Discovery and long-term study of hard X-ray emission of SN1987A with MIR/KVANT

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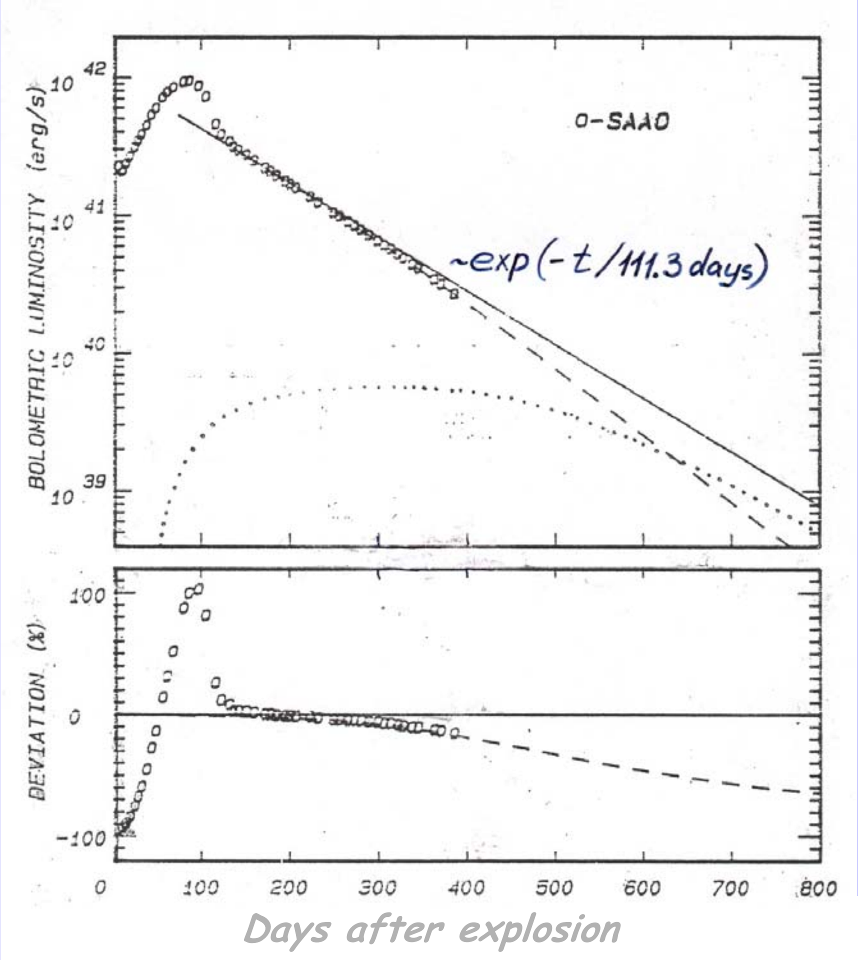
Radioactive ^{56}Co in the envelope

We celebrated this year the 20-years anniversary of the Supernova 1987A exploded in the Large Magellanic Cloud on February 21, 2007. It was the first local supernova for the last ~400 years.

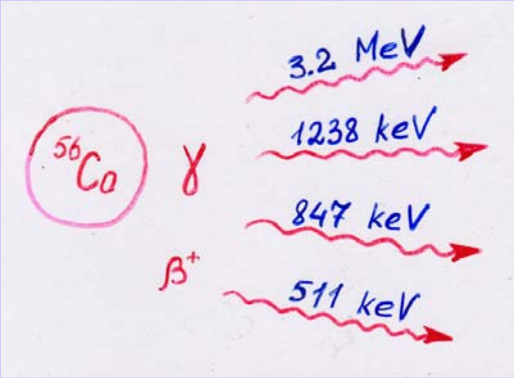
Optical light curves of SN1987A took an exponential shape (with a decay time of 111 days) in ~100 days after the explosion that indicates the formation of 0.07 $M_\odot$ of radioactive ^{56}Co inside the envelope.



Radioactive decay $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Co$

$^{56}Ni \rightarrow {}^{56}Co$ (8.8 days)

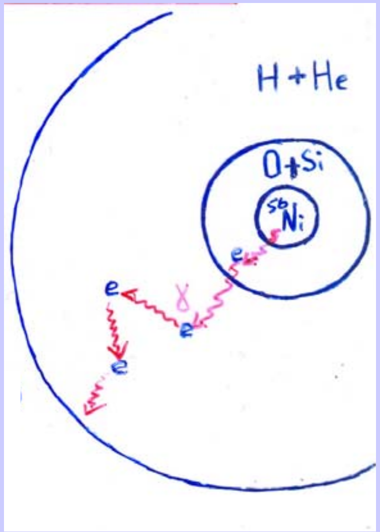
$^{56}Co \rightarrow {}^{56}Fe$ (111.3 days)



$\langle N\gamma \rangle$ ~ 2 photons/decay

$\langle E\gamma \rangle$ ~ 3.6 MeV/decay

Photon transport in the envelope



Thomson depth $\tau_T = \int \sigma_T \, Ne(r)\, dr \sim 25\,(t/yr)^{-2}$

Average number of scatterings $N_s \sim \tau_T^2/2$

Average change of photon energy $\frac{\Delta E\gamma}{E\gamma} \sim \begin{cases} -1/3, & E\gamma \sim m_e c^2 \\ -E\gamma/m_e c^2, & E\gamma < m_e c^2 \end{cases}$

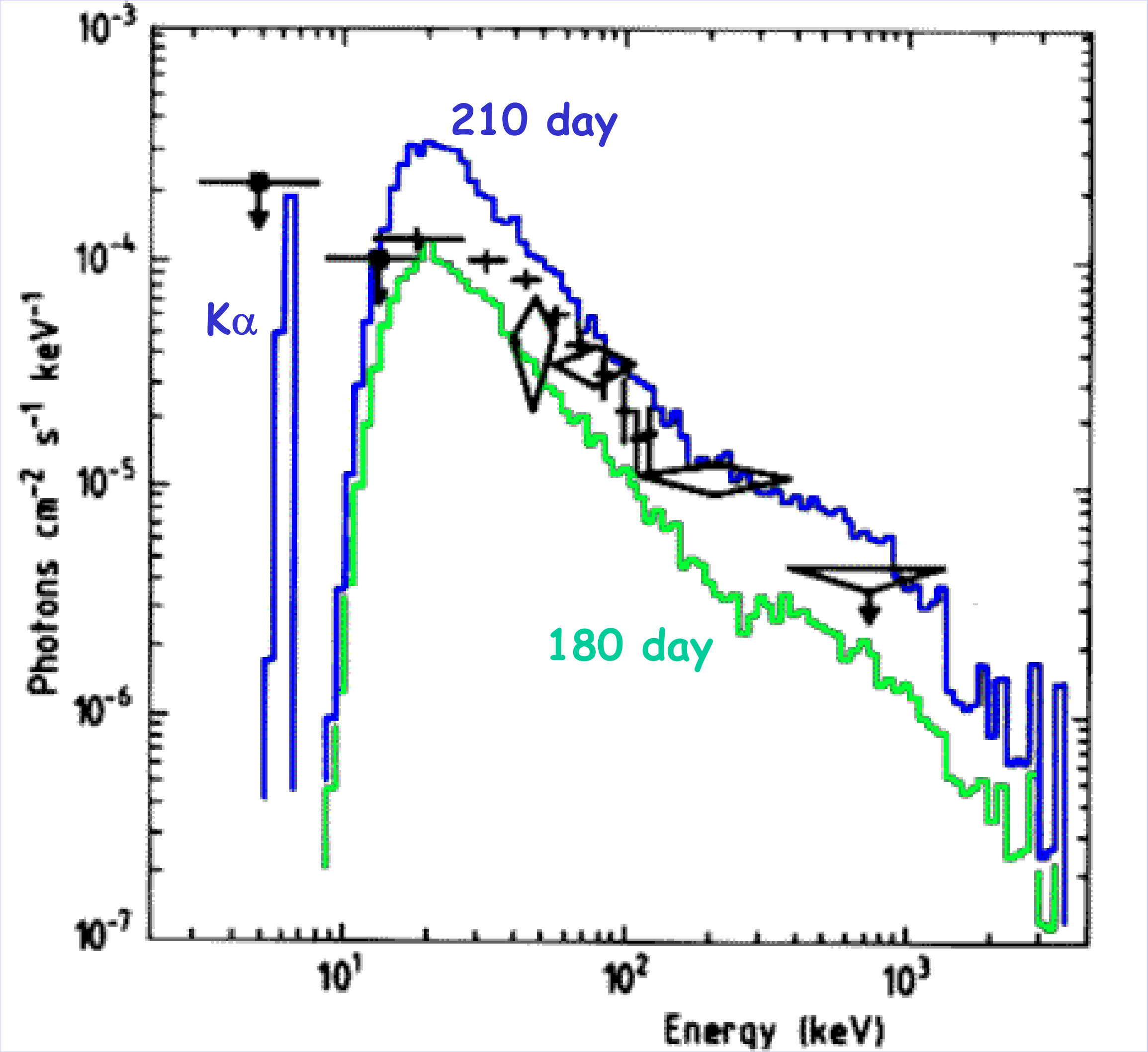
Photoabsorption $\tau_a = \tau_T\,(Z/Z_\odot)(E\gamma/\,10\ keV)^{-3}$

Z - abundance of iron group elements

Hard X-rays from radioactive ^{56}Co

Monte-Carlo computations of multiple Compton scatterings of gamma-rays in the SN1987A envelope emitted due to the ^{56}Co decay (Grebenev, Sunyaev, 87, based on the hydrodynamical model by Utrobin, Imshennik, 87) have shown that hard X-rays should appear at the detectable level already in half a year after the explosion. This conclusion stimulated earlier MIR-KVANT observations and led to the discovery of the continuum emission in August 1987.

