Focusing on supernova γ-rays

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Focusing Telescopes in Nuclear Astrophysics - Bonifacio

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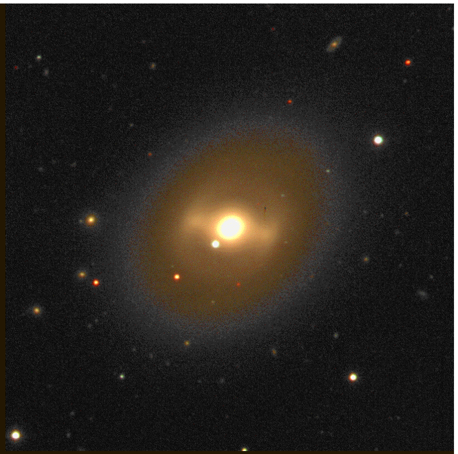
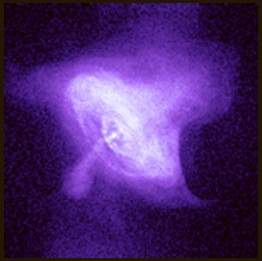
Supernovae: brief intro



Two different engines, coincidentally similar in appearance:

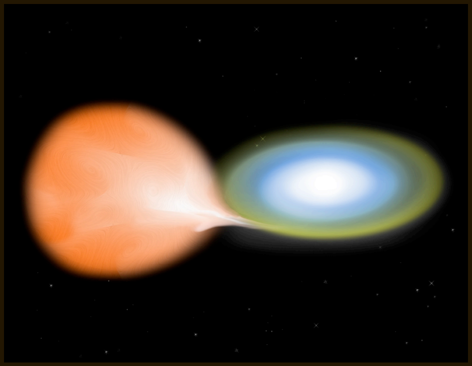
Core-collapse of massive star

Si --> Fe is last exothermic fusion



Spectra: *Type II, Ib, Ic, …*

Thermonuclear explosion of white dwarf (in binary star system)

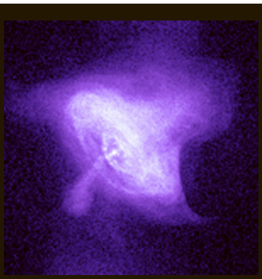


P_{deg} support; fusion reactions speed up, no expansion --> runaway

Spectra: *Type Ia*

Supernovae: energetics

	Core-collapse of massive star	Thermonuclear explosion of white dwarf (in binary star system)
source	Gravitational potential $GM_{Fe}^2\left(\frac{1}{R_{ns}}-\frac{1}{R_{Fe}}\right)$ ~3 10^{53} ergs	Fusion of 10^{55} ^{56}Fe nuclei from ^{12}C ^{16}O (10^{51} ergs)
kinetic	1-2 10^{51} ergs 10-15 $M_\odot$ ejected <v> ~ 3000 km/s	6-8 10^{50} ergs 1.4-2 $M_\odot$ ejected <v> ~ 10,000 km/s
radiated	10^{49} ergs	4 10^{49} ergs



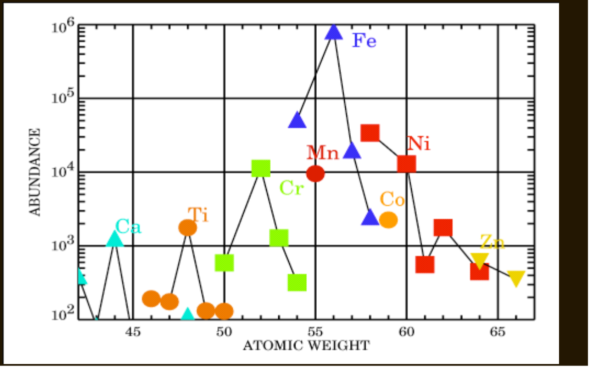
Spectra:
Type II,
Ib, Ic, …

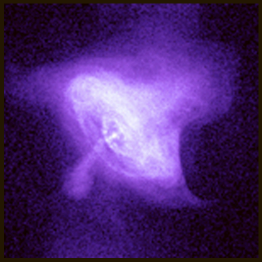
Spectra:
Type Ia

Supernovae: nucleosynthesis & rates

Core-collapse of massive star

Thermonuclear explosion of white dwarf (in binary star system)

Elements produced	O, F, Ne, Na, Mg, Al, Si, S, …. A≥70 (r-process)	Fe-peak elements 
Milky way rates	2.5 ± 1 century^{-1}	0.5 ± 0.3 century^{-1}



Spectra: *Type II, Ib, Ic, …*

Spectra: *Type Ia*

Supernovae: major questions

Core-collapse of massive star

Thermonuclear explosion of white dwarf (in binary star system)

