A Hard X-ray Study of Supernova Remnants

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0. Talk plan:

1. Introduction of CR acceleration
2. Unsolved problems
3. Observational results for SN 1006
4. Discussion about filaments
5. Application for other SNRs
6. Discussions about time evolution of CR acceleration
7. Future plans
8. Summary

1. Introduction

"How are cosmic rays accelerated up to TeV?"

Basic concept: Diffusive Shock Acceleration (DSA)

(Bell 1978; Blandford & Ostriker 1978...)

$E_{shock} \rightarrow E_{CR}$ like table tennis game

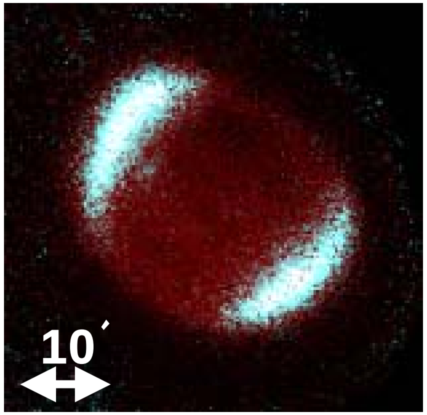
How to search the accelerators?

TeV electron → sync. emission in hard X-rays

IS B (~μG) X-rays are the best indicator

Koyama et al.(1995)

Discovery of sync. X-rays from the shell of SN 1006



SN1006: type Ia d=2.18kpc

Shocks of SNRs = cosmic ray accelerators!

.... but details are unsolved

2. Unsolved problems and how to solve?

There are many unsolved issues!

The maximum energy?
The direction and strength of mag. field?
The injection efficiency?
Time evolution of the system?

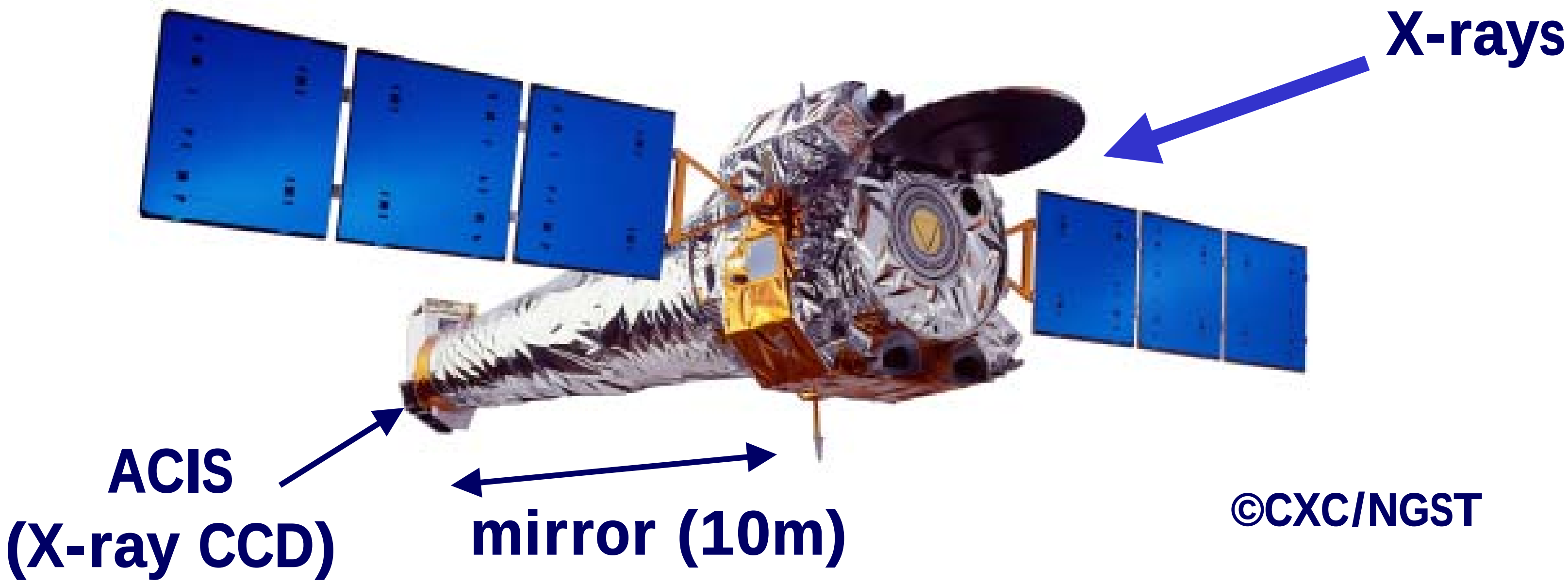
Observational information to solve

- ✓ The spatial distribution
  - their gyro radius, the turbulence of B, ...
- ✓ The spectrum of synchrotron emission
  - the maximum energy, B, ...
- ✓ The age of the system
  - the evolution of acceleration

→ Spatial resolution!

SNR Observations with Chandra (0”.5)

X-ray observatory *Chandra*



✓Excellent spatial resolution (0.5 arcsec!)

→ distributions of particles

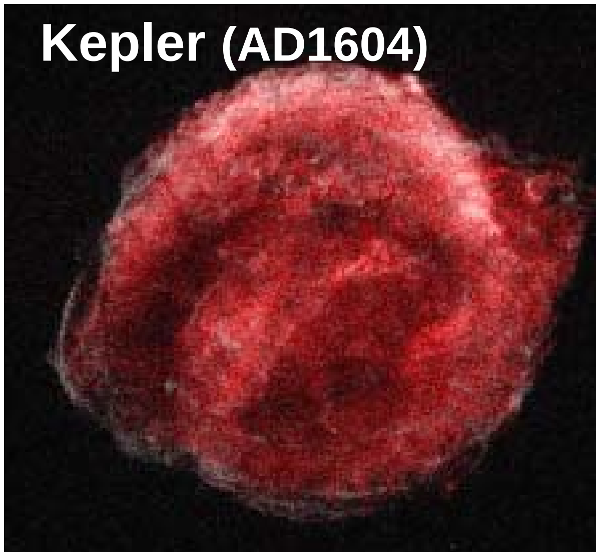
✓Good energy resolution (CCD: 130 eV@6.4 keV)

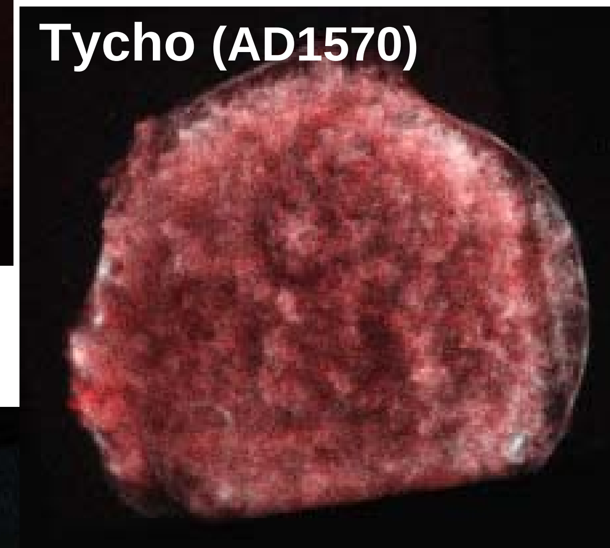
✓Wide energy range (0.3 – 10 keV)

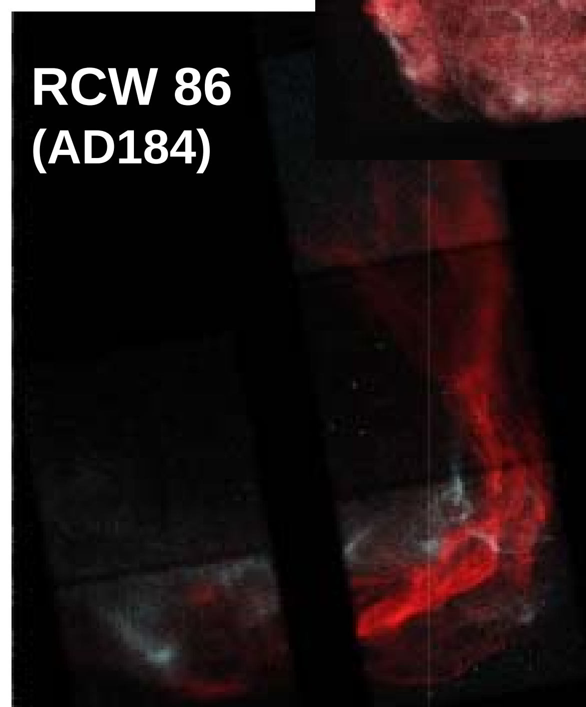
✓Wide Field of view (17arcmin x 17arcmin)

The best instrument for our study

Chandra images







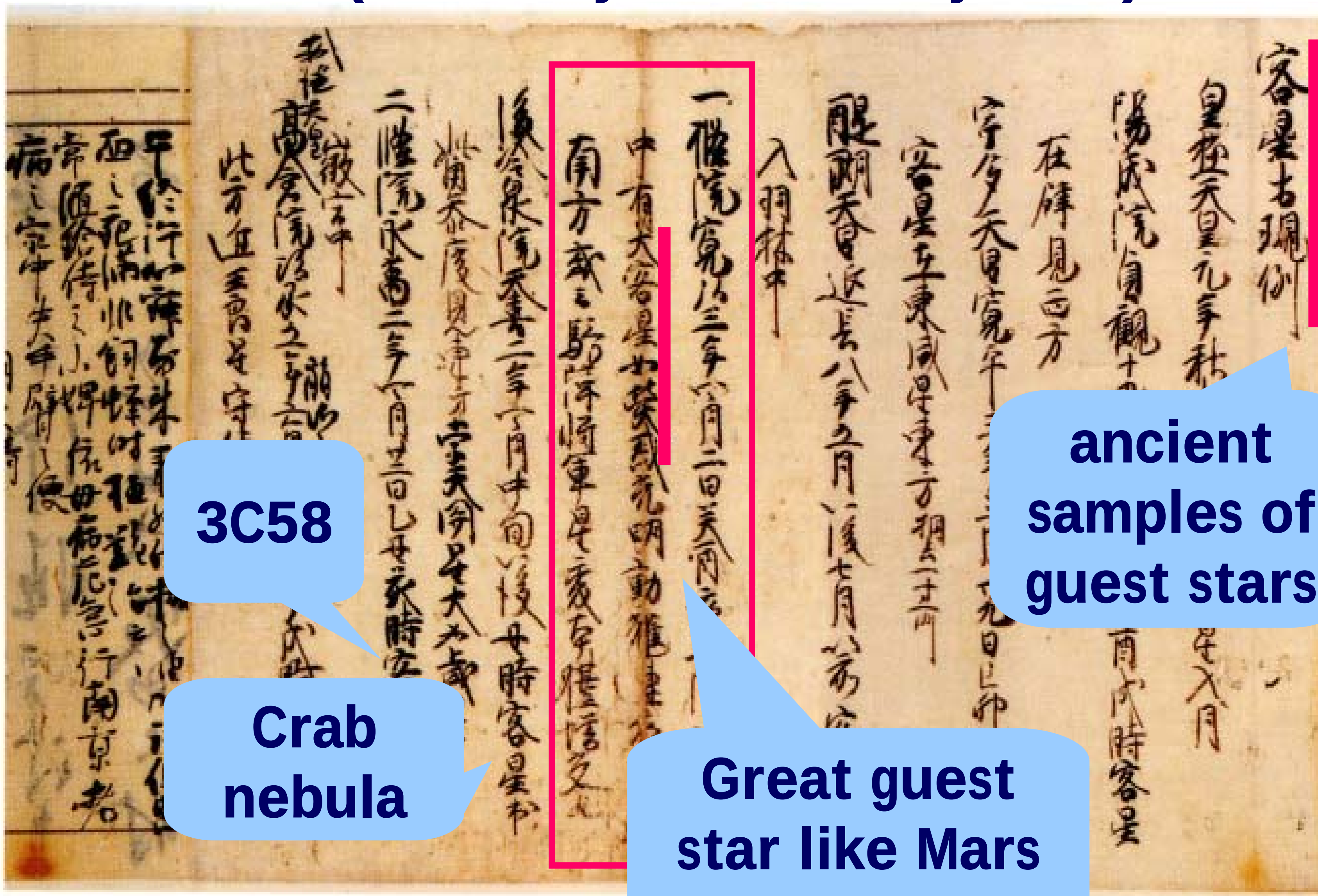
Observed targets

	Cas A	Kepler	Tycho	SN1006	RCW 86	30DorC
Age (yrs)	320	396	428	994	1816	...
Distance (kpc)	3.4	4.8	2.3	2.18	2.8	50
Radius (arcsec)	160	110	260	900	1260	120
Exp. (ksec)	50	49	49	68	92	99

