Cosmic-ray Acceleration at RCW 86

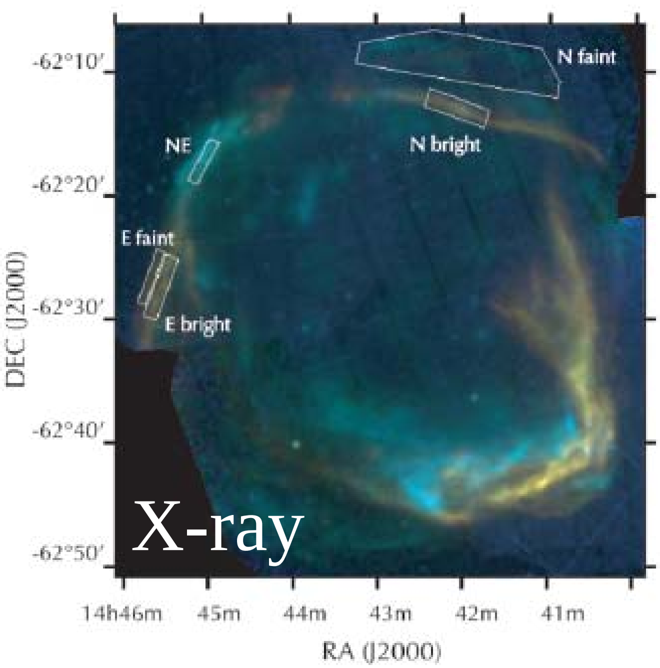
Ryo Yamazaki
(Hiroshima University)

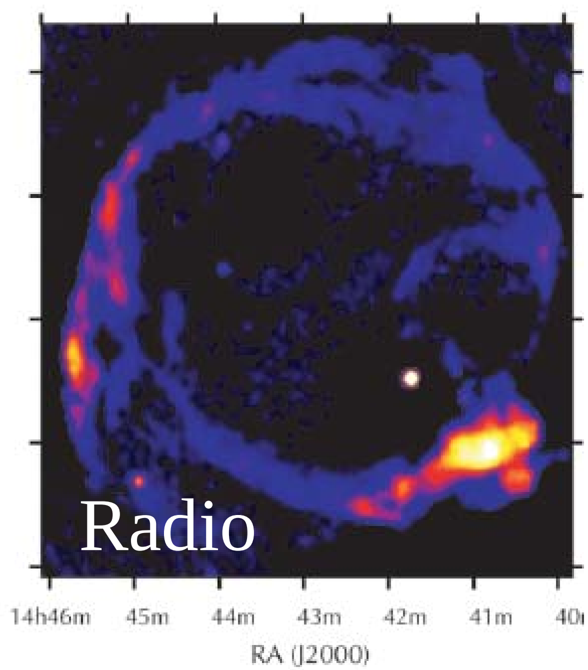
With Eveline Helder, Jacco Vink, Aya Bamba,…

Ref. Helder +09, Science ; Vink +06, ApJL

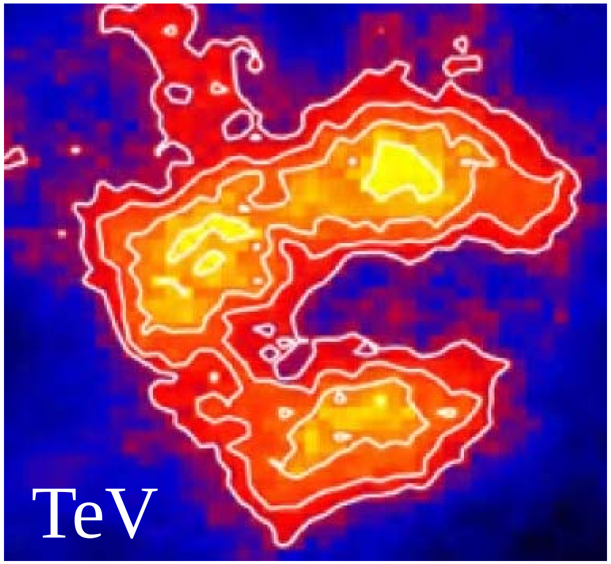
RCW 86 : a young supernova remnant

- Renmant of SN185 ; Distance 2.5kpc (OB assoc.)
- Exploded in a superbubble ? (not yet conclusive)
- Synch. X, TeV γ detected => particle acceleration