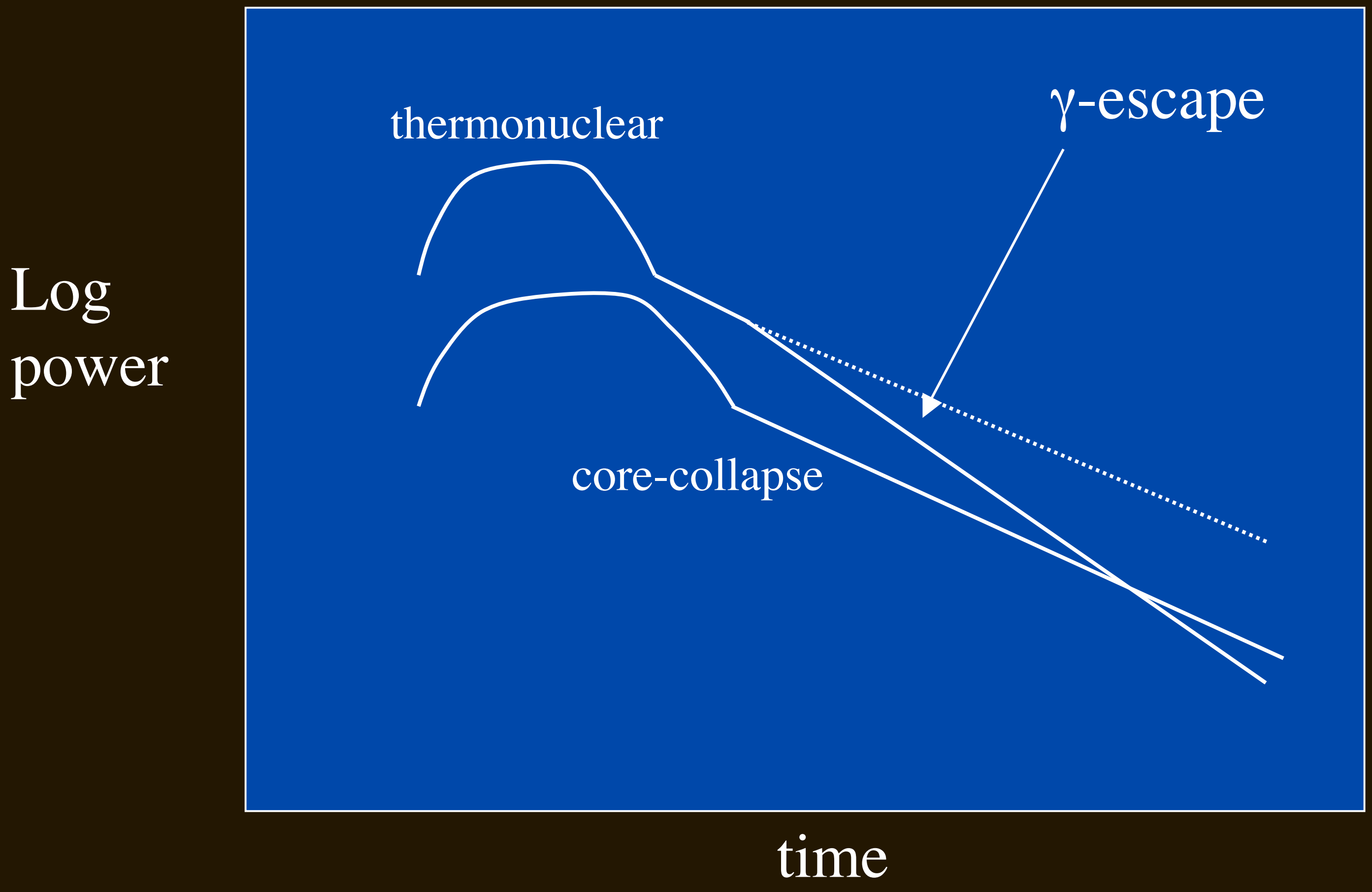
How is large n-star binding energy transferred to star? (models do not explode)	What are the progenitor systems?
What are the dynamical complexities (mixing due to instabilities, jets, etc.)? c.f. gamma-ray bursts	How does the nuclear flame ignite and propagate? detonations out; deflagrations unlikely; *combination*?

