Internal conversion electrons and SN light curves

Max Planck Institute for Astrophysics

International School of Nuclear Physics

32nd Course: Particle and Nuclear Astrophysics

September 23, 2010, Erice

Ivo Rolf Seitenzahl

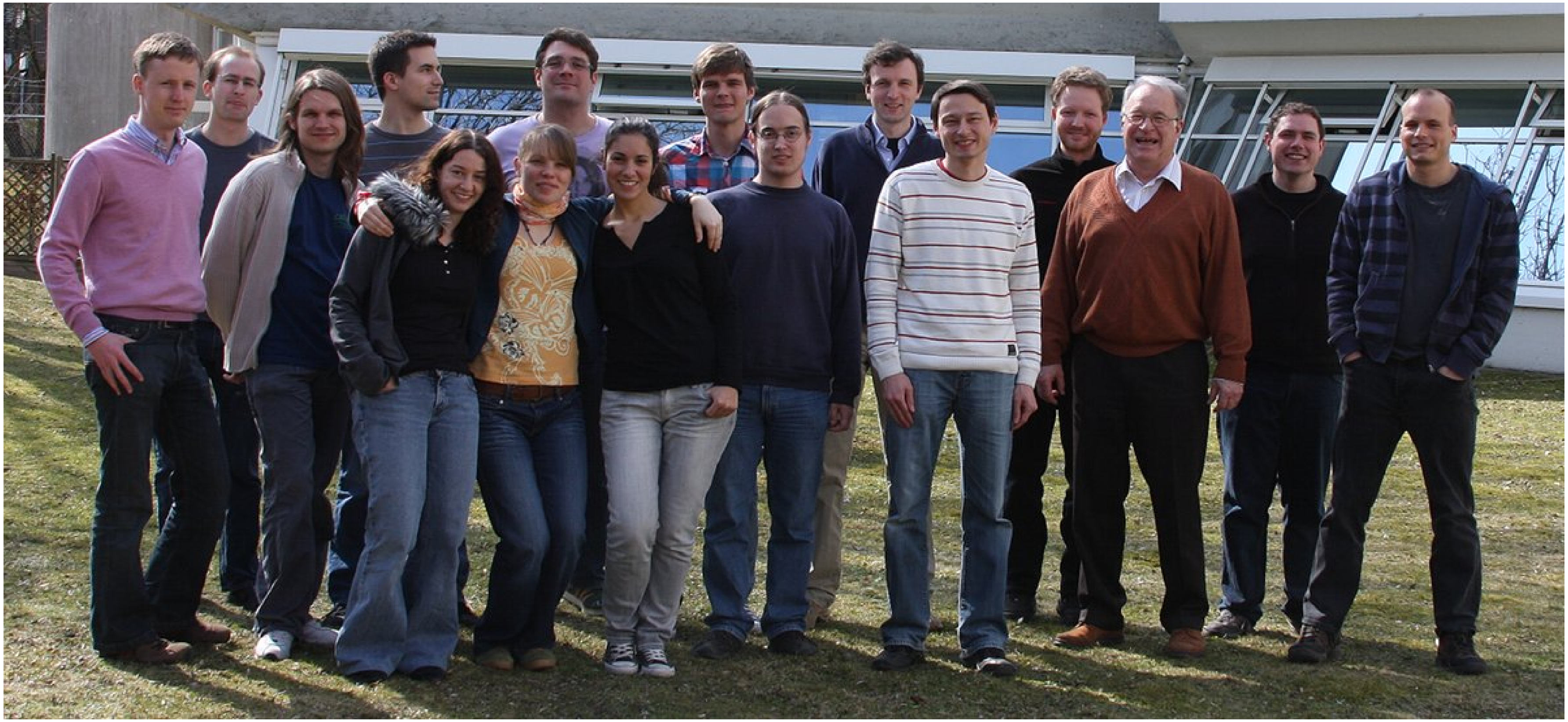
DFG Emmy Noether Research Group

Max-Planck-Institut für Astrophysik, Garching

Emmy Noether Research Group

SN Ia

Collaborators at MPA



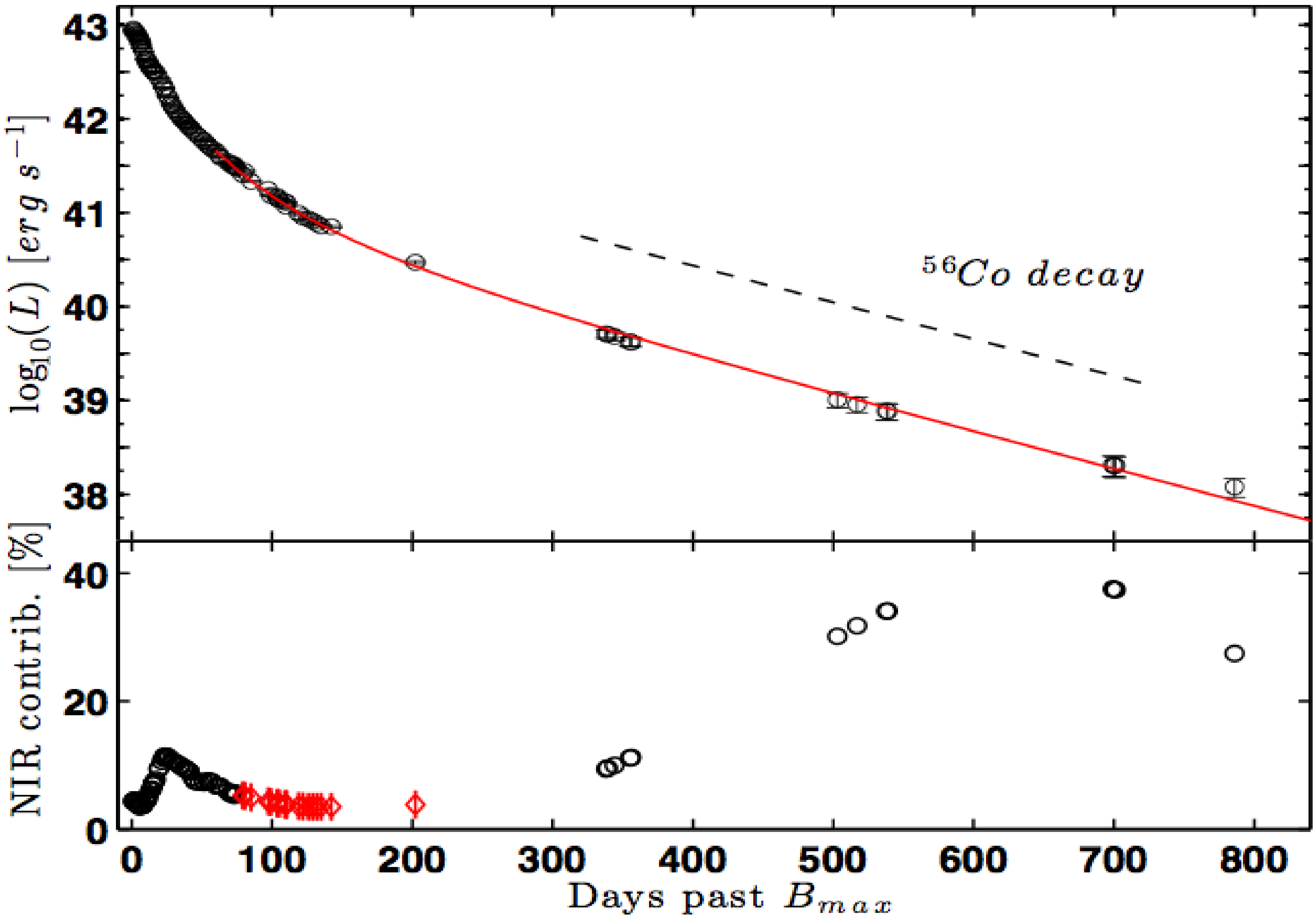
Supernova Light Curve Considerations

- Energy liberated during the explosion (either gravitational or thermonuclear) is converted to kinetic energy
- Ejecta re-heats as γ-rays from radioactive nuclei synthesized in the explosion thermalize via Compton scattering and photoelectric absorption and deposit energy
- Column density and hence opacity to γ-rays decreases as t^{-2}
- SN Ia become increasingly transparent to γ-rays after ~200 days, CC supernovae much later due to large envelope mass
- X-rays produced in the inner regions are still mostly absorbed several years after the explosion
- After maximum light, most electrons have recombined and ionization states higher than Fe III are rare

Bolometric light curves

- ^{56}Ni --> ^{56}Co --> ^{56}Fe releases gamma-rays . This powers initial light curve until gamma-rays escape and other heating channels take over
- At late times, when most gamma-rays escape and positrons dominate the energy input, the bolometric light curve should fall with the ^{56}Co half life.
- Local and complete deposition of positron kinetic energy is usually assumed
  - Escape fraction of positrons at late times remains an open question
- Usually, bolometric light curves are reconstructed from UVOIR (UV Optical InfraRed)
- IR bands are progressively more important at late times as the wavelength of the peak emission shifts into further and further into the red → infrared catastrophe
- Unfortunately, only very few IR observations exist, especially at late times
- Detailed models must treat radiative transfer of photons
  - Abundances and density/velocity profile needed for source terms, opacities, and time evolution

Bolometric light curve for SN 2003hv



Leloudas et al. 2009

Hypernova 1998bw (SN Ic)

