High-resolution studies of X-ray filaments in supernova remnants

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0. Talk plan

1. Introduction of X-ray study of cosmic ray acceleration in SNRs
2. Chandra observation of SN 1006
3. Discussion of acceleration parameters; time scale, magnetic field, and maximum energy of electrons
4. Application to other SNRs
5. Summary

1. Introduction

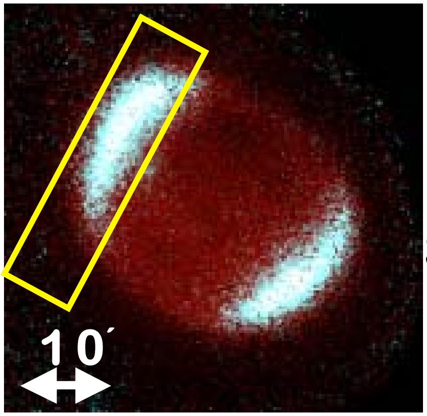
"How are cosmic rays accelerated up to TeV?"

Basic concept: Diffusive Shock Acceleration (DSA)

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

Koyama et al.(1995)

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



SN1006:
type Ia
d=2.18kpc

Next:

More realistic models

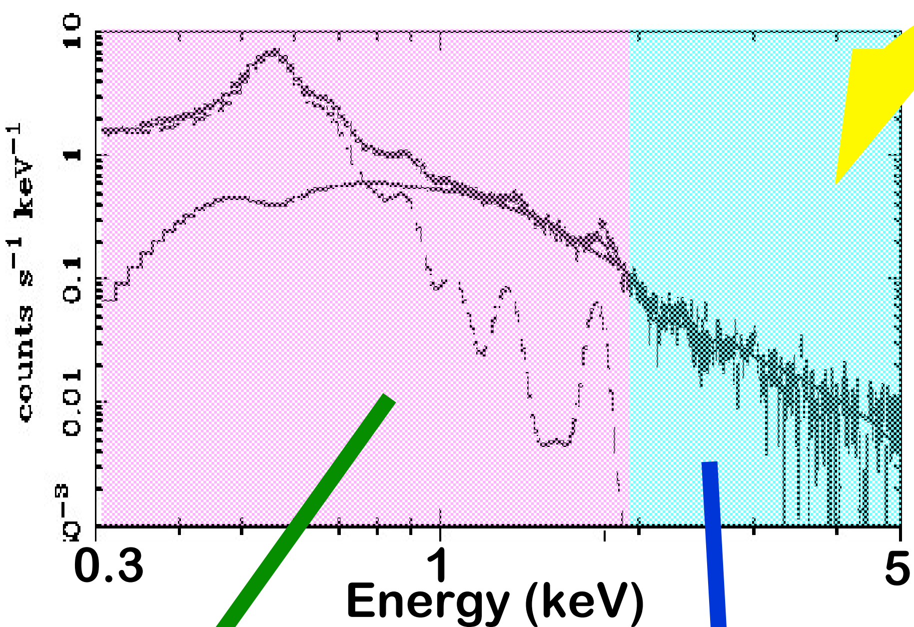
B, E_{max}, distribution of electrons on the shock.....

More sample SNRs (More GLAST target candidates)

SNRs with sync. X-rays

→ Spatial and spectral capability of Chandra

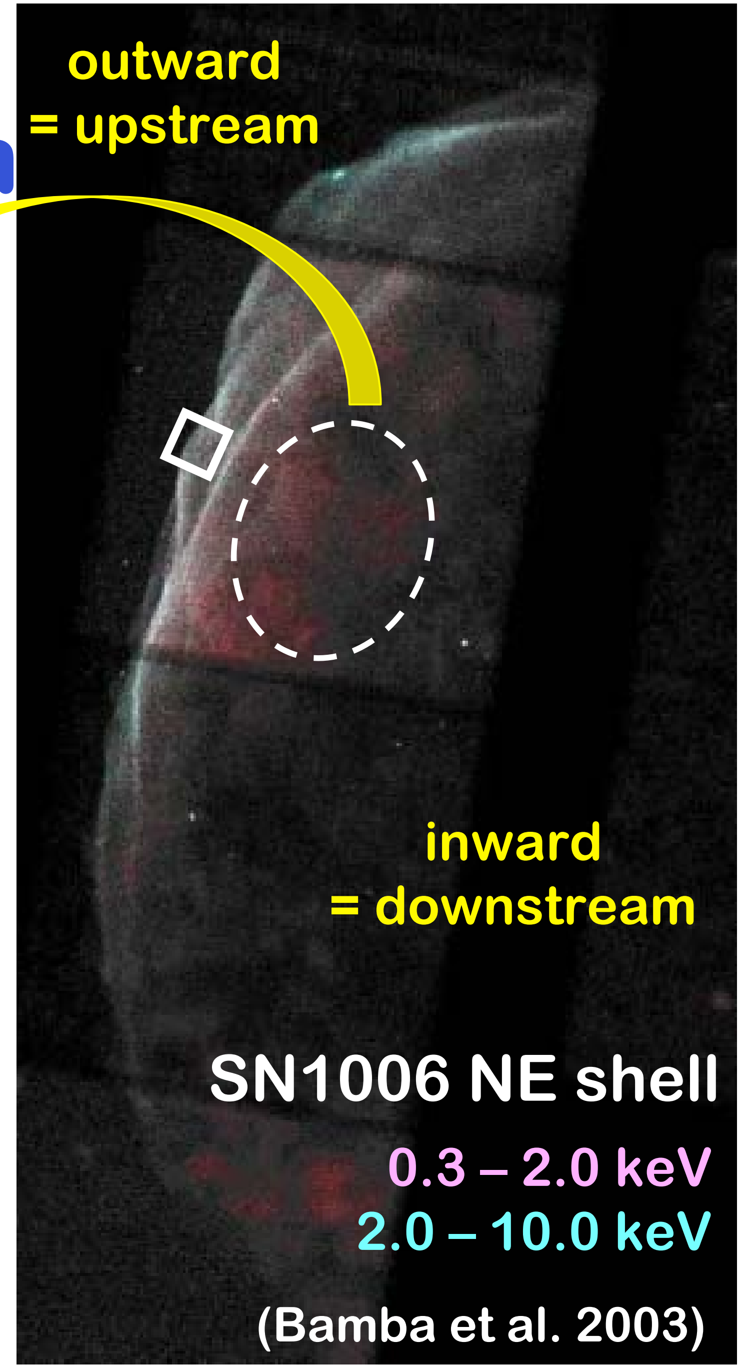
2.1. Chandra Image and spectrum



thermal
extended

non-thermal
sharp

How wide are the
non-thermal filaments?



