The Fast and the Furious:
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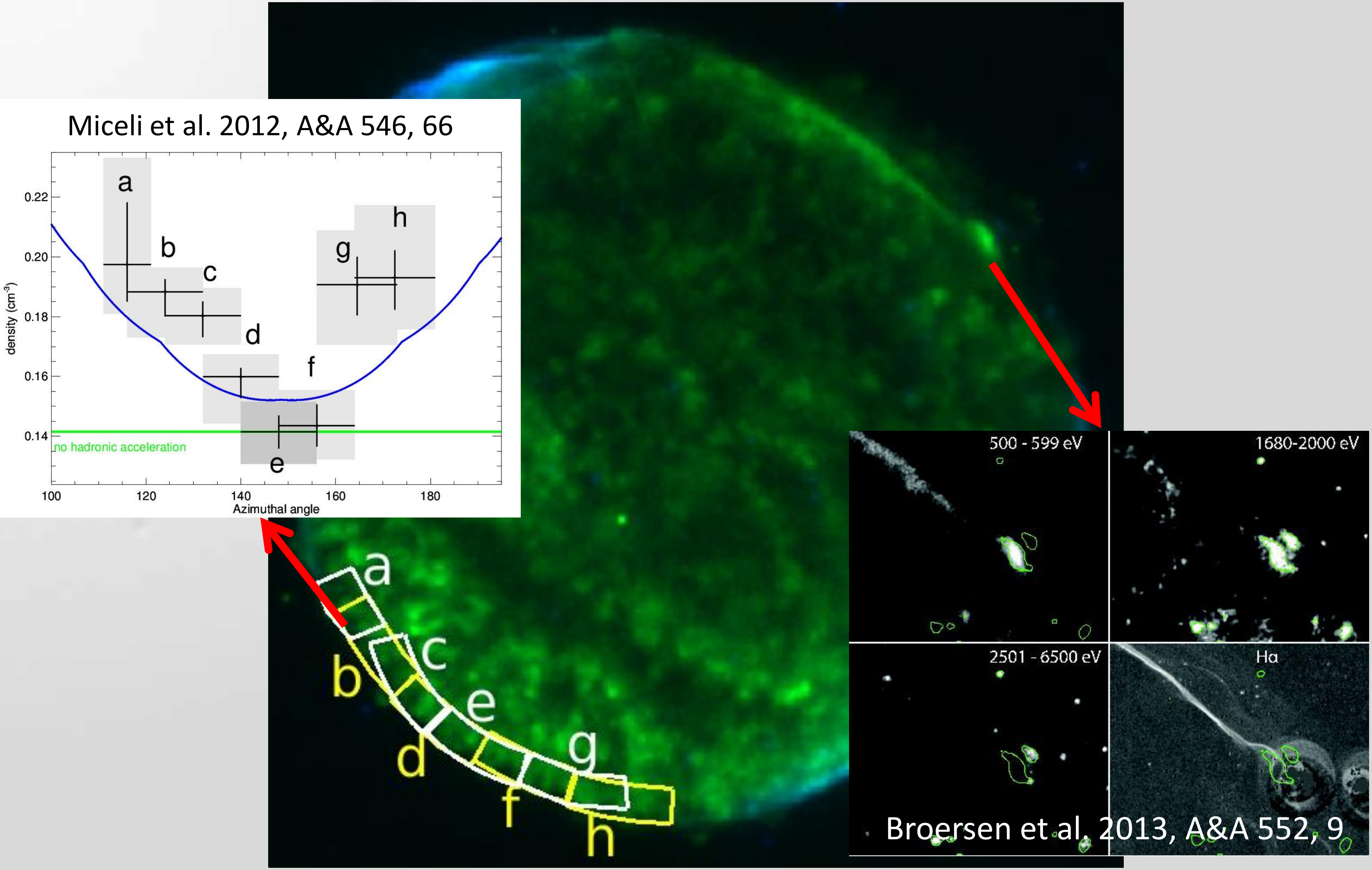
The shape of the cutoff in the synchrotron emission of SN 1006 observed with XMM-Newton

Marco Miceli
INAF-Osservatorio Astronomico di Palermo

Collaborators
Fabrizio Bocchino, Anne Decourchelle, Sjors Broersen, Jacco Vink, Salvatore Orlando

