Hard X-ray continuum emission of young SNRs

Hard X-ray (> 10 keV) emission is significant only in young supernova remnants (less than a few thousand years). It is associated with accelerated electrons. The emission mechanism is twofold:

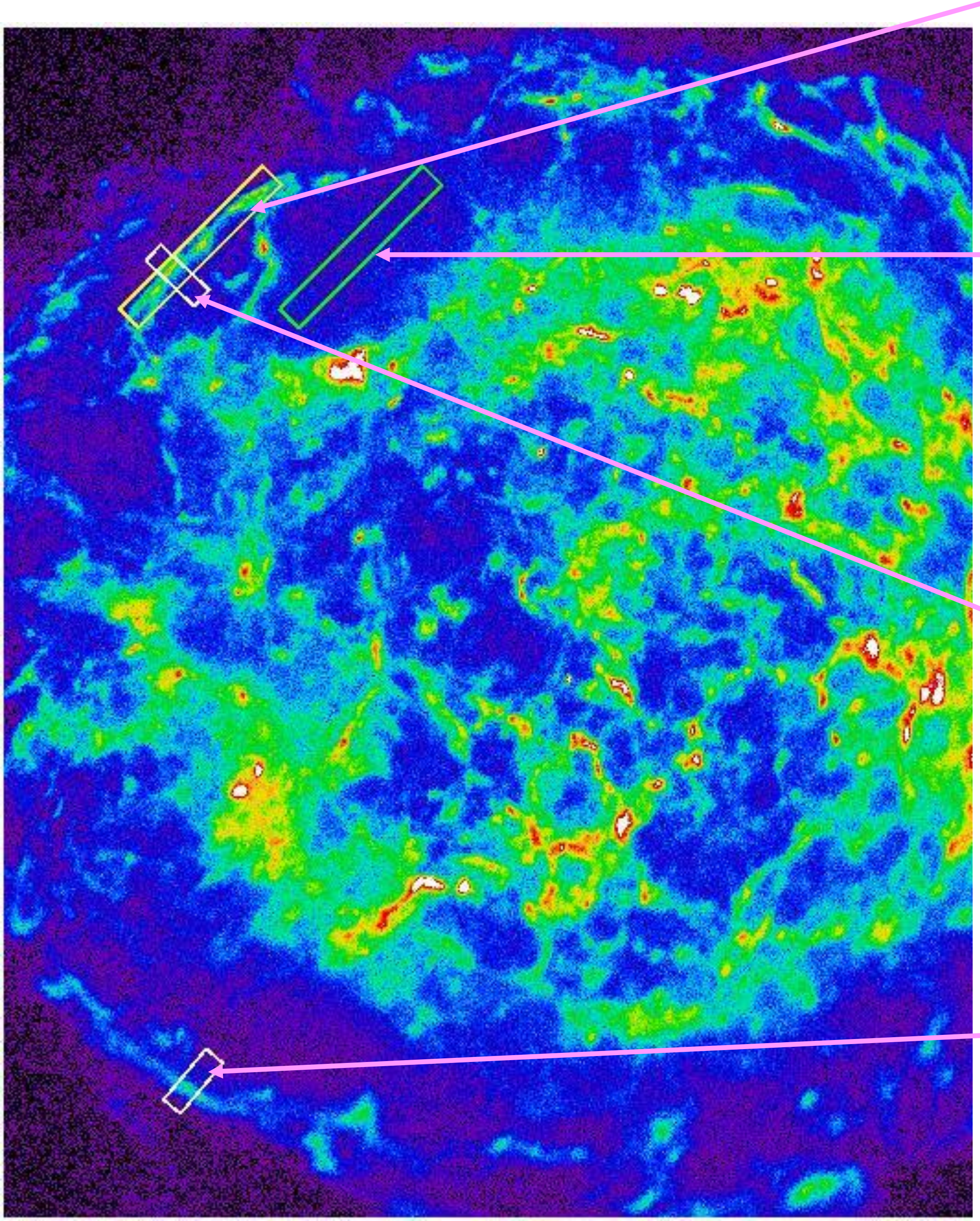
❑ Synchrotron due to very high energy (> 1 TeV) electrons, close to the maximum energies reached by electrons

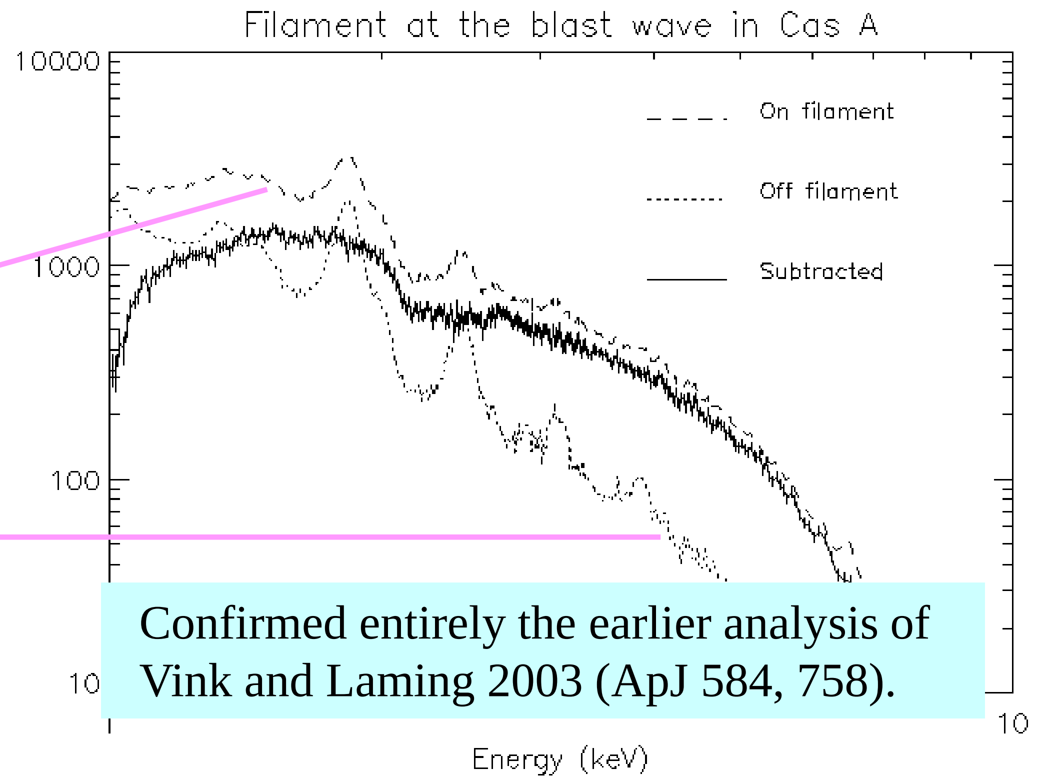
❑ Bremsstrahlung due to low energy (< 1 MeV) electrons, close to the injection energy