Vink +06



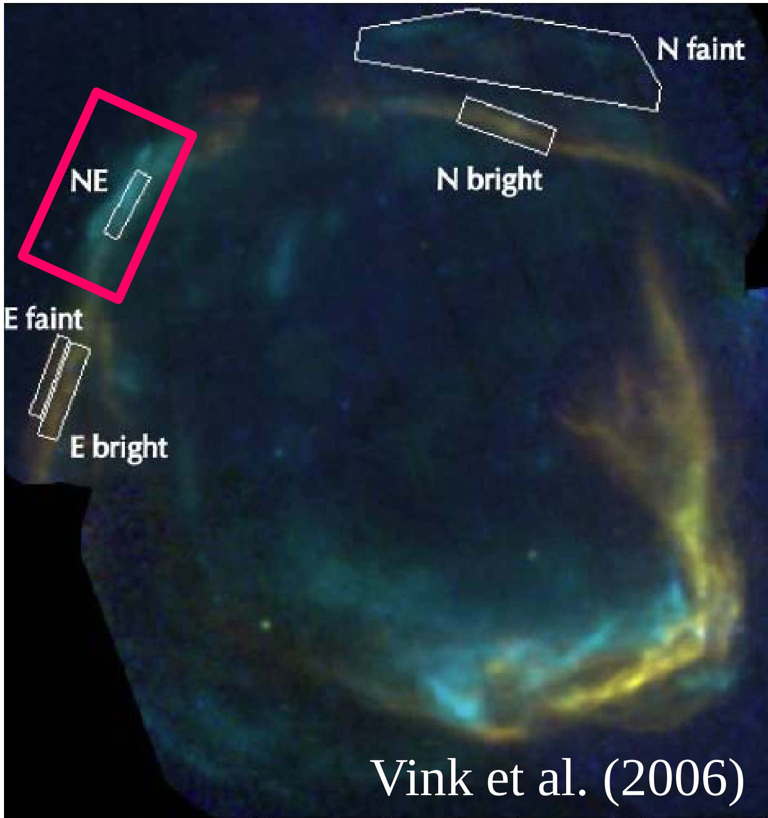
H.E.S.S. (08)

Outline of this talk

Rich observational information have been obtained so far in NE region of RCW86.

In this talk, we discuss if the observed properties on this region is consistent with the predictions of nonlinear model of CR acceleration, i.e.,

- Concaved particle spectrum:
  Radio index softer than 0.5.
- Low temperature downstream.
- Amplified magnetic field.



Vink et al. (2006)

Shock parameters in inefficient case

Shock compression ratio: $r = \frac{4{M_s}^2}{{M_s}^2 + 3}$, M_s : Mach number.
($\gamma_g = 5/3$)

Electron energy spectrum: $N(E_e)\,dE_e \propto {E_e}^{-p}\,dE_e$, $p = \frac{r+2}{r-1}$

Radio spectrum: $F_\nu \propto \nu^{-\alpha}$, $\alpha = \frac{p-1}{2}$

(Standard : $r \to 4$, $p \to 2$, $\alpha \to 0.5$ as $M_s \to \infty$.)

Name of Historical SNR	Radio spectral index (α)	Electron power-law Index (p)	Comp. ratio for test-particle limit (r)	Mach number (M_s)
Cas A	0.78	2.56	2.92	2.85
Kepler	0.7	2.4	3.14	3.31
Tycho	0.52	2.04	3.88	10.0
SN 1006	0.57	2.14	3.63	5.44
RCW 86	0.6	2.2	3.5	4.58

Shock parameters in inefficient case

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Very small "r" and "M_s" !!

cf. typical values are:

shock velocity v_s > *10^3 km/s,

sound speed ~ *10 km/s,

M_s > 100

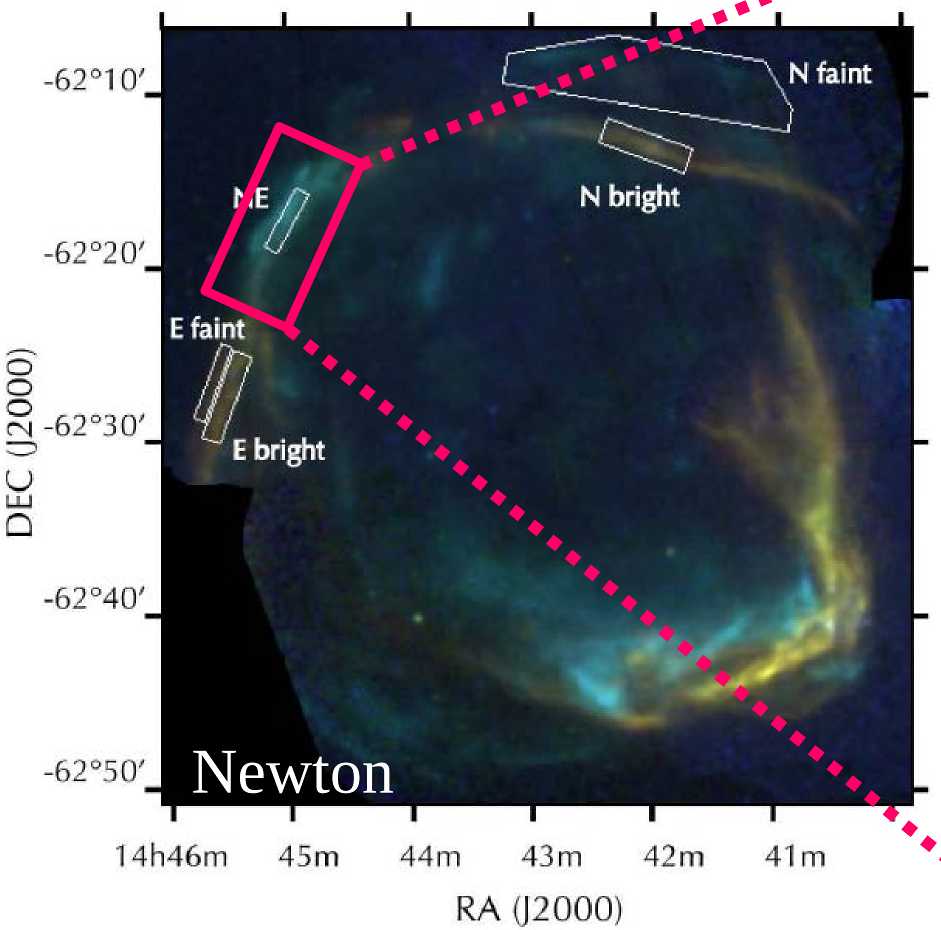
Possible solution:

Soft spectrum as a result of nonlinear effect.

Comp. ratio for test-particle limit (r)	Mach number (M_s)
2.92	2.85
3.14	3.31
3.88	10.0
3.63	5.44
3.5	4.58

Very Low downstream temperature

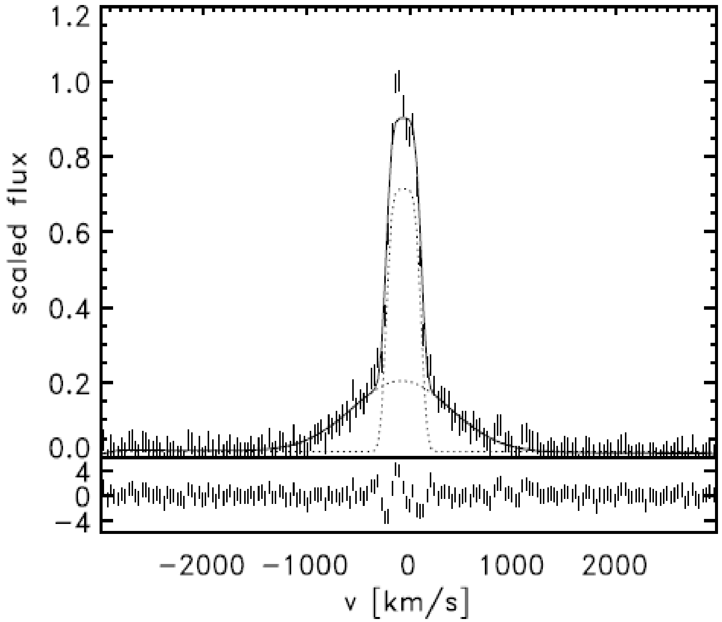
RCW 86 (t_{age} ~ 1800 yrs)



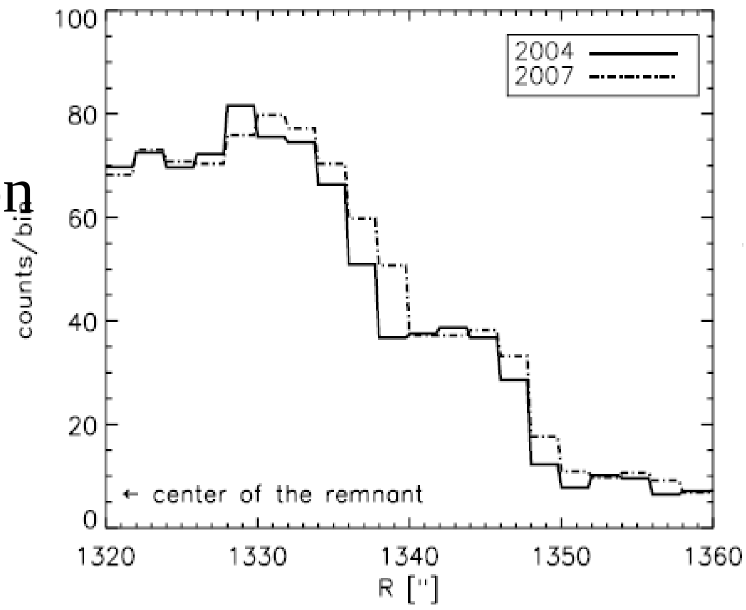
Vink et al. (2006)

Very Low downstream temperature

VLT:
Hα line
(broad+narrow)
(optical)



Chandra:
Proper motion
(X-ray)



Very Low downstream temperature

Helder, RY et al. (2009)

Expansion rate（w/ X-rays）:

$V_{shock} \sim (6.0 \pm 2.0) \times 10^8$ cm/s

=> predicted downstream temp.

$kT \sim (3/16)\, \mu\, m V_{shock}^2$

~ 42 keV (or more).