Crosses - HEXE
Upper limits - TTM
Diamonds - PulsarX1

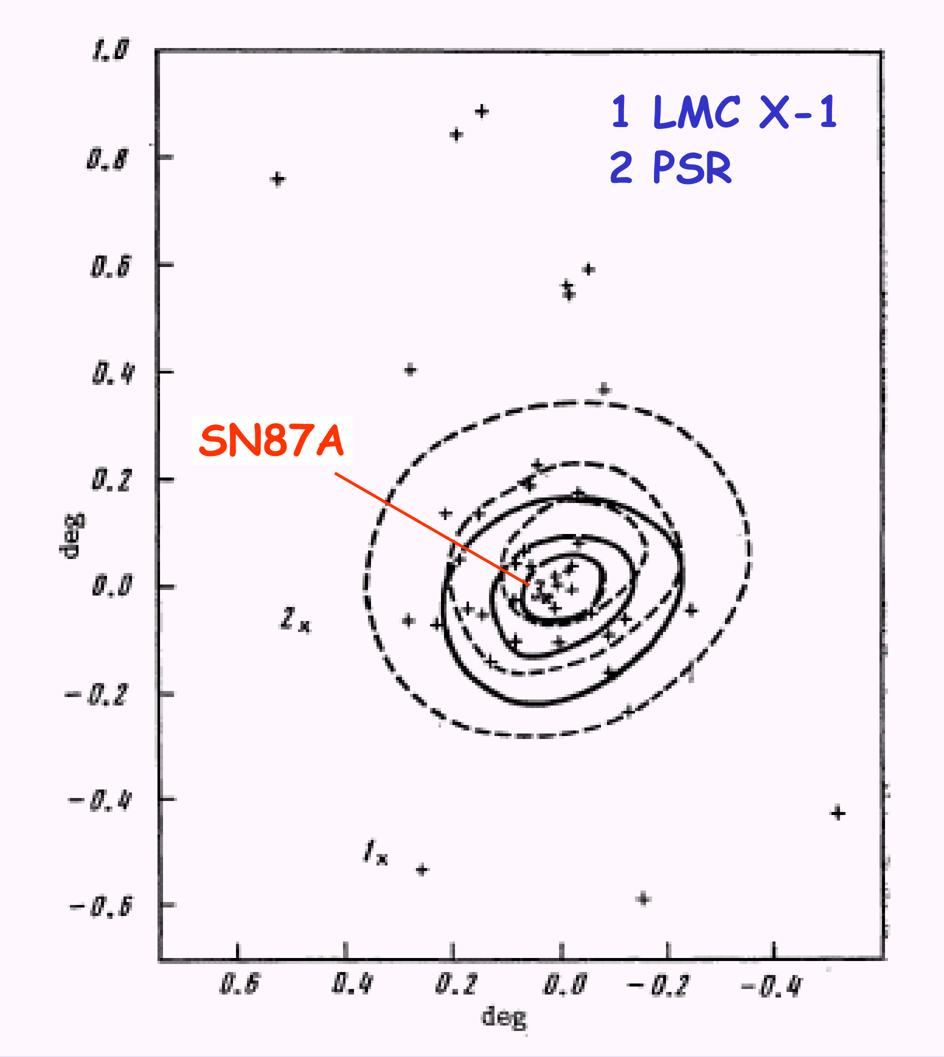


from Sunyaev et al. (Nature 1987)

Localization of the hard X-ray source

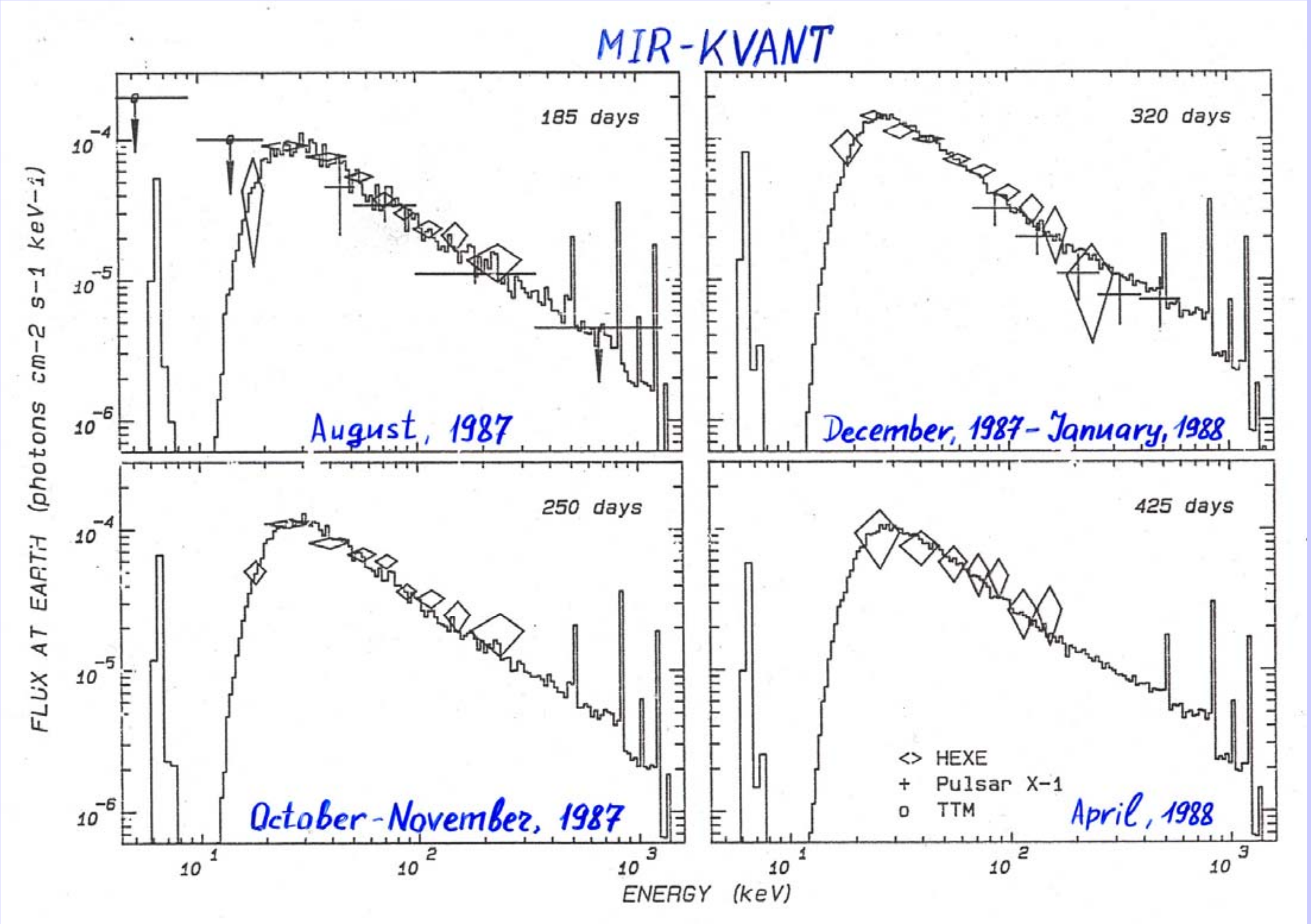
HEXE is a collimated instrument with the narrow field of view (< 1 deg). We pointed the observatory to slightly different directions to show that SN 1987A is indeed the source of the unusually hard X-ray emission discovered from the region.

Contours are given at 67, 99 and 99.9% confidence levels (dashed and solid lines - for 15-45 and 45-105 keV energy bands).



from Sunyaev et al. SvAL, 16, 171 (1990)

