Suzaku X-ray Universe (San Diego, Dec 2007)

New Insights into Cosmic-ray Acceleration in SNRs

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mainly with
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Outline

✤ *Introduction*

- Why do we care about Cosmic Rays (CRs) in SNRs?

✤ *X-ray Variability: "Seeing" Acceleration of Cosmic Rays!*

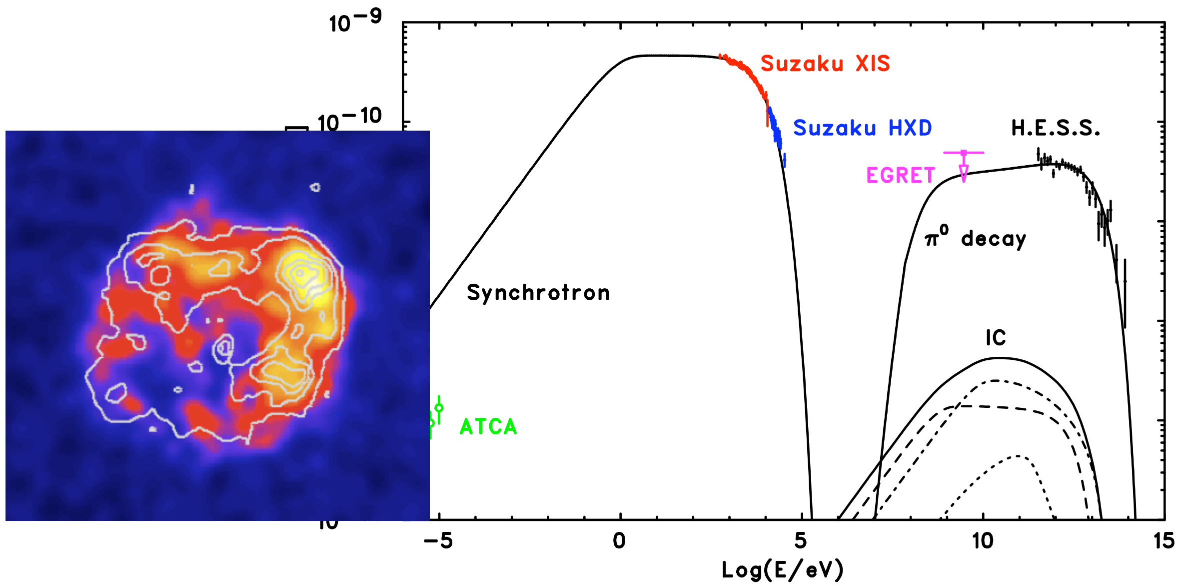
- RX J1713.7-3946
- Cassiopeia A

✤ *Suzaku x HESS*

- (RX J1713.7-3946 in Tanaka's talk)
- Vela Jr ***(preliminary)***

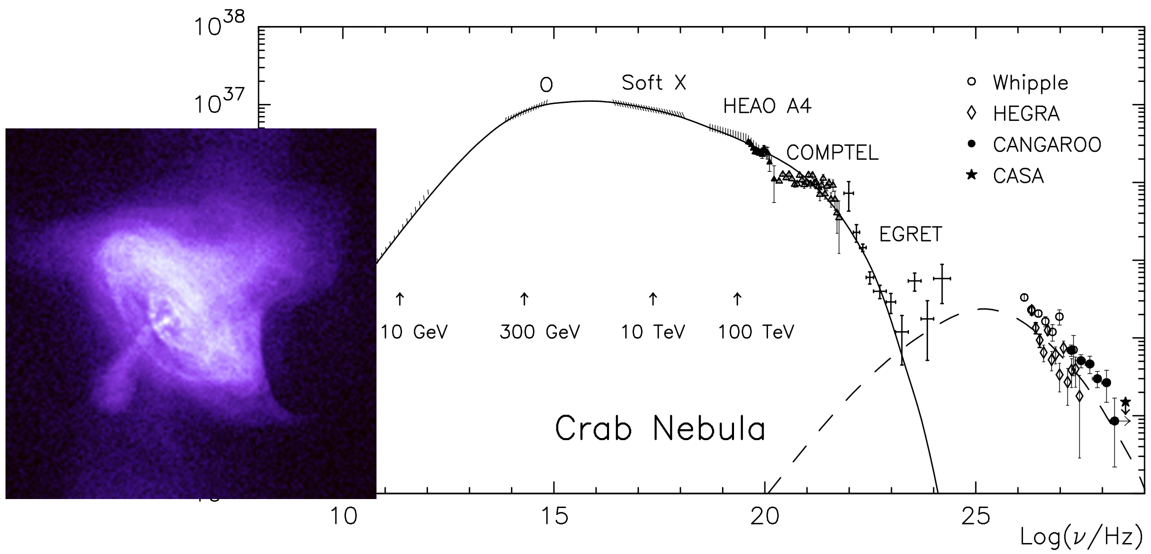
Why we care CRs in SNRs

3 Major Objects in Very-High-Energies



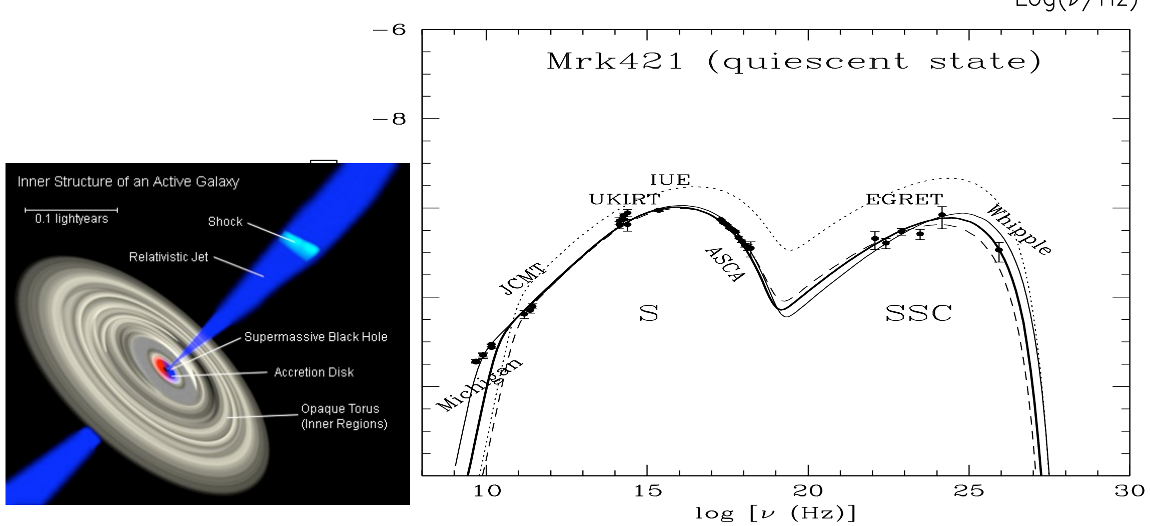
1. Young SNRs

SED: Sync + Pion-decay (proton) ?
Engine: Supernova
Dynamics: Non-relativistic ejecta



2. Pulsar Wind Nebulae

SED: Sync + IC (electron)
Engine: Rotating NS
Dynamics: Relativistic wind

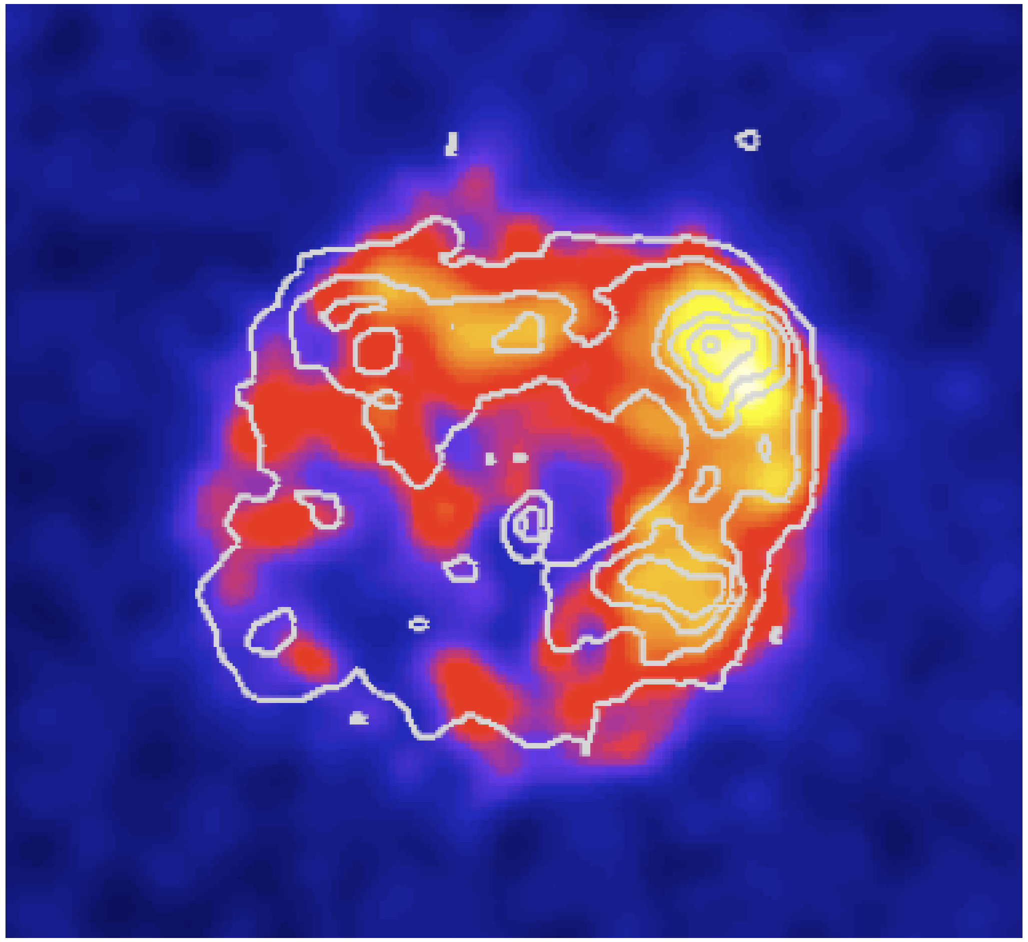


3. TeV Blazars

SED: Sync + IC (electron)
Engine: Supermassive BH
Dynamics: Relativistic jet (beaming)

X-ray Variability (1) RX J1713.7-3946

Basic Information



HESS (color)
ASCA (contours)

Distance: ~ 1 kpc
Age: ~1600 yr
Radius: ~ 9 pc

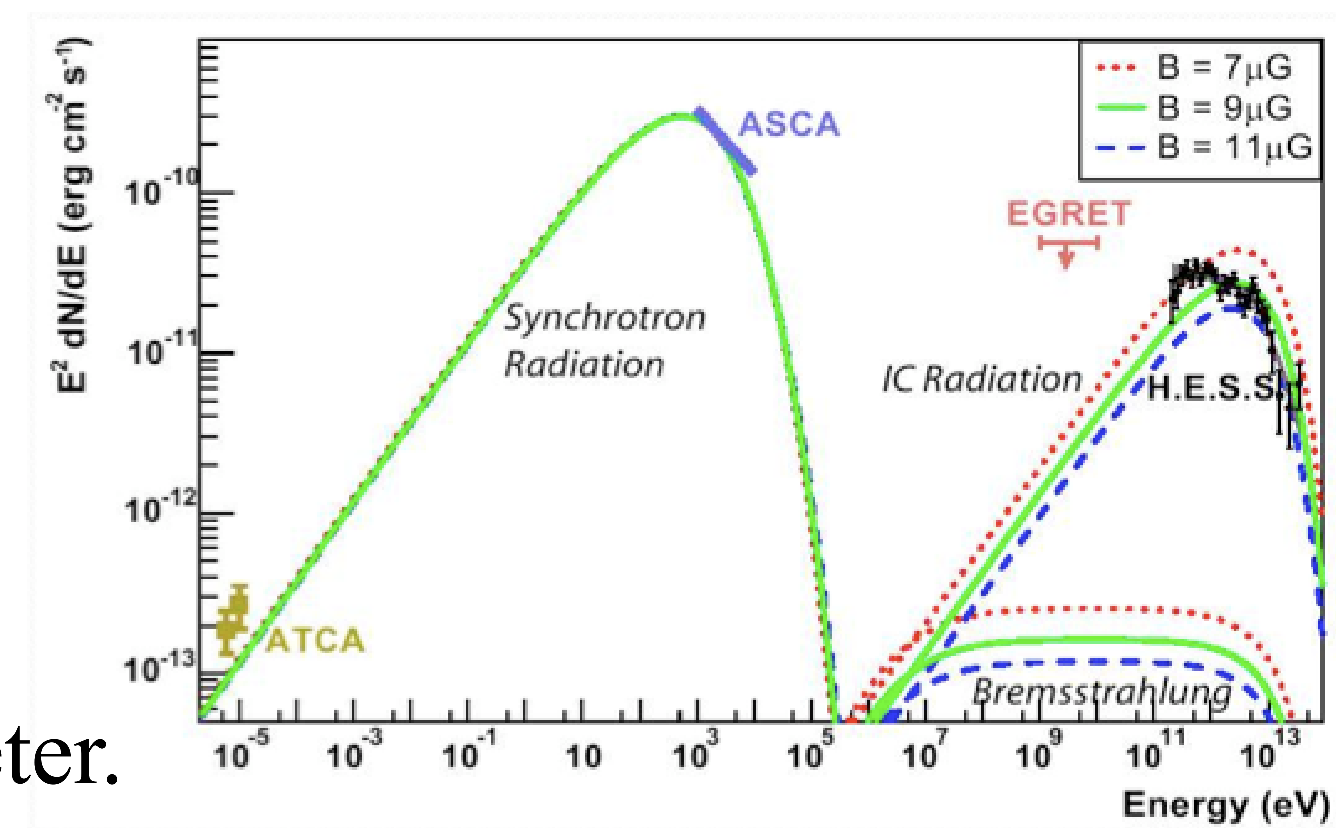
Dominated by non-thermal X-ray
(Koyama et al. 1997, Slane et al. 1999)