SN 1006: the XMM-Newton Large Programme

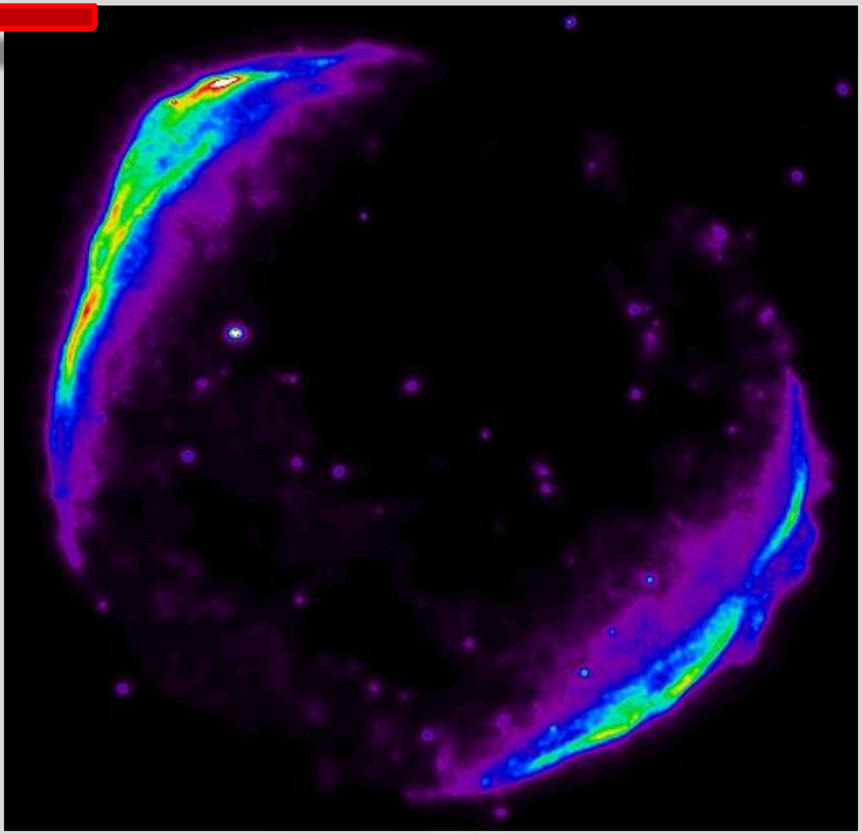
Set of EPIC and RGS observations (700 ks, PI A. Decourchelle)



Introduction

We focus on the **nonthermal limbs** to study the high-energy tail of the electrons accelerated at the shock front.

We aim at obtaining information on the **physical mechanism that limit the electron energy**.

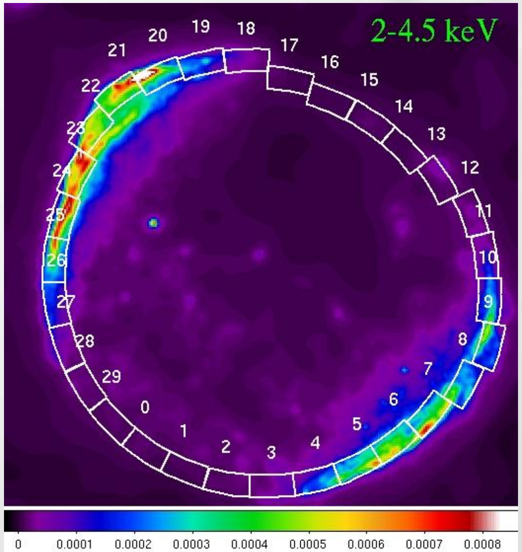


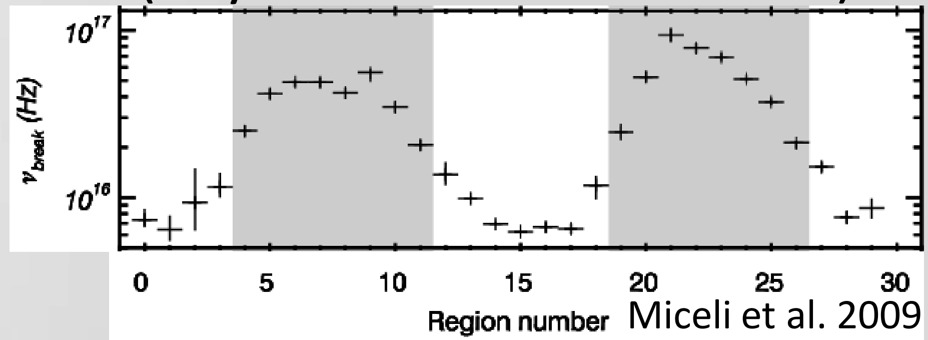
Three possible scenarios have been proposed (Reynolds 2008):

- **Loss limited:** energy limited by the radiative losses ($E_{max} \propto B^{-0.5}$)
- **Time limited:** limited acceleration time ($E_{max} \propto B$)
- **Escape limited:** change in the availability of MHD waves above some wavelength ($E_{max} \propto B$)

The nonthermal emission in SN 1006

SRCUT model: radiation from a power law distribution of electron energies with an exponential cutoff (Reynolds & Keohane 1999).