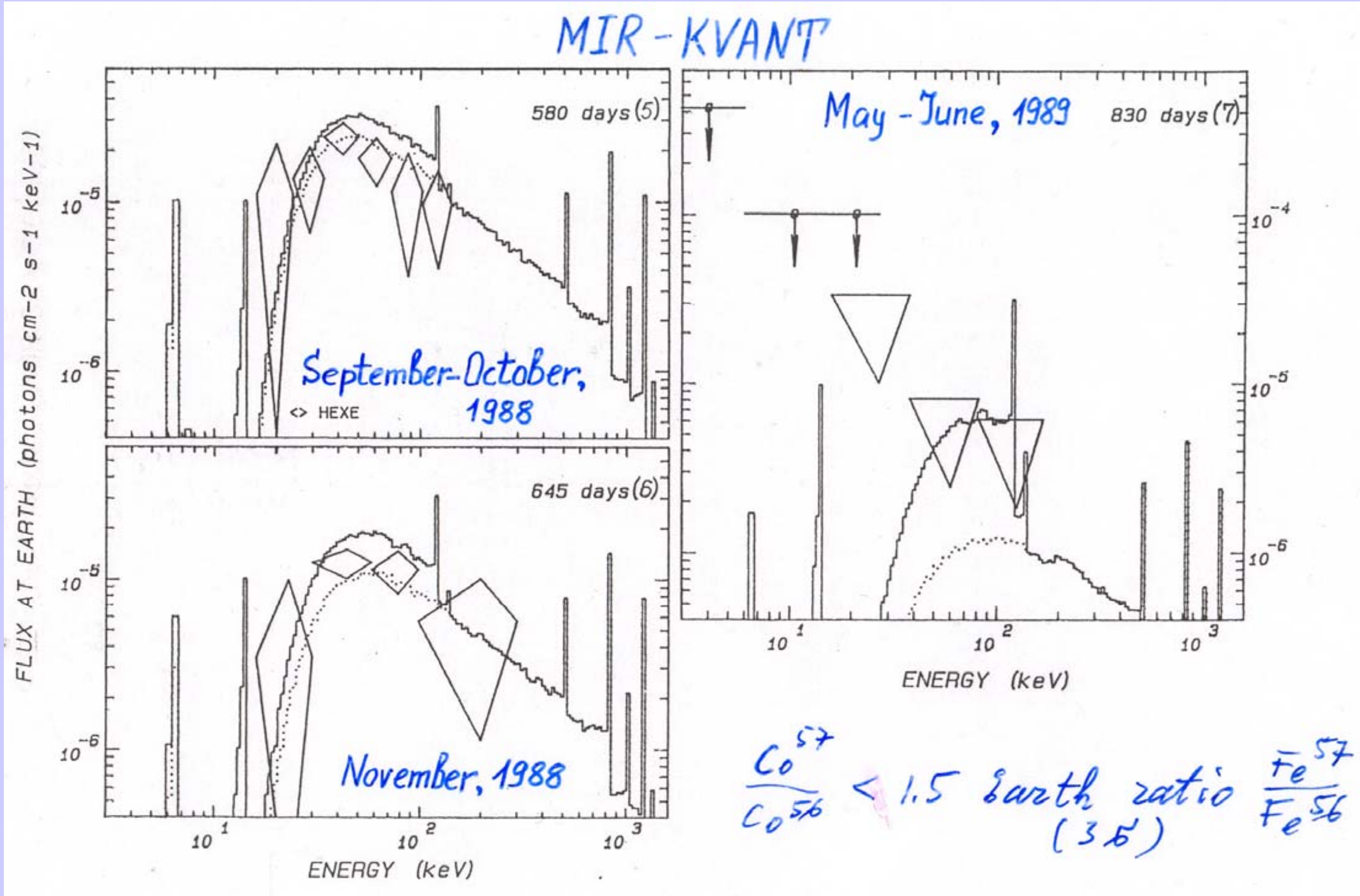
Hard X-rays from radioactive ^{56}Co



Evolution of the hard X-ray spectrum of SN1987A as measured by MIR-KVANT and its explanation by radioactive decay of ^{56}Co and Comptonization.

from Sunyaev et al. SvAL, 16, 171 (1990)

Hard X-rays from radioactive ^{56}Co



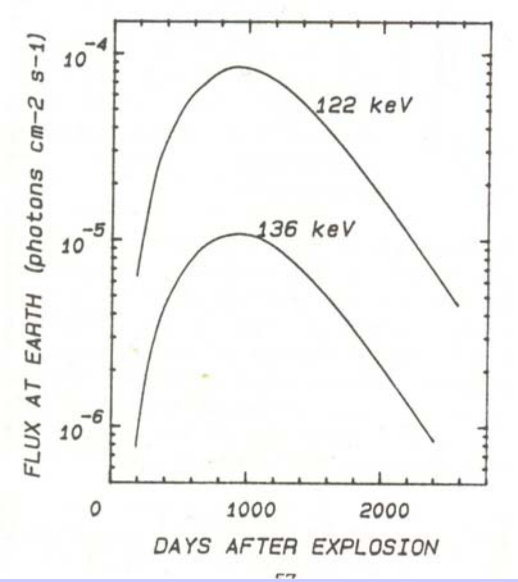
Late evolution of the hard X-ray spectrum of SN1987A as measured by MIR-KVANT and its explanation by radioactive decay of ^{56}Co-^{57}Co and Comptonization.

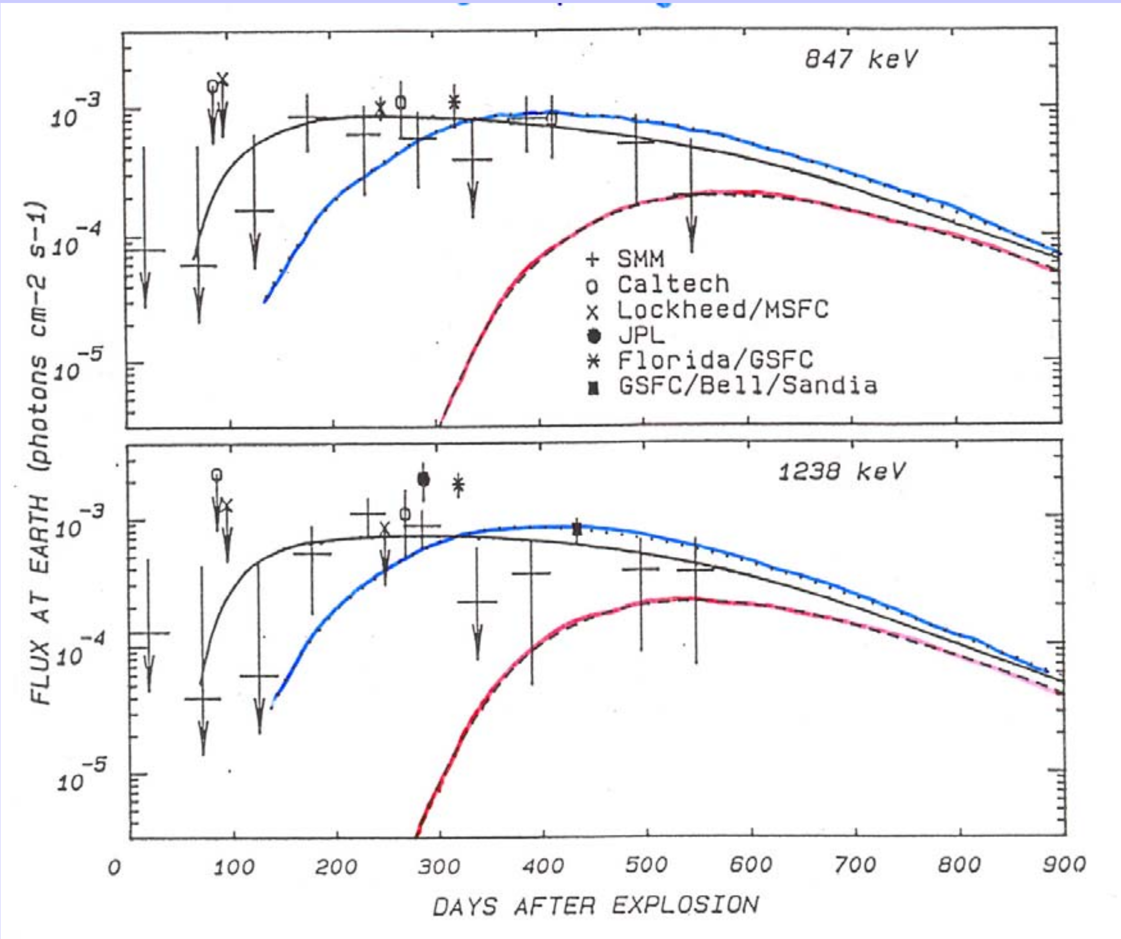
Time scale for ^{57}Co decay is longer (391 days) and the emitted lines are softer (136, 122, 7.3 keV)

from Sunyaev et al. SvAL, 16, 171 (1990)

Gamma-ray lines from radioactive ^{56}Co and ^{57}Co

Direct escape gamma-ray lines at 847 and 1238 keV from radioactive decay of ^{56}Co in the envelope were detected by several balloon experiments and the SMM satellite.



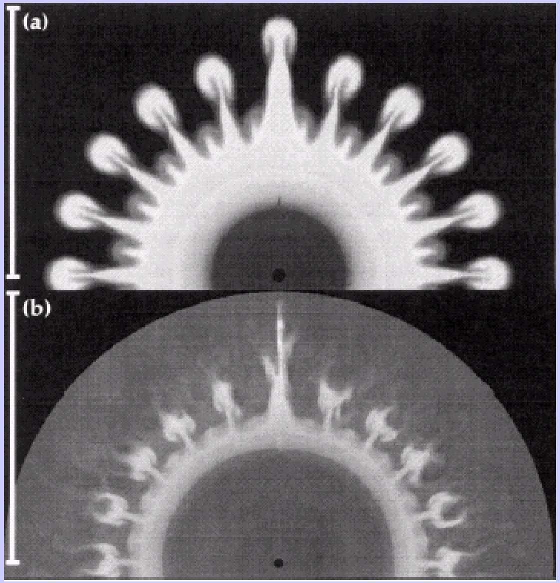


Opportunity to do the same for ^{57}Co gamma-ray lines has been missed (HEXE 3σ limit corresponds to ^{57}Co/^{56}Co ratio 6 times exceeding the Earth's ^{57}Fe/^{56}Fe ratio).

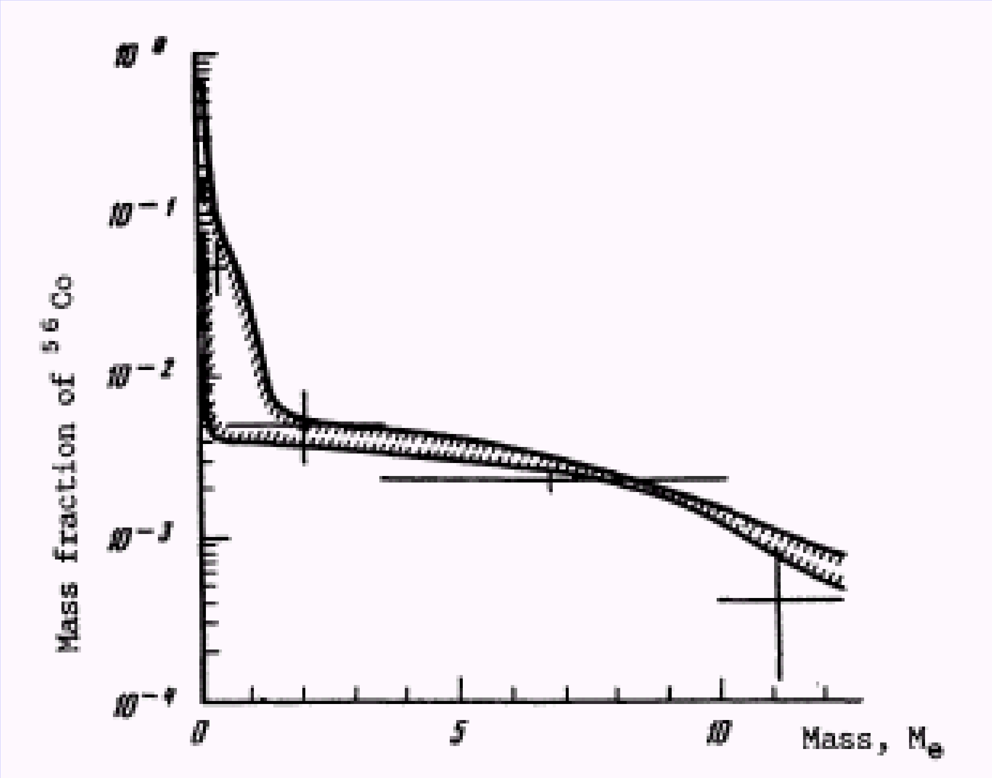
Mixing of radioactive ^{56}Co in the envelope

The observed evolution of hard X-ray spectra measured with HEXE (and the evolution of flux in direct-escape gamma-ray lines) can be explained by strong mixing of radioactive ^{56}Co over the envelope (mushroom structure, asymmetry/jets).