TeV gamma-ray imaging by HESS
(Aharonian et al. 2004, 2006, 2007)

TeV ??
(1) leptonic
Inverse Compton

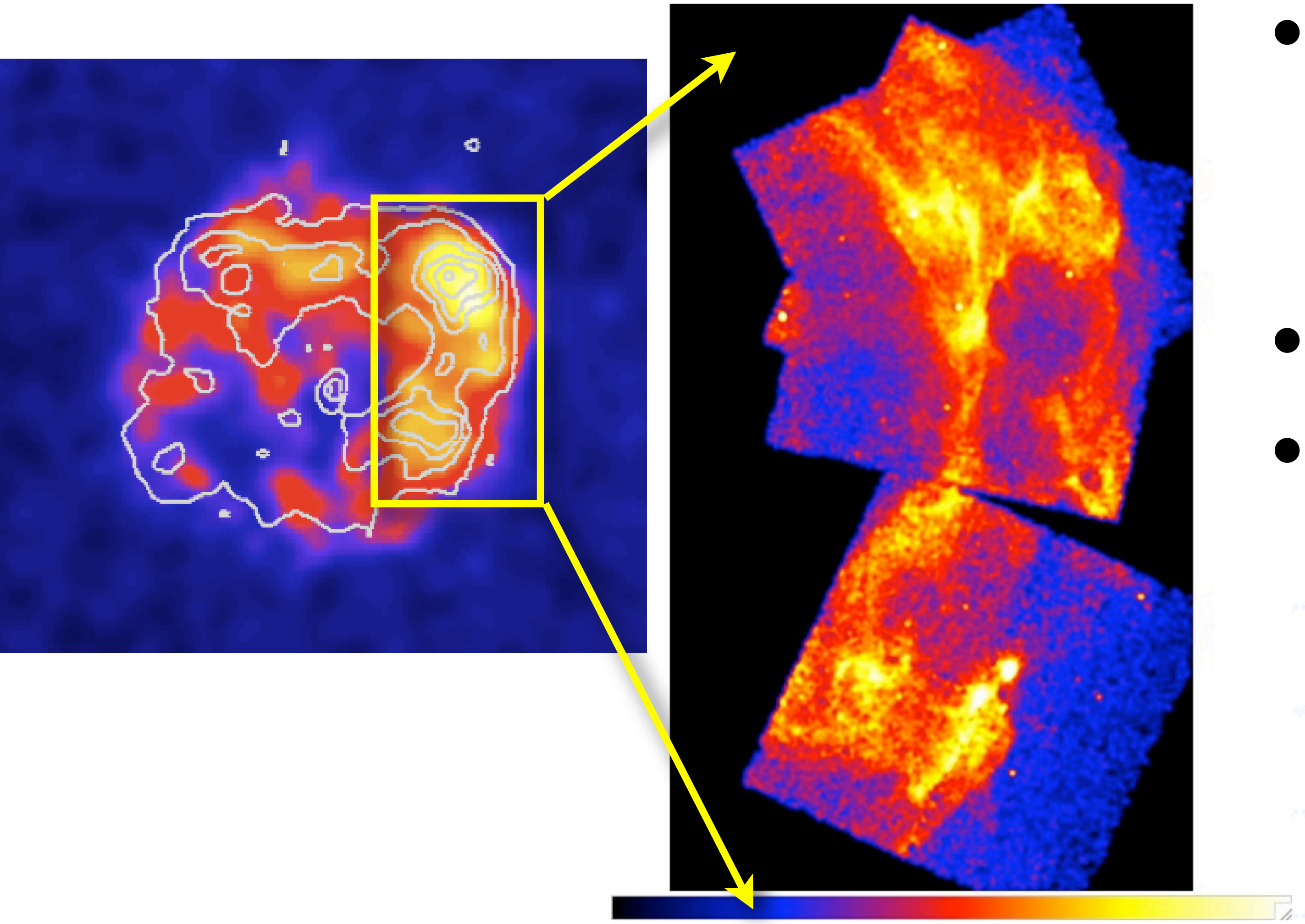
(2) hadronic
Pion decay

B-field is a key parameter.



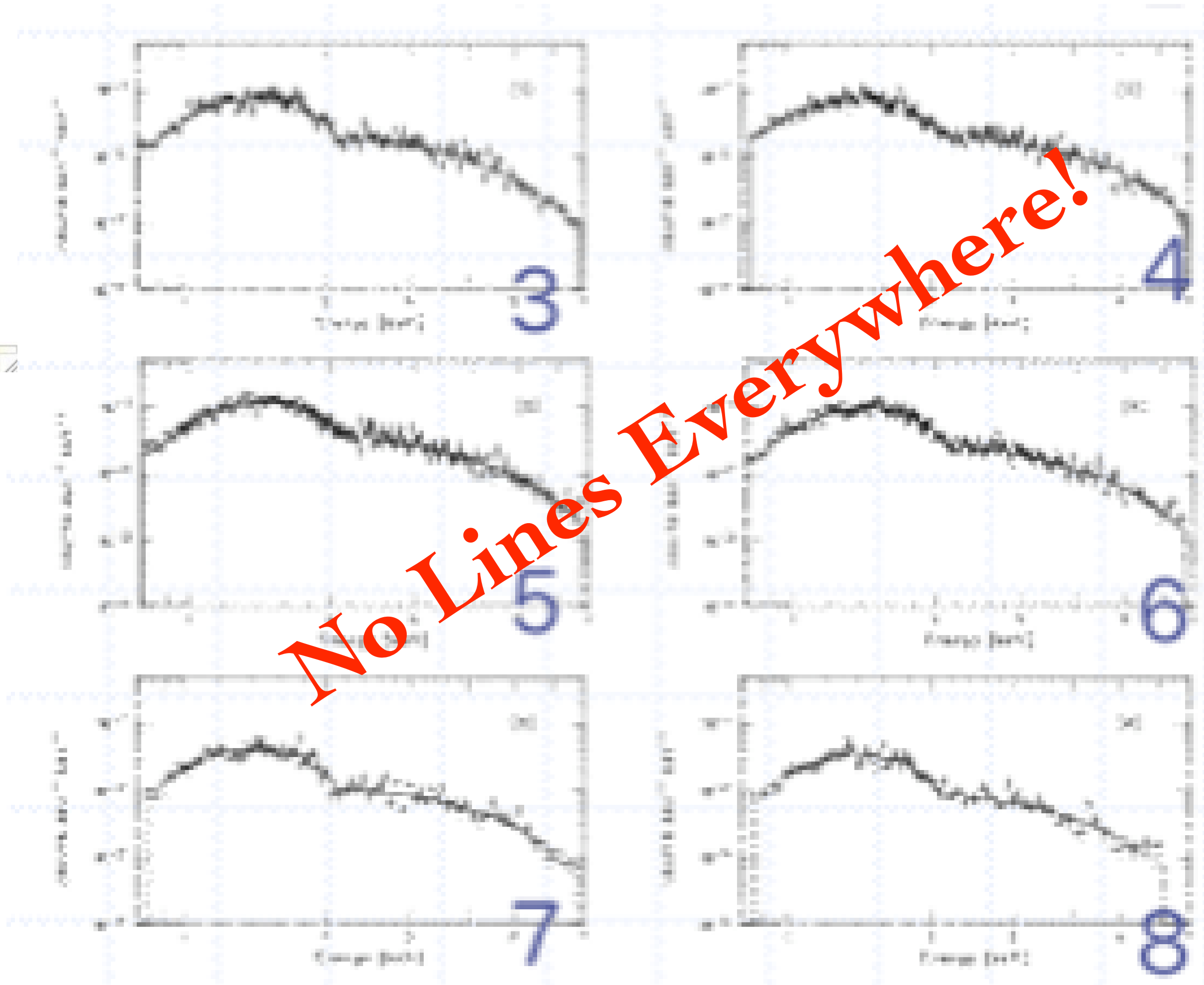
X-ray Variability (1) RX J1713.7-3946

Basic Information (conti.)



Chandra ACIS-I
(sqrt scaling)

- X-ray spectra : power-law type
  photon index 2.1-2.5 by ASCA and Chandra (Koyama et al. 1997; Slane et al. 1999; Uchiyama et al. 2003)
- Hard X-rays by RXTE (Pannuti et al. 2003)
- Synchrotron radiation by shock-accelerated multi-TeV electrons (Reynolds 1996)



Uchiyama et al. (2003)

Power-law Spectra (0.5 - 10 keV)

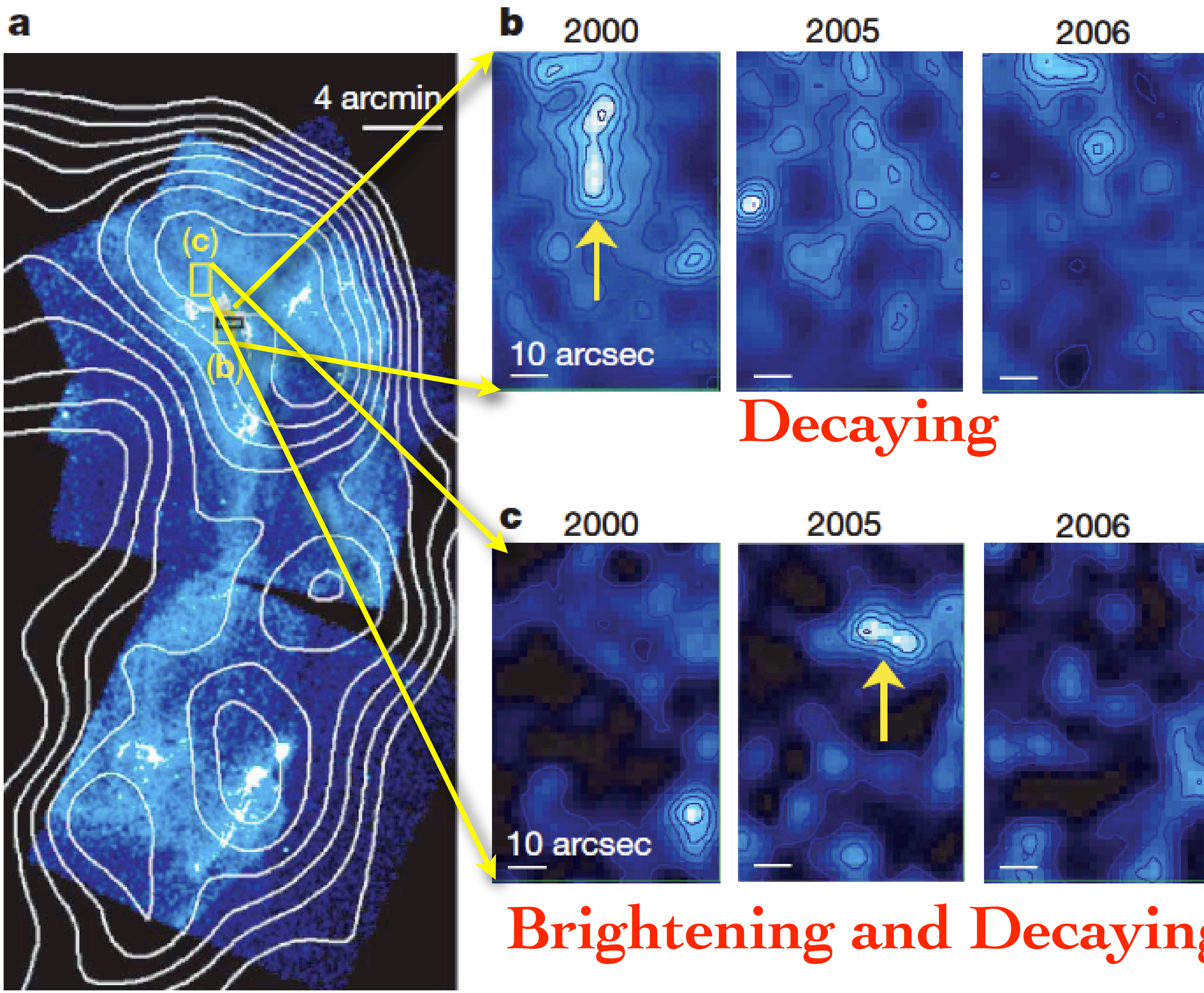
photon index $\Gamma \simeq 2.3$

$N_H \simeq 0.8 \times 10^{22}\ \mathrm{cm}^{-2}$

(almost) everywhere!