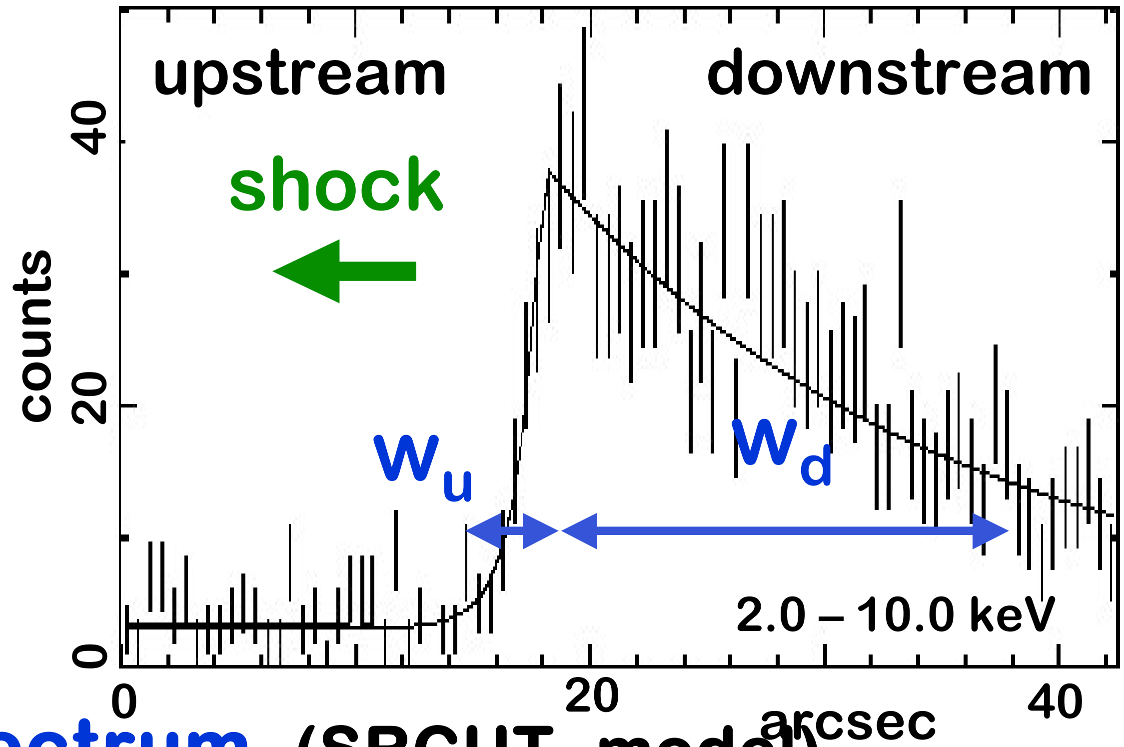
2.2. Properties of the Filaments

1. Width of non-thermal X-ray filaments

Scale length of nonthermal X-rays

$w_u = 0.01 - 0.1 \mathrm{pc}$
$w_d = 0.06 - 0.4 \mathrm{pc}$

Distance : 2.18 kpc
(Winkler et al. 2003)



2. Wide band spectrum (SRCUT model)

$\nu_{roll} = (2.6 \pm 0.7) \times 10^{17} \mathrm{Hz}$

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

[Reynolds & Keohane (1999)]

3.1. Discussion: three time scales

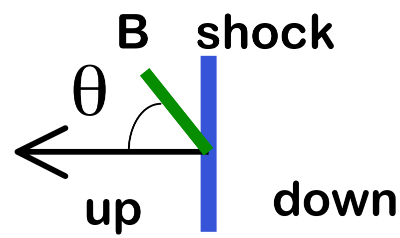
→ E_{max}, B

1. t_{age}: The age of SN 1006 ~ 10^3 years

2. t_{loss}: energy loss time scale (synch. loss)

$$t_{\rm loss} = \frac{6\pi m_{\rm e}^2 c^3}{\sigma_T E B^2} = 1.25 \times 10^3 \ {\rm yrs} \ \left(\frac{E_{\rm max}}{100{\rm TeV}}\right)^{-1} \left(\frac{B}{10\mu{\rm G}}\right)^{-2}$$

3. t_{acc}: acceleration time scale



$$t_{\rm acc} = \frac{3}{u_{\rm u} - u_{\rm d}} \left(\frac{K_{\rm u}}{u_{\rm u}} + \frac{K_{\rm d}}{u_{\rm d}}\right)$$

$u_u = 4u_d$ =2890 km/s

m.f.p. of e = ηr_g

$$\eta \sim \left(\frac{dB}{B}\right)^{-2} > 1$$

$$\begin{cases} K_{\rm u} = \dfrac{cE_{\rm max}}{3{\rm e}B_{\rm u}} \eta_{\rm u} \left(\cos^2\theta + \dfrac{\sin^2\theta}{1+\eta_{\rm u}^2}\right) \\ K_{\rm d} = \dfrac{cE_{\rm max}}{3{\rm e}B_{\rm d}} \eta_{\rm d} (\cos^2\theta + r^2\sin^2\theta)^{-1} \left(\cos^2\theta + \dfrac{r^2\sin^2\theta}{1+\eta_{\rm d}^2}\right) \end{cases}$$

3.2. From equations to parameters

known parameters: u_u, $\nu_{rolloff}$, w_u, w_d → **unknown parameters:** E_{max}, B_u, B_d, η_u, η_d, θ