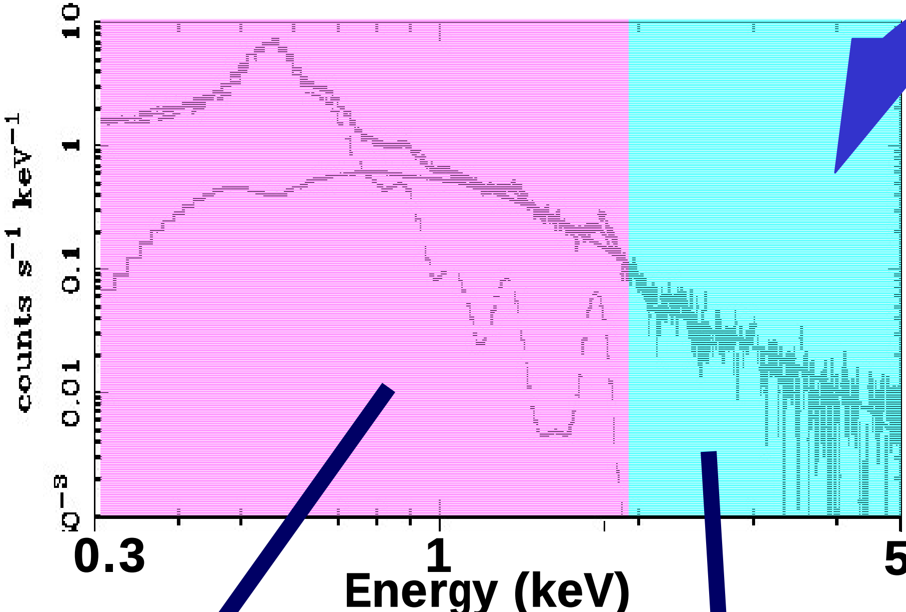
Young SNRs in Sedov phase
Almost all historical shell-like SNR sample

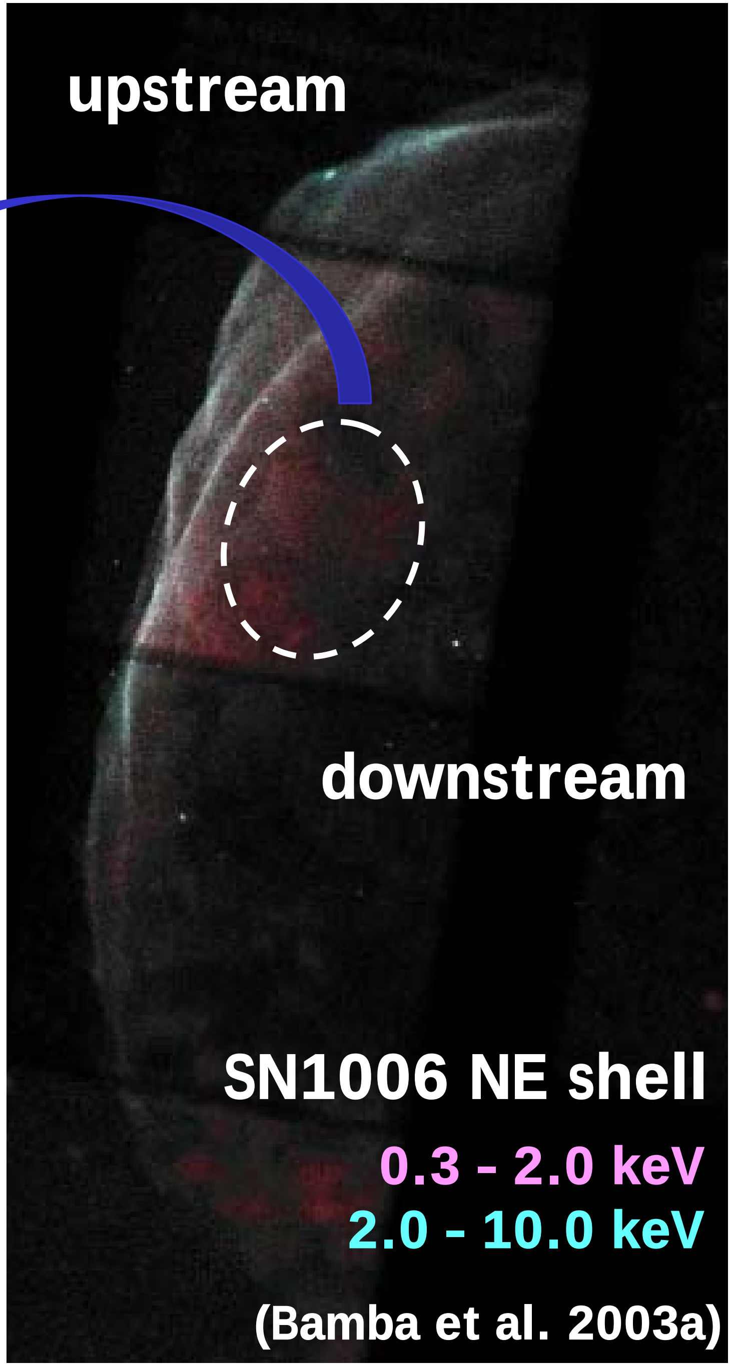
3.1. In the case of SN 1006

Mei-Getsu-Ki (The diary of Teika Fujiwara)



3.2. SN 1006 image





thermal (0.24 keV)
extended

non-thermal
sharp

Scale length of the filaments?

3.3. Filament analyses (1) method

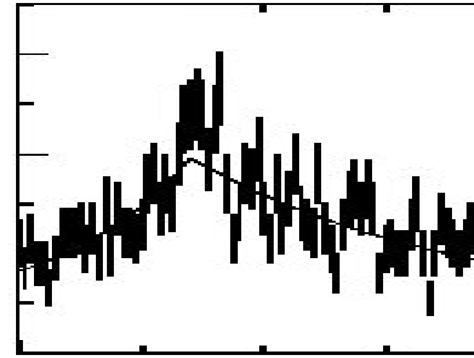
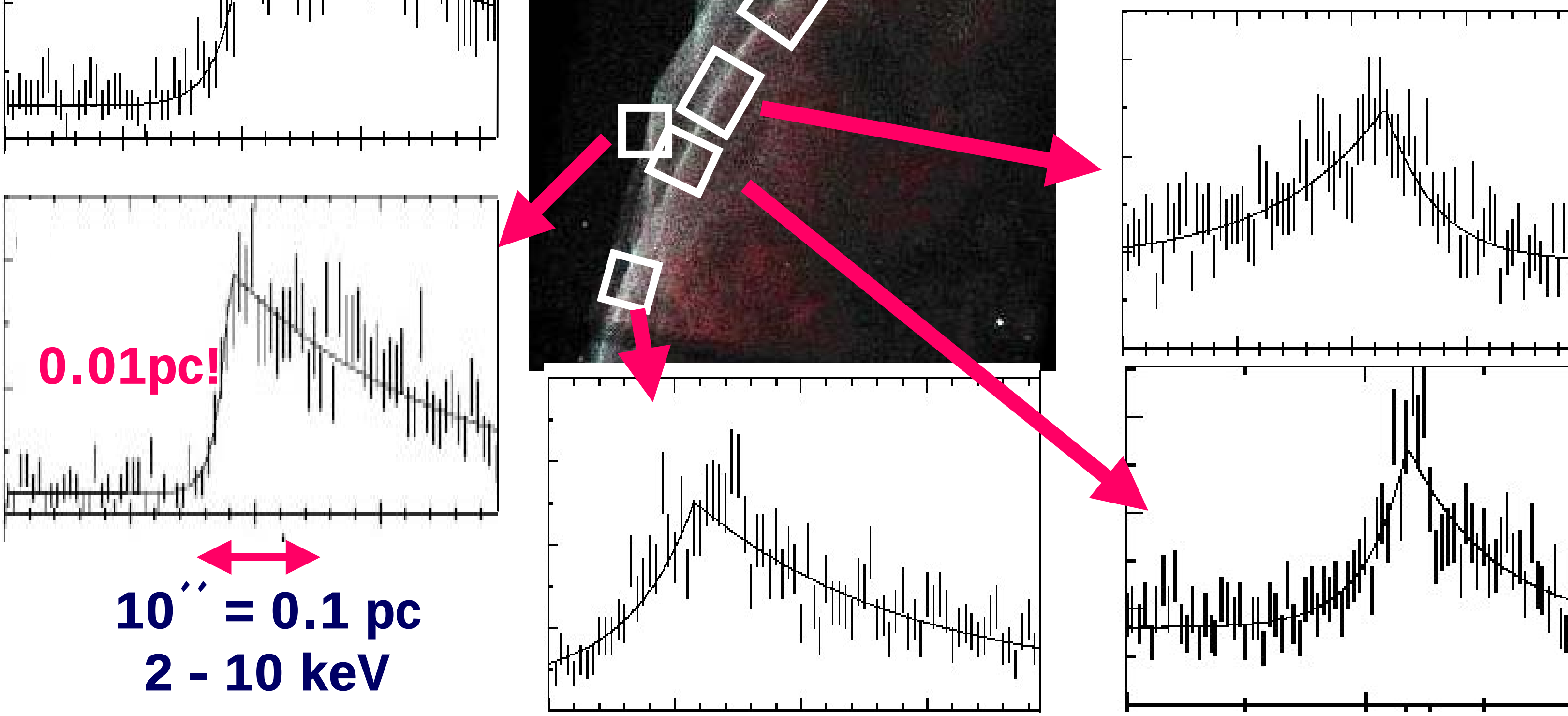
1. Make profiles in the 2.0 – 10.0 keV band
2. Fit them with filament model

$$f(x) = C + \begin{cases} A \exp\left(-\left|\dfrac{x_c - x}{w_u}\right|\right) & \text{upstream} \\ A \exp\left(-\left|\dfrac{x_c - x}{w_d}\right|\right) & \text{downstream} \end{cases}$$

C: background, A: normalization
x_c: peak position, w: width of filament
u: upstream, d: downstream

3. Make the spectra of the filament

3.3. (2): Fitting results

First measurement of the width of filaments

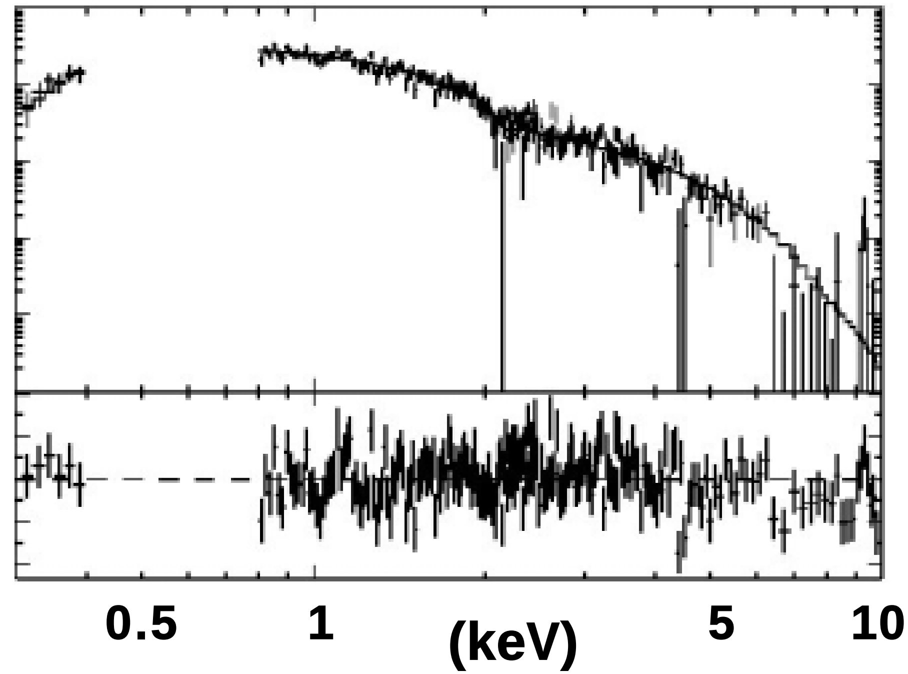
	Upstream	Downstream
Mean value..................	0.04 pc	0.2 pc
Minimum value...........	0.01 pc	0.05 pc

3.4. Spectral Fitting

spectrum

- ✓Hard
- ✓No line

➡ Non-thermal!