What is known today above 10 keV ? Integrated flux and power law index. No spatial information…pending NuSTAR

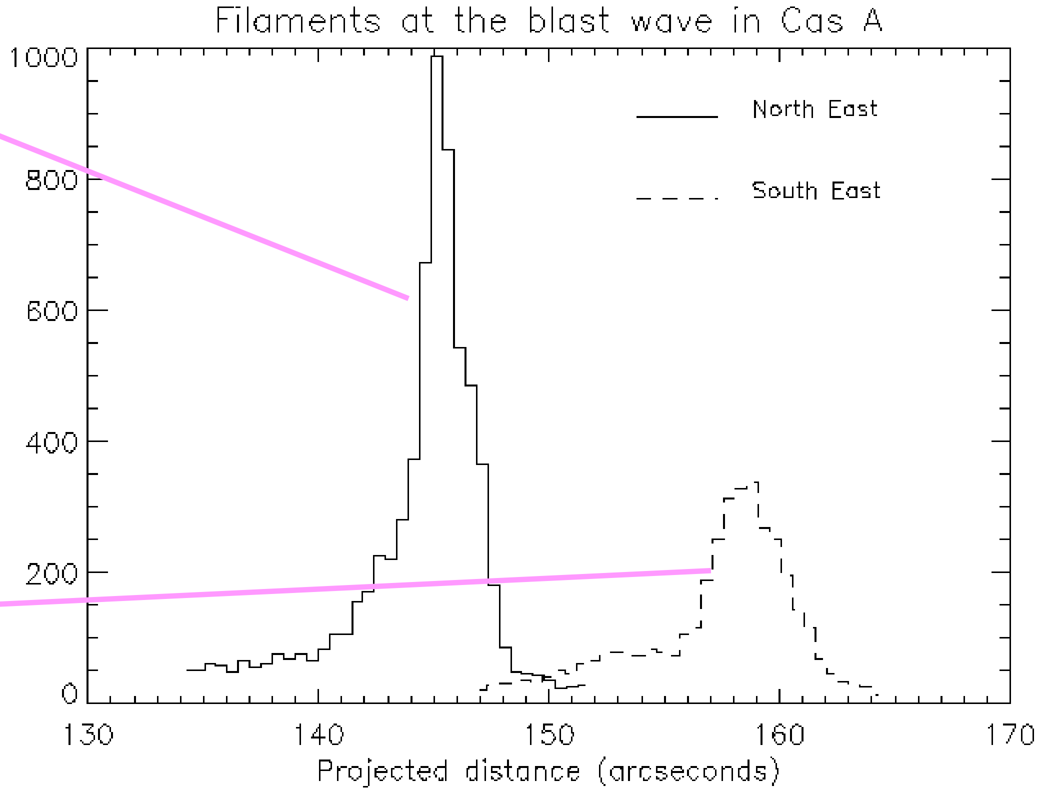
Cas A, continuum band (4 to 6 keV)

1 Ms, square root color coding

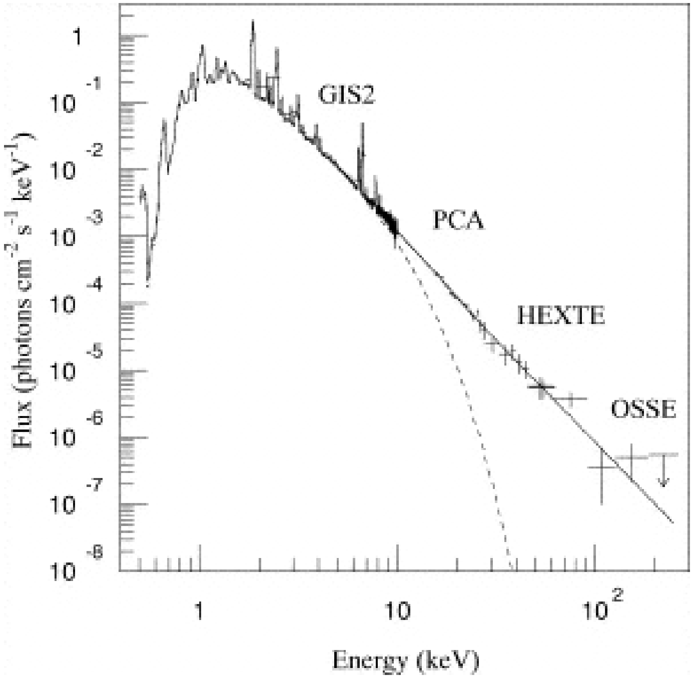




Confirmed entirely the earlier analysis of Vink and Laming 2003 (ApJ 584, 758).



