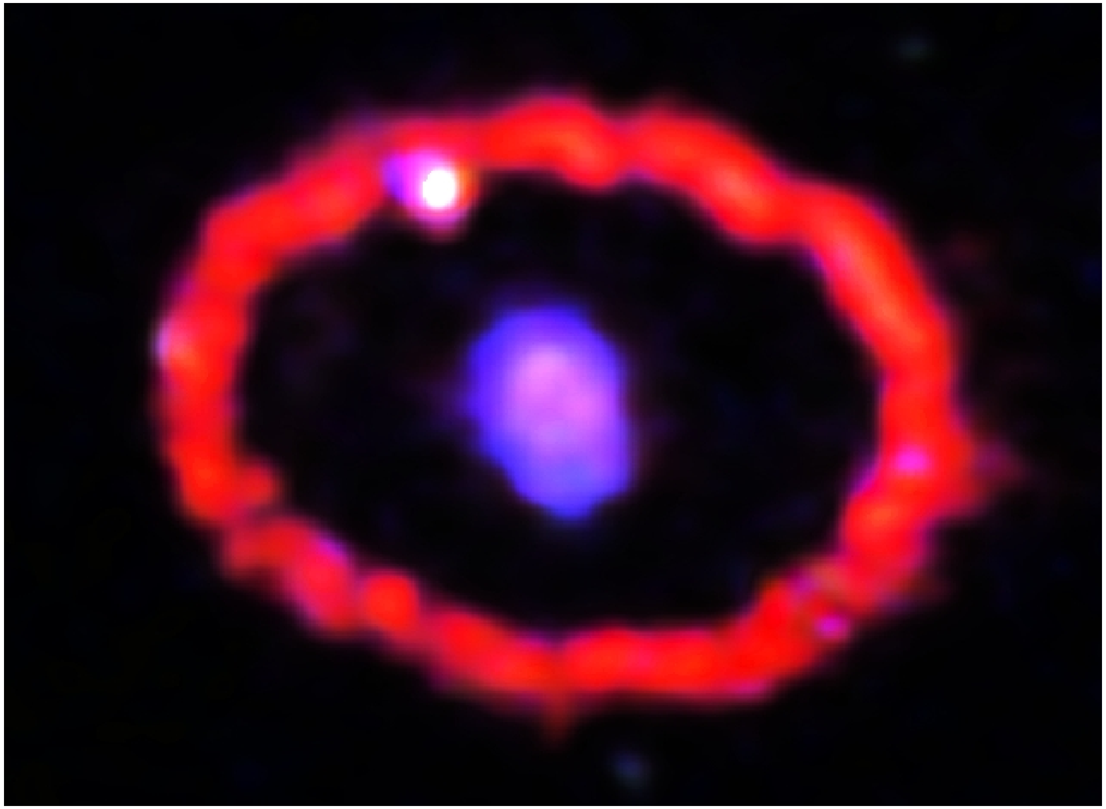
Spectroscopic modeling of the 1987A ejecta

Anders Jerkstrand, Stockholm University

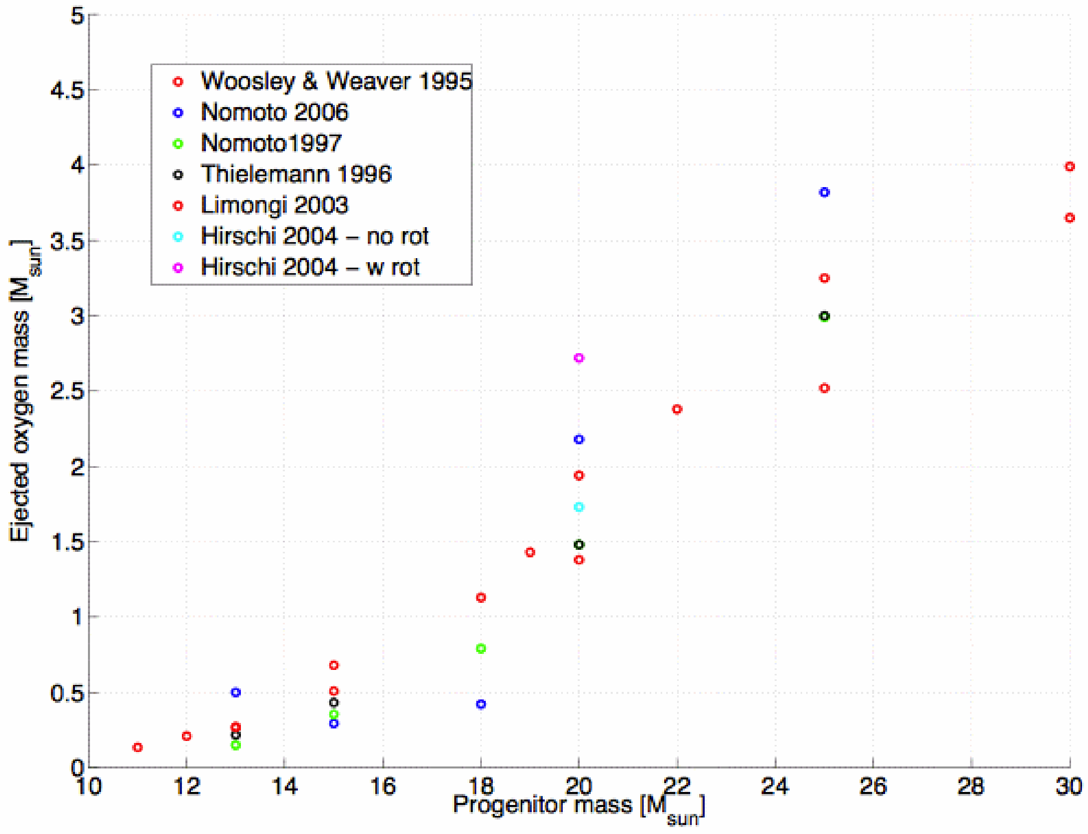


- Kjaer, K., Leibundgut, B., Fransson, C., Jerkstrand, A., Spyromilio, J., A&A 2010, 517, 51

- Jerkstrand, A., Fransson, C., Kozma, C., A&A 2011, 530, 45

Background

- Only in the **nebular phase**, after the photosphere has disappeared, can we see inside the exploded star to diagnose what it contains.