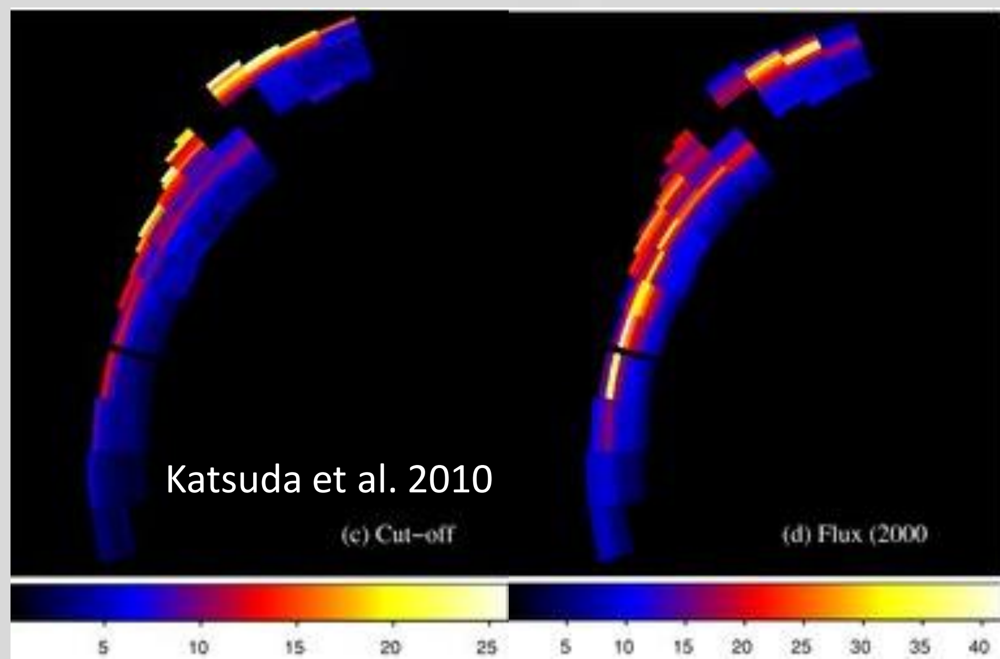


Miceli et al. 2009

Large-scale variations in cutoff energy (Rothenflug et al. 2004, Miceli et al 2009)

Small-scale variations (Katsuda et al. 2010, Decourchelle et al., in prep.)

Correlation between the flux and the cutoff frequency ➡ the cutoff frequency $\nu_{break} \propto E^2_{max} B$ depends on B? **No loss limited**



Importance of radiative losses

Radiative time scale vs. age of SN 1006

Different estimates indicate $B{\sim}100$ μG in the nonthermal limbs (Parizot et al. 2006; Morlino et al. 2010; Berezhko et al. 2012)

$$t_{sync} = 12.5 E_{100}^{-1} B_{100}^{-2} \text{ yr}$$

E_{100}: electron E in units of 100 TeV
B_{100}: magnetic field in units of 100 μG

By equating this time to the age of SN 1006 (with $B_{100}=1$) ➡ $E^*_{100}=0.012$

$$h\nu^*_{peak} = 1.8 \times 10^4 \, E_{100}^2 B_{100} = 2.7 \text{ eV}$$

At energies > E^*_{100} the spectrum is steeper by one power of E_{100}

Radiative time-scale vs. acceleration time scale

$$t_{acc} = 3/(V_1 - V_2)\,(D_1/V_1 + D_2/V_2)$$ (Drury 1983)

where, for Bohm diffusion

$$D_{1,2} = p(1/3)c^2/(qB_{1,2})$$

if B_2=100 μG and $B_1=B_2/\sqrt{11}$

- $t_{acc}=0.5\, t_{sync}$ for e^- with $h\nu_{peak}=1$ keV
- $t_{acc}=t_{sync}$ for e^- with $h\nu_{peak}=2$ keV

Signatures of a loss dominated spectrum should be detected in X-rays

Loss limited spectra vs. SRCUT

Zirakashvili & Aharonian 2007 (see also Blasi 2010) have shown that the **electron spectrum** at the shock in the loss-dominated case is

$$N(E) \propto E^{-2}[1 + a(E/E_0)^b]^c \exp[-(\mathrm{E}/\mathrm{E}_0)^2]$$ **Loss limited**

where $a = 0.66\ (0.523)$, $b = 5/2\ (9/4)$, $c = 9/5\ (2)$, for $B_2=B_1$ ($B_2=\sqrt{11}B_1$)

To be compared with the SRCUT distribution

$$N(E) \propto E^{-s} \exp(-\mathrm{E}/\mathrm{E}_{\mathrm{cut}})$$ **SRCUT**

The corresponding downstream **photon spectra** are

$$S_X^{ll} \propto h\nu^{-2}[1 + l(h\nu/h\nu_0)^m]^n \exp\left(-\sqrt{h\nu/h\nu_0}\right)$$ **Loss limited**