954 J. Sollerman et al.: SN 1998bw, the final phases

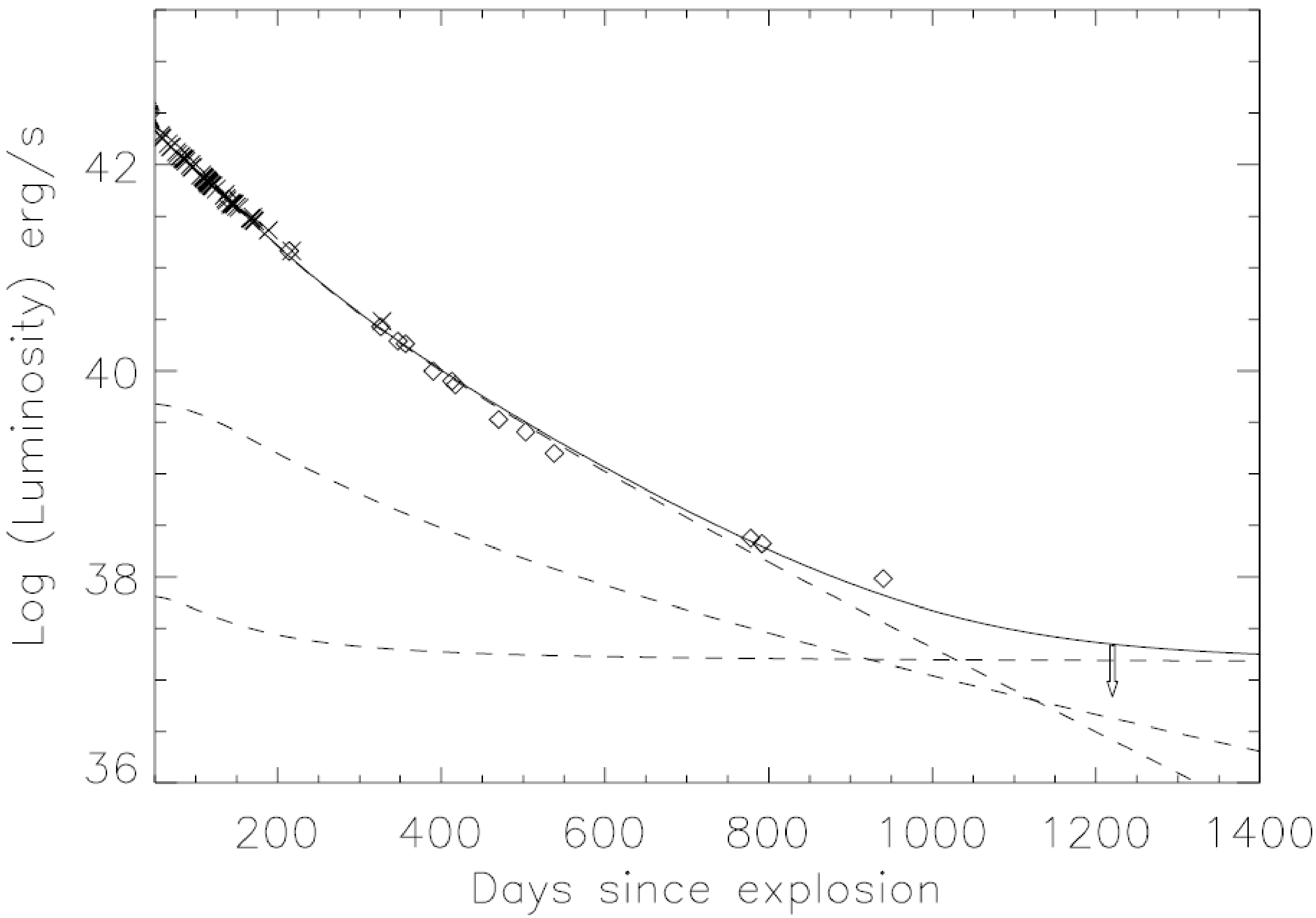


Fig. 5. Using a very simple model for the radioactive powering of SN 1998bw, a reasonable fit to the data can be achieved. The model is described in the text. The powering of ^{56}Co, ^{57}Co, and ^{44}Ti contributes at progressively later phases. The early observations marked by crosses are from P01 and shifted to a distance of 35 Mpc.

Relevant Nuclear Decay Modes

Positron emission:

- Proton in the nucleus decays into a neutron, positron, and electron neutrino. The positron and neutrino are ejected.
- Nuclei that have an open positron channel always also have an admixture of electron capture

Orbital (usually K/L-shell) electron capture by a proton in the nucleus:

- Daughter has a hole in the inner atomic electron structure
  - Hole is generally filled by higher lying electrons transitioning to lower lying levels emitting X-rays in the cascade