For the case of spherically symmetric mixing the following distribution of ^{56}Co was obtained

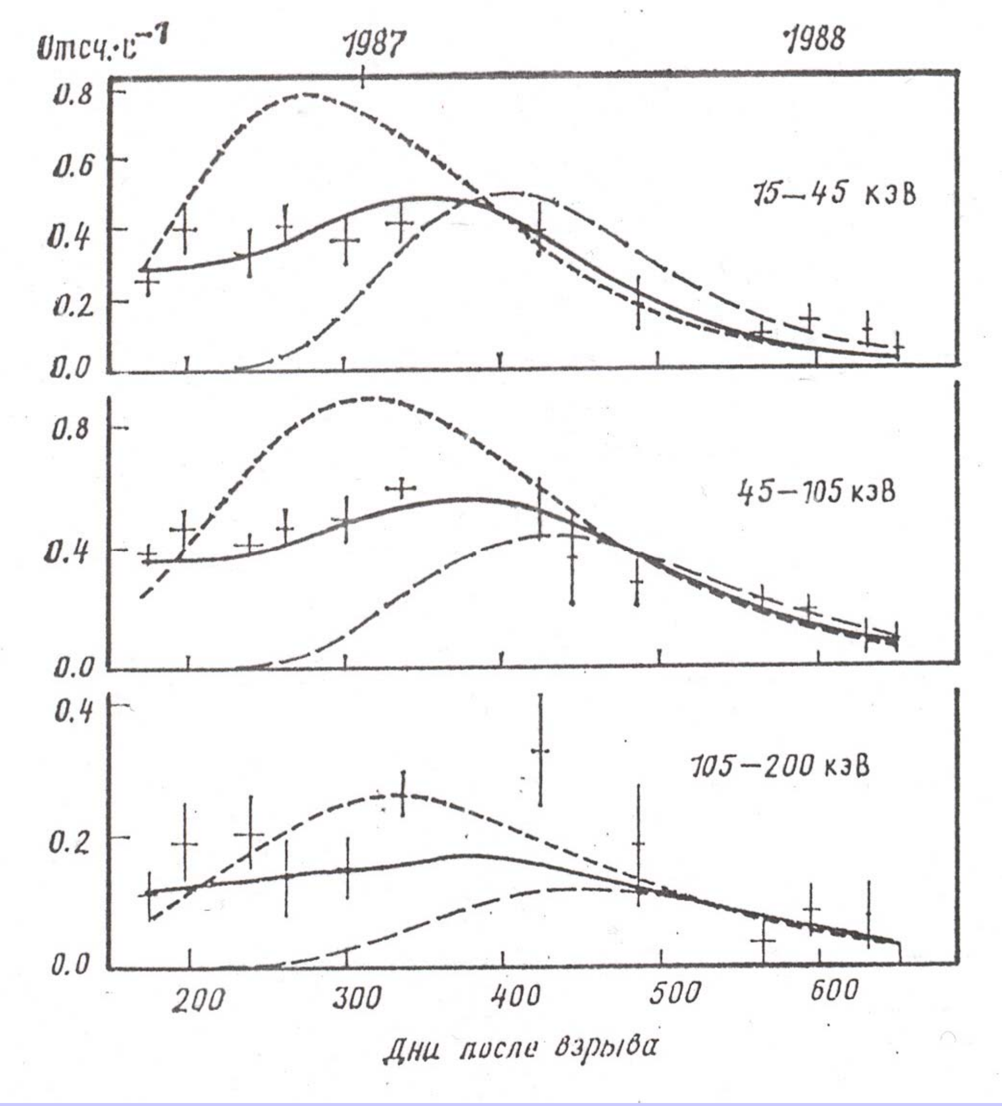


Kane, Arnett et al. (2000)



Sunyaev et al. (1990)

X-ray light curves as indicators of ^{56}Co mixing



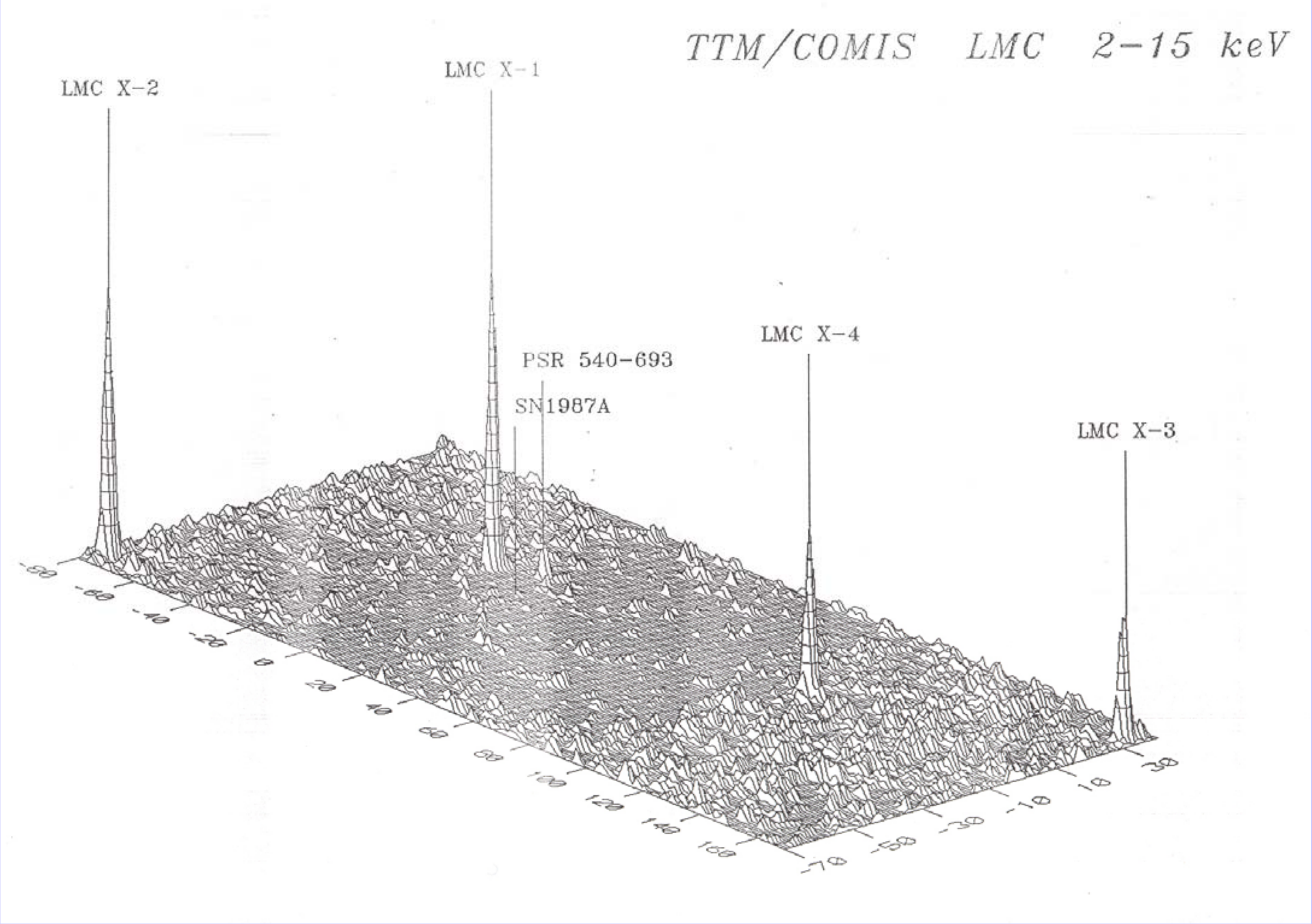
Evolution of X-ray flux from SN1987A as measured at different energies with HEXE and its sensitivity to ^{56}Co mixing.