SRCUT model

power-law
exponential cutoff } Sync. emission from electrons

$$\nu_{rolloff} = 5\text{x}10^{17}\text{Hz}\left(\frac{B}{10\mu G}\right)\left(\frac{E_{max}}{100\text{TeV}}\right)^2$$

[Reynolds & Keohane (1999)]

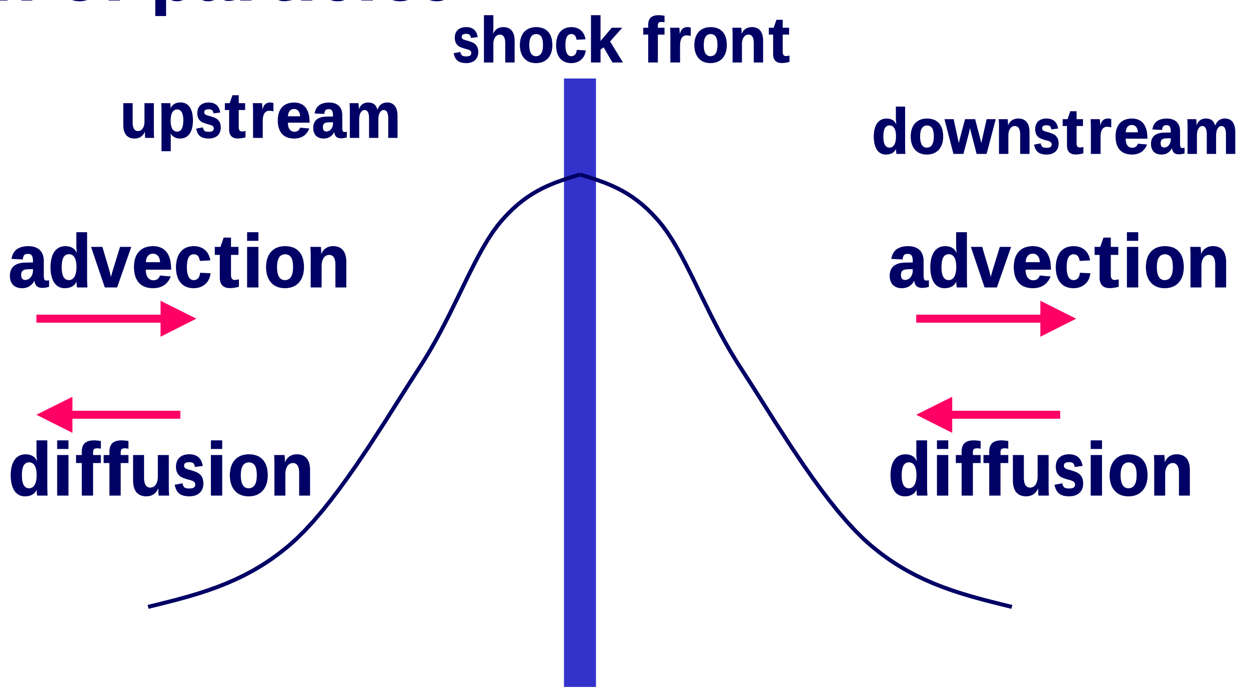
α = 0.57 @1GHz (fixed) (Allen et al. 2001)

➡ $\nu_{rolloff}$ = 2.6 (1.9 - 3.3) x 10^{17} Hz

Flux = 1.8 x10^{-12} ergs cm^{-2}s^{-1}

4.1. What determines the scale length

Distribution of particles



Up: advection = diffusion

$$u_u t = \sqrt{K_u t}$$

Down: advection = diffusion

$$u_d t = \sqrt{K_d t}$$

Anyway,

$$w = \frac{K}{u_s} \sim r_g u_s^{-1}$$

4.2. Why are filaments so thin?

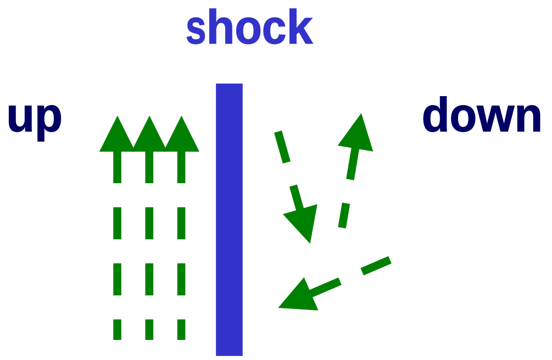
….. Small diffusion in direction to shock normal!

Scenario 1: relatively strong, perpendicular B

(Bamba et al. 2003, Yamazaki et al. 2004)

Diffusion occurs only along the magnetic field

The angle: > 85 deg.
The strength: 10 - 80 μG

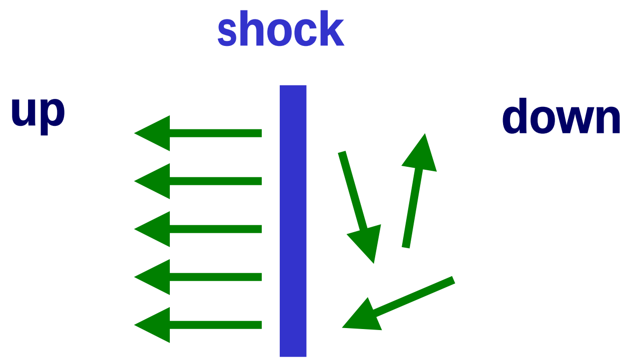


Scenario 2: very strong, parallel B

(Berezhko et al. 2004)

Strong B makes the gyro radius small
→ diffusion becomes small

B ~ 100 - 400 μG

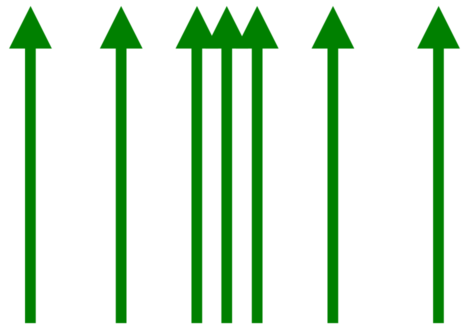


Anyway, Turbulent magnetic field (Bohm limit)
Very efficient acceleration (equipartition)

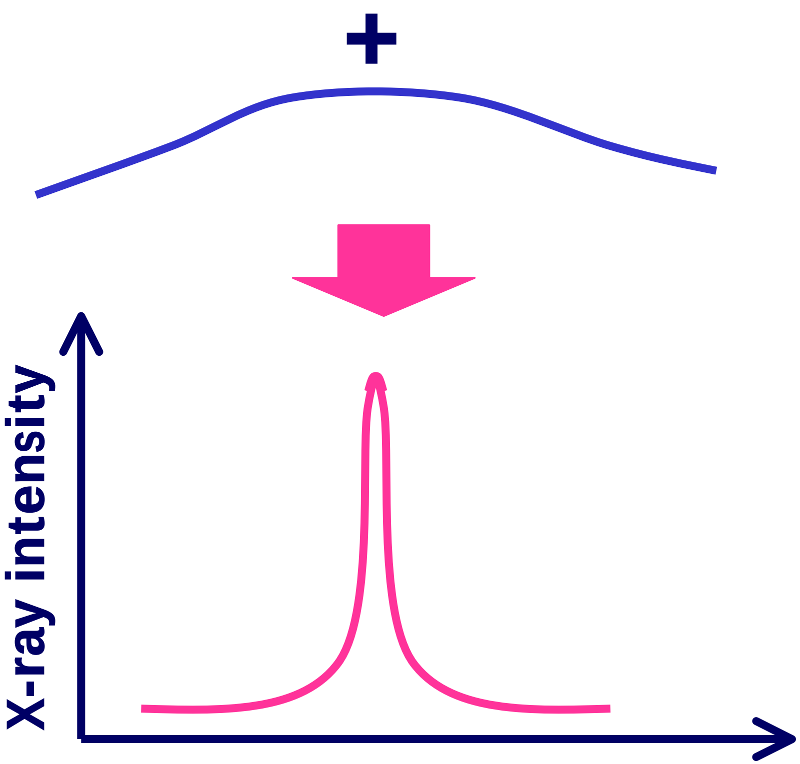
First estimation of magnetic field structure

Scenario 3: “magnetic filaments”

(Lyutikov 2004, Pohl et al. 2005)