Spectra:
Type II,
Ib, Ic, …

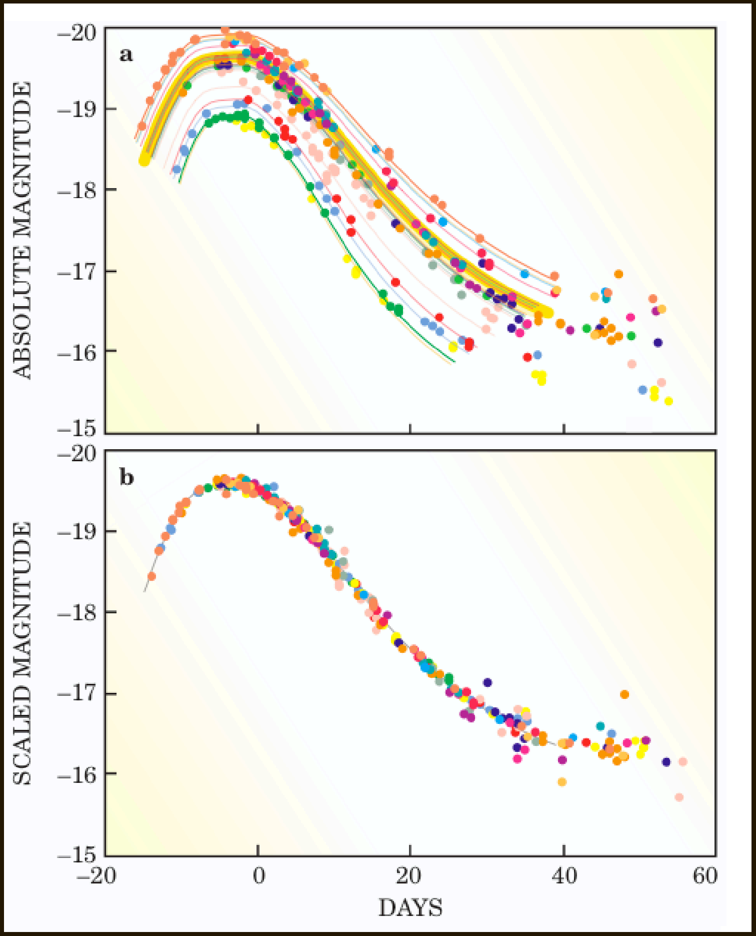
Spectra:
Type Ia

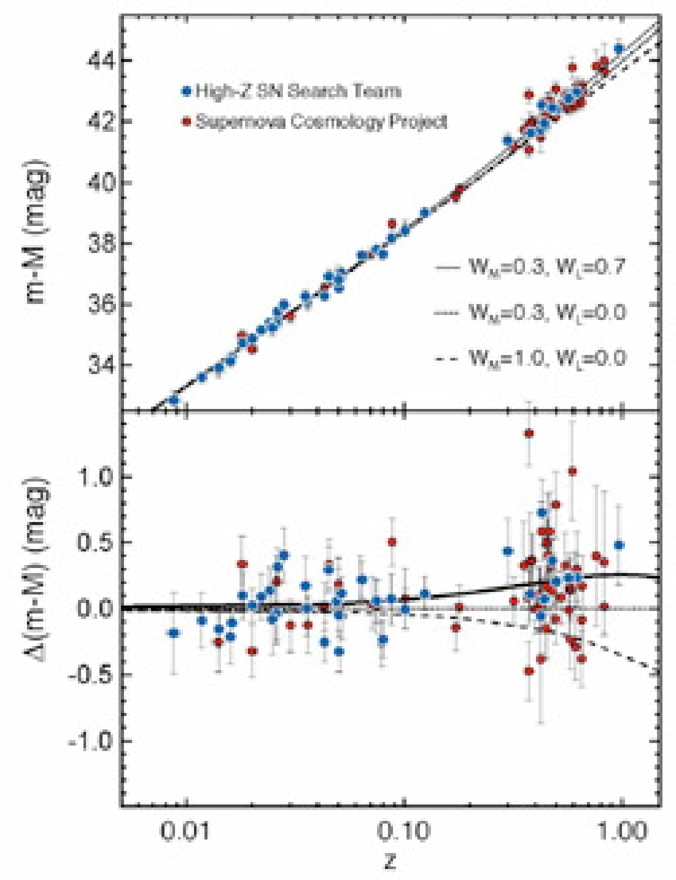
Supernovae: visible light evolution

$$^{56}Ni \xrightarrow{8.8\text{d}} {}^{56}Co \xrightarrow{113\text{d}} {}^{56}Fe$$



Thermonuclear SN and Cosmology

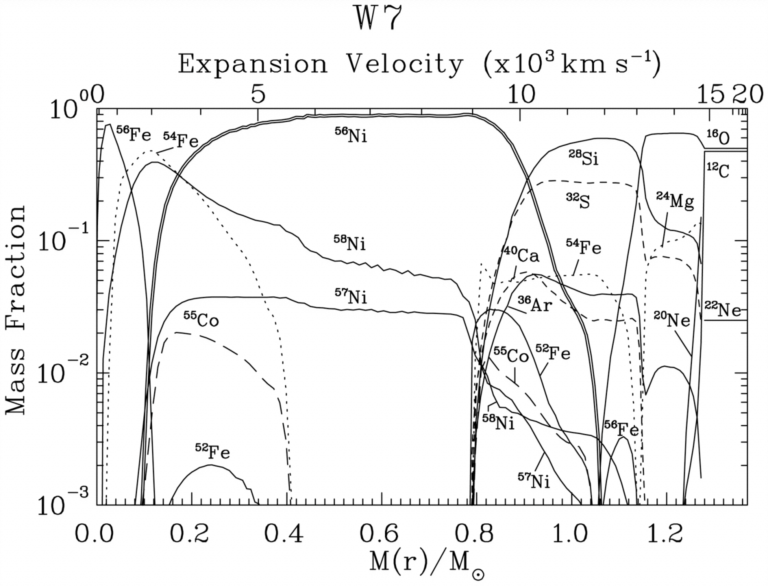


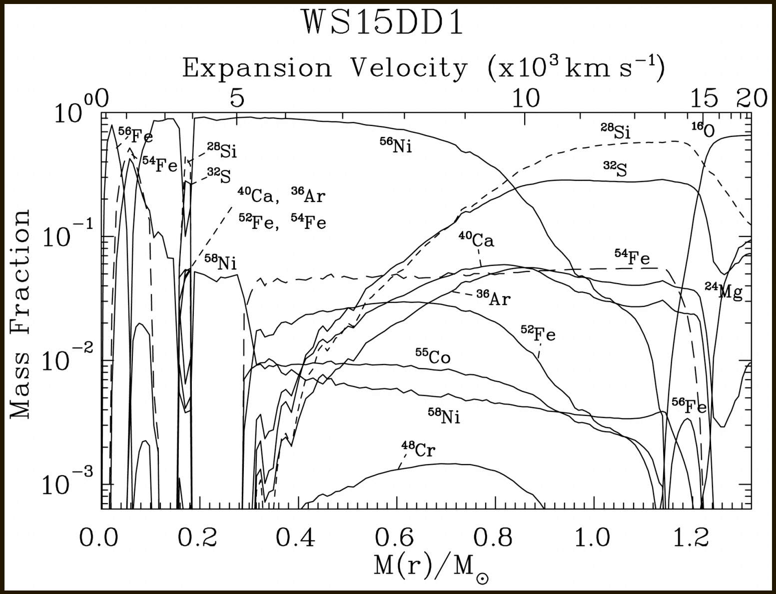


Do these objects follow a 1-parameter family?
Were they the same at 1/2 present age of universe?

Thermonuclear SN models

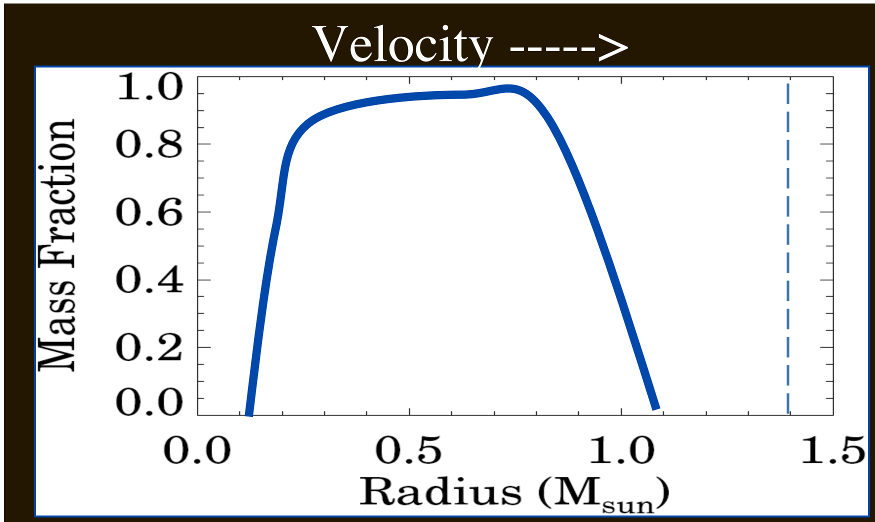
Model (in spherical symmetry): mass, composition, flame prescription…