Measured downstream temp. (w/ Hα):

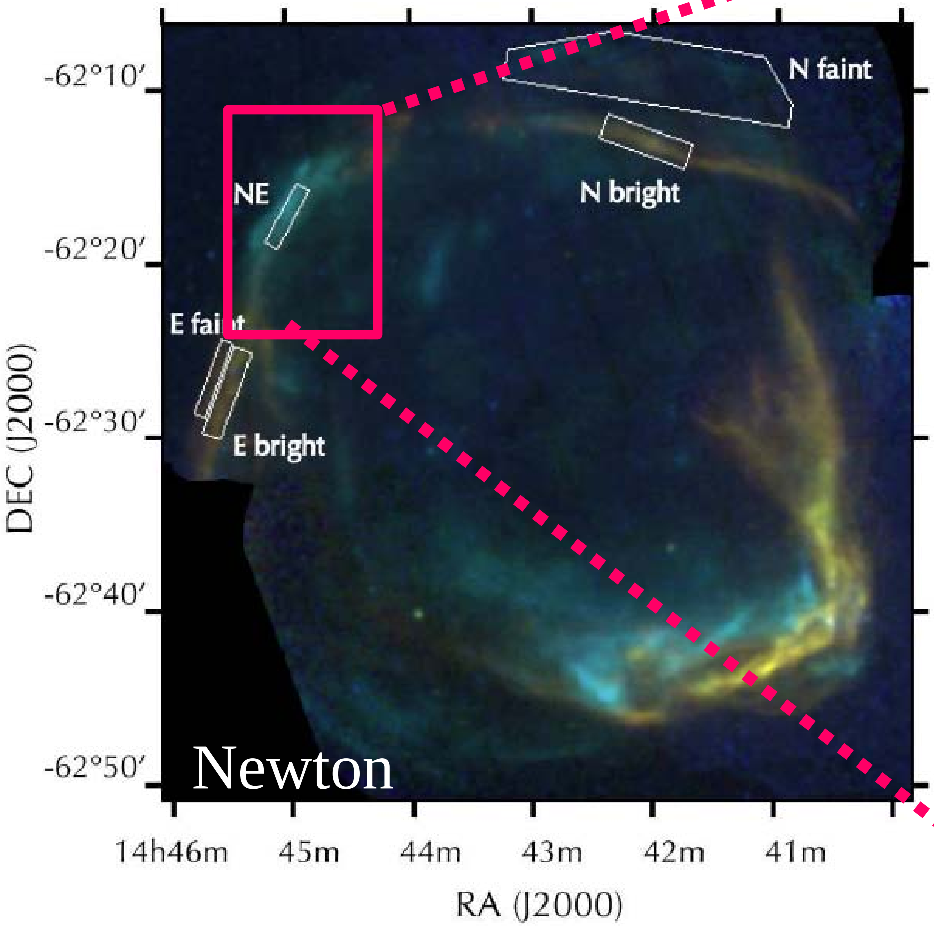
$kT_p \sim 2.3 \pm 0.3$ keV.

Measured downstream temperature much lower than predicted by simple shock-jump condition.

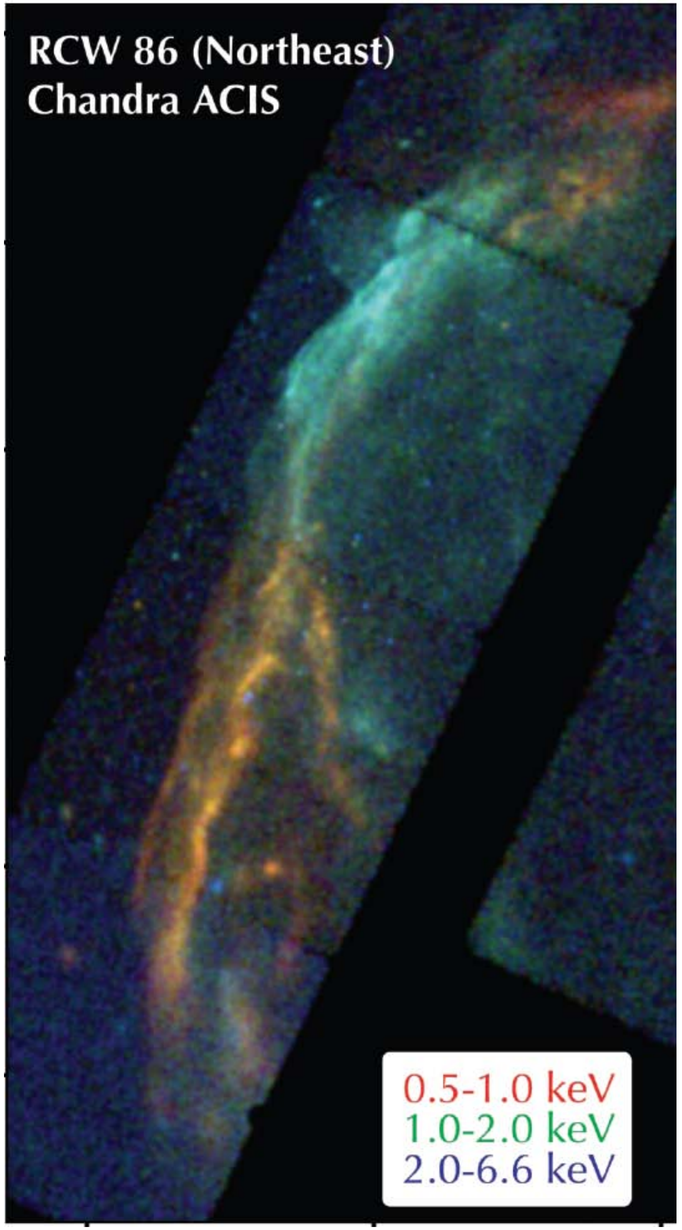
⇒ Missing thermal energy goes into the CR acceleration.

