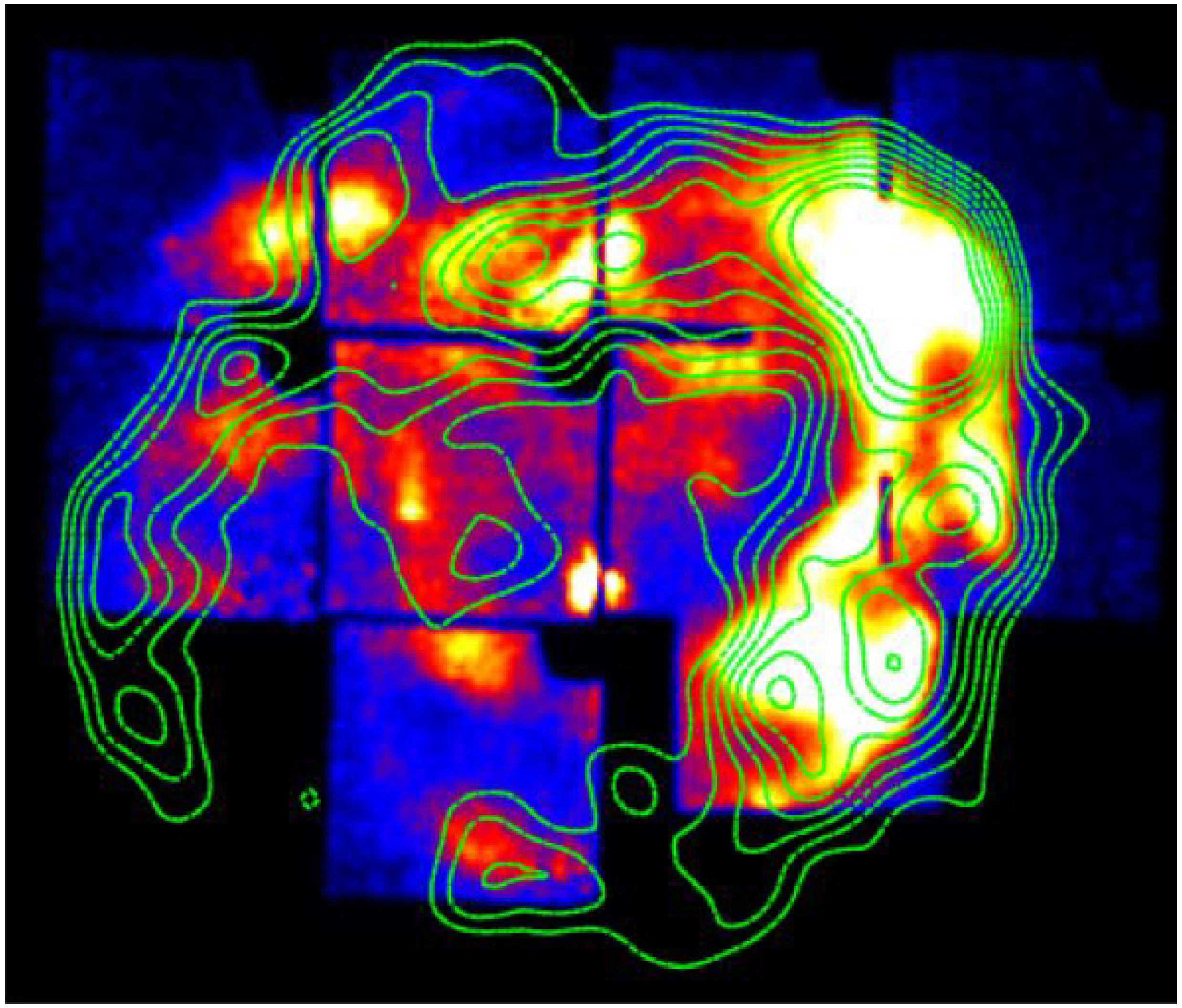
THEORETICAL INSIGHTS INTO NONTHERMAL AND THERMAL VARIATIONS IN SUPERNOVA REMNANTS

DANIEL PATNAUDE (SAO)

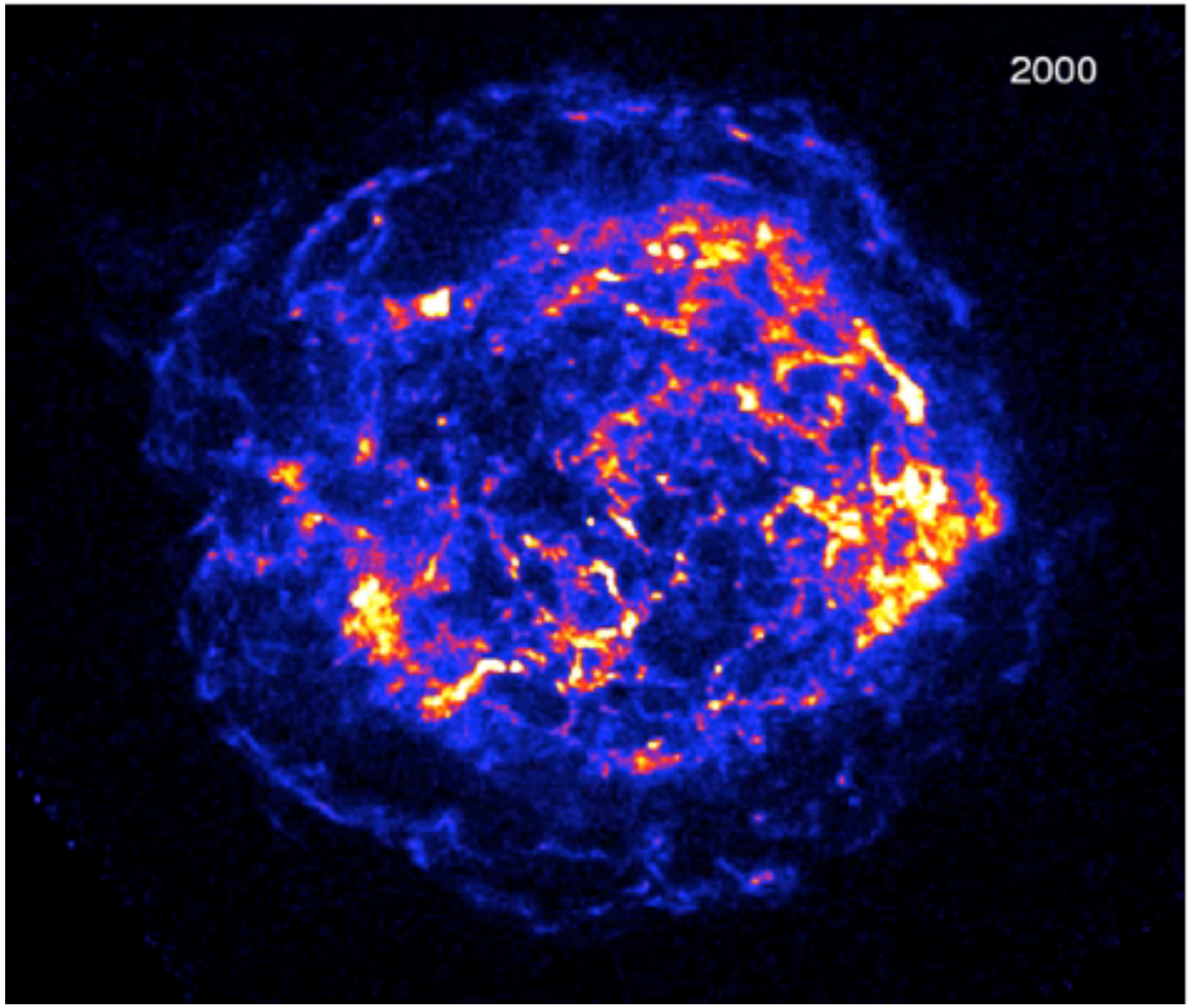
with:
Don Ellison (NCSU)
Pat Slane (SAO)
Rob Fesen (Dartmouth)
Jacco Vink (Utrecht)
J. Martin Laming (NRL)

NONTHERMAL EMISSION

Many young Galactic SNRs show a featureless nonthermal continuum

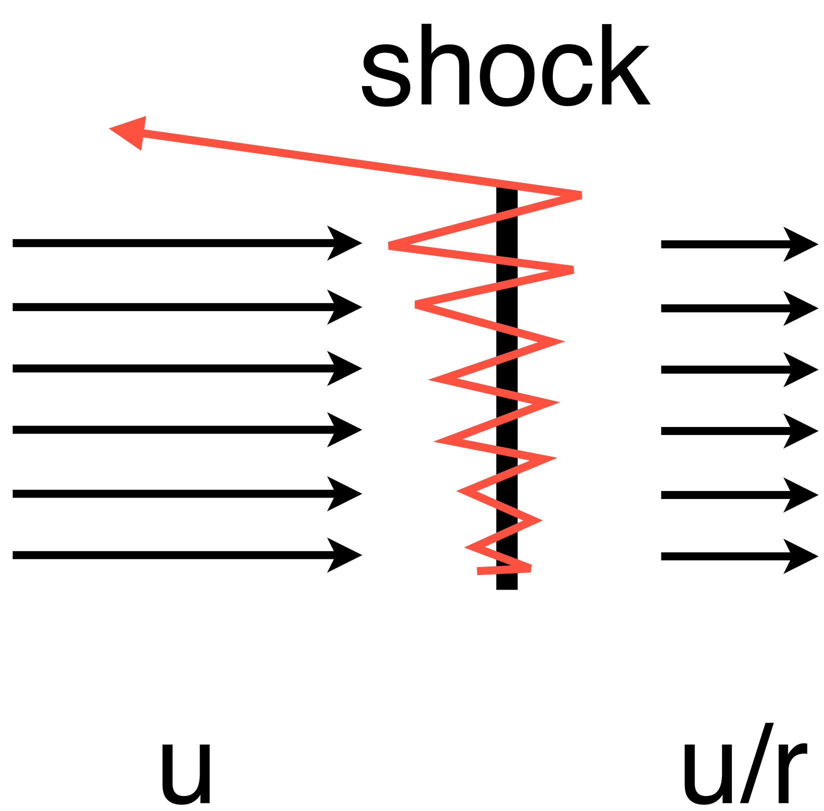


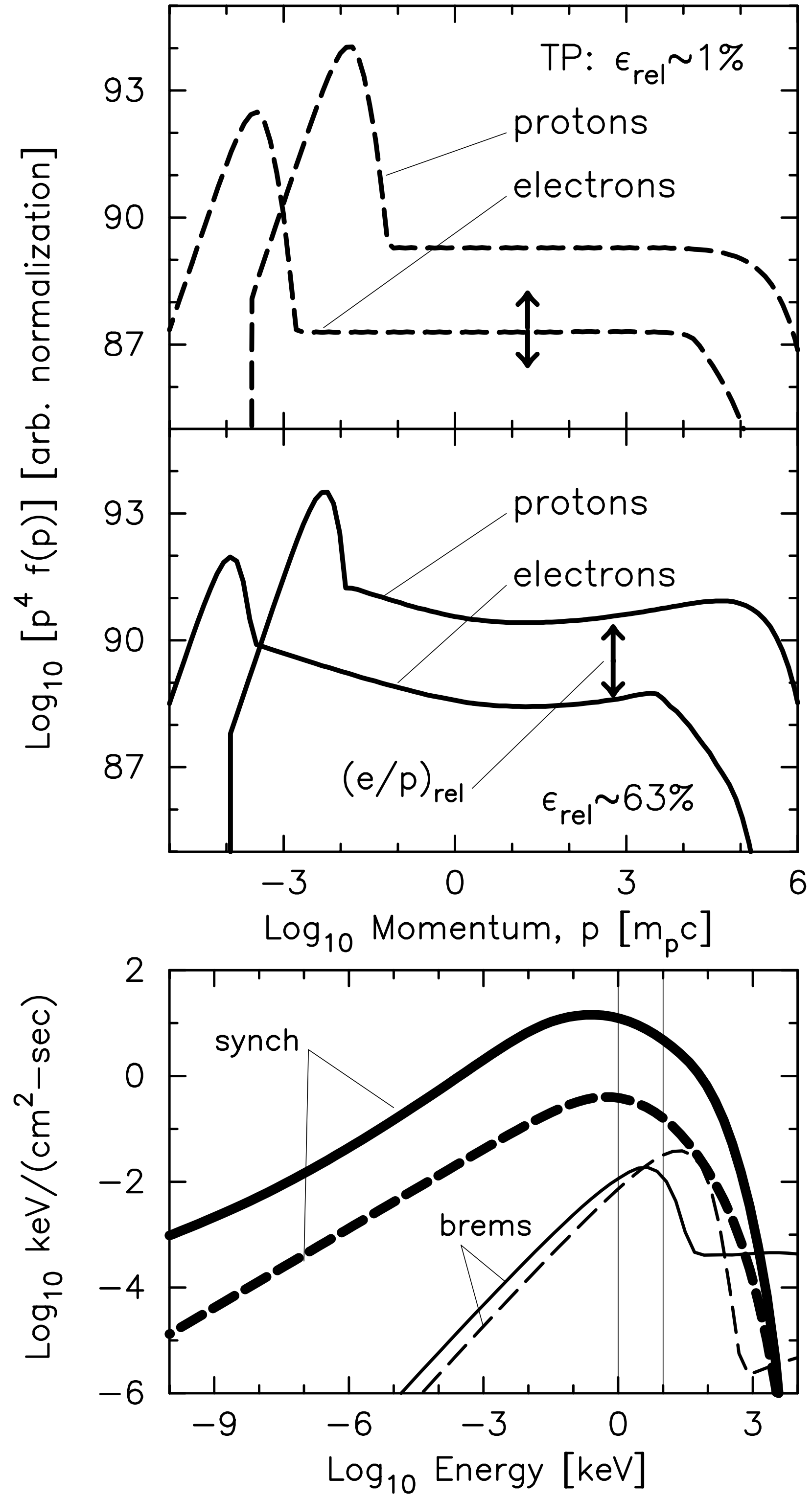
Above: Suzaku XIS mosaic of RX J1713.7-3946 with H.E.S.S. contours overlaid (Tanaka et al. 2008). Left: 4.2-6.0 keV emission from Cas A shown between 2000-2009 (Patnaude et al. 2011).