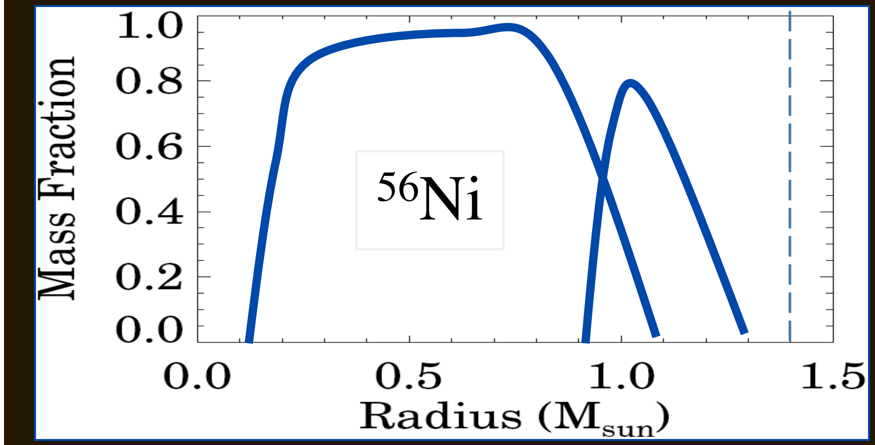


Iwamoto et al.

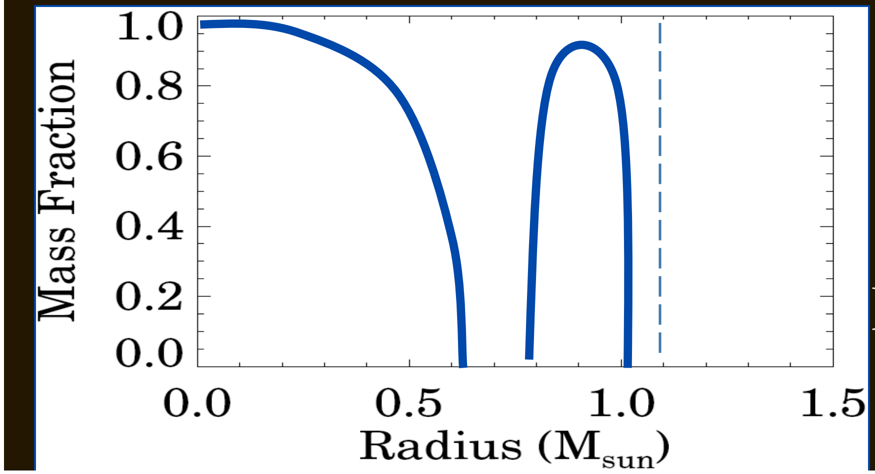
Thermonuclear SN Models - schematic



Deflagration



Delayed detonation



He-detonation

γ-ray lines: come only from ‘optically’ thin regions.

We can watch the attenuating medium lift off -- flux vs. time

We can see the doppler profiles of the emission regions -- spectra

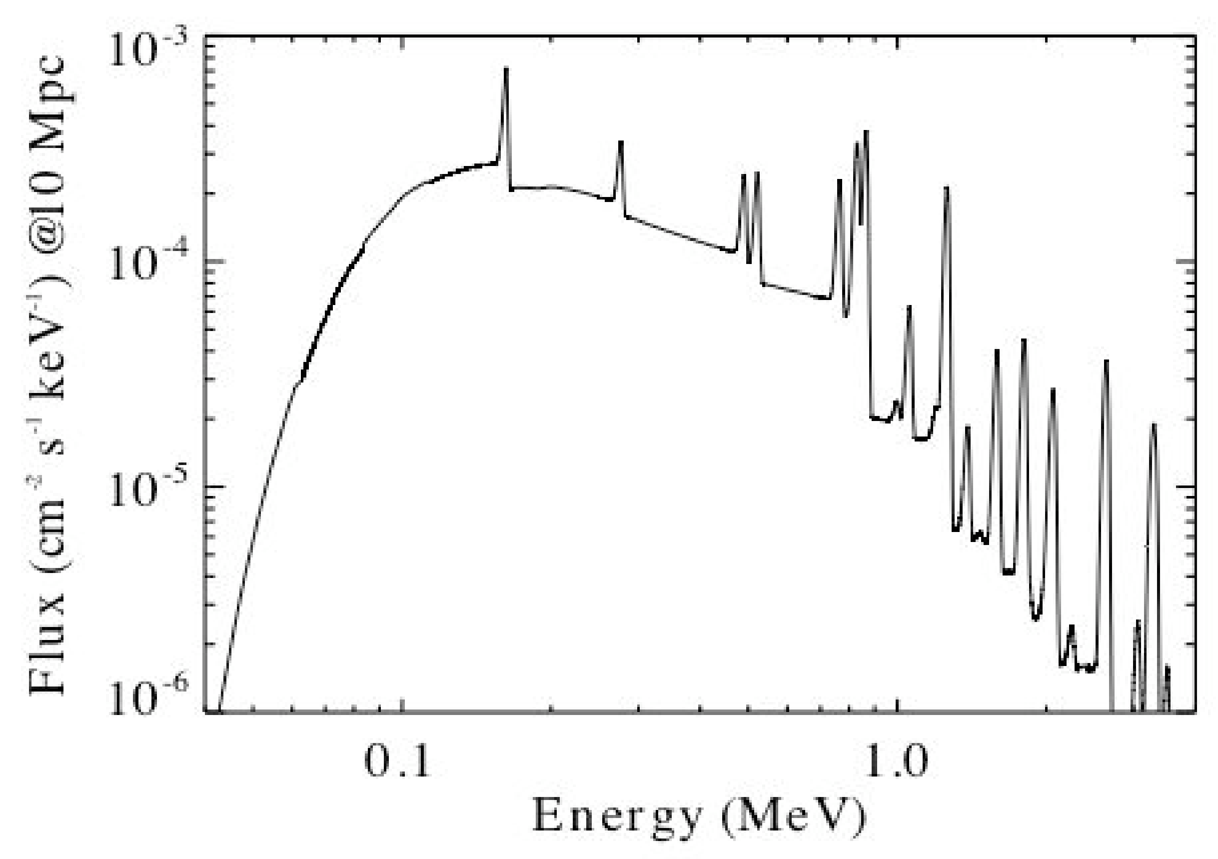
Thermonuclear supernova γ-rays

$$^{56}Ni \xrightarrow{8.8\text{d}} {}^{56}Co \xrightarrow{113\text{d}} {}^{56}Fe$$

158 keV
812 keV
etc.