A. Age limited case

$t_{acc} = t_{age} < t_{loss}$

$w_u = K_u/u_u$

$w_d = K_d/u_d$

B. Loss limited case

$t_{loss} = t_{acc} < t_{age}$

$w_u = \min\{K_u/u_u, (K_u t_{cool})^{1/2}\}$

$w_d = \max\{u_d t_{cool}, (K_d t_{cool})^{1/2}\}$

Both cases,

$B_d = B_u(\cos^2\theta + r^2\sin^2\theta)^{1/2}$

$\nu_{lolloff} \sim BE^2$

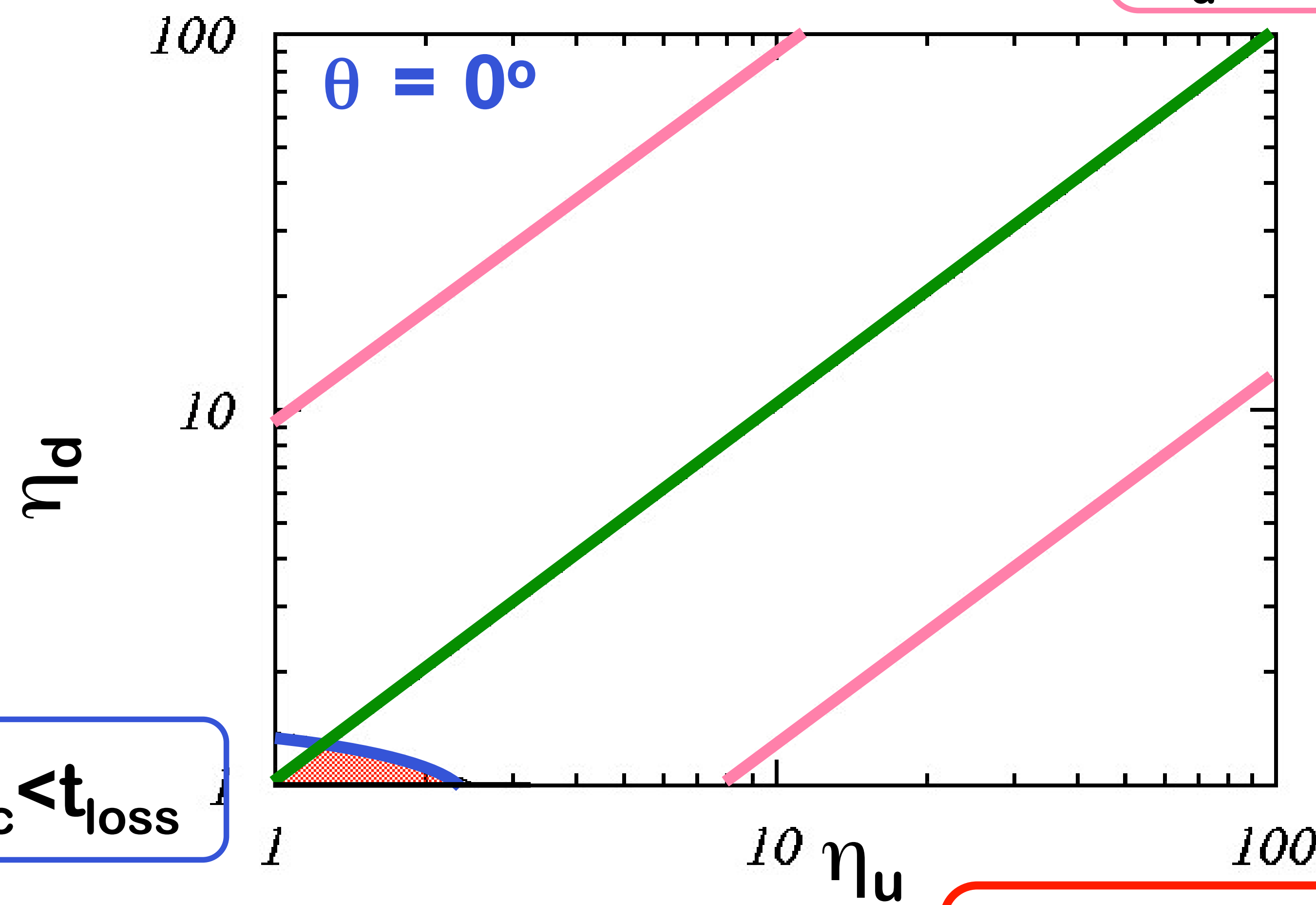
$\eta_d < \eta_u$

→ **Restriction of parameters!**

3.2.A. Age limited case: $t_{acc}=t_{age}<t_{loss}$

$w_u=K_u/u_u$, $w_d=K_d/u_d$

w_u = 0.01-0.1pc
w_d = 0.06-0.4pc