magnetic field
cocentrated on the shock front

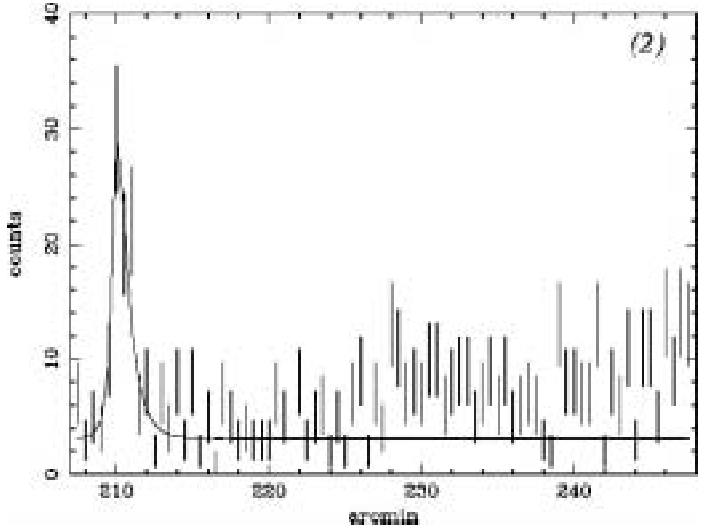


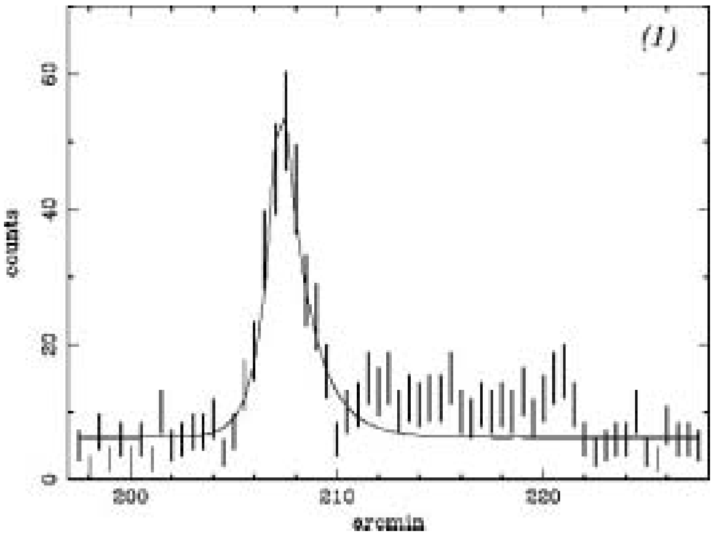
widely spread electrons

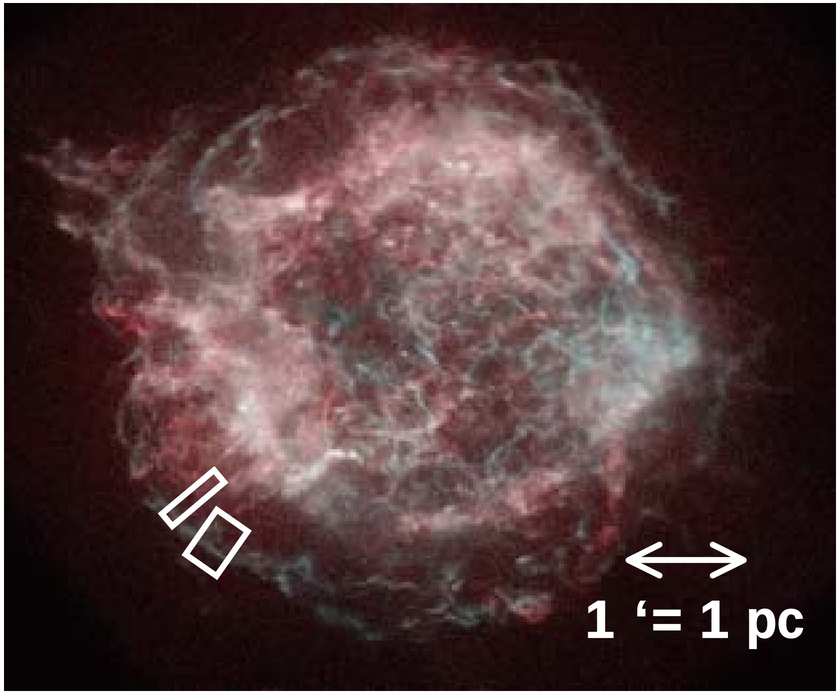
Apparently sharp filaments!
(“magnetic filaments”)

5.1. Application for other historical SNRs

Cas A: The youngest historical SNR non-thermal filaments (Vink & Laming 2003)







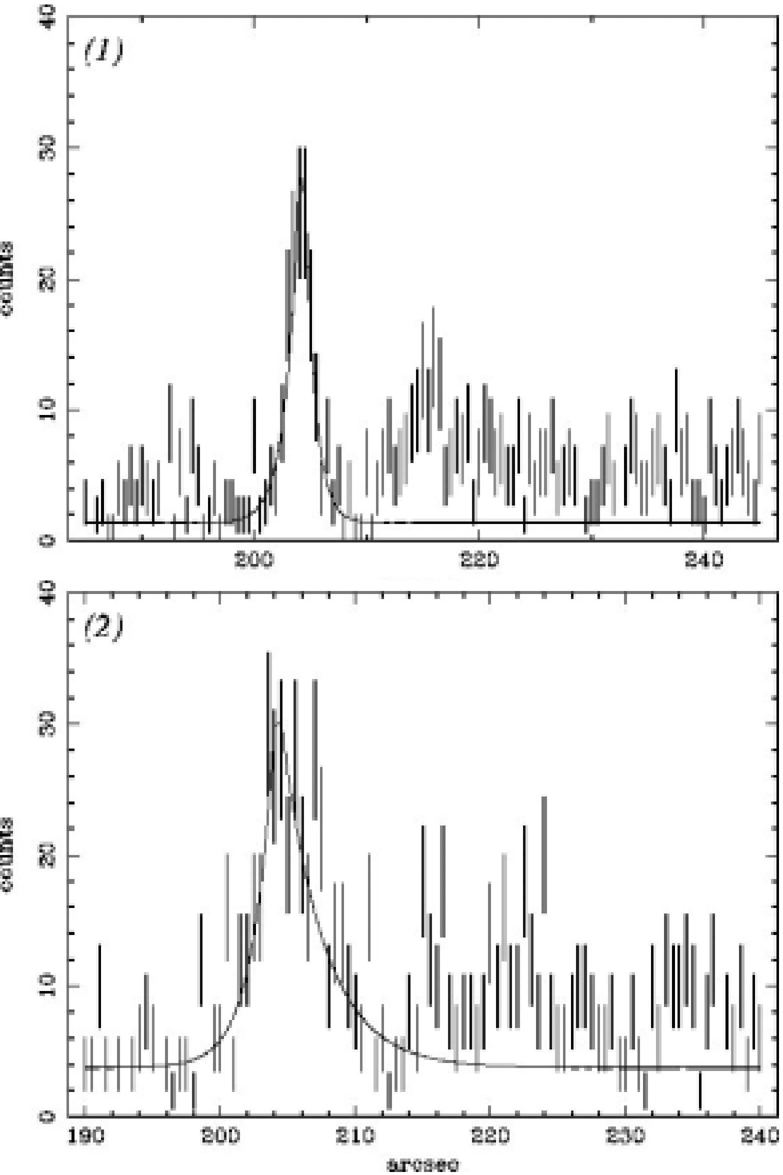
First measurement of ws

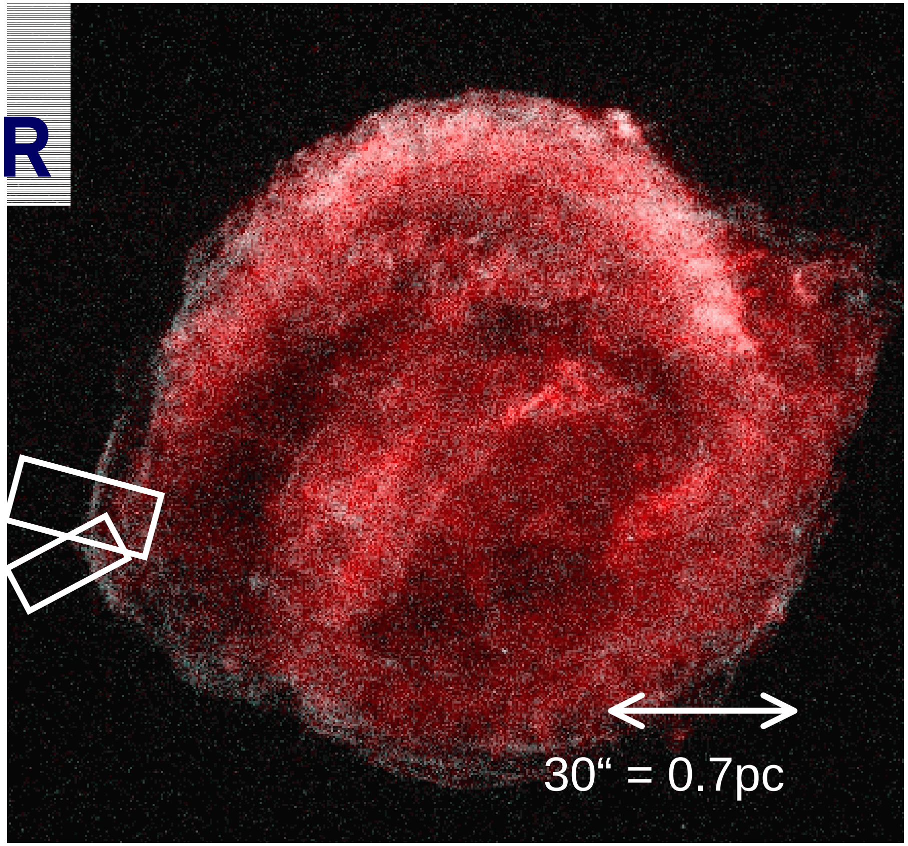
w_u = 9.6 (6.8–13.2) x10^{-3} pc

w_d = 1.8 (1.3 - 2.9) x10^{-2} pc

$\nu_{rolloff}$ = 2.4 (>0.18) x10^{18} Hz

Kepler:
The second youngest SNR





The first detection of nonthermal X-rays!