X-ray Variability (1) RX J1713.7-3946

Our Chandra Monitoring Observations



Decaying

Brightening and Decaying

Chandra (color)
HESS (contours)

Most filaments (spatially extended) are variable in time!!

Timescale ~ 1 year

X-ray spectra:
a power law
with photon index ~2

Uchiyama et al. (2007)

Variability Timescales

Light crossing time

$$t_{\rm lc} \sim 0.1 \left(\frac{\theta}{6 \ \rm arcsec} \right) \ \rm year$$

variability timescale $\Delta t_{\rm var} \sim 10 \times t_{\rm lc}$

: impossible for non-relativistic plasma waves/motion

Decaying = Synchrotron Cooling

$$t_{\rm sync} \sim 1.5 \left(\frac{B}{\rm mG} \right)^{-1.5} \left(\frac{\epsilon}{\rm keV} \right)^{-0.5} \ \rm year \longrightarrow B \sim 1 \ \rm mG$$

Brightening = Acceleration of Fresh Electrons

$$t_{\rm acc} \sim 1 \ \eta \left(\frac{B}{\rm mG} \right)^{-1.5} \left(\frac{\epsilon}{\rm keV} \right)^{0.5} \left(\frac{V_s}{3000 \ \rm km \ s^{-1}} \right)^{-2} \ \rm years \longrightarrow B \sim 1 \ \rm mG, \ \eta \sim 1$$

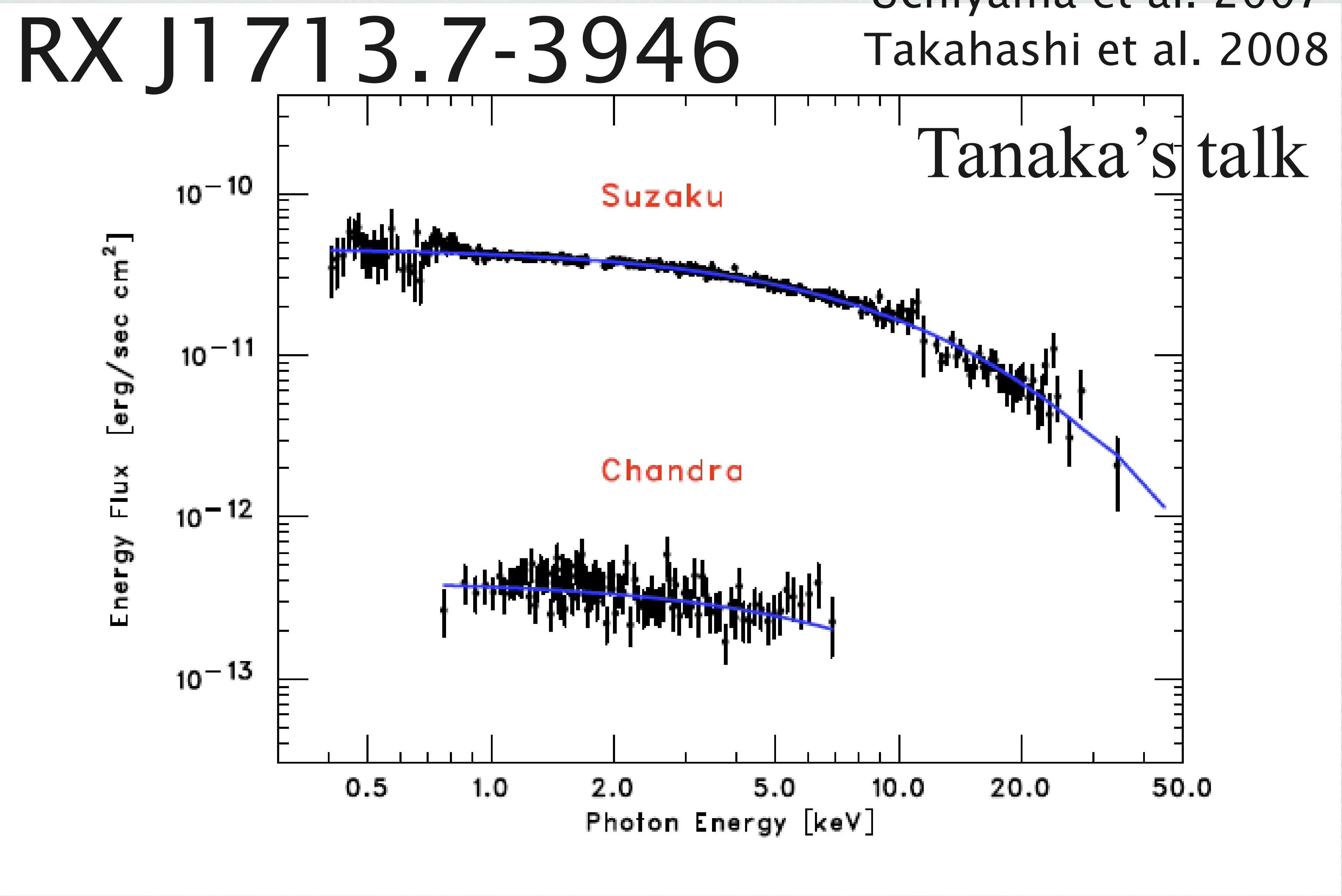
Diffusive shock acceleration $\eta \equiv \left(\frac{\delta B}{B} \right)^2$

"gyro-factor"

Consistent with Suzaku
(Takahashi et al. 2008)

Suzaku Broadband Spectrum

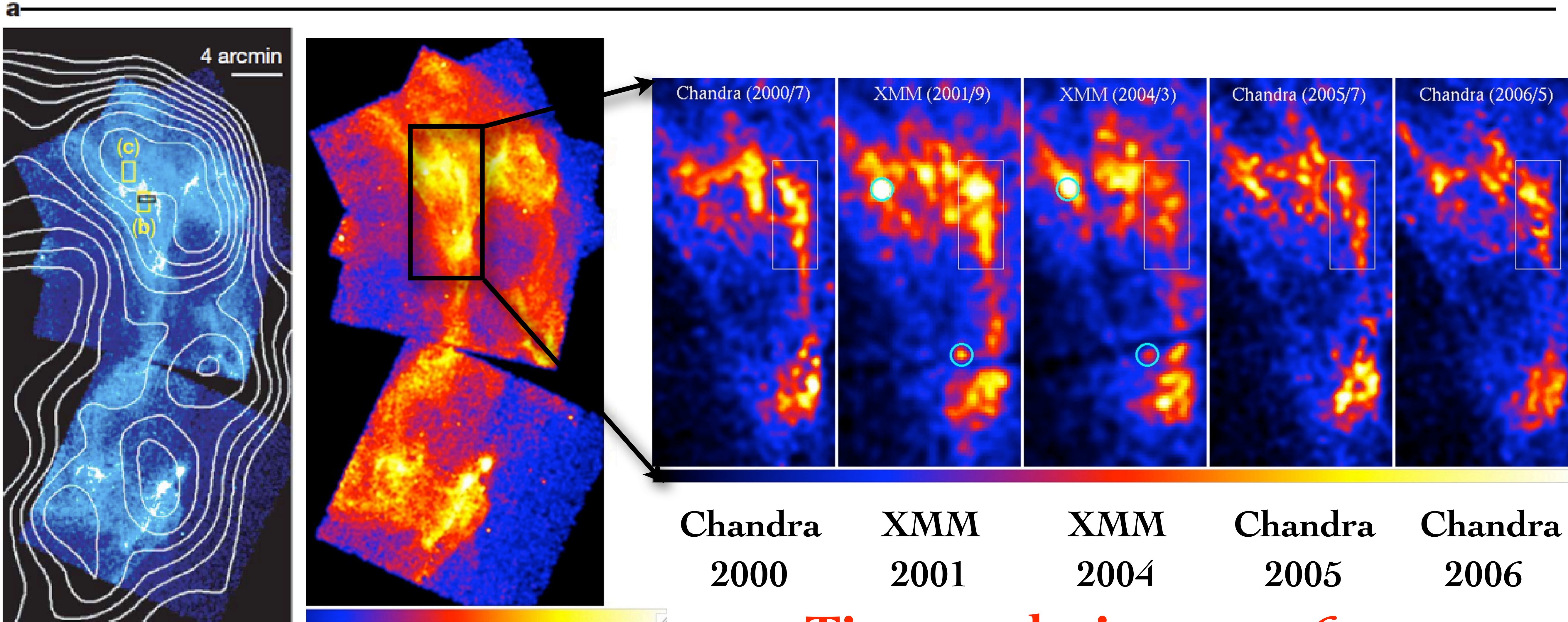
Uchiyama et al. 2007
Takahashi et al. 2008



- ⭐ Spectral cutoff
- ⭐ Shock acceleration in the Bohm regime! $\eta \sim 1$

X-ray Variability (1) RX J1713.7-3946

Combined with previous XMM data



Chandra 2000 | XMM 2001 | XMM 2004 | Chandra 2005 | Chandra 2006

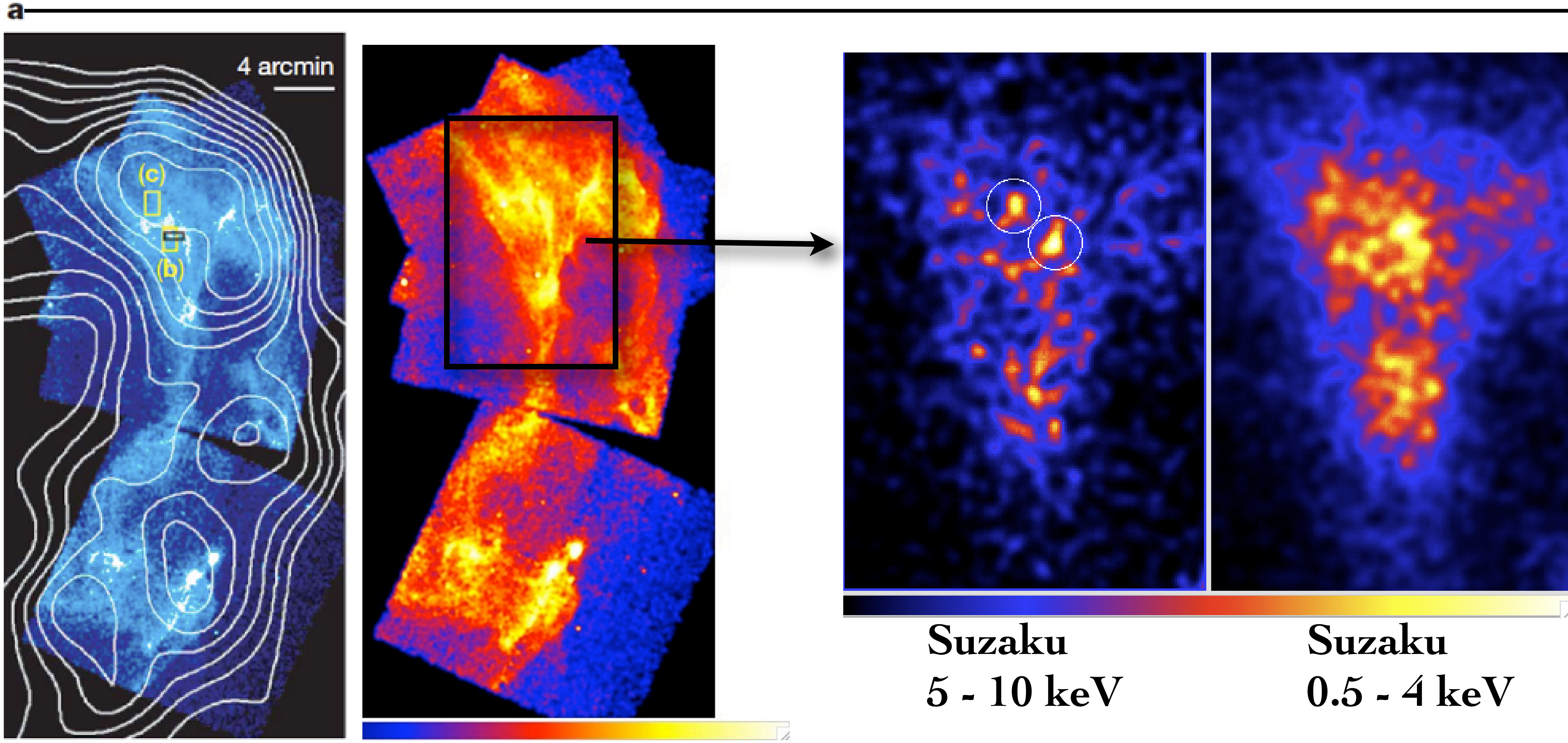
Chandra (color)
sqrt scaling

Time evolution over 6 yrs

- Synchrotron origin of X-rays is verified
- → Variability: fast synchrotron cooling and fast CR acceleration
- B-field ~ 1 mG is necessary to account for the variability