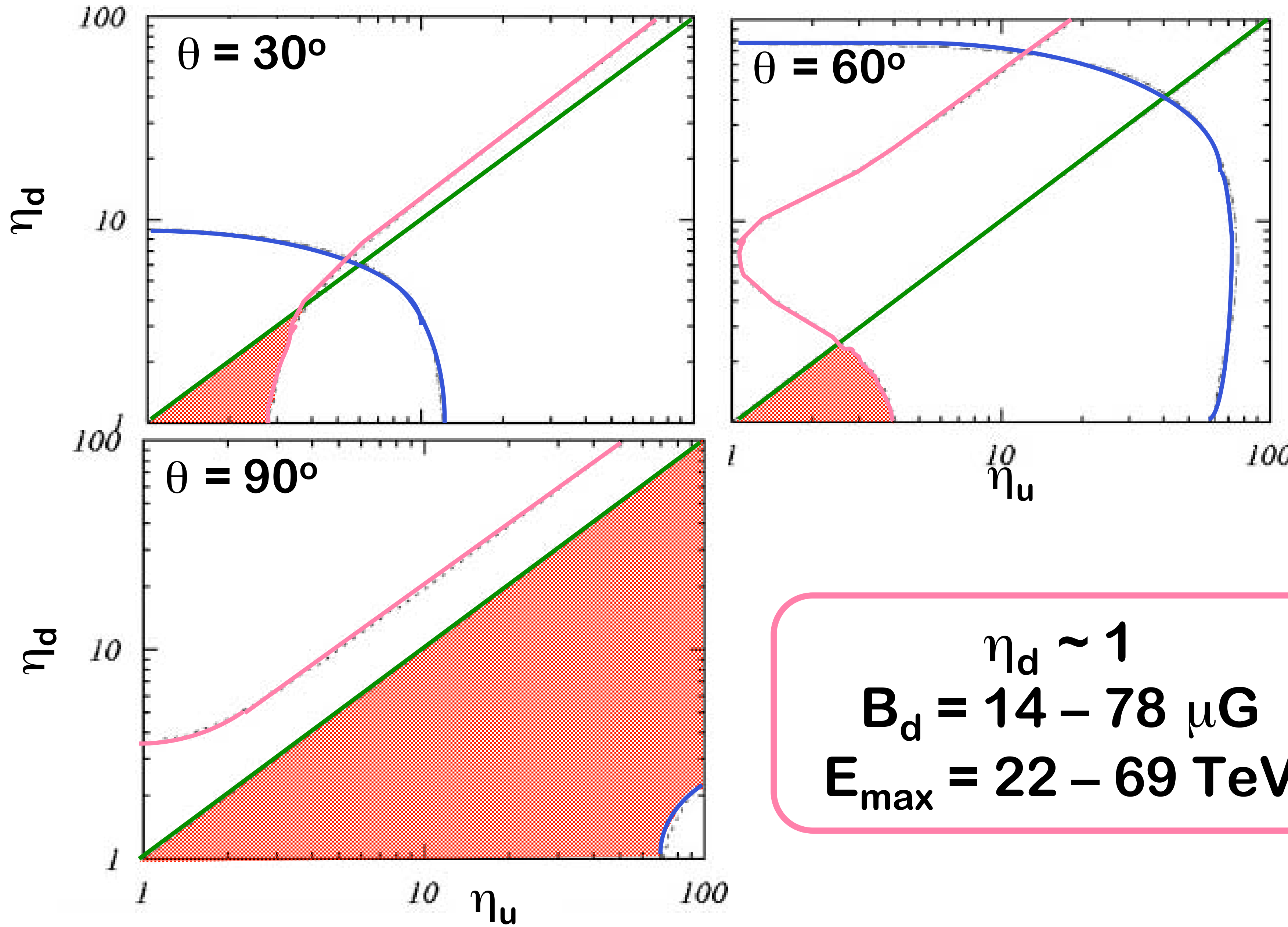


$\eta_d<\eta_u$

$t_{acc}<t_{loss}$

B_d ~ 78μG
E_{max} = 22-29TeV

On the other angle….



$\eta_d \sim 1$

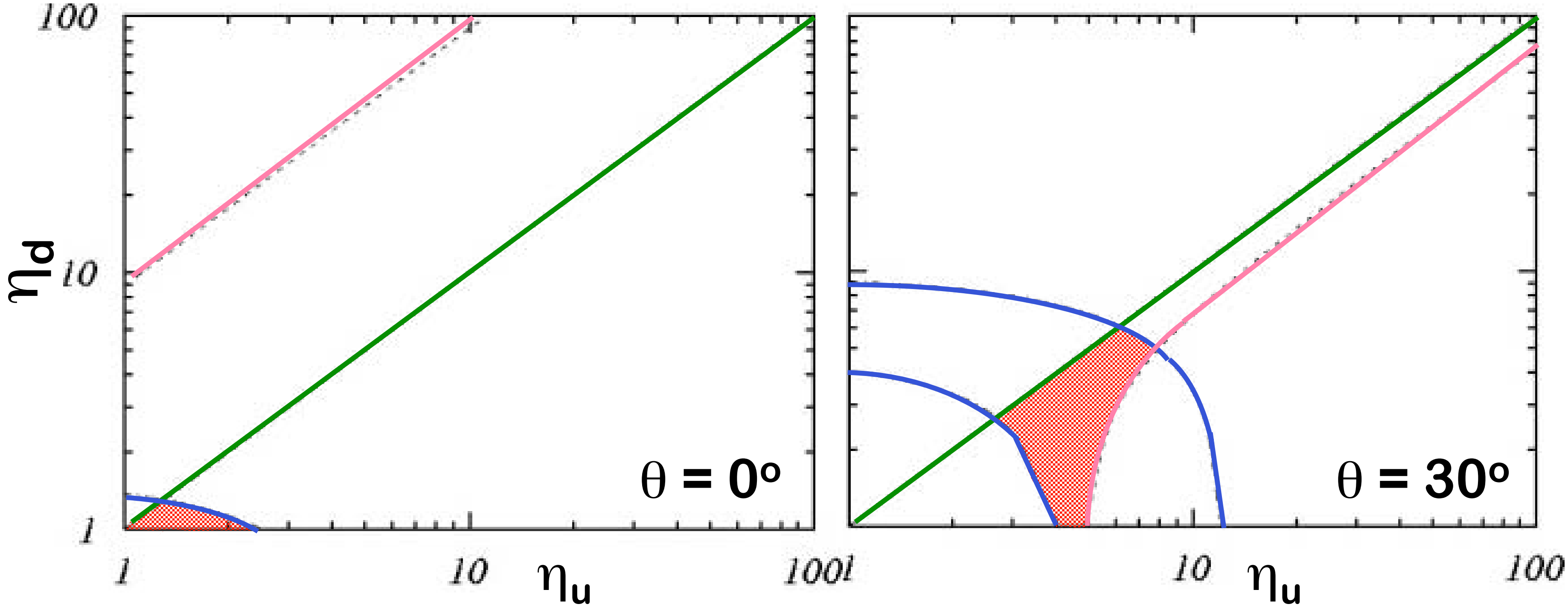
$B_d = 14 - 78\ \mu G$

$E_{max} = 22 - 69$ TeV

3.2.B. Loss limited case: $t_{acc}=t_{loss}<t_{ag}$

$w_u = \min\{K_u/u_u, (K_u t_{cool})^{1/2}\}$

$w_d = \max\{u_d t_{cool}, (K_d t_{cool})^{1/2}\}$



$\theta < 30^o$, $\eta_d \sim \eta_u \sim 1$

$B_d = 23 - 85\ \mu G$, $E_{max} \sim 21 - 54$ TeV

3.3. Given restrictions for SN 1006

Age limited case;