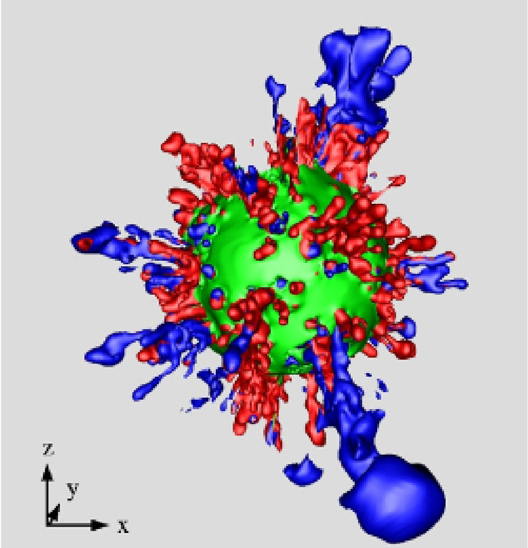


Ejected oxygen mass versus progenitor ZAMS mass for E ~ 1 Bethe.

What have we learned so far from nebular analysis of 1987A?

Xu & McCray 1992, Li & McCray 1992, Meikle 1993, Li & McCray 1993, Chugai 1994

- **The explosion:**
  - Most line profiles are similar --> the explosion produced **strong mixing** in velocity space of the different zones.
  - The number of ^{56}**Ni fragments** is $\sim 10^2$, and the number of **O fragments** is $\sim 10^3$.
  - The **zone filling factors** (inside 2500 km/s) are:
    - ^{56}Ni clumps: >~ 0.3
    - O clumps : ~ 0.1
    - H clumps : ~ 0.5



3D explosion model from Hammer et al. 2010

What have we learned so far from nebular analysis of 1987A?

Li & McCray 1992, Chugai1994, Li & McCray 1995, Kozma & Fransson 1998, deKool & McCray 1998

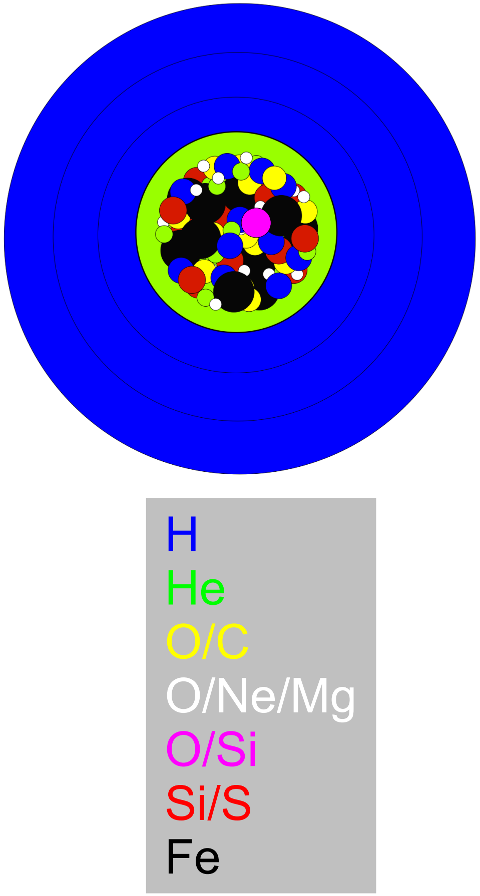
- **The composition** :
  - **He mass : 2 - 7 $M_{\odot}$**
  - **H mass: 4 - 5 $M_{\odot}$**
  - **O mass : 1 - 2 $M_{\odot}$**
  - No clear results for any other masses! But likely **M_{others} : <~ 1 $M_{\odot}$**

    → M_{ejecta} : ~ 11 $M_{\odot}$
  - The O mass corresponds to the production of *non-rotating* stars with **M_{ZAMS} = 18 - 20 $M_{\odot}$**.