X-ray Variability (1) RX J1713.7-3946

Suzaku reveals hard filaments



Chandra (color)
sqrt scaling

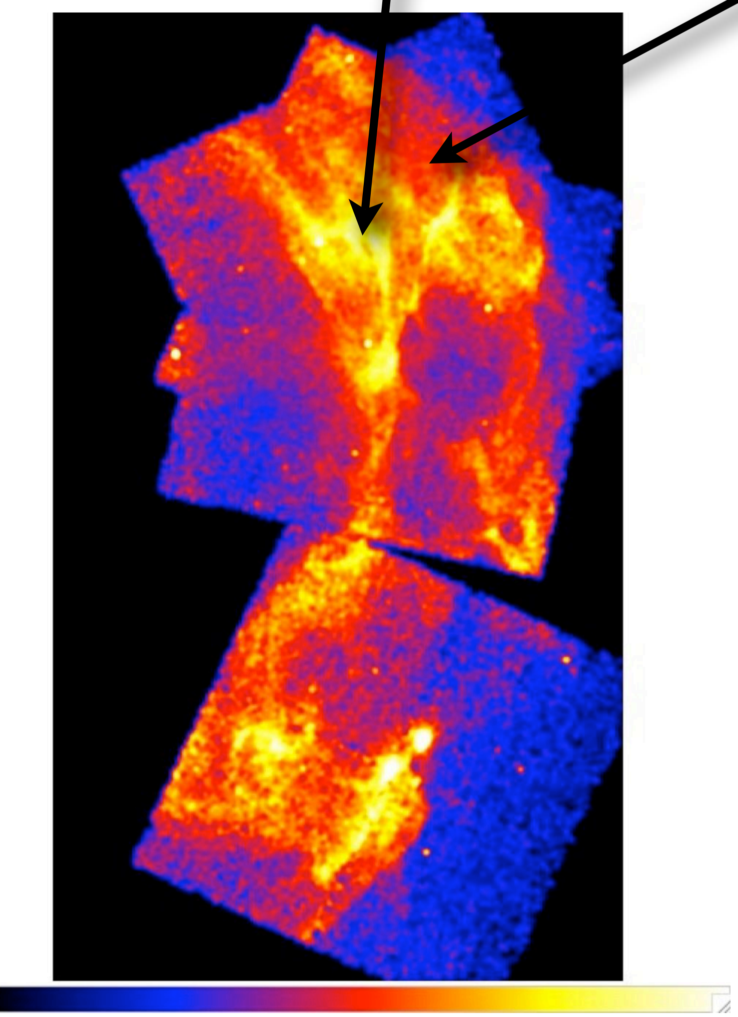
Hard filaments are expected to be violently variable.

- We ask for monitoring observations (AO3, AO4,...):
- twice a year, for ~4 years

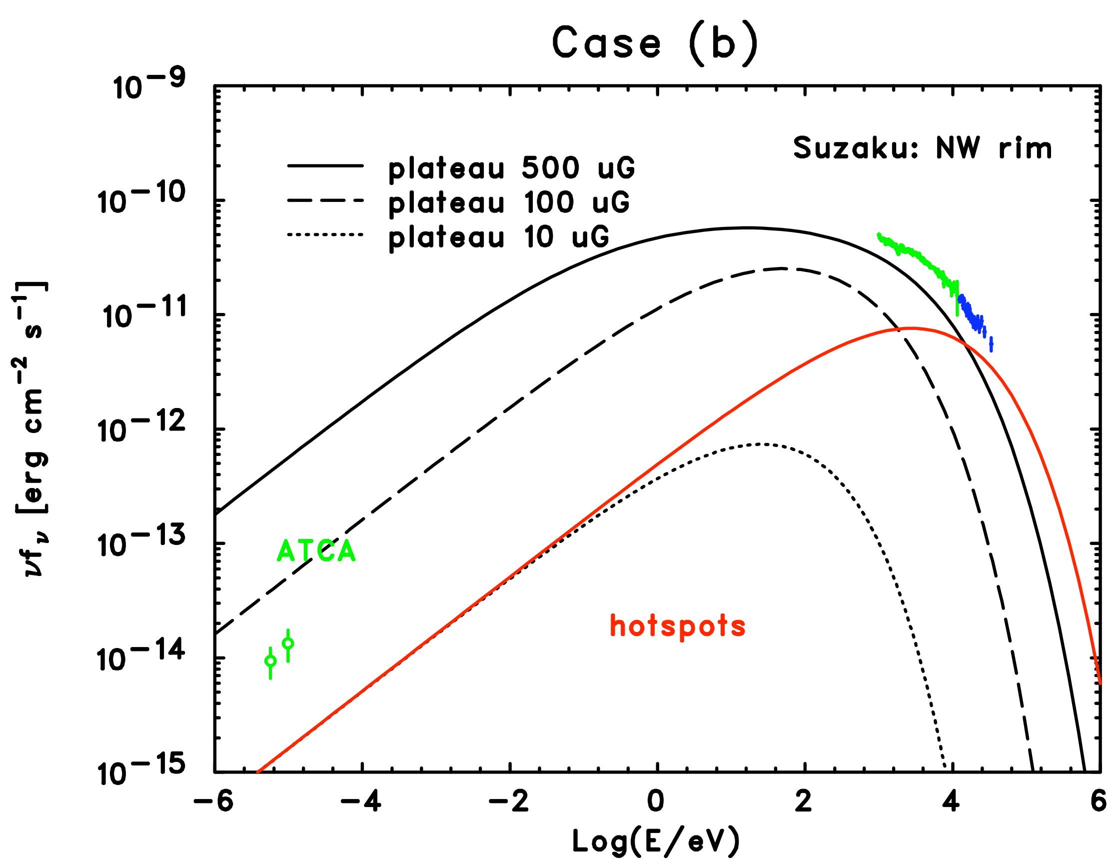
X-ray Variability (1) RX J1713.7-3946

Magnetic Field Strength

- Filamentary regions: B ~ 1 mG



- How about more diffuse regions?
  (Direct relation to TeV gamma-rays)



To account for:

Spectral shapes

Fluxes

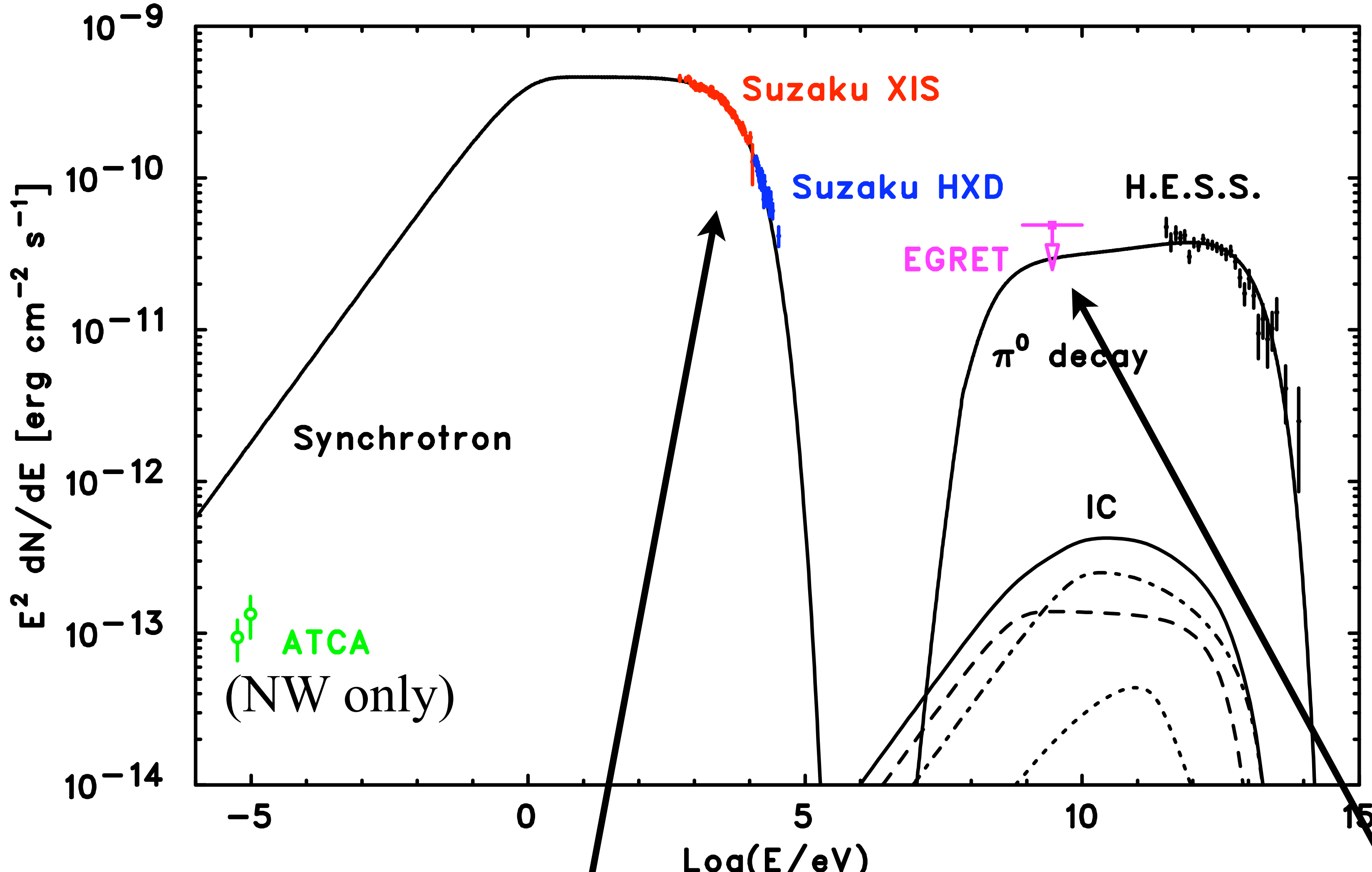
Radio constraints

⟶ • B ~ 0.2 mG

X-ray Variability (1) RX J1713.7-3946

Hadronic Origin of Gamma-rays

Average field of B ~ 0.2 mG ⟶ **IC (leptonic) unlikely**



TeV has hadronic origin:

total proton energy

$$W_{\rm p} \sim 3 \times 10^{50}\ n^{-1}\ {\rm ergs}$$

proton roll off

$$E_{\rm p,roll} \sim 100\ {\rm TeV}$$

> electron cutoff

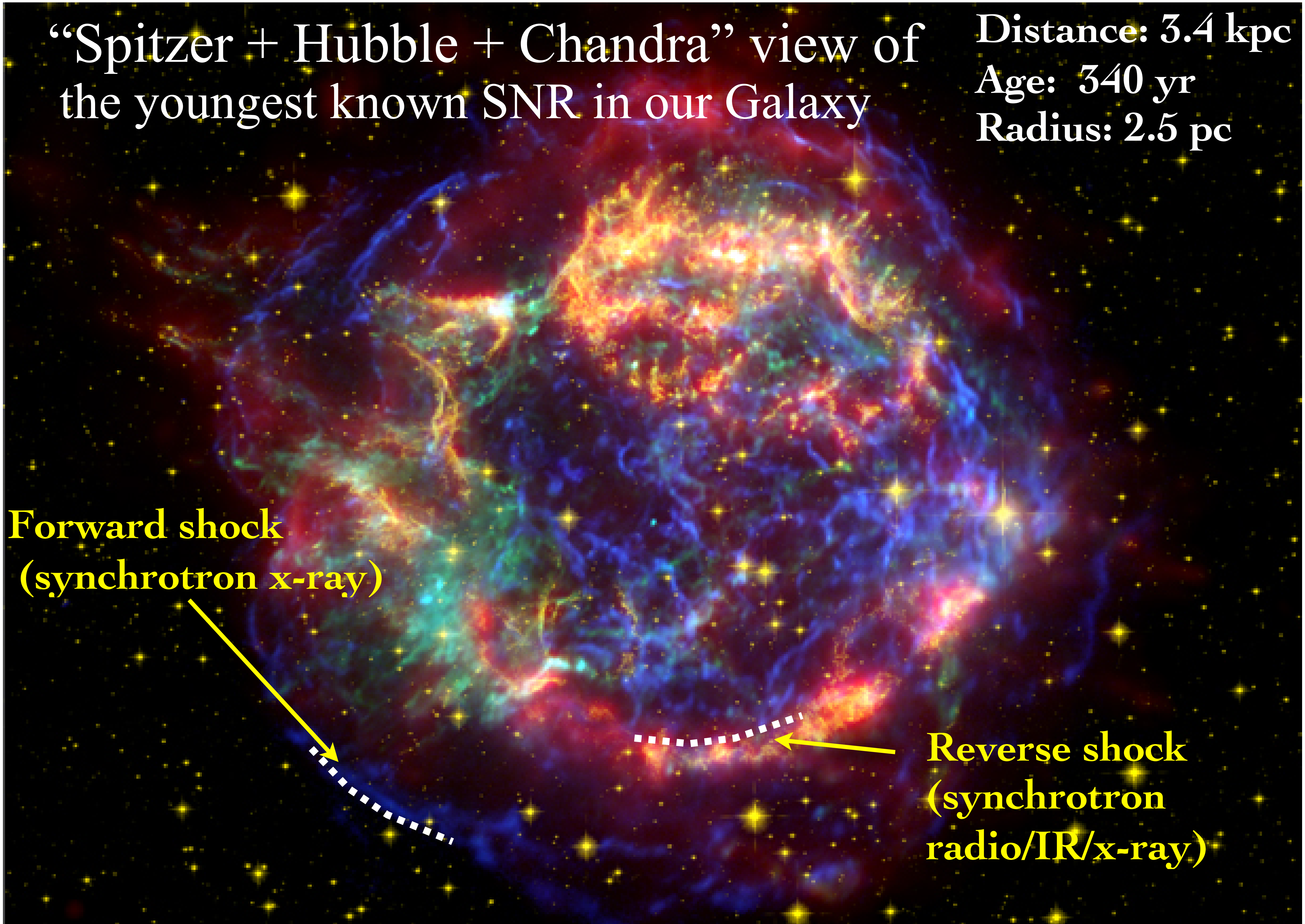
$$E_{\rm e,cutoff} \sim 10\ {\rm TeV}$$

***Suzaku* wide band**
Tanaka's talk for details

GLAST
will determine proton index

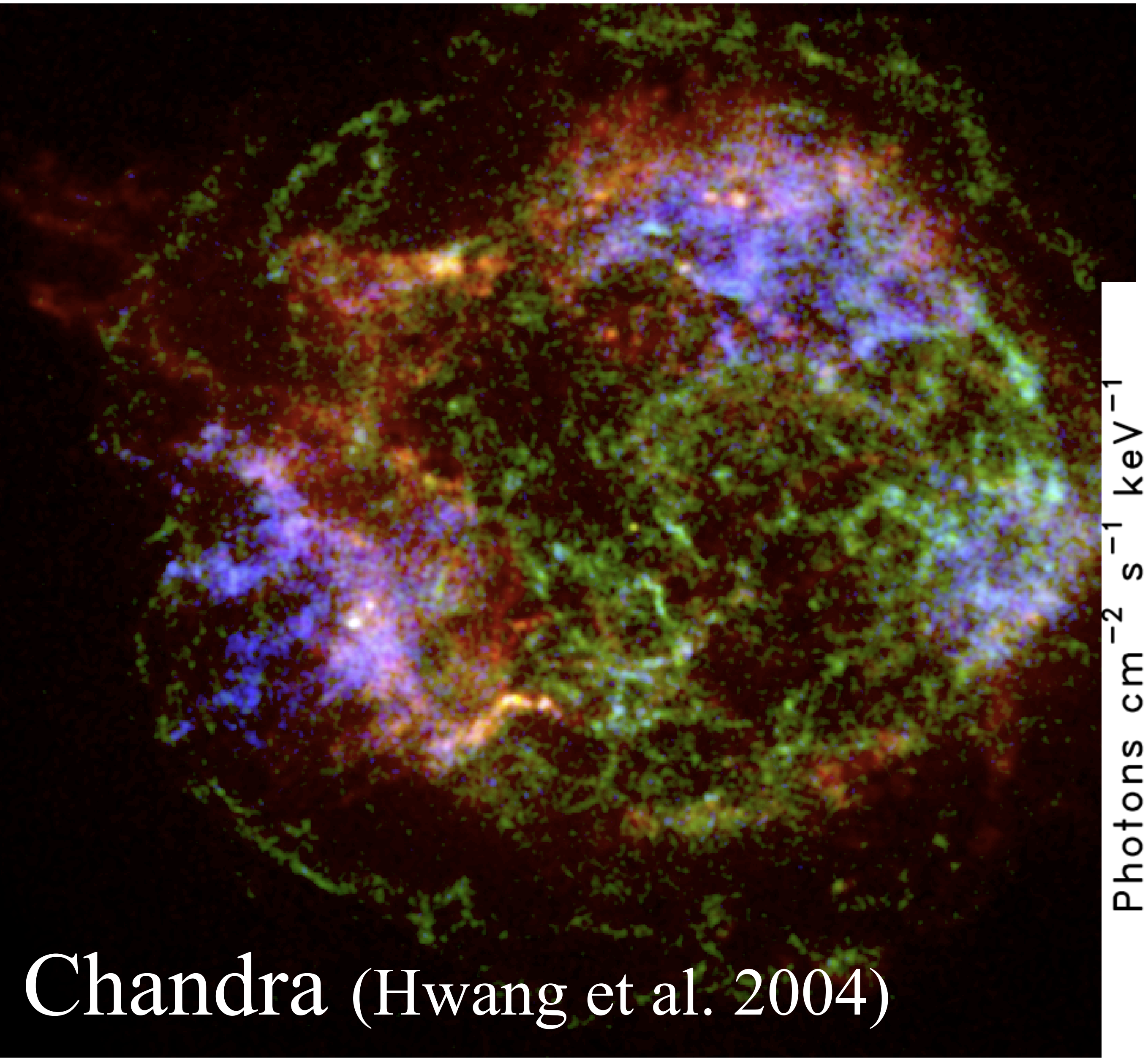
X-ray Variability (2) Cassiopeia A

Basic Information



X-ray Variability (2) Cassiopeia A

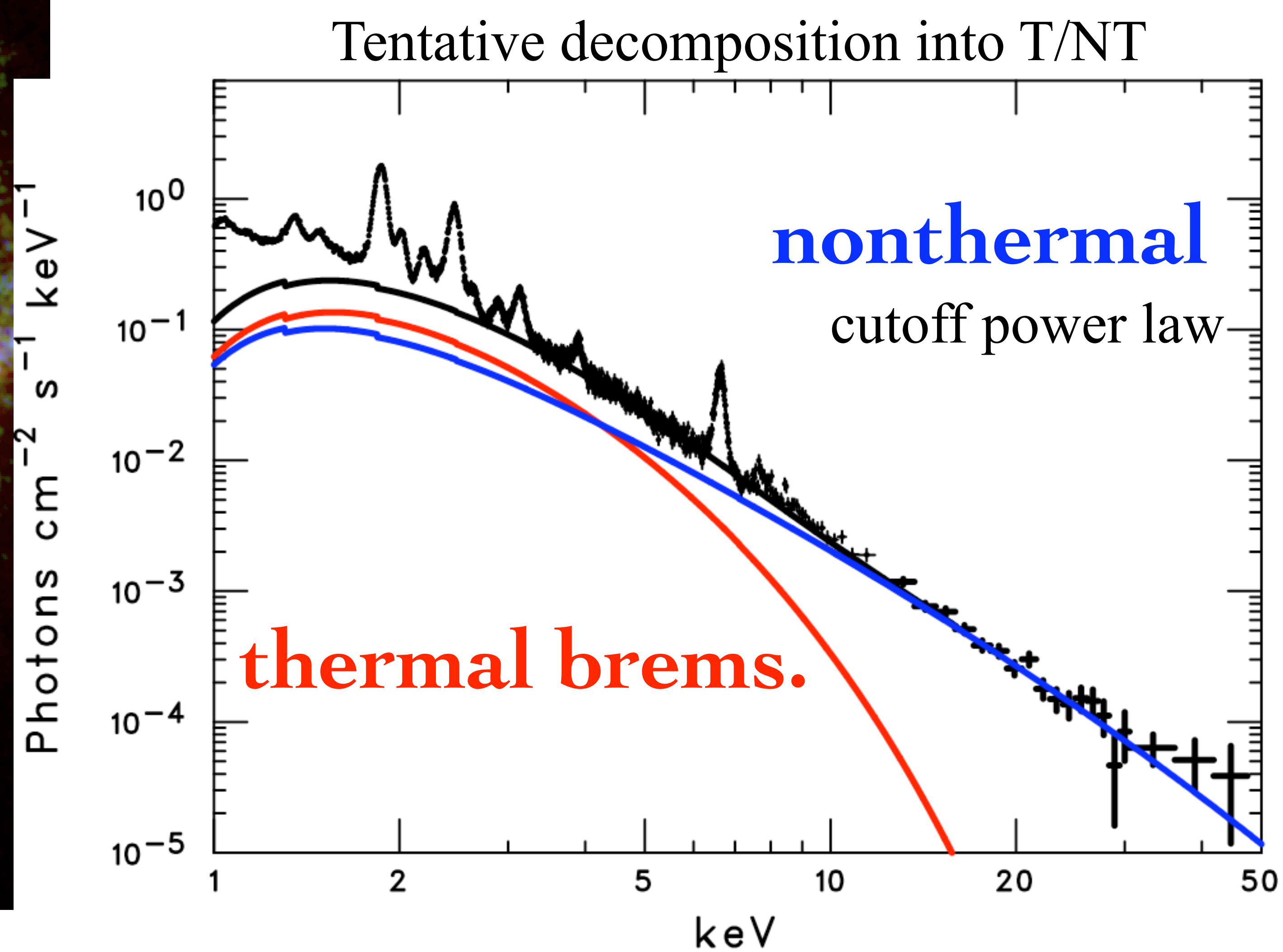
X-ray Image and Spectrum



Si-K Fe-K 4-6 keV

Suzaku XIS+PIN spectrum

(Data from Y. Maeda)

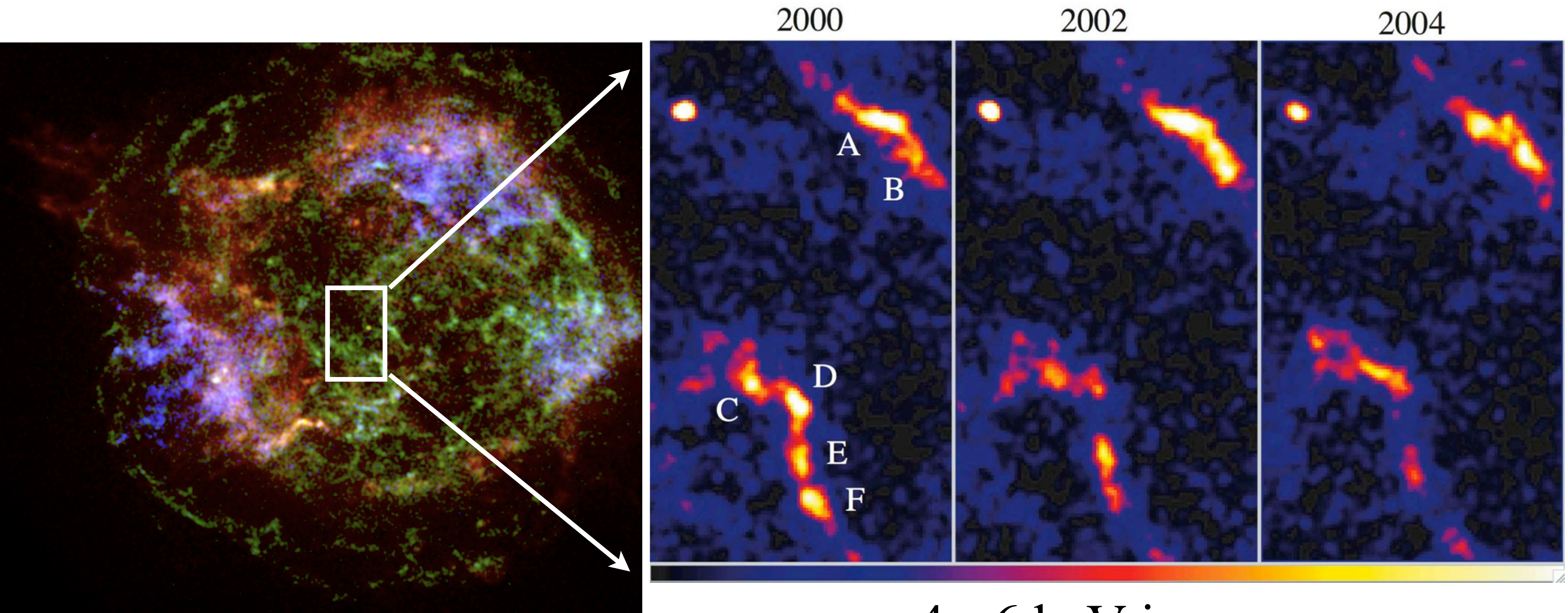


Both T/NT:
Reverse-shock dominated

What is the origin of nonthermal X-ray?

X-ray Variability (2) Cassiopeia A

Time Sequence of Chandra Images Uchiyama et al.



4 - 6 keV images

2000, 2002, 2004 data have almost identical ACIS settings: aim point, roll angle, etc.