Synchrotron X- ray filament

RCW 86 (t_{age} ~ 1800 yrs)



Vink et al. (2006)



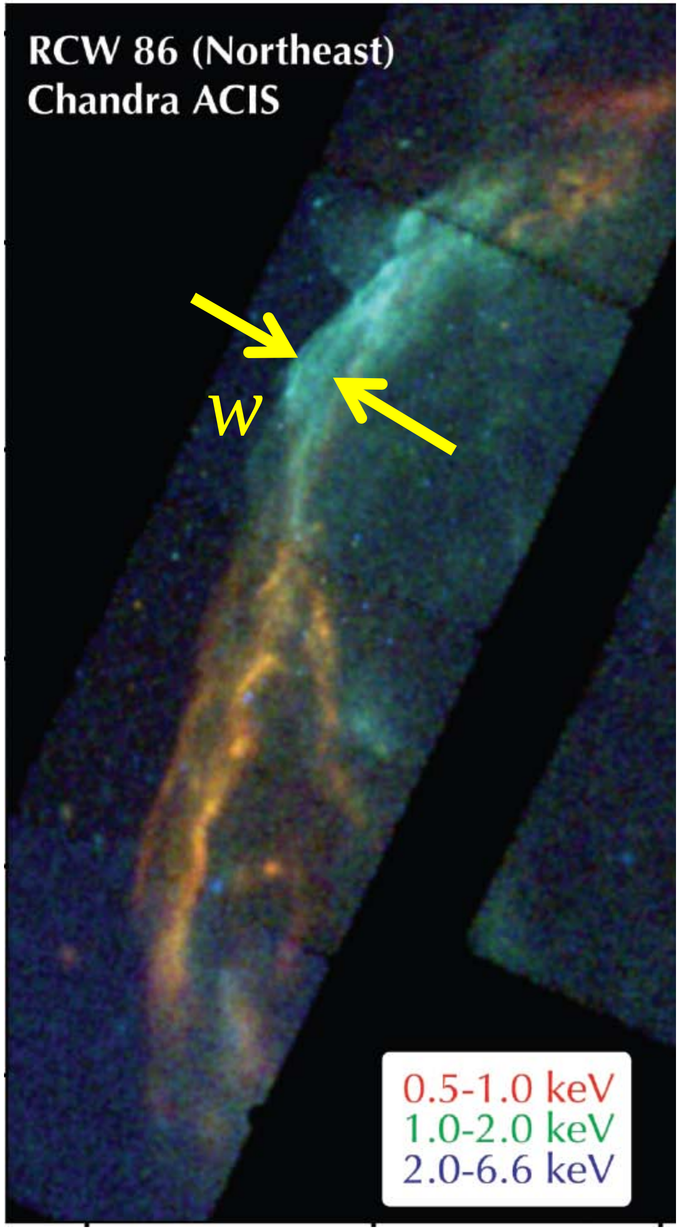
Synchrotron X- ray filament

w of X-ray filament is relatively thick ~pc.
=> Electron cooling not so significant ?
=> Not so strong magnetic field ?

$w = u_0 t_{cool} / R_{tot}$

$$t_{cool} = 1.6 \times 10^3 \text{ yr} \left(\frac{B}{10 \ \mu\text{G}} \right)^{-3/2} \left(\frac{h\nu_{syn}}{\text{keV}} \right)^{-1/2}$$

$$B \sim 17 \ \mu\text{G} \left(\frac{R_{tot}}{4} \right)^{-2/3} \left(\frac{w}{3.7 \times 10^{18} \text{cm}} \right)^{-2/3} \times \left(\frac{u_0}{6000 \text{ km s}^{-1}} \right)^{2/3} \left(\frac{h\nu_{syn}}{\text{keV}} \right)^{-1/3}$$



Summary of observations

At RCW NE region, we find:

- Radio index : $\alpha = 0.6$. (p=2.2)
- Downstream temperature : T_2= 2.3±0.3 keV.
- Shock velocity : u_0 = 6000±2000 km/s
- Width of synch-X filament : w ~pc (=> B~20μG?)

We discuss if nonlinear model of cosmic-ray acceleration can account for the observed properties or not.

Blasi's formalism of NL CR acc.