847 keV
1238 keV
etc.

DD2002c
Hoeflich et al.
@25 days



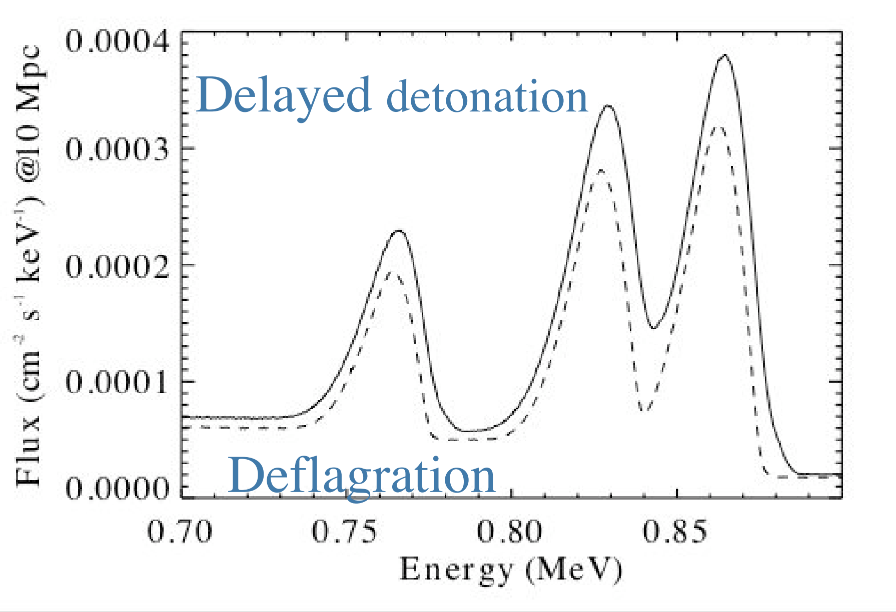
Lines are doppler broadened to 3-5%

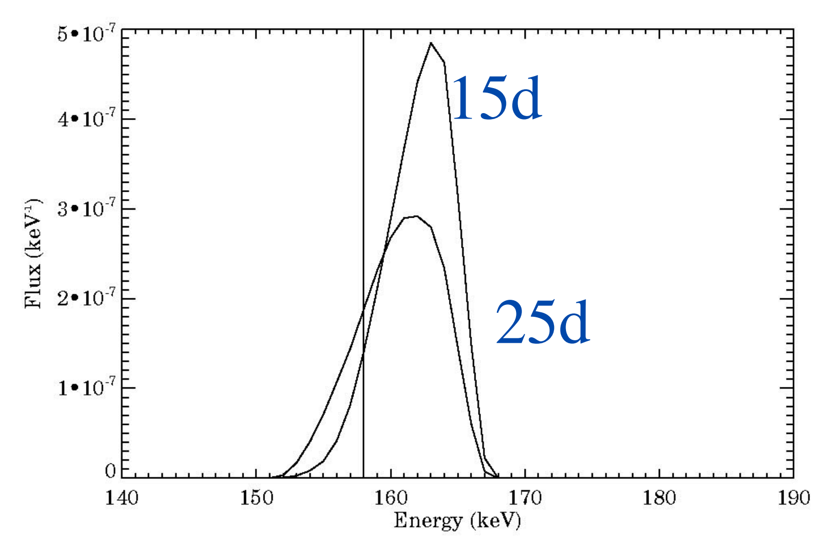
Model discrimination

For a given instrument sensitivity, variation with time is slightly more sensitive test than spectra.

Unfolding the actual ^{56}Ni distribution is the ultimate goal.

Biggest difference:
Some models have fast ^{56}Ni at surface. Changes in 10^6 sec.