Solid - accepted model

Long-dashed - no mixing

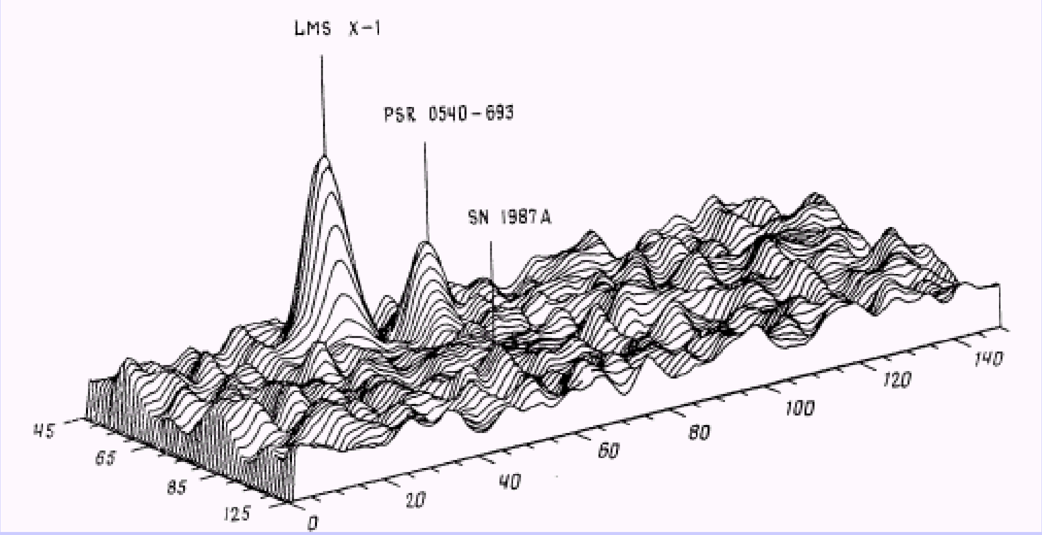
Short-dashed - mixed over inner 6 $M_{\odot}$

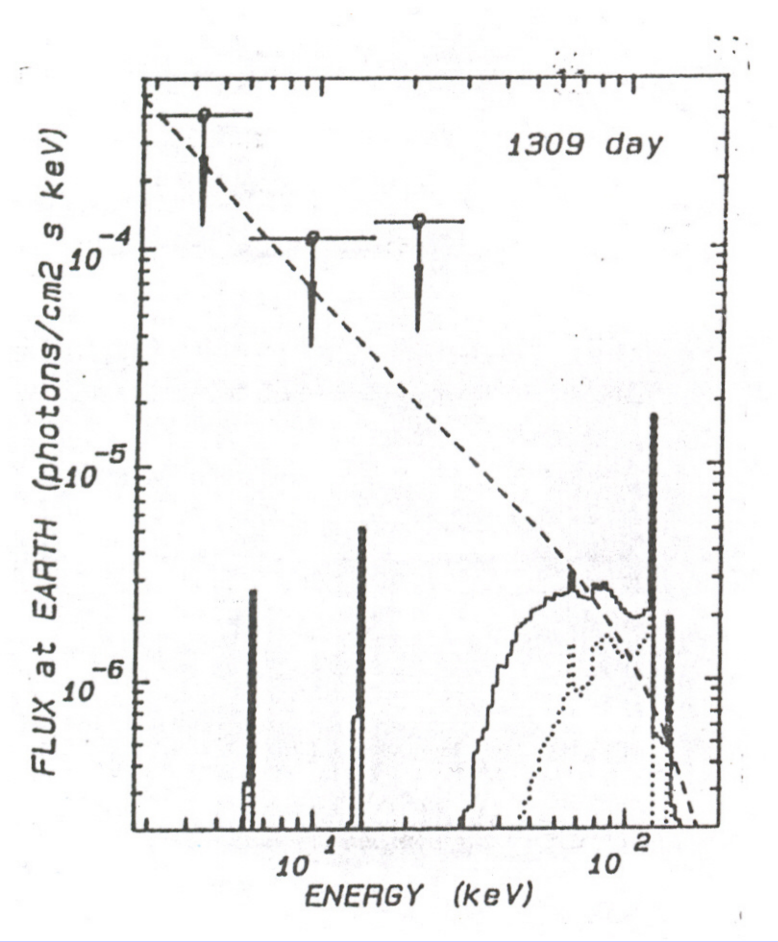
Observations in the standard X-ray band



Nothing below 15 keV has been detected that confirms our conclusion on strong low energy cut-off in the X-ray spectrum of SN1987A (connected with photoabsorption).

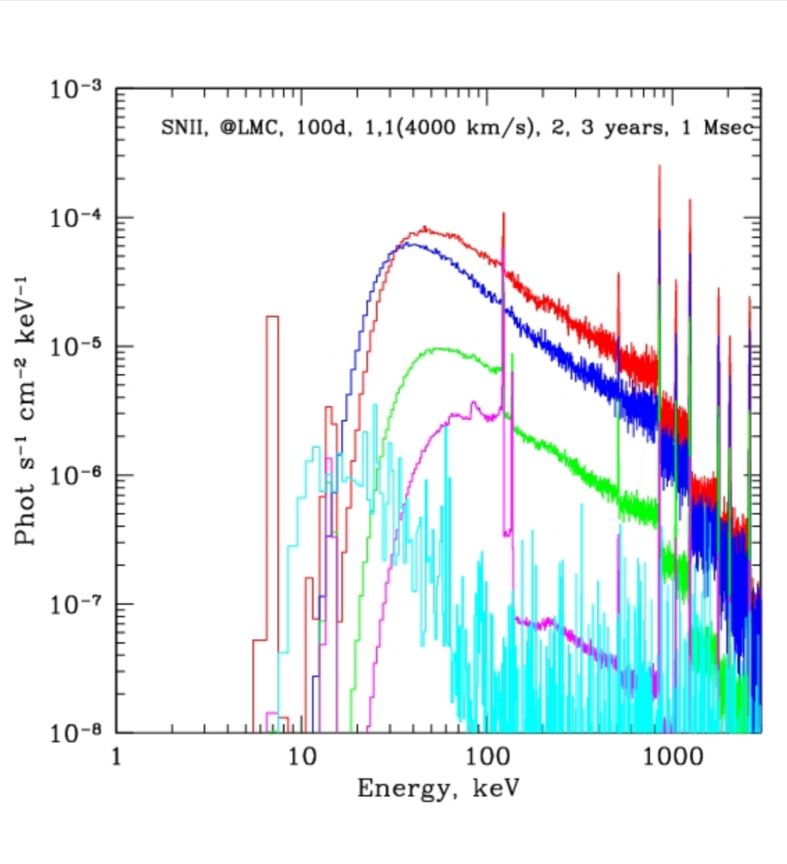
Observations in the standard X-ray band

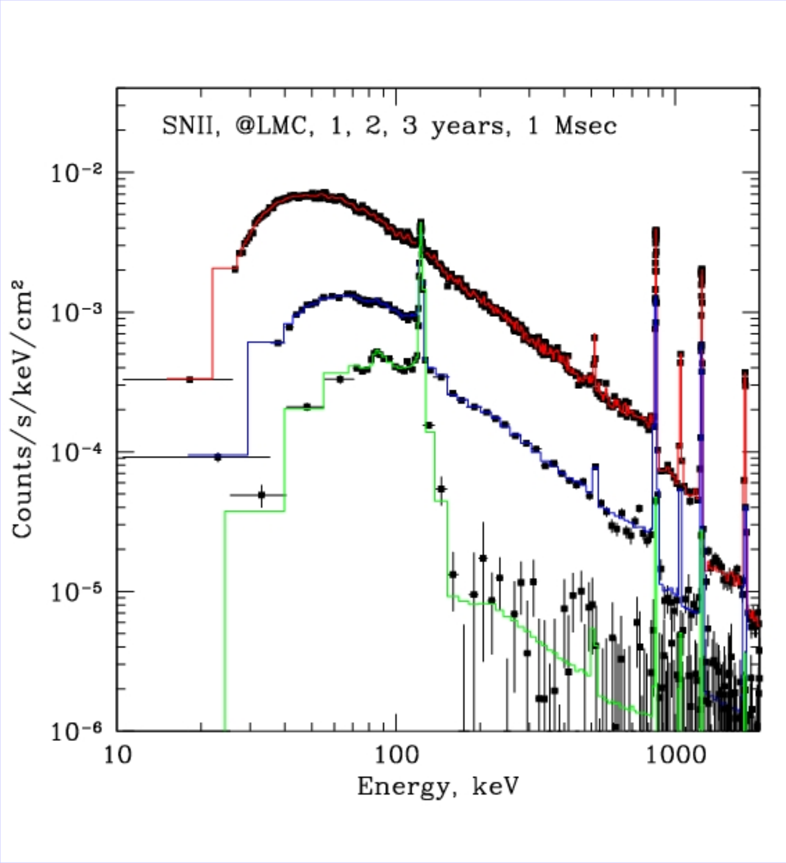




GRANAT/ART-P observed SN1987A at 1309 day after the explosion. The figure on the left shows as Cyg X-1 hidden in the center of the envelope could be observed that time.