Finding steady-state solution $f_0 = f(0,p)$ to :

- CR transport eq.

$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f\right] + u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{\partial u}{\partial x}p\frac{\partial f}{\partial p} + Q = 0$$

$$Q(x,p) = Q_0(p)\delta(x)$$

$$Q_0(p) = \frac{N_{inj}u_1}{4\pi p_{inj}^2}\delta(p - p_{inj}) \qquad N_{inj} = \eta N_{gas,1}$$

- Fluid continuity eqs.

$$\rho_0 u_0 = \rho_p u_p$$

$$\rho_0 u_0^2 + P_{g,0} = \rho_p u_p^2 + P_{g,p} + P_{CR,p}$$

Blasi's formalism of NL CR acc.

Assumption :

No effects from amplified B-field is considered.

Input parameters (only 4!) :

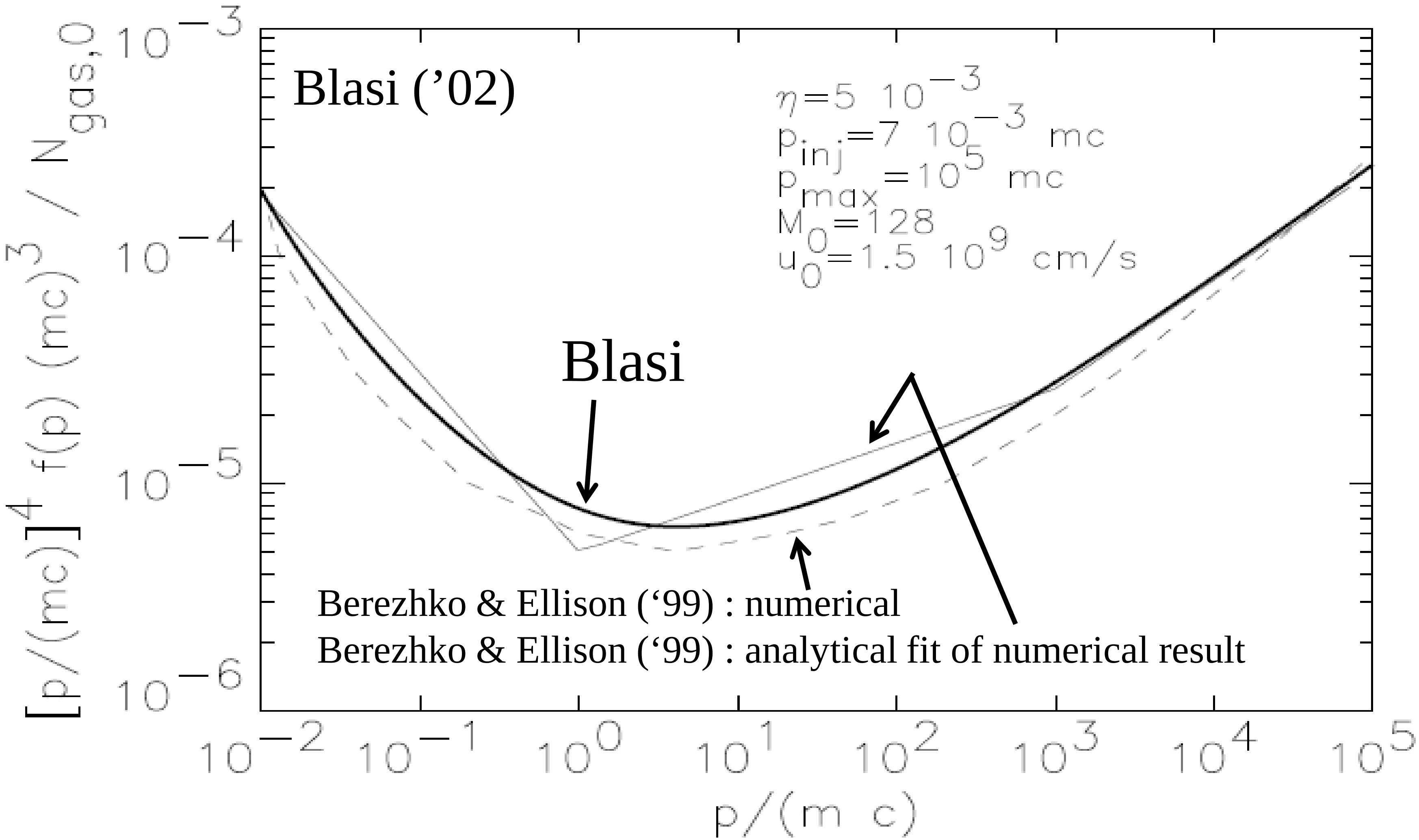
- M_0 : shock Mach number
- u_0 : shock velocity
- p_{max} : Maximum (proton) energy
- $\xi = p_{inj}/p_{th,2}$: ratio of injection (minimum) momentum to downstream temp. : $p_{th,2}=(2mkT_2)^{1/2}$

Outputs:

- $N_p(p) = 4\pi p^2 f_0(p)$: proton spectrum (at the shock front)
- T_2 : downstream fluid temperature
- R_{tot} : total shock compression ratio
- and many others…

Blasi's formalism of NL CR acc.