NONTHERMAL EMISSION

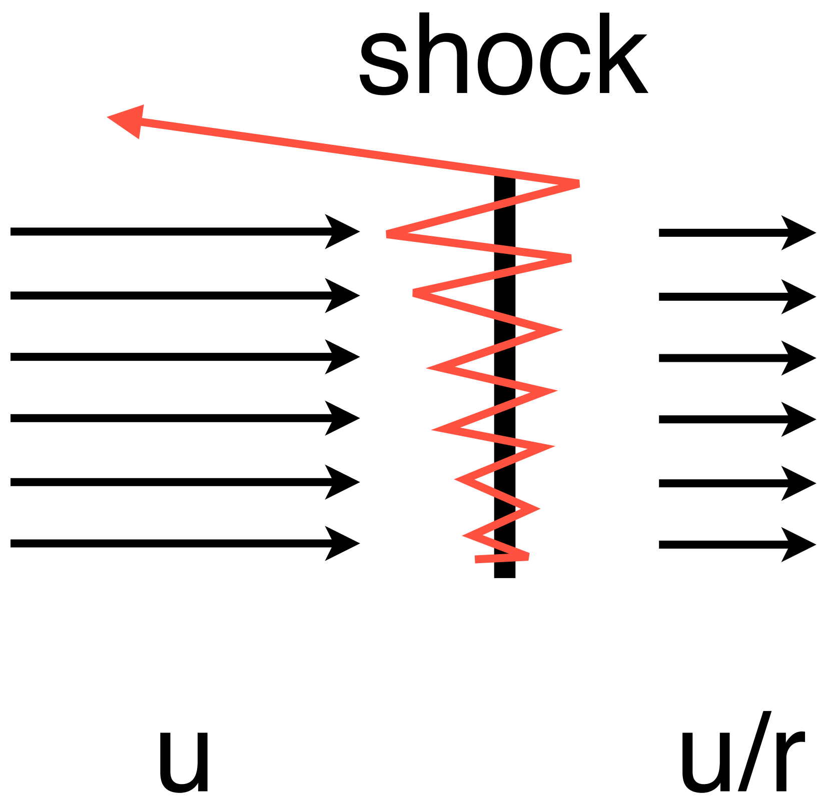
Thermal particles with energies ~ keV “leak” to higher energies via 1st-order Fermi Acceleration (DSA)

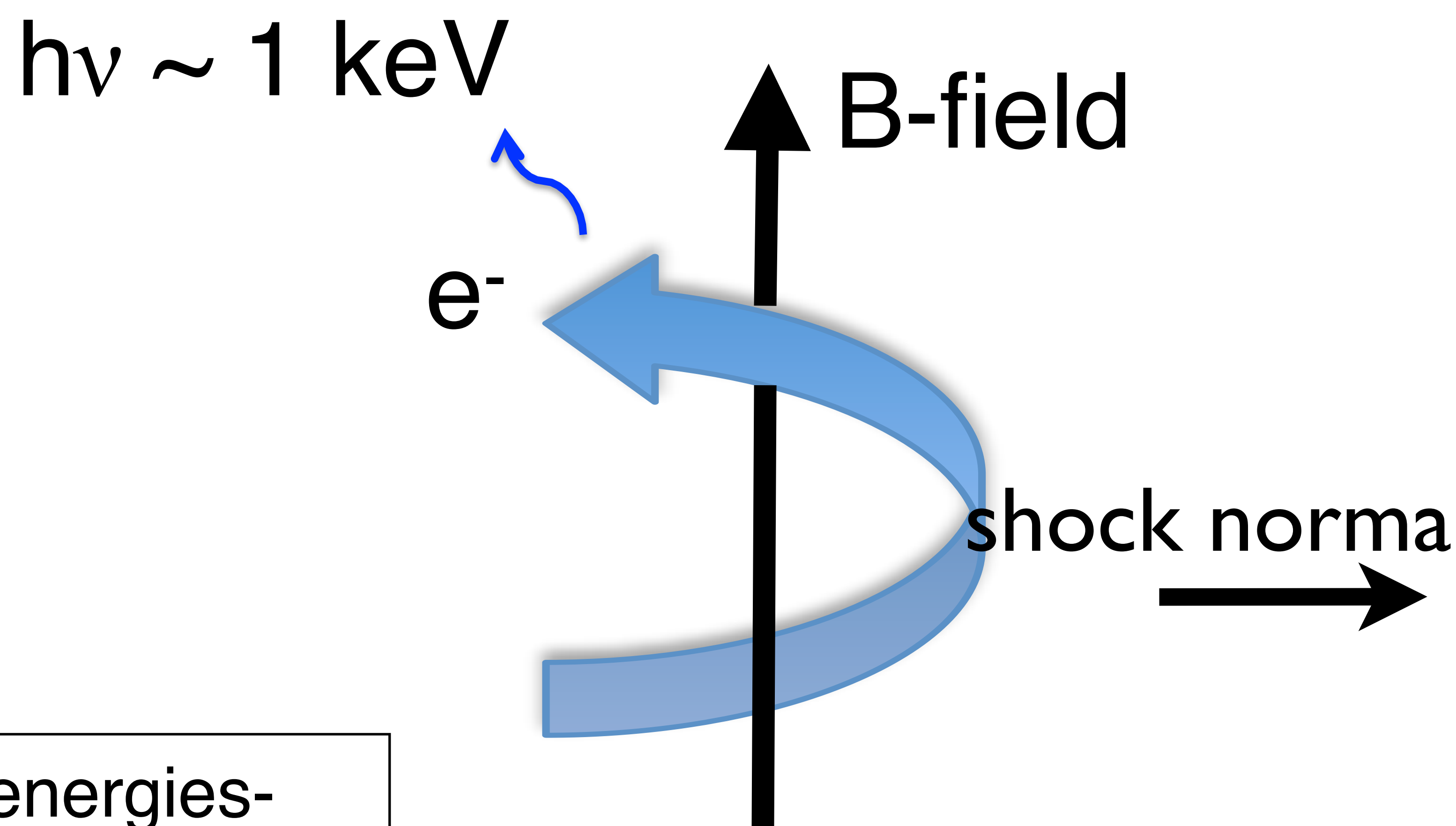




PDF and continuum emission (from Ellison et al. 2007)

1st-Order Fermi Acceleration

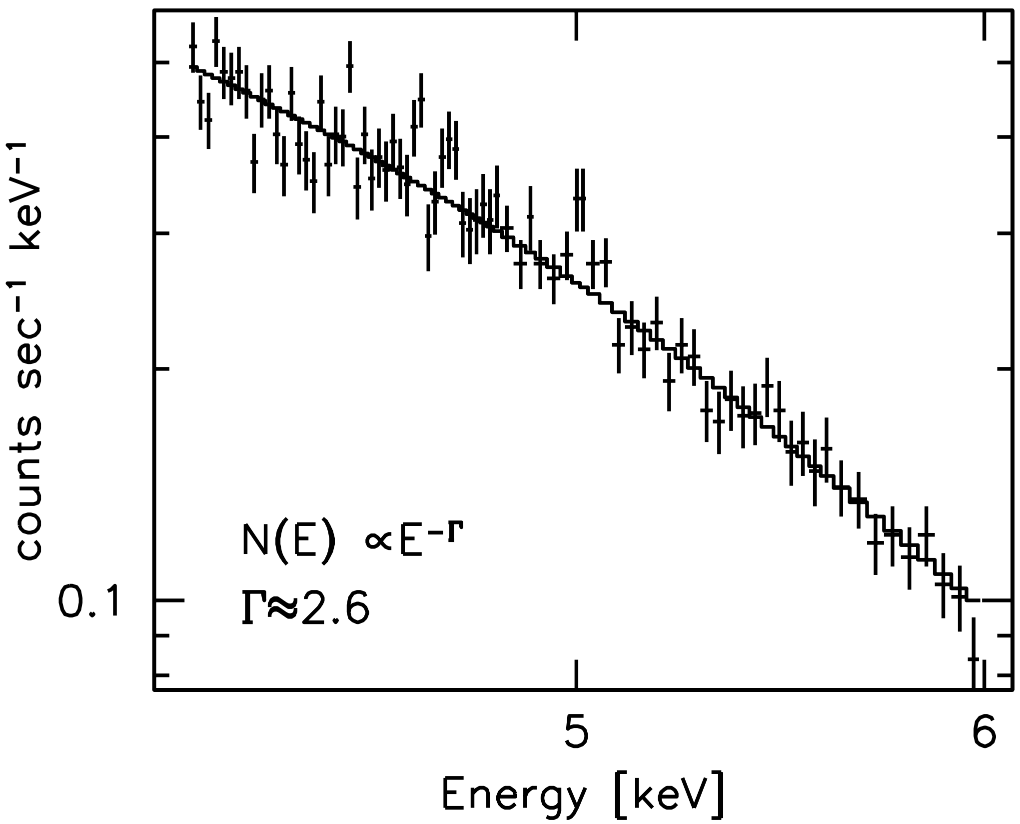




Thermal particles leak to high energies- over time they reach ~ 10^{15} eV!

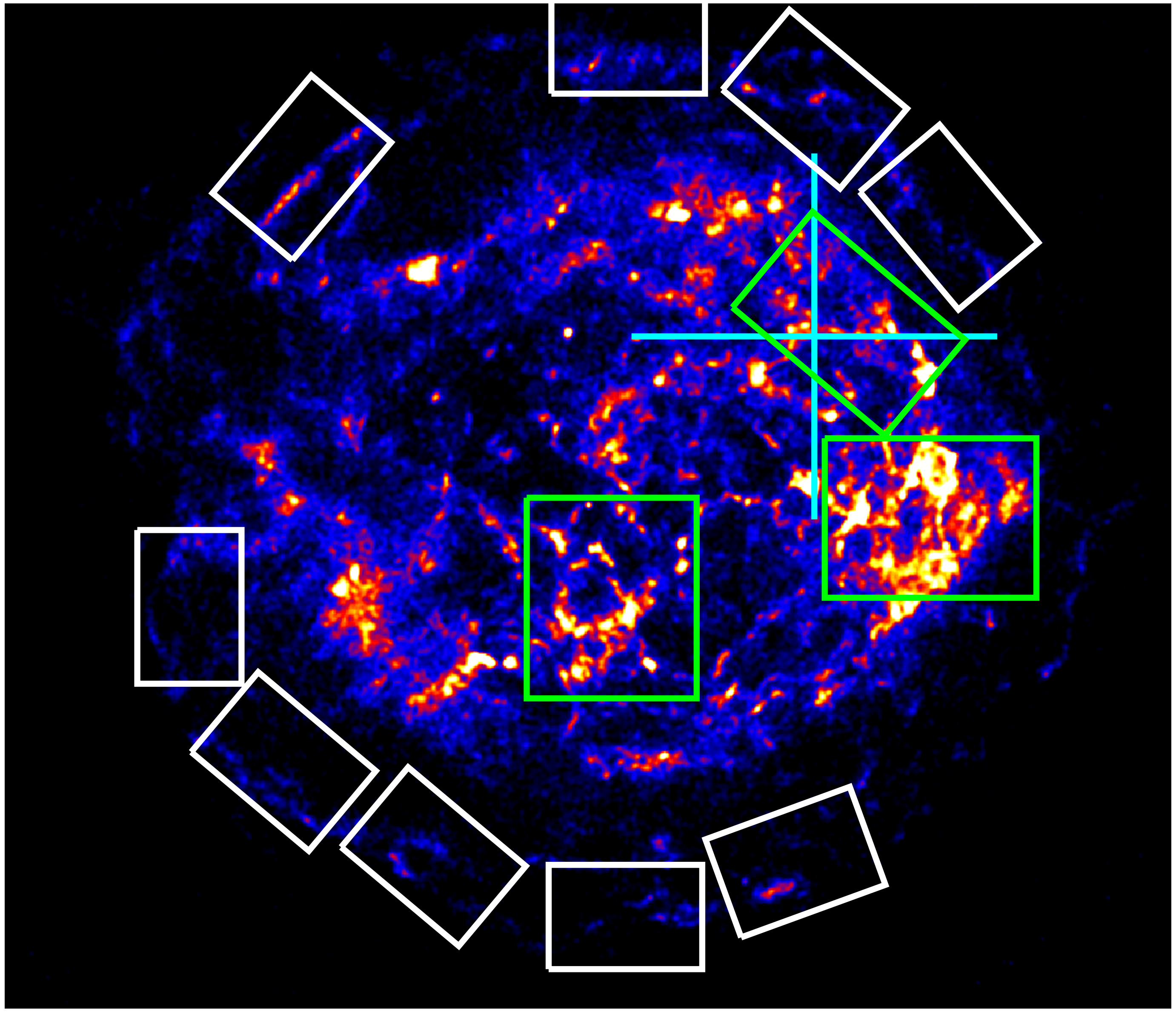
$$N(E) = \phi\, B^{\Gamma_0} \times E^{-\Gamma_0} \exp\left(-\sqrt{\frac{E}{E_c}}\right)$$

NONTHERMAL X-RAY EMISSION



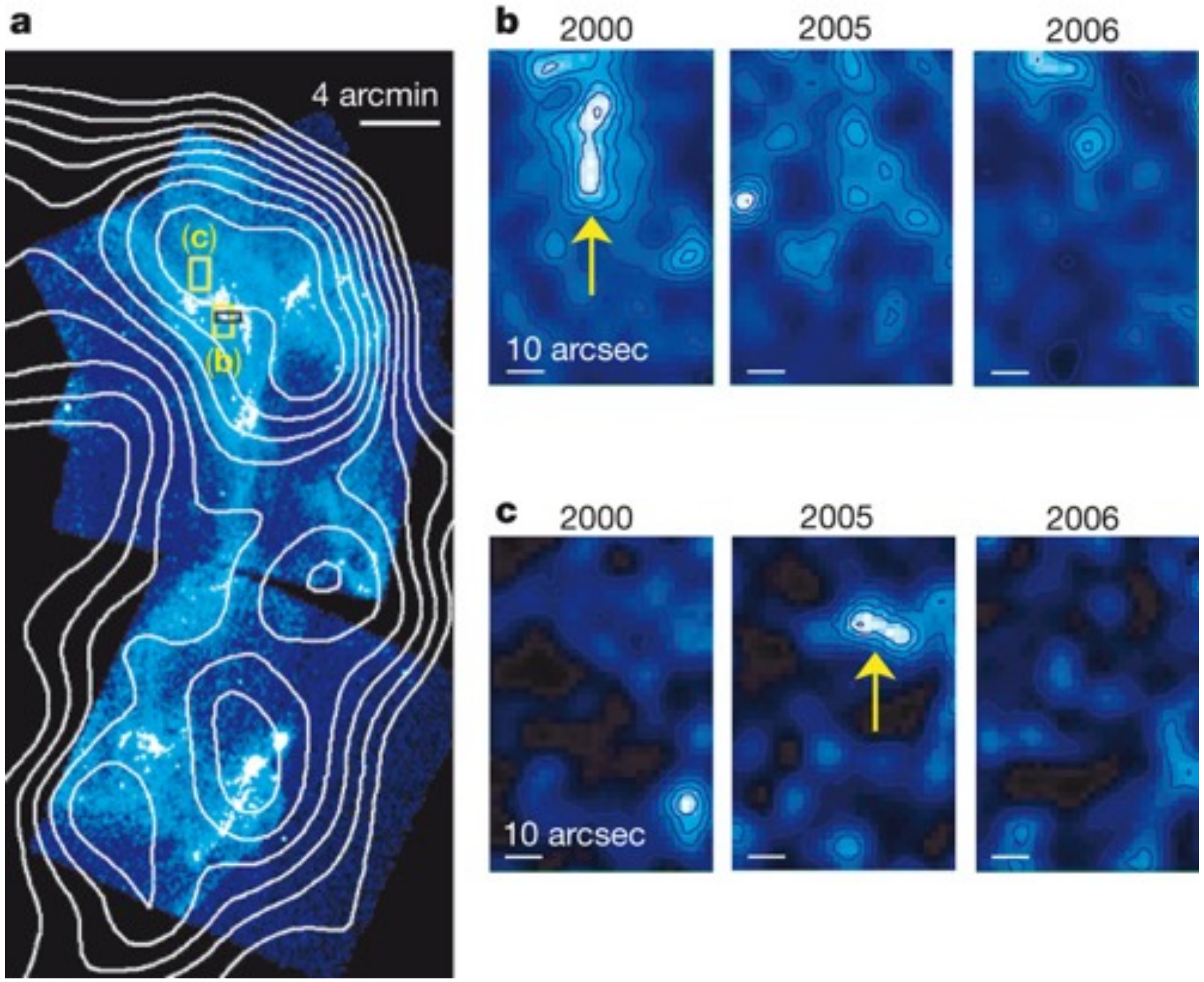
Continuum emission from Cas A forward shock filaments.

Evidence for efficient acceleration of particles to TeV energies?



Cas A with boxes which mark the approximate location of spectral extraction regions.

RX J1713- A Cosmic Tevatron



Rapid variations are evidence that electrons are accelerated to TeV energies on timescales of years

Chandra view of RX J1713, showing variations in nonthermal emission on timescales of a few years (Uchiyama et al. 2007).