High energy X-ray continuum in Cas A



Allen et al. 1997, ApJ 487, L97

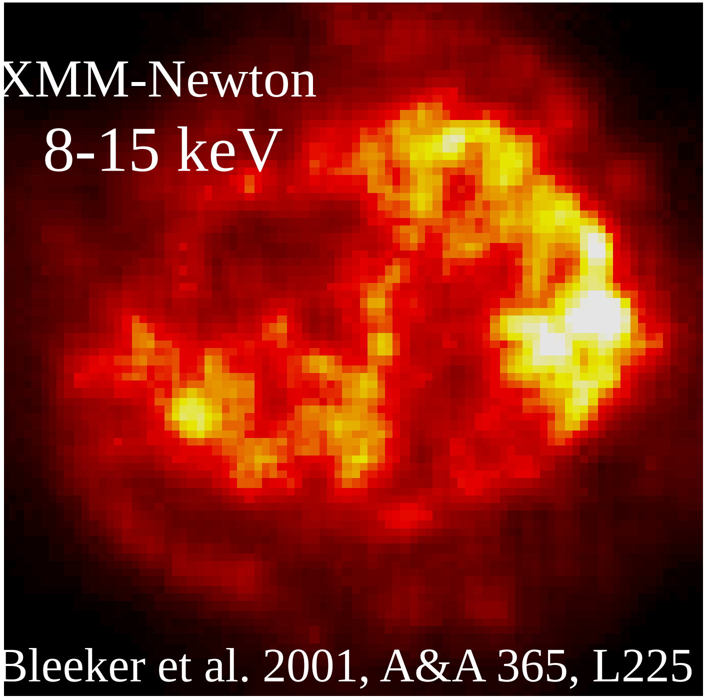
Strong radio, weak inverse Compton on IR

⇒ large B ~ 1 mG

High energy continuum associated with the ejecta => **possibly not X-ray synchrotron but non-thermal bremsstrahlung at the interface**

Particle acceleration at secondary shocks

(Vink & Laming 2003, ApJ 584, 758)



XMM-Newton

8-15 keV

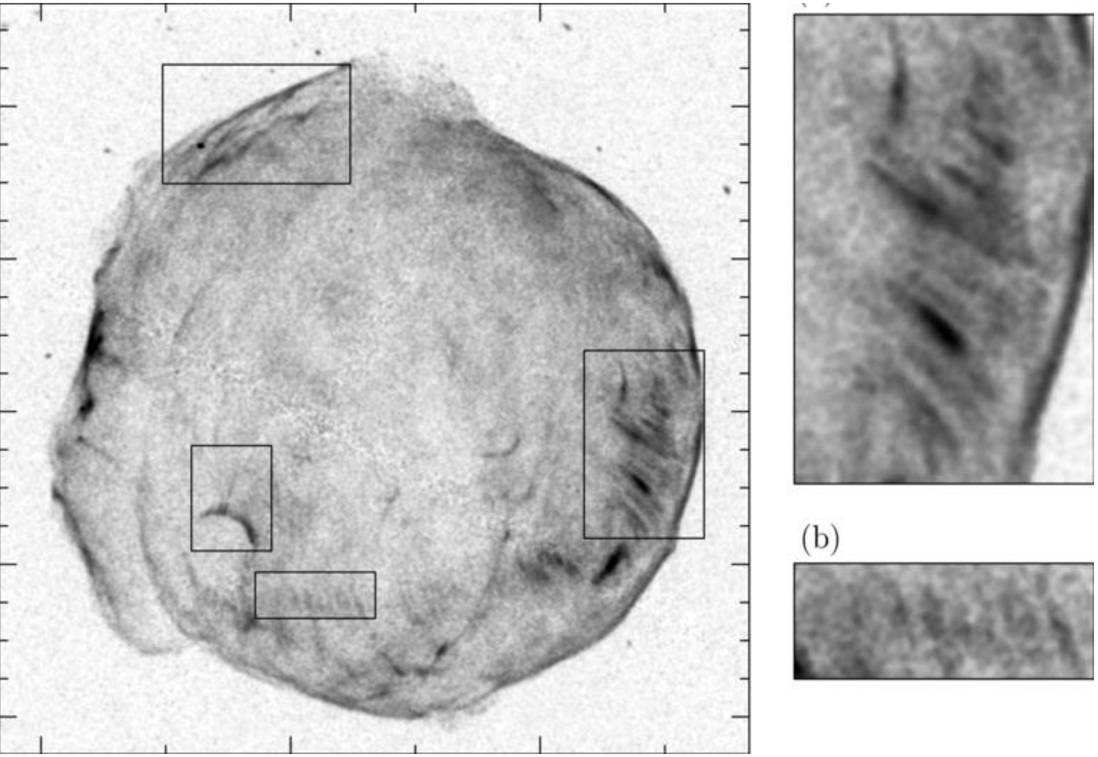
Bleeker et al. 2001, A&A 365, L225

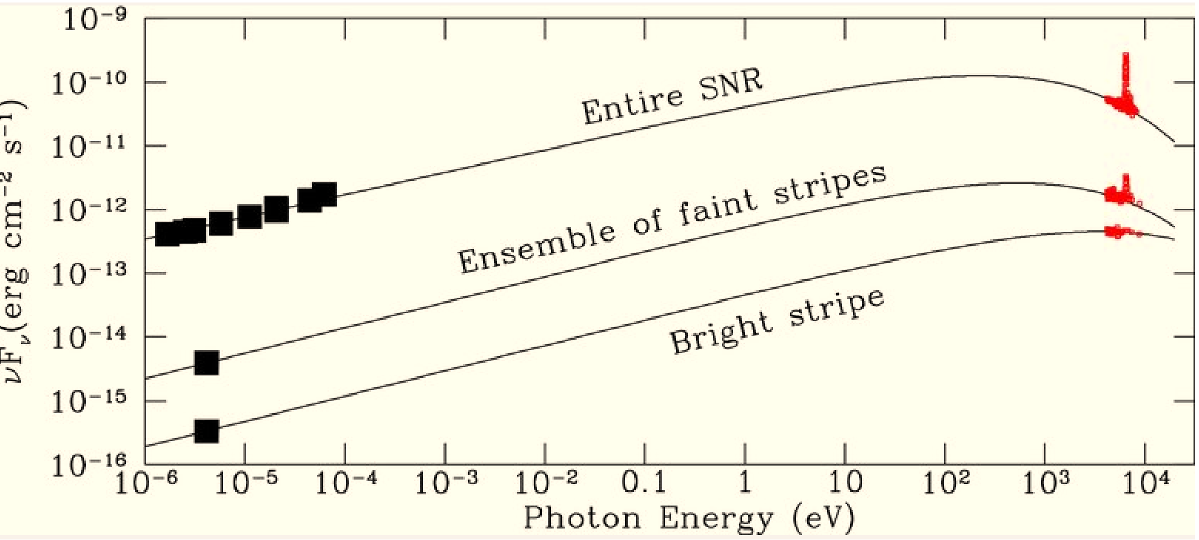
Relatively soft power-law (Γ ~ 3).