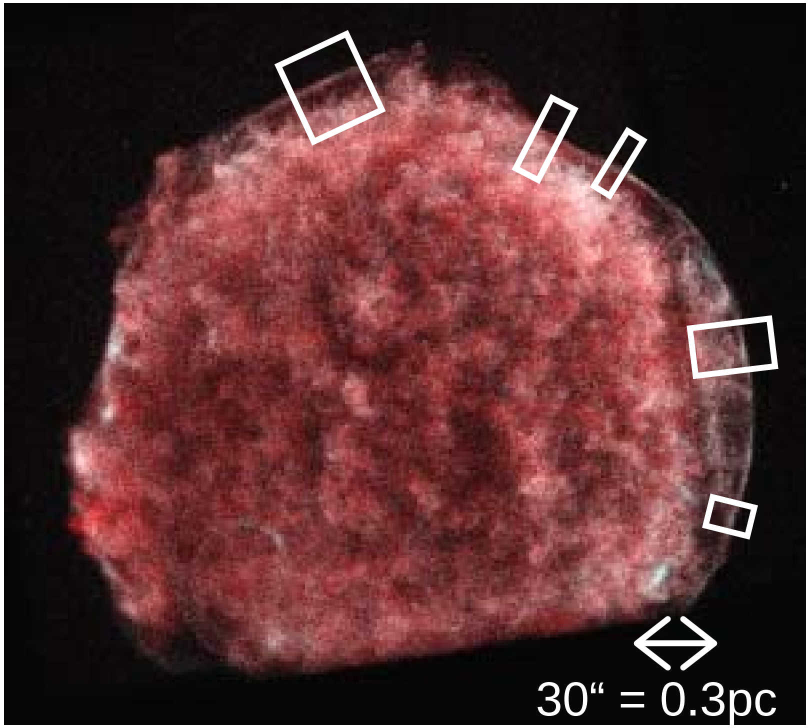
w_u = 3.0 (2.0-4.0) x10^{-2} pc

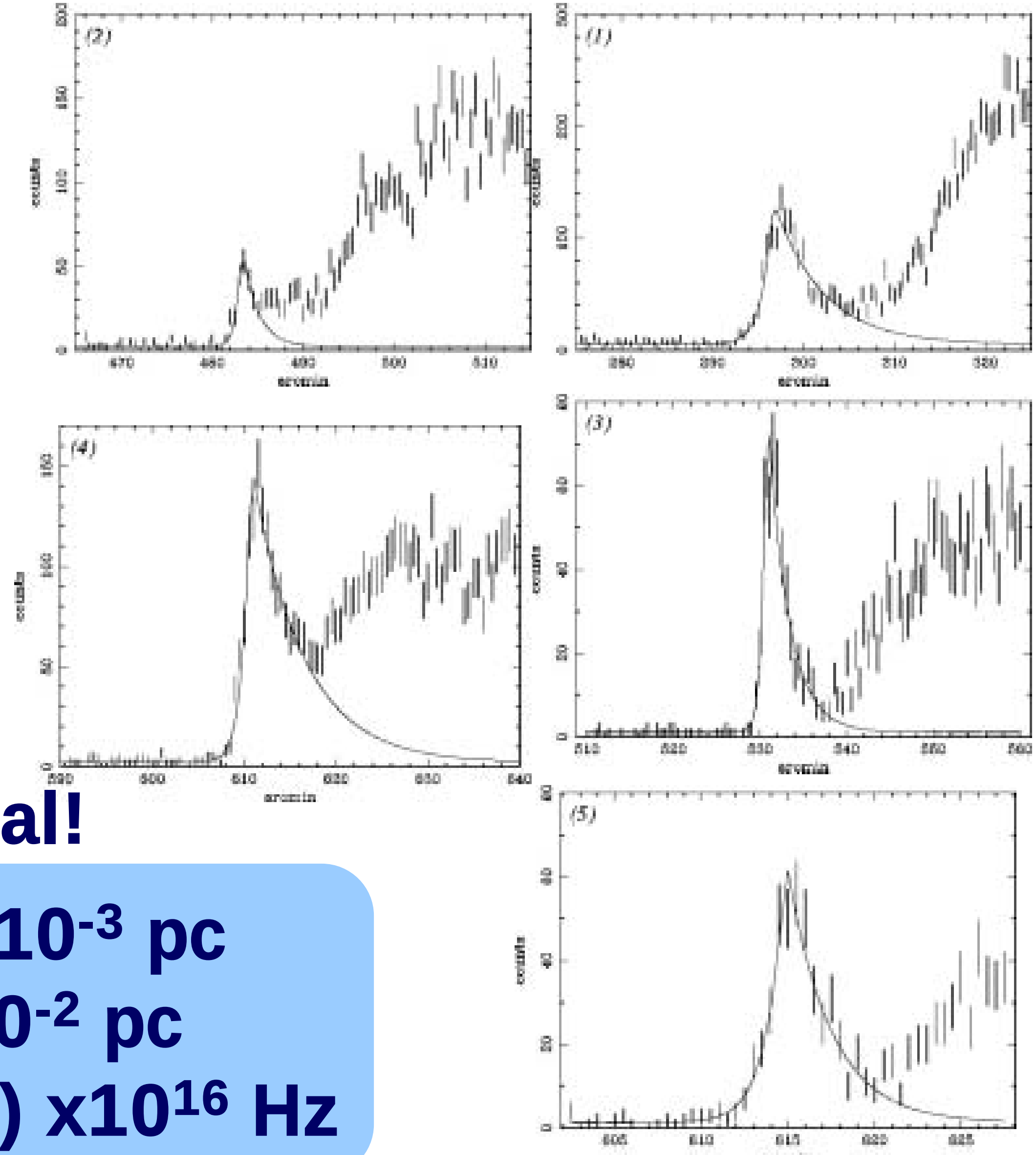
w_d = 5.0 (4.0-6.0) x10^{-2} pc

$\nu_{rolloff}$ = 3.6 (2.0-7.9) x10^{17} Hz

Tycho: “filaments with small E.W.”

(Hwang et al. 2002)





Appriciate BG

→non-thermal!

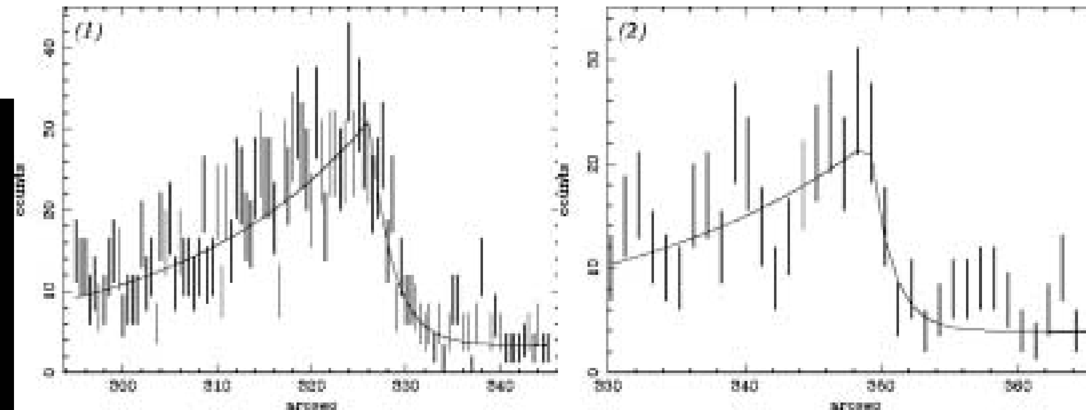
w_u = 9.7 (8.5-11.2) x10^{-3} pc

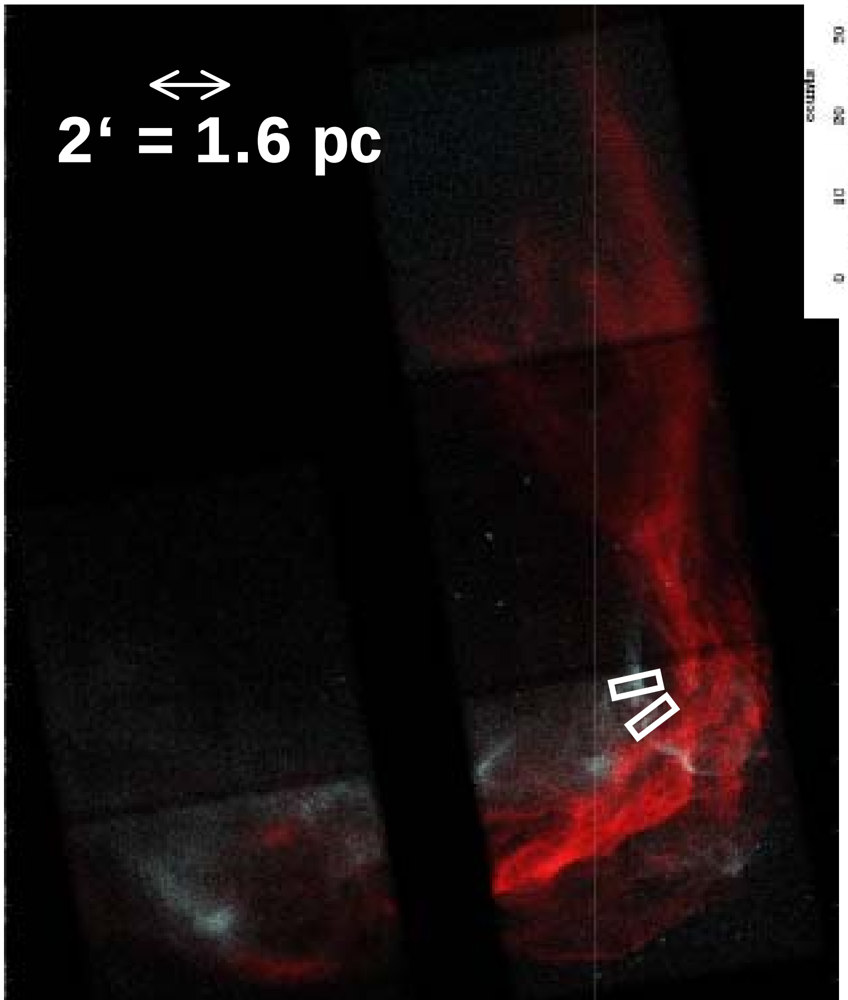
w_d = 4.5 (4.0-5.3) x10^{-2} pc

$\nu_{rolloff}$ = 8.3 (5.9-11.7) x10^{16} Hz

RCW 86: synchrotron X-ray emission
The oldest historical SNR

(Rho et al. 2002)





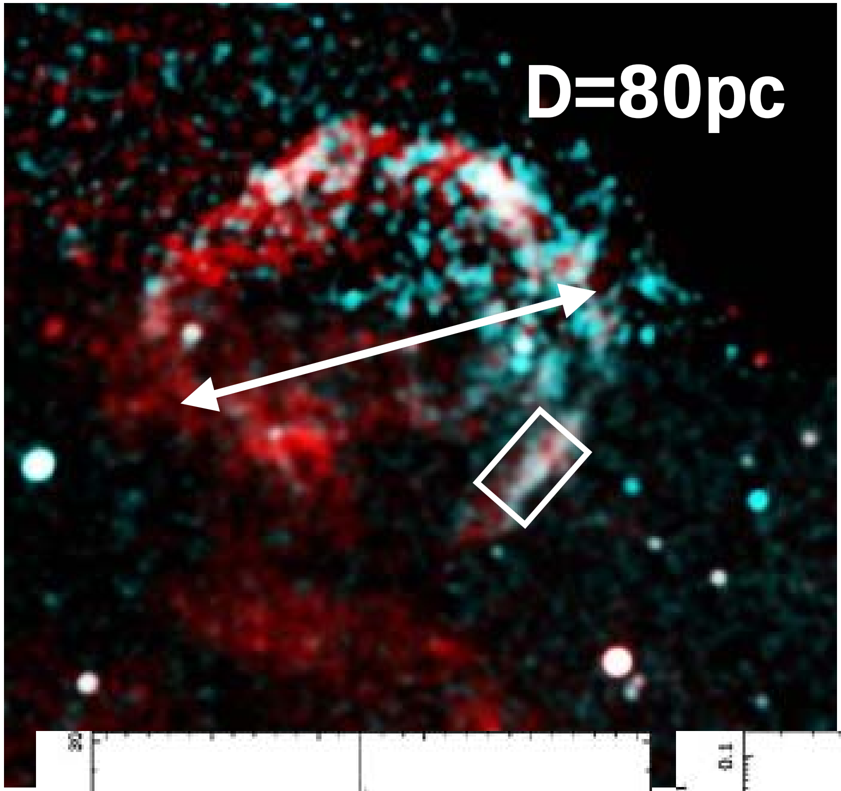
Detection of thin filaments from such a old SNR

w_u = 2.8 (1.5-5.3)x10^{-2} pc

w_d = 0.26 (2.1-3.9) pc

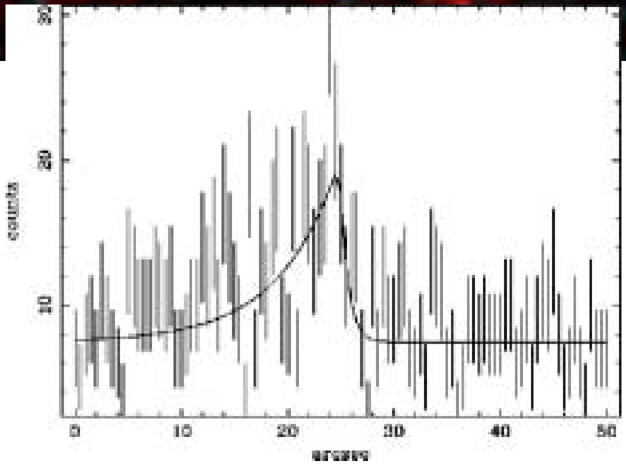
$\nu_{rolloff}$ = 2.1 (1.0-5.9) x10^{17} Hz