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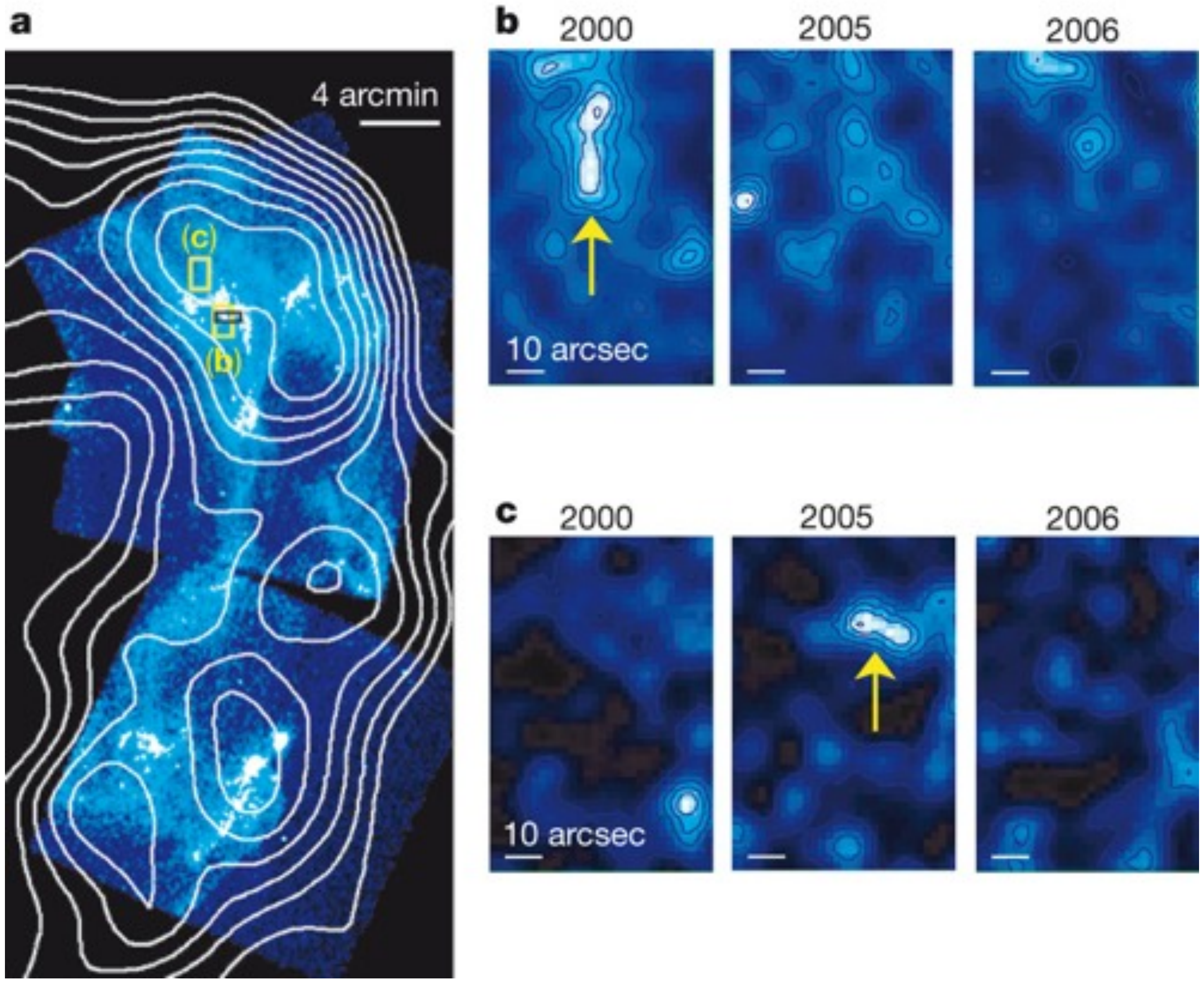


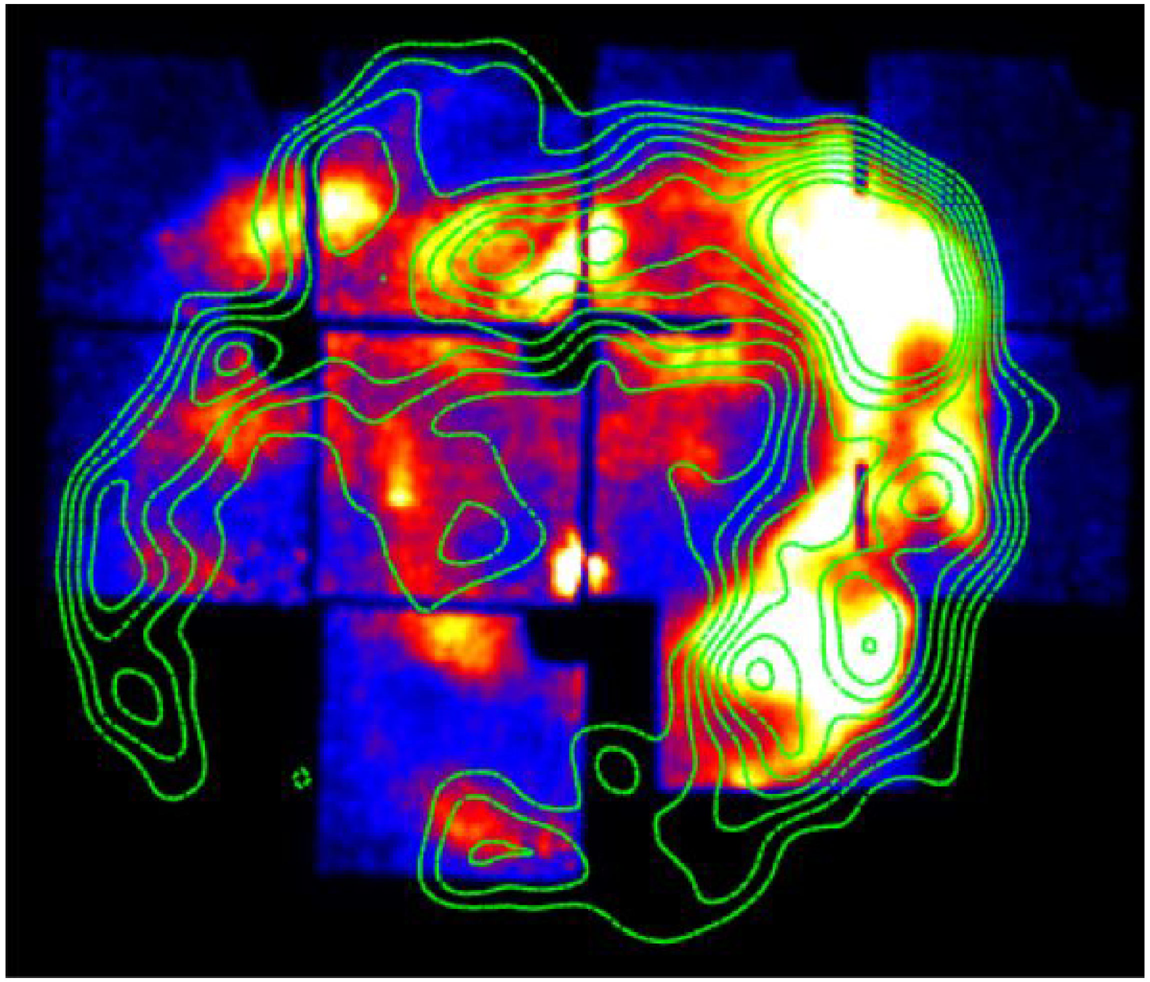
Chandra view of RX J1713, showing variations in nonthermal emission on timescales of a few years (Uchiyama et al. 2007).

Rapid variations are evidence that electrons are accelerated to TeV energies on timescales of years

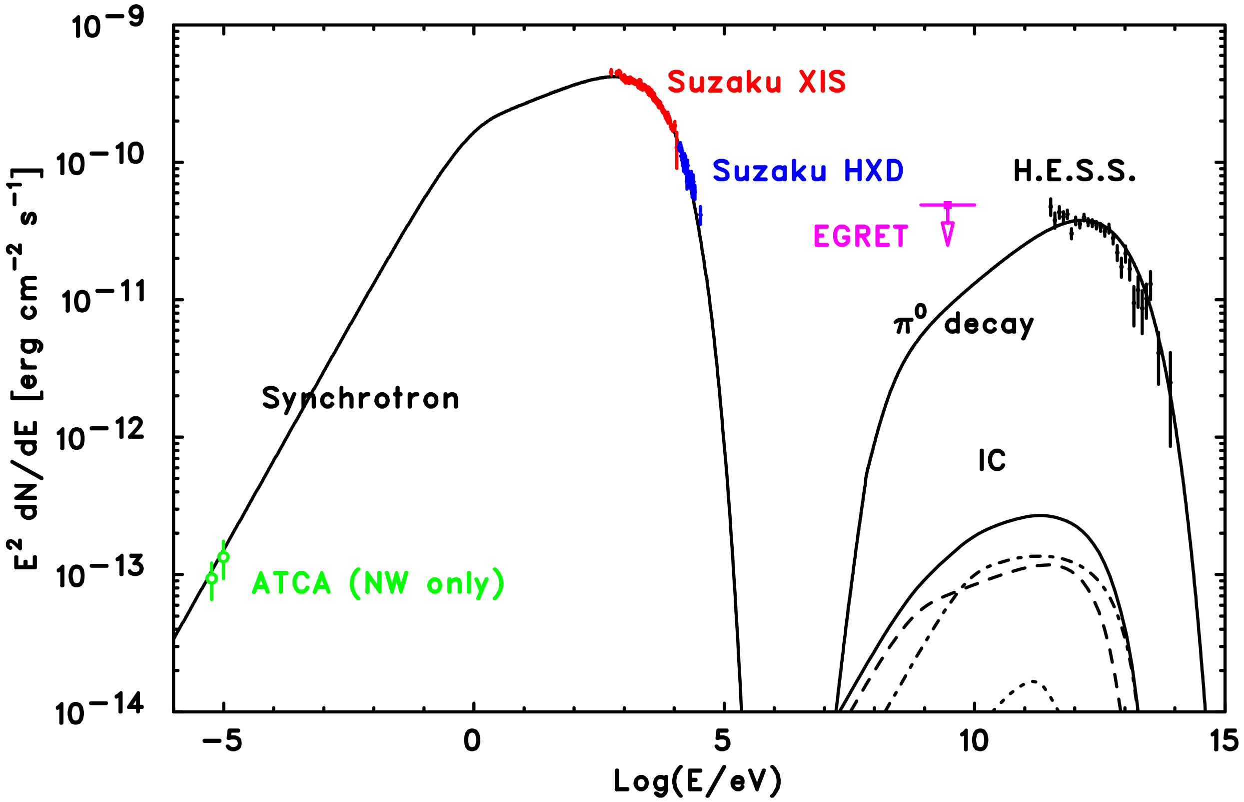
Authors claimed that if the acceleration is the same for protons and ions, then they can achieve PeV energies on the same timescale

Protons, unlike electrons, are not synchrotron-loss limited

RX J1713- A COSMIC TEVATRON



RX J1713 shown in X-rays (Suzaku; Tanaka et al 2008). H.E.S.S. contours are overlaid.



Broadband SED of RX J1713. Best fit model assuming a hadronic origin to TeV emission is shown (Tanaka et al. 2008).

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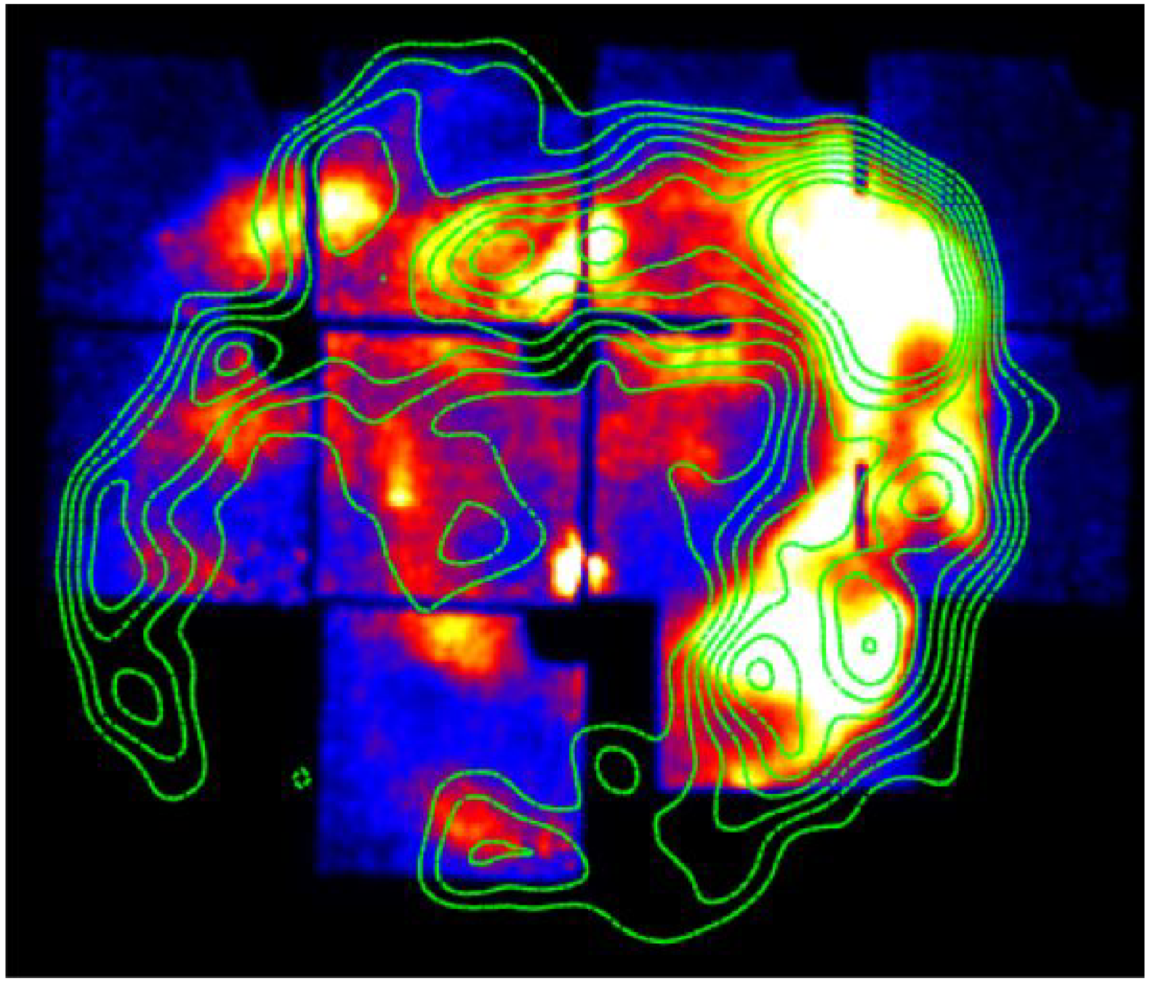

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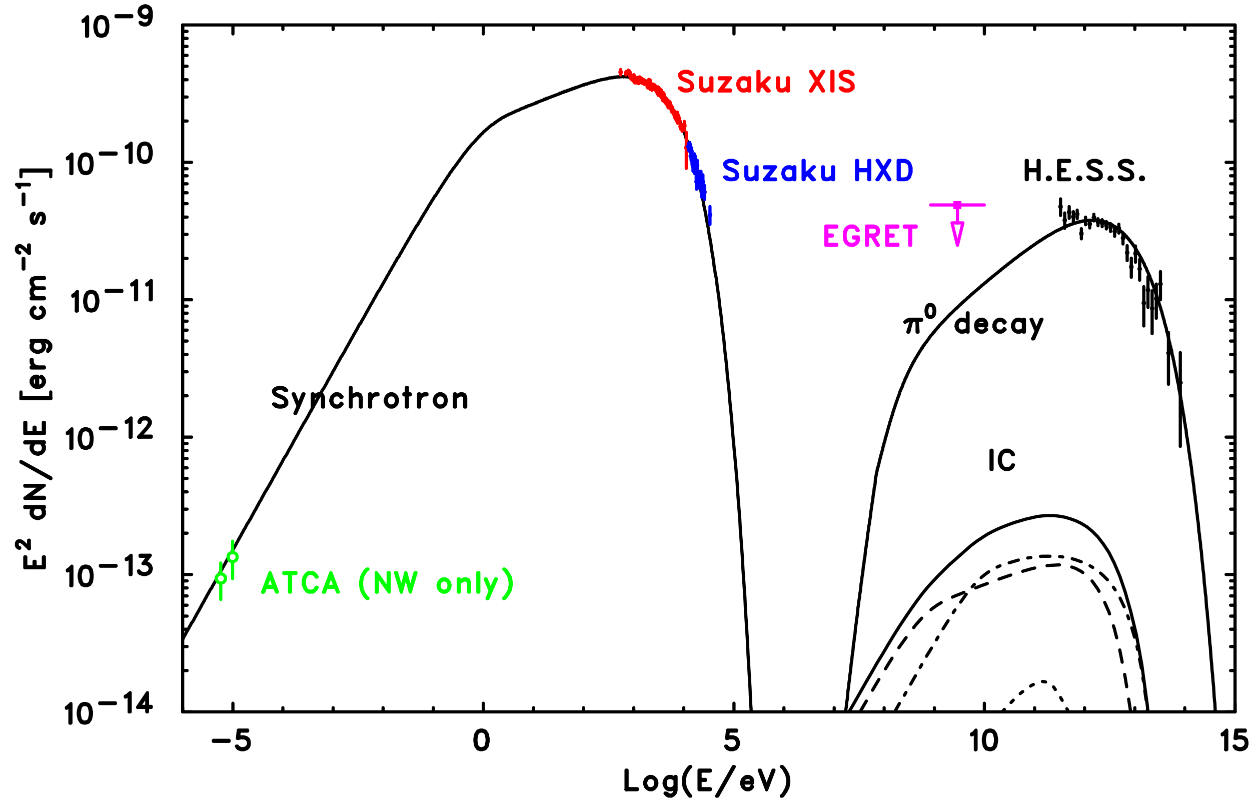

Broadband SED of RX J1713. Best fit model assuming a hadronic origin to TeV emission is shown (Tanaka et al. 2008).