Resolving it spatially important to associate the hard X-ray emission with the complex X-ray morphology. Requires an XMM-like PSF (FWHM 6”, HEW 15”).

Interesting to see how it merges with the continuum emission below 6 keV. Can the thermal precursor to the accelerated particles be identified ?

High energy X-ray continuum in Tycho





Eriksen et al. 2011, ApJ 728, L28

Image between 4 and 6 keV (no lines)

Tycho (SN Ia) is much smoother than Cas A (SN II). Probably due largely to the ambient medium (ISM vs wind)

Smaller contribution than in Cas A from the ejecta

Stripes in western region. Periodicity possibly associated to Larmor radius of highest energy protons (10^{15} eV)

Bright stripe also has particularly hard spectrum ($\Gamma = 2.1$), interpreted as smaller diffusion coefficient

Bright stripe is about 30 x 10”

Measure curvature from X-rays (as Miceli et al 2013, A&A 556, A80 tried in SN 006)

Bright rims at the forward shock

Source	Distance	Shock speed	Age	Diameter	Peak brightness (4-6 keV)
Cas A	3.4 kpc	5200 km/s	320 yr	4.5 arcmin	0.50 ph/cm^2/ks/arcmin^2
Kepler	4.8 kpc	5400 km/s	400 yr	4 arcmin	0.06 ph/cm^2/ks/arcmin^2
Tycho	3-4 kpc	5000+	430 yr	8 arcmin	0.10 ph/cm^2/ks/arcmin^2
SN 1006	2.2 kpc	5000 km/s	1000 yr	30 arcmin	0.02 ph/cm^2/ks/arcmin^2
RX J1713	1.3 kpc	4000 ?	1620 yr ?	60 arcmin	0.02 ph/cm^2/ks/arcmin^2
Vela Jr	0.75 kpc	3000 ?	3000 yr?	120 arcmin	0.02 ph/cm^2/ks/arcmin^2

All those sources are accessible with SIMBOL-X above 10 keV in 100 ks.

Cas A, Kepler and Tycho (ejecta dominated) are relatively bright but small.

The interior of Cas A is much brighter (factor 6).

The other (synchrotron dominated) SNRs are fainter and larger.

Hard X-ray continuum emission of young SNRs

- ☐ We think we have a pretty good picture of diffusive shock acceleration in young supernova remnants, but we do not have a very good measure of the X-ray curvature (predicted by theory), because the range is too narrow.
- ☐ The hard X-ray emission in Cas A is predominantly due to the interface between the ejecta and the shocked ambient medium, but its origin is poorly understood.

- ✓ Because the spectrum is so steep, extending the range beyond 50 keV will not make a big difference
- ✓ The key instrumental issue for such objects are the PSF (associate with X-ray features) and the field of view. Can be improved over NuSTAR
- ✓ The TeV is an alternative way to measure the high-energy electrons. Easier to interpret (does not depend on structured B field) but at present far behind in terms of sensitivity and PSF (several arcmin even with CTA).