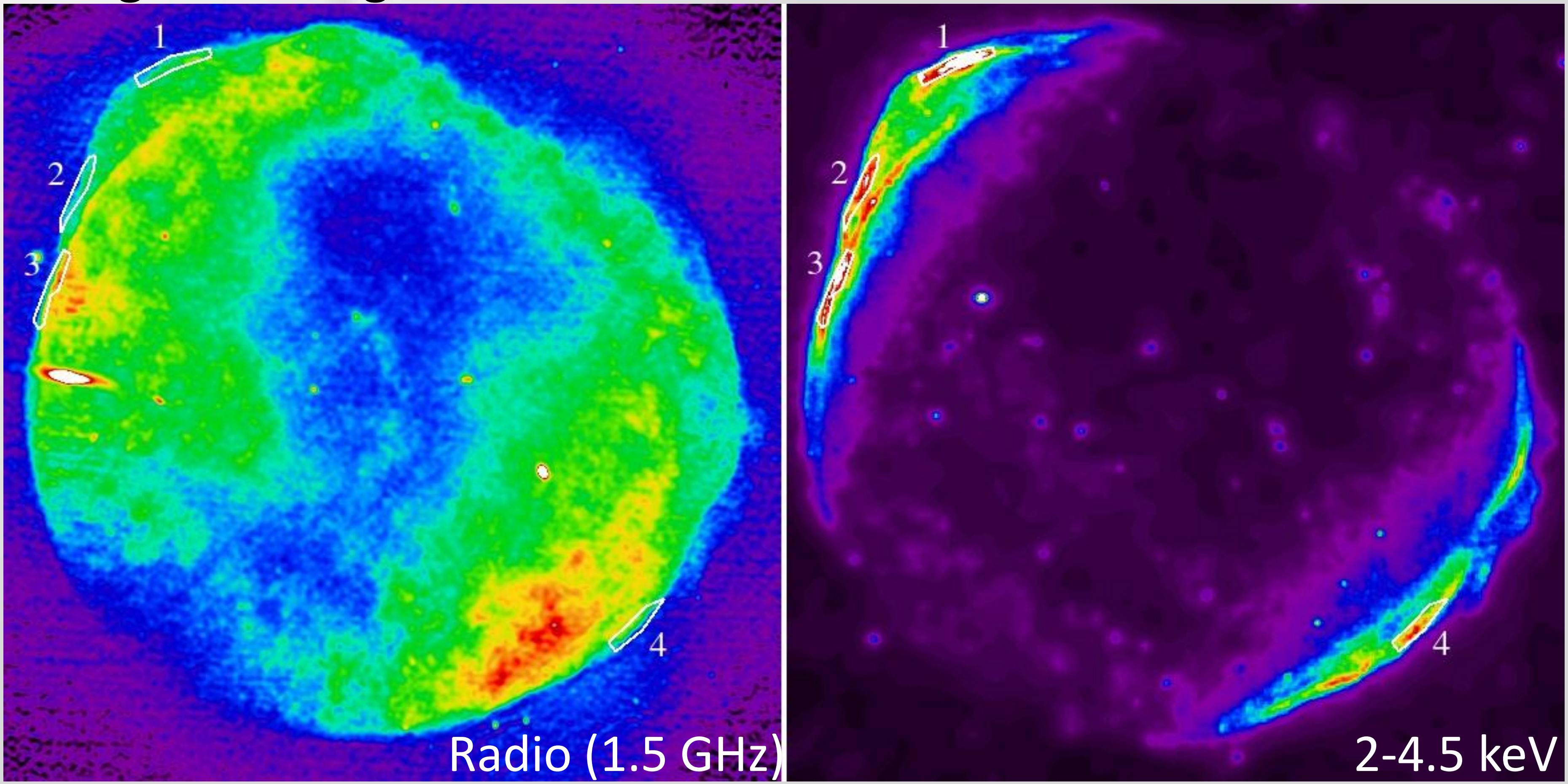
$l = 0.46\ (0.38)$, $m = 0.6\ (0.5)$, $n = 11/4.8\ (11/4)$ for $B_2=B_1$ ($B_2=\sqrt{11}B_1$)

$$S_X^{sr} \propto \nu^{-(s+1)/2} \exp[-\beta(\mathrm{h}\nu/\mathrm{h}\nu_{\mathrm{cut}})^{0.364}]$$ **SRCUT**