Small scale flickering of nonthermal emission is taken as evidence for efficient magnetic field amplification and acceleration of CR ions - this does not account for CR ions efficiently escaping, thus damping the field amplification process

VHE Emission: Pion decay vs IC Emission

$p+p \rightarrow \pi^0 \rightarrow 2\gamma$

high energy protons or ions collide with target material to produce a pion, which decays to two gamma-rays

$h\nu + e^- \rightarrow h\nu' + e^-$

low energy photons scatter off of TeV electrons and gain some of the energy, at the expense of the electron

VHE Emission: Pion decay vs IC Emission

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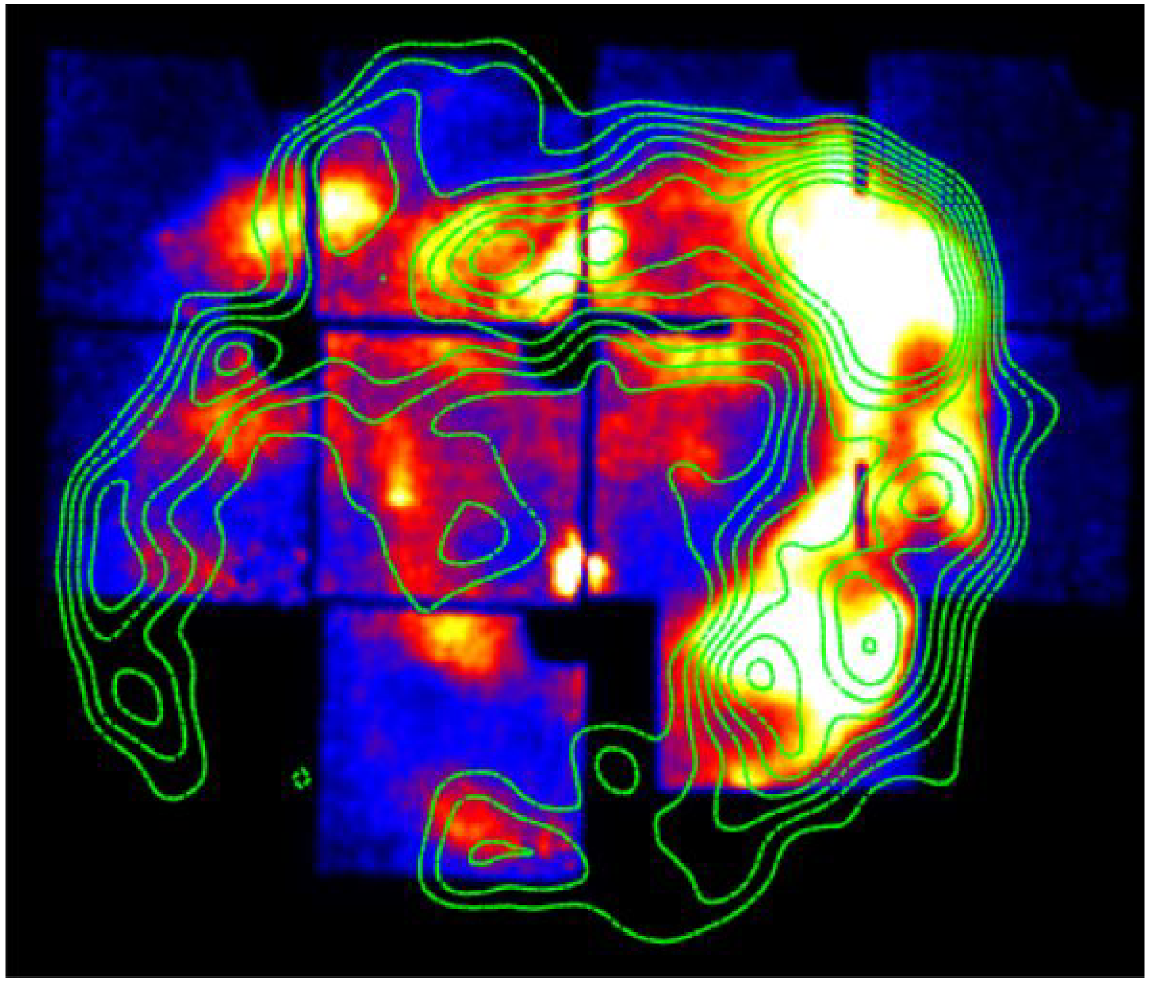
Requires target material for CR protons!

$h\nu + e^- \rightarrow h\nu' + e^-$

low energy photons scatter off of TeV electrons and gain some of the energy, at the expense of the electron

Requires a large number of TeV electrons!

RX J1713- A Cosmic Tevatron



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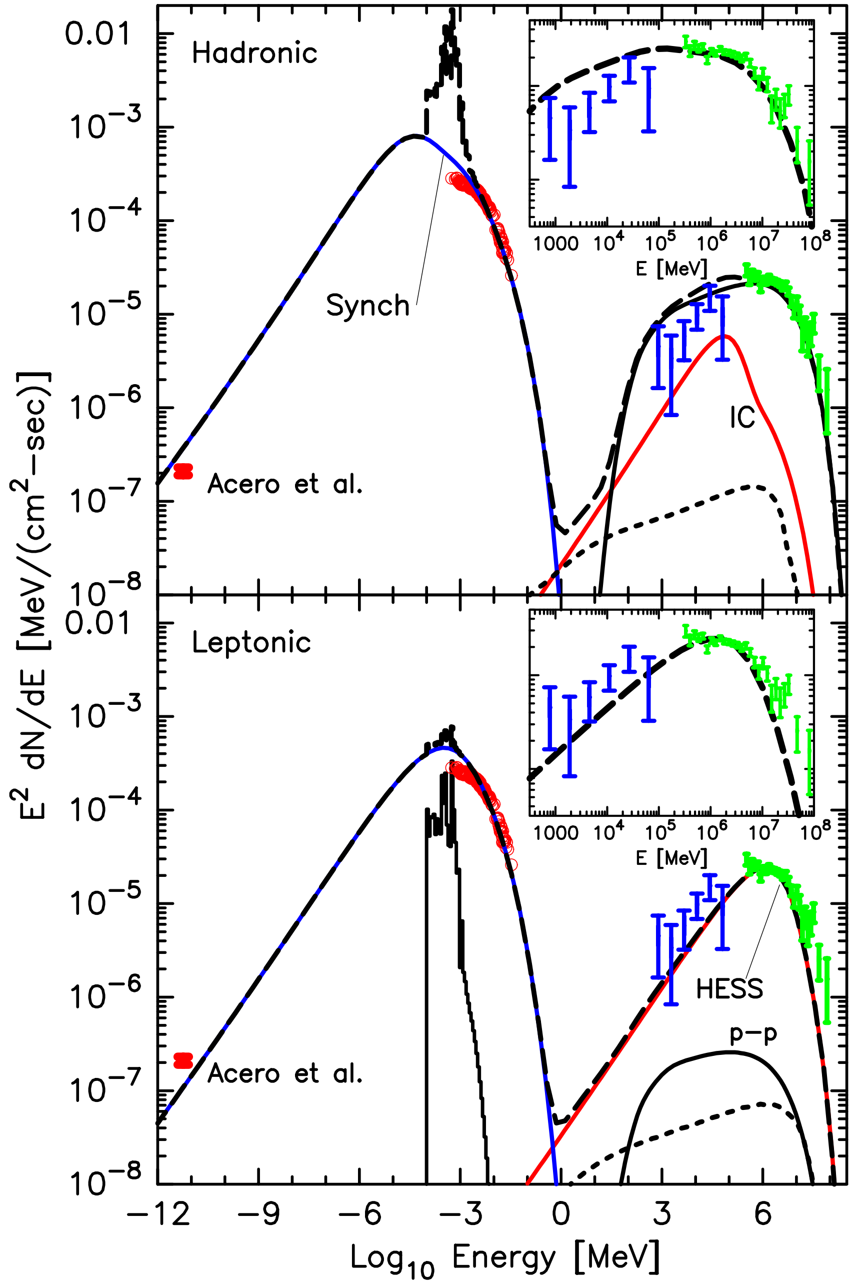
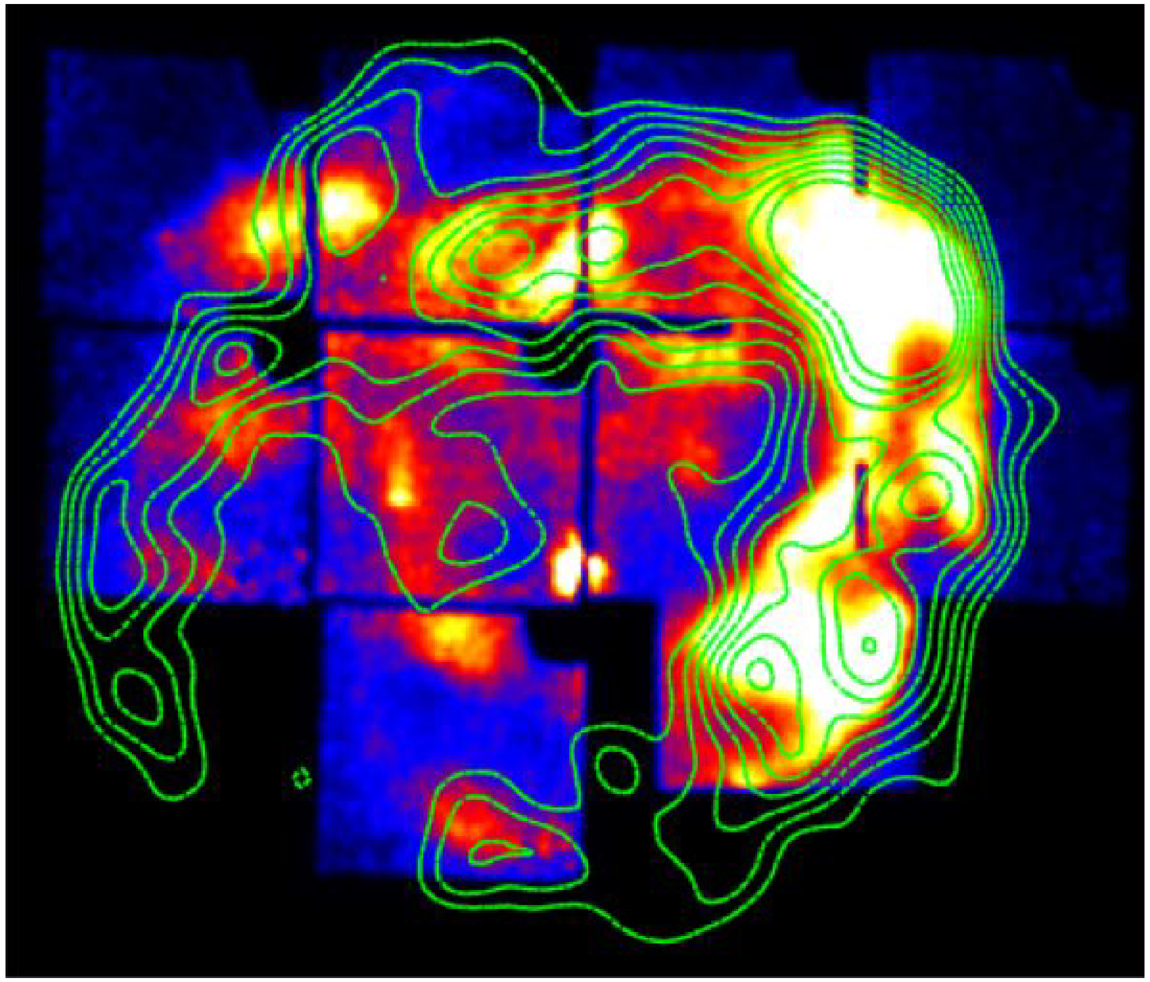


Broadband SED fit to hadronic (top) and leptonic TeV emission models, including effects of thermal X-rays (Ellison et al. 2010).