Modeling

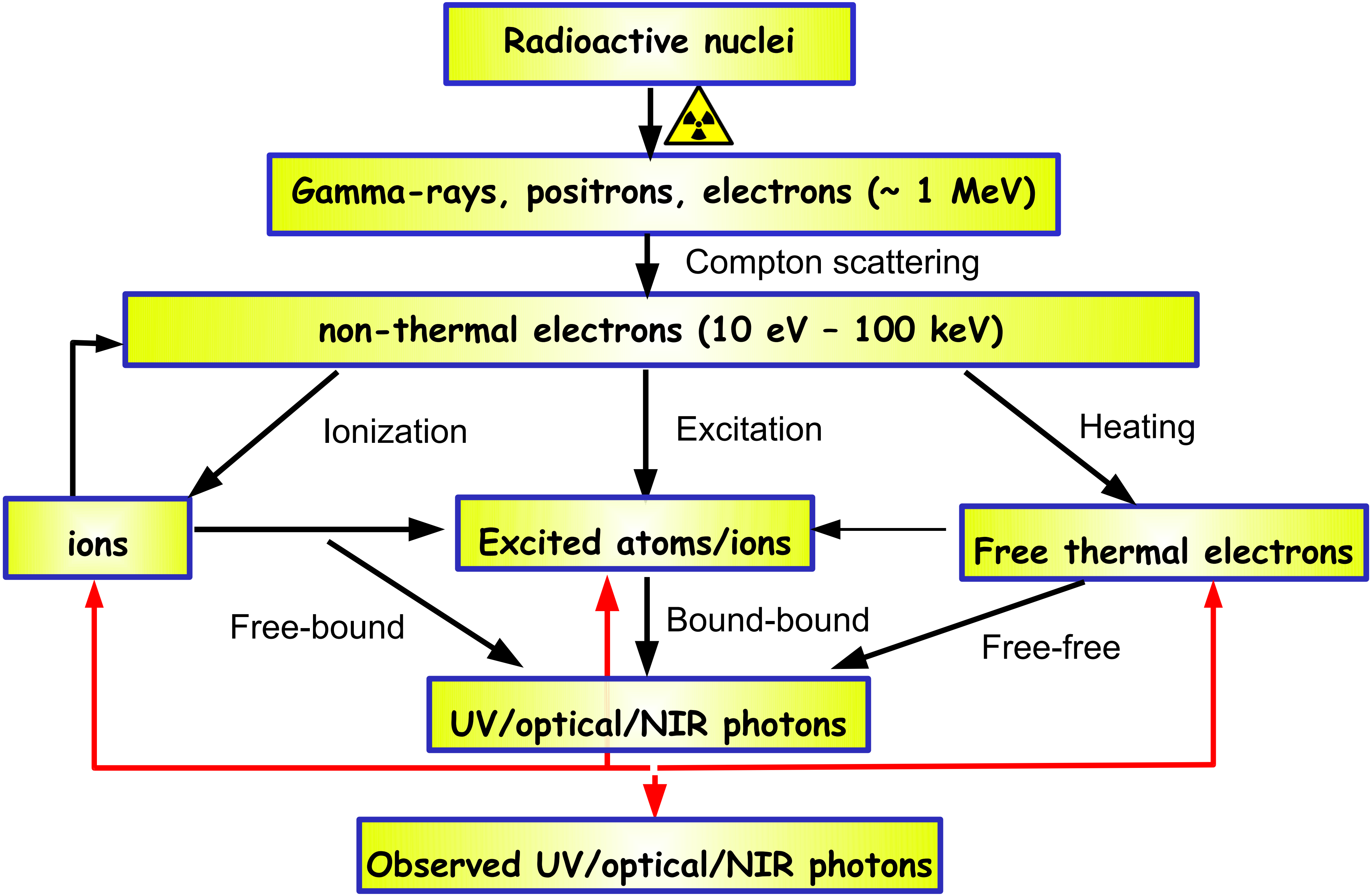
Jerkstrand, Fransson & Kozma 2011

- Our model assumes the SN to be..
  - ..**1D.**
  - ..in **homologous expansion.**
    - *t > few days.*
  - ..in **steady-state.**
    - *t ~ 150-700 days, for IIP's.*
  - ..have complete ***macroscopic* mixing** in the core, but no ***microscopic* mixing**.
- Explosion models from Woosley & Heger 2007.