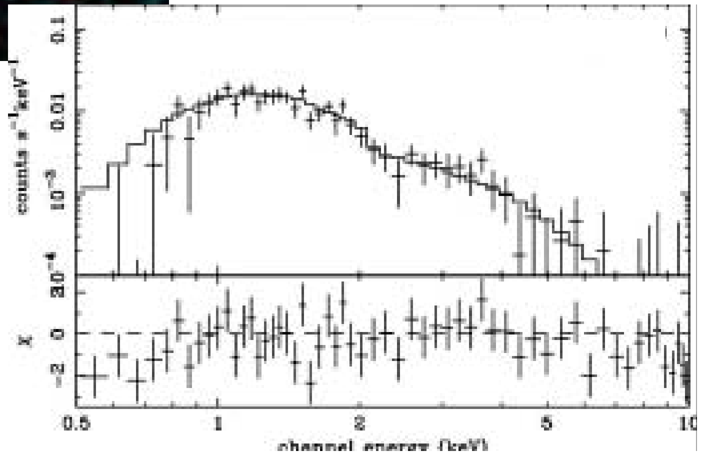
30 Dor C: Super-bubble in LMC



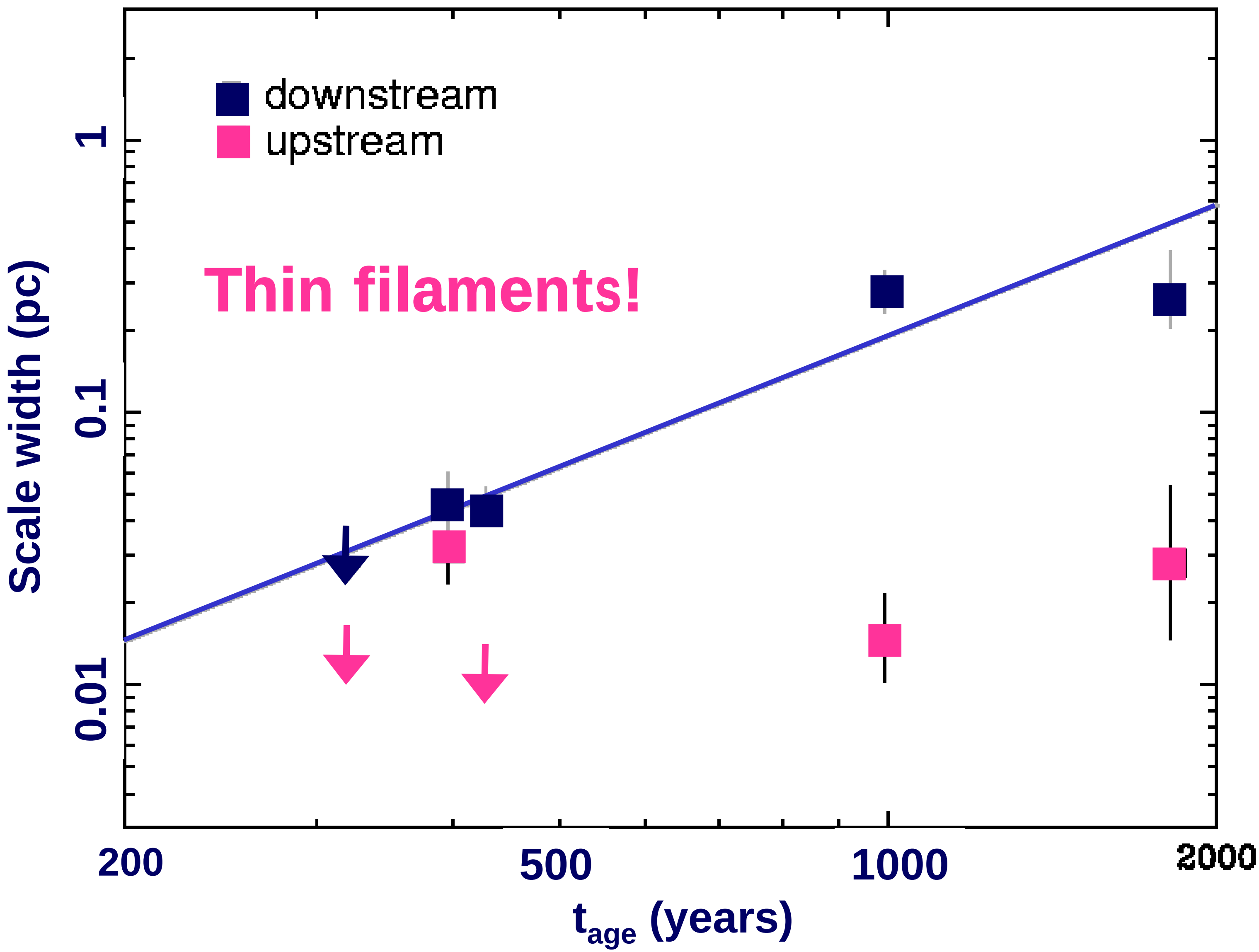
First detection of NT X-rays from extra-galactic super-bubble

w_u = 0.18 (0.06-0.29) pc
w_d = 1.0 (0.49-2.2) pc





6.1. Time evolution of w_u and w_d



They glow wider!

6.2. Time evolution of B

observational facts

$w_d \sim r_g u_s^{-1}$

$\quad \sim E_{max} B_d^{-1} u_s^{-1}$

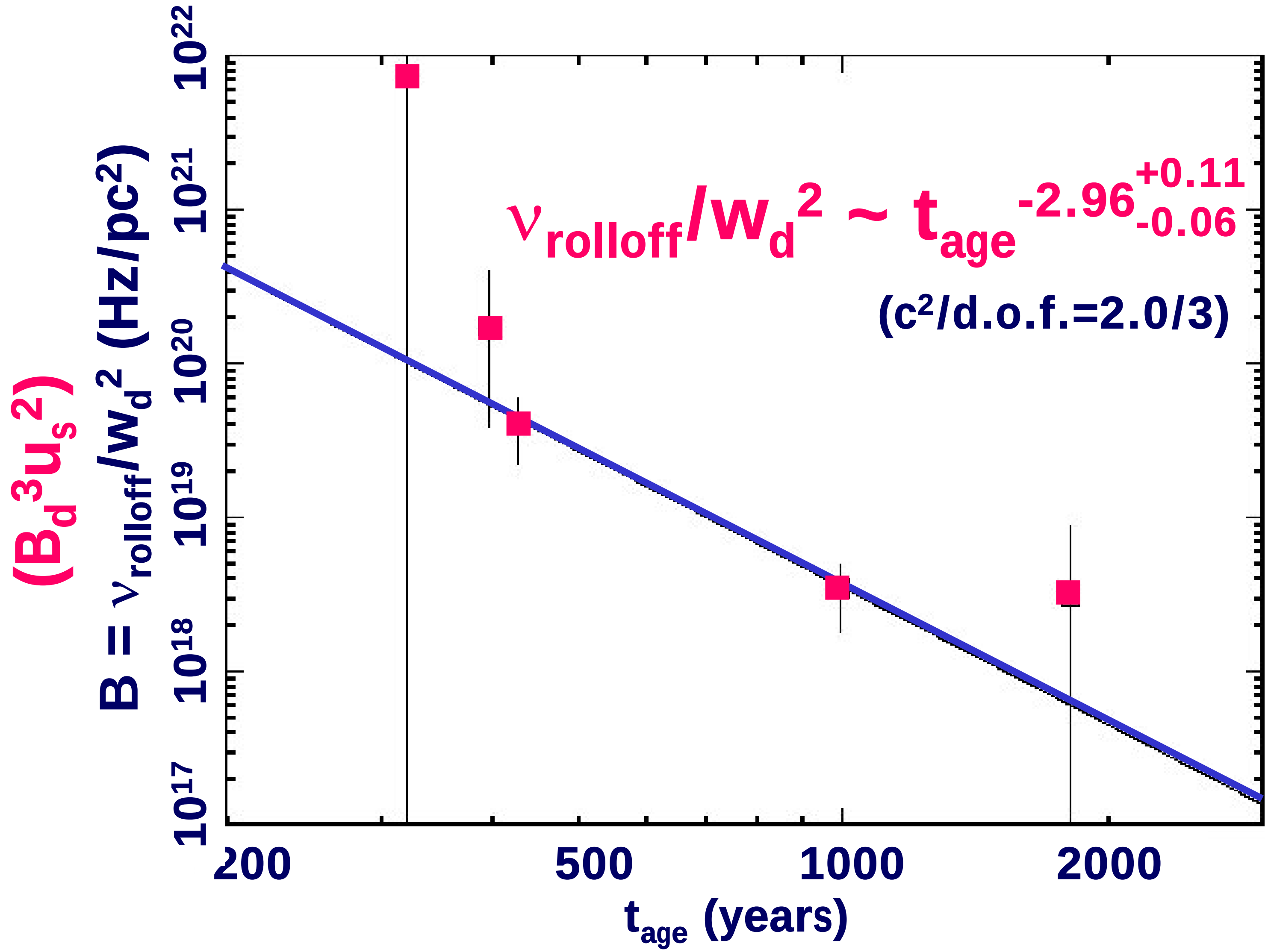
$\nu_{rolloff} \sim E_{max}^2 B_d$

func. of B_d

$B = \nu_{rolloff} w_d^{-2} \sim B_d^3 u_s^2$

$$\left(\begin{array}{l} u_s \sim t^0 \text{ (free exp.)} \\ \quad \sim t^{-0.6} \text{ (Sedov)} \end{array} \right)$$

Direct estimations of the evolution of B
ONLY from the observational facts!



$$B_d \sim \begin{cases} t_{age}^{-1} \text{ (free exp.)} \\ t_{age}^{-0.6} \text{ (Sedov)} \end{cases}$$

6.3. Time evolution of energy densities

Sedov $\rightarrow$ thermal u_{th}: $\sim T \sim t_{age}^{-1.2}$

kinetic u_{kin}: $\sim u_s^2 \sim t_{age}^{-1.2}$

Our result ($B_d \sim t_{age}^{-0.6}$)

Magnetic energy density u_B: $\sim B_d^2 \sim t_{age}^{-1.2}$

CR energy density u_{CR}:

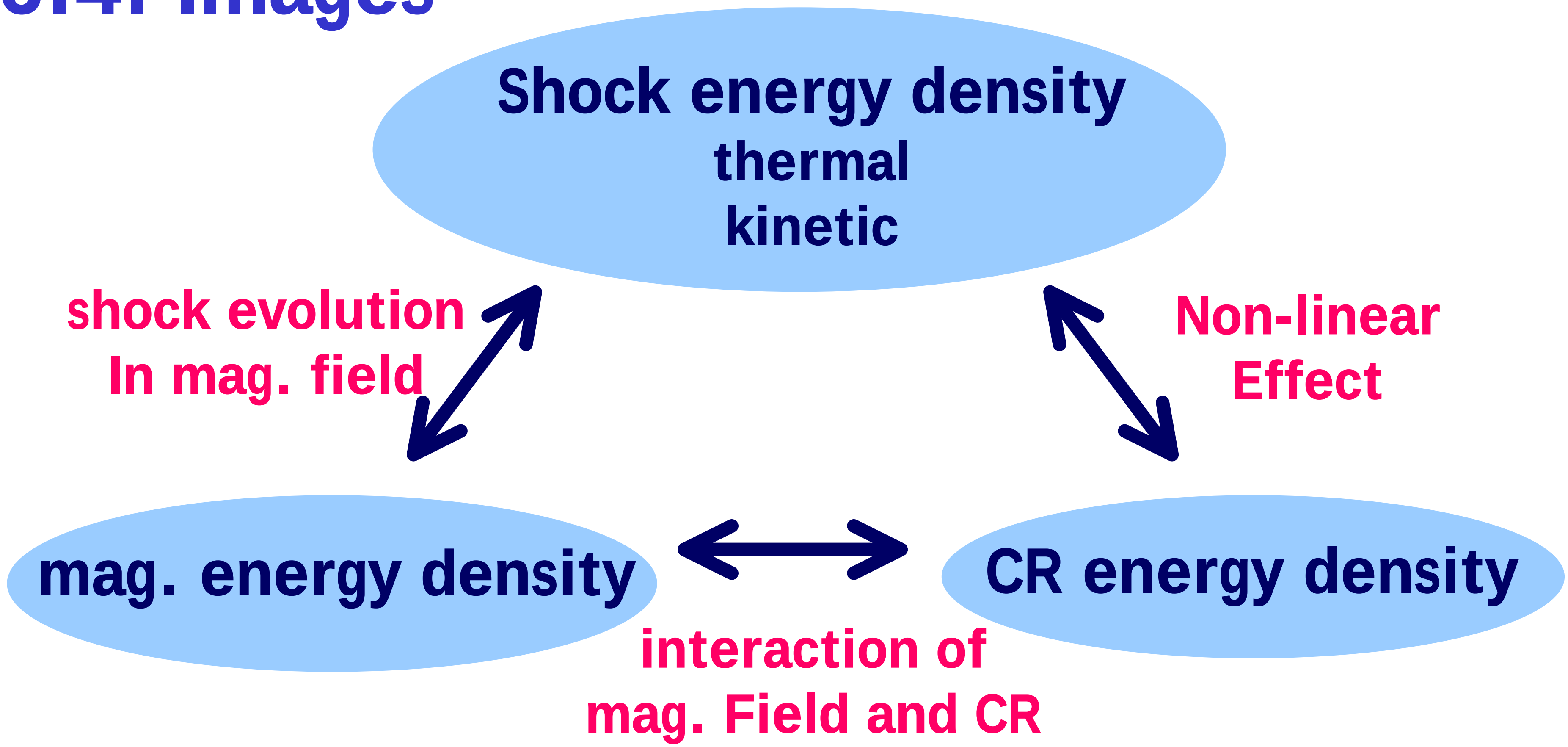
assumption: $u_B = \frac{u_A}{u_s} u_{CR}$

$$u_A = \frac{B}{\sqrt{4\pi\rho}}$$ (Lucek & Bell 2000)

$$u_{CR} \sim B_d u_s \sim t_{age}^{-1.2}$$

All energy densities have same time dependence!