SNII, 50 kpc, 1 Msec, 1,2,3 years

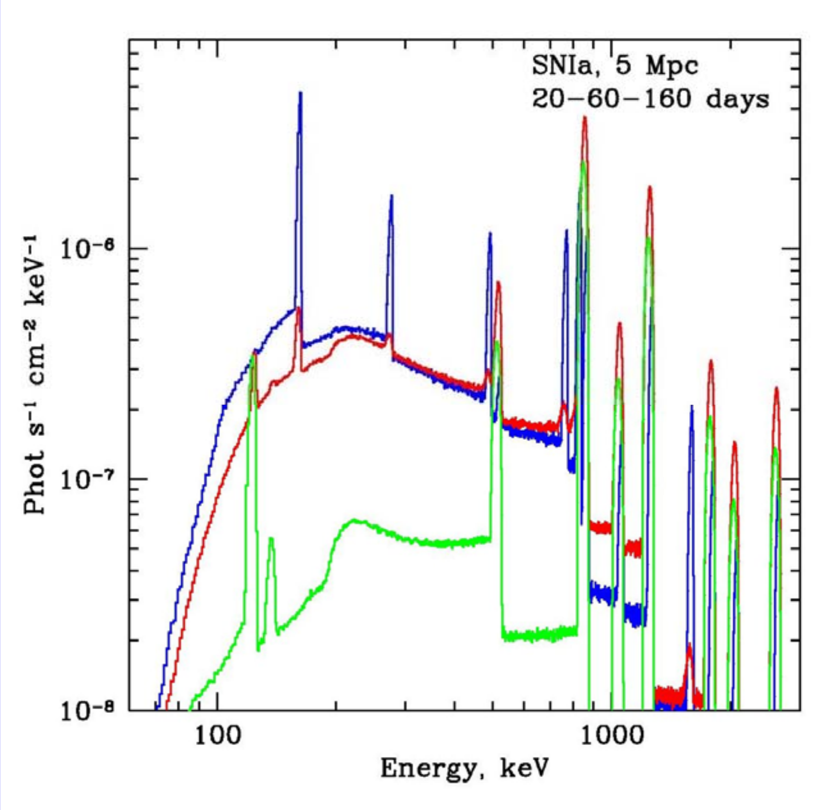


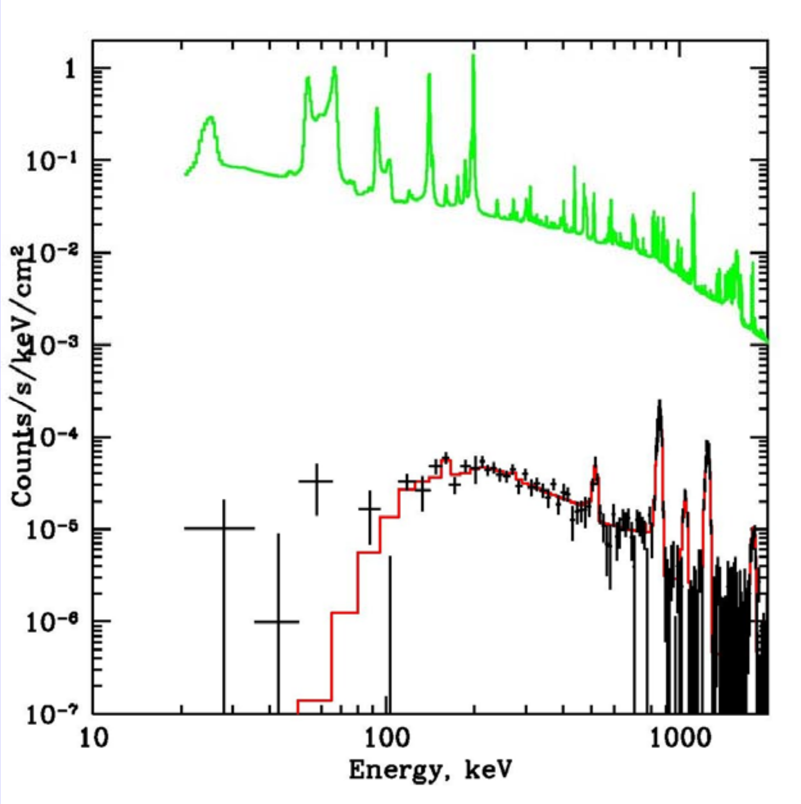


SPI capability simulated by Churazov (2007)

SPI will be able to detect SNII at ~1 Mpc !

SNIa, 5 Mpc, 1 Msec, 60 days, v=10000 km/s



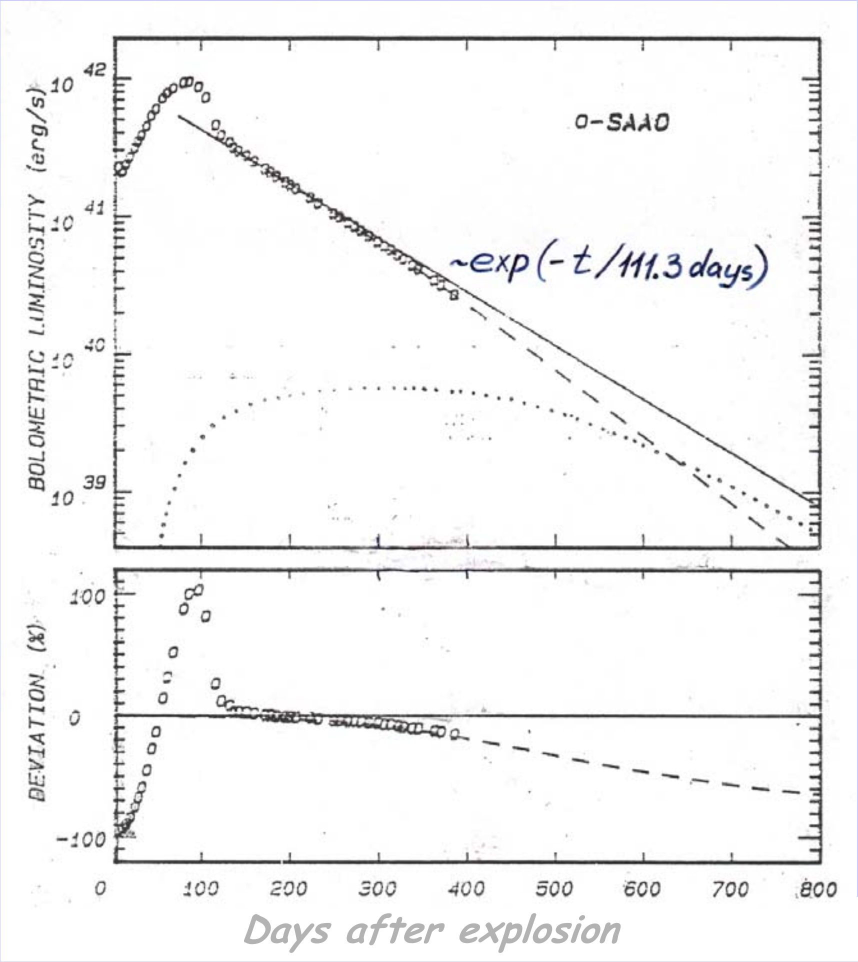


SPI capability simulated by Churazov (2007)

Long-term photometric light curve

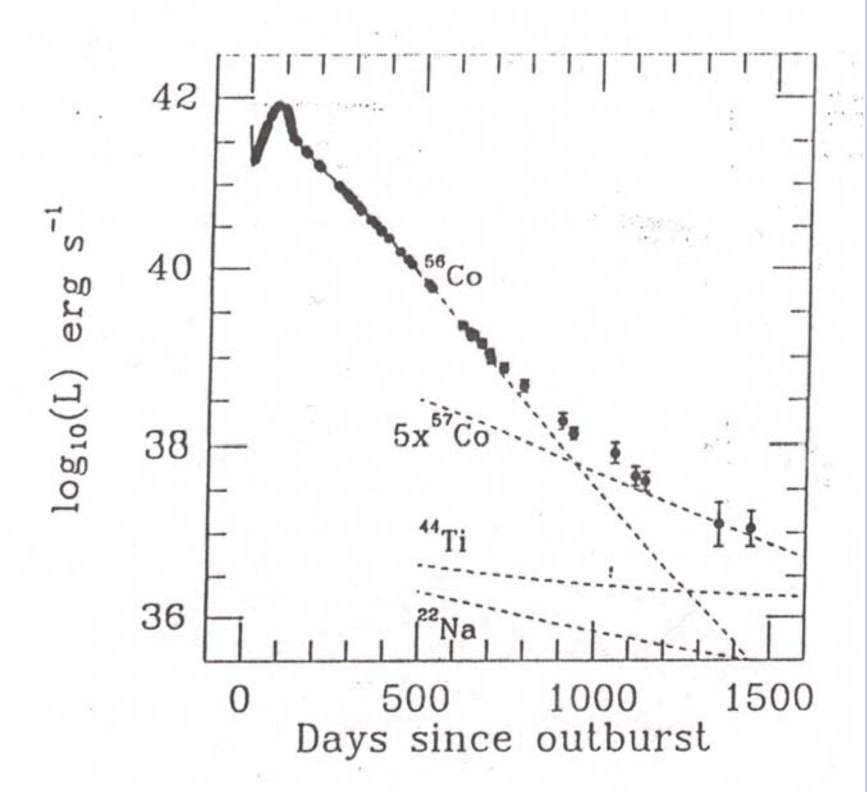
Other energy sources in SN1987A (other isotopes, shock wave, and stellar remnant)?

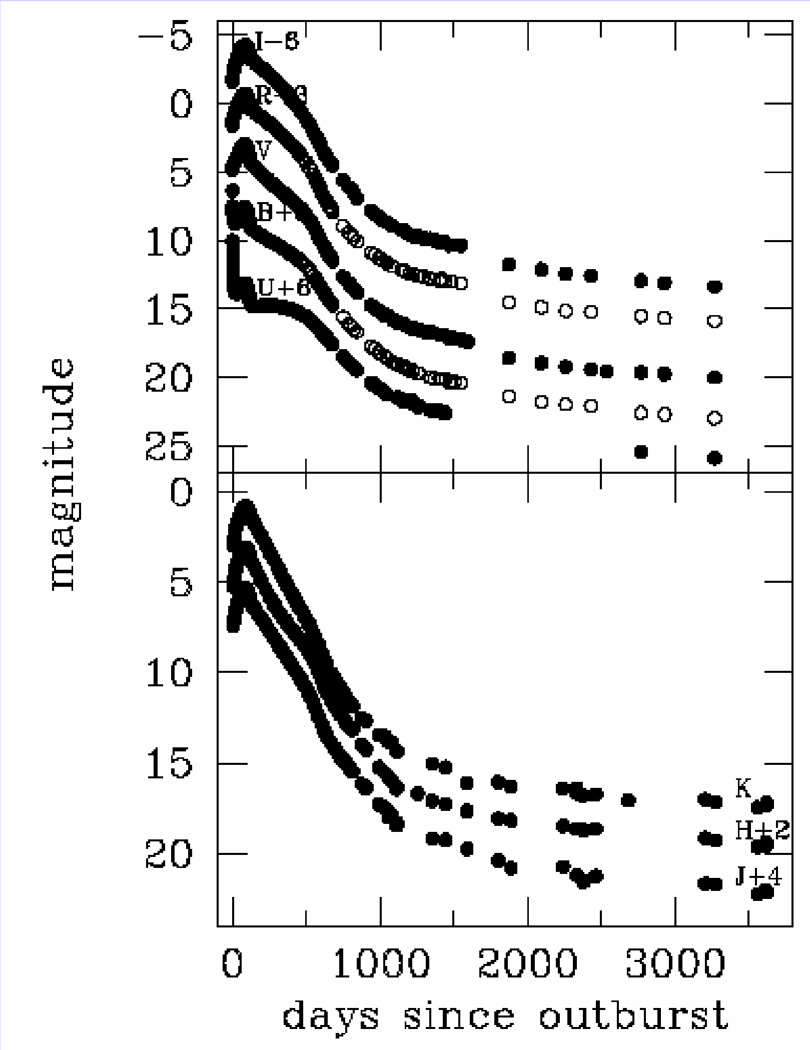
The light curve began to deviate from the exponential law in one year when the envelope became more transparent and the energy taken by X- and gamma-rays became to be notable.