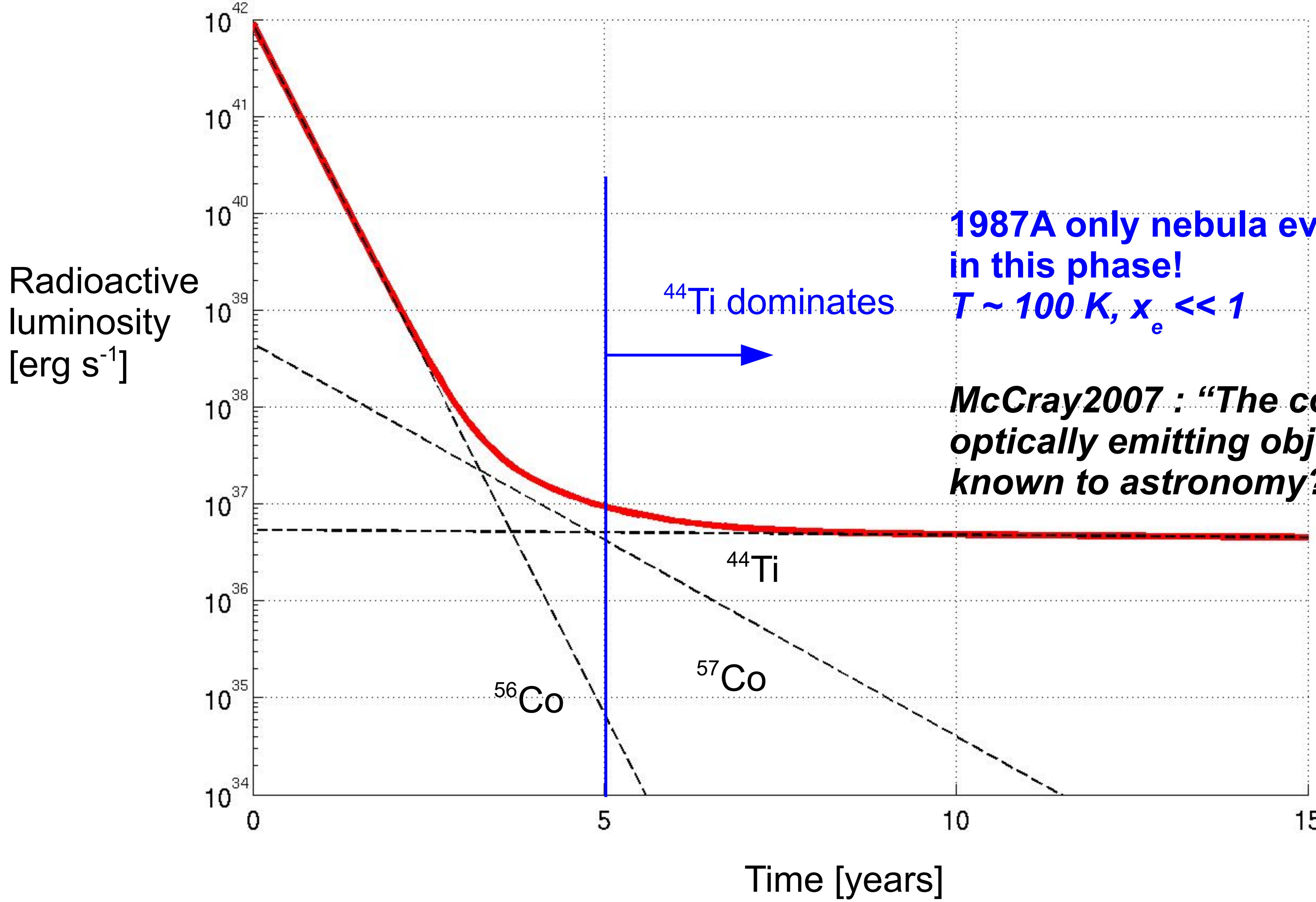


Modeling

Jerkstrand, Fransson & Kozma 2011



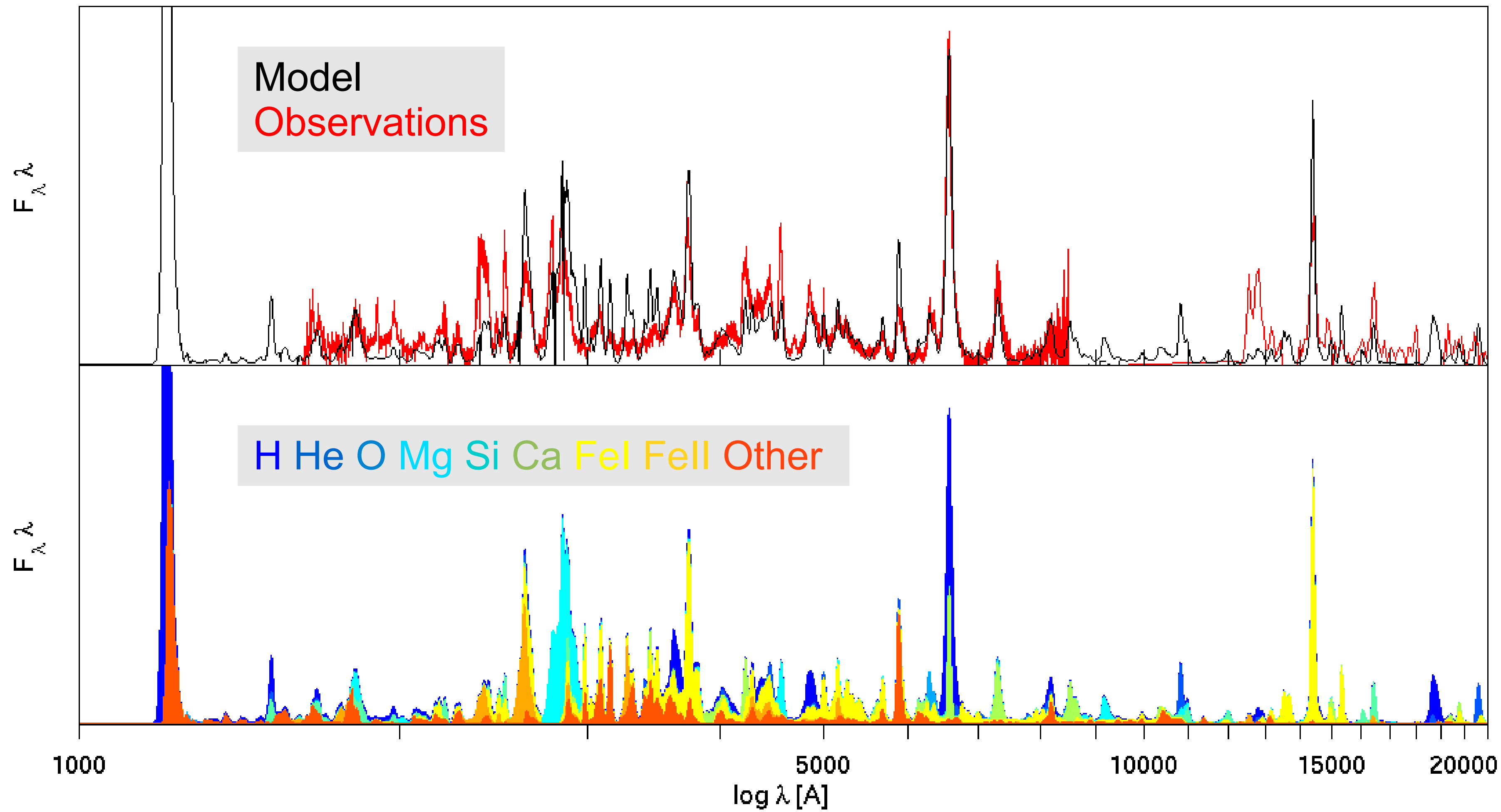
Evolution of powering



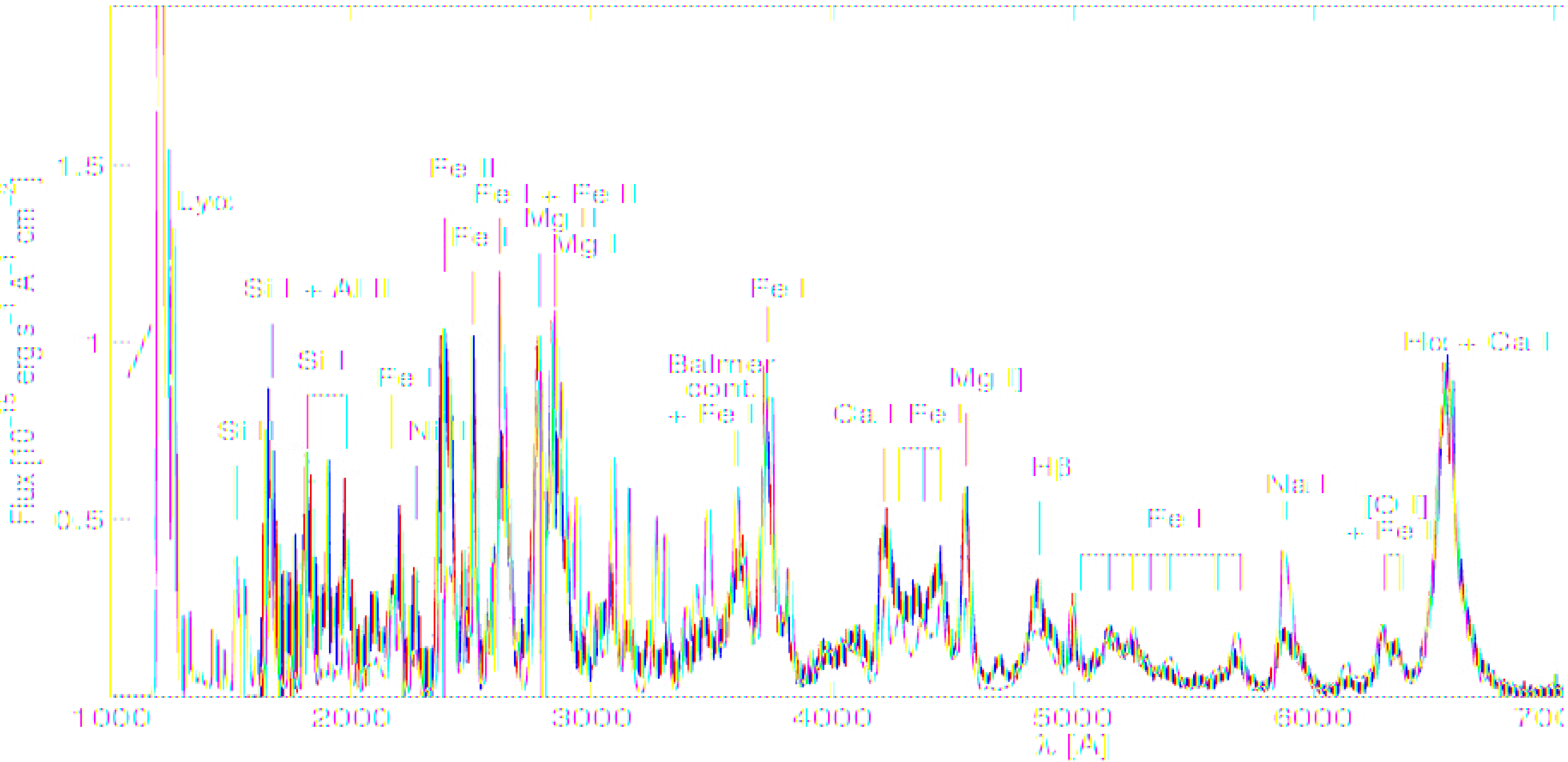