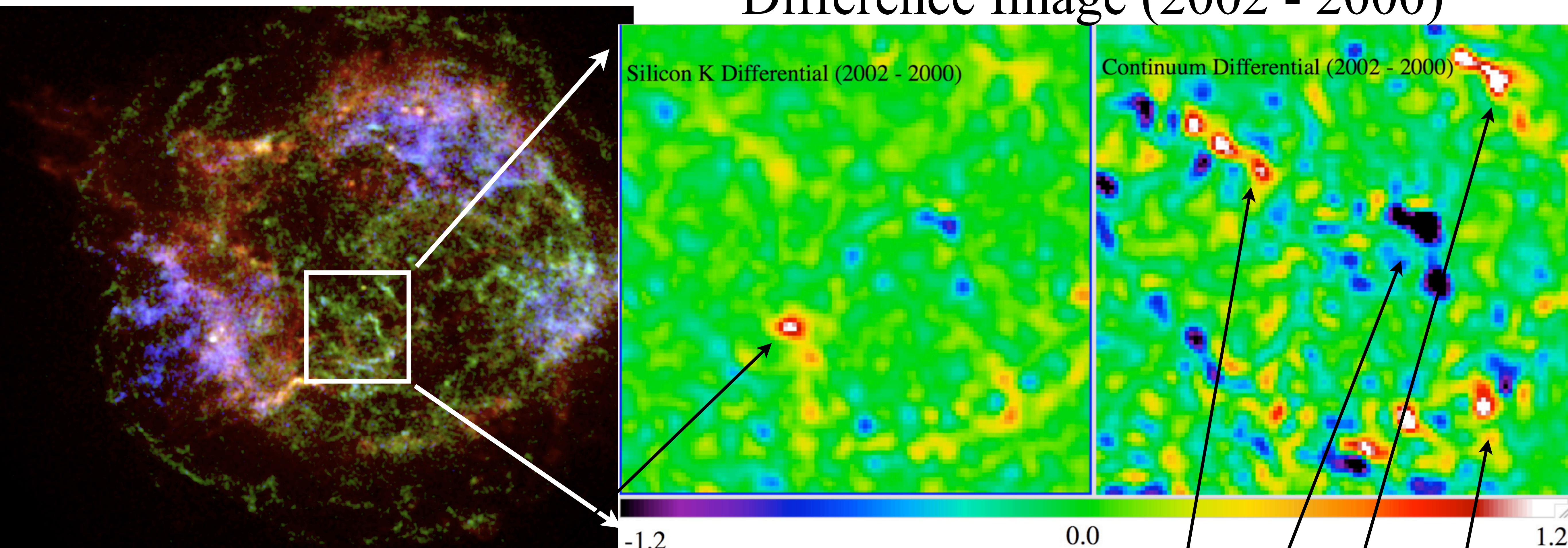
DeLaney & Rudnick (2003)
Hwang et al. (2004)

Time evolution over 4 yrs
brightening and decaying
spatially extended (few arcsecs)

Sequence of Chandra Images

Uchiyama et al.

Difference Image (2002 - 2000)



Si-K band

4 - 6 keV

Si-K: silent
4-6 keV: violent

thermal origin

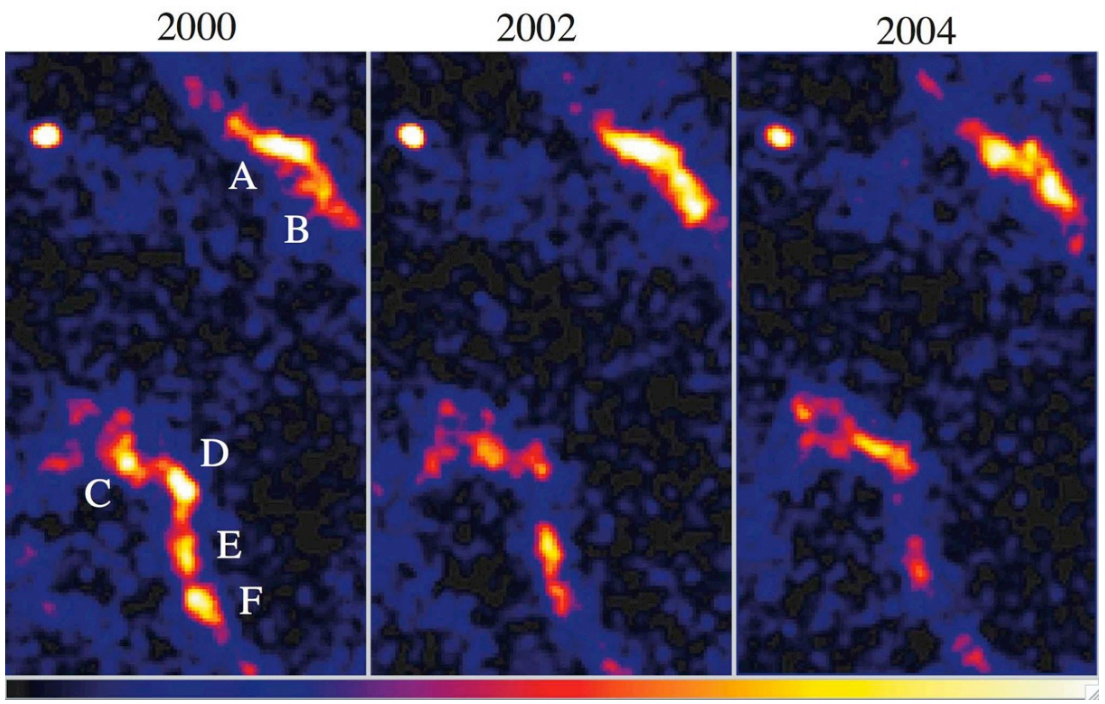
Similar to variable components found by Patnaude & Fesen (2007)

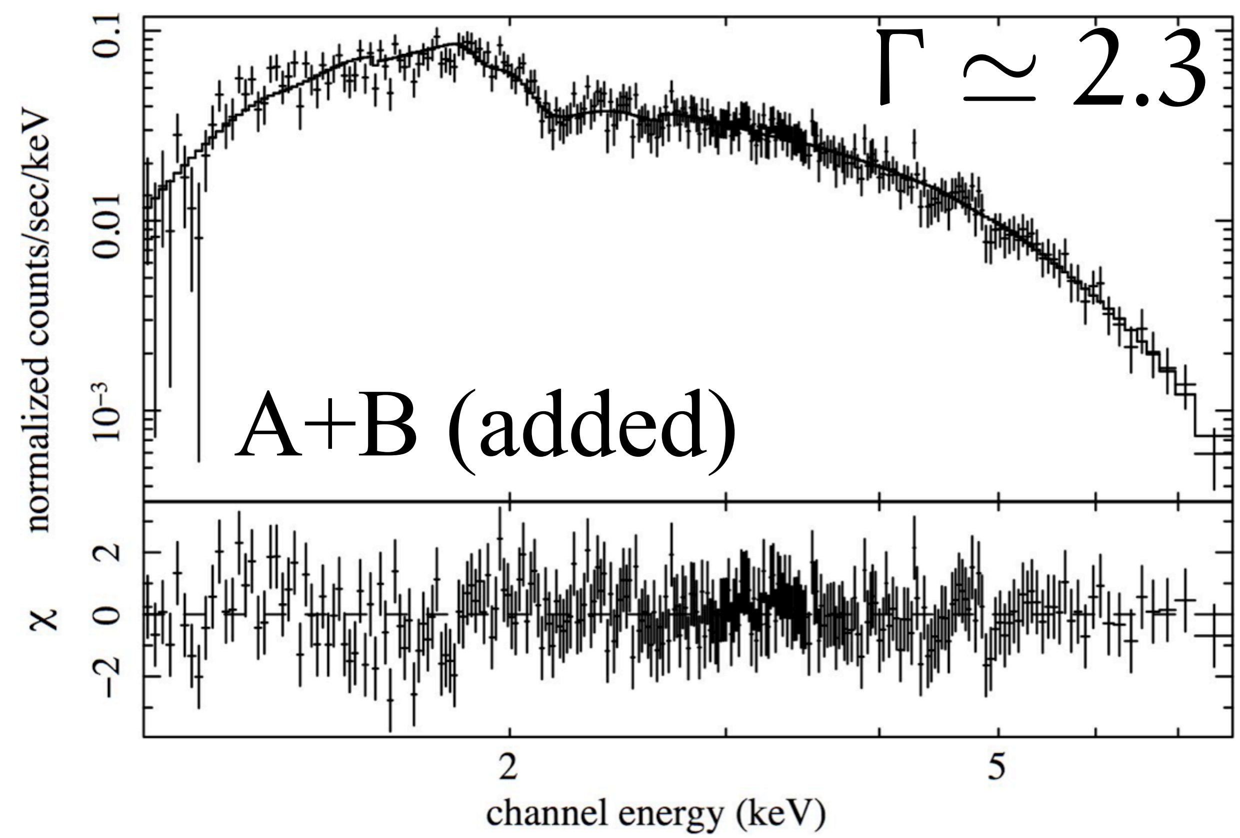
synchrotron origin

X-ray Variability (2) Cassiopeia A

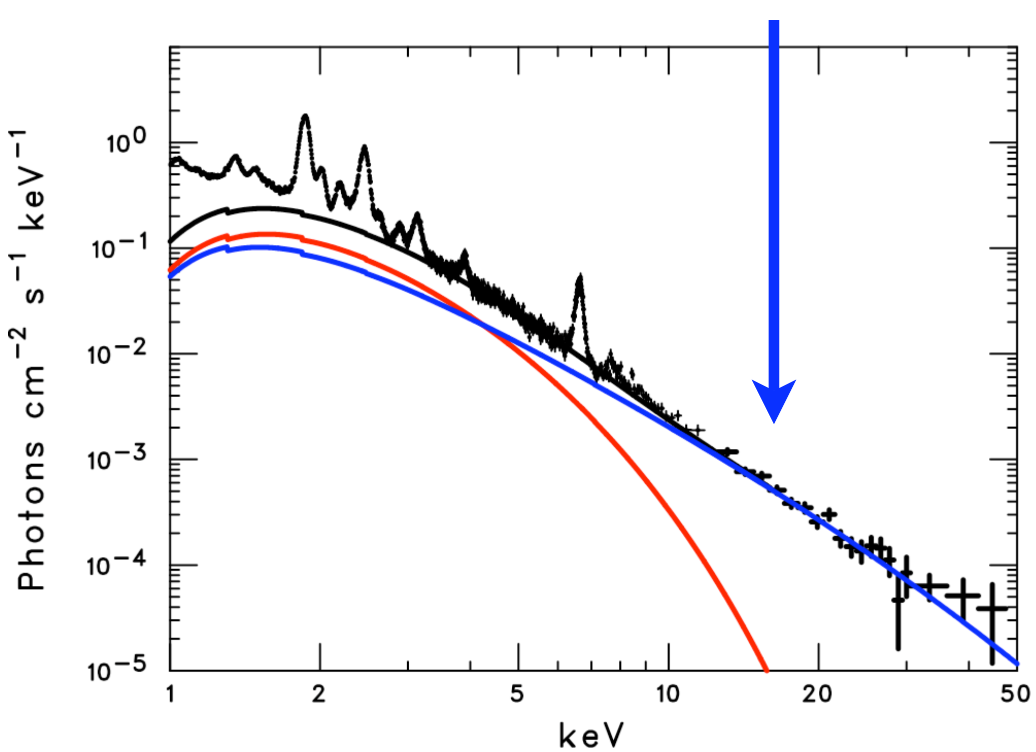
Spectra of Variable Filaments

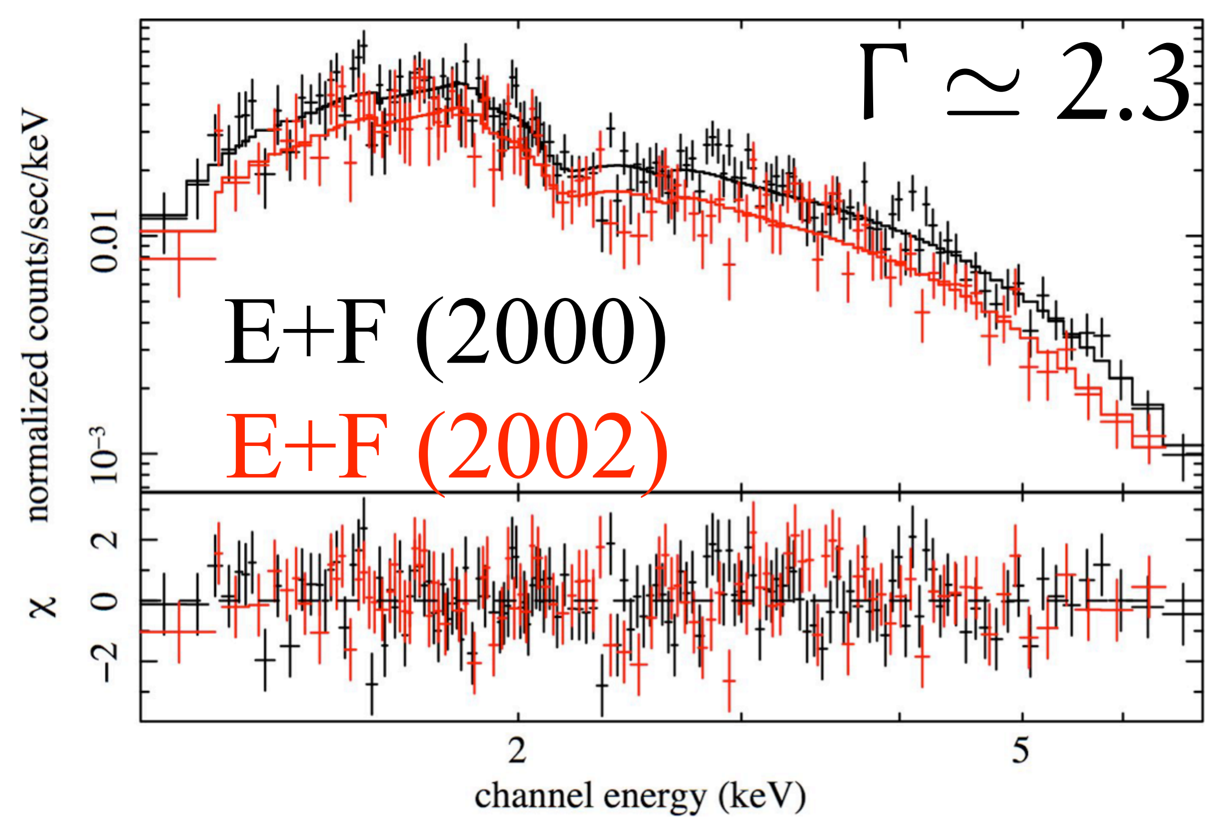
Uchiyama et al.