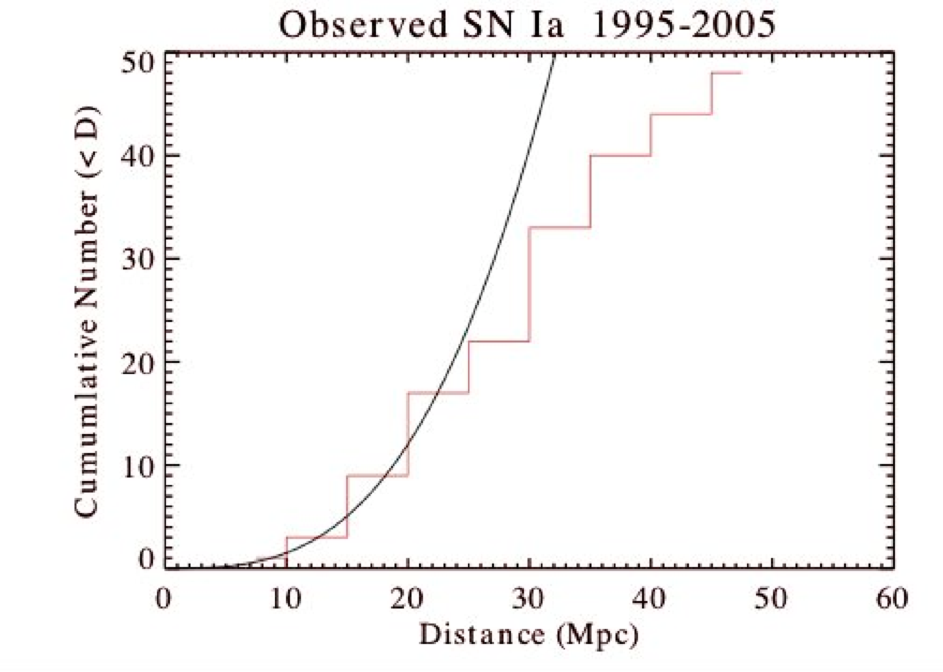
On the number of SNe we can study…

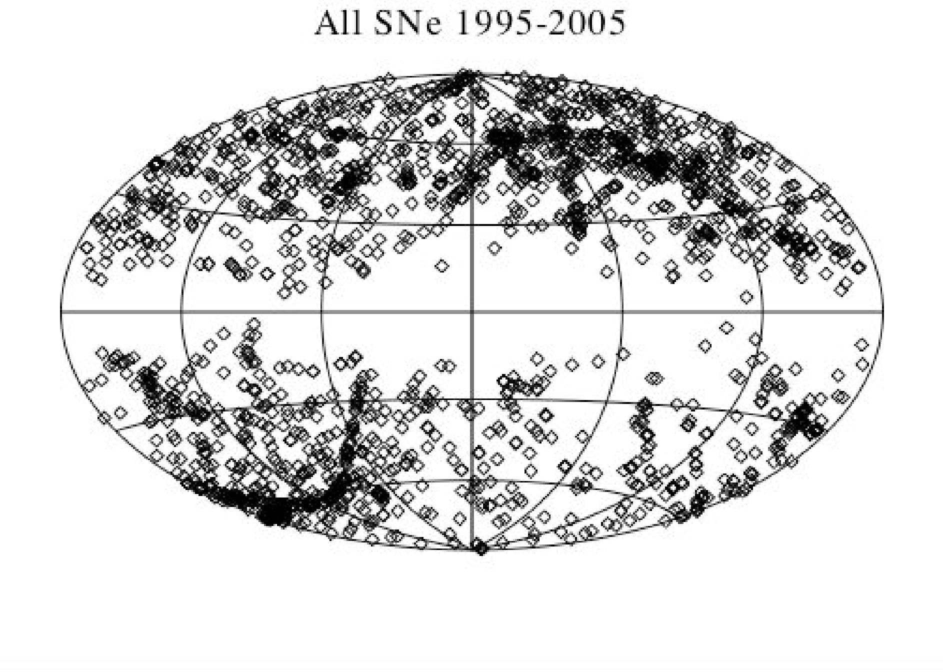
Calan/Tololo Survey --> 0.21 SN Ia / $10^{10} L_{sun}$(B) / century

SDSS --> 0.017 $10^{10} L_{sun}$(B) / Mpc^{-3}

- ➢ 19 y^{-1} SN Ia within D = 50 Mpc (Peak 847 keV Flux ≥ 1.2 10^{-6} cm^{-2} s^{-1})

But, how good are these numbers? Take confirmed SNIa, Tully Nearby GC Distances

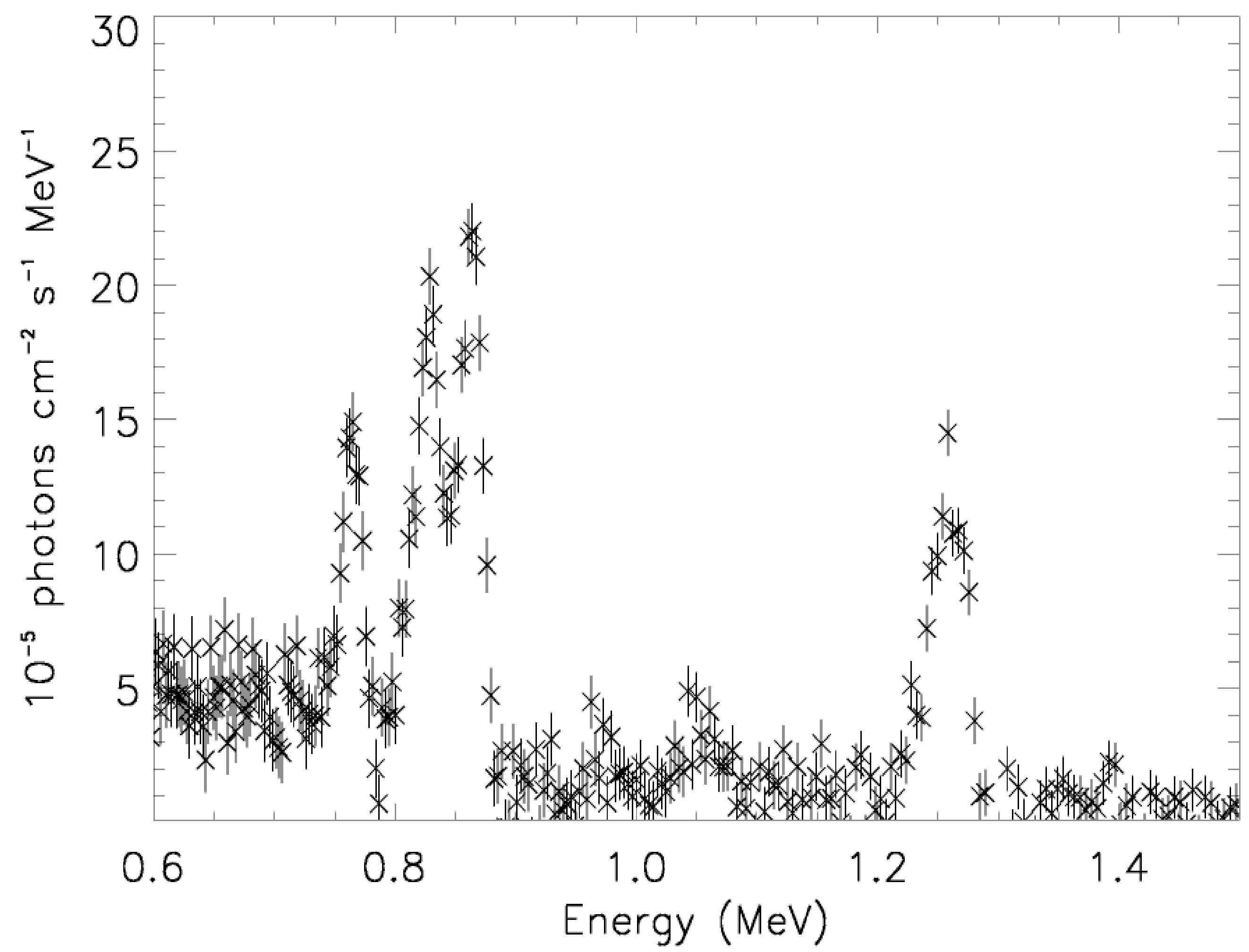




1 y^{-1} at D < 20 Mpc seems safe (> 20σ for $F_{3\sigma}$= 1 10^{-6})