1987A only nebula ever observed in this phase!
$T \sim 100$ K, $x_e << 1$

McCray2007 : "The coldest optically emitting object known to astronomy?"

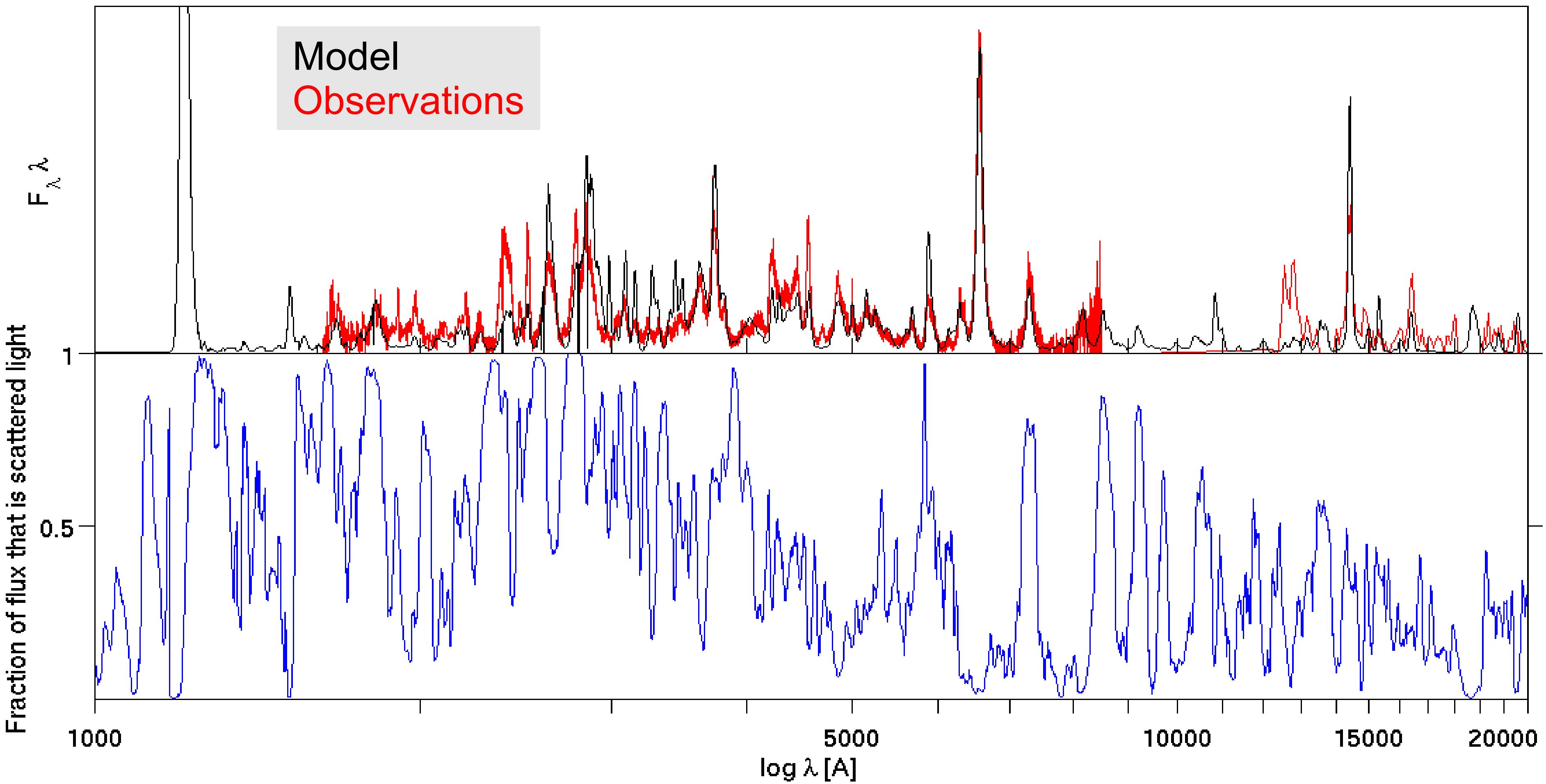
1987A ejecta at 8 years : What are we looking at?