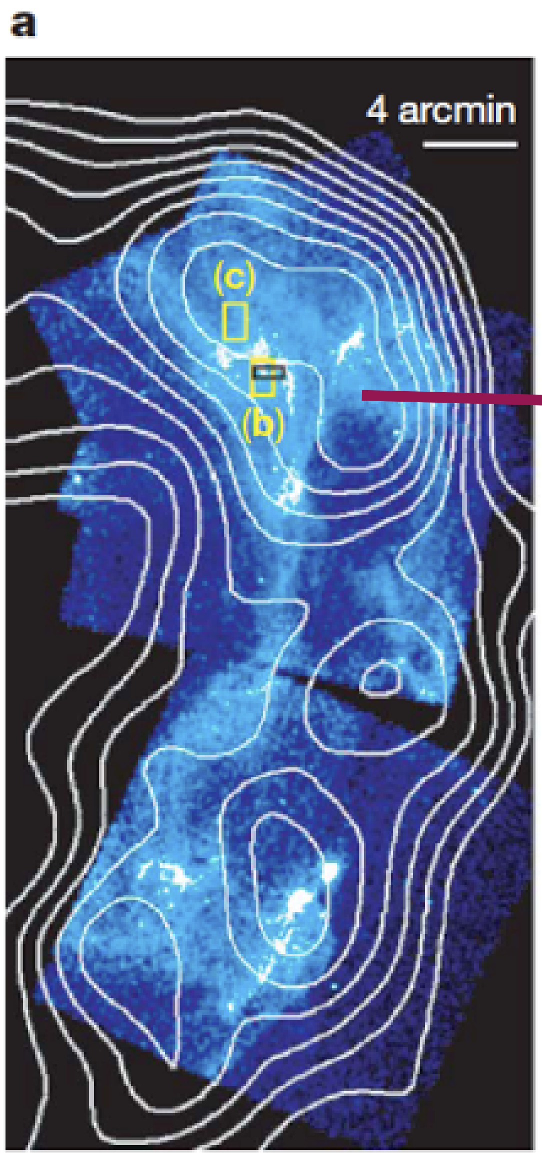
Synchrotron radiation from reverse-shocked ejecta

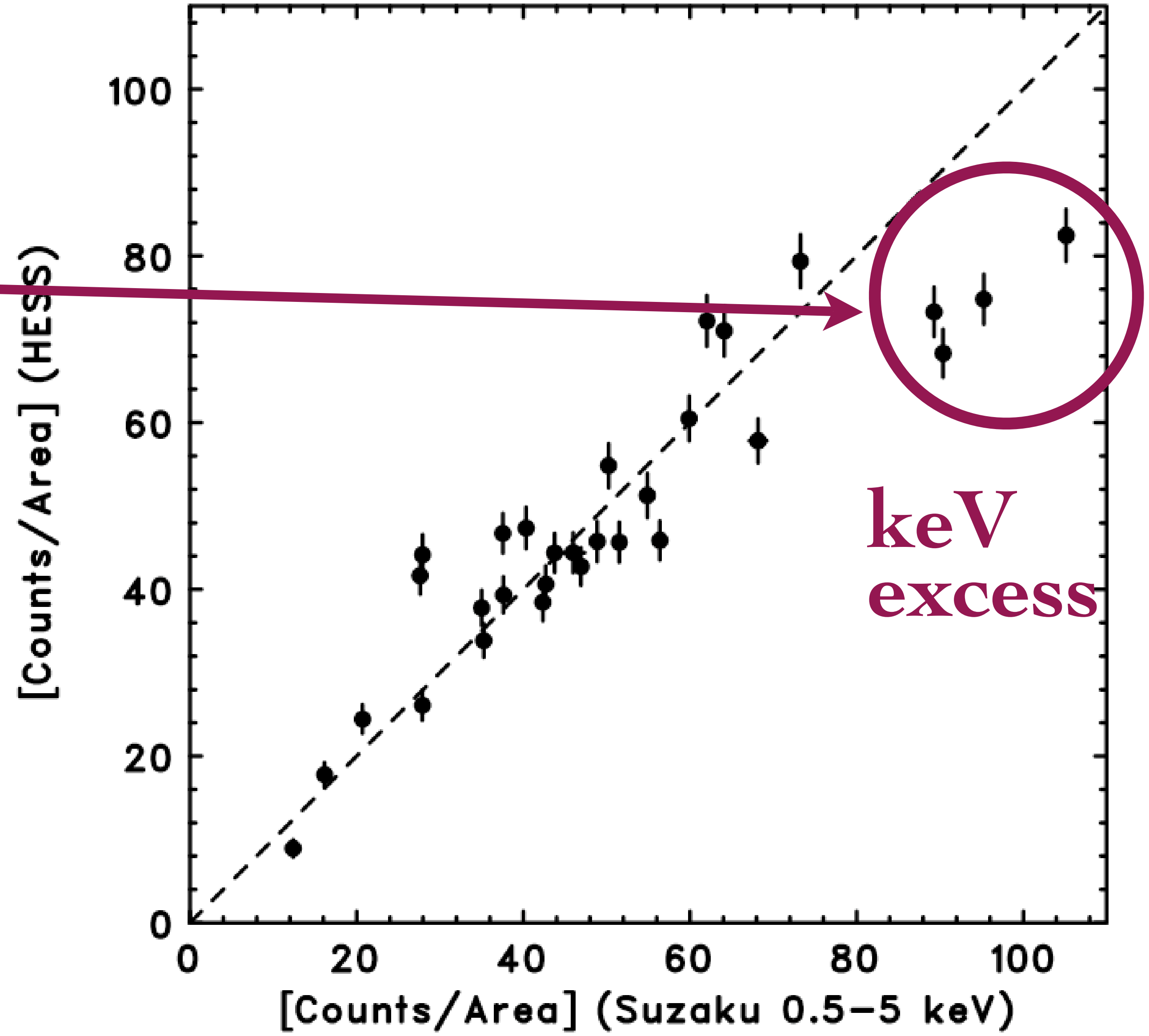




Suzaku vs HESS (1) : RX J1713.7-3946 *(Tanaka's talk)*

Position Dependence of "KeV/TeV"



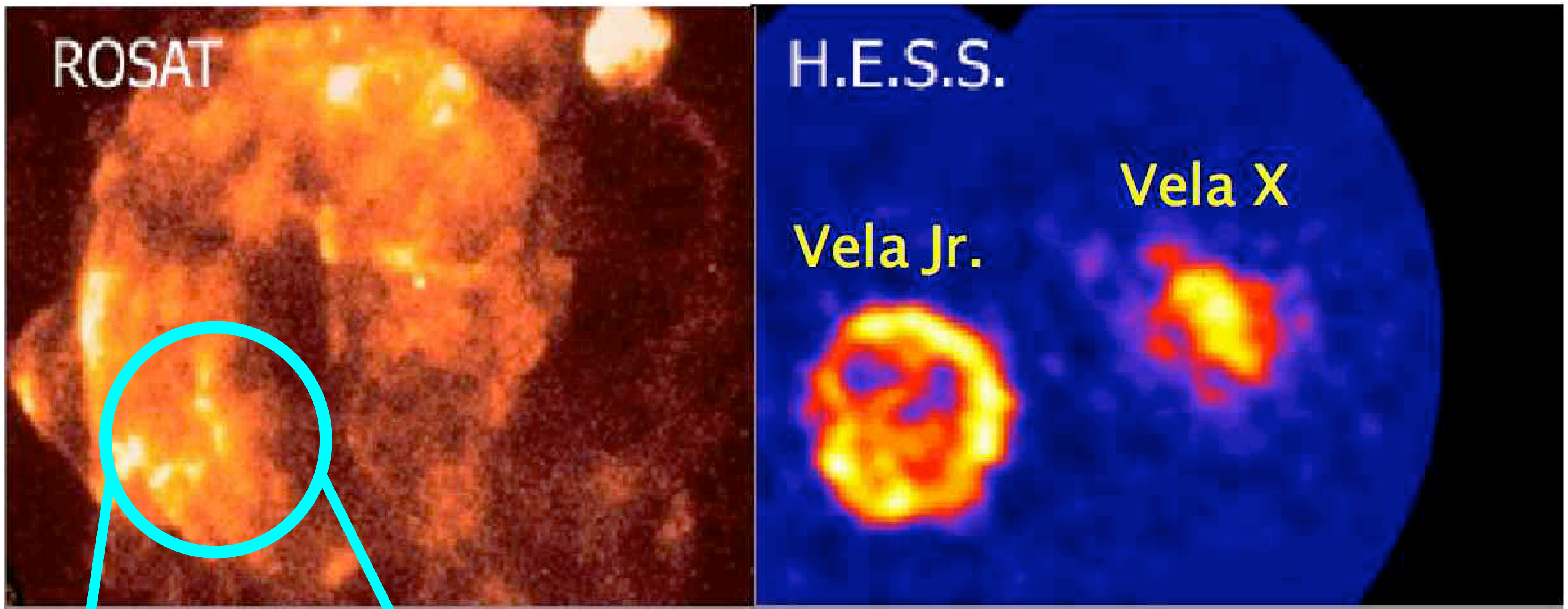


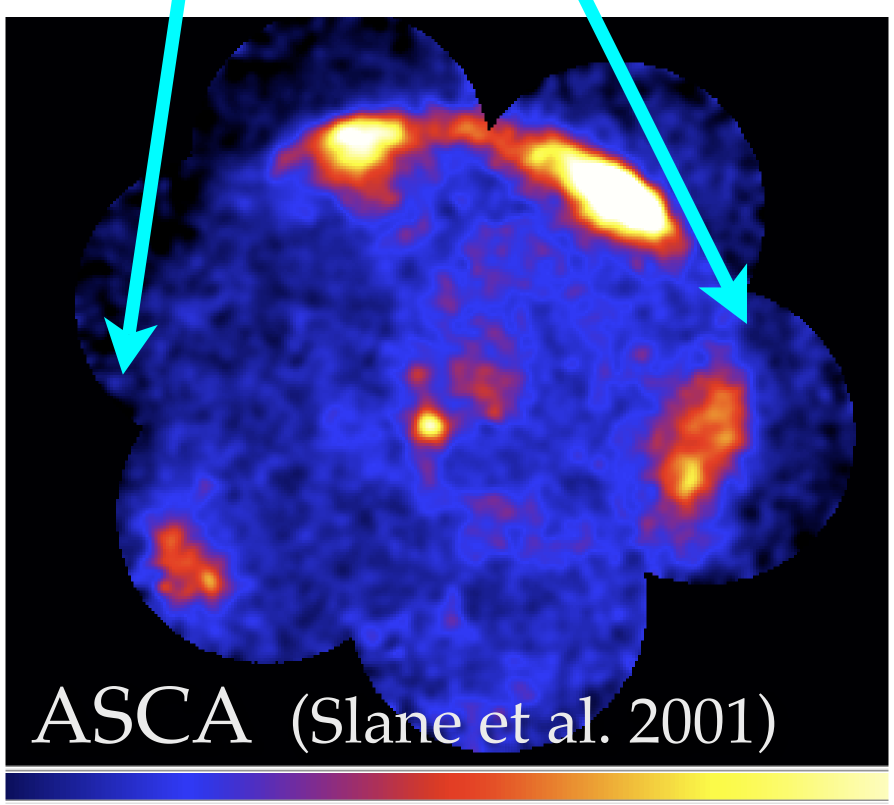
KeV excess in NW = Variable filaments

CR acceleration in this region would have become active in recent years. (Tanaka's talk)

Suzaku vs HESS (2) : Vela Jr *(Preliminary)*

Basic Characters





Distance: 0.2 ~ 1 kpc (uncertain)