$\eta_d \sim 1$

$B_d = 14 - 78\ \mu G$

$E_{max} = 22 - 69$ TeV

Loss limited case;

$\theta < 30^o$

$\eta_d \sim \eta_u \sim 1$

$B_d = 23 - 85\ \mu G$

$E_{max} = 21 - 54$ TeV

Anyway,

B_d: fully turbulent (Bohm limit)

$14 - 85\ \mu G$

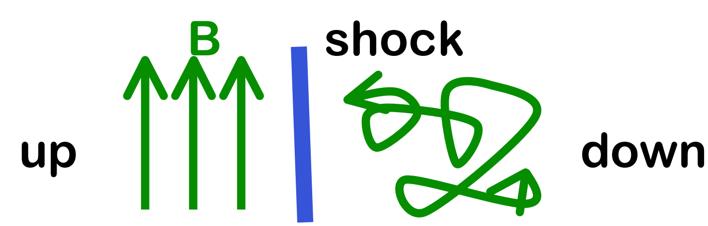
B_u: $3.5 - 85\ \mu G$

E_{max}: $20 - 70$ TeV

CANGAROO suggests

$B \sim$ a few μG .

(Tanimori et al. 2001)



In age limited case!

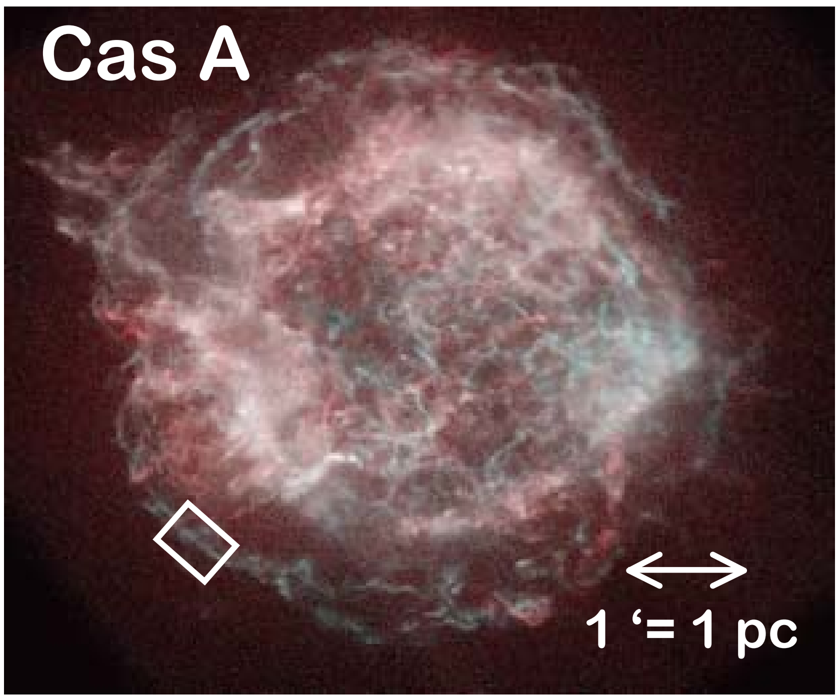
In the future,

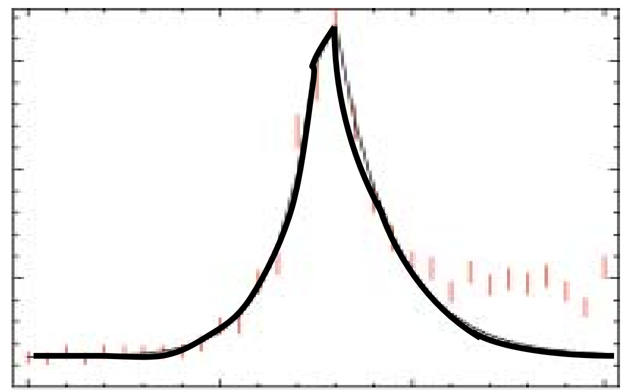
More detailed models
Multi-wavelength obs. → accurate accel. history

4.1. Application to the other SNR

Is SN1006 the lonely SNR
with non-thermal filaments? ……No!

Spatial resolution of Chandra → Vink & Laming (2003) found non-thermal filaments in Cas A