  - Energy difference and quantum numbers can also be transferred to an outer electron, which is ejected : Auger electrons

In both cases the transition can be either to an excited state or the ground state:

- If the transition is to an excited state, generally a cascade of gamma-rays is emitted
- Energy difference of nuclear states and quantum numbers can also be transferred to an (inner) atomic electron, which is ejected : Internal conversion electrons

Relevant nuclear decay chains

$$^{56}\mathrm{Ni} \xrightarrow{t_{1/2}=\,6.08d} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}=\,77.2d} {}^{56}\mathrm{Fe}$$

$$^{57}\mathrm{Ni} \xrightarrow{t_{1/2}=\,35.60h} {}^{57}\mathrm{Co} \xrightarrow{t_{1/2}=\,271.79d} {}^{57}\mathrm{Fe}$$

$$^{55}\mathrm{Co} \xrightarrow{t_{1/2}=\,17.53h} {}^{55}\mathrm{Fe} \xrightarrow{t_{1/2}=\,999.67d} {}^{55}\mathrm{Mn}$$

$$^{44}\mathrm{Ti} \xrightarrow{t_{1/2}=\,58.9y} {}^{44}\mathrm{Sc} \xrightarrow{t_{1/2}=\,3.97h} {}^{44}\mathrm{Ca}$$