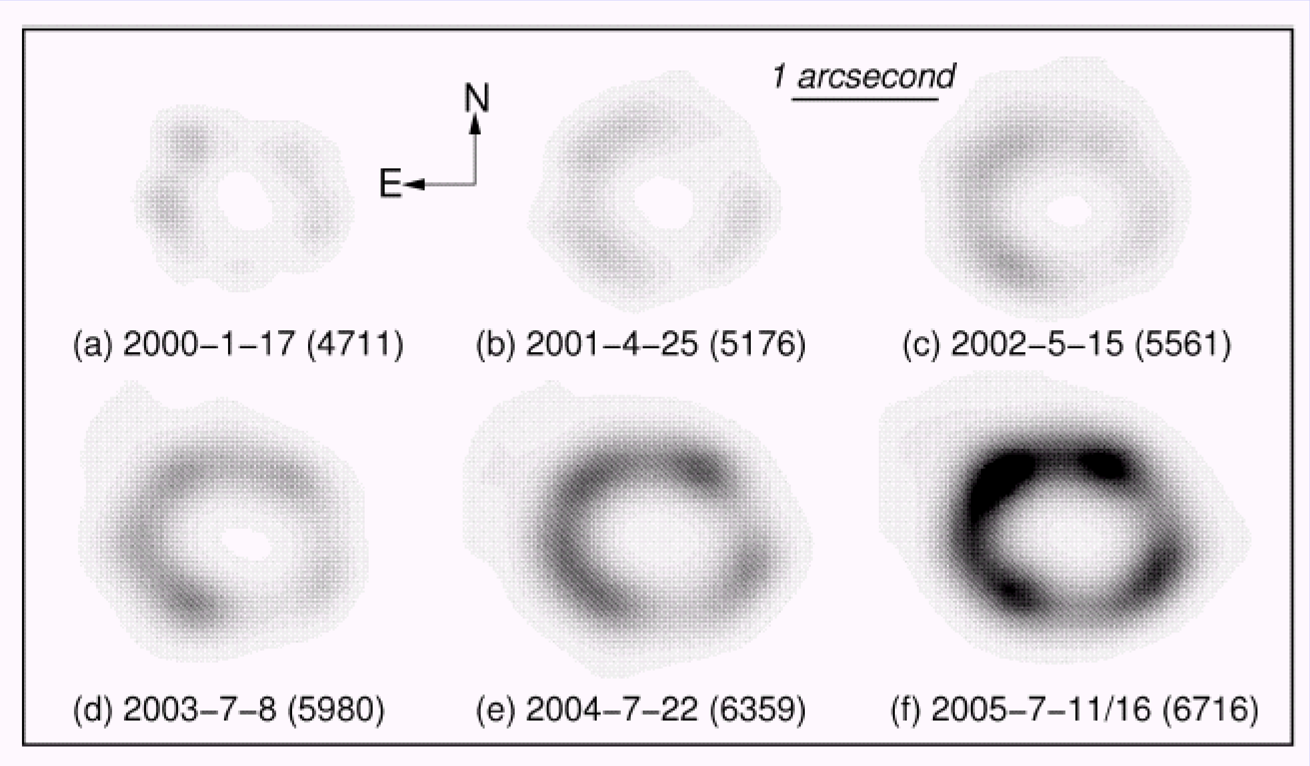
Long-term photometric light curve

After 3 years the contribution of an additional energy source (most likely ^{44}Ti) led to another change in the slope of the light curve. According to Suntzeff (1997) the remnant's luminosity was equal to (1.3-2.5)x10^{36} erg/s and changes very slowly in 10 years after explosion.



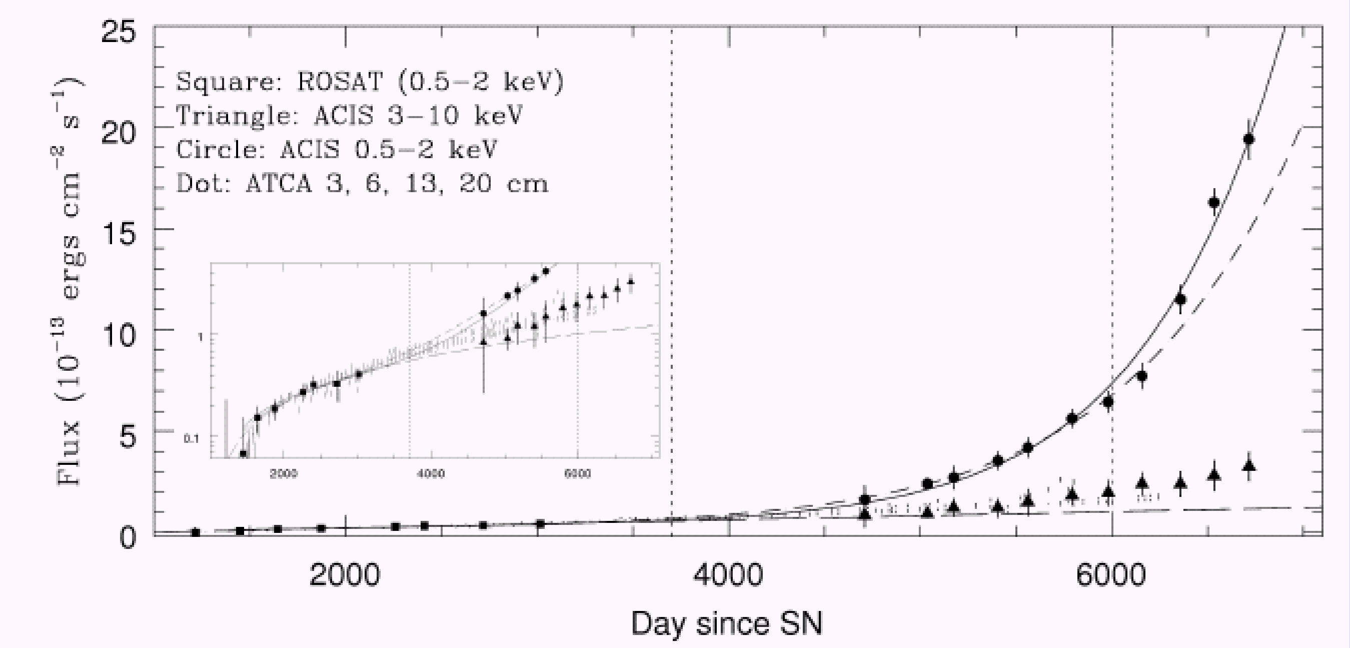


X-ray emission from the shock wave



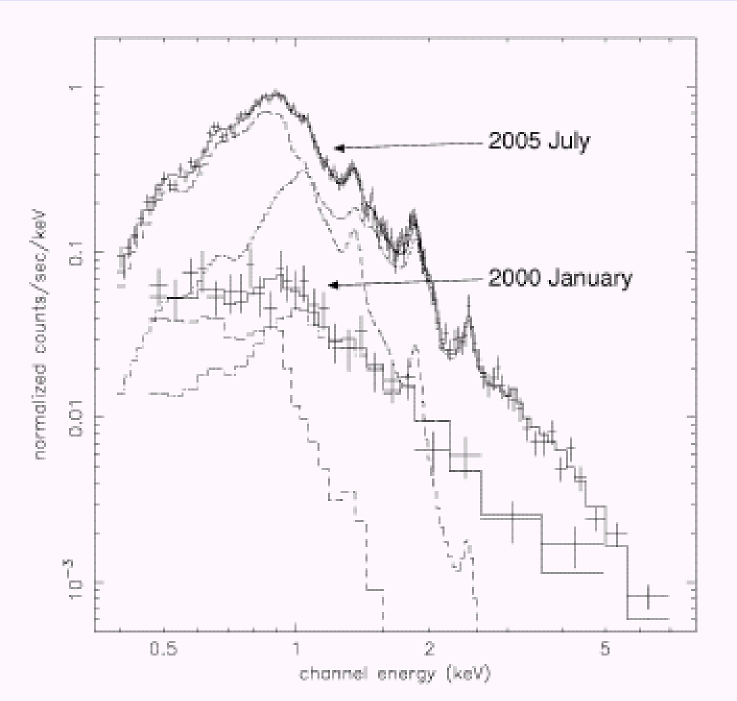
During last years Chandra observes a notable increase in the flux of soft thermal emission which is connected with interaction of the shock wave with the "inner equatorial ring" of SNR 1987A. The 0.3-8 keV ACIS images are shown (from Park et al. 2006).