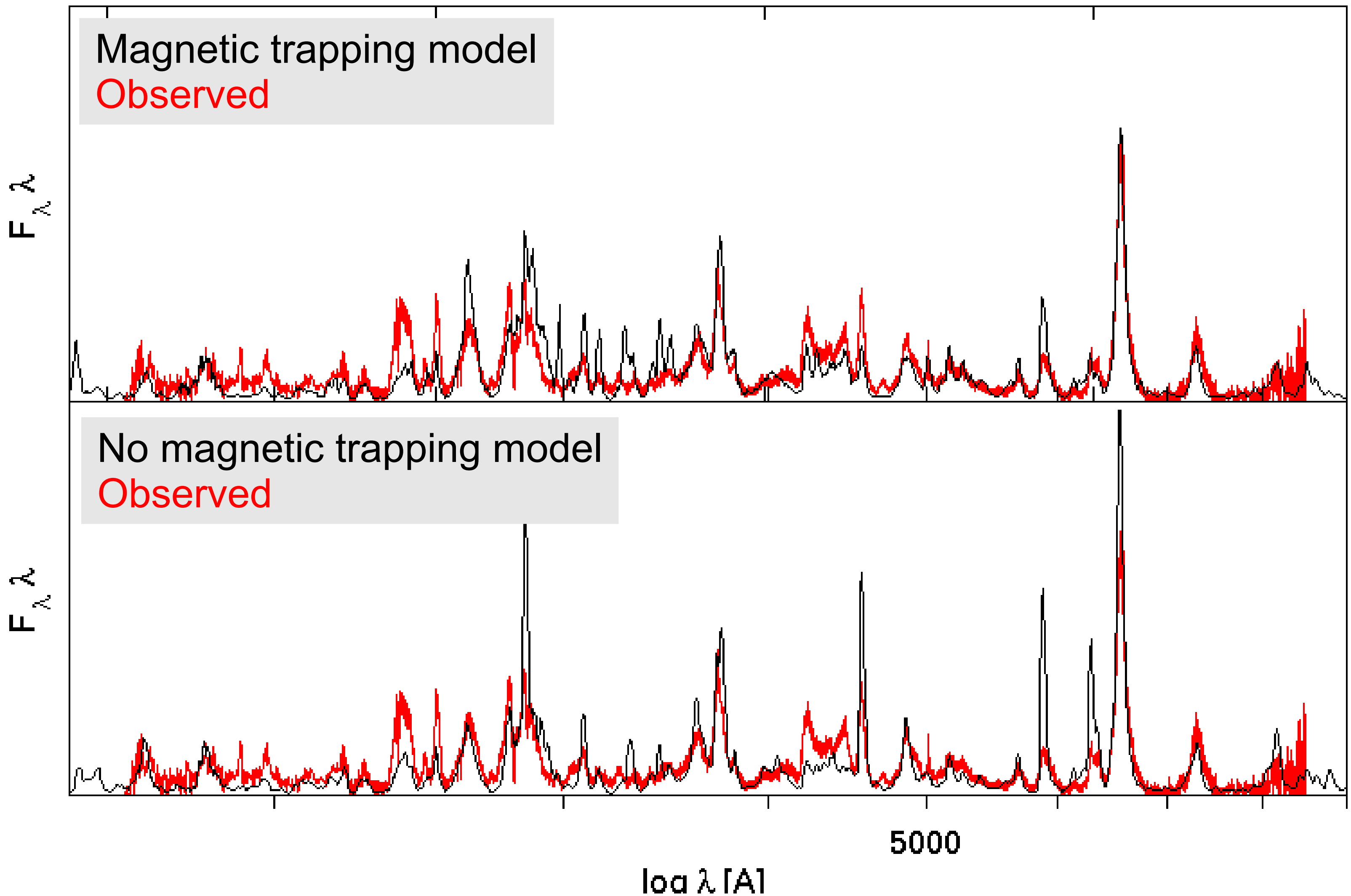
1987A ejecta at 8 years : What are we looking at?



Is nebular nebular? Not really...scattering/fluorescence has strong influence on spectrum!