RX J1713- A Cosmic Tevatron



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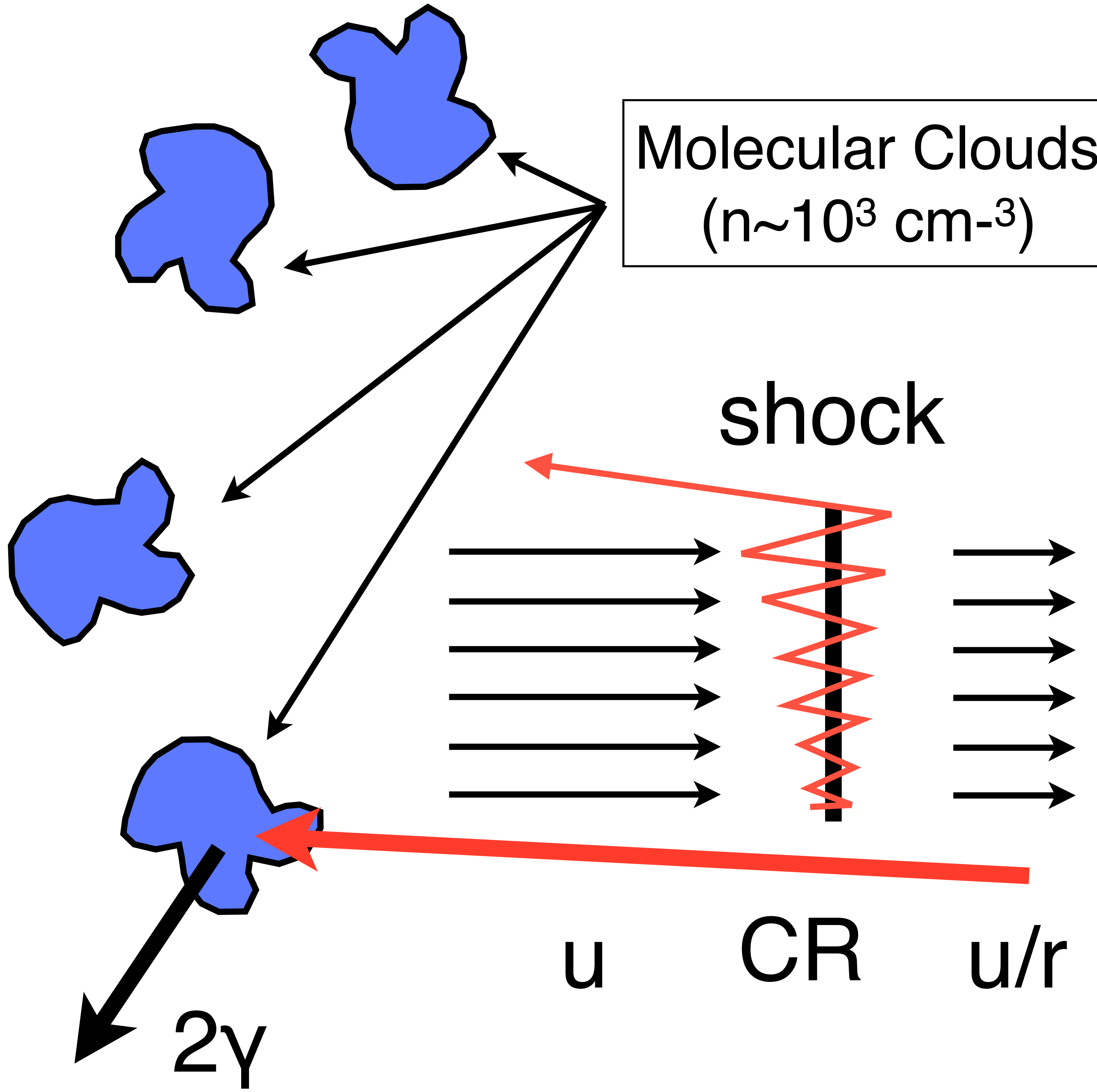
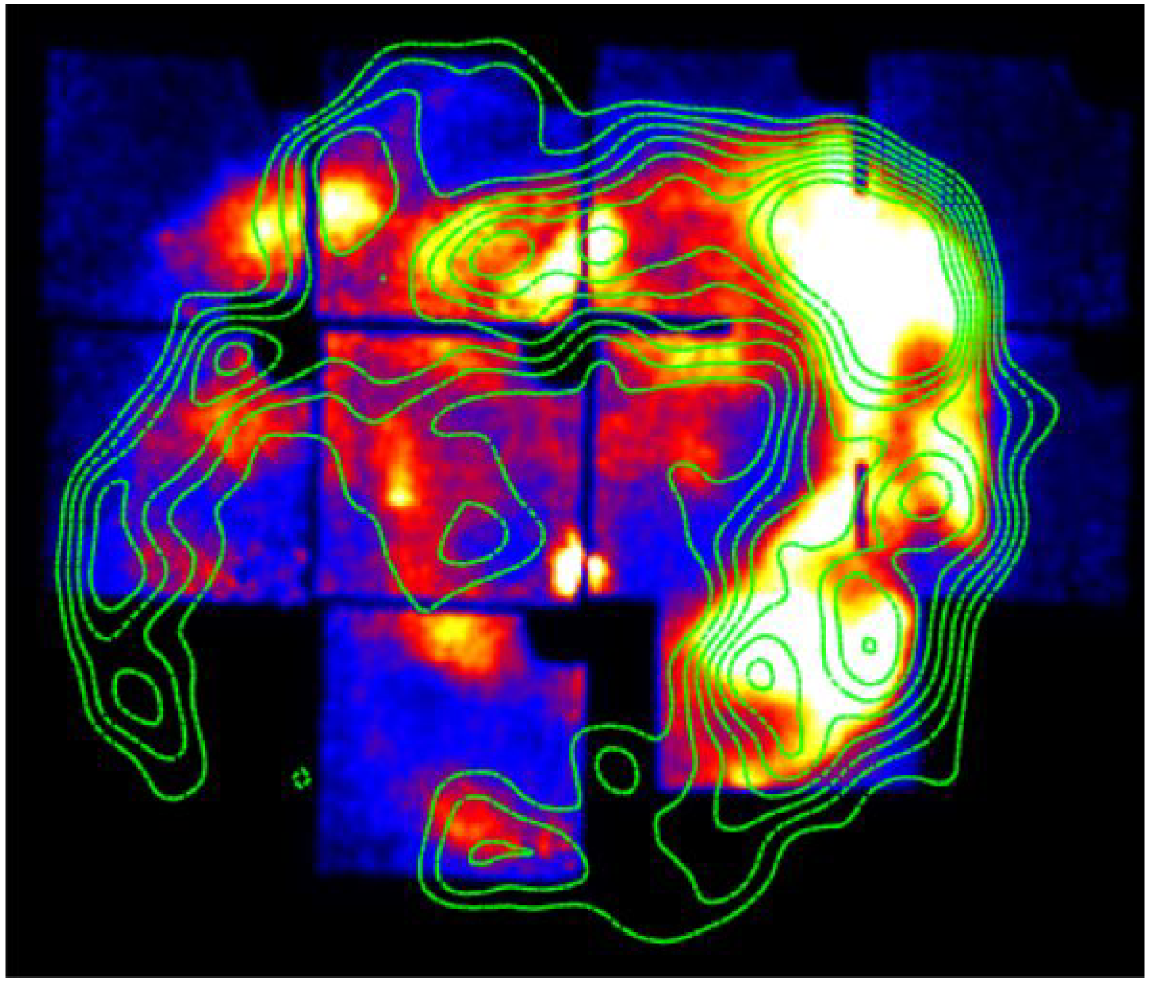


What about escaping cosmic rays?

RX J1713- A Cosmic Tevatron



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The basic idea is that the progenitor wind cleared out a cavity and escaping CRs are illuminating the dense cavity wall

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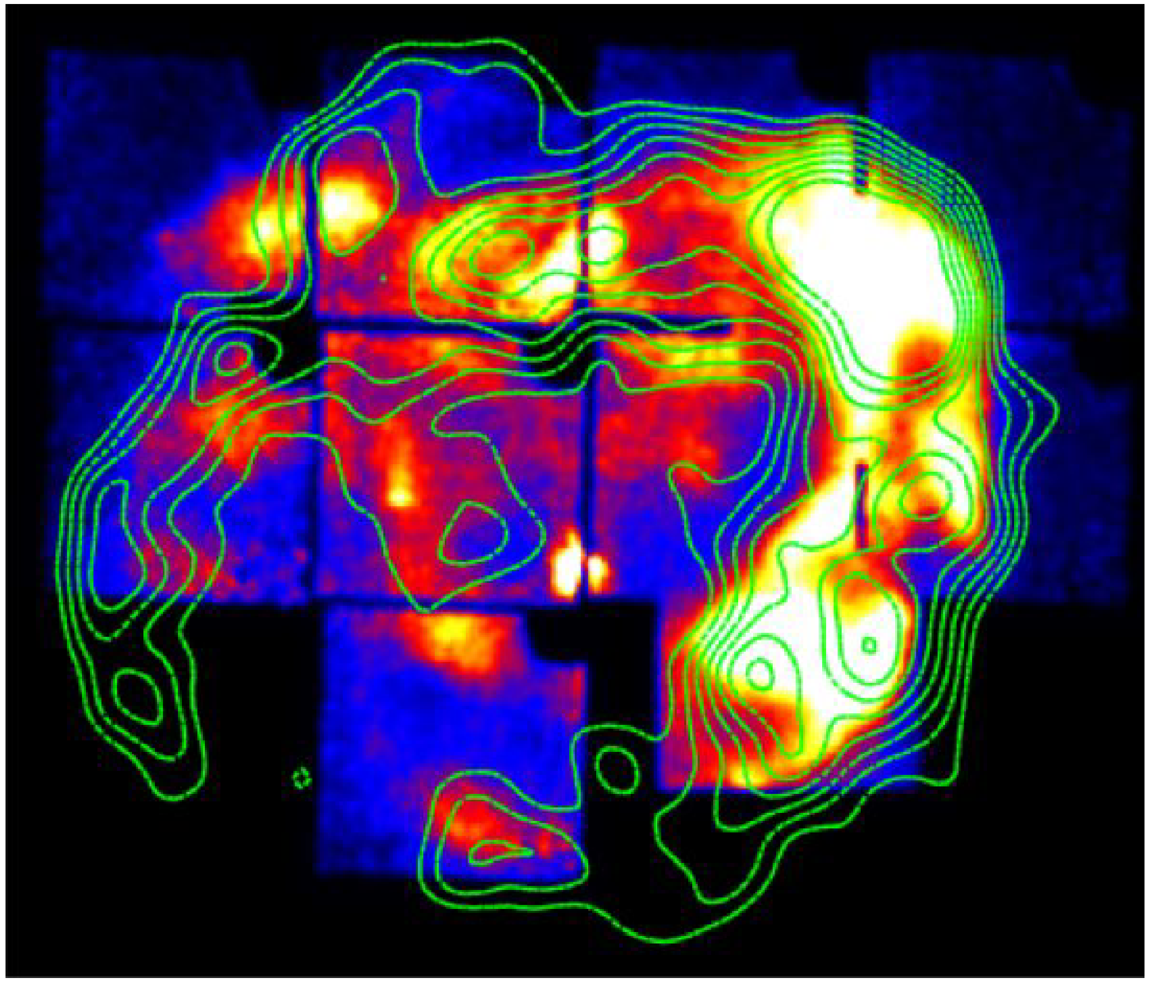
RX J1713- A Cosmic Tevatron



RX J1713 shown in X-rays (Suzaku; Tanaka et al 2008). H.E.S.S. contours are overlaid.

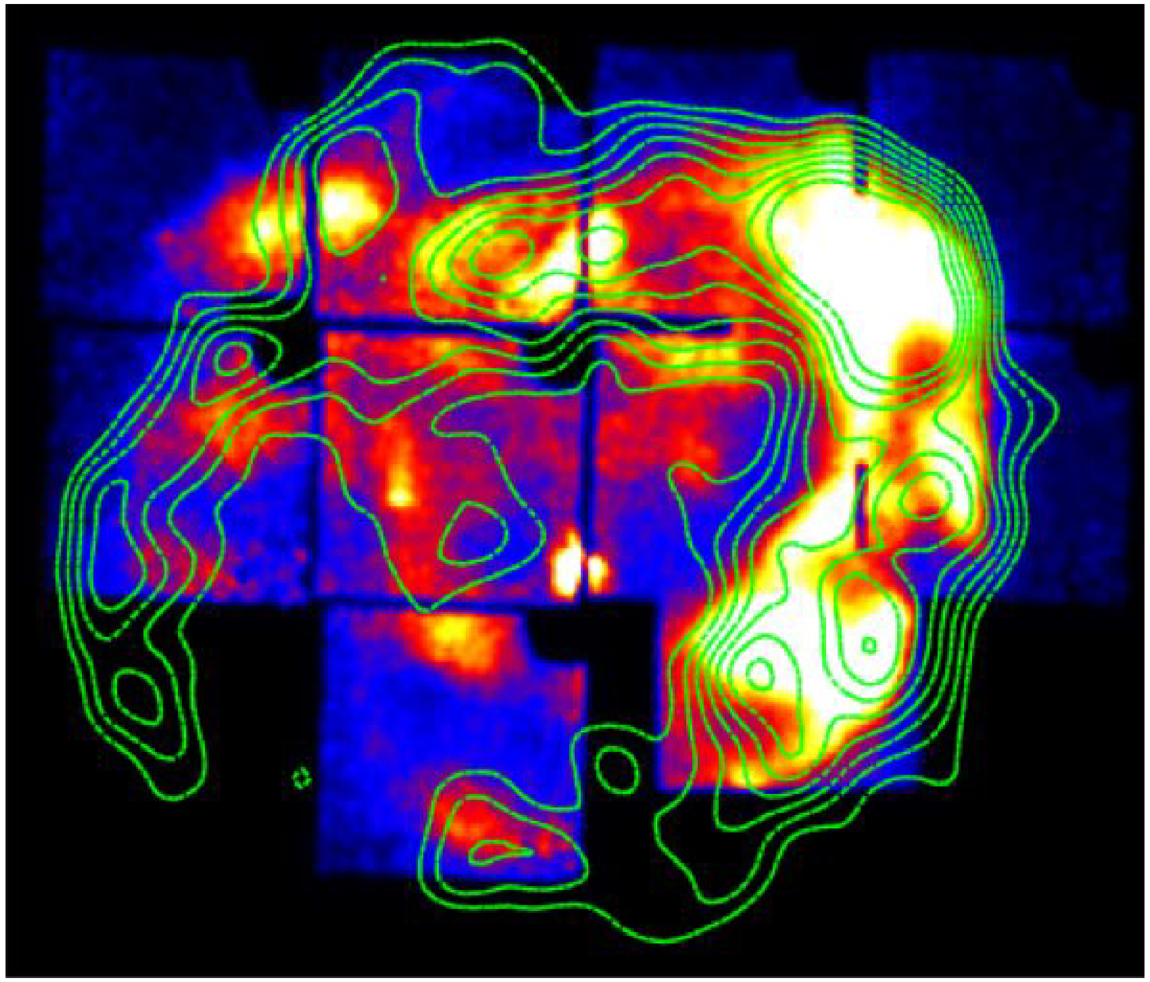
Radius of cavity is set by (e.g. Chevalier 1999):

$$\frac{1}{2}\dot{M}v_{\rm wind}^2 t_{\rm age} = \left(\frac{4}{3}R_b^3\right)\frac{3}{2}p_0$$

For RSG, $R_b \sim 6$ pc (less than observed size of ~ 10 pc)

What about escaping cosmic rays?