6.4. Images



strong interaction for each other

SN1006: equipartition

➡ evolution keeping equipartition?

We must consider these three energy density simultaneously!

6.5. How to get amplified B-field?

(Yamazaki et al. submitted)

Plasma Instabilities make large B field

SNRs: (non-relativistic shocks)

Lucek & Bell instability ?? (Lucek & Bell 2000)
origin: accelerated particles
budget: $B^2/8\pi$ ~1% of thermal energy density

GRBs: (relativistic shocks)

Weibel instability ??
origin: temperature anisotropy
budget: $B^2/8\pi$ ~1% of thermal energy density

... common physics???

7. Future observational plans

detailed obs. ⟷ survey obs.

measurement of acc. efficiency

non-linear effect?

polarization

X-ray survey

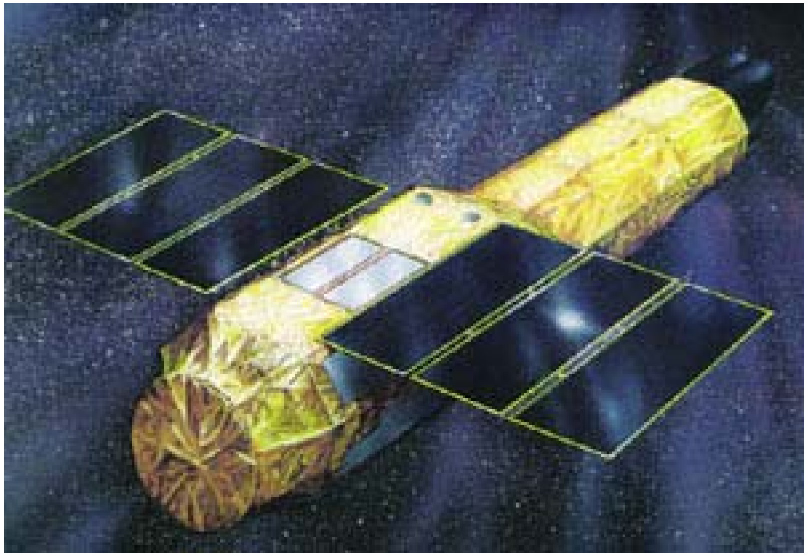
radio follow-up

Estimation of energy budget in one SNR

Estimation of the number of SNRs

7.1. Detailed observation with Astro E-II

Astro E-II (2005 ~)



wide energy band
(HXD: 10 – 600 keV)
high energy resolution
(XRS: △E ~ 5 eV)
large effective area
(XIS: 0.3 – 12 keV)

✓ **measurement of**
electron kT
ion kT

difference?

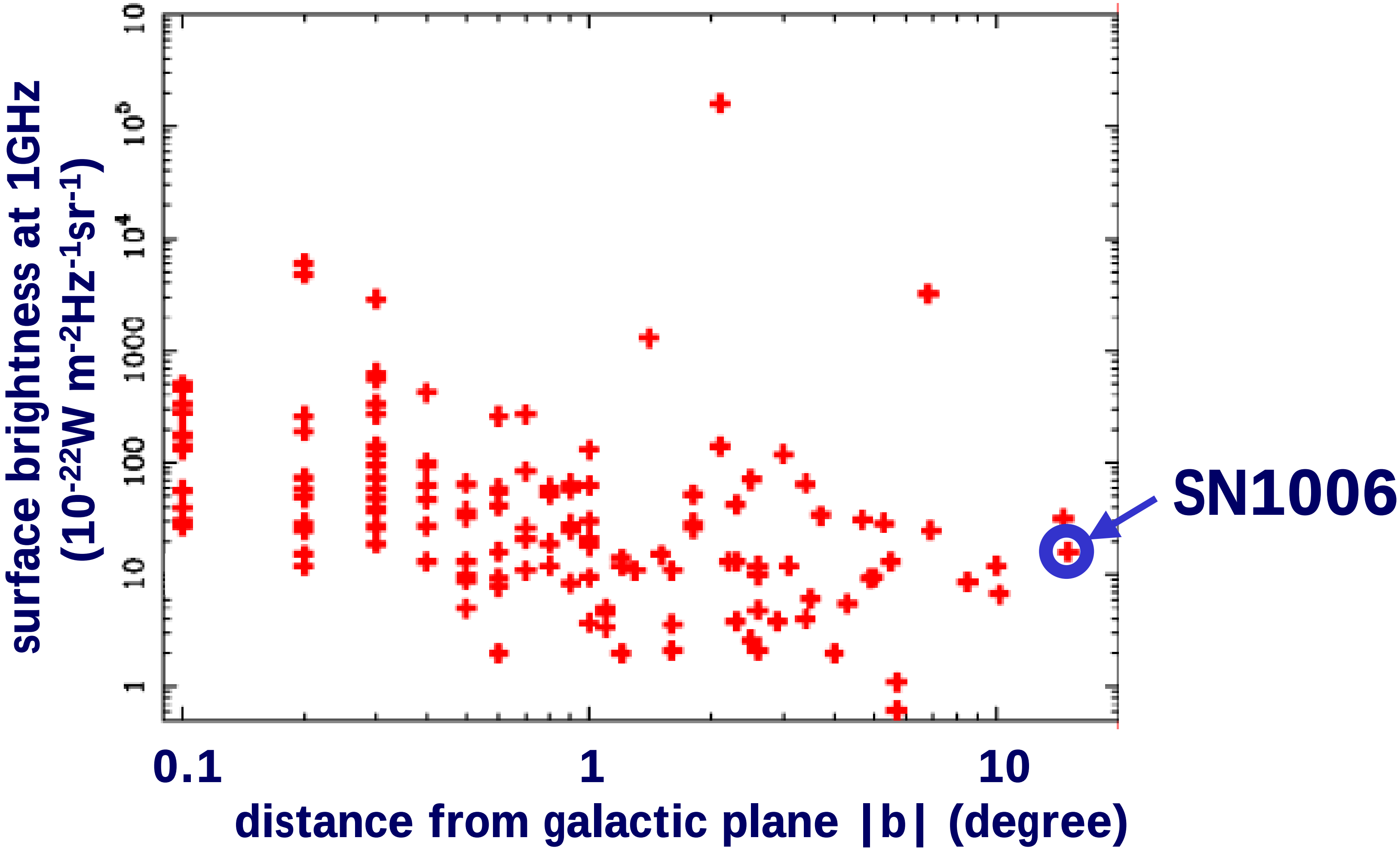
✓ **shock speed**

✓ **Rankine-Hugoniot relation**

→ **First measurement of injected energy into accelerated particles**

7.2. Search for undiscovered SNRs

previous search: radio → X-rays



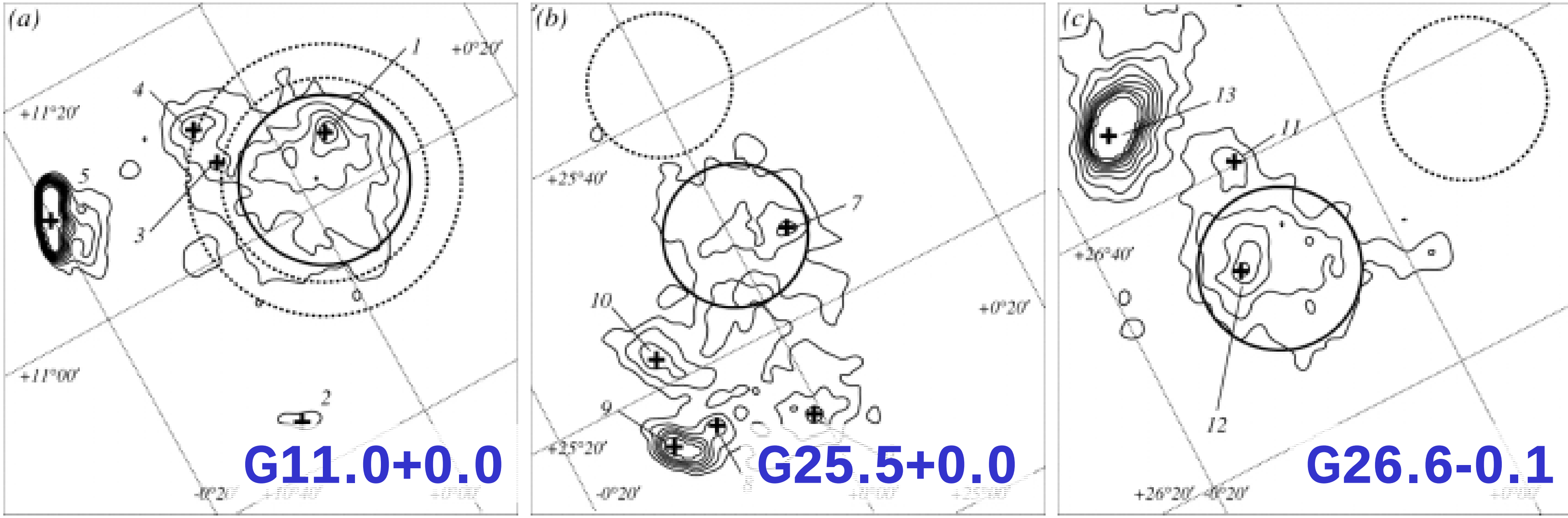
Radio surveys cannot find SNRs near Galactic plane → **hard X-ray survey**

ASCA Galactic plane survey

surveyed region:
$|l|<45^o, |b|<0.4^o$

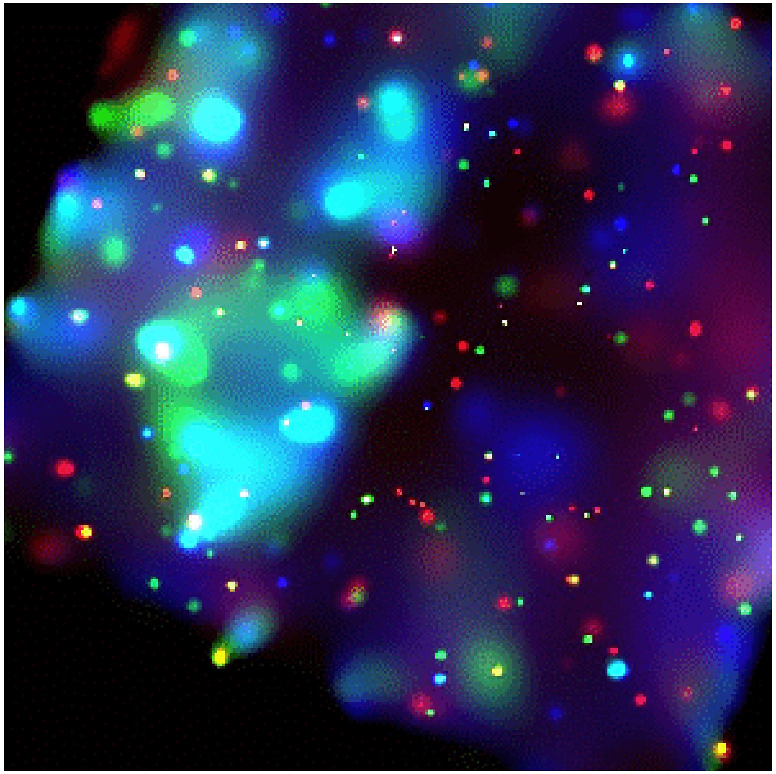
the widest and highest sensitivity survey in the X-ray band