- ^{56}Ni is produced most abundantly by far → most important decay chain
- ^{57}Ni has lower average gamma-ray energy → higher opacity
- ^{55}Co decay chain generally ignored since it's 100% electron capture to the ground-state
- ^{44}Ti decay chain important due to its long half life and the energetic ^{44}Sc positron
- For late supernova light curves, other decay chains are generally thought to be insignificant (cf. last two slides)

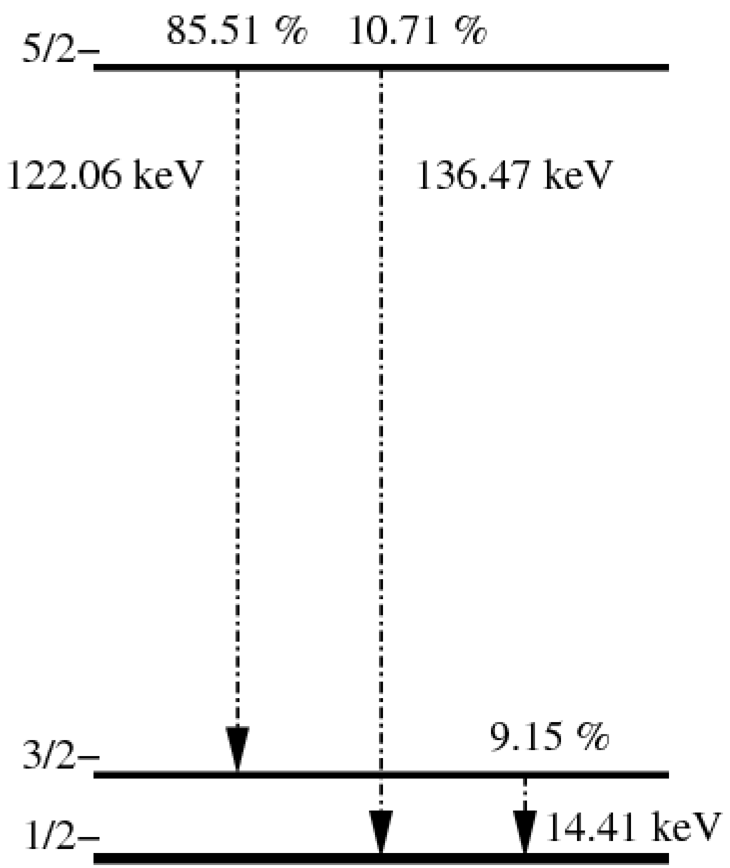
- Energy deposition considered is $\varepsilon(t) = N(t)\,\lambda\,Q(t)$
- N(t) solution to Bateman equations, $\lambda=\ln(2)/t_{1/2}$ and Q(t) is energy deposited per decay

Internal conversion for ^{57}Co

- Internal conversion electrons are significant due to a fortuitously low lying 3/2- state in the daughter ^{57}Fe
- Combined with Auger electrons about 18 keV/Bq/s of kinetic energy, which can compete with the positron of ^{56}Co decay due to the longer half life of ^{57}Co

Table 1. Radioactive decay energies (keV decay^{-1}).