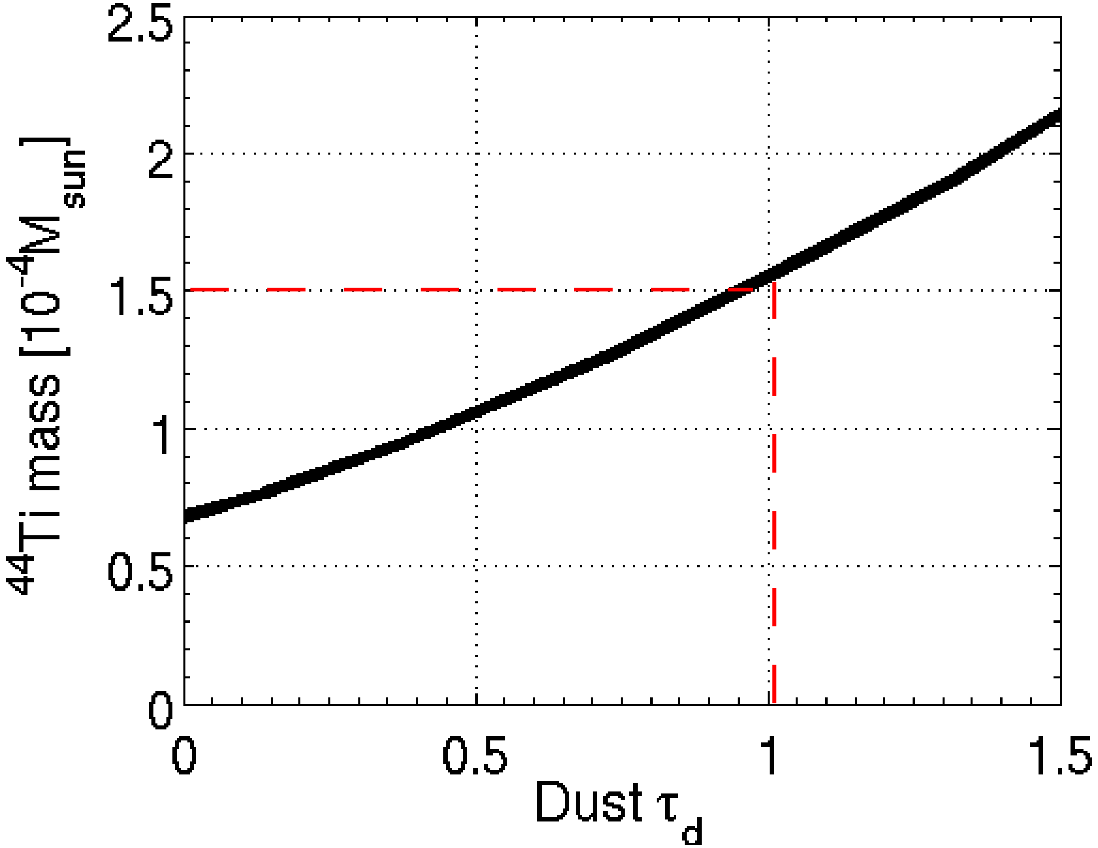


Does there exist a magnetic field to trap the positrons? Yes!



The ^{44}Ti mass

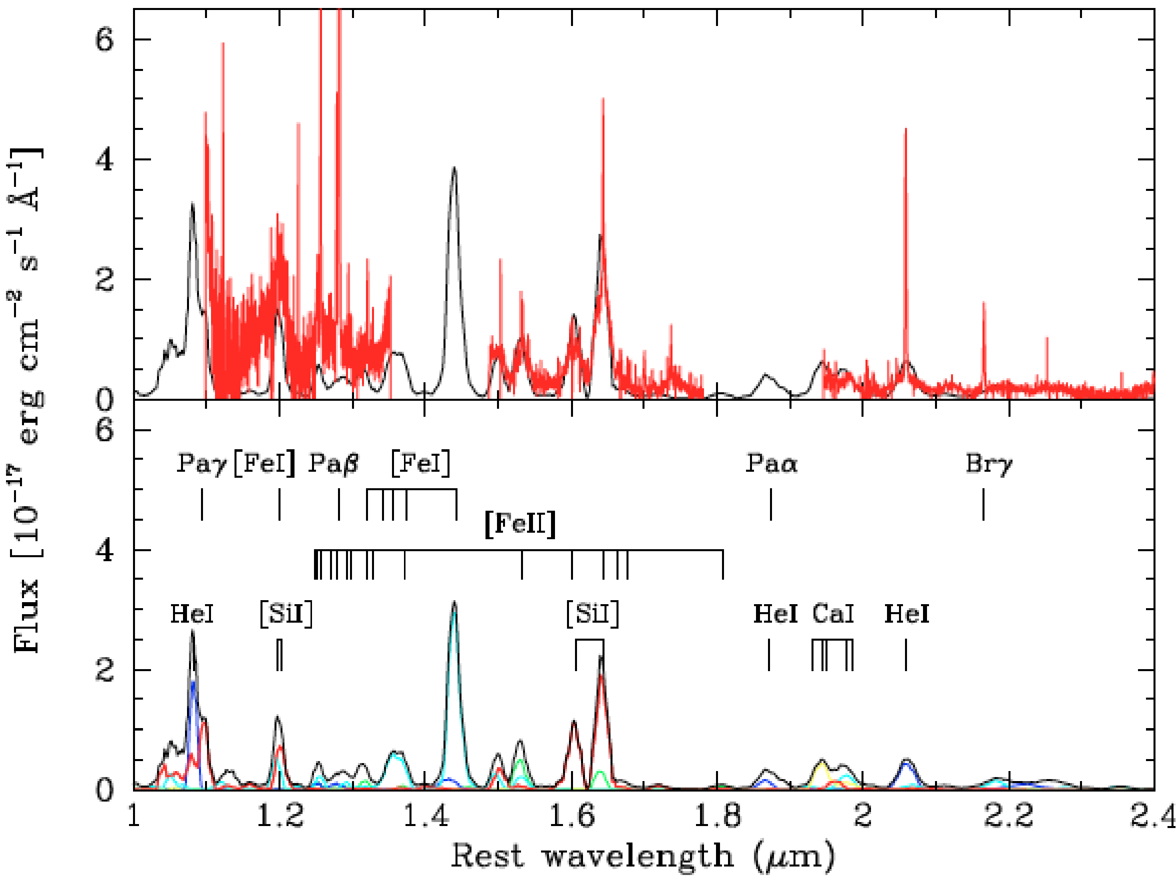
- A ^{44}Ti mass of **$(1.5\pm0.5)\cdot10^{-4}$ M$_{sun}$** is our best fit to reproduce the overall flux level of the spectrum.