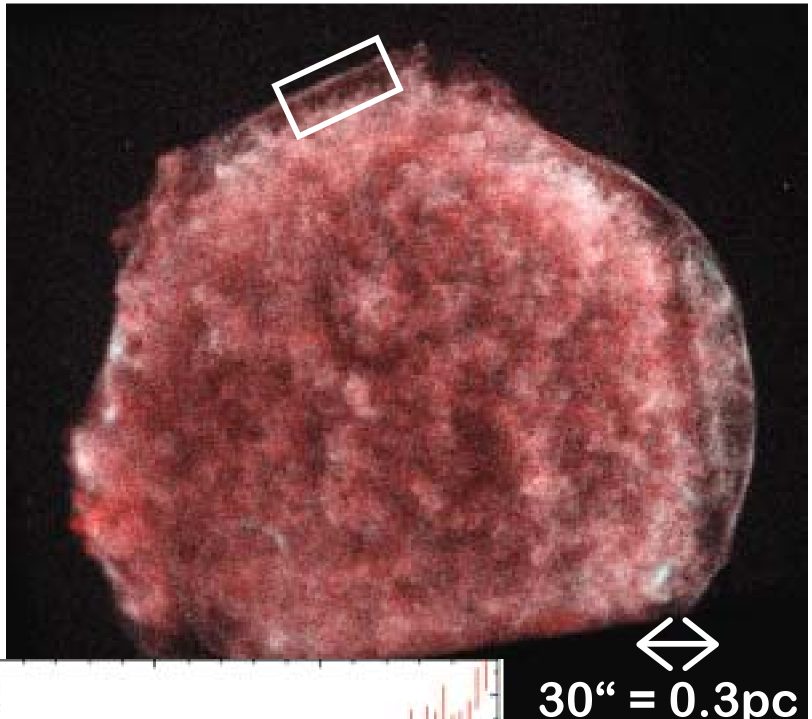


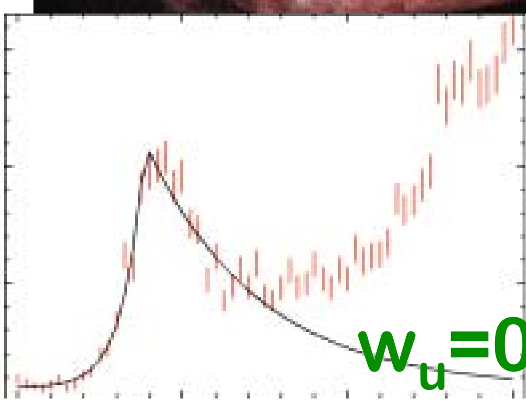


$w_u = 0.017^{+0.002}_{-0.002}$ pc

$w_d = 0.024^{+0.004}_{-0.003}$ pc

Tycho



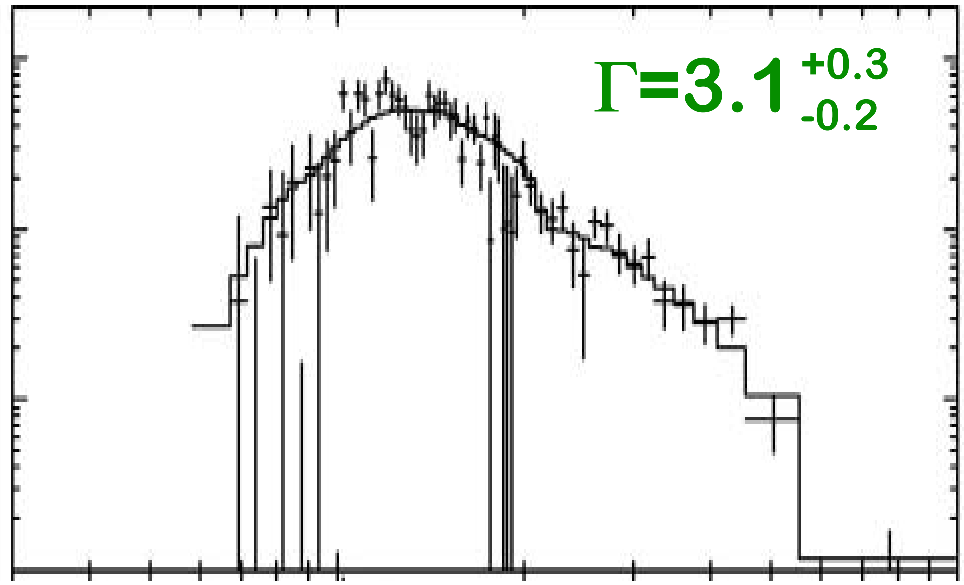


$w_u = 0.015^{+0.002}_{-0.002}$ pc

$w_d = 0.079^{+0.012}_{-0.009}$ pc

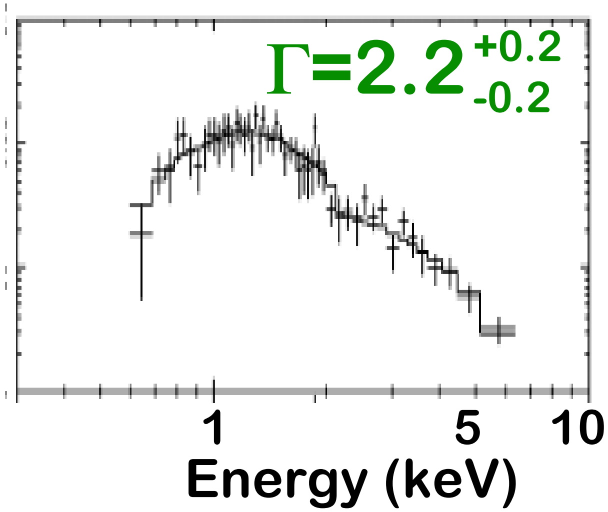
Hwang et al. (2002)

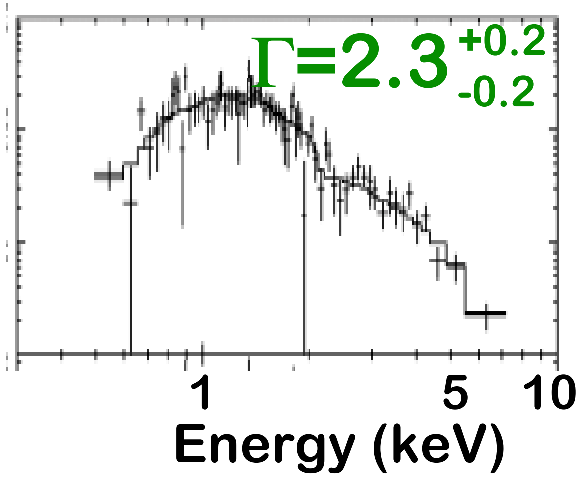
“filaments with small E.W.”