RX J1713- A Cosmic Tevatron



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For WR progenitor, $R_b \sim 10$ pc

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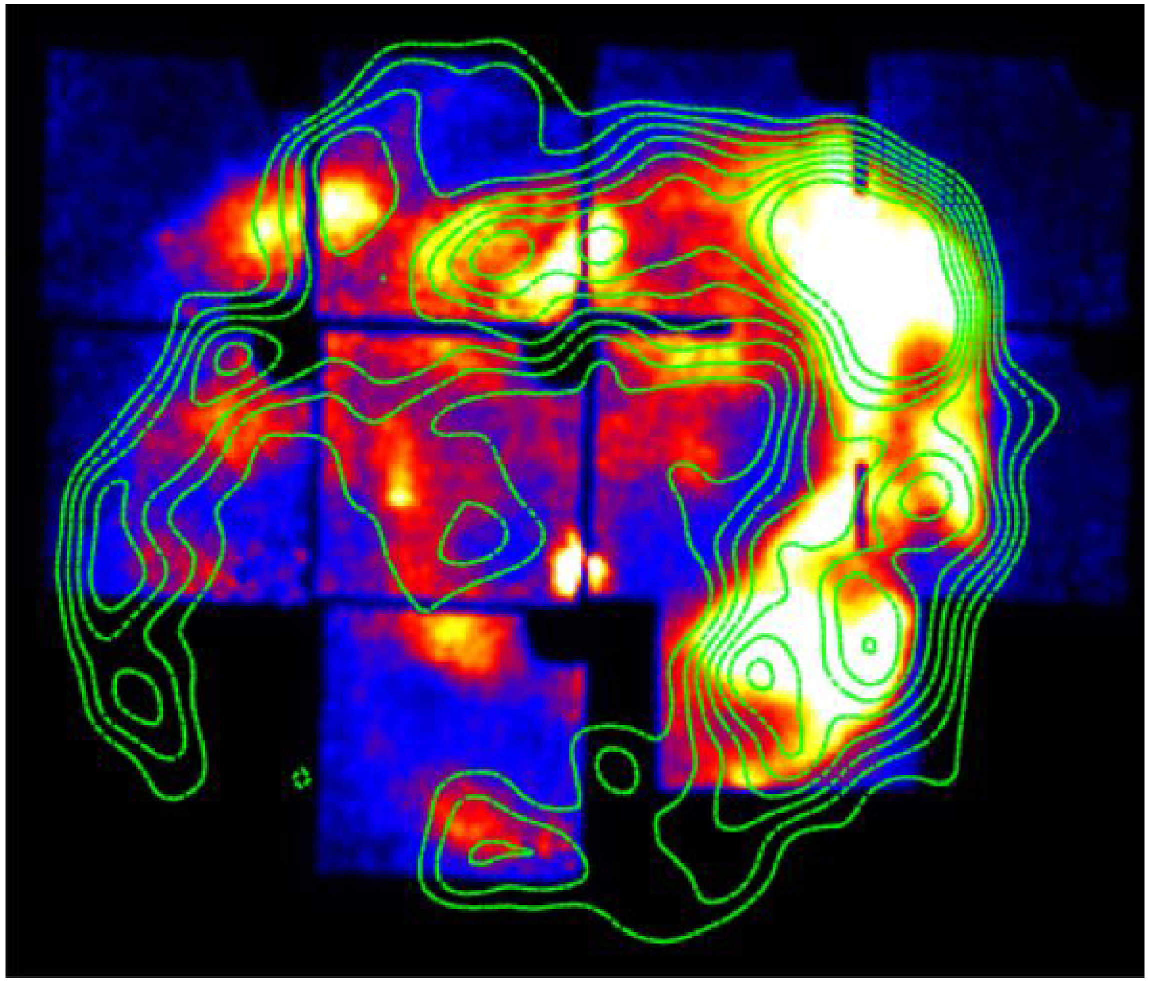

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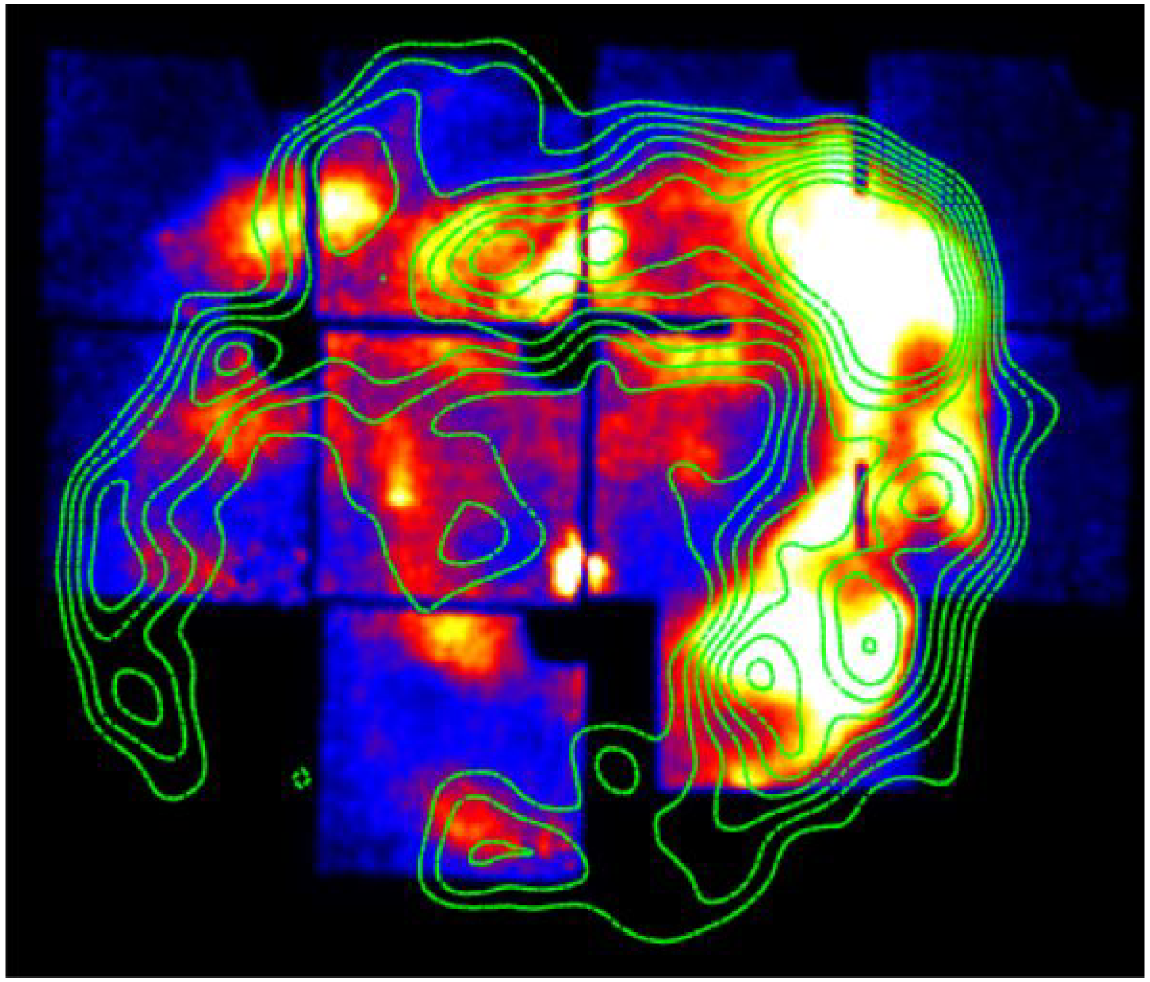
For WR progenitor, $R_b \sim 10$ pc

But, the bubble density ~ 10^{-3} cm^{-3} and $R_{\rm shock}$(1600yrs) > 10 pc

What about escaping cosmic rays?

RX J1713- A Cosmic Tevatron



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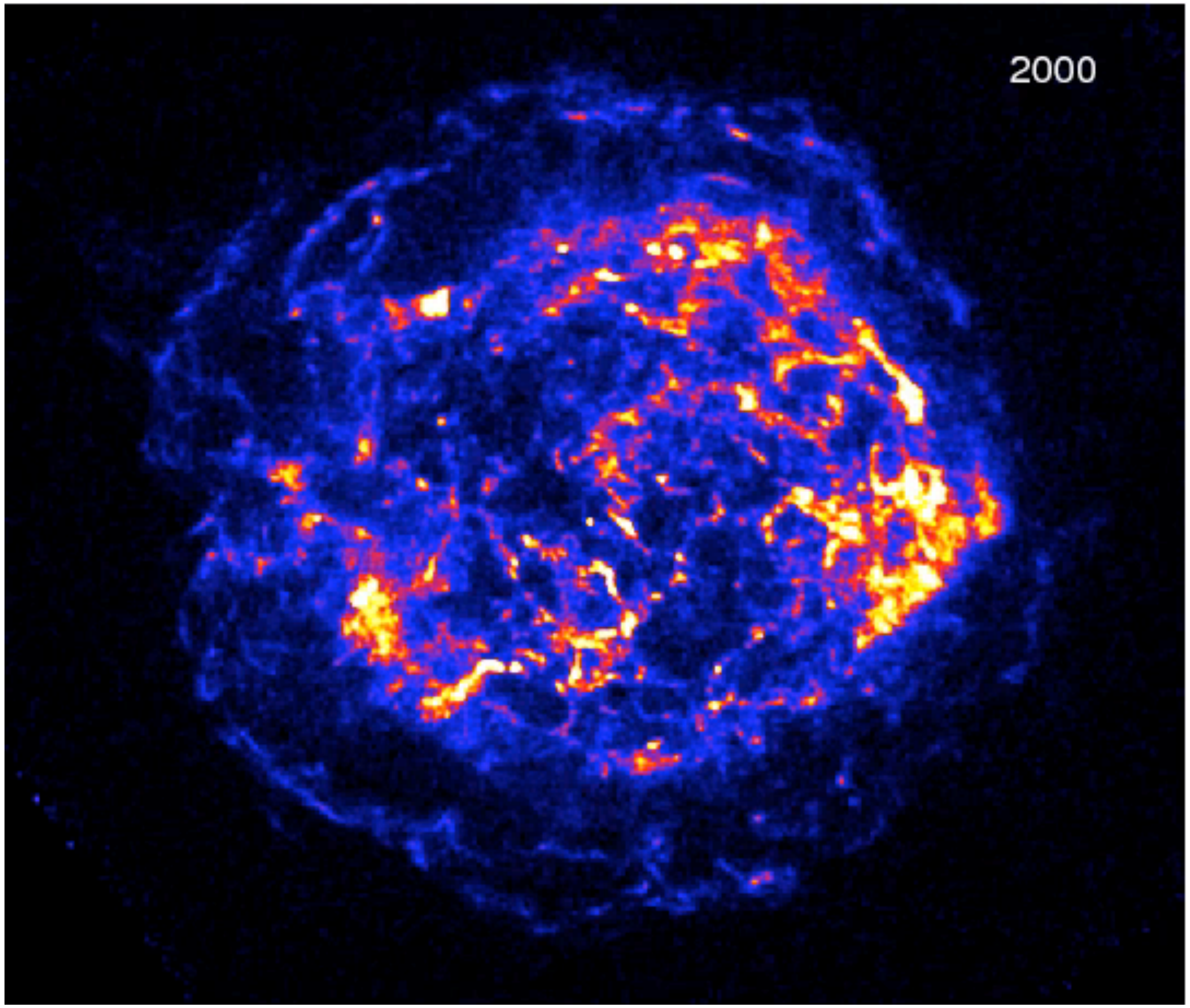
pion decay is ruled out as the source of TeV emission:

- A RSG wind cannot make a bubble of 10 pc in lifetime
- A WR wind can clear out a cavity, but density in cavity is too low and shock hits cavity wall too soon
- TeV emission is likely due to inverse-Compton emission (see, e.g. recent Fermi consortium paper which rules out pion decay)

What about escaping cosmic rays?

Cas A: A (less) efficient accelerator

SNR shell shows bright nonthermal filament both at the forward shock and also projected interior



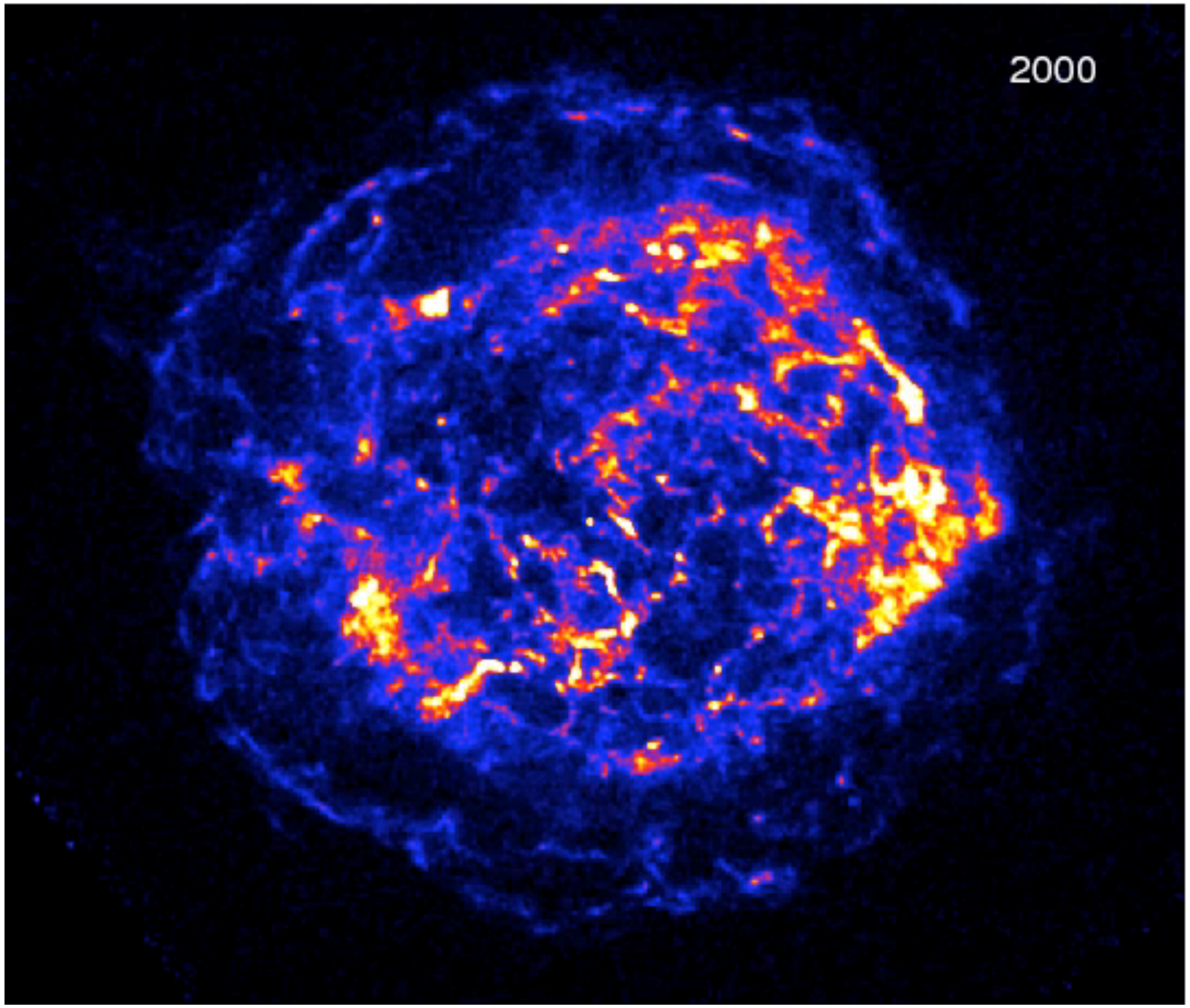
Cas A in 4-6 keV emission from 2000-2009. The blastwave is seen to expand with V ~ 5000 km s^{-1}.