We discovered new nonthermal SNR candidates

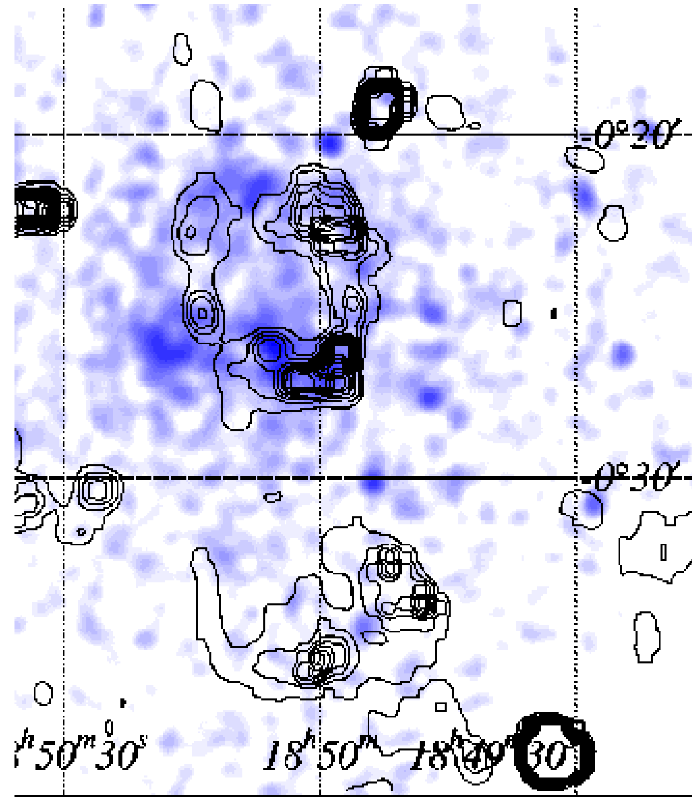


Bamba et al. (2003b)

Follow-up observations with Chandra·Newton



G28.6-0.1 (Bamba et al. 2001, Ueno et al. 2003)



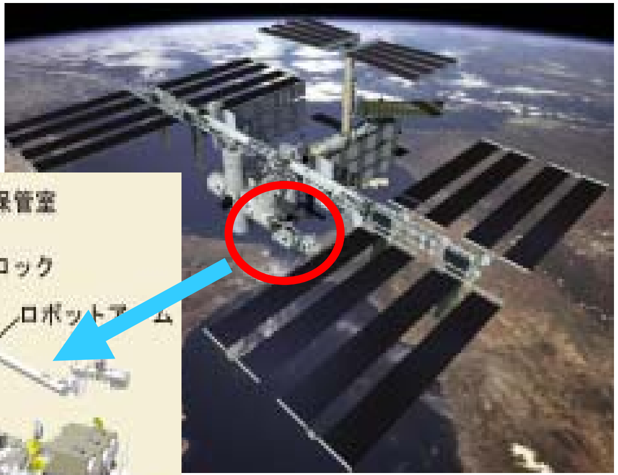
G32.45+0.0 (Yamaguchi et al. 2004)

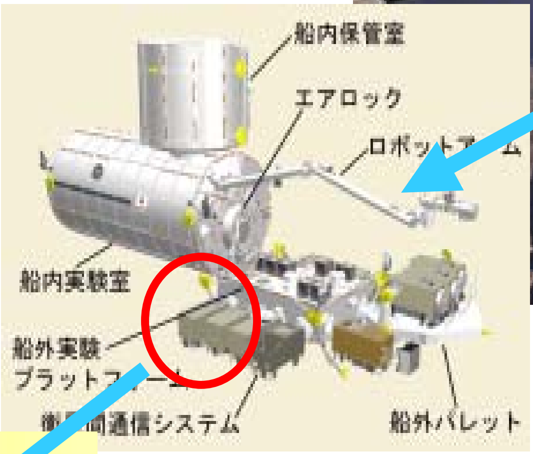
new candidate ~ more than 20???
(Bamba et al. 2003b, Ueno 2005)

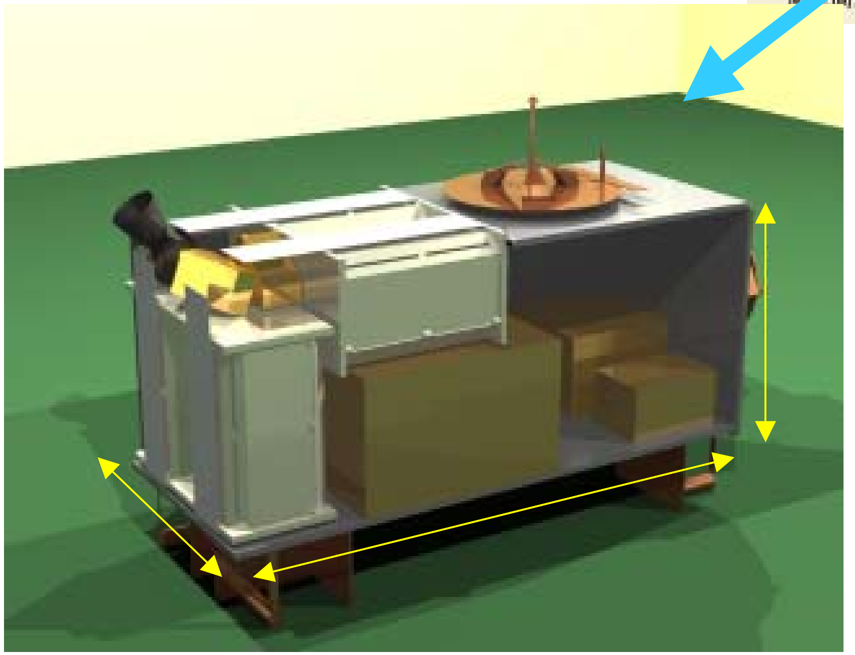
All detected candidates are nearer than GC.

MAXI (Monitor of All-sky X-ray Image)

- the first mission for monitoring
- onboard ISS
- launch: 2008







effective area

～5000cm^2

energy band

0.5～30keV

spatial resolution

6 arcmin

Survey of nonthermal SNRs with MAXI

SN1006: 3.4×10^{-11} ergs $cm^{-2}s^{-1}$ ~ 1mCrab @2-10keV

(Ozaki & Koyama 1998)

2.18 kpc (Winkler et al. 2003)

→ **detectable with 1 week obs.**

SN 1006 on the 20kpc distance?

(the most distant SNR in Galaxy)

F ~ 4.0×10^{-13} ergs $cm^{-2}s^{-1}$ ~ 0.01mCrab

→ **detectable 84 week ~ 1.6 yrs obs.**

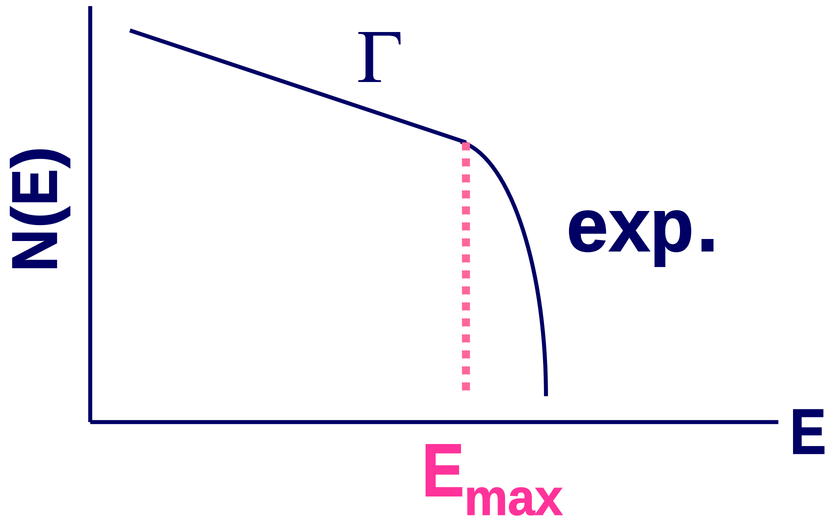
almost nonthermal SNRs will be detected!

8. Summary

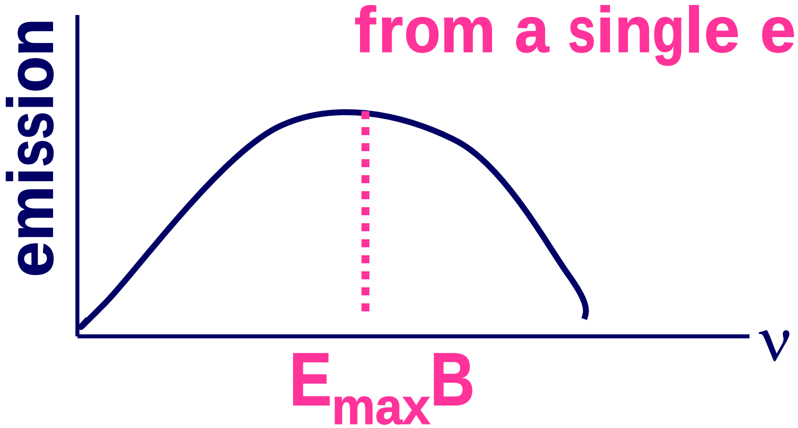
1. We detected synchrotron X-rays from filaments in SN1006 with Chandra.
2. Filaments are very thin!
3. Relatively strong and perpendicular B or very strong and parallel B is needed to explain the thin filaments.
4. Electrons are accelerated efficiently in thin filaments.
5. We found thin filaments in 5 historical SNRs and 1 super-bubble.
6. B decays as $t_{age}^{-0.6}$.
7. The energy densities of the thermal plasma, shock, mag. field, and CRs show the same time dependencies.

SRCUT model

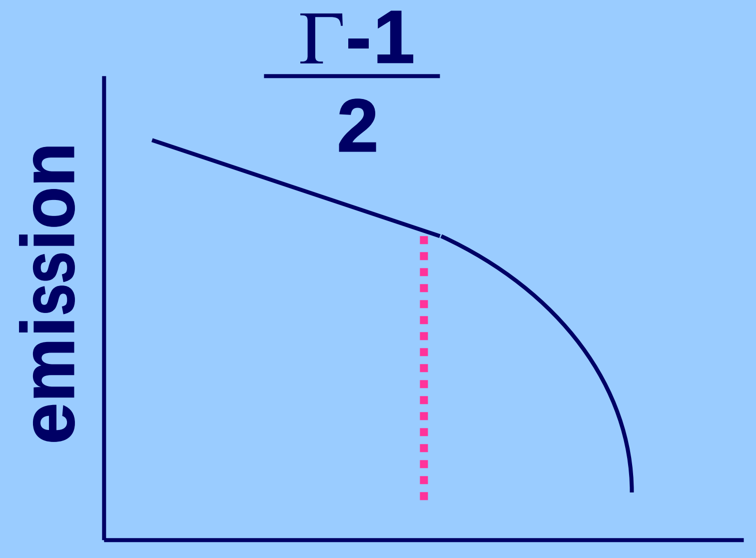
Spectrum of electrons



Synchrotron emission from a single e



Synchrotron emission from power-law electrons



$\nu_{rolloff} \sim E_{max}^{2} B$