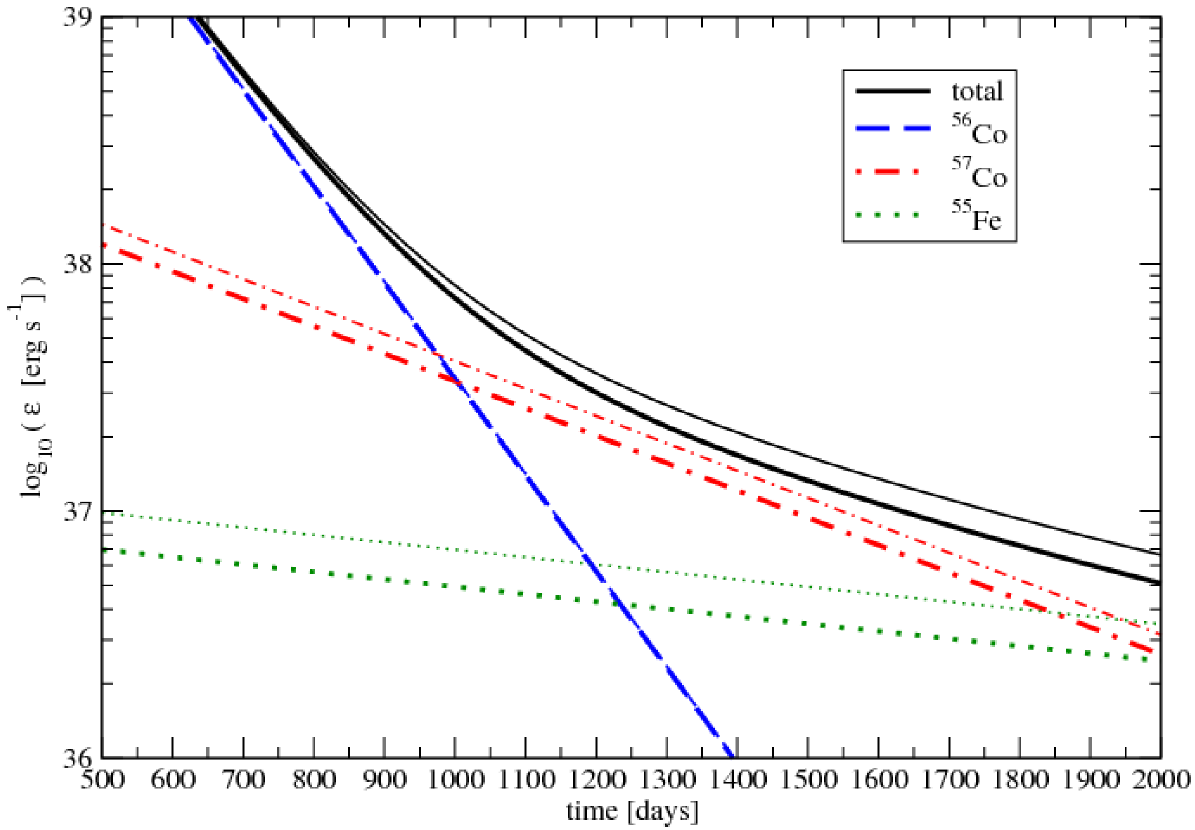
Nucleus	Auger e^-	IC e^-	e^+	X-ray
^{57}Co	7.594	10.22	0.000	3.598
^{56}Co	3.355	0.374	115.7	1.588
^{55}Fe	3.973	0.000	0.000	1.635
^{44}Ti	3.519	7.064	0.000	0.768
^{44}Sc	0.163	0.074	595.8	0.030