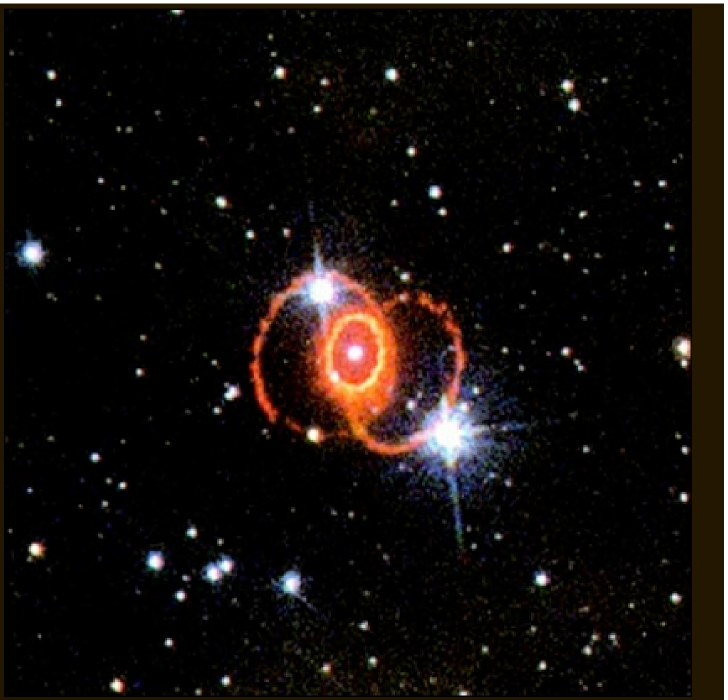
Detecting many is fine, but it will be the best few of each -- bright, normal, subluminous -- that will be most important.

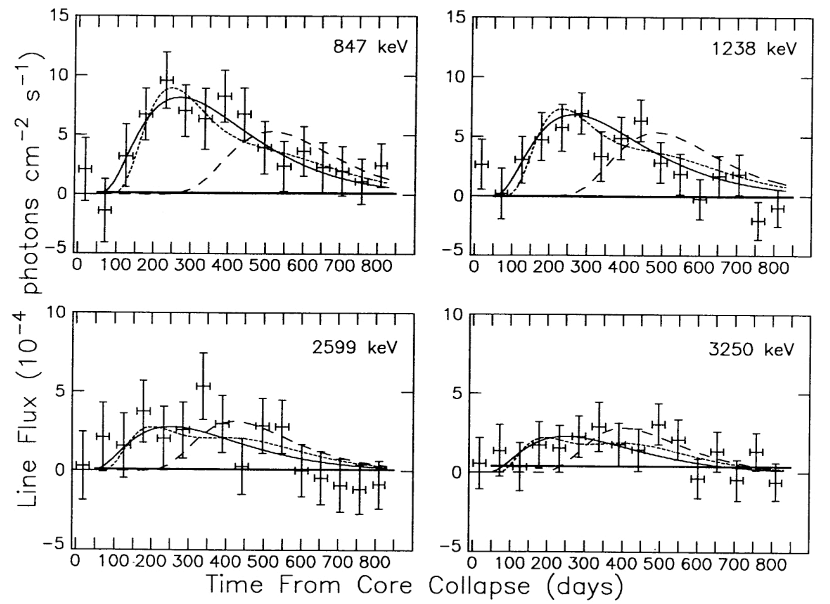
W7 minimum
annual event----->



Core collapse objectives:

- Dynamics
    - At the ‘mass cut’
    - Jets
- Nucleosynthesis
- Circumstellar matter/wind interactions
- Cosmic ray acceleration





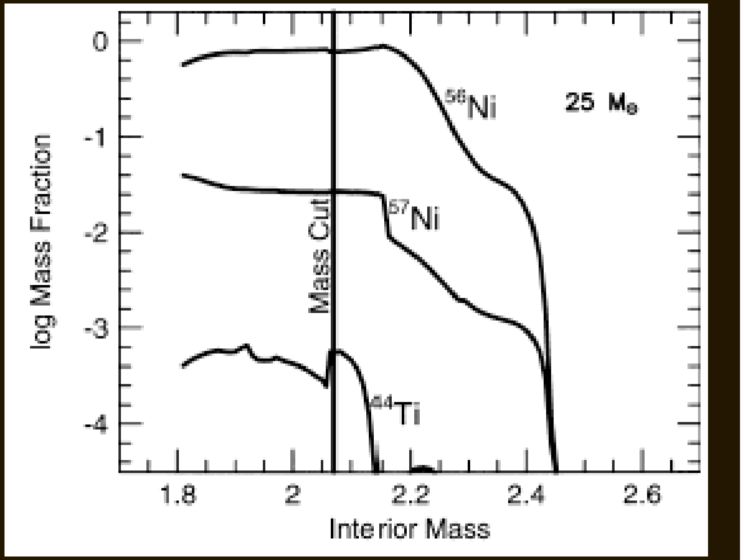
Dynamics - at the mass cut

How is ~1% of the n-star binding energy transferred to the star?