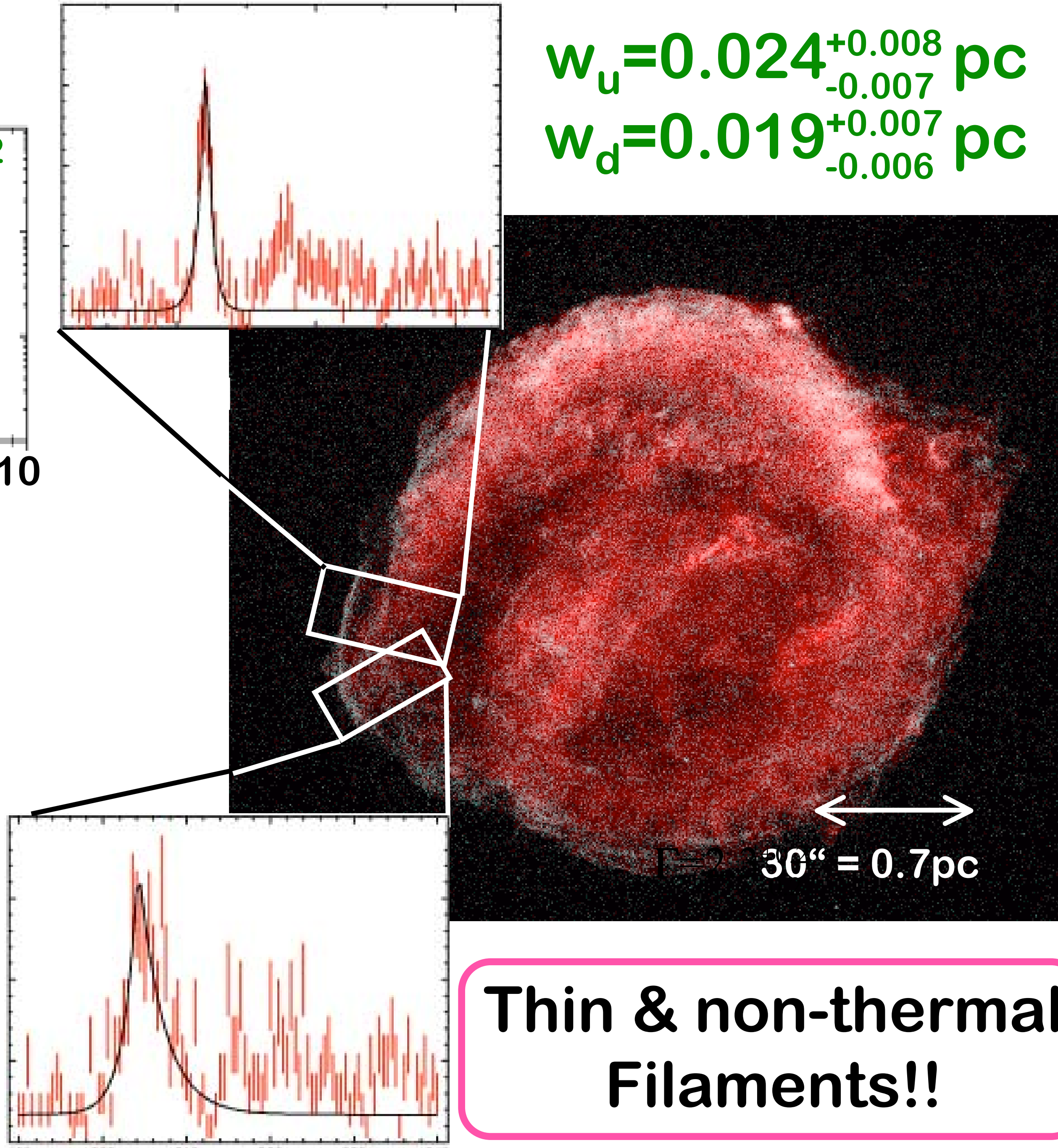


The filament is non-thermal!