The model well reproduces the results of numerical simulations with the same parameters (talk by Dr. Tom Jones).



Electron spectrum

Electron spectrum is given by:

$$N_{\rm e}(p) \propto N_{\rm p}(p) \left(1 + \frac{p}{p_b}\right)^{-1} e^{-(p/p_{\rm max,e})^2}$$

Effect of cooling
(Longair 94;
Zirakashvili & Aharonian 07)

$$E_b = 69 \text{ TeV} \left(\frac{B}{10\ \mu\text{G}}\right)^{-2} \left(\frac{t_{\rm age}}{1800 \text{ yr}}\right)^{-1}$$

Spectral slope v.s. downstream temp.

Inputs: M_0, u_0, p_{max}, ξ

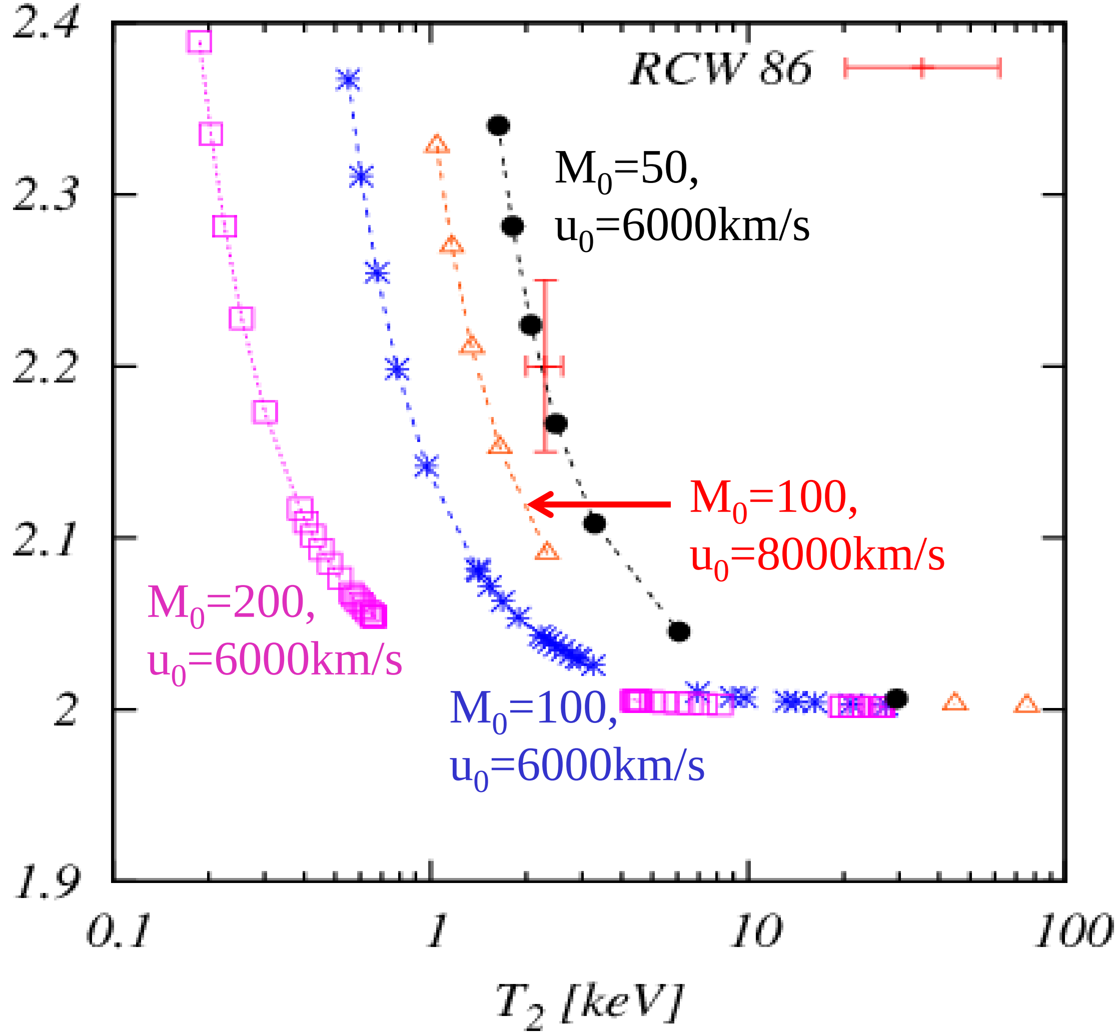
For given (M_0 , u_0, p_{max}) $q_{p=0.01mc}$ is plotted as a function of T_2 ; q and T_2 are one-parameter family of ξ.

(In the right Fig., we adopt p_{max} ~20TeV.)