CAS A: A (LESS) EFFICIENT ACCELERATOR

SNR shell shows bright nonthermal filament both at the forward shock and also projected interior

Filaments show flickering with timescales of ~ 2 yrs (Patnaude and Fesen 2007, 2009)

$$t_{acc} \propto B_{\rm mG}^{-3/2} \varepsilon_{\rm keV}^{1/2} V_{1000}^{-2} \ {\rm yr}$$



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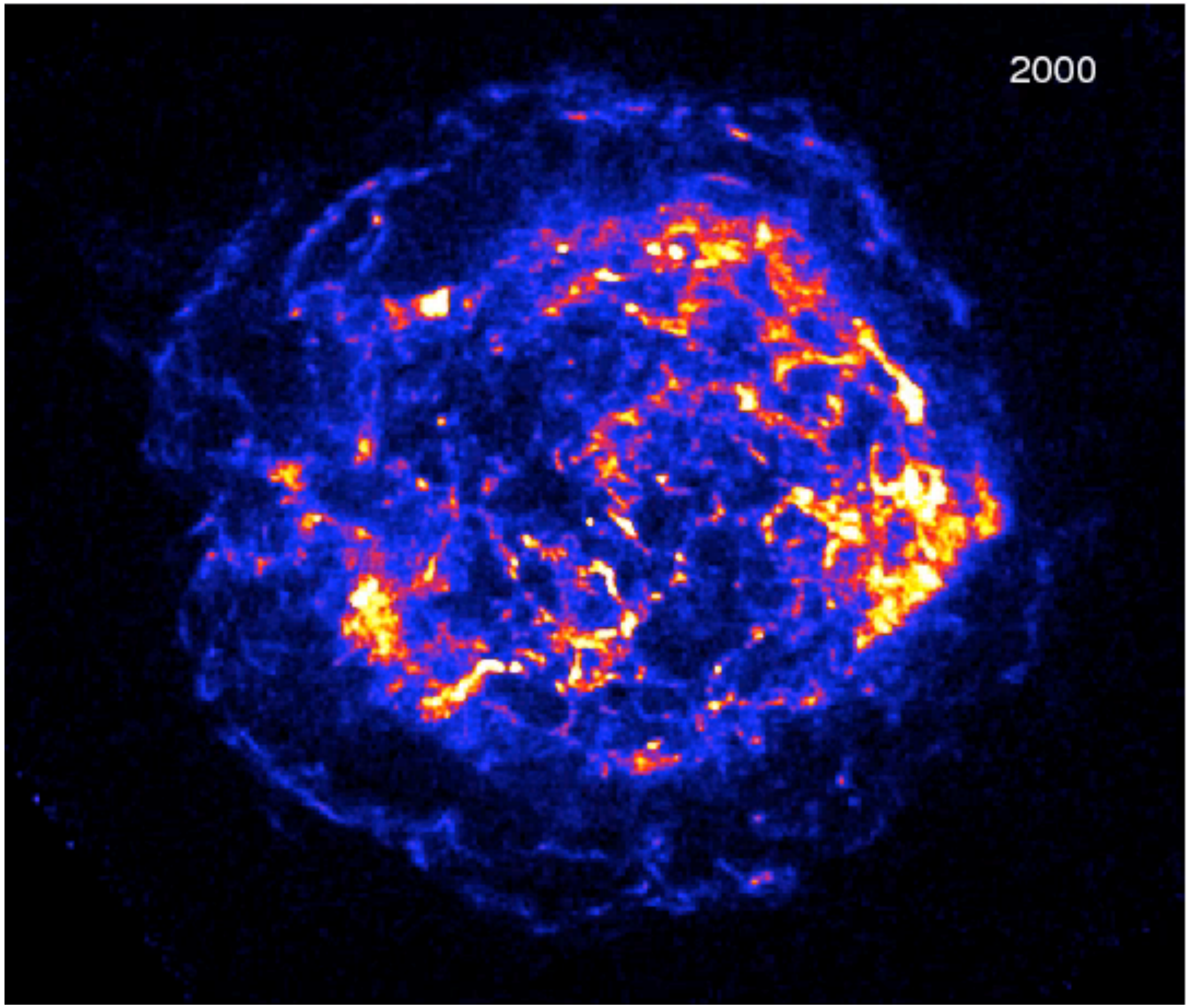
B = 0.1 - 0.3 mG



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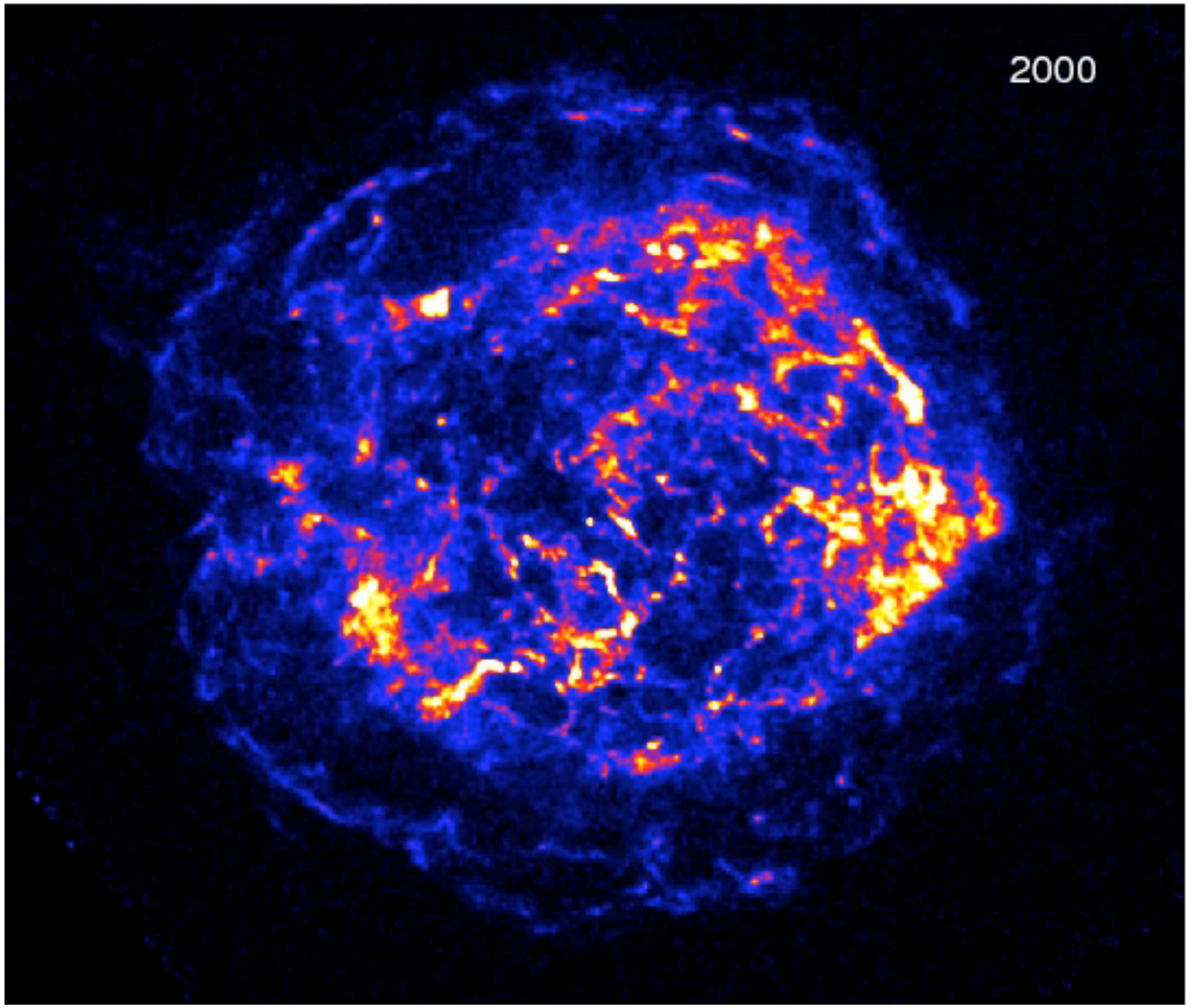
SNR shell shows bright nonthermal filament both at the forward shock and also projected interior

Also appears to show a steady decline in nonthermal X-ray emission between 2000-2010.

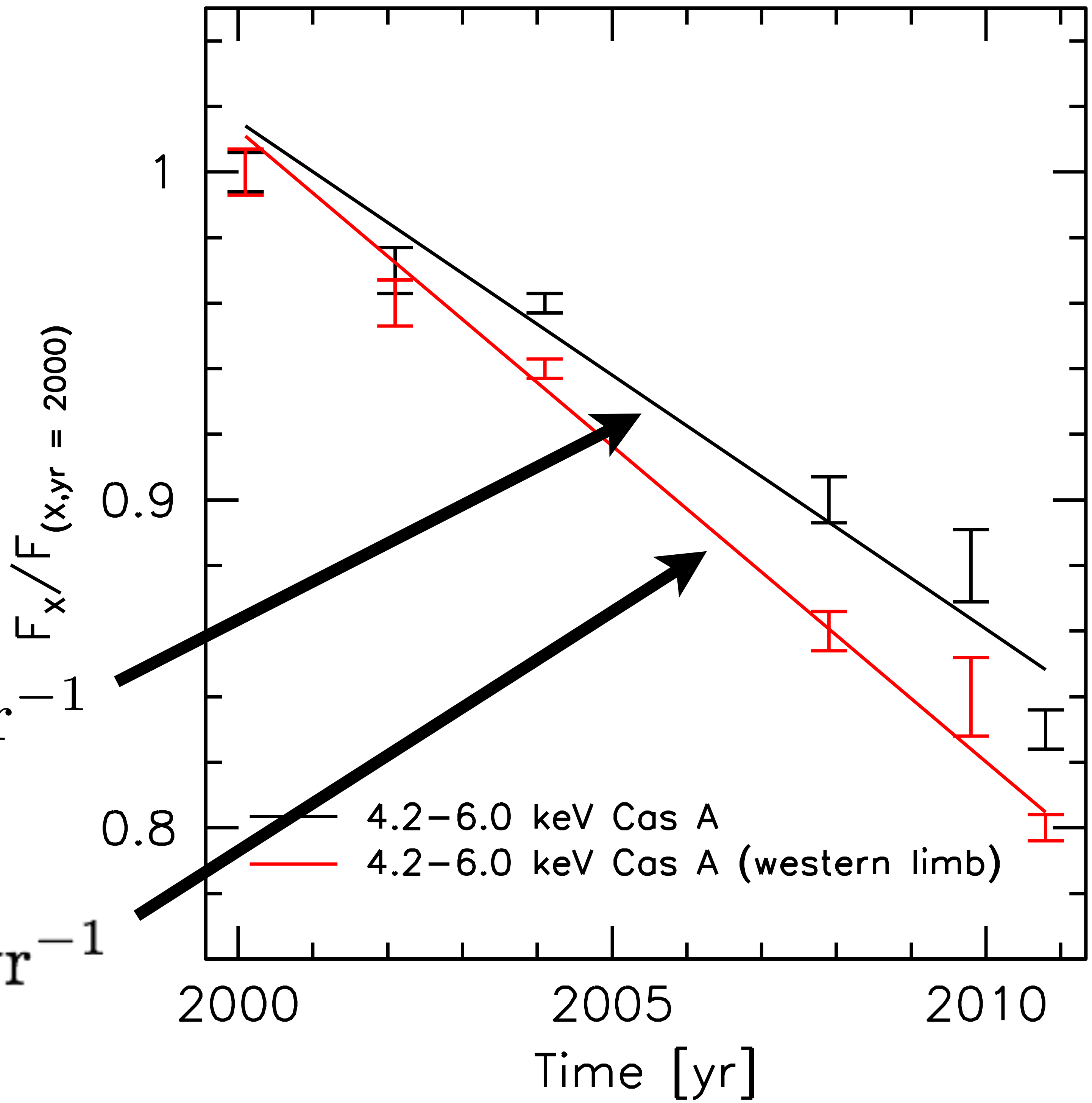


Cas A in 4-6 keV emission from 2000-2009. The blastwave is seen to expand with V ~ 5000 km s^{-1}.

10 years worth of observations show a clear decline in the nonthermal emission across the whole SNR and a steeper decline in the west

$$\frac{1}{F_X}\frac{dF_X}{dt} = -(1.5 \pm 0.17)\%\,\mathrm{yr}^{-1}$$

$$\frac{1}{F_X}\frac{dF_X}{dt} = -(1.9 \pm 0.10)\%\,\mathrm{yr}^{-1}$$



Comparison of the 4.2-6.0 keV flux in Cas A compared to the year 2000 observations (Patnaude et al. 2011).

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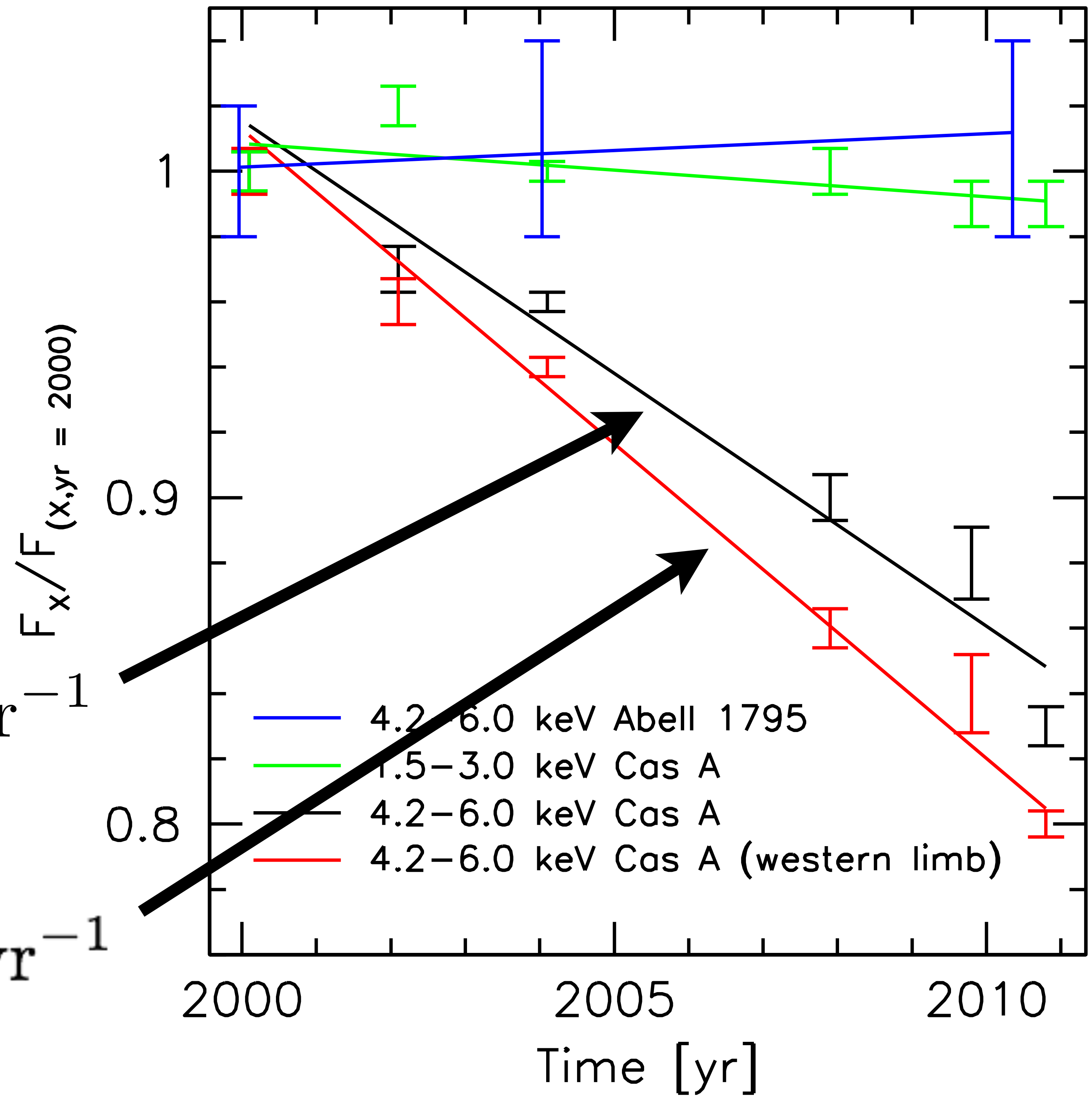