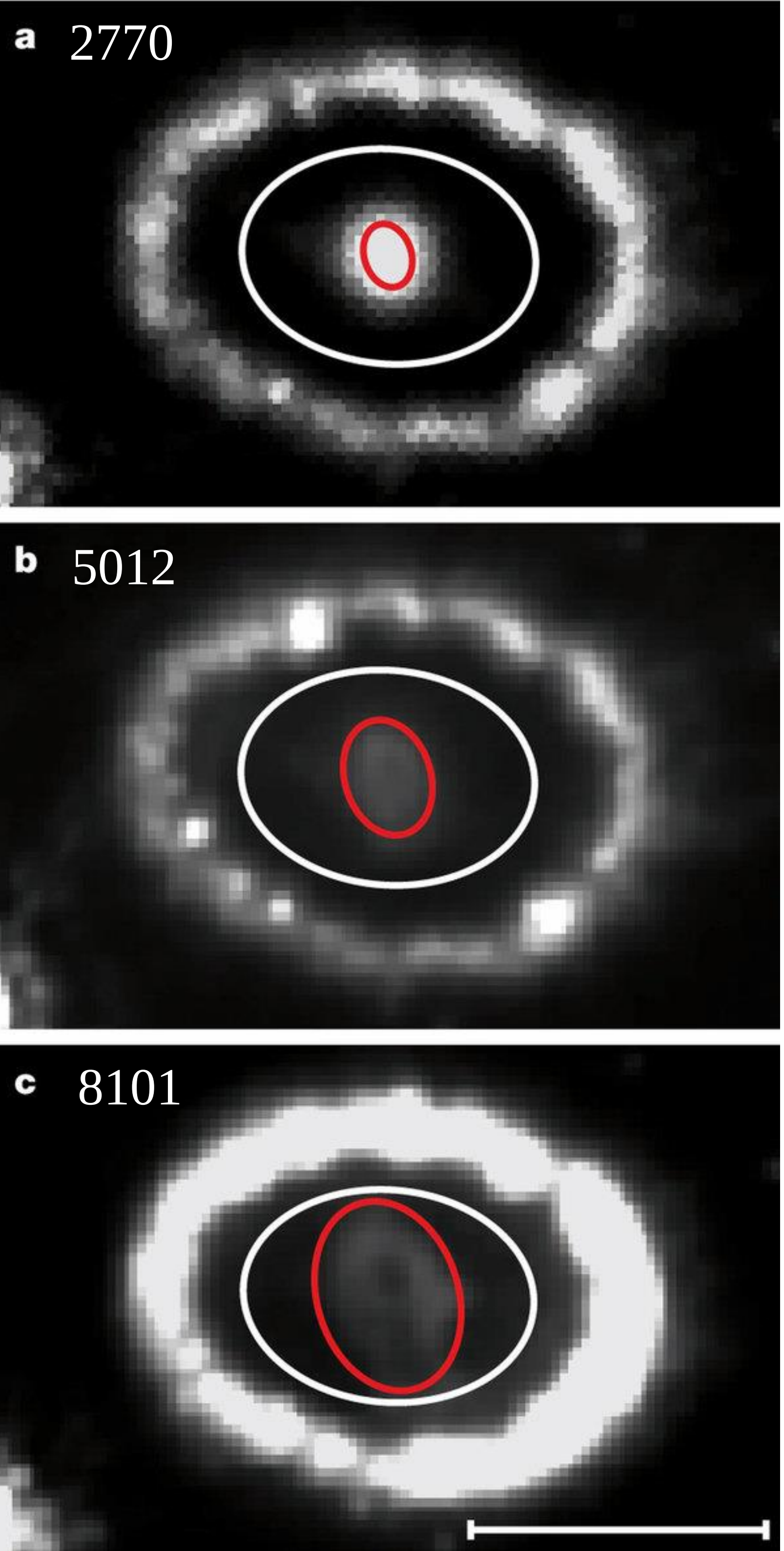
Hard X-ray line emission in young SNRs

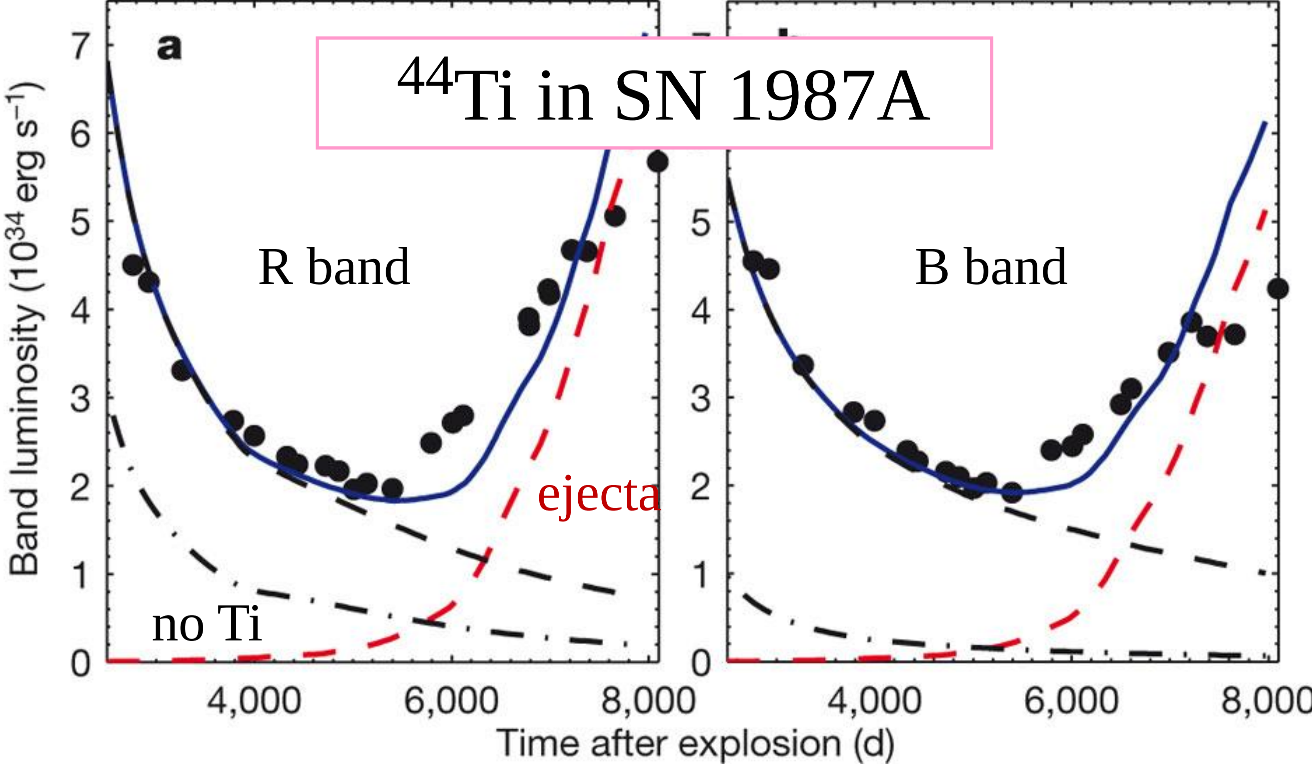
Drawing largely on M. Renaud's work

Radioactive ^{44}Ti line emission at 67.9 and 78.4 keV (nearly equal strength). Can be measured only in young supernova remnants (lifetime = 85.3 yr). Sensitive diagnostic of explosive nucleosynthesis.