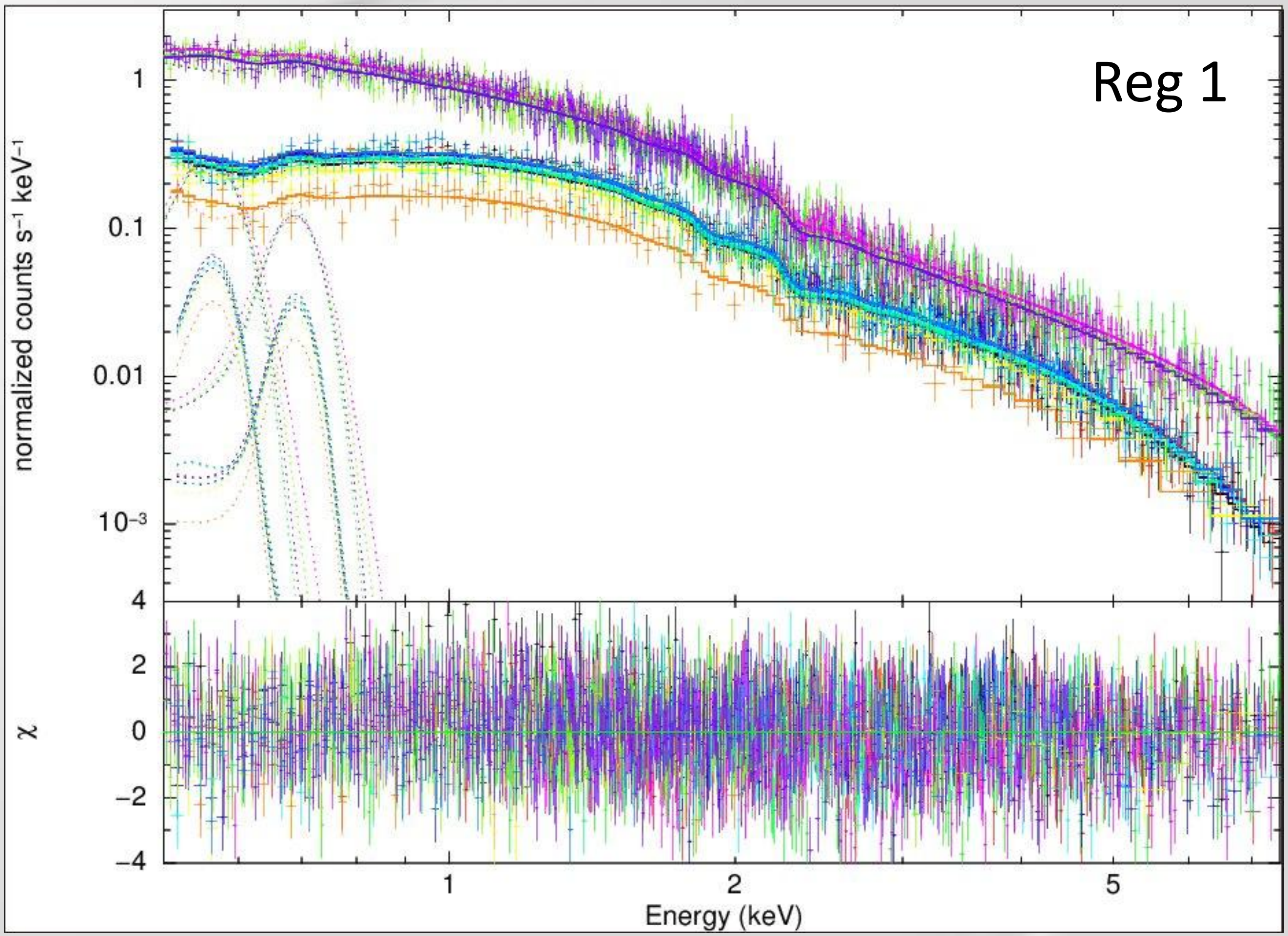
Spatially resolved spectral analysis

The loss limited model well describes the global spectrum of RX J1713.7-3946 (Zirakashvili & Aharonian 2010, Tanaka et al. 2008, Uchiyama et al. 2007) and of Tycho (Morlino& Caprioli 2012).

We here analyze X-ray spectra extracted from **narrow and spectrally homogeneous regions** at the nonthermal limbs of SN 1006

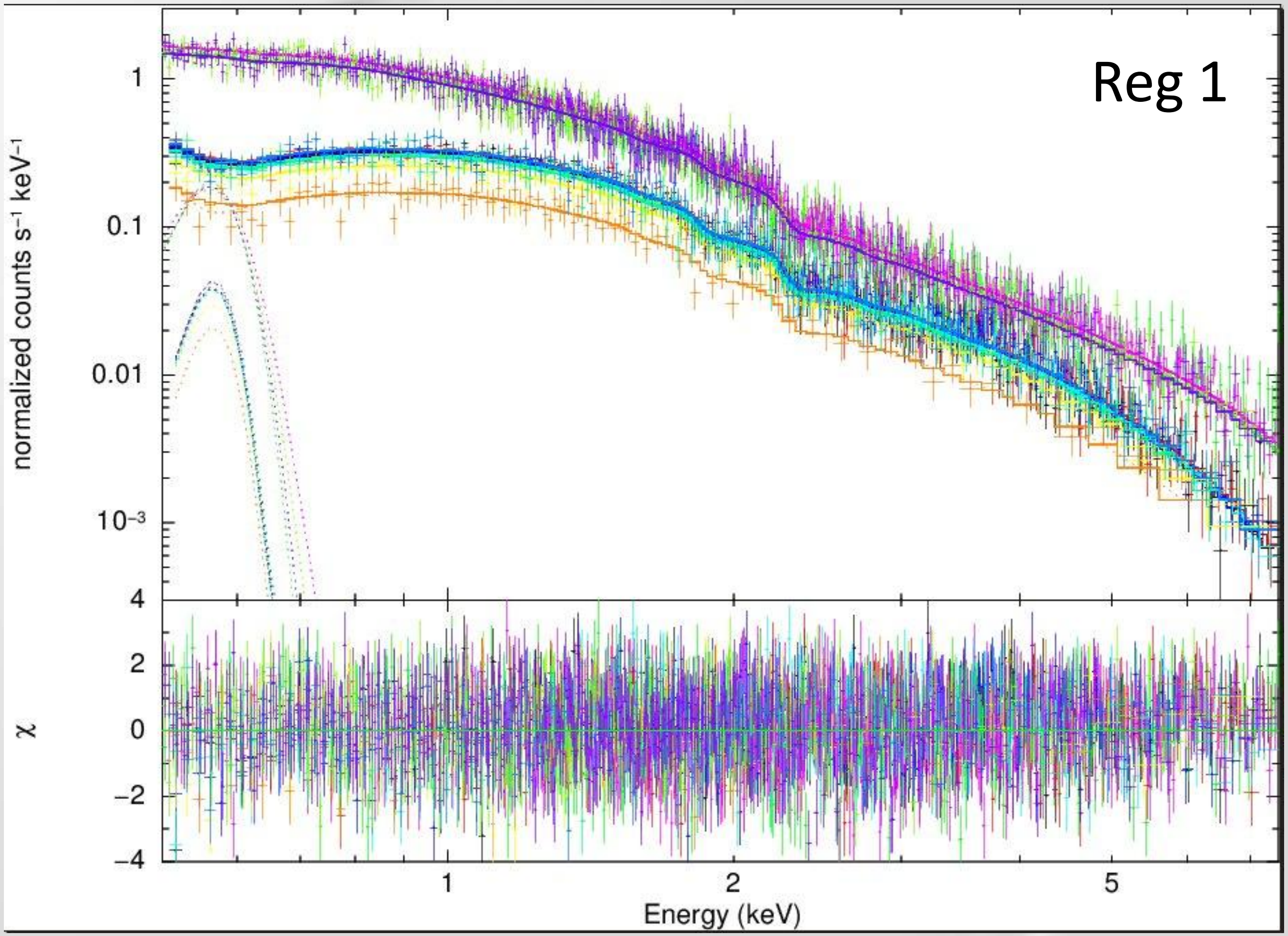


Spatially resolved spectral analysis



SRCUT: χ^2=4132.1 (3630 d. o. f.)