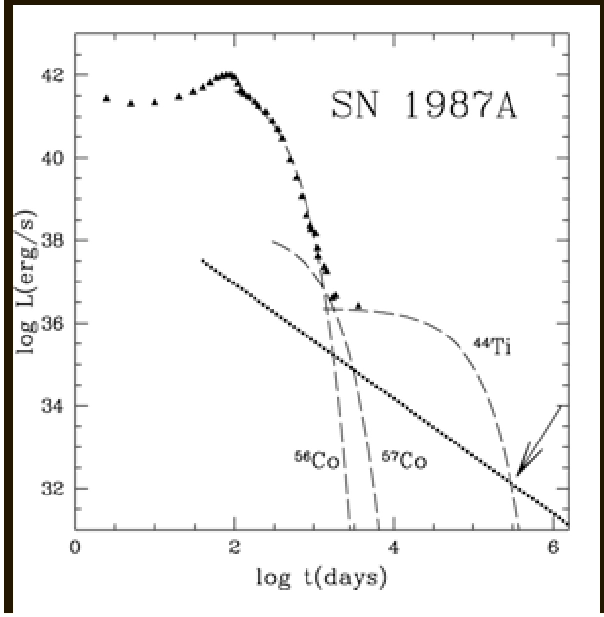
Observations are well ahead of theory -
^{56}Ni, ^{57}Ni masses, ^{44}Ti masses?

Measurements needed -

New SN*	^{56}Co (847, 1238, 50-150 keV) light curve ^{57}Co (122, 136 keV)
SNR*	^{44}Ti (68, 78, 1157 keV)



Woosley & Weaver 1995



* ^{56}Co detectable to ~2 Mpc --> local group SN

* SN 1987A, e.g., ^{44}Ti yield to ~10%

c.f. also NUSTAR

$$^{44}\mathrm{Ti} \xrightarrow[68,\ 78]{63\mathrm{y}} {}^{44}\mathrm{Sc} \xrightarrow[1157\ \mathrm{keV}]{4\mathrm{h}} {}^{44}\mathrm{Ca}$$

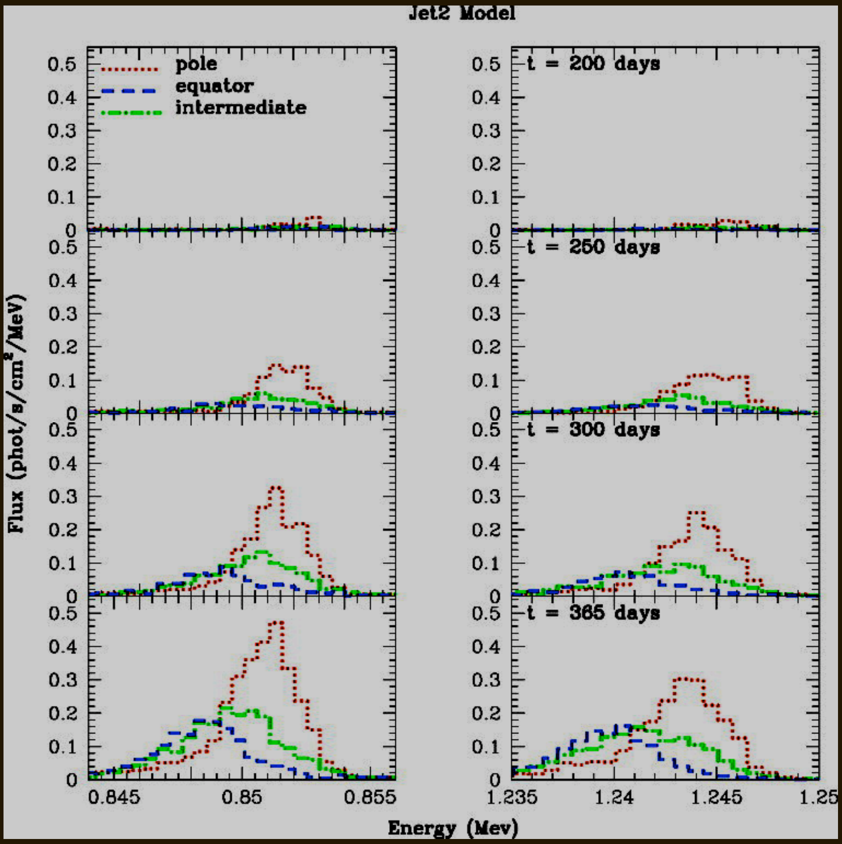
Dynamics - jets (see also grb’s)

^{56}Co fluxes can be ~5 times higher (Hungerford et al. 2003, 2005) --> D~6 Mpc (need either sample of several angles or very good spectroscopy)

^{44}Ti / ^{56}Ni ratio might vary substantially in jets. Where we can measure ^{44}Ti well (e.g., Cas A) can we measure ^{56}Ni?

map

modest spectroscopy (~1000 km/s) might also reveal jets in brightest ^{44}Ti sources. (several snr in galaxy)



Core collapses - nucleosynthesis

In principle, many isotopes accessible in gamma-ray lines.

- Galactic SNR
- Local group SN
- Galactic SN!

^{7}Be	478 keV	53 d
^{22}Na	1275 keV	2.6 y
^{26}Al	1809 keV	0.7 My
^{59}Fe	1099, 1292 keV	44 d
^{60}Fe	59 keV	1.5 My
^{60}Co	1173, 1332 keV	5.3 y
r-process	various	various
e.g. ^{126}Sn	87 keV	0.1 My

$F_{est} \sim 10^{-7}$ cm^{-2} s^{-1}, fluctuations? jets?

Core collapse - shock/csm interaction

- distinguish forward shock/csm (kT~10^9) from reverse-shock/ejecta at ~50--150 keV.

- determine wind density profile and/or binary effects

- see SN 1993J

- GRI - a few per year, quick response needed (days)

Summary

- Sensitive γ-ray observations can answer the fundamental questions about supernovae (thermonuclear, especially)
- Broad line flux sensitivity $\sim 10^{-6}$ cm^{-2} s^{-1} is essential
- In a narrow-field instrument, this should be achieved in $\sim 10^{5}$ sec (maybe 3 10^{5} sec) because multiple observations are essential.