- ☐ Synthesized both in core-collapse and thermonuclear SNe
- ☐ Sensitive to mass-cut in CC Sne, can reflect asymmetries
- ☐ Flux directly related to amount of ^{44}Ti if age is known (small correction if Ti is highly ionized)
- ☐ Cas A detected long ago, well measured with ISGRI. Yield 2 10^{-4} Mo, on the high end

^{44}Ti in SN 1987A





Definite need for ^{44}Ti in light curve of central ejecta

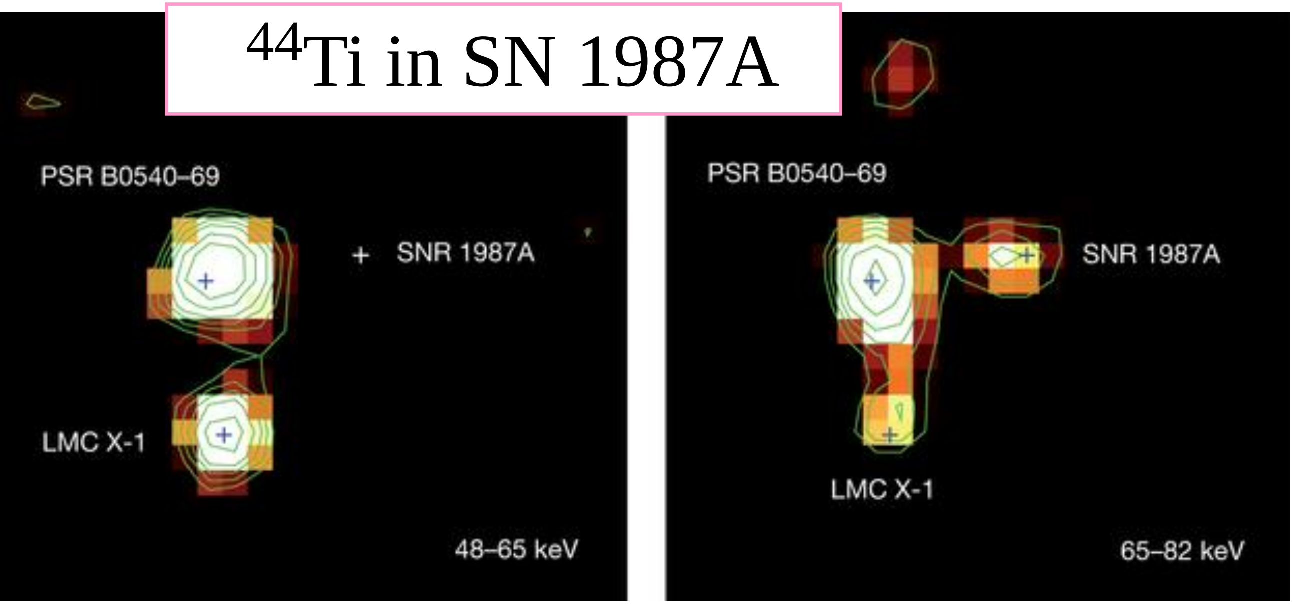
Dominated by X-ray heating from SNR after 15 years

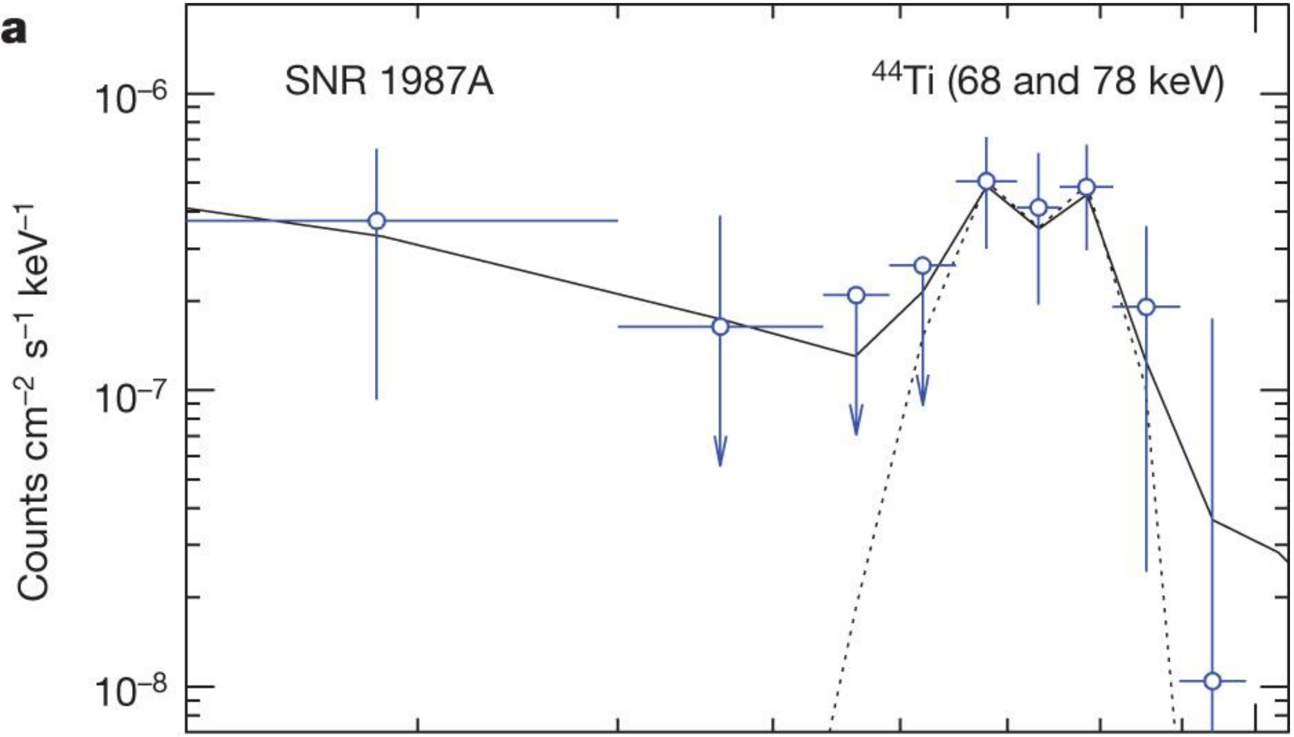
Relatively subtle modelling due to dust absorption

Requires about 1.4 10^{-4} Mo of ^{44}Ti

Larsson et al. 2011, Nature 474, 484

^{44}Ti in SN 1987A





Grebenev et al. 2012, Nature 490, 373

ISGRI 1.5 Ms in 2003 (16 yr) + 4.5 Ms in 2010-11 (24 yr)