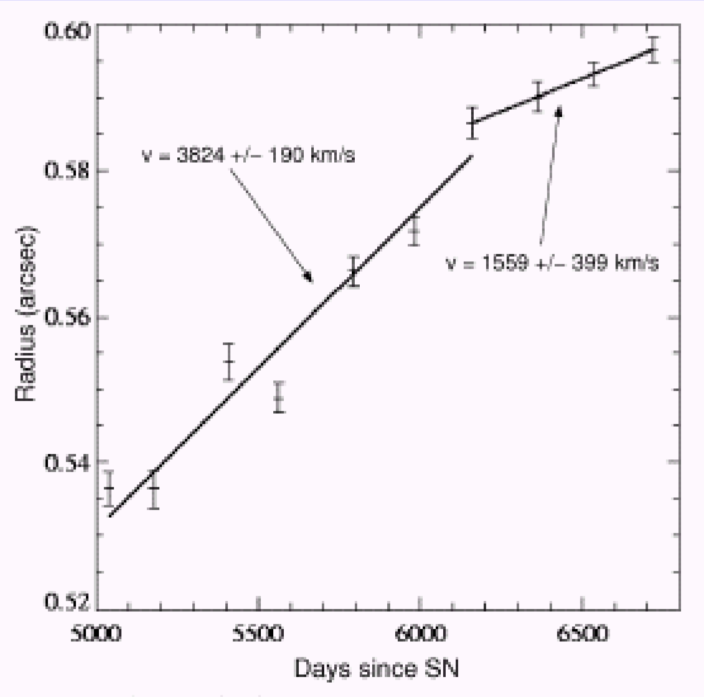
X-ray emission from the shock wave



The increase is different in the soft (0.5-2 keV) and hard (3-10 keV) bands. The hard flux correlates well with the radio flux. The luminosity of this emission increased 10 times during last 5 years and reached the value 1.6 x 10^{36} ergs/s (Park et al. 2006).

X-ray emission from the shock wave





This evolution is accompanied by softening the spectrum (from kT~3 keV at day 4600 to 2.2 keV at day 6200) and reducing the X-ray radial expansion rate (Park et al. 2006).

Chandra and XMM limits on the point source

The Chandra/ACIS 90% confidence upper limit on the observed 2-10 keV luminosity of the point source (stellar remnant of SN1987A) was 5.5×10^{33} ergs/s (Park et al. 2004).

The XMM-Newton can not resolve the source and provides a higher limit 5×10^{34} ergs/s (2-10 keV, Shtykovskiy et al. 2005, Haberl et al. 2006).

Unfortunately photoabsorption is still very strong in this rather soft energy band. For the adopted ^{56}Co distribution

$$\tau_a \sim 6\ (E_\gamma / 10\ \mathrm{keV})^{-3}\ (t/6000\ \mathrm{days})^{-2}$$

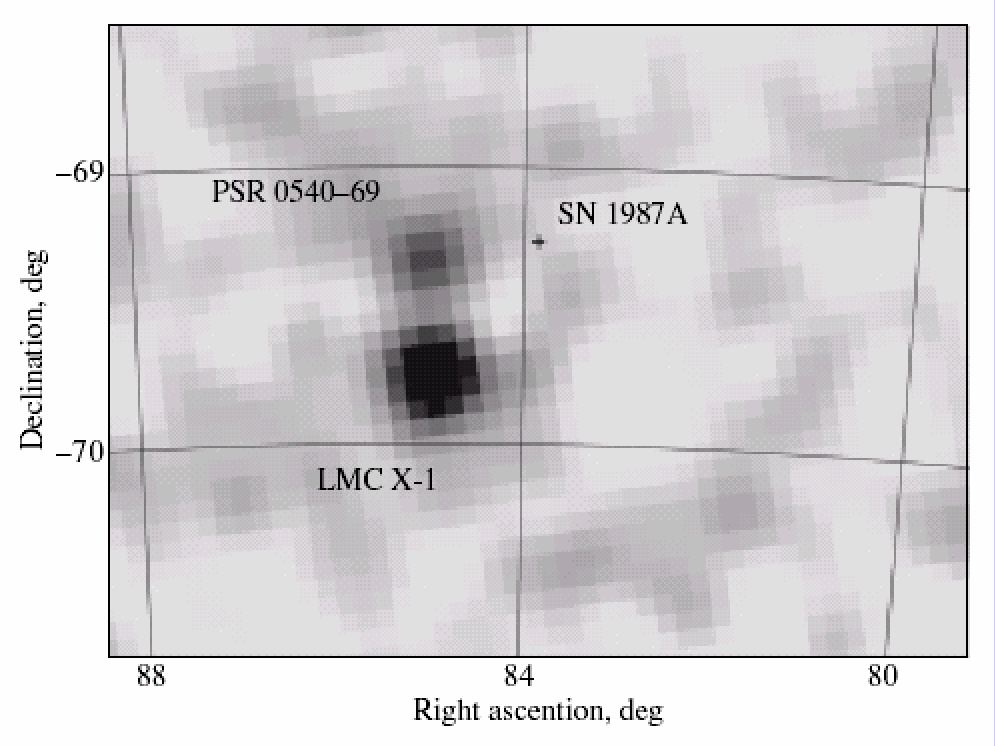
at the epoch of obtaining the above limits. The corrected luminosity will exceed 2×10^{36} ergs/s in the case of Chandra.

INTEGRAL observations

The LMC field was observed by INTEGRAL in January, 2003, with a total exposure of about 1 Ms (it was one of the first targets of INTEGRAL).

The limit (2σ) for the 20-60 keV luminosity of SN1987A was equal to 1.1 x 10^{36} ergs/s. Being extrapolated to the soft X-ray band (2-10 keV) it gives the luminosity (0.6-1.6) x 10^{36} ergs/s (Shtykovsky et al. 2004). Till now it is the strongest direct limit on the luminosity of a stellar remnant in SN1987A !!!

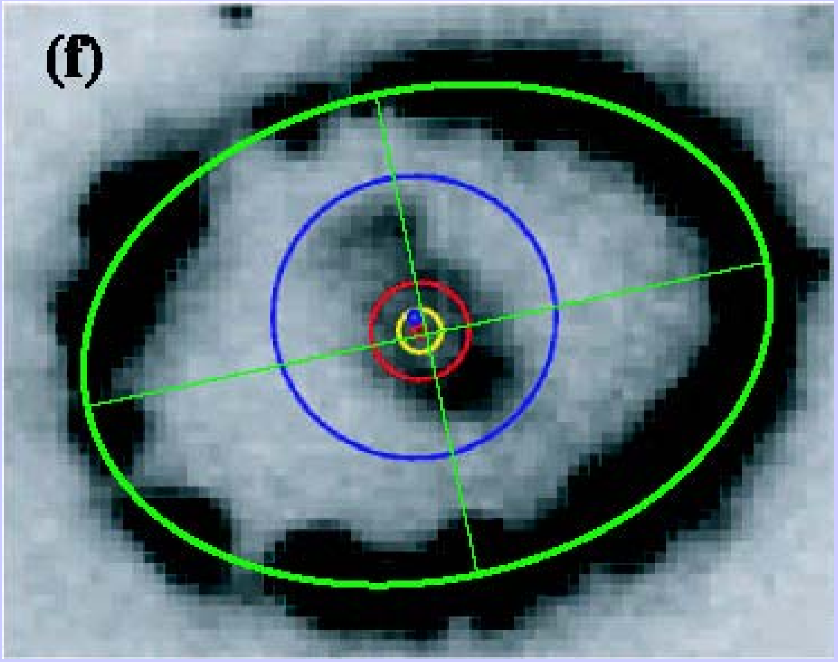
The upper limit on the mass of ^{44}Ti, $M_{44} \leq 1x10^{-3} M_{\odot}$ was obtained by measuring the flux in the lines of 68 and 78 keV. The theoretical estimate is $1.2x10^{-4} M_{\odot}$.



ISGRI/IBIS (20-60 keV)

Hubble limit on the point source

The limit for any continuum emitter in the broad optical band at the center of SNR 1987A was found to be L_{opt}=8x10^{33} ergs/s (Graves et al. 2005).



Comparison with point source in other SNRs

TABLE 4
Comparison with Point Sources in Other SNRs

SNR	Source	log L_X (ergs s^{-1})	log L_{opt} (ergs s^{-1})	Age (yr)	Possible in SN 1987A?
SN 1987A	Point source	$\leq$33.74	$\leq$33.9	16.75	...
Young Pulsars					
Kes 75	PSR J1846−0258	>34.6	...	1700	N
Crab	PSR B0531+21	36.2	33.8	950	N
N158A	PSR B0540−69	36.4	33.9	1660	N
N157B	PSR J0537−6910	35.5	$\leq$33.1	5000	N
MSH 15−52	PSR B1509−58	35.3	...	1800	N
Vela	PSR B0833−45	31.3	28.8	1.1×10^4	Y
Monogem Ring	PSR B0656+14	30.2	28.2	1.1×10^5	Y
Geminga	PSR J0633+1746	30.2	27.5	3.4×10^5	Y
Nonplerionic X-Ray Point Sources in SNRs					
Cas A	Point source	33.8-34.6/33.3[c]	$\leq$29.1[d]	400	N/Y
Pup A	1E 0820−4247	33.6[e]	$\leq$30.3[d]	3000	Y
RCW 103	1E 1614−5055	33.9[e]	$\leq$30.8[d]	8000	N
PKS 1209−52	1E 1207−5209	33.1[e]	$\leq$30.1[d]	7000	Y
Anomalous X-Ray Pulsars					
Kes 73	1E 1841−045	35.5	...	$\leq$2000	N
G29.6+0.1	AX J1845−0258	38.6/34.9[e]	...	$\leq$8000	N
CTB 109	1E 2259+586	36.9[f]	...	8800	N
Soft Gamma Repeaters					
G42.8+0.6?	SGR 1900+14	34.6[d]	...	10^4	N
G337.0−0.1?	SGR 1627−41	35.8	...	5000	N

from Graves et al. (2005).