Spatially resolved spectral analysis

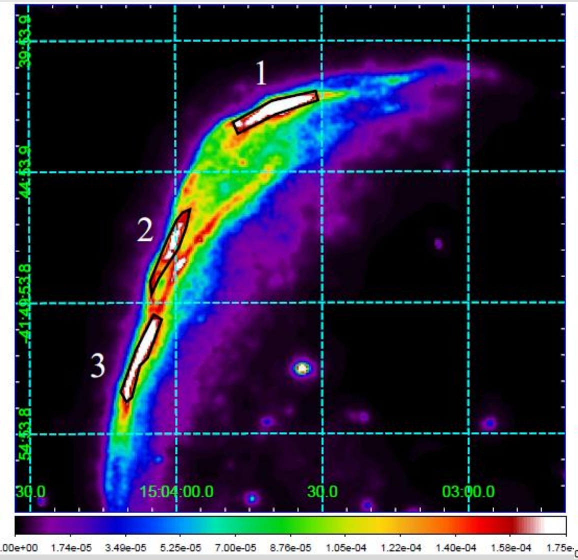


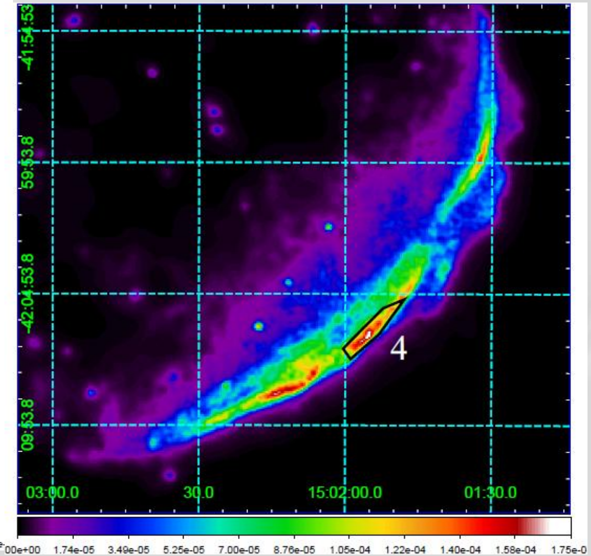
Loss limited: χ^2=3791.1 (3632 d. o. f.)

Spatially resolved spectral analysis

Parameters	Region 1	Region 2	Region 3	Region 4
SRCUT+Gaussians				
α	$0.5000^{+0.001}$	$0.5000^{+0.001}$	$0.5000^{+0.001}$	$0.5000^{+0.001}$
$h\nu_{cut}$ (keV)	$0.525^{0.002}_{-0.003}$	$0.490^{+0.002}_{-0.003}$	0.386 ± 0.002	0.423 ± 0.003
Line E1 (keV)	0.565 ± 0.004	0.56 ± 0.01	$0.569^{+0.001}_{-0.002}$	$0.572^{+0.003}_{-0.004}$
Line Norm1 (cm^{-2}/s)	$8.7 \pm 0.7 \times 10^{-5}$	$2.1 \pm 0.5 \times 10^{-5}$	$2.25 \pm 0.08 \times 10^{-5}$	$1.24 \pm 0.07 \times 10^{-5}$
Line E2 (keV)	0.69 ± 0.01	–*	0.685 ± 0.006	0.69 ± 0.01
Line Norm2 (cm^{-2}/s)	$2.0 \pm 0.3 \times 10^{-5}$	–*	$6.1 \pm 0.4 \times 10^{-5}$	$3.2^{+0.4}_{-0.3} \times 10^{-5}$
χ^2 (d. o. f.)	4132.1 (3630)	3187.5 (3016)	4505.6 (3285)	2103.9 (1512)
Loss limited+Gaussians				
$h\nu_0$ (keV)	0.448 ± 0.009	0.44 ± 0.01	0.289 ± 0.005	0.303 ± 0.008
Line E1 (keV)	0.567 ± 0.005	–*	0.569 ± 0.002	$0.569^{+0.004}_{-0.005}$
Line Norm1 (cm^{-2}/s)	$6.0 \pm 0.8 \times 10^{-5}$	–*	$1.88 \pm 0.09 \times 10^{-5}$	$9.0 \pm 0.8 \times 10^{-5}$
Line E2 (keV)	–*	–*	0.671 ± 0.008	$0.65^{+0.02}_{-0.01}$
Line Norm2 (cm^{-2}/s)	–*	–*	$3.6^{+0.5}_{-0.4} \times 10^{-5}$	$2.2 \pm 0.5 \times 10^{-5}$
χ^2 (d. o. f.)	3791.1 (3632)	3058.1 (3018)	3496.1 (3285)	1554.8 (1512)

* Model components with normalization consistent with zero at three sigmas were not included.