Level scheme and intensities for Fe57

Leptonic and X-ray heating for SNe Ia

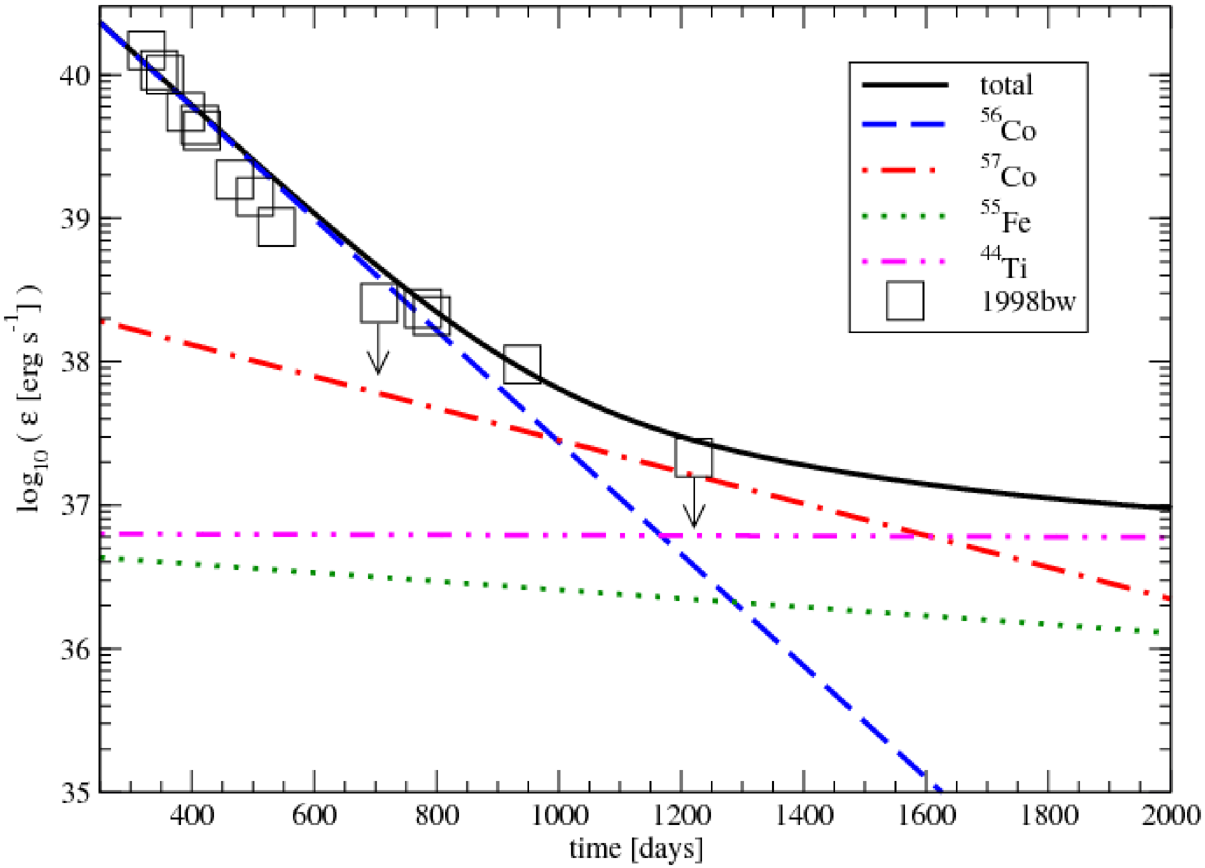
- Consider radioactive energy generation due to positrons and electrons for W7 model yields (thick lines; thin lines also include X-rays)
- Slow down of light curve expected due to ^{57}Co after ~800 days
- Further slow down of light curve expected due to ^{55}Fe after ~1500 days



Seitenzahl, Taubenberger & Sim, MNRAS 2009

Hypernova 1998bw

- Observed slow down of light curve at 940 days naturally explained by nucleosynthesis predictions of Nakamura et al. 2001
- No unrealistic extremely super solar enhancements of ^{57}Ni required
- Detailed modeling of light curve can give production ratio ^{57}Ni/^{56}Ni



Seitenzahl, Taubenberger & Sim, MNRAS 2009

Summary slide

- Internal conversion & Auger electrons produced in the decay of ^{57}Co can be dominant heat source for some phases of stripped CC and thermonuclear SNe
- Auger electrons produced in the ground-state to ground-state electron capture decay of ^{55}Fe predicted to cause a further slow down of the light curves of SNe Ia after ~1500 days (no observations exist that late)
- Indication that signature of ^{57}Co e^- has already been observed in 1998bw and 2003hv
- Nearby supernova in the Local Group required for reliable determinations of ^{57}Ni, ^{44}Ti (and possibly even ^{55}Fe) masses.