Age: ? yr

X-ray = nonthermal dominated

(Slane et al. 2001) $\Gamma \simeq 2.7$

HESS imaging

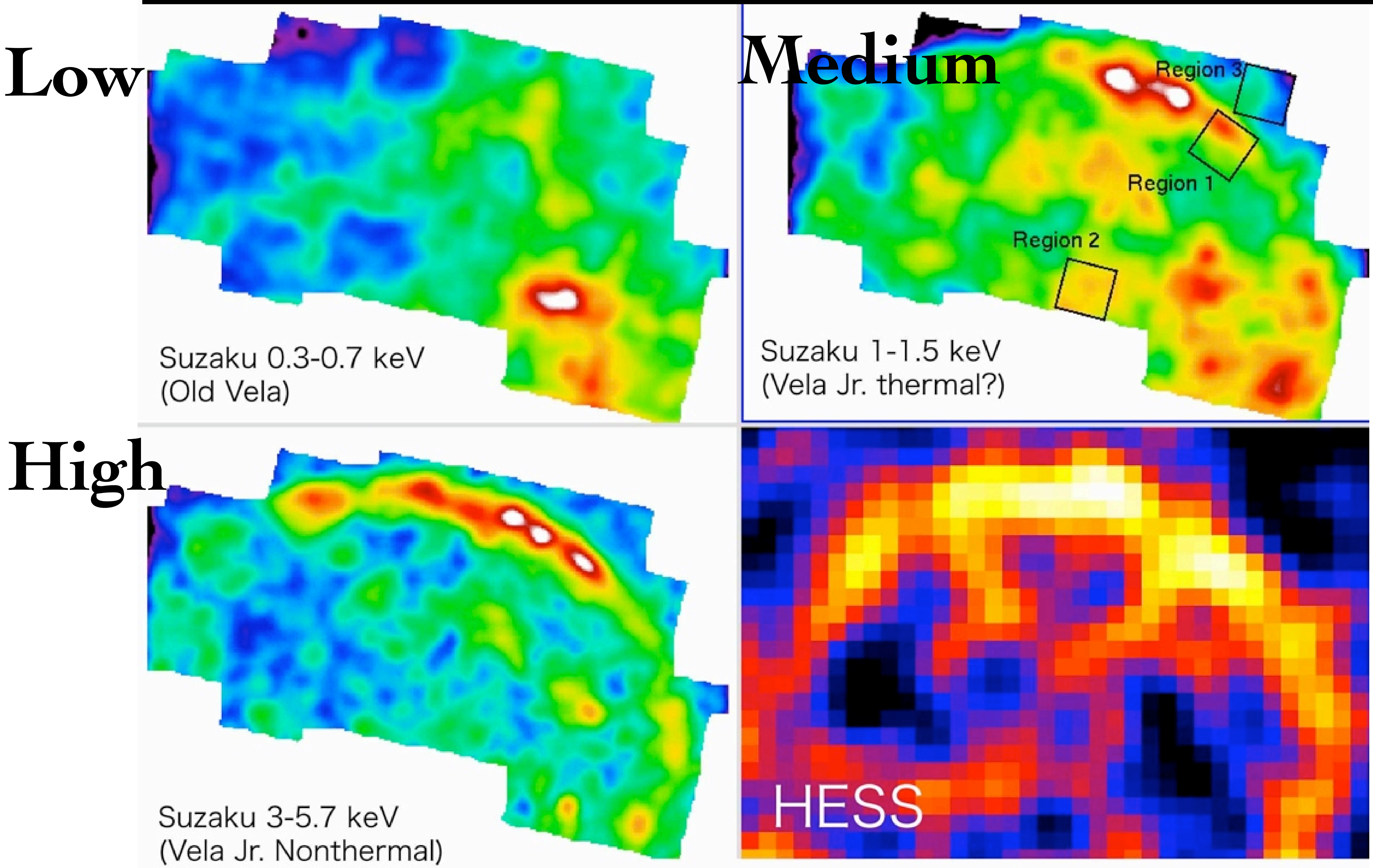
Largest TeV object in the sky

(Aharonian et al. 2005)

Suzaku vs HESS (2) : Vela Jr *(Preliminary)*

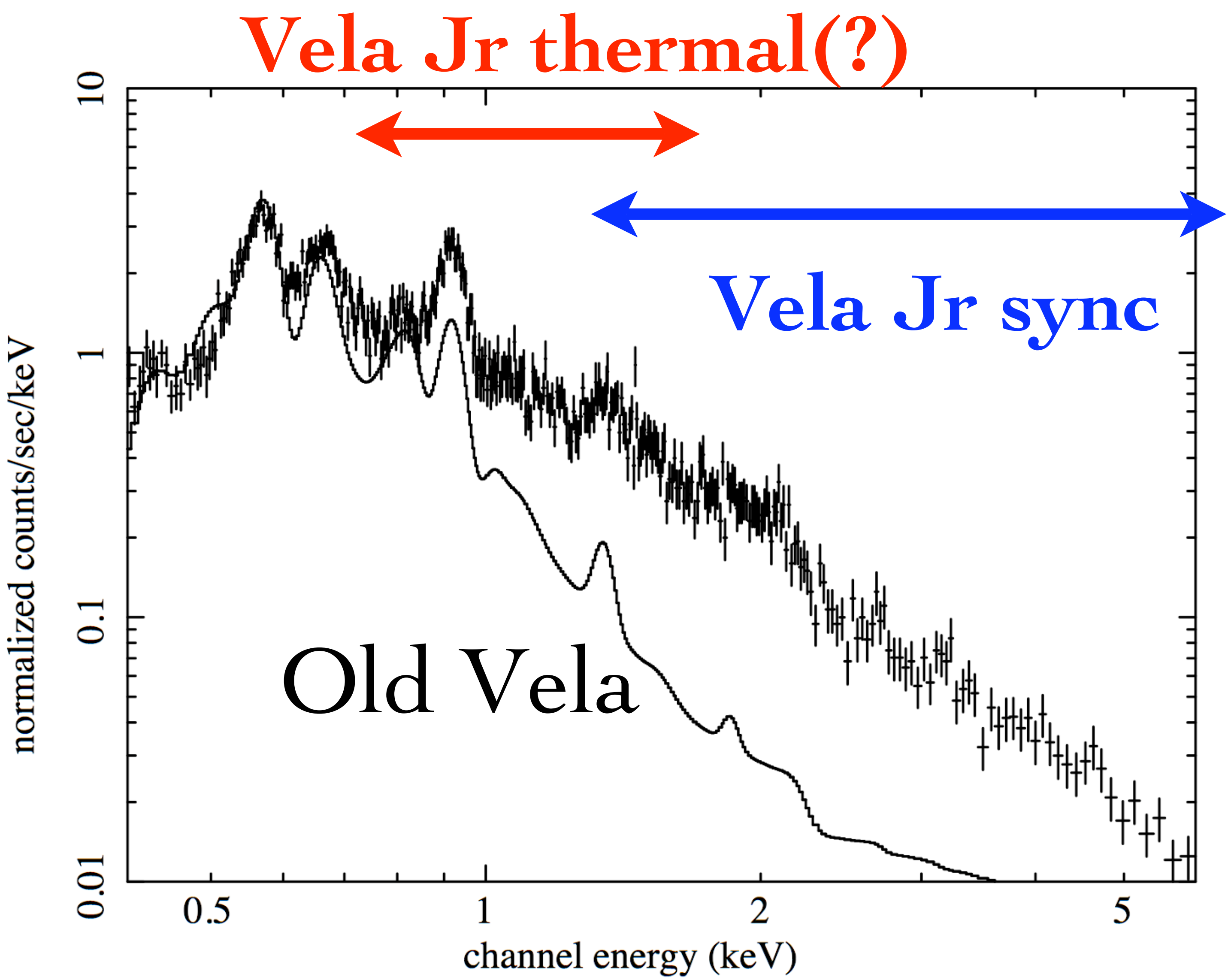
Suzaku Mapping Uncovered 3 Components!

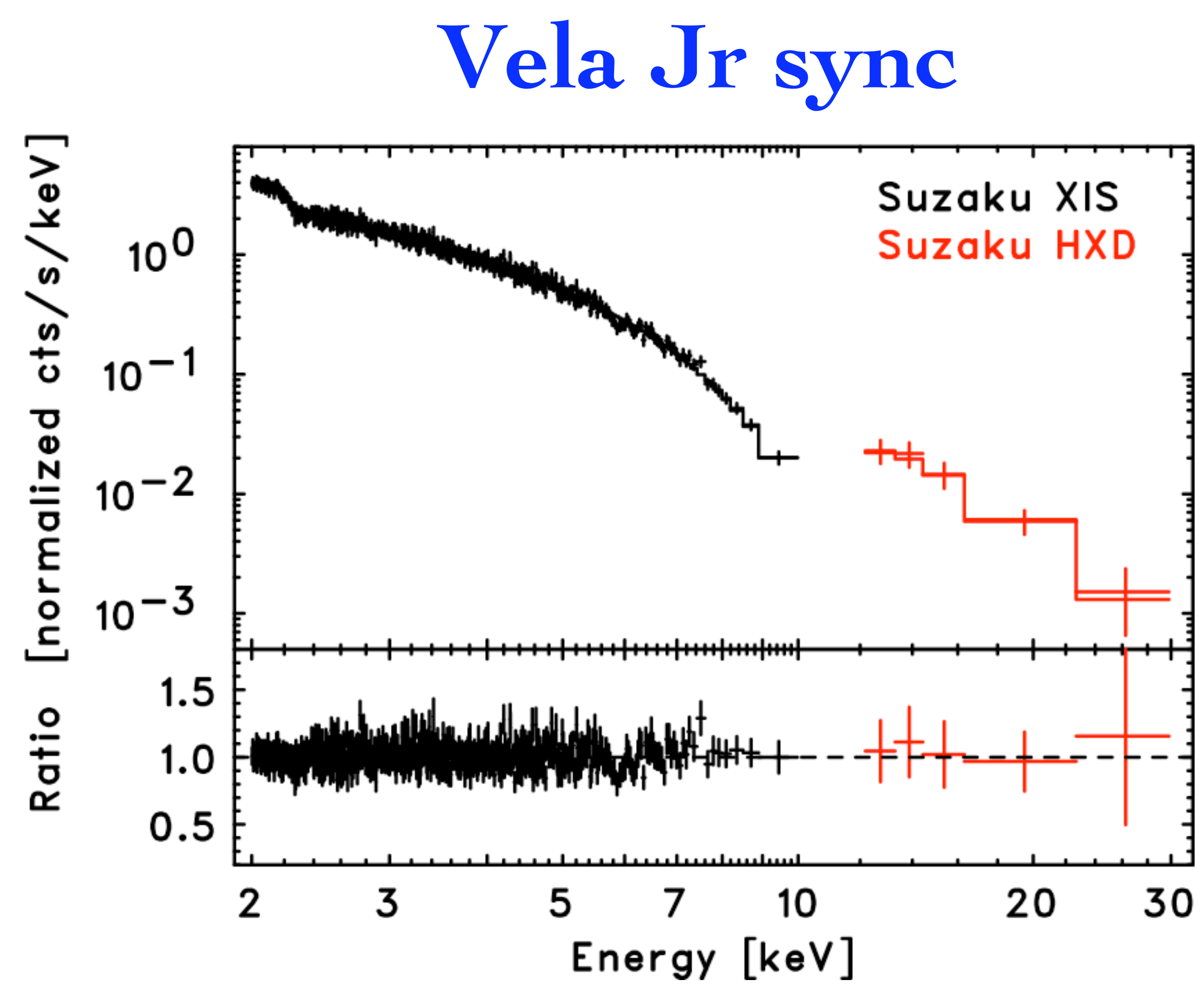
Northern hemisphere 10 ks x 18 pointings (AO 2)



Suzaku vs HESS (2) : Vela Jr *(Preliminary)*

Suzaku Mapping Uncovered 3 Components!





If confirmed, we will get a robust estimate of CR proton energetics based on Suzaku-HESS comparison:

$$W_{\rm p} \sim 3 \times 10^{50}\, n^{-1}\ {\rm ergs} \qquad \text{(for D = 1 kpc)}$$

End Remarks

6 things we uncovered in this year

- ***Presence of X-ray Variability***
  decaying = synchrotron cooling
  brightening = CR acceleration (and B-field amplification)
- ***Evidence for synchrotron origin of X-ray emission***
  synchrotron origin of X-ray emission is verified (especially in Cas A)
- ***Evidence for B-field amplification***
  B ~ 1 mG amplified by CR themselves (in forward and reverse shocks)
- ***Evidence for Hadronic origin of TeV gamma-rays***
  TeV gamma-rays are hadronic (especially in RX J1713.7-3946)
- ***PeV acceleration***
  CRs can be accelerated to PeV energies, given B~mG and gyro-factor~1.
- ***Presence of Thermal X-rays in Vela Jr (preliminary)***
  We will get a robust estimate of proton contents.

Summary

- ***Variability***
  decaying = synchrotron cooling
  brightening = CR acceleration (and B-field amplification)
- ***Synchrotron origin***
  synchrotron origin of X-ray emission is verified (especially in Cas A)
- ***Witnessing CR acceleration***
  "real time" observations of CR acceleration processes
- ***B-field amplification***
  B ~ 1 mG amplified by CR themselves (in forward and reverse shocks)
- ***Hadronic TeV gamma-rays***
  TeV gamma-rays are hadronic (especially in RX J1713.7-3946)
- ***PeV acceleration***
  CRs can be accelerated to PeV energies, given B~mG and gyro-factor~1.