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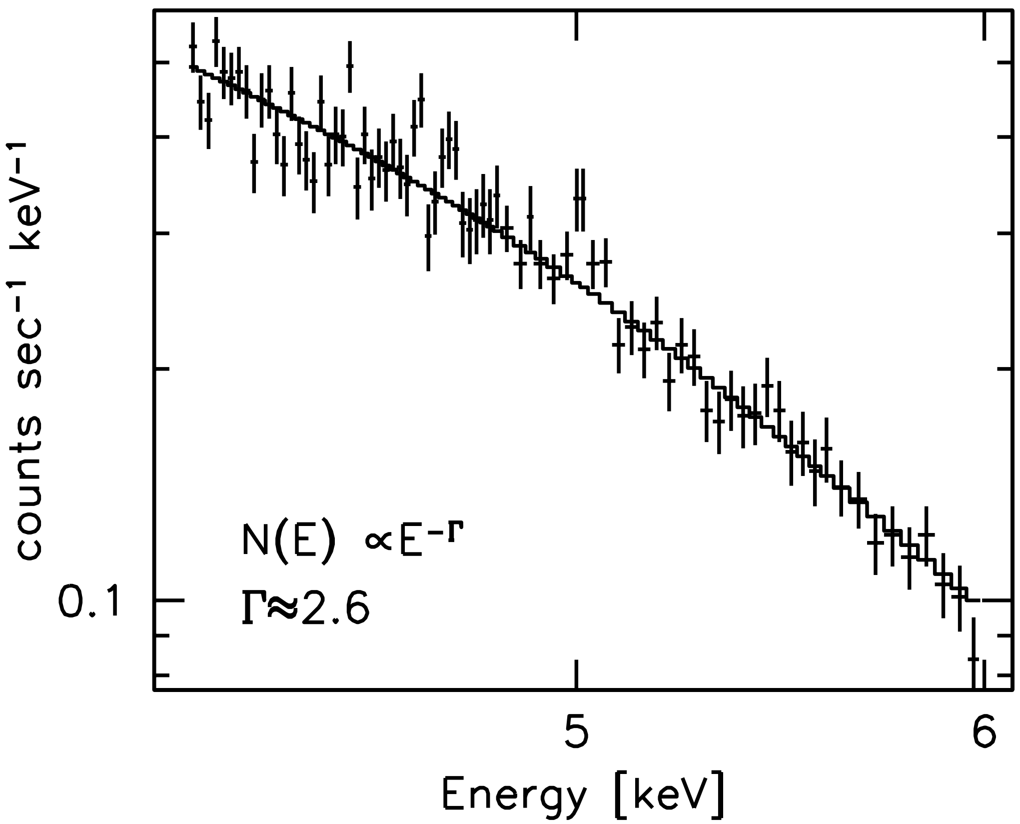
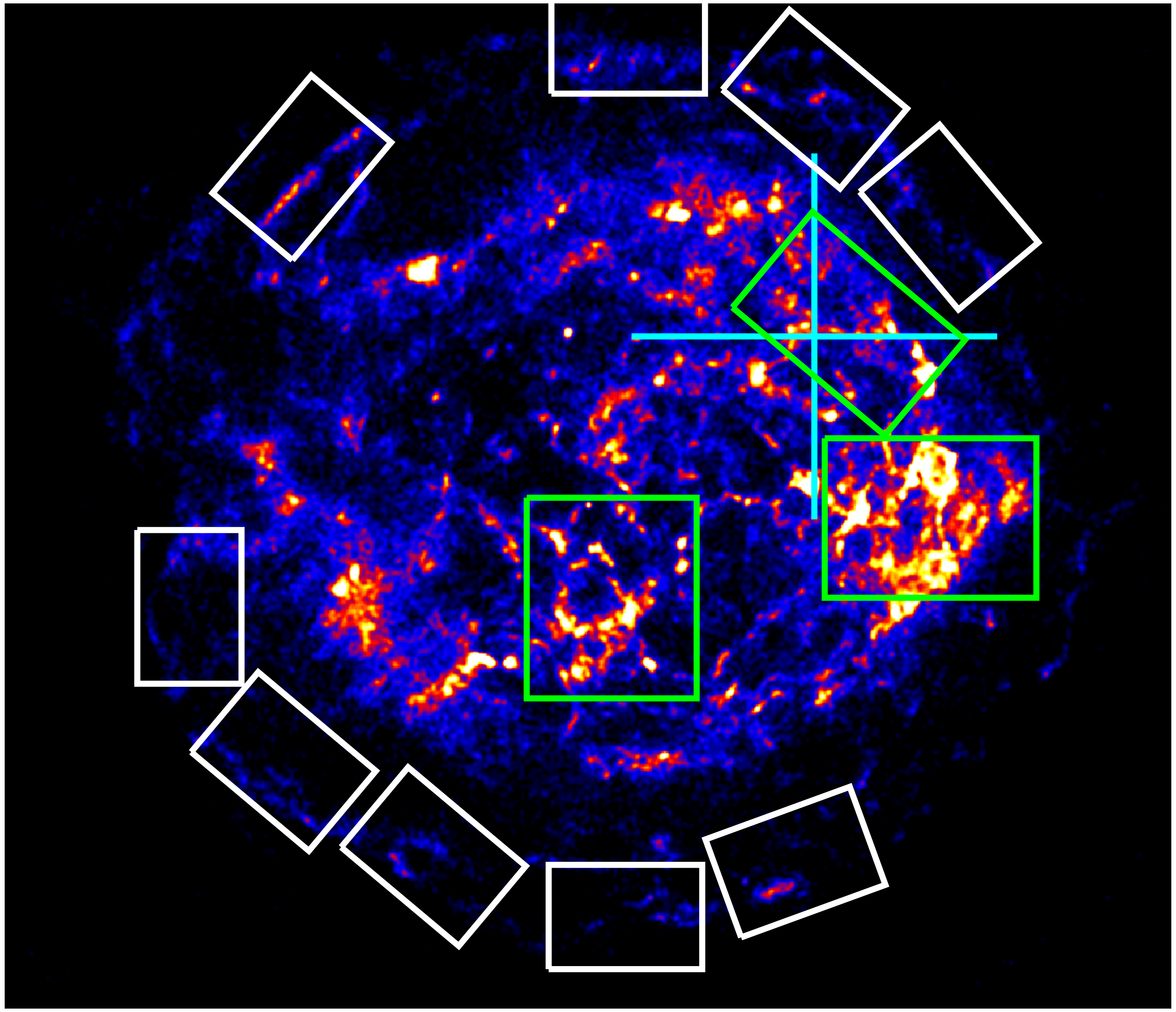
NONTHERMAL X-RAY EMISSION



Continuum emission from Cas A forward shock filaments.



Cas A with boxes which mark the approximate location of spectral extraction regions.

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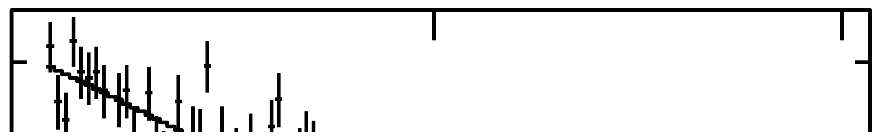


TABLE 1
CHANDRA OBSERVATIONS OF CAS A AND SPECTRAL FITTING RESULTS

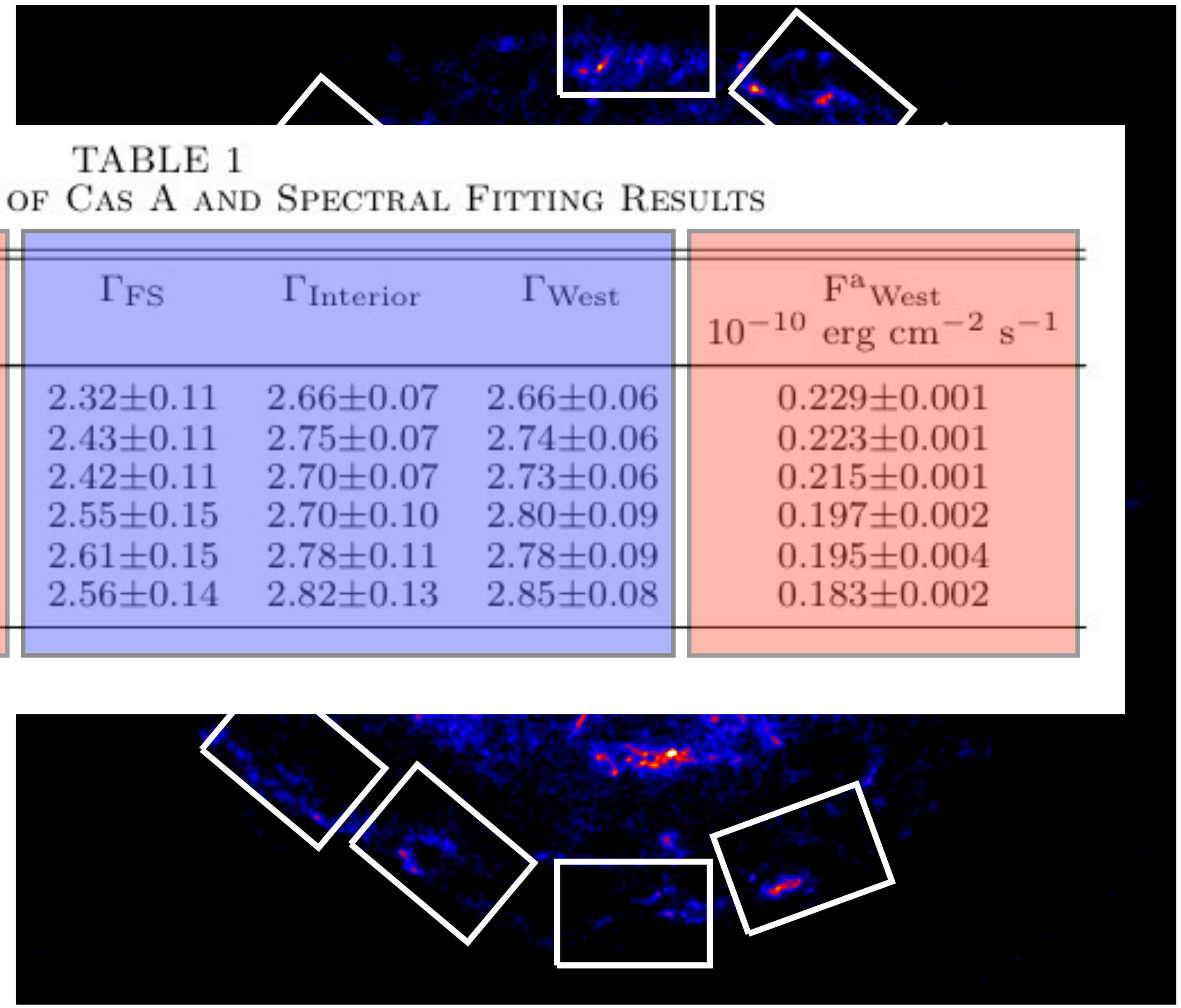
Epoch yr	Γ_{SNR}	F^a 10^{-10} erg cm^{-2} s^{-1}	Γ_{FS}	$\Gamma_{Interior}$	Γ_{West}	F^a_{West} 10^{-10} erg cm^{-2} s^{-1}
2000.1	2.81±0.03	1.61±0.01	2.32±0.11	2.66±0.07	2.66±0.06	0.229±0.001
2002.1	3.01±0.03	1.56±0.01	2.43±0.11	2.75±0.07	2.74±0.06	0.223±0.001
2004.1	2.99±0.03	1.54±0.01	2.42±0.11	2.70±0.07	2.73±0.06	0.215±0.001
2007.9	2.98±0.04	1.45±0.02	2.55±0.15	2.70±0.10	2.80±0.09	0.197±0.002
2009.8	2.99±0.05	1.42±0.04	2.61±0.15	2.78±0.11	2.78±0.09	0.195±0.004
2010.8	3.07±0.04	1.34±0.01	2.56±0.14	2.82±0.13	2.85±0.08	0.183±0.002

[a] 4.2 – 6.0 keV flux

Continuum emission from Cas A forward shock filaments.

$$\frac{d\Gamma_{FS}}{dt} = 0.022\ \mathrm{yr}^{-1}$$

$$\frac{d\Gamma_{West}}{dt} = 0.018\ \mathrm{yr}^{-1}$$



Cas A with boxes which mark the approximate location of spectral extraction regions.

- A much slower decline of 0.6-0.7% yr^{-1} in the nonthermal emission is observed in the radio (Baars et al. 1977; Reichart & Stephens 2000)

- Decline in the radio is the result of adiabatic expansion (Shklovskii 1960)

- X-ray synchrotron emission is associated with the exponential tail of the electron PDF and is thus more sensitive to changes in cutoff energy

Synchrotron emission can be approximated by (e.g. Zirakashvili & Aharonian 2007):

$$N(E) = \phi\, B^{\Gamma_0} \times E^{-\Gamma_0} \exp\left(-\sqrt{\frac{E}{E_c}}\right)$$

Γ_0 = 1.78
E = 5.1 keV
E_c = 1.0-2.0 keV

Or, the spectral slope can be written as (Vink et al. 1999):

$$\Gamma = \Gamma_0 + \frac{1}{2}\sqrt{\frac{E}{E_c}}$$

and the change in cutoff energy is:

$$\frac{dE_c}{dt} = -4\sqrt{\frac{E_c}{E}}\,E_c\,\frac{d\Gamma}{dt}$$

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Using our measured values of $d\Gamma/dt$ we calculate a change in the cutoff energy of:

and the change in cutoff energy is:

$$\frac{dE_c}{dt} = -4\sqrt{\frac{E_c}{E}}\, E_c \frac{d\Gamma}{dt}$$

$$\frac{dE_c}{dt}|_{\rm FS} = -\,(0.039 \pm 0.004 - 0.101 \pm 0.008)\ \ {\rm keV\,yr^{-1}}$$

$$\frac{dE_c}{dt}|_{\rm W} = -\,(0.032 \pm 0.008 - 0.090 \pm 0.010)\ \ {\rm keV\,yr^{-1}}$$

Can relate cutoff energy to shock velocity:

$$E_c \approx 2.2\eta^{-1} \left(\frac{V_s}{3000\mathrm{km\ s^{-1}}}\right)^2 \ \mathrm{keV}$$

And the change in cutoff energy to the shock acceleration:

$$\frac{dV_s}{dt} = 2.0 \times 10^6 \left(\frac{V_s}{\mathrm{km\ s^{-1}}}\right)^{-1} \eta \frac{dE_c}{dt}$$

In the forward shock, the deceleration is measured to be:

$$\frac{dV_s}{dt} = -(16 \pm 3 - 40 \pm 5)\ \mathrm{km\ s^{-1}\ yr^{-1}}$$

Finally, we can look at the change in N(E) and relate them to our observations:

$$\frac{dN(E)}{dt} = E^{-\Gamma_0} \exp\left(-\sqrt{\frac{E}{E_c}}\right) \times \left[\frac{d\phi}{dt} B^{\Gamma_0} + \phi \frac{dB^{\Gamma_0}}{dt} - 2\phi\, B^{\Gamma_0} \frac{d\Gamma}{dt}\right]$$

Relates to a change in the number of particles

Relates to a decline in MFA efficiency

Relates to a change in the cutoff energy

Finally, we can look at the change in N(E) and relate them to our observations:

$$\phi \propto 4\pi r^2 \rho V_s \propto t^{m-1}$$
$$\rightarrow \frac{1}{\phi}\frac{d\phi}{dt} \propto (m-1)t^{-1}$$
$$\approx -0.1\% \text{ yr}^{-1}$$

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$$B^{\Gamma_0} \propto (\rho V_s^{\beta})^{\Gamma_0/2} \propto (t^{-2m} t^{(m-1)\beta})^{\Gamma_0/2}$$
$$= t^{\Gamma_0[m(\beta-2)-\beta]/2}$$
$$\frac{1}{B^{\Gamma_0}}\frac{dB^{\Gamma_0}}{dt} = (t^{-2m} t^{(m-1)\beta})^{\Gamma_0/2}$$
$$= t^{\Gamma_0(m(\beta-2)-\beta)/2}$$
$$\approx -(0.45 - 0.54)\% \ \mathrm{yr}^{-1}$$

WHY DO SOME SNRS VARY?

- Cas A and RX J1713.7-3946 are two core collapse SNR which show emission variations (now, also 1E0102!)
- Type Ia SNe such as Tycho, Kepler, and SN 1006 (Katsuda et al. 2010) show no flickering
- Are the variations endemic to the explosion or circumstellar environment?
    - Cas A and Kepler are both expanding into very similar circumstellar environments (e.g. Hwang & Laming 2008; Chiotellis et al. 2011), so likely not a CSM effect (small number statistics)
    - Points to variations being driven by structural differences in SNe ejecta

WHY DO SOME SNRS VARY?

- While the thermal emission does not seem to vary as dramatically as the nonthermal emission, disentangling the changes in the nonthermal emission make analysis of the thermal spectrum difficult
- For calibration purposes, a SNR such as Kepler, which is comparable in brightness and size to Cas A, would be a more suitable Galactic standard candle for thermal X-rays