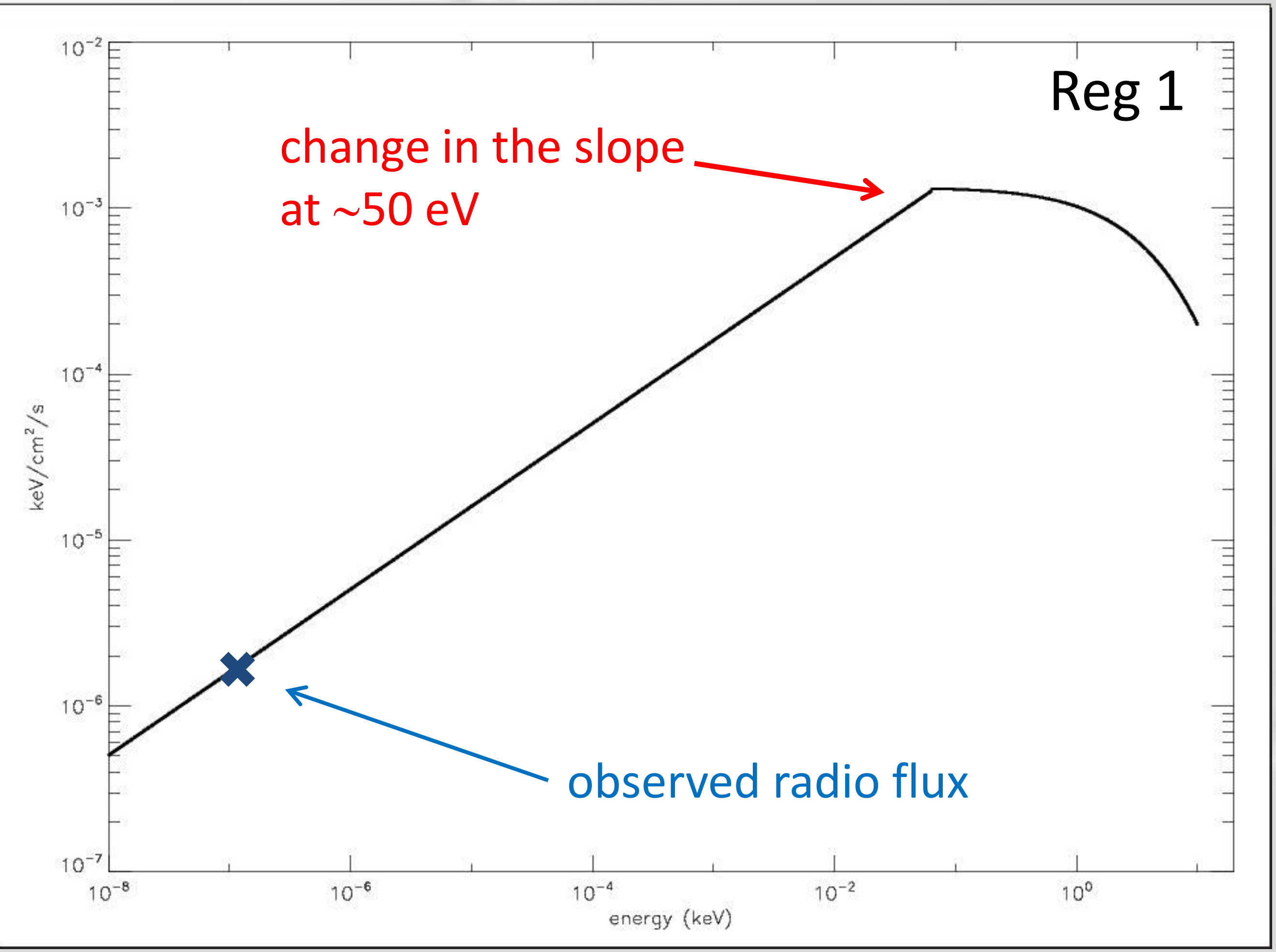




The loss limited model describes the observed emission much better than the SRCUT model **in all the regions**

Radio-X-ray emission

In the loss limited model the electron spectrum gets steeper by one power of E when the age of the remnant $\sim t_{sync}$



By using:

