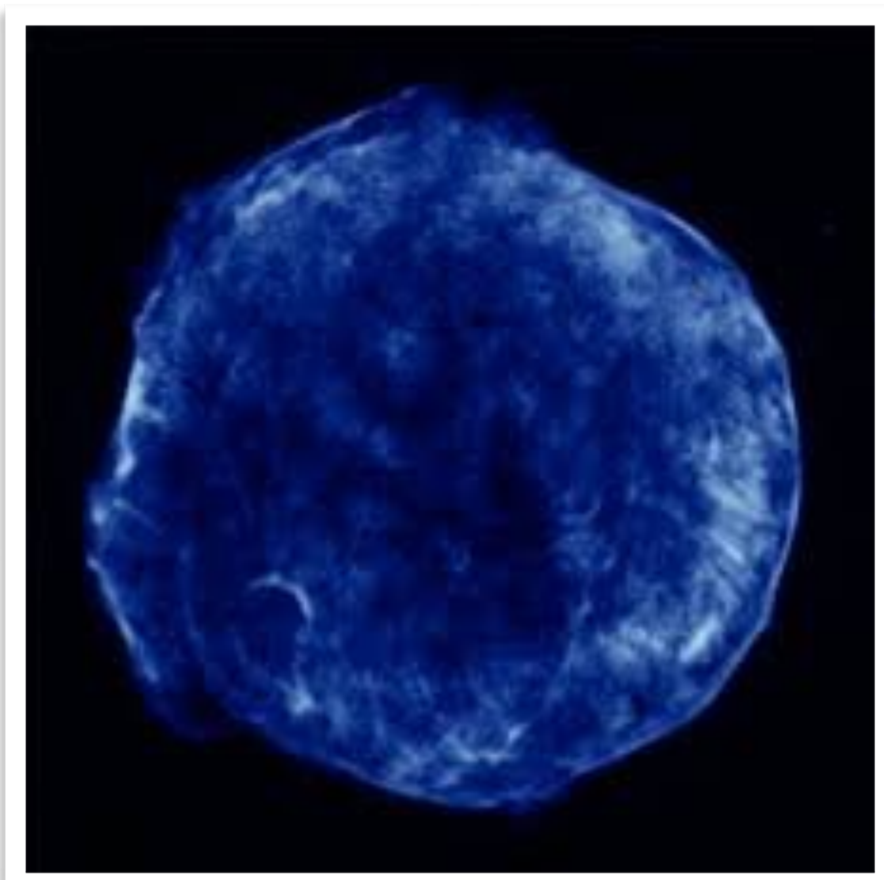
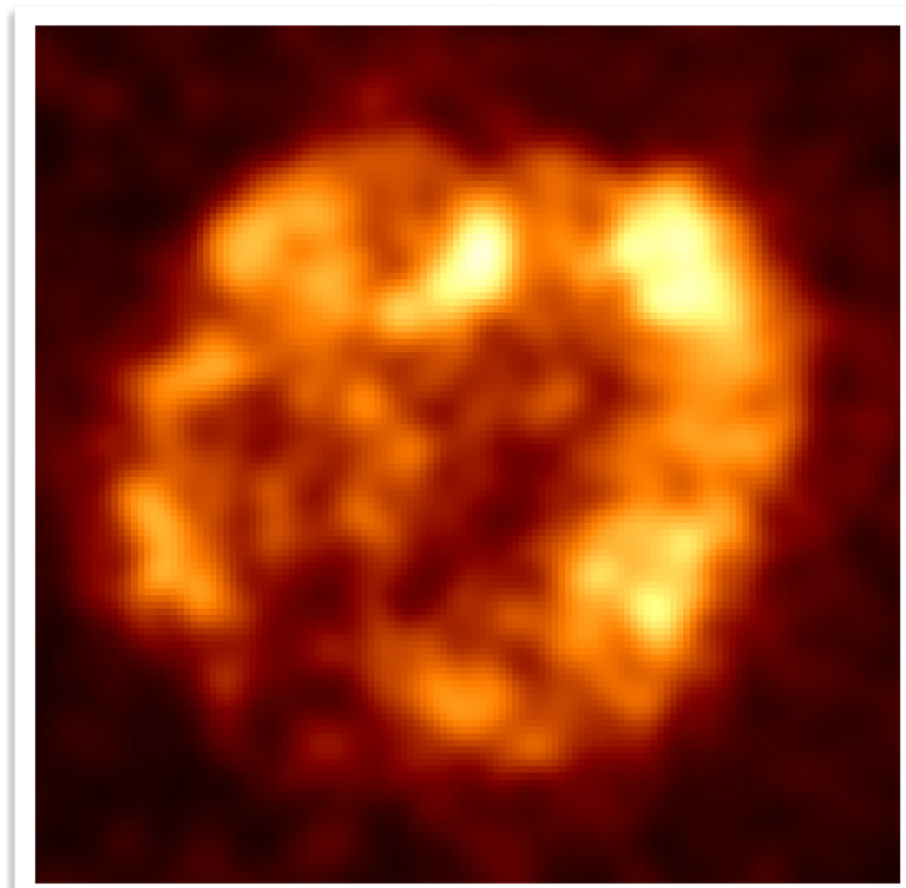
# Recent Results on Supernova Remnants at Highest Energies





**Takaaki Tanaka**

**Konan University**

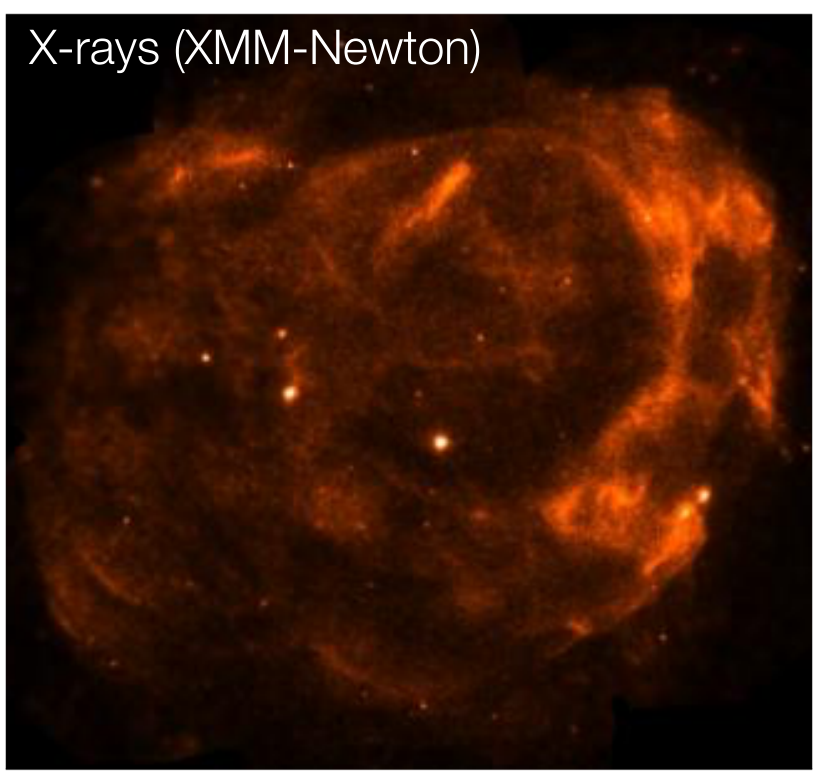
KONAN

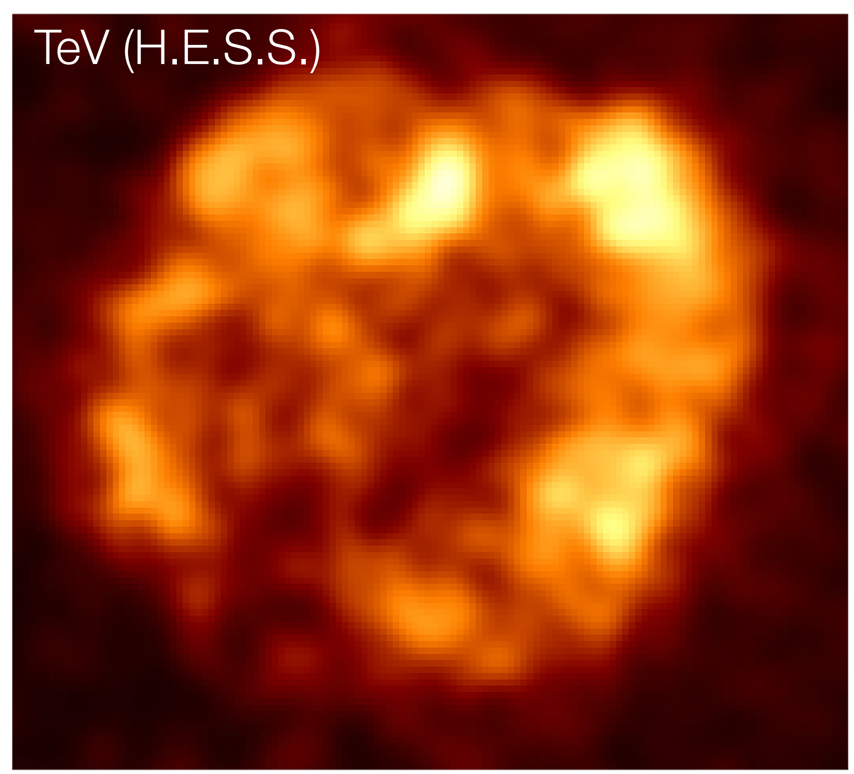
The 7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma 2022) @ Barcelona

# Status of the Field

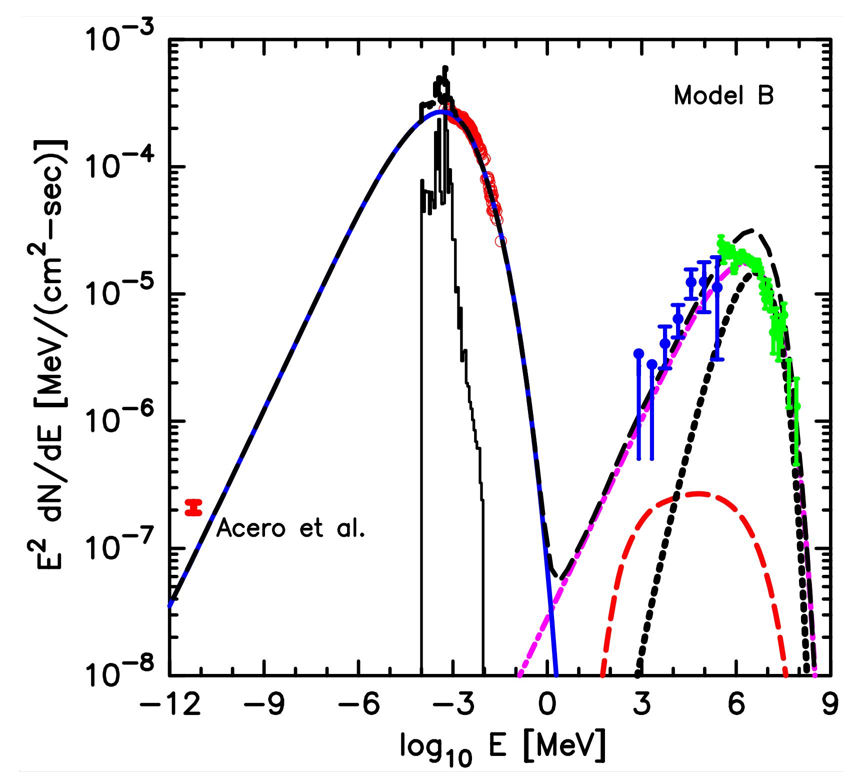
- Detection of synchrotron X-rays and TeV γ-rays from supernova remnants (SNRs)
  → Evidence for particle acceleration up to ~ TeV through the **diffusive shock acceleration (DSA)** mechanism
- Multi-wavelength (radio, X, GeV–TeV γ, …) morphological and spectral information
  → Discussion on emission mechanisms (e.g., hadronic v.s. leptonic) and particle acceleration to the extent that was not possible ~ 20 years ago

**Example of RX J1713.7–3946**



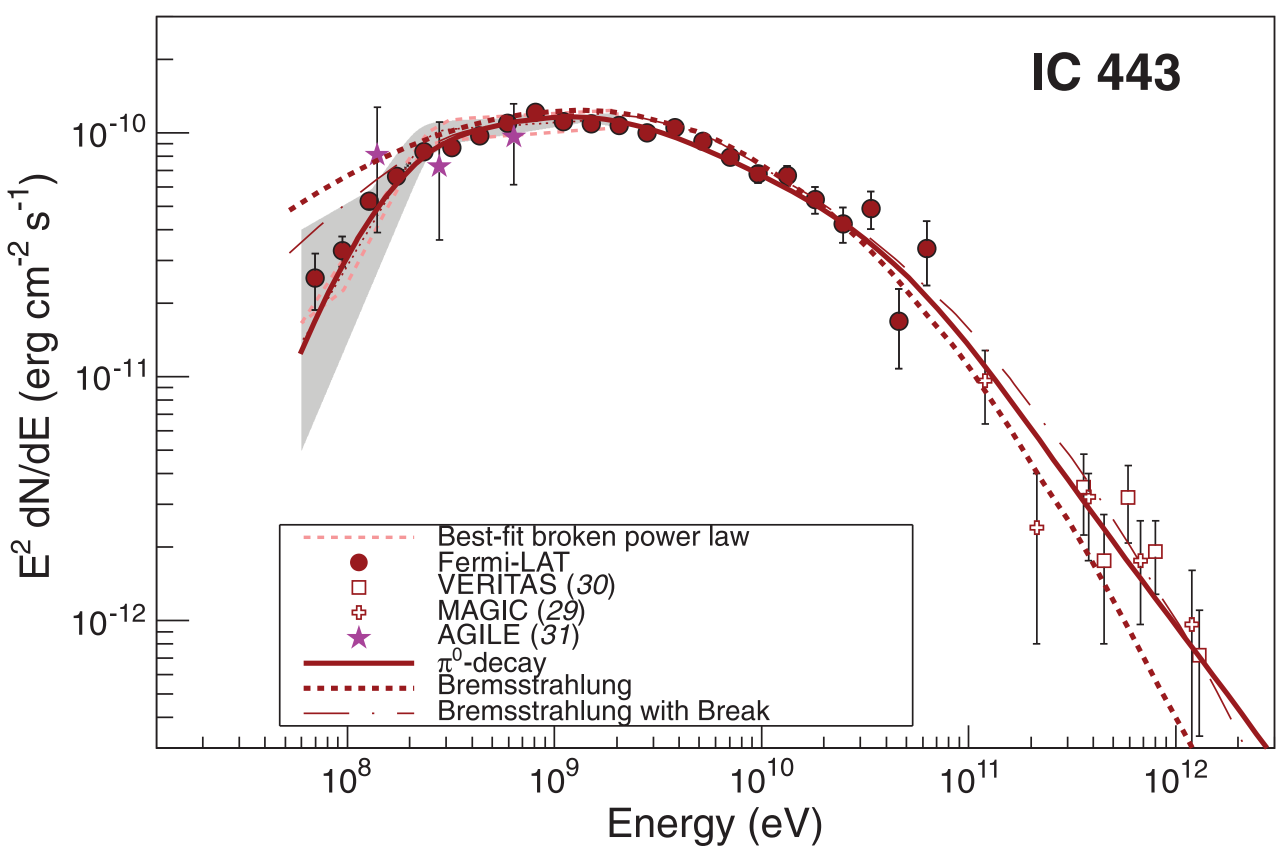

H.E.S.S. Collaboration (2018)

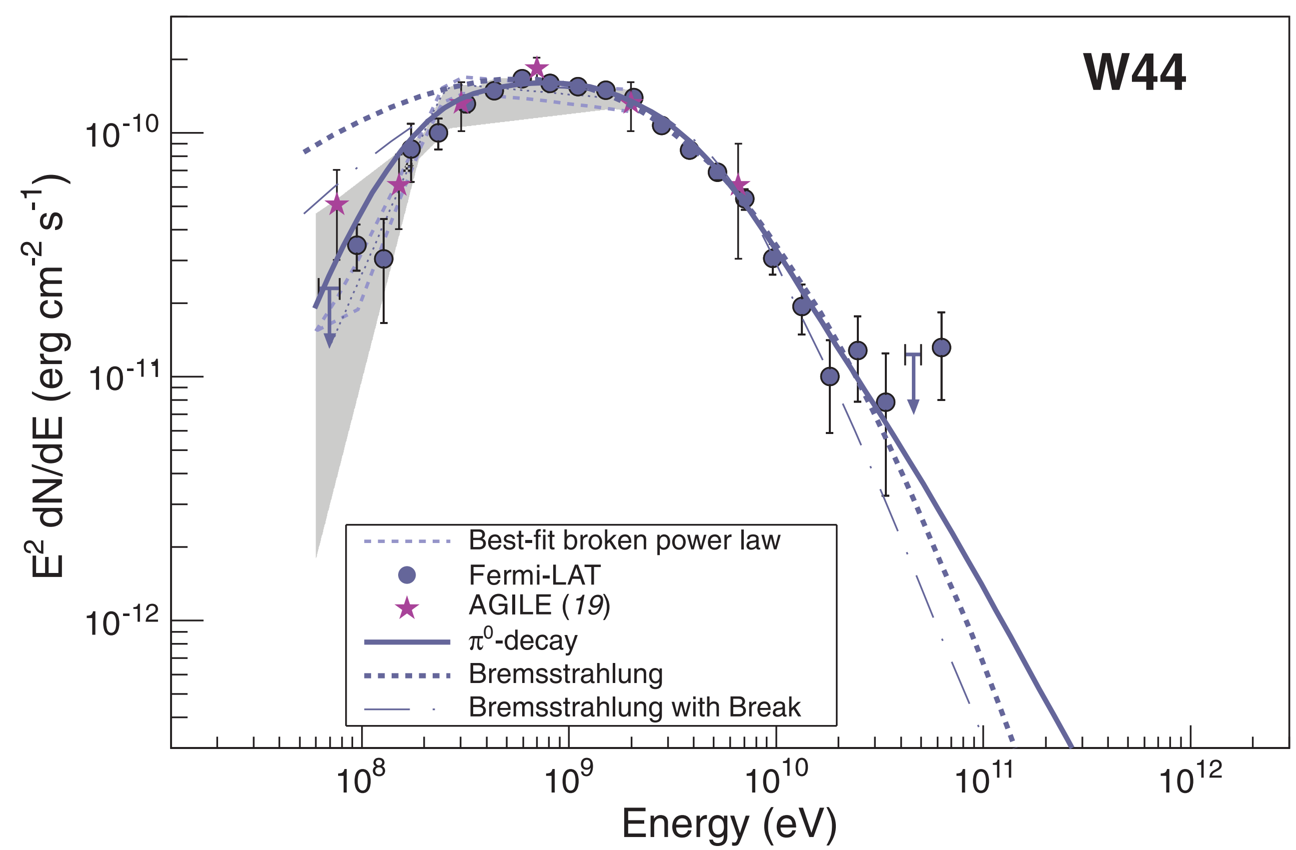



Ellison+ (2012)

# SNRs = PeVatrons?

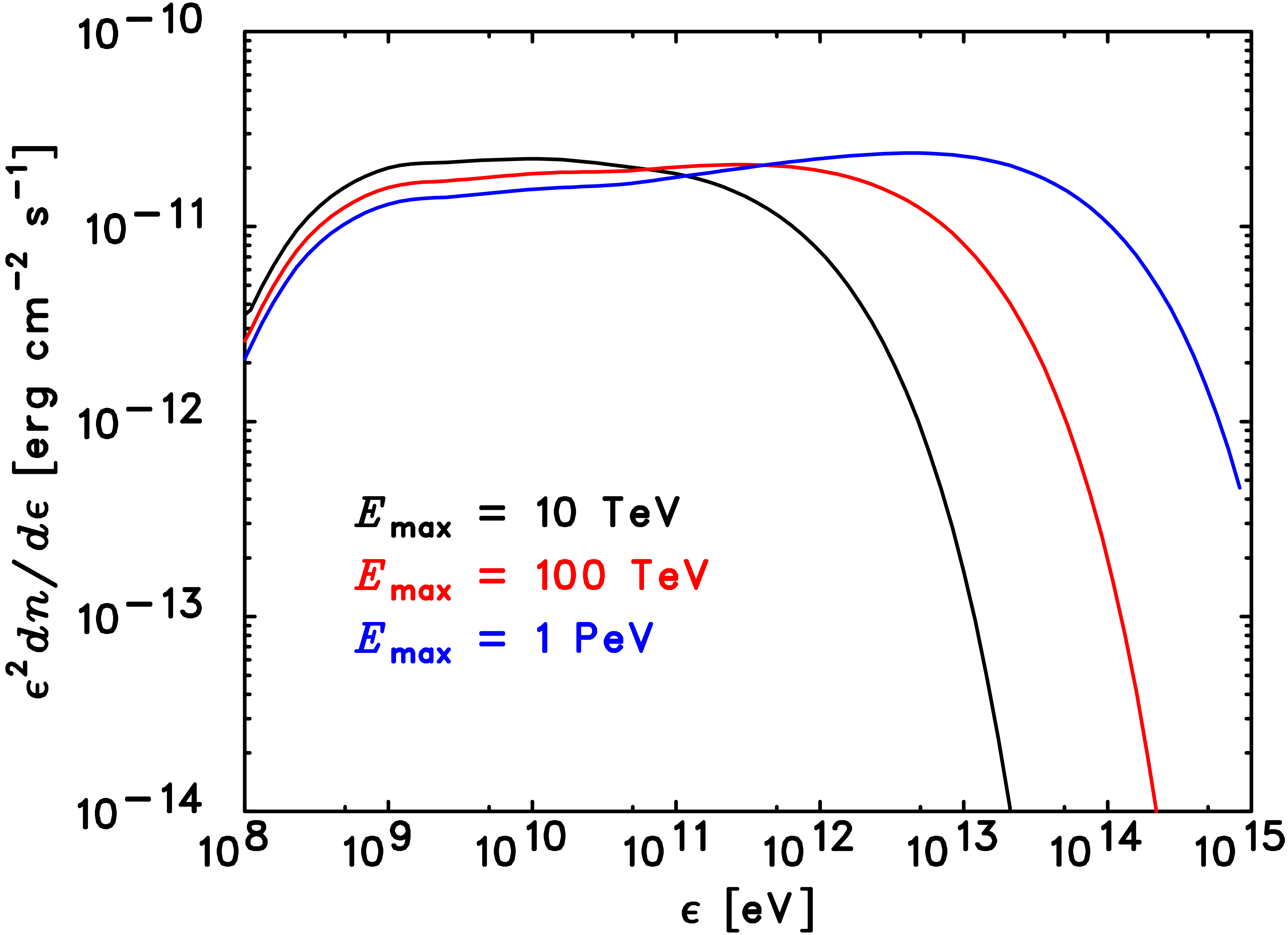
- If SNRs are Galactic cosmic-ray origins, they should accelerate **protons up to the knee at ~ PeV**
- Spectra of only a handful of SNRs (e.g., IC 443, W44, W51C, …) found to agree well with $\pi^0$-decay emission model
- Evidence for proton acceleration provided for those cases
- However, their proton spectra seem to have a break or a cutoff far below ~ PeV
- **Are SNRs really PeVatron?**



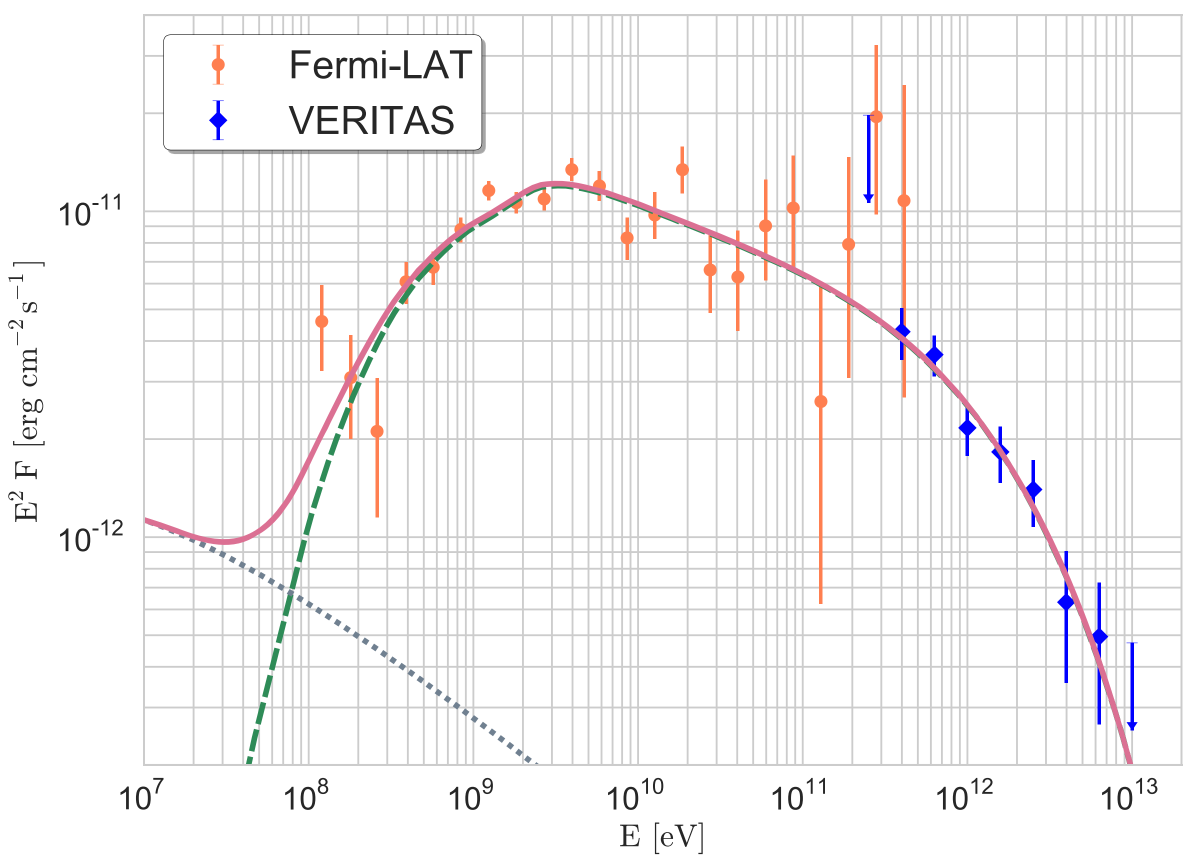

Ackermann+ (including TT as a corresponding author) (2013)

# PeVatron Spectra



# Spectra of Young SNRs

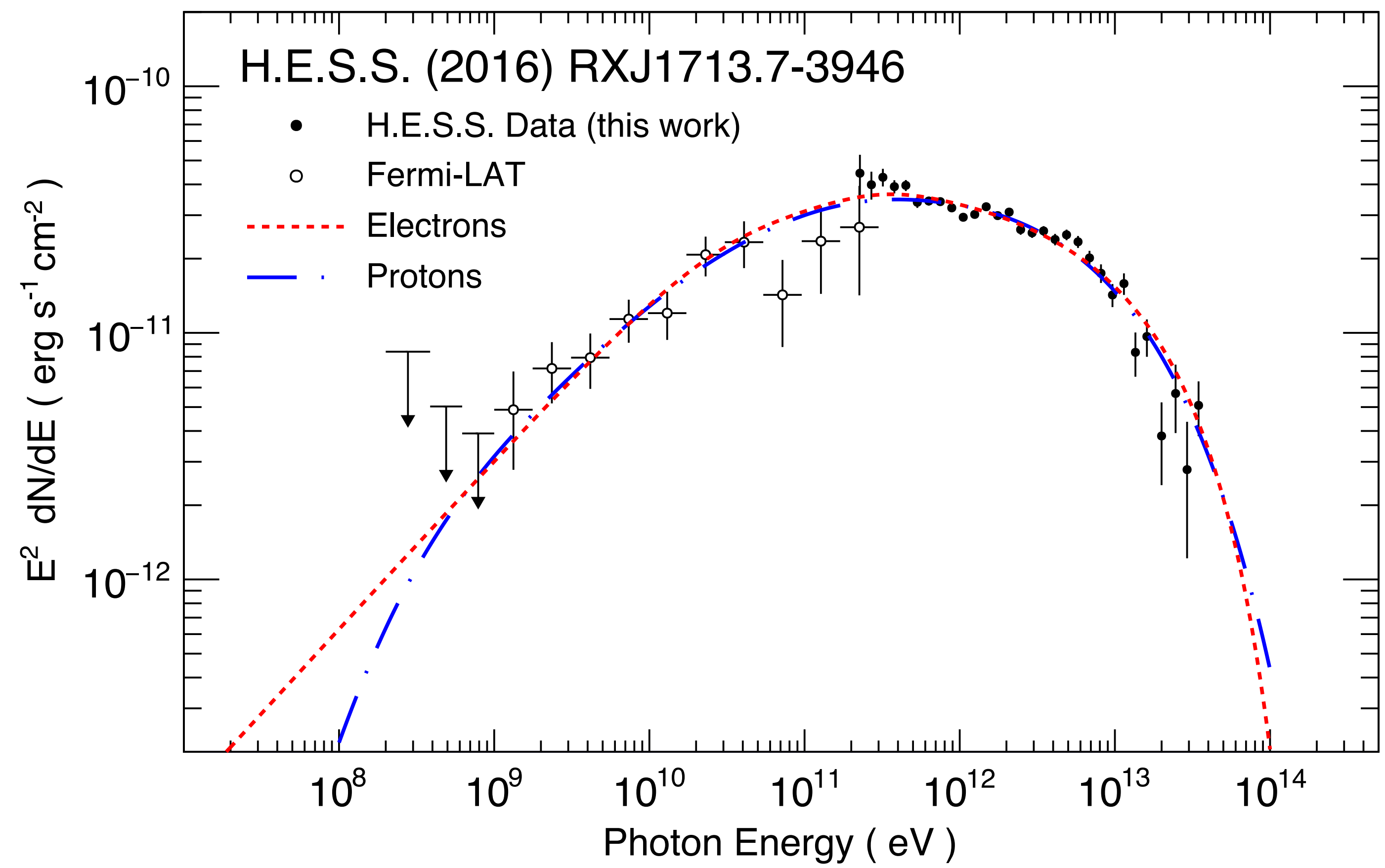
**Cassiopeia A**




Abeysekara+ (2020)

$E_{max}$ = 21 TeV

**RX J1713.7–3946**



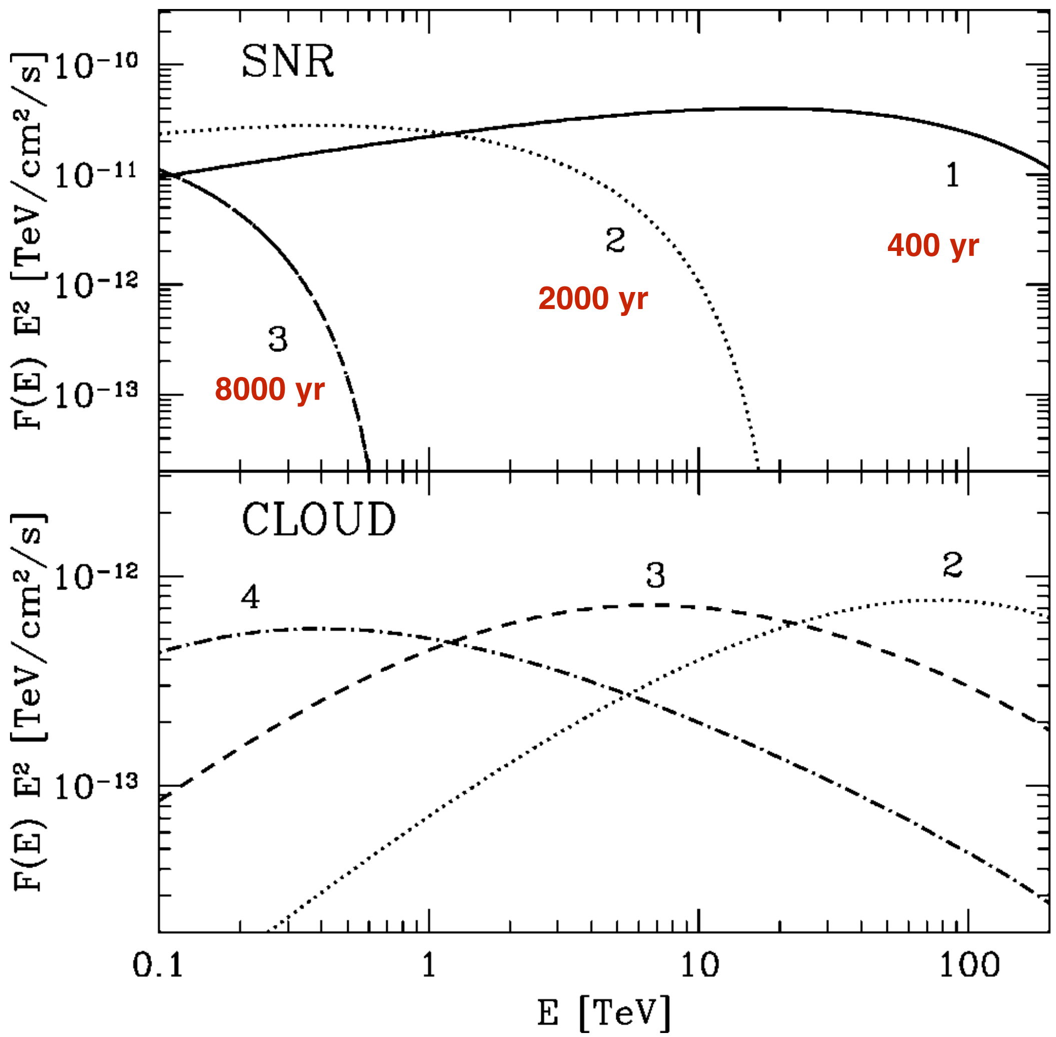

H.E.S.S. Collaboration (2018)

$E_{max}$ = 93 TeV

# Why No PeVatrons Observed?

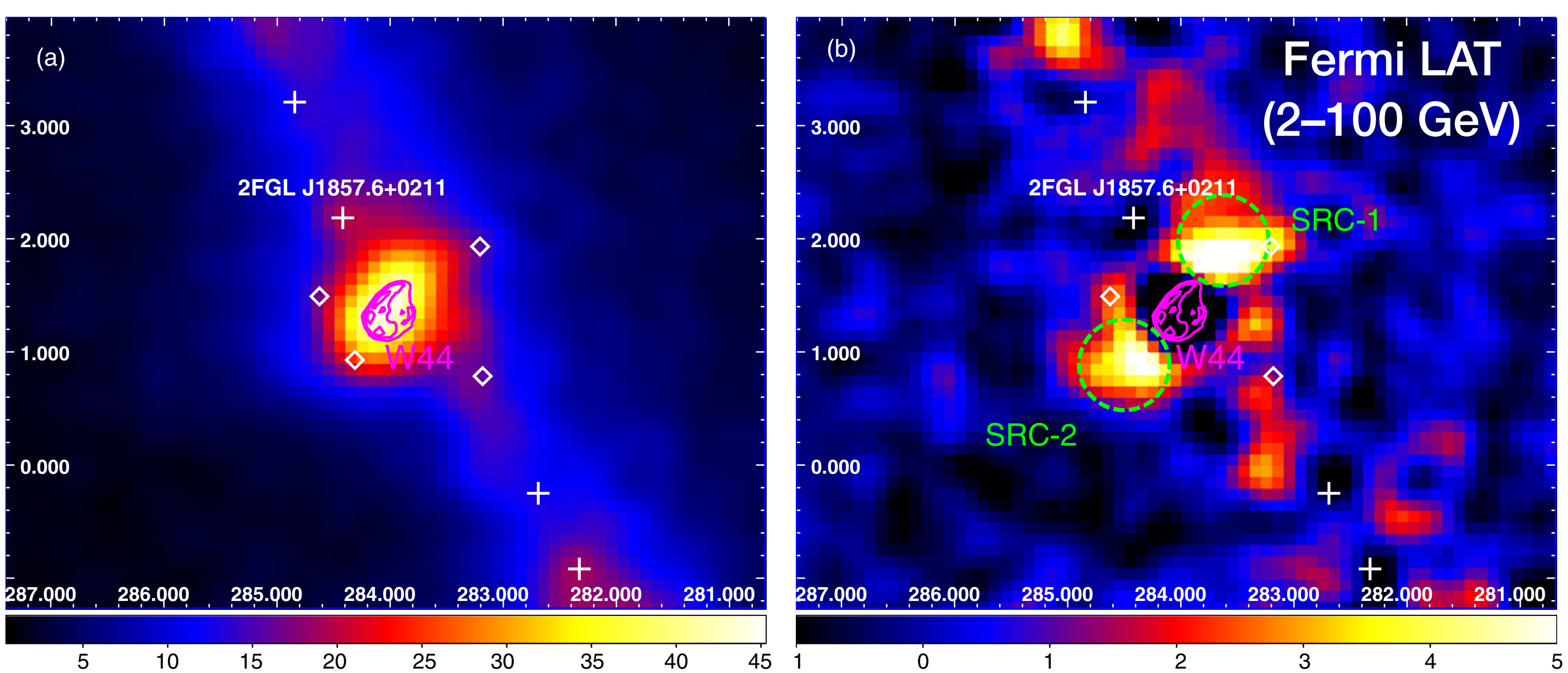
- SNRs are PeVatrons only for a short period of time during their lives?
- If so, we expect hard hadronic emission from nearby dense gas clouds illuminated by protons accelerated in SNR shocks in the past
- For direct evidence for PeVatrons, sub-PeV observations of both SNRs and nearby clouds are important

Gabici & Aharonian (2007)




W44

Uchiyama, TT+ (2012)



# Air Shower Telescopes

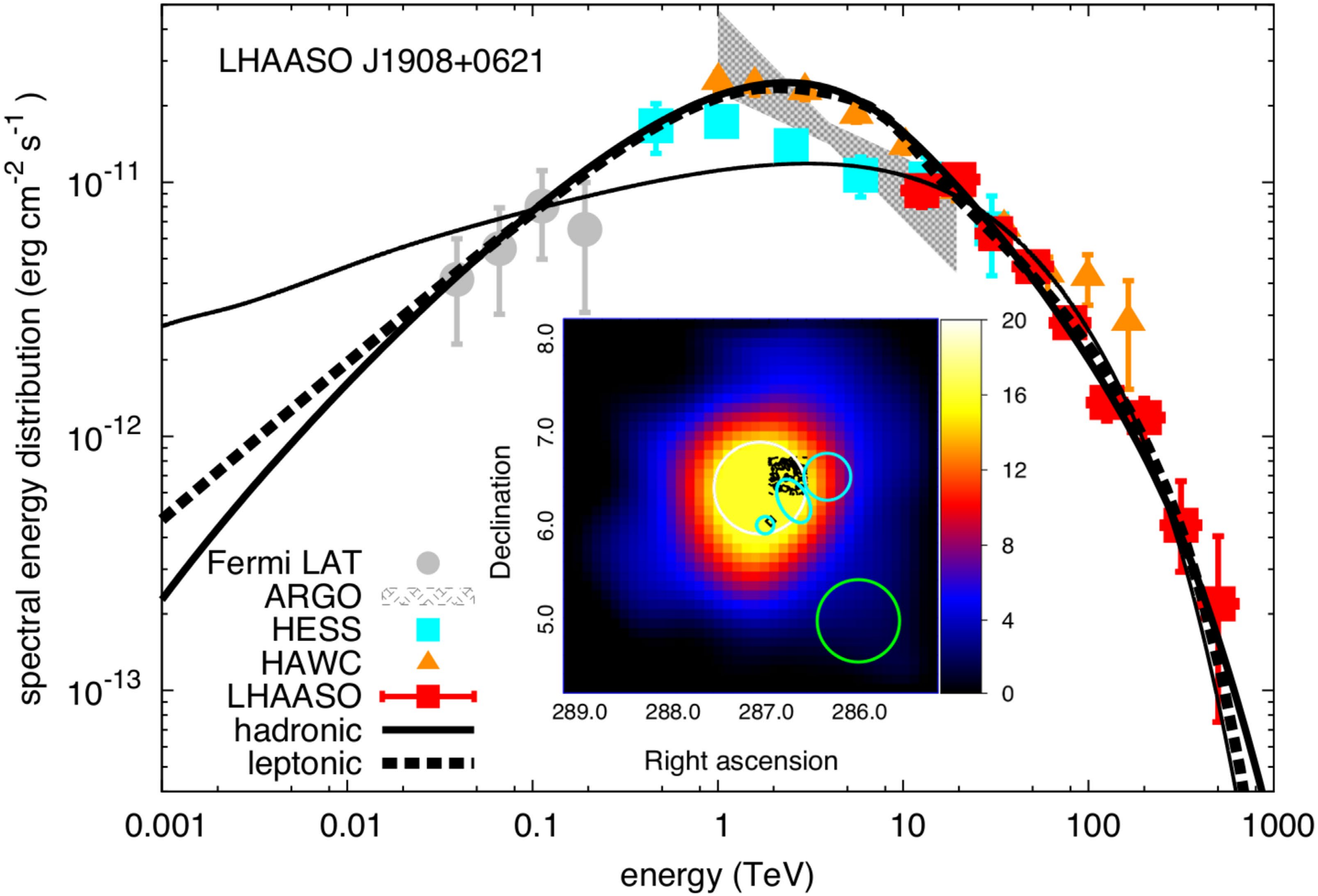
LHAASO

Tibet ASγ

HAWC

# LHAASO J1908+0621

Cao+ (2021)

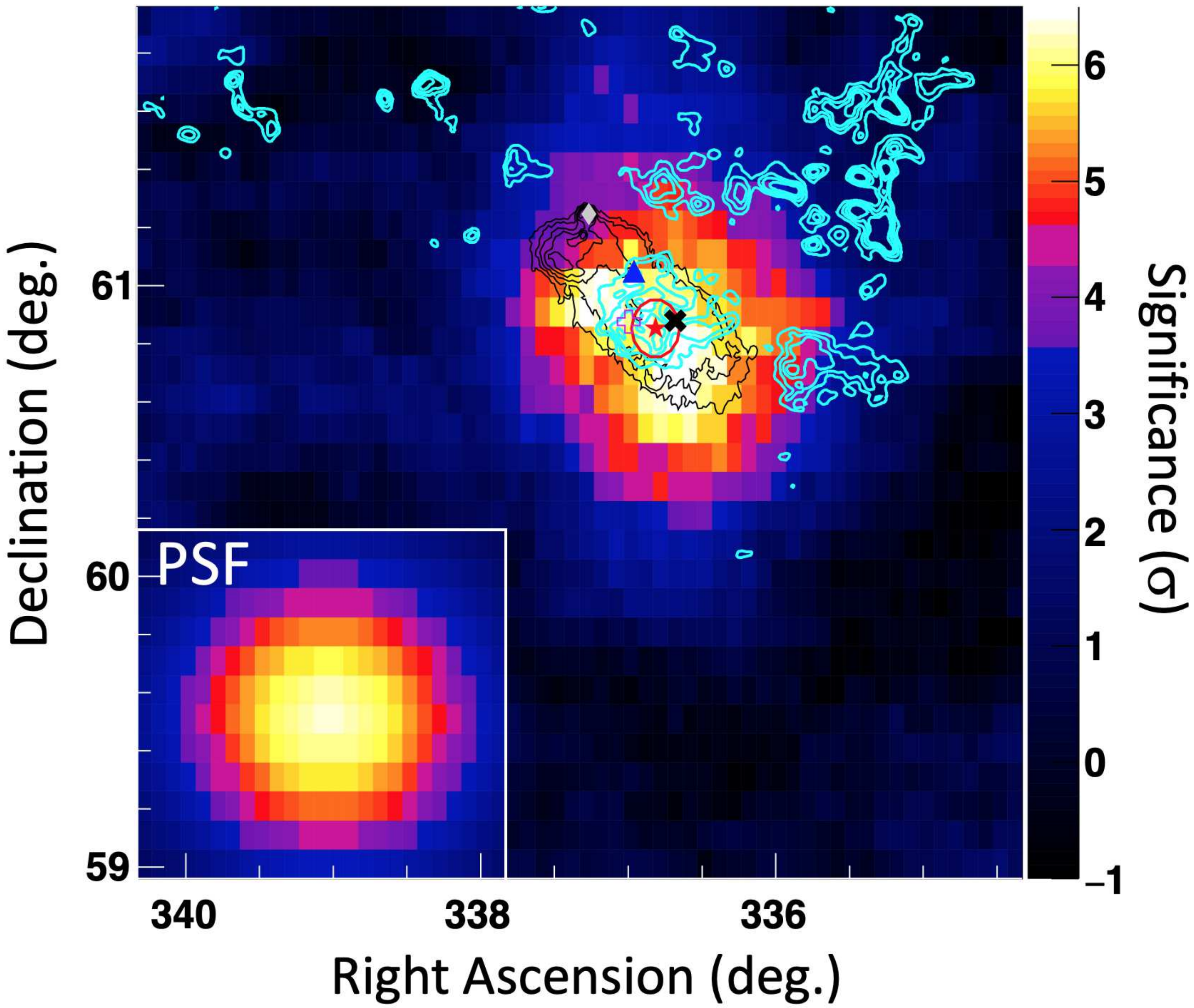


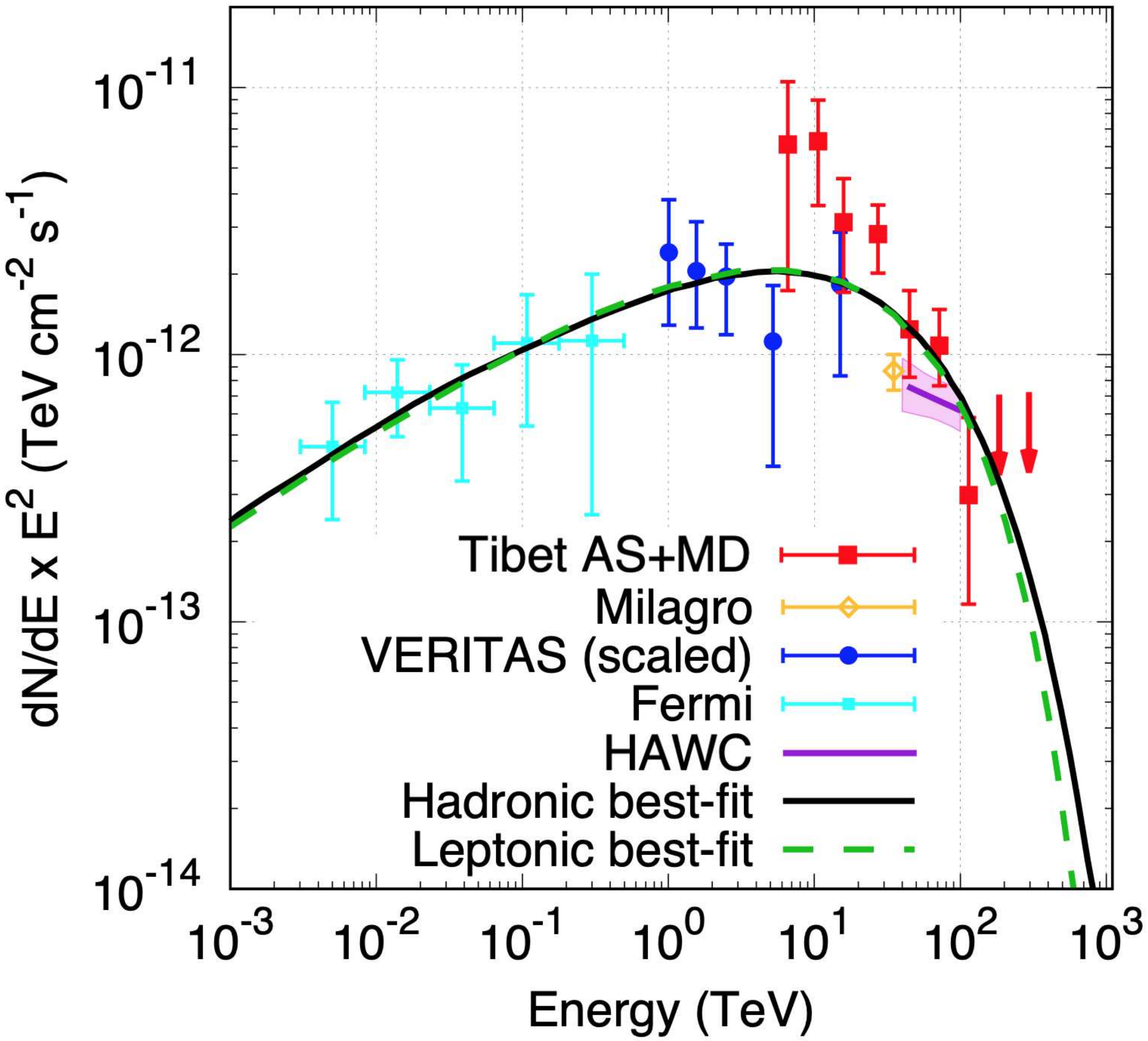

- Detection of gamma rays up to 440 TeV by LHAASO
- Associated with SNR G40.5–0.5?
- Emission from dense gas illuminated by protons escaped from the SNR?

# G106.3+2.7

## Results from Tibet ASγ

Amenomori+ (2021)

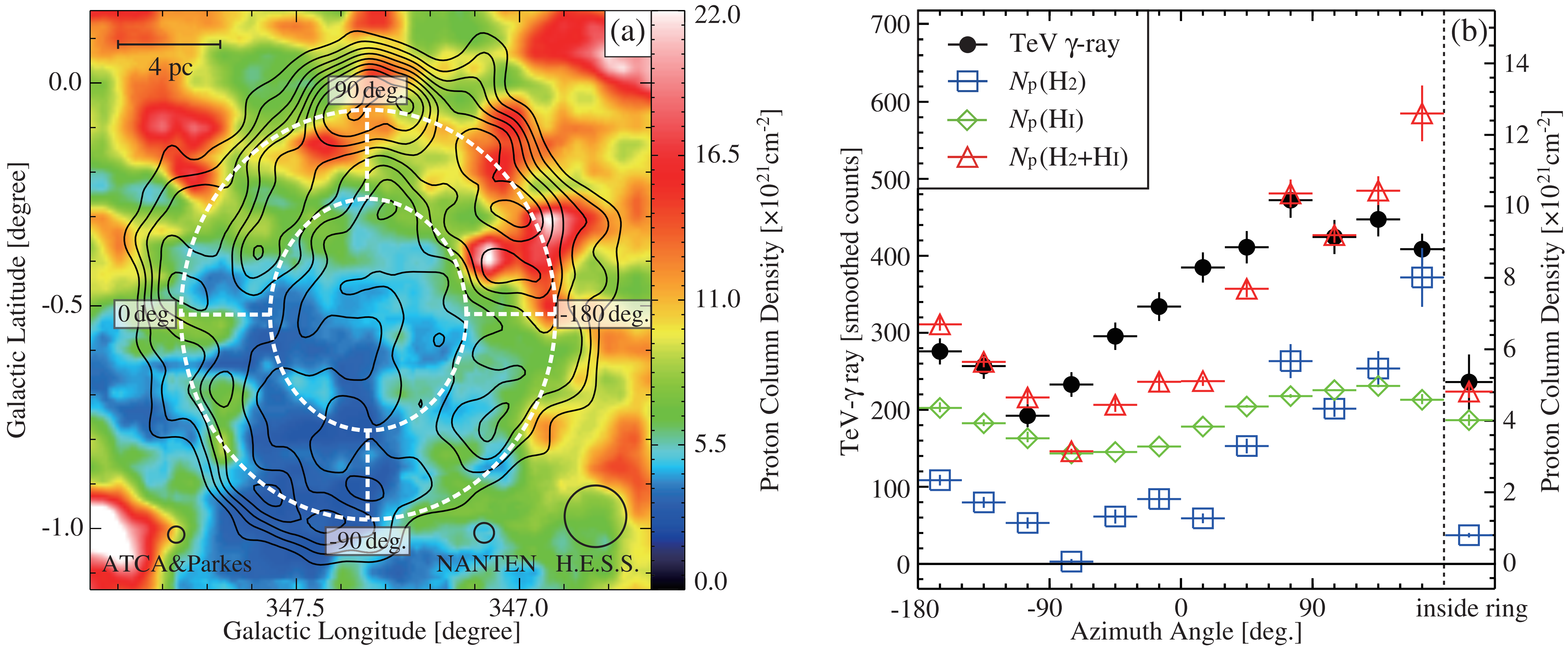



- Detection of gamma rays up to ~ 100 TeV
- Hadronic model favored
- Recent MAGIC result indicates sub-PeV emission is coincident with the southern part (“tail” region) of the SNR where molecular gas is present (see T. Saito’s talk on Monday)

# γ-ISM Comparison

- ISM gas serves as targets for $\pi^0$ production through pp interactions
- If hadronic model is the case, γ-ray emission and ISM gas are expected to show strong correlation
- Such correlation indeed found in RX J1713
- How to reconcile with the hard GeV γ-ray spectrum?




Fukui+ (2012)

# Hard π⁰-Decay Spectrum

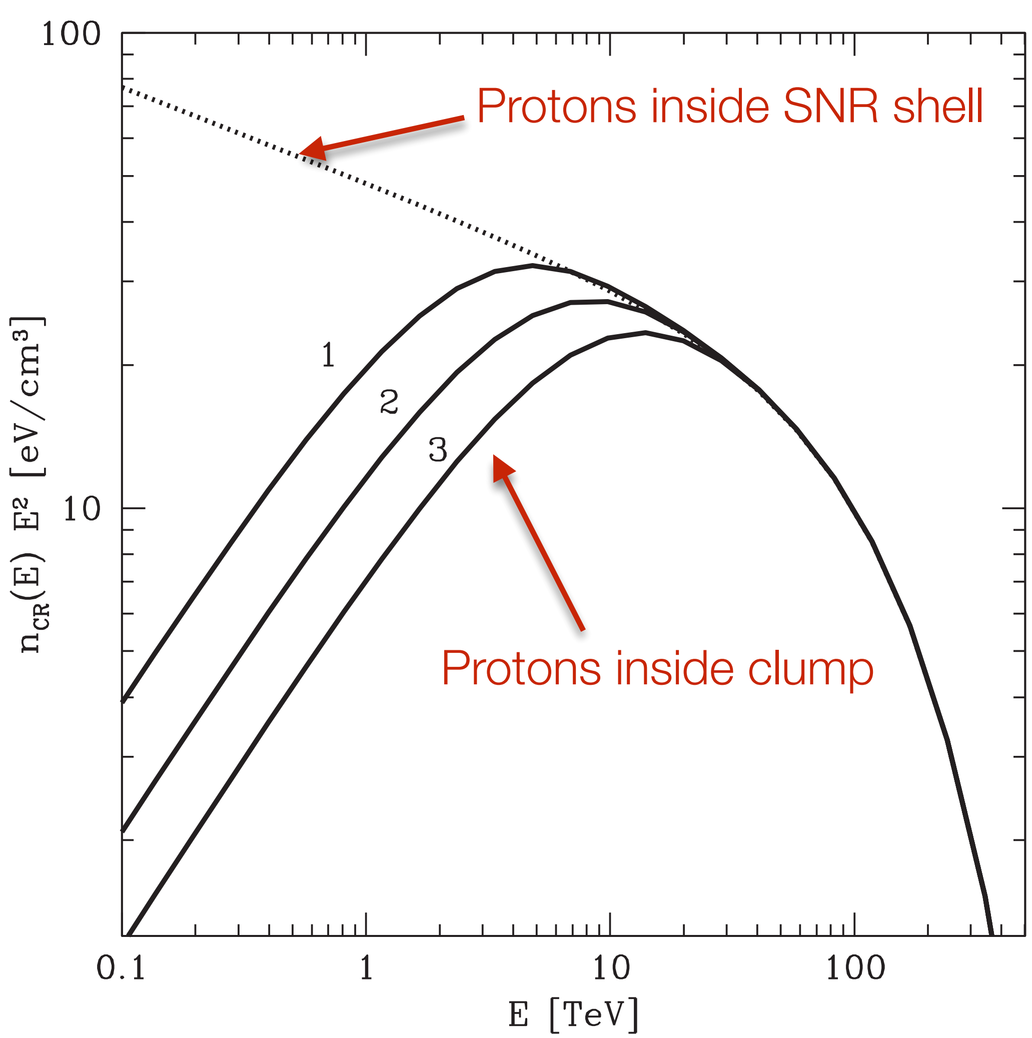
**Clumpy target gas can make π⁰-decay spectrum harder (Inoue+ 2012)**

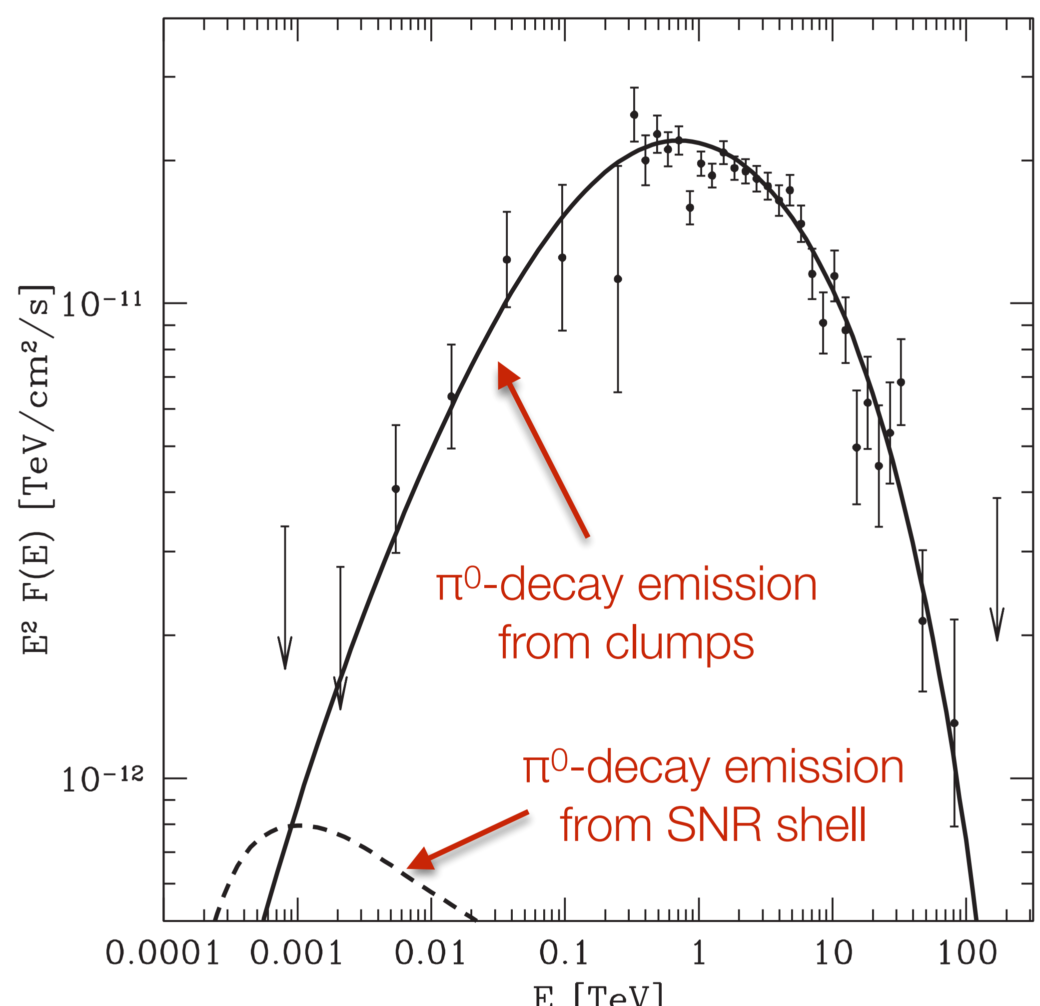
Penetration depth of accelerated protons into a cloud

$$l_{\rm pd} = 0.1\,\eta^{1/2}\left(\frac{E}{10\ {\rm TeV}}\right)^{1/2}\left(\frac{B}{100\ \mu{\rm G}}\right)^{-1/2}\left(\frac{t_{\rm age}}{10^3\ {\rm yr}}\right)^{1/2}\ {\rm pc}$$

$$N_\gamma(E) \propto l_{\rm pd}(E)\,E^{-s} \propto E^{-s+1/2}$$

Therefore, Γ = 1.5 is expected if protons have a “standard” spectral index of $s$ = 2.0

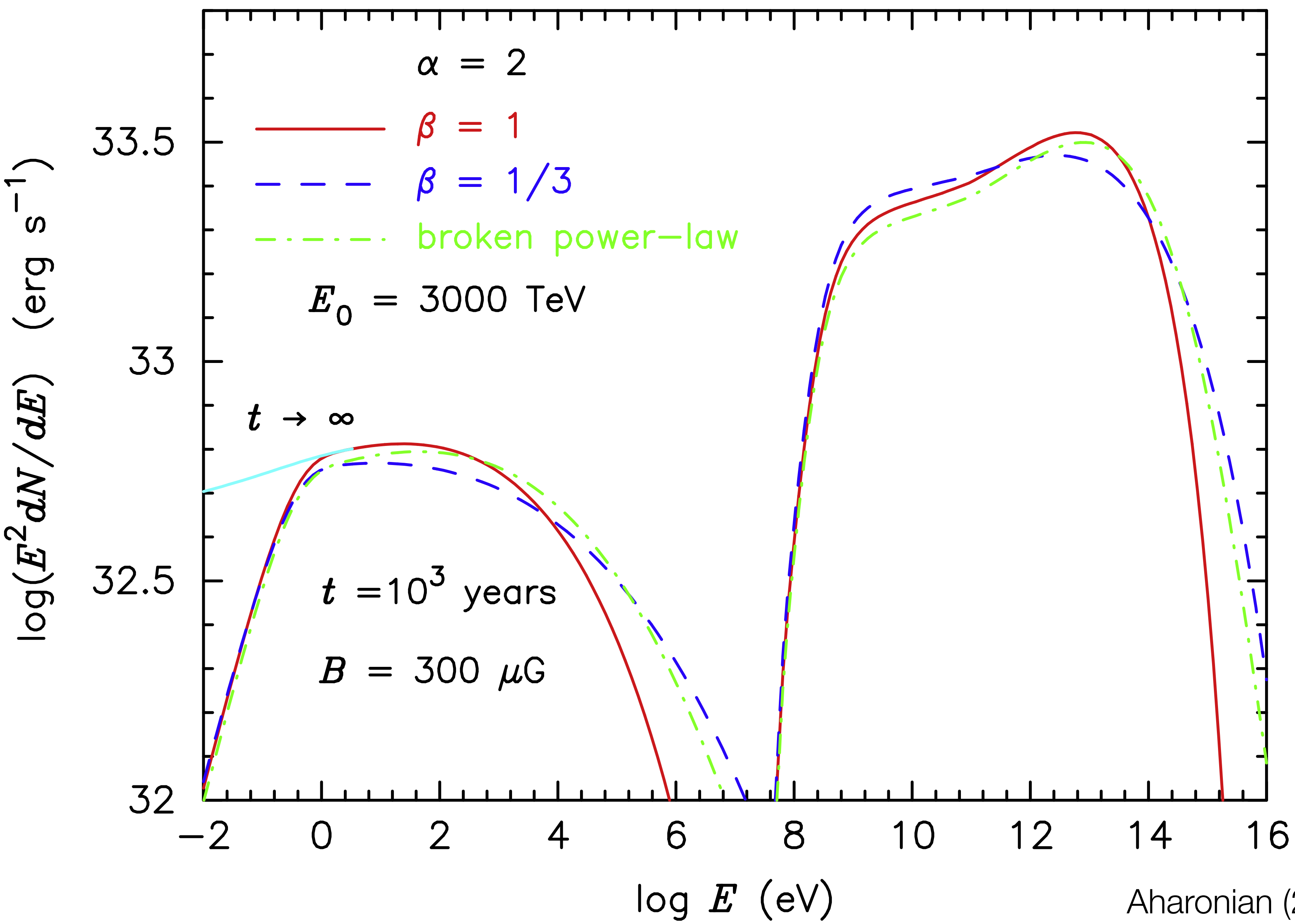



Gabici & Aharonian (2014)

# Secondary Synchrotron

$$p\,p \rightarrow \pi^+\,X \rightarrow \mu^+\,\nu_\mu\,X \rightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu\,X$$
$$p\,p \rightarrow \pi^-\,X \rightarrow \mu^-\,\bar{\nu}_\mu\,X \rightarrow e^-\,\bar{\nu}_e\,\nu_\mu\,\bar{\nu}_\mu\,X$$




Aharonian (2013)

**Future sensitive hard X-ray observations (e.g., FORCE; HEX-P) also can give smoking-gun signatures of PeVatrons**

# Indirect Evidence for PeVatrons

Age of an SNR: $t_{\rm age} = R/v_s$

Acceleration timescale: $t_{\rm acc} = \frac{20}{3}\frac{cr_g}{v_s^2}\eta$

Equating the two quantities ($t_{\rm acc} = t_{\rm age}$) gives a simple estimate for maximum energy of accelerated particles as

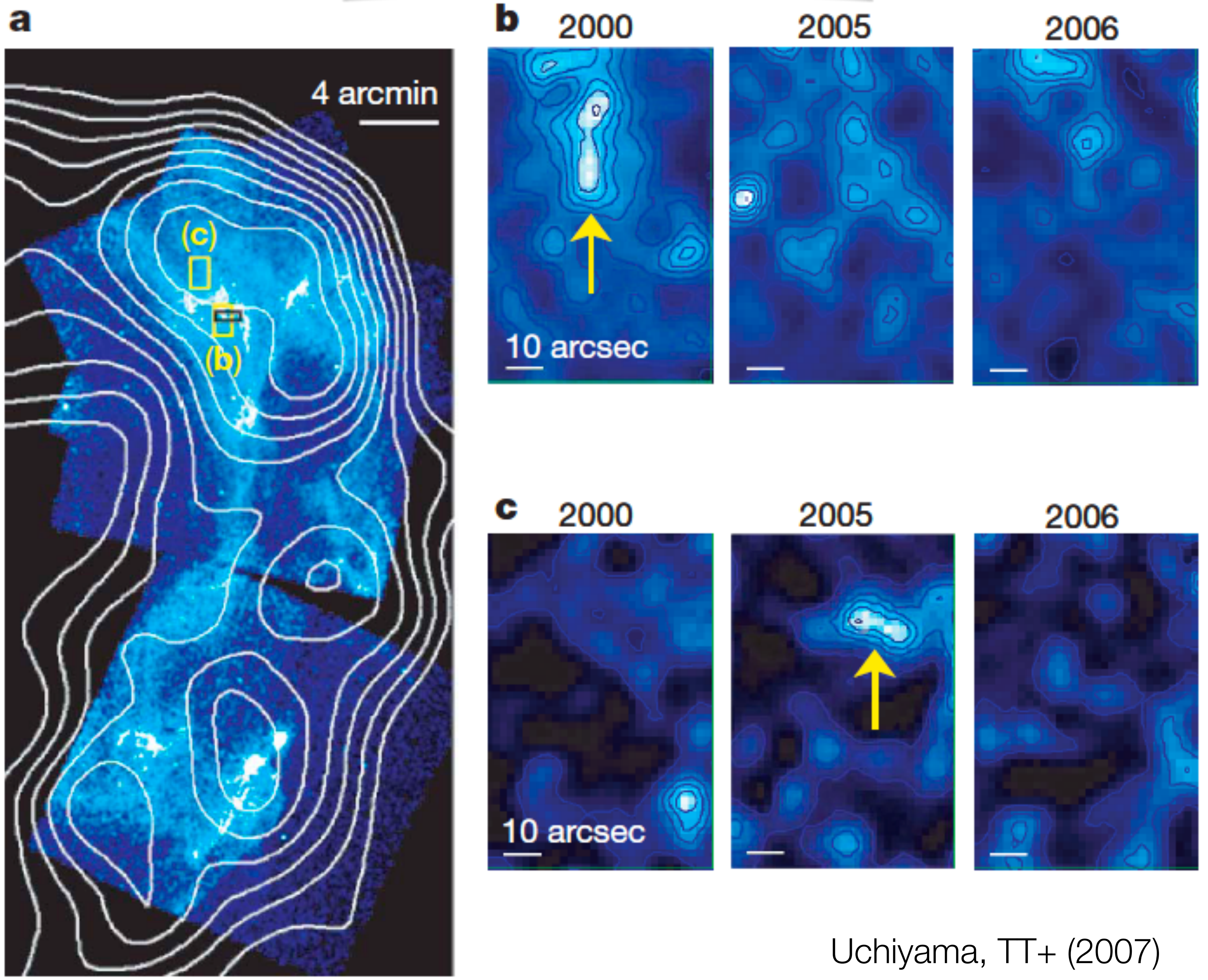
$$E_{\rm max} = \frac{3}{20}\frac{1}{\eta}\frac{v_s}{c}ZeBR$$

$$\approx 460\,\frac{Z}{\eta}\left(\frac{v_s}{10^4\ {\rm km\ s^{-1}}}\right)\left(\frac{B}{10\ \mu{\rm G}}\right)\left(\frac{R}{10\ {\rm pc}}\right)\ {\rm TeV}$$

- Magnetic field amplification essential for particles accelerated in SNRs to reach PeV
- If magnetic field is significantly amplified, SNRs are in principle able to accelerate particles up to ~ PeV

# Synchrotron X-ray Variability

**RX J1713.7–3946**




Uchiyama, TT+ (2007)

$$t_{\rm sync} \sim 1.5 \left(\frac{B}{\rm mG}\right)^{-1.5} \left(\frac{\varepsilon}{\rm keV}\right)^{-0.5} \ {\rm yr}$$

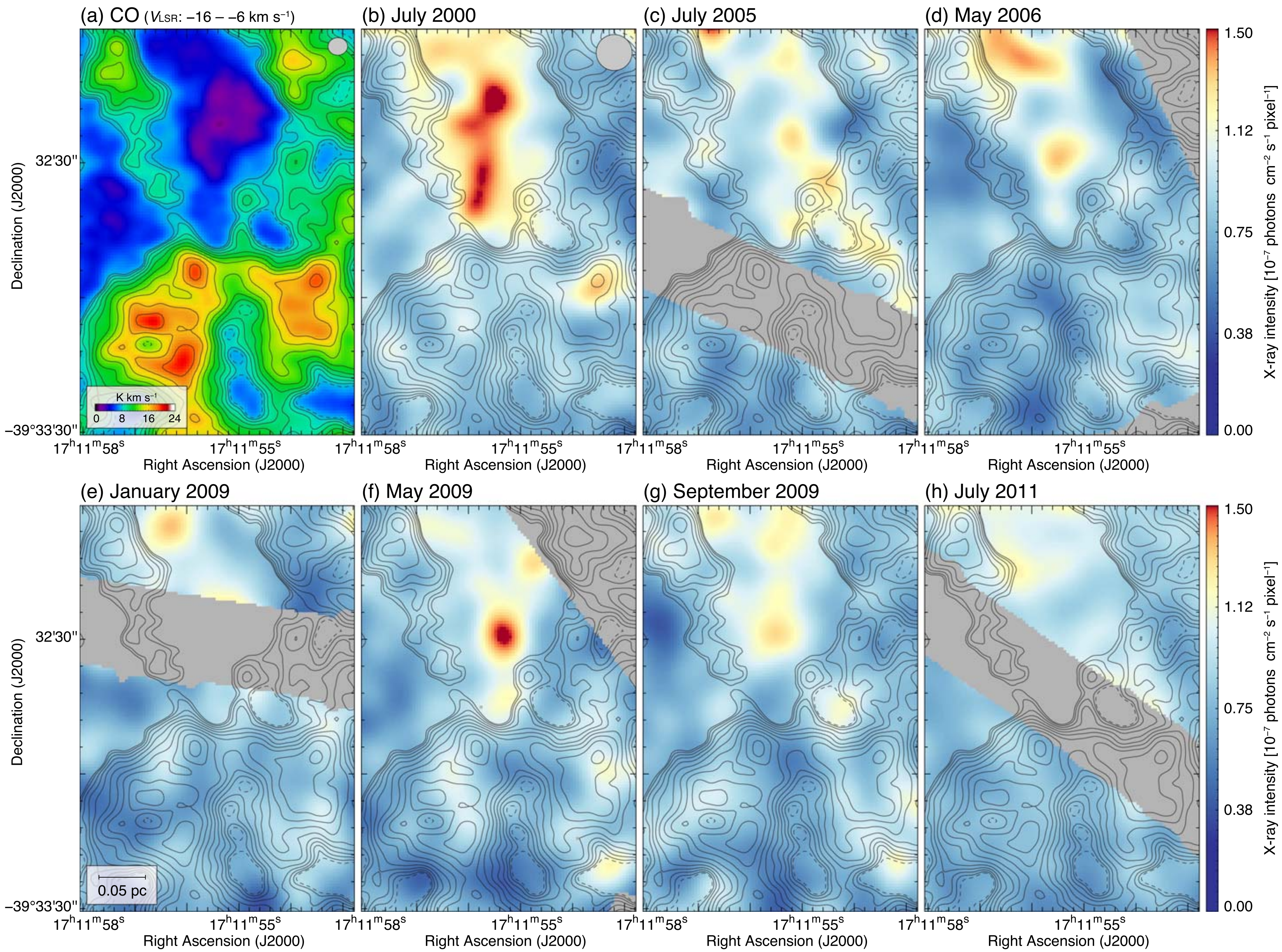
$$t_{\rm acc} \sim 1\,\eta \left(\frac{B}{\rm mG}\right)^{-1.5} \left(\frac{\varepsilon}{\rm keV}\right)^{-0.5} \left(\frac{V_s}{3000\ {\rm km\ s^{-1}}}\right)^{-2} \ {\rm yr}$$

→ $B \sim 1\ {\rm mG}$

# Shock-Cloud Interaction?

**ALMA CO Map**

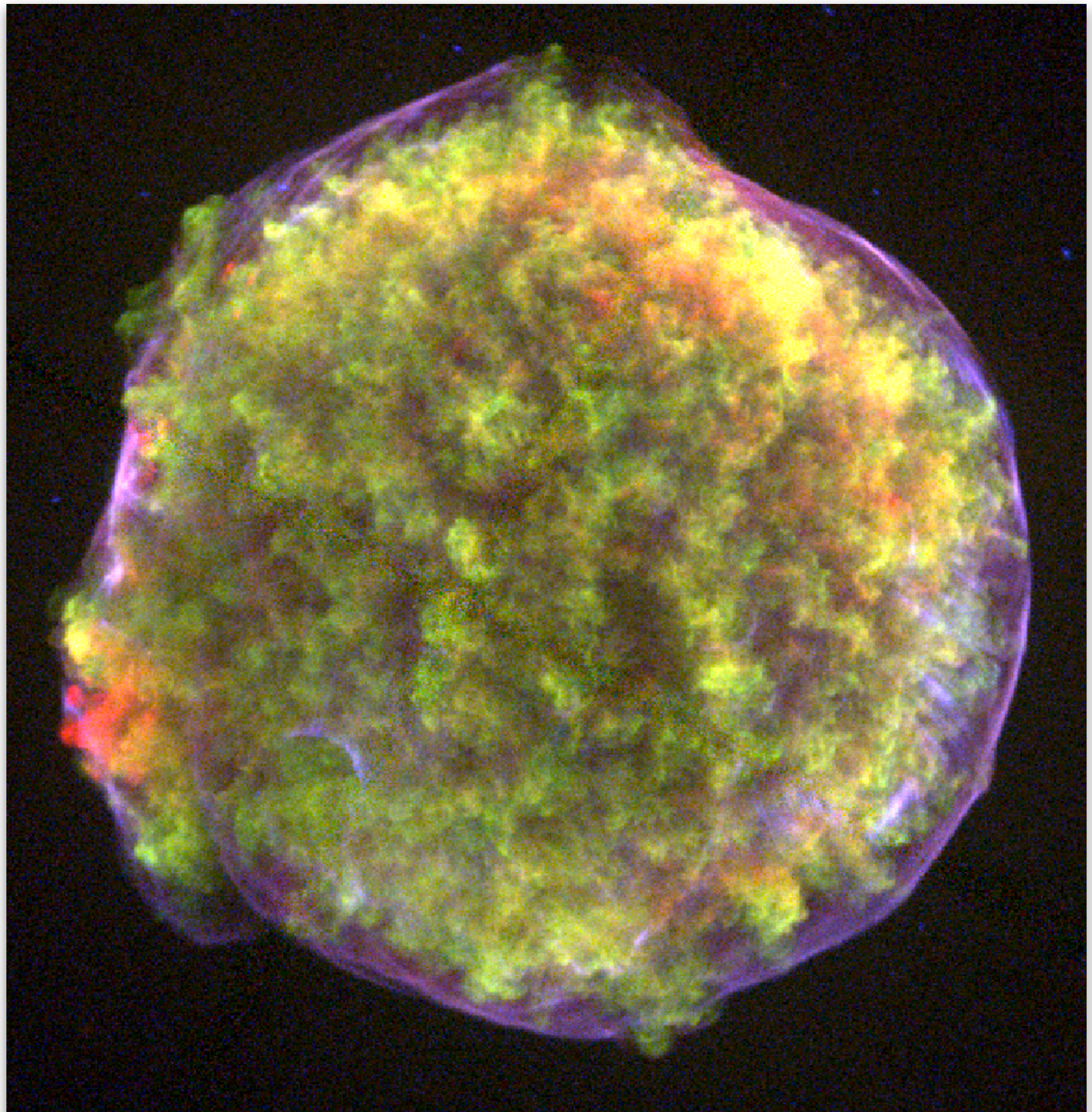
Sano, Inoue, Tokuda, TT+ (2020)

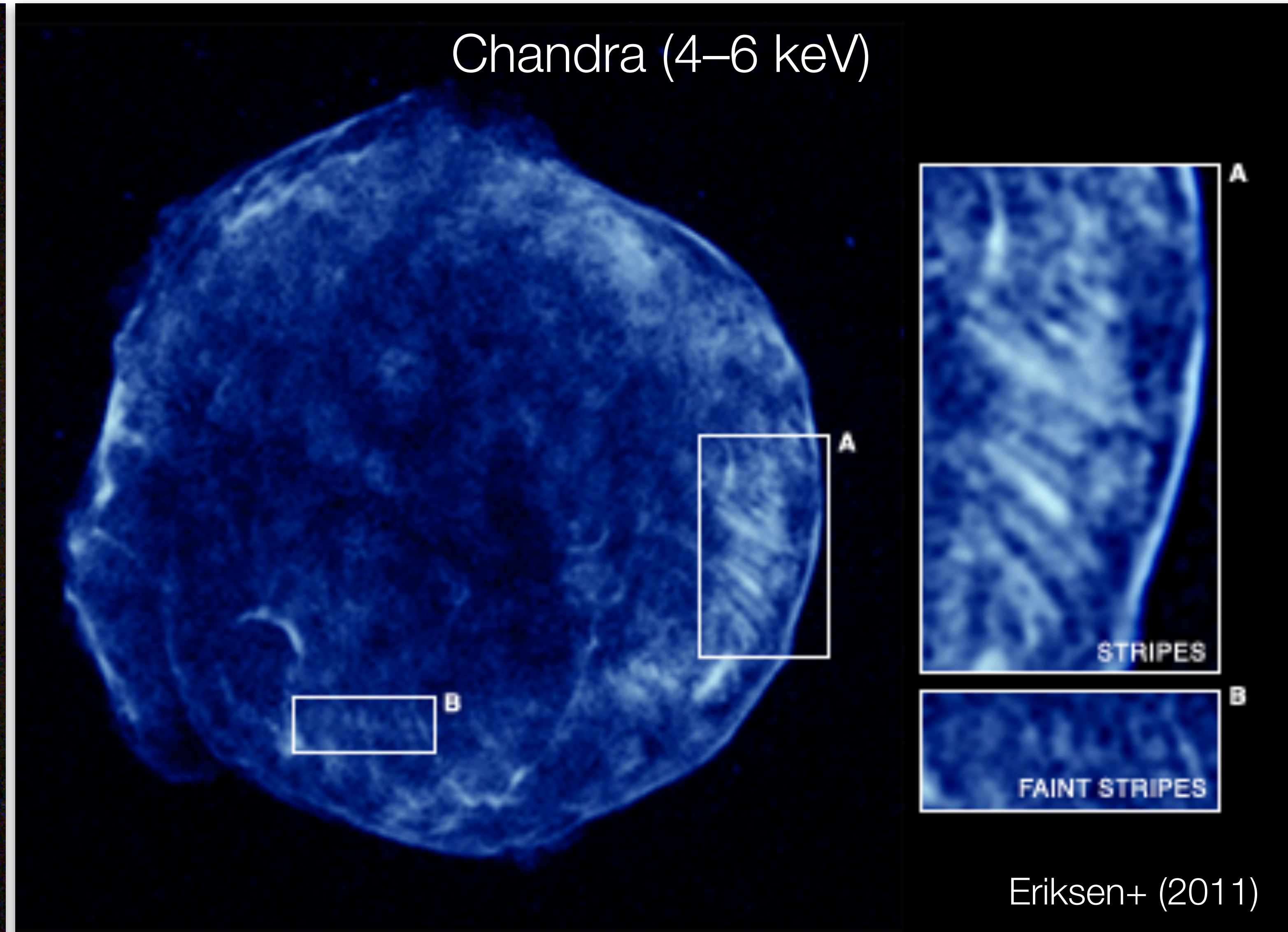



**See Talk by H. Sano**

- Magnetic field amplification due to shock-cloud interactions?
- See also theoretical works by Inoue+ (2012), Celli+ (2019)

# Stripes in Tycho's SNR





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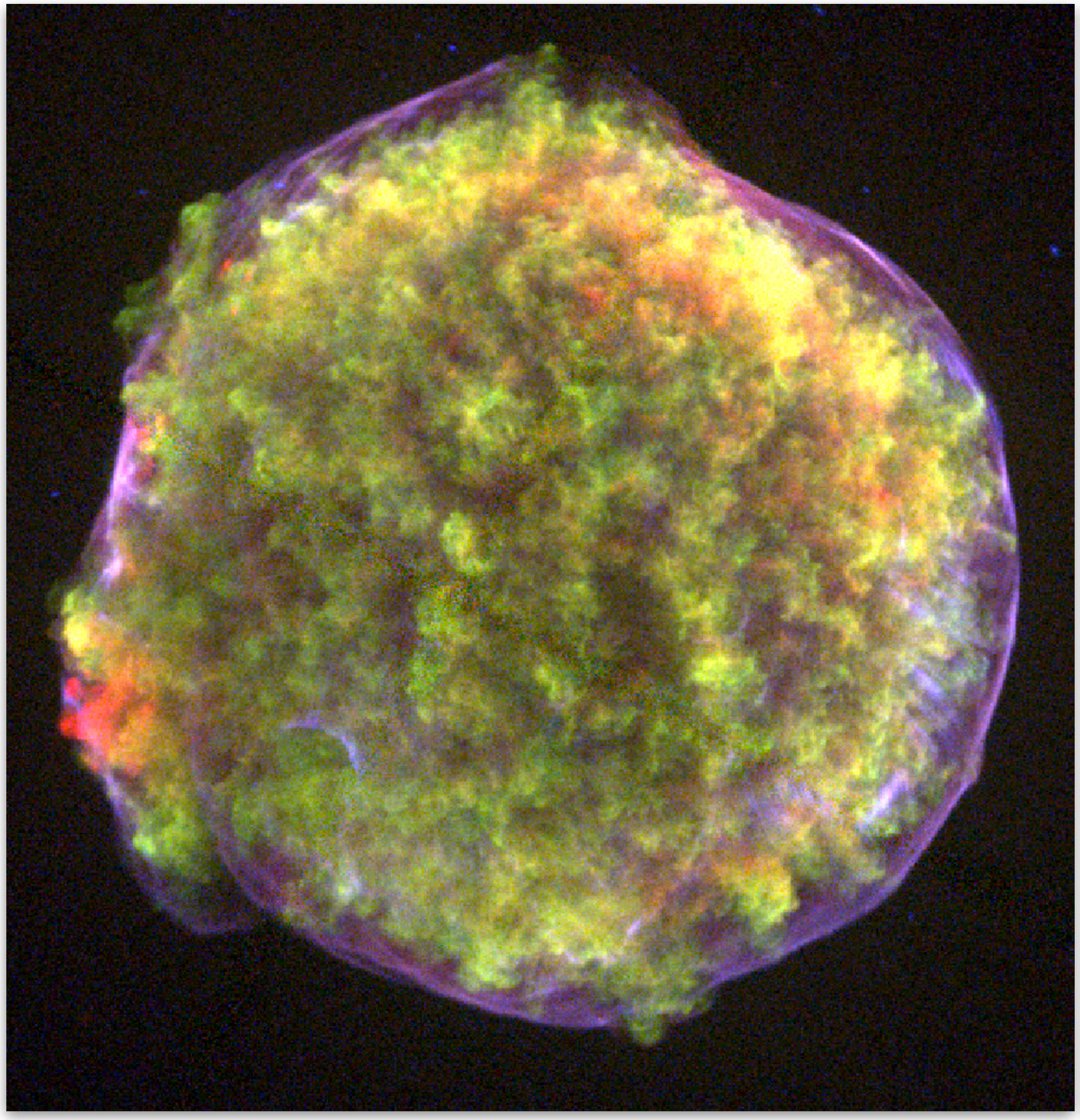
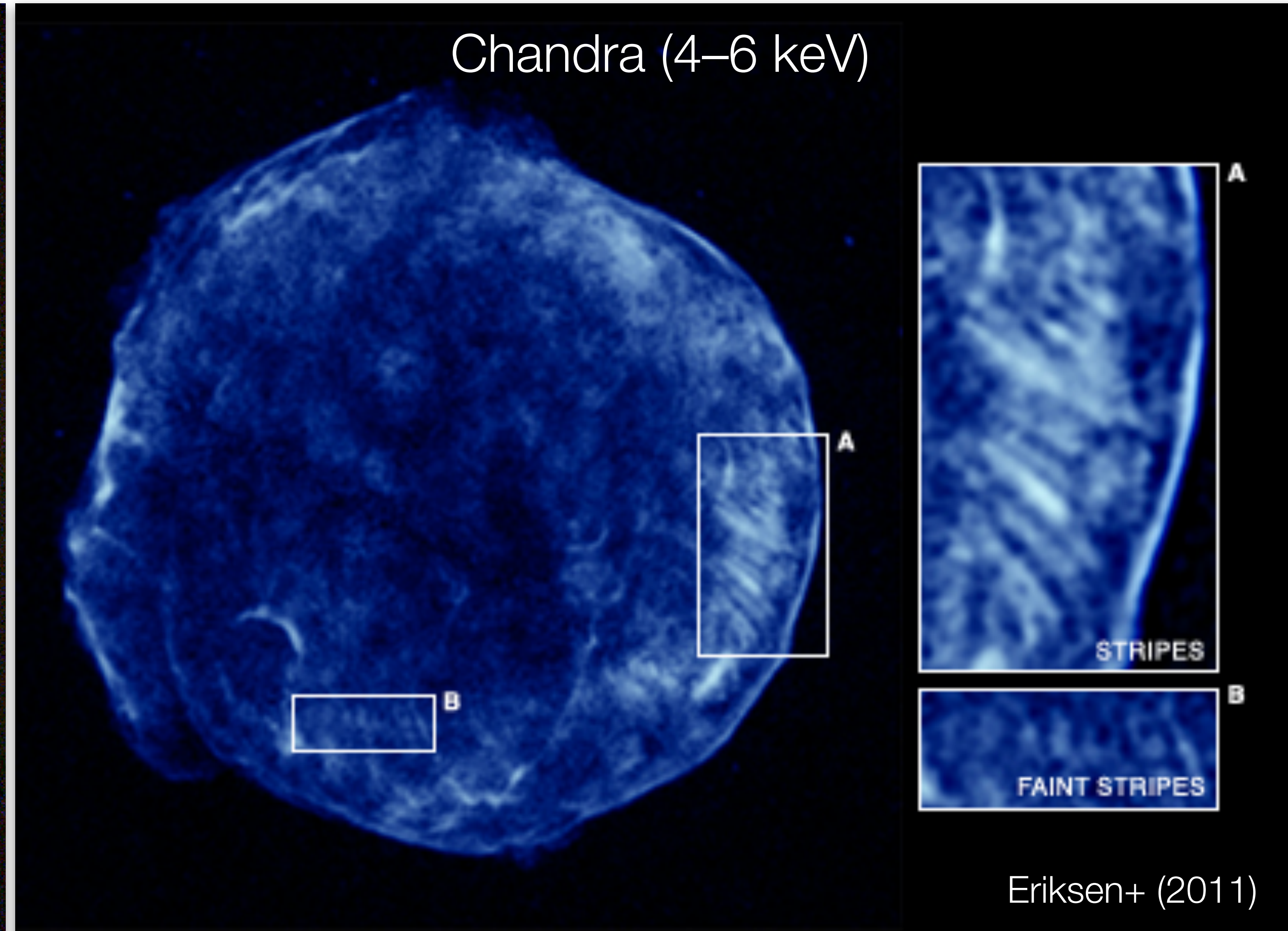




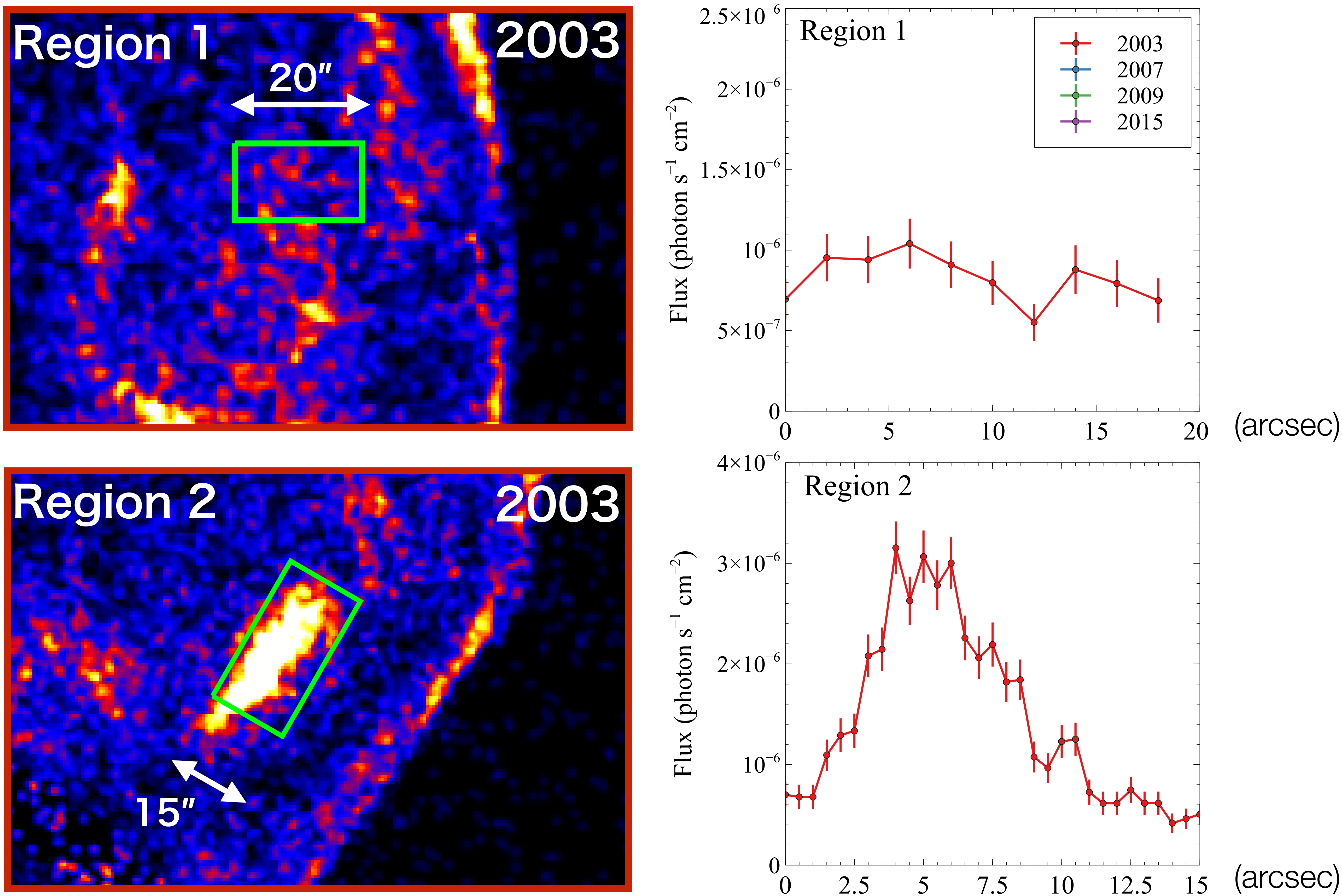

**Stripes of synchrotron X-rays**

If the stripe gaps correspond to 2 × gyroradius of protons, the proton energy must be close to the knee

$$E_{\rm CR} = 9\left(\frac{l_{\rm gap}}{1''}\right)\left(\frac{D}{4.0\ {\rm kpc}}\right)\left(\frac{B}{\mu{\rm G}}\right) \times 10^{12}\ {\rm eV} \Rightarrow E_{\rm CR} = 2 \times 10^{15}\ {\rm eV}$$

# Variability of Stripes

Okuno, TT+ (2020)



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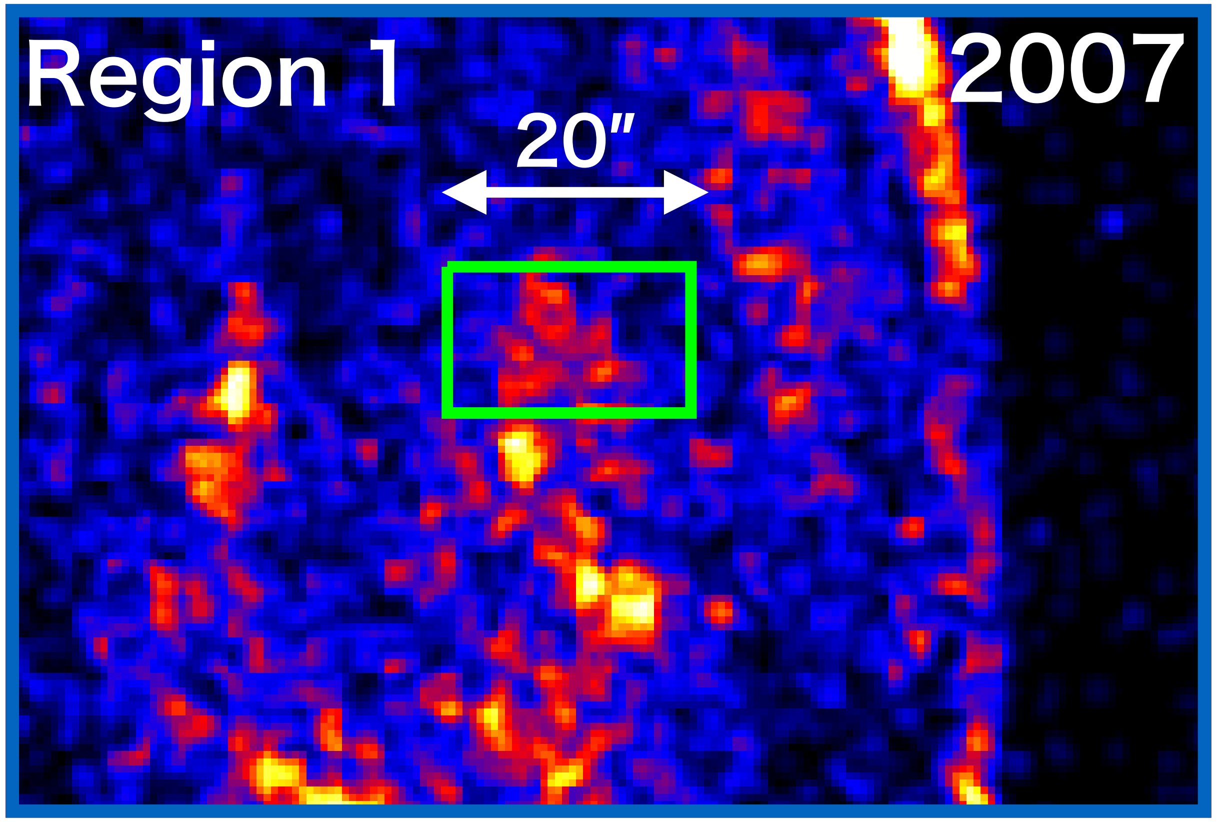


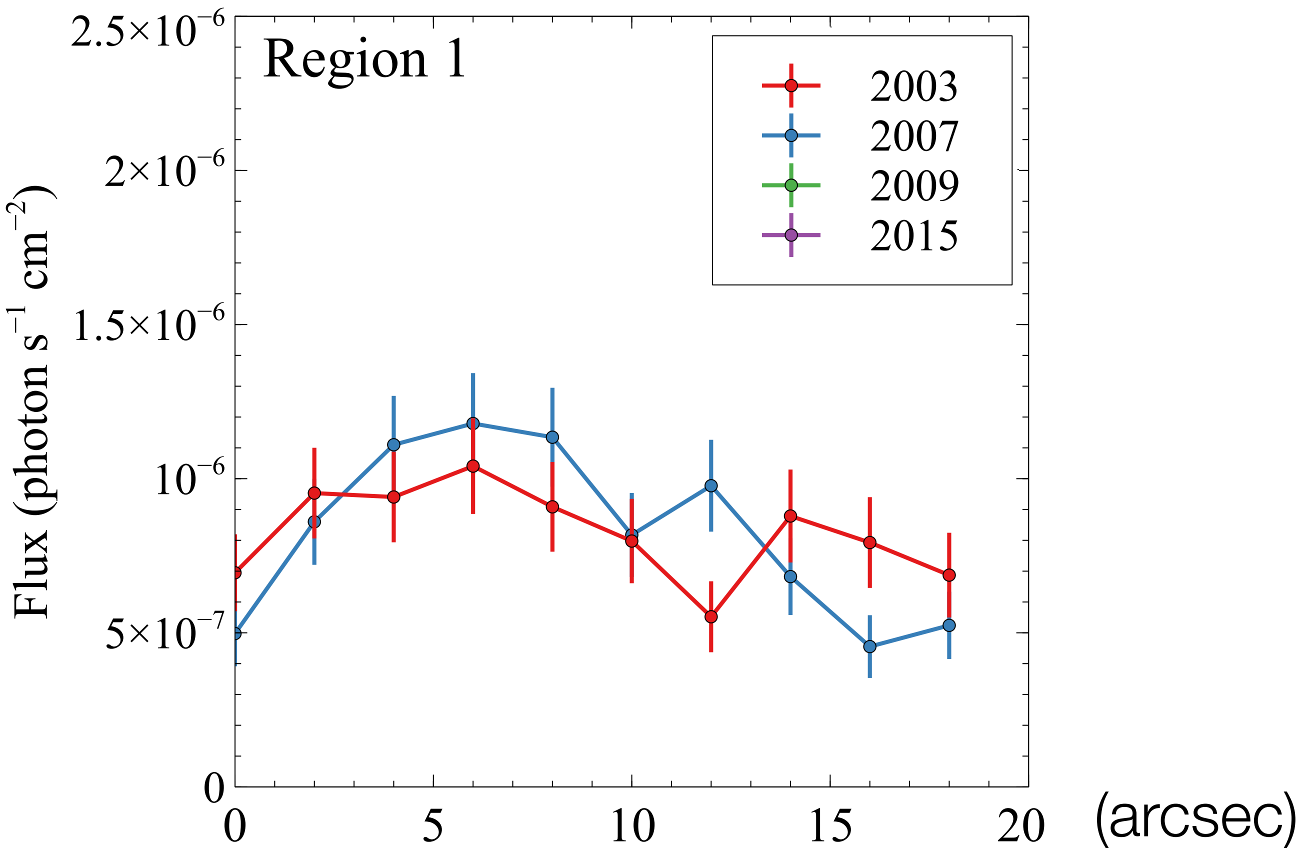


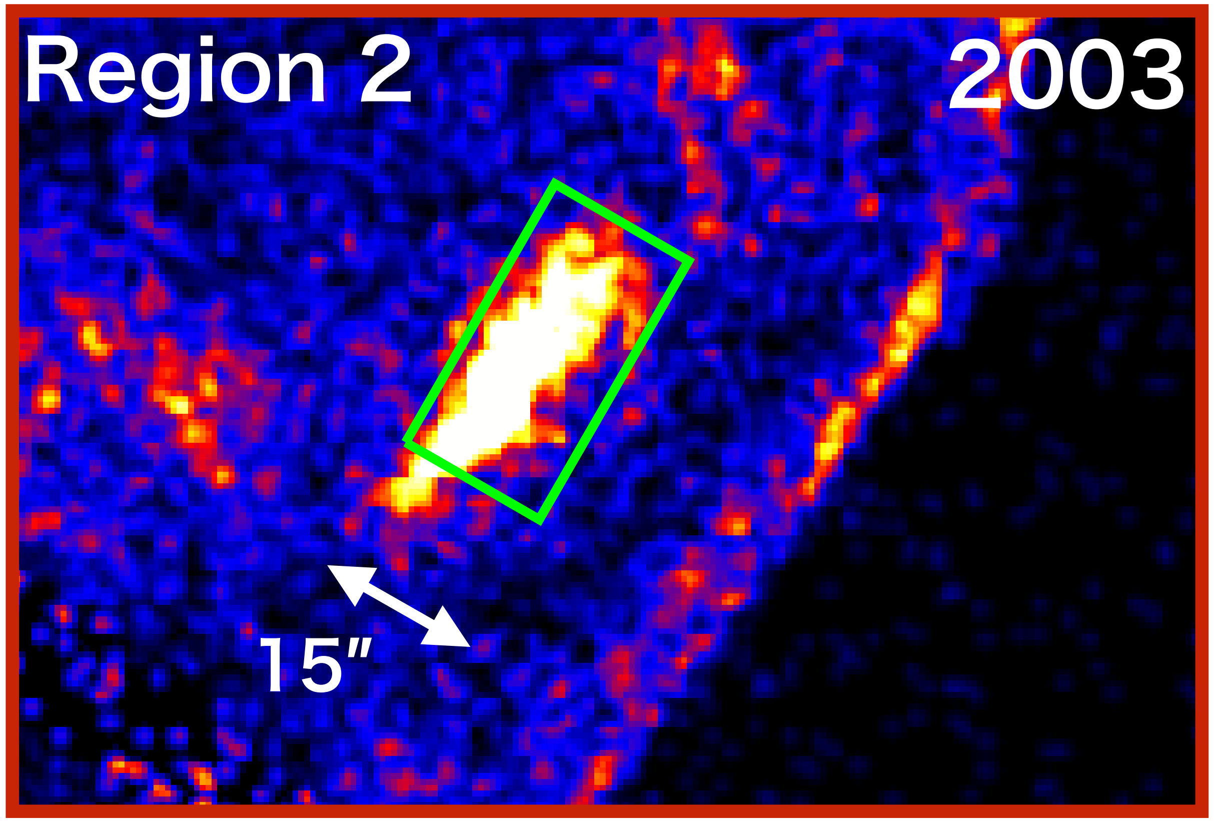


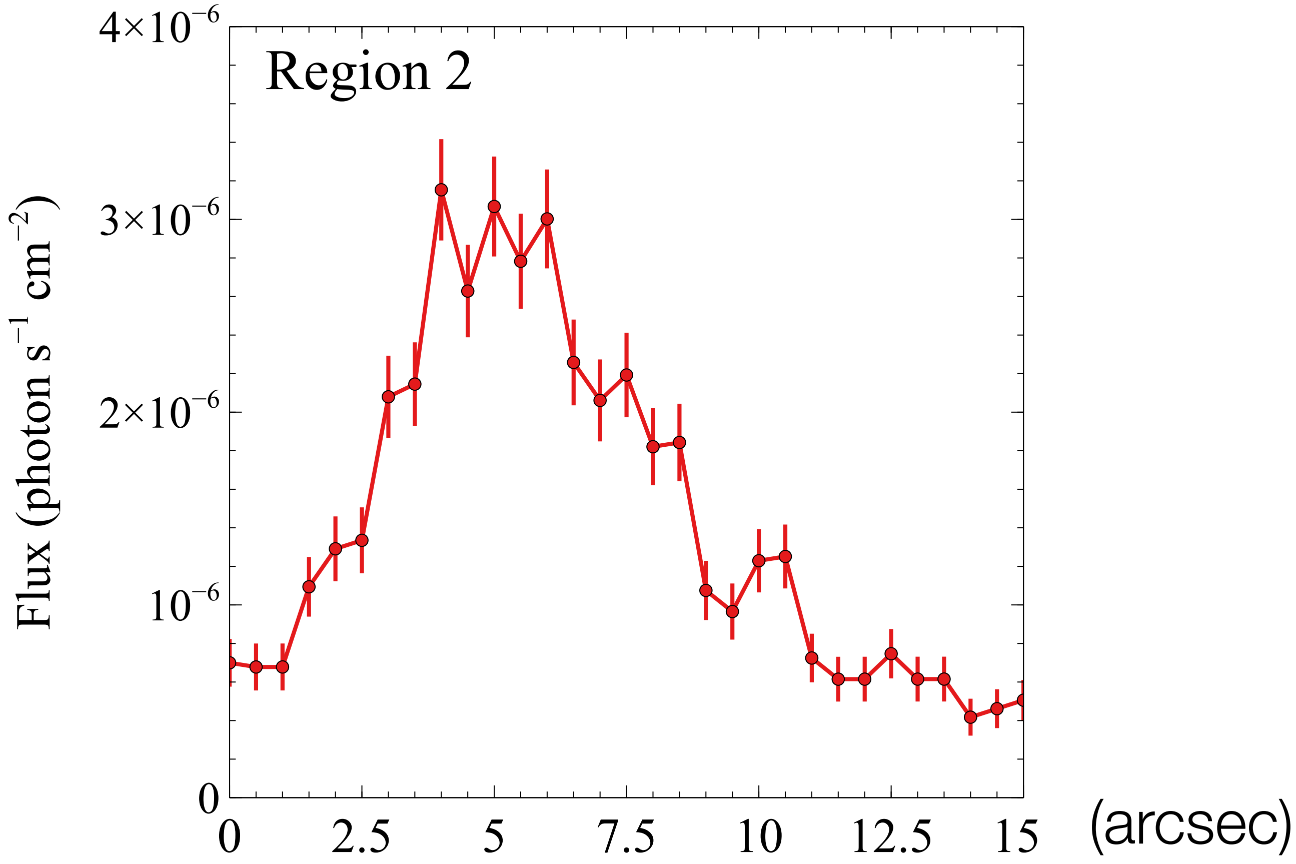

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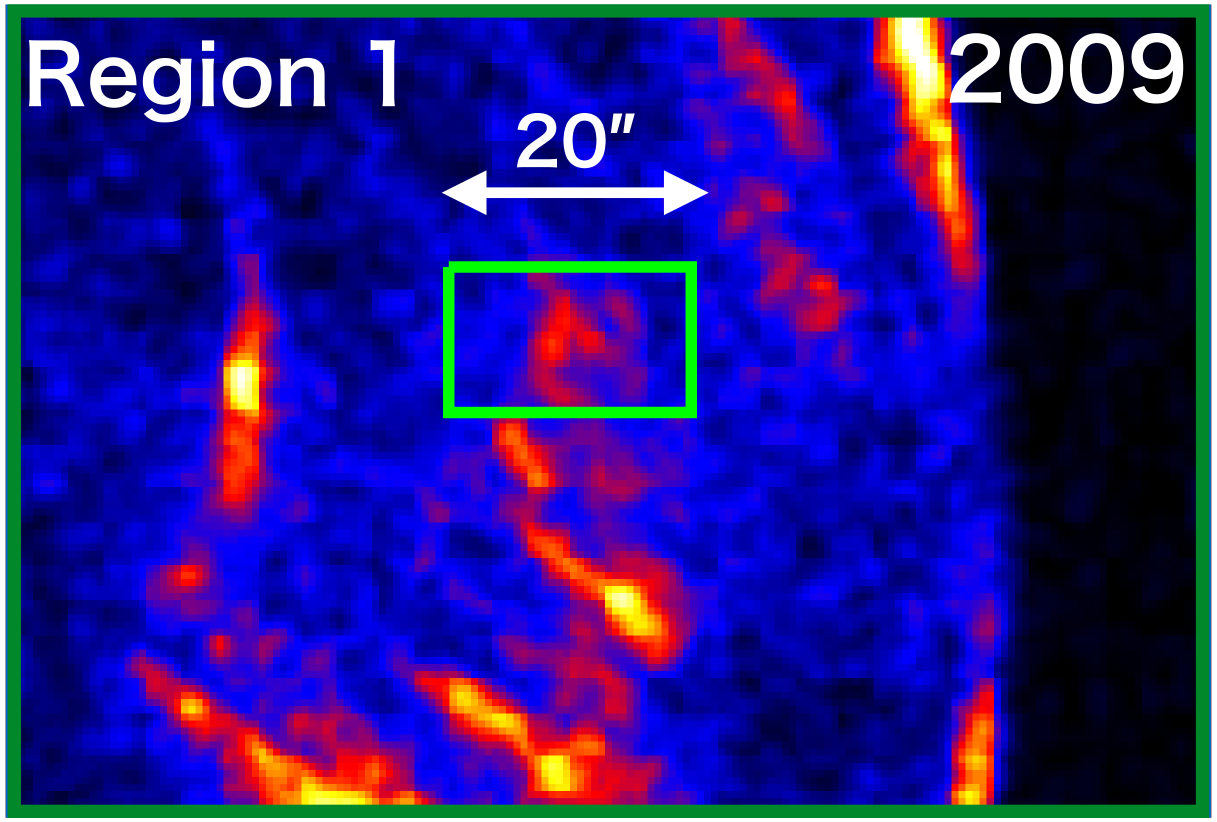


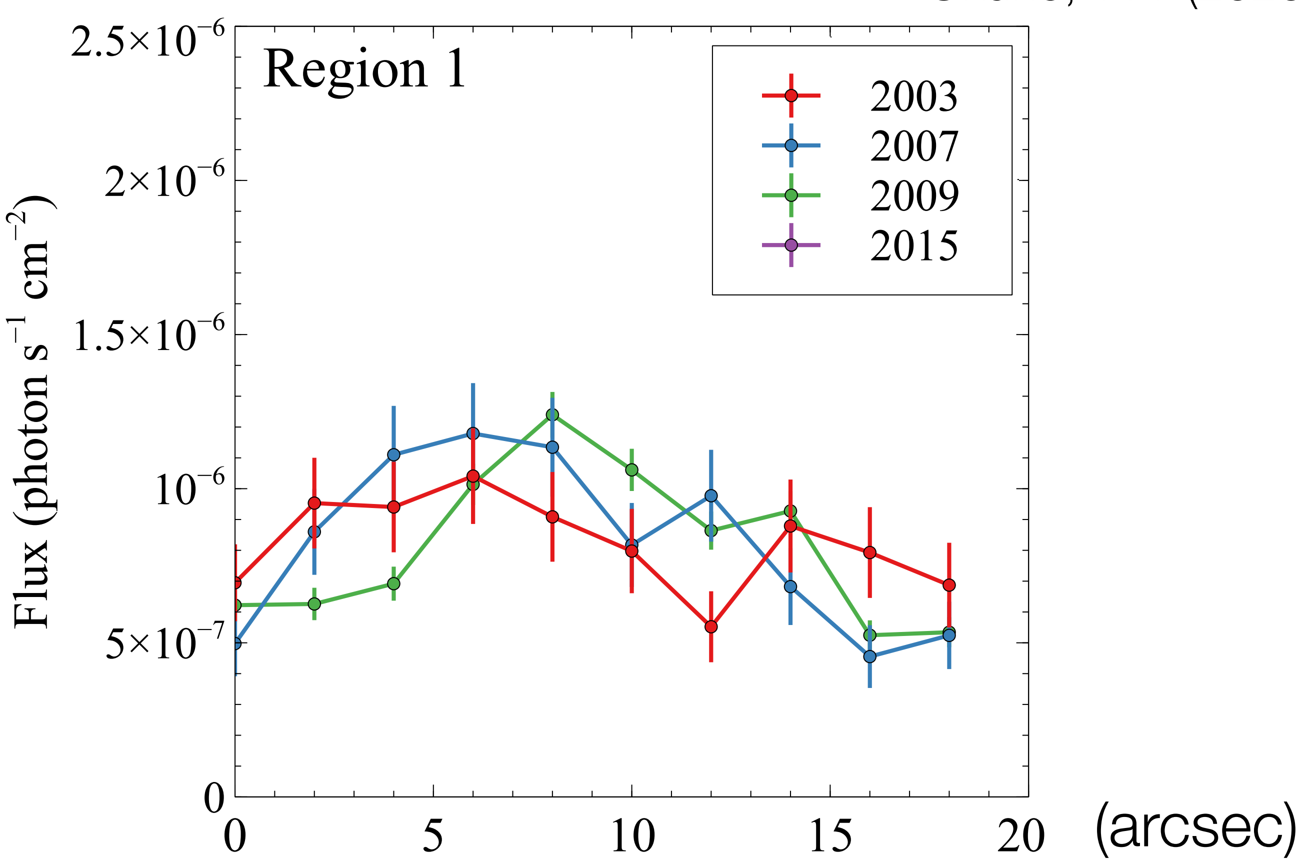


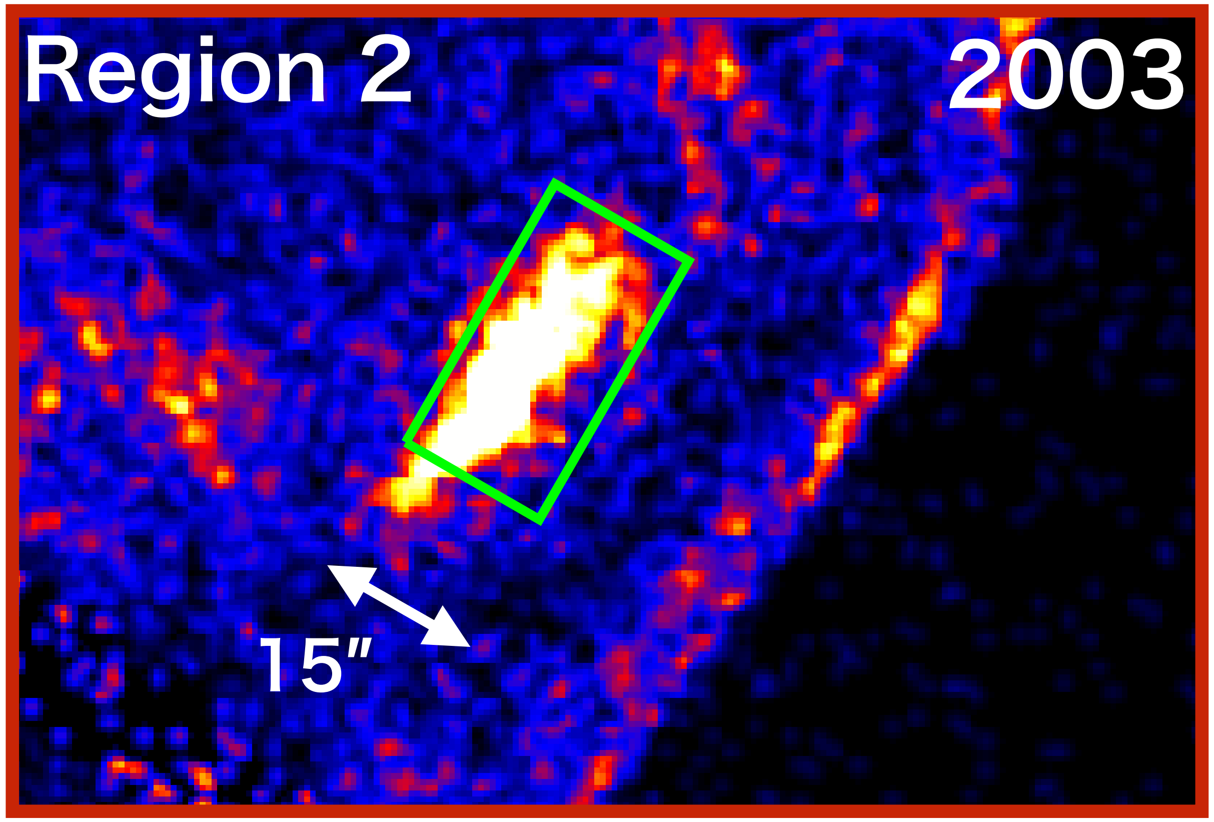


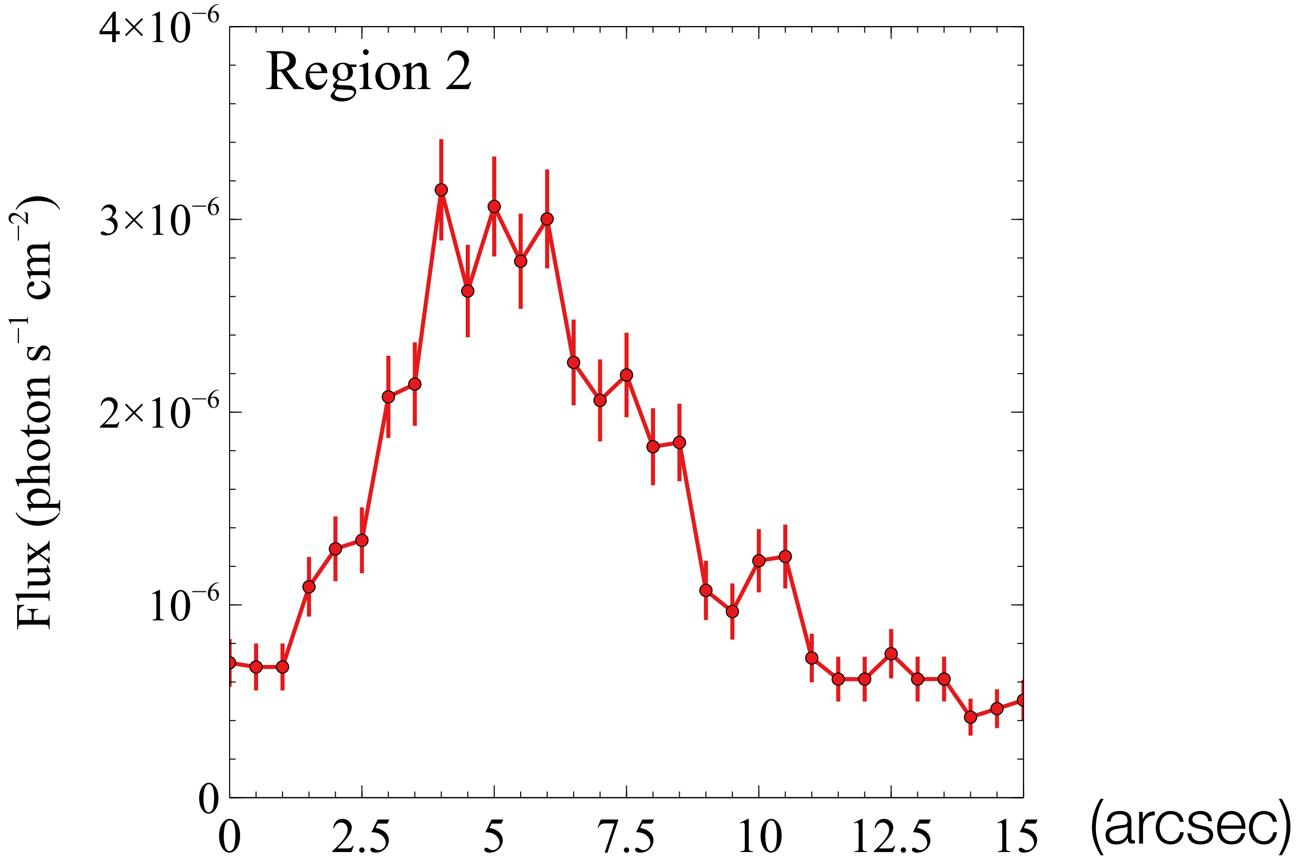

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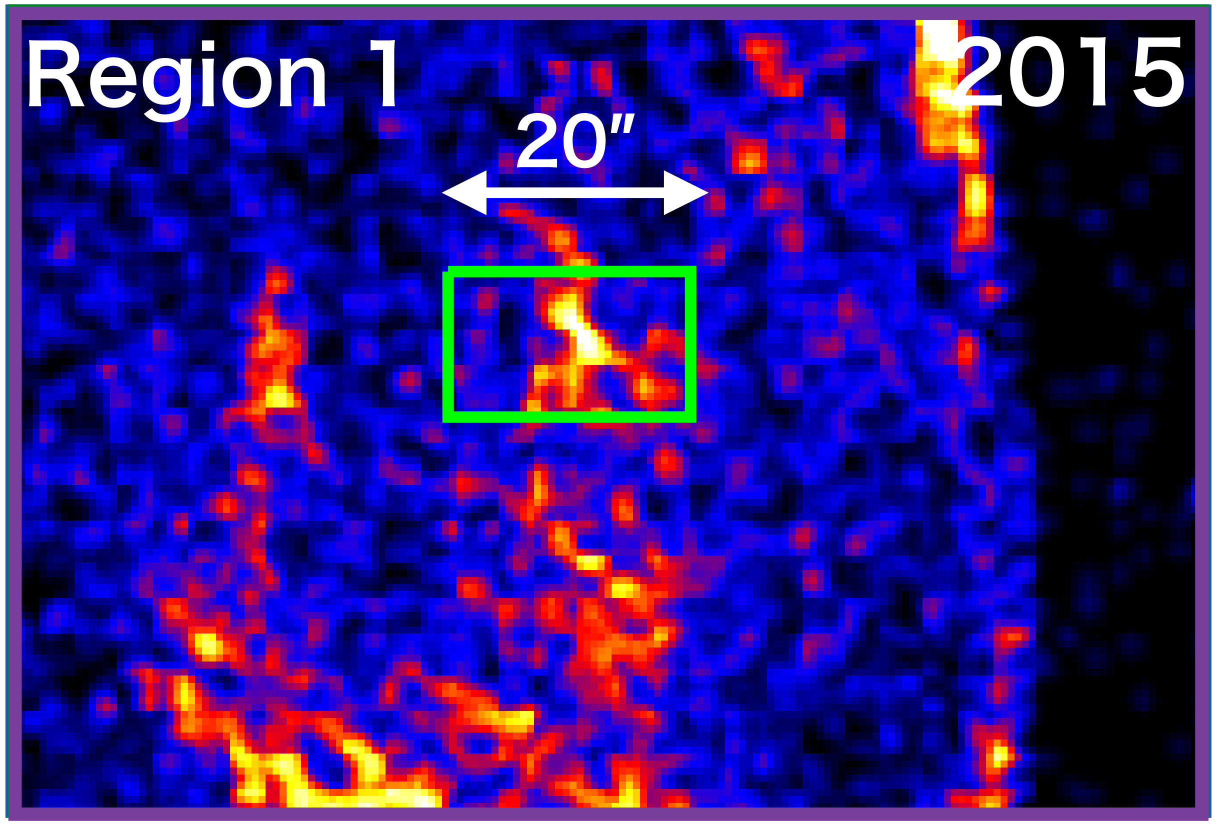


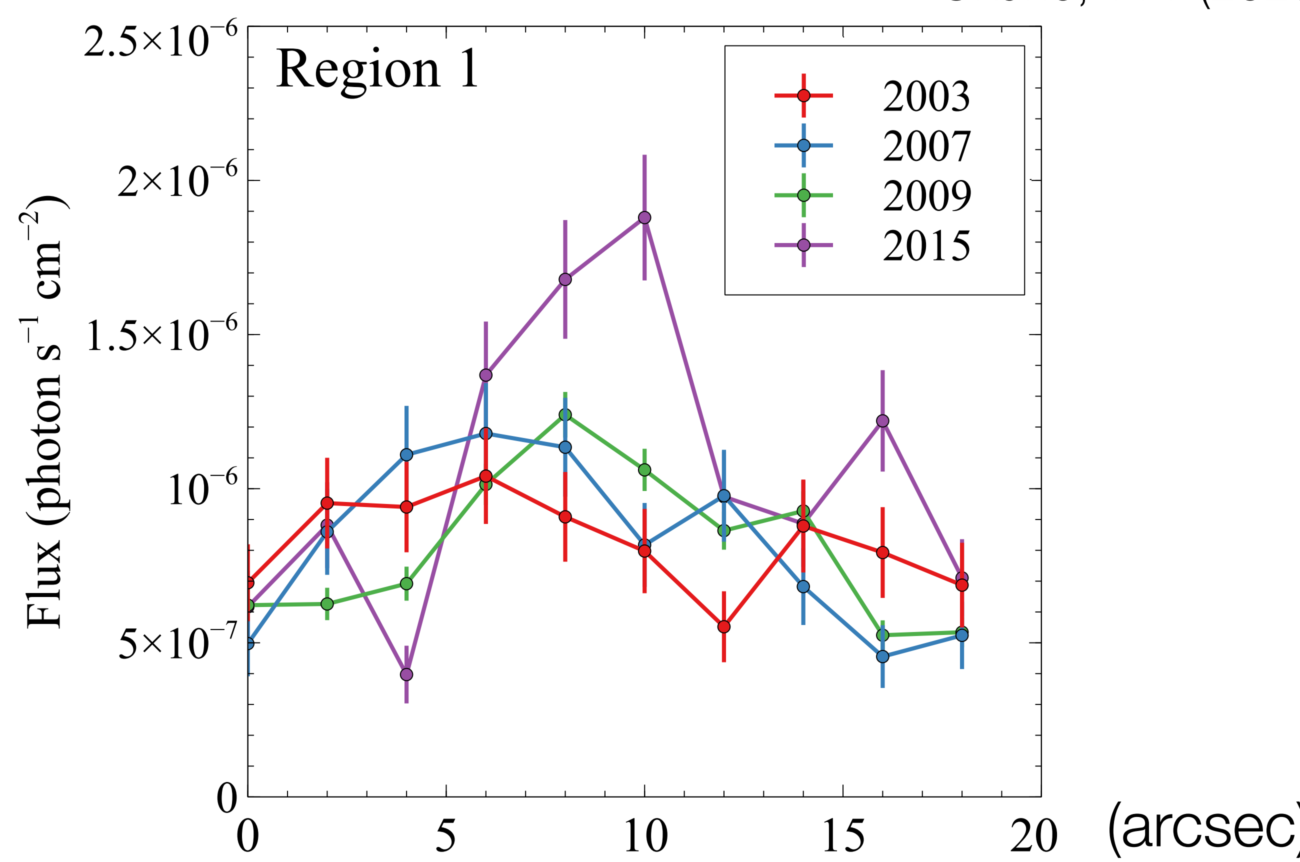


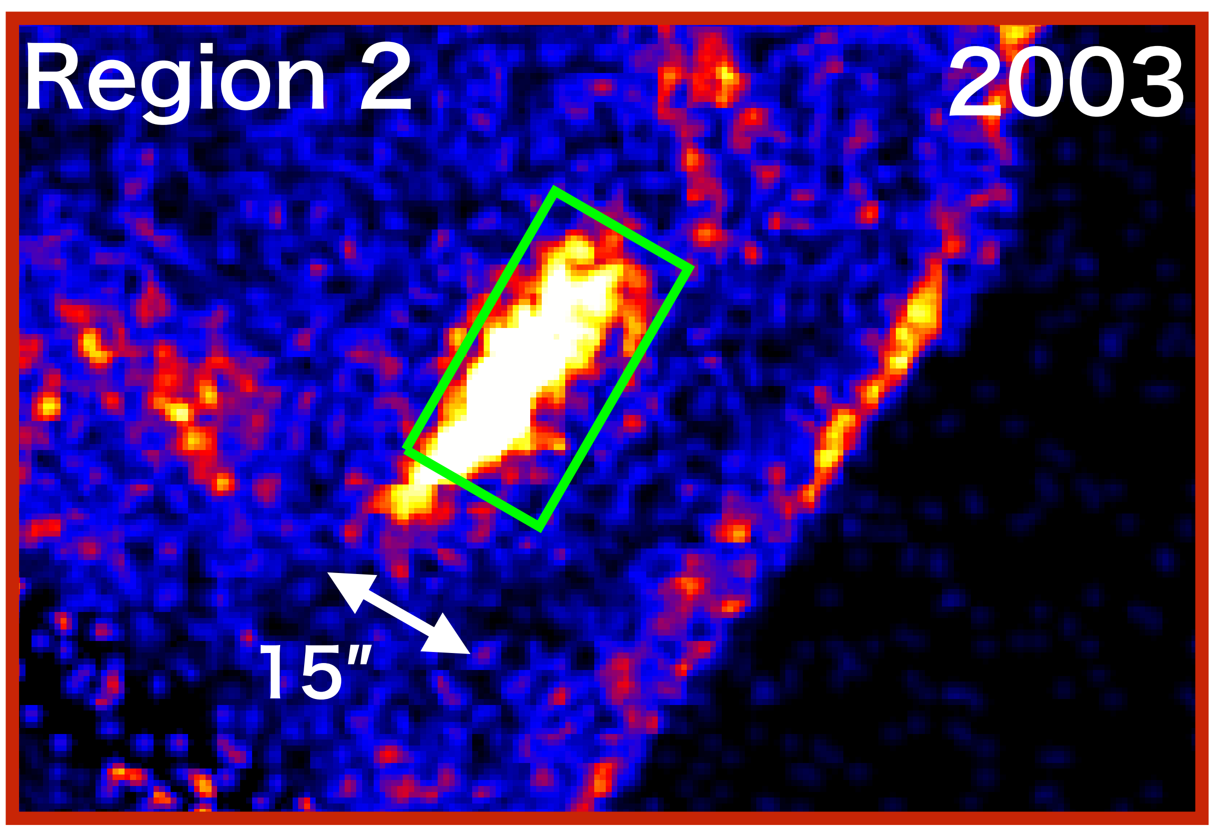


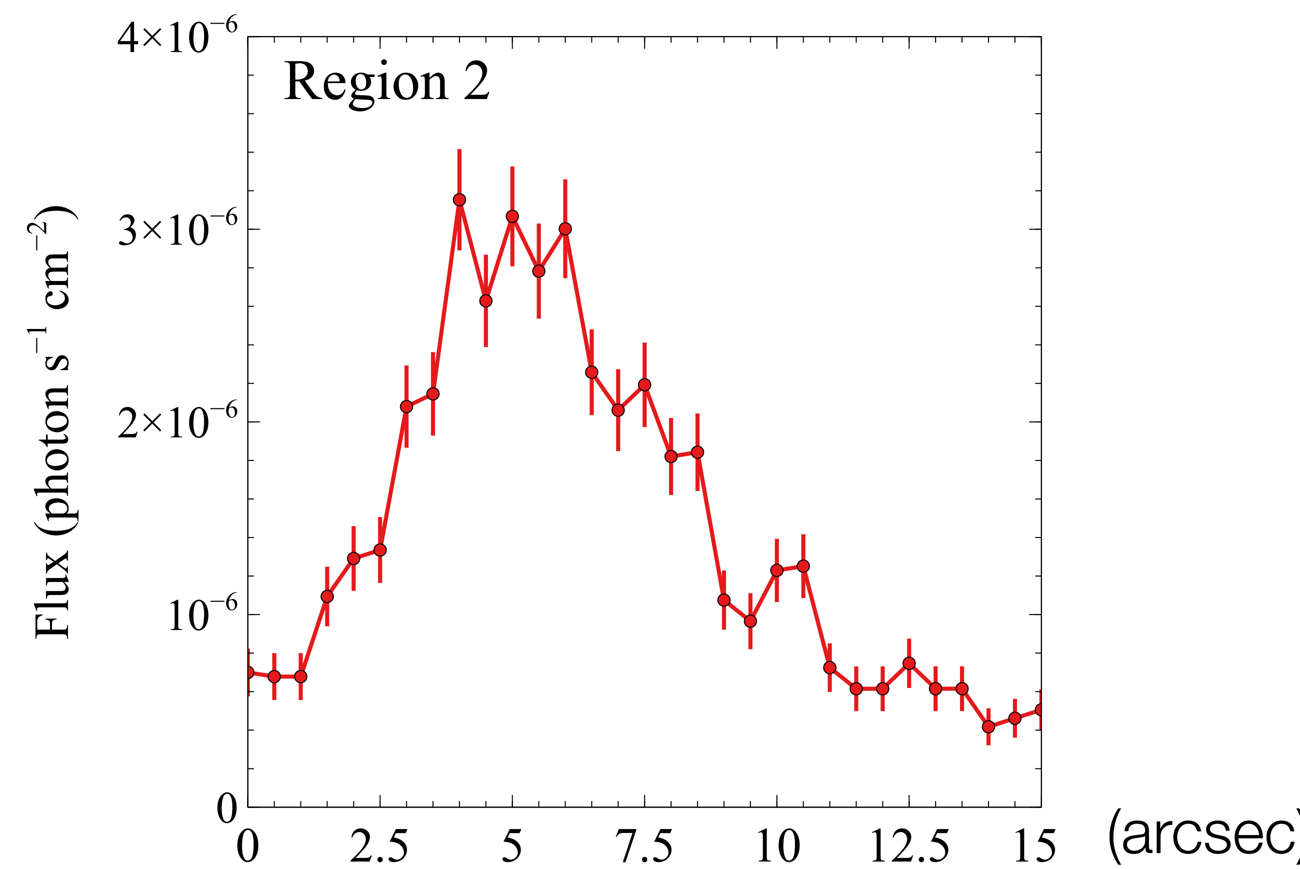

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