1987A ejecta in the NIR at 19 years

Kjaer et al. 2010

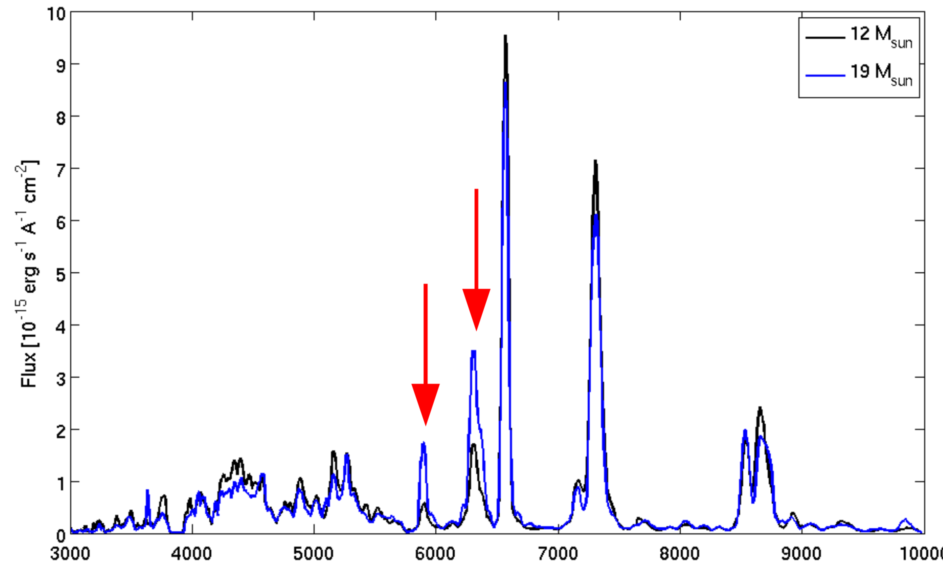
- Local positron deposition model gives good match also here.
- 3D mapping at 1.64 μm follows the distribution of synthesized silicon.
- X-ray illumination seems to have little impact in the NIR.

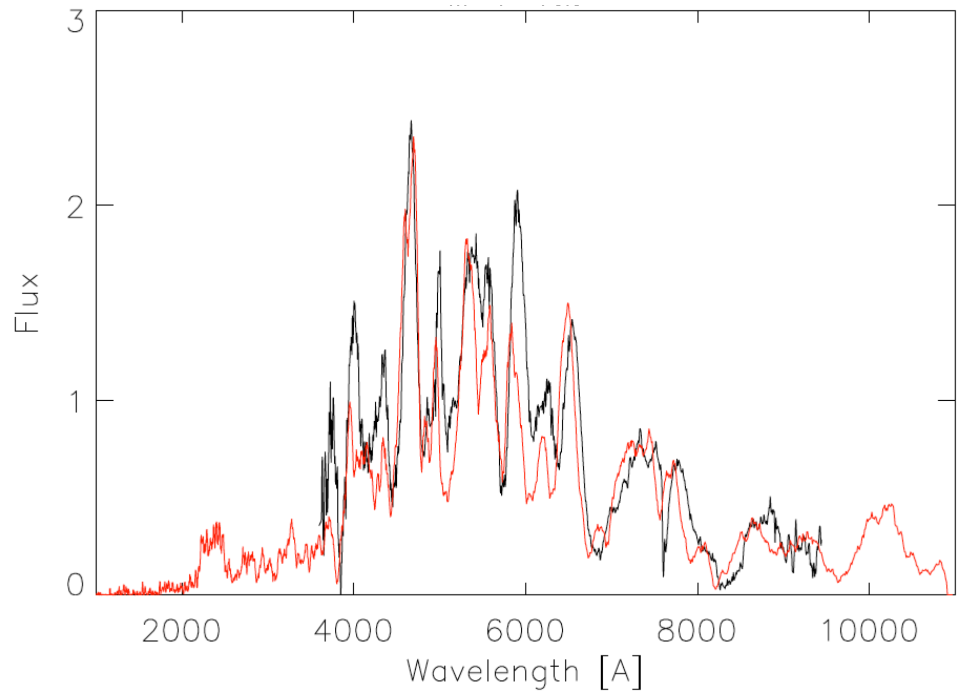


Other modeling going on

Maurer et al. 2011, Jerkstrand et al. 2011, in prep., Maguire et al. 2011, in prep.

- <u>Type IIPs.</u> *Comparison between a **12 M_{sun}** and **19 M_{sun}** model at 400 days.*
- <u>Type Ia's</u>. *Emergent spectrum of **W7 explosion model** compared to **SN 2005cf** at 94 days.*





Dust

- The line profiles still show blue-shifted peaks at 8 years --> dust clumps are still optically thick!
- This fact may be used to put a lower limit on the dust mass.
- $M_{dust} > 4\pi/3\ R_o^{\ 2}\ f^{2/3}\ N^{1/3}\ \kappa_{optical}^{\ \ -1}$. For f = 0.1 and N = 20 (Lucy1989), we get

$$M_{dust} > 3.1\ M_{\odot} / \kappa_{optical}$$

What type of dust can still cause optical extinction at 8 years?

Dust type	$\kappa^{abs}_{optical}$	M_{dust} [$M_\odot$]	
• Al_2O_3	$8 \cdot 10^{-3}$	> 400	Ruled out!
• Mg_2SiO_4	10	> 0.3	Ruled out!
• Fe_3O_4	$2 \cdot 10^{3}$	> $1 \cdot 10^{-3}$	Problematic
• Fe whiskers	$4 \cdot 10^{4}$	> $8 \cdot 10^{-5}$	Problematic
• Graphite	10^{4}	> $3 \cdot 10^{-4}$	OK
• AC	10^{4}-10^{5}	> $3 \cdot 10^{-5}$	OK

Summary

- Analysis of **nebular phase spectra** can reveal what the exploded star is made of, and thereby what type of main-sequence star it was. We have developed detailed computational tools to perform such analysis.
- Application to the late spectrum of the 1987A ejecta suggests
  - About **$1.5 \cdot 10^{-4}$ M_{sun} of ^{44}Ti** was produced in the explosion, which is a challenge for many explosion models.
  - A (non-combed) **magnetic field** is present in ejecta to trap positrons.
  - The most important component in the spectrum is from **neutral iron**.
  - Emission lines are also seen from **magnesium**, **silicon** and **oxygen**, which can constrain dust models.
  - Much of the optical/NIR spectrum in Type II SNe is produced by **scattering / fluorescence** of UV emission, even as the nebula is many years old. These processes are much more efficient in SNe than in static nebulae.
  - At least 10^{-4} M_{sun} of **carbon dust** seems to be present.