Global detection at 4.1 σ

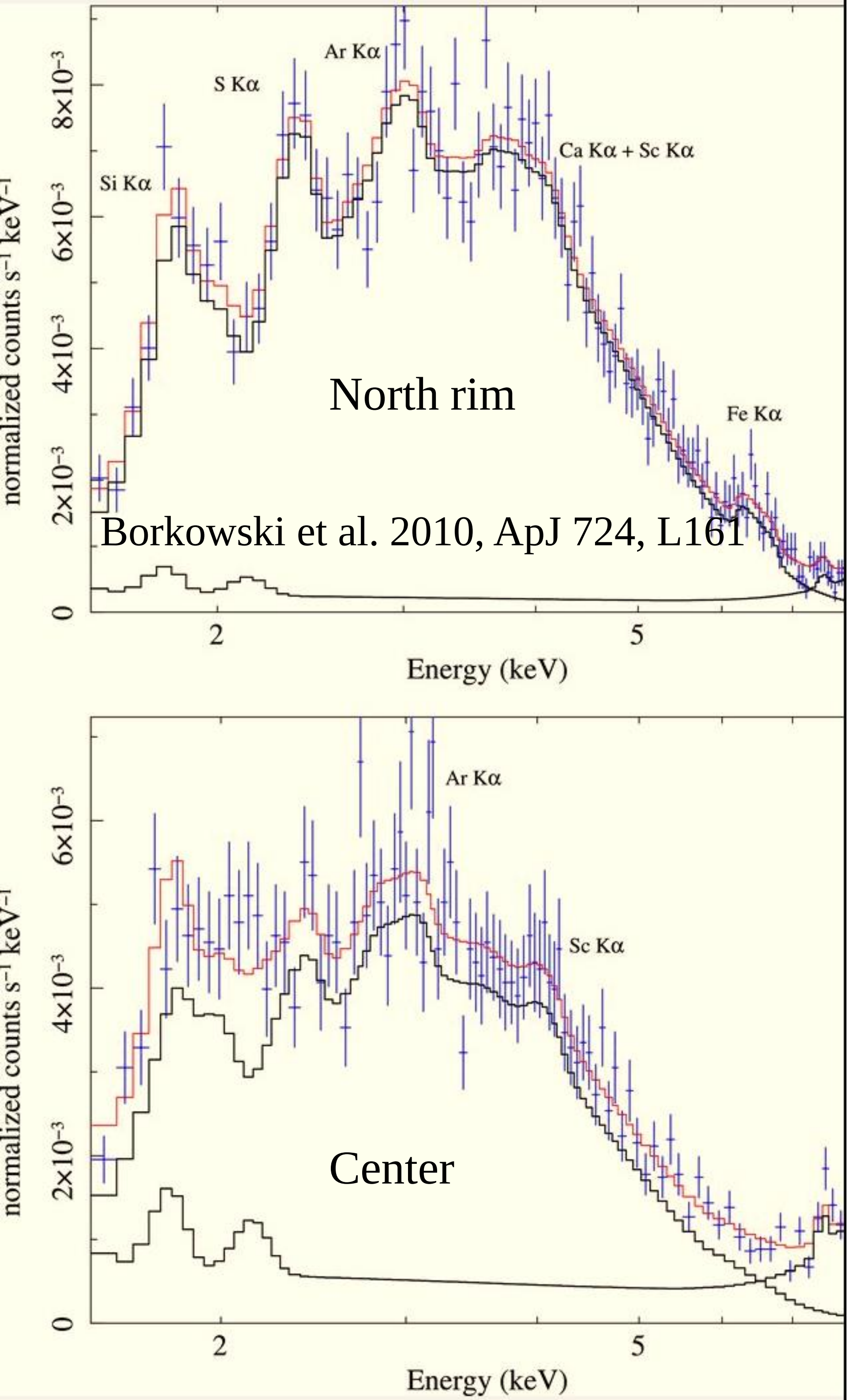
4.7 σ using the two lines

Known distance and age, no free parameter

Requires about 3 10^{-4} Mo of ^{44}Ti, at the high end of predictions

G 1.9 +0.3

Chandra 237 ks



Borkowski et al. 2010, ApJ 724, L161

Youngest SNR in the Galaxy

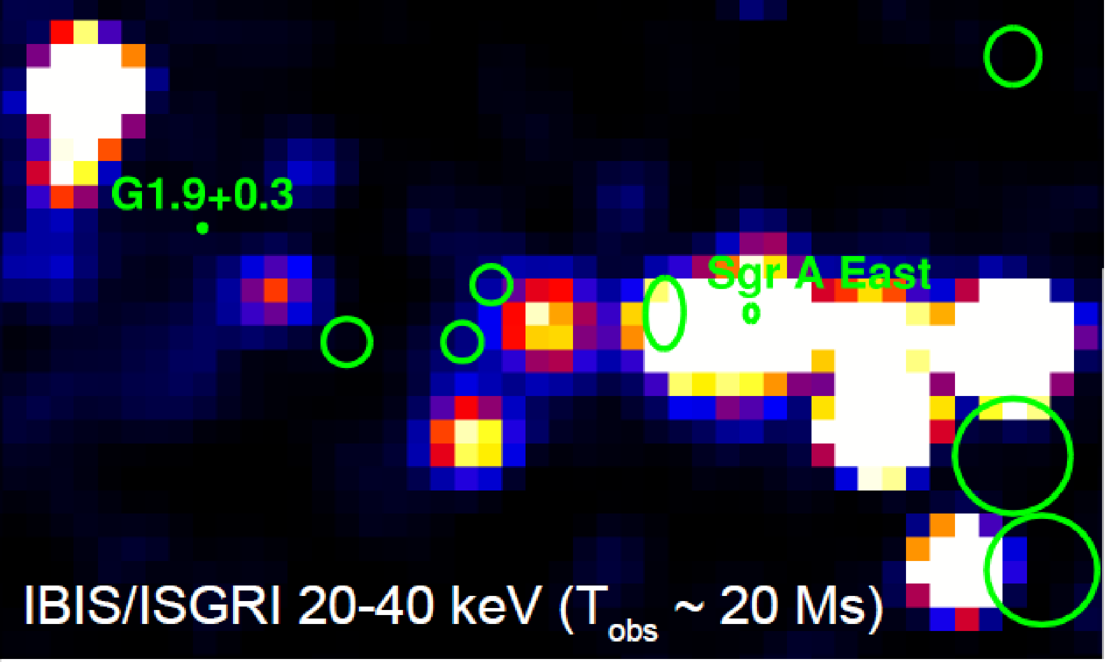
About 100 yr from radio expansion measurement between 1985 and 2008