We find:

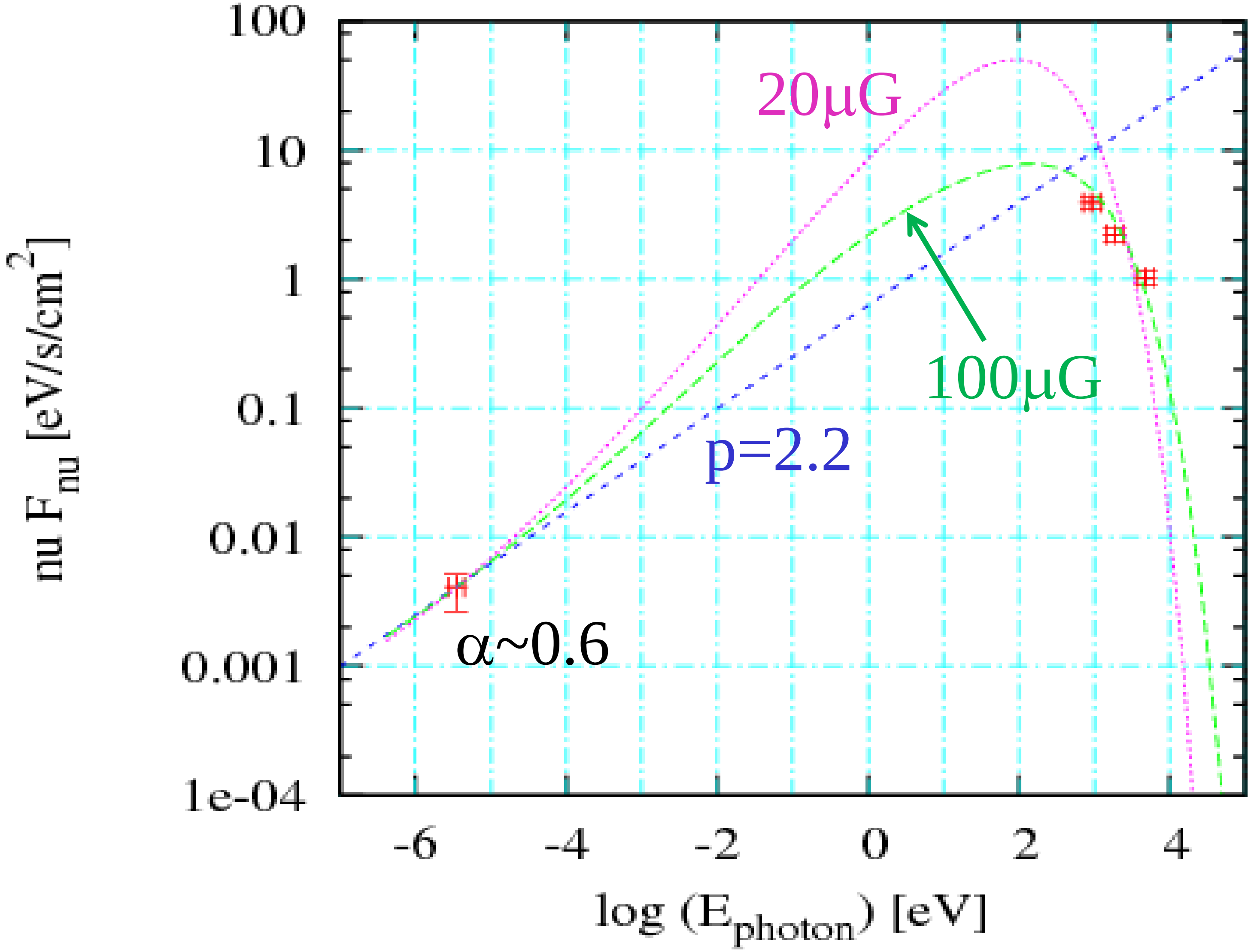
* q –T_2 curve hardly depends on p_{max}.
* M_0~50 are needed to reproduce obs.

$$q(p) = -\frac{d \log N_e(p)}{d \log p}$$ at $p=0.01m_pc$ as a function of T_2



Radio- X synchrotron spectrum

For M_0~50 case, B~100μG is needed to fit radio-X synch.



Summary & Discussion

Observed radio index α=0.6 (q=2.2) and T_2~2keV are explained if M_0~50, u_0~7000km/s, ξ =3.5.

However,

* For these parameters, upstream T_0 =1.4x10^6K.
  Unusually high even if we consider the SN explosion in a superbubble.

* B~100μG is needed to fit radio-X synch.
  Much higher than that estimated by the width of synch-X filament (B~20μG).

Summary & Discussion

Therefore, we feel that Blasi's simple model fails to explain observed properties of RCW86 NE region.

What's wrong?

* Interpretation of Synch-X filament?
(but, $T_0=10^6$K is unlikely even if B~100μG…)

* Modification of nonlinear model?
--- back-reaction of amplified magnetic field
(talks by Kang, Vladimirov, Voelk) , …

* Or, simply the wrong observational argument ?
--- e.g., distance estimation,
interpretation of Hα broad line…