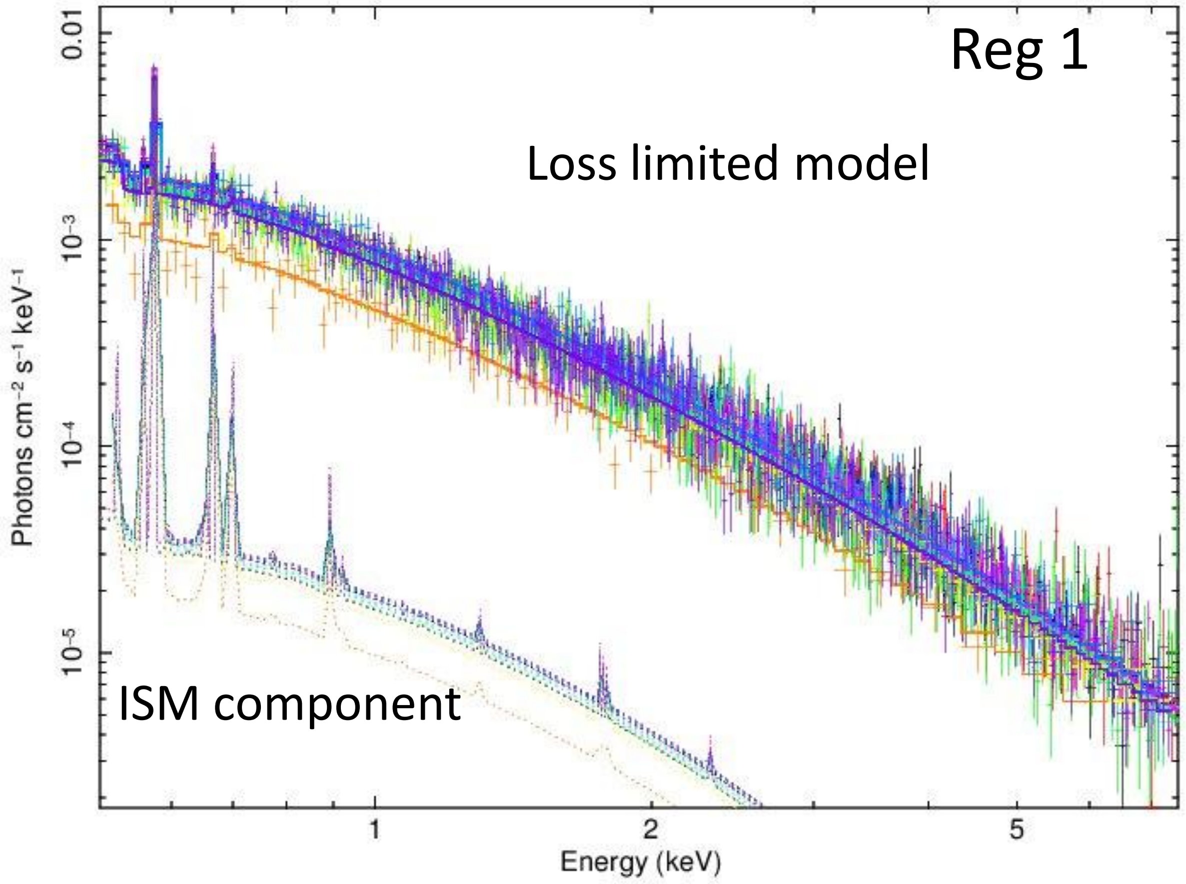
$$h\nu^*_{peak} = 1.8 \times 10^4 \; E^{*2}_{100} B_{100}$$

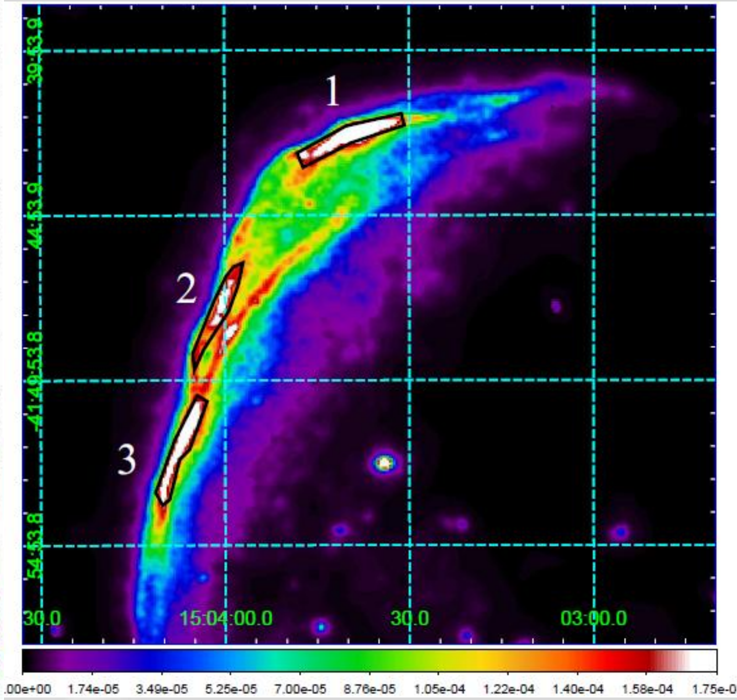
$$t_{sync} = 12.5 E^{-1}_{100} B^{-2}_{100} \; \text{yr}$$

We get an order-of-magnitude estimate of $B \sim 40$ μG, in agreement with more accurate estimates

Thermal emission

In region 1 the O VII and OVIII line emission likely originates in the shocked ISM (the ejecta are further away from the shock). We verified that it can be fitted by the ISM component adopted by Miceli et al. 2012 (by letting only the EM free to vary).





We obtain n_{ISM}~0.29 cm^{-3} in agreement with expectations

Conclusions

- The SRCUT model does not describe correctly the SN 1006 nonthermal emission
- The loss limited model provides the best description of the spectra in both nonthermal limbs
- Radiative losses shape the electron and photon spectrum and limit the maximum electron energy
- We detected shocked ISM in the nonthermal limbs and confirmed the reliability of previous estimates of the post-shock density

The correlation between cutoff frequency and X-ray flux observed by Katsuda et al. 2010 can be consistent with the loss limited scenario if the rate of particle injection and/or acceleration depends on effects not yet accounted for, as, for example the shock obliquity.