Kepler







$w_u=0.024^{+0.008}_{-0.007}$ pc

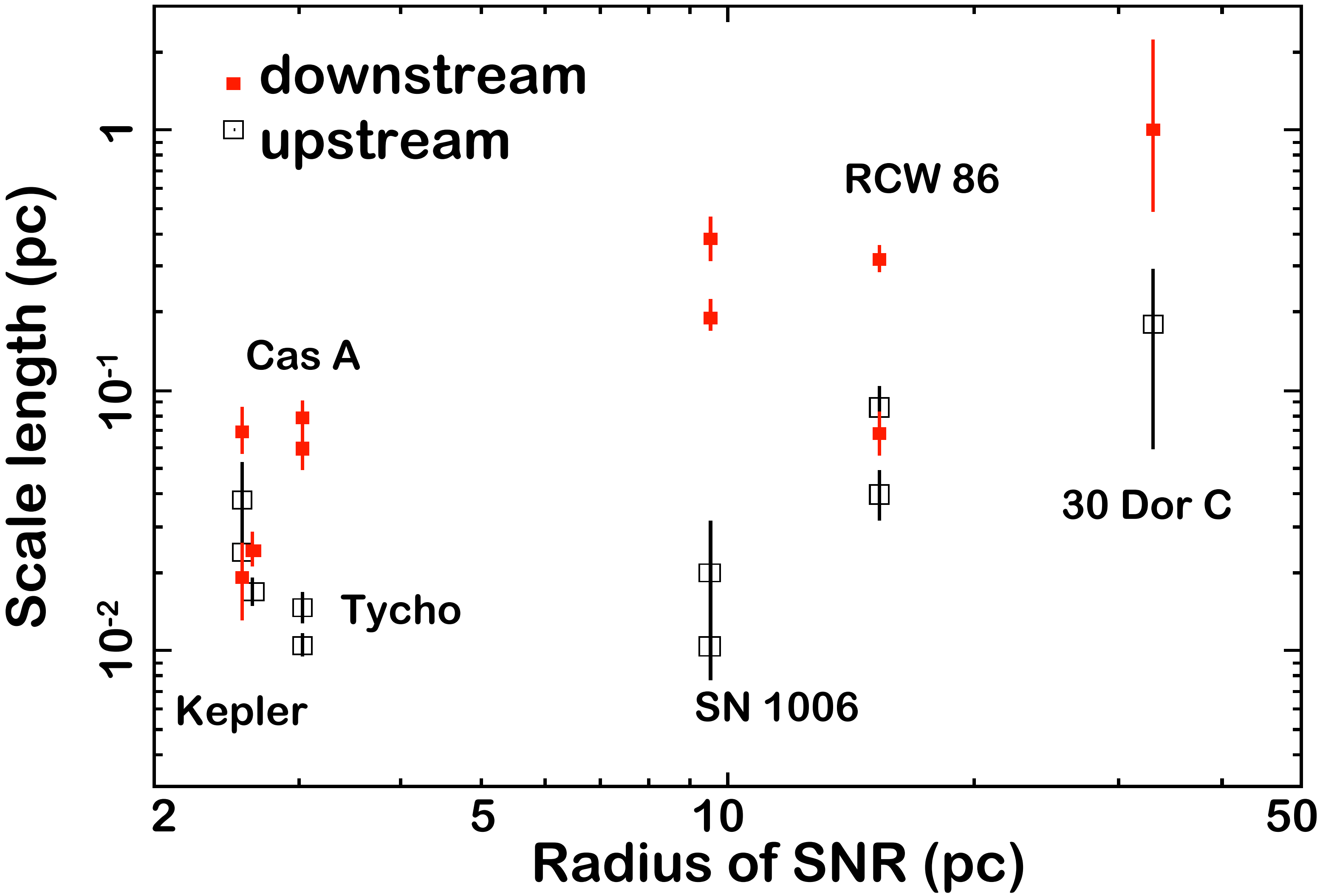
$w_d=0.019^{+0.007}_{-0.006}$ pc

$w_u=0.038^{+0.015}_{-0.011}$ pc

$w_d=0.069^{+0.017}_{-0.012}$ pc

Thin & non-thermal Filaments!!

4.2. The scale length vs. radius



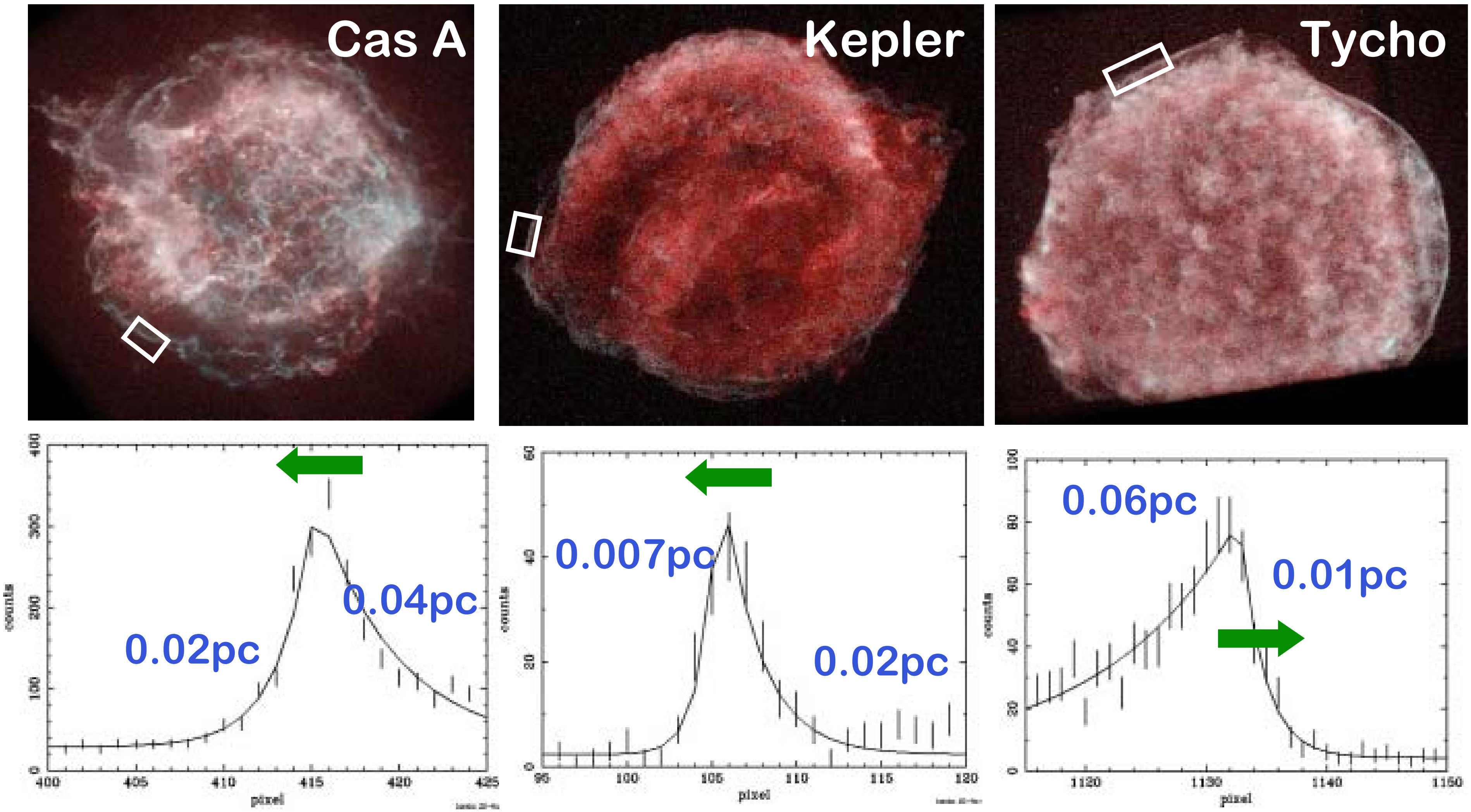
The scale length is ~ % of the radius.
The scale lengths grow larger as the SNRs age.

5. Summary

1. Non-thermal and thin filaments are discovered at the outer edge of SN1006.
2. The scale length is very small, w_u = 0.01 – 0.1 pc and w_d = 0.06 – 0.4 pc.
3. Both in age limited case and loss limited case, we can make restrictions such as;
   magnetic field in downstream is turbulent.
   electrons are accelerated to 20 – 70 TeV.
4. We found thin non-thermal filaments in many SNRs.
5. The filaments glow wider as SNRs age older.
6. To find more GLAST sources,
   hard X-ray observations with excellent spatial resolution can be a good pilot.

4. Application to other SNRs

Do other SNRs have non-thermal filaments?



Many SNRs have thin filaments!