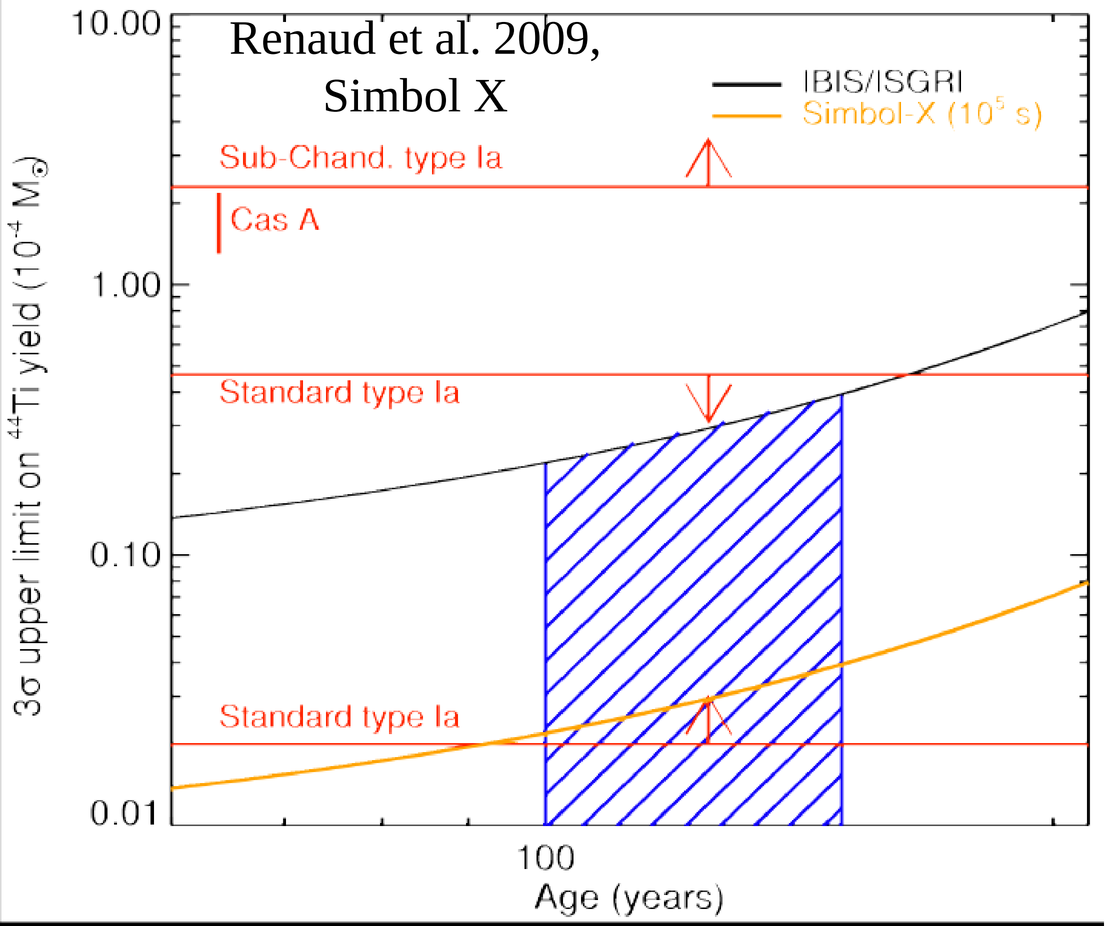
Shock velocity 14,000 km/s (assuming GC distance), tenuous ambient medium

Bright limbs synchrotron dominated in X-rays, hard spectrum

Tentative 3.4 σ detection of 4.09 keV ^{44}Sc line (child of ^{44}Ti) in interior, merged with Ca

^{44}Ti in G 1.9 +0.3




Renaud et al. 2009, Simbol X

Crowded region for ISGRI

No detection of ^{44}Ti lines

ISGRI upper limit at 2 10^{-5} Mo of ^{44}Ti for age 100 yr, slightly below the estimate from ^{44}Sc (3 10^{-5} Mo) and at the low end of predictions

Expected to be very broad (σ ≈ 3.5 keV)

Hard X-ray line emission in young SNRs

- ❑ ^{44}Ti only bright radioactive element detectable hundreds of years after explosion. Flux allows estimating precisely synthesized amount.
- ❑ Produced in both types of SNe but yield not precisely predicted

- ✓ Requires large effective area up to 80 keV
- ✓ Important to measure width (1000 km/s ⇔ 0.25 keV) and resolve for asymmetries
- ✓ Not a large number of targets
- ✓ Other line at 1.157 MeV, same strength
- ✓ X-ray ^{44}Sc can be an alternative, but not as reliable and merged with other lines. Optical light curve model dependent (and requires early observations).

Hard X-ray emission in young SNRs

Two very different scientific objectives in the same sources

- ❑ ^{44}Ti lines at 70 – 80 keV from supernova (nucleosynthesis)
- ❑ Non-thermal continuum from electrons (shock acceleration)

- ✓ Lines require good spectroscopy and band up to 100 keV
- ✓ Continuum requires good PSF and large enough FOV (XMM-like)
- ✓ No timing requirements
- ✓ Cannot be driver for hard X-ray instruments (too few objects) but important complement
- ✓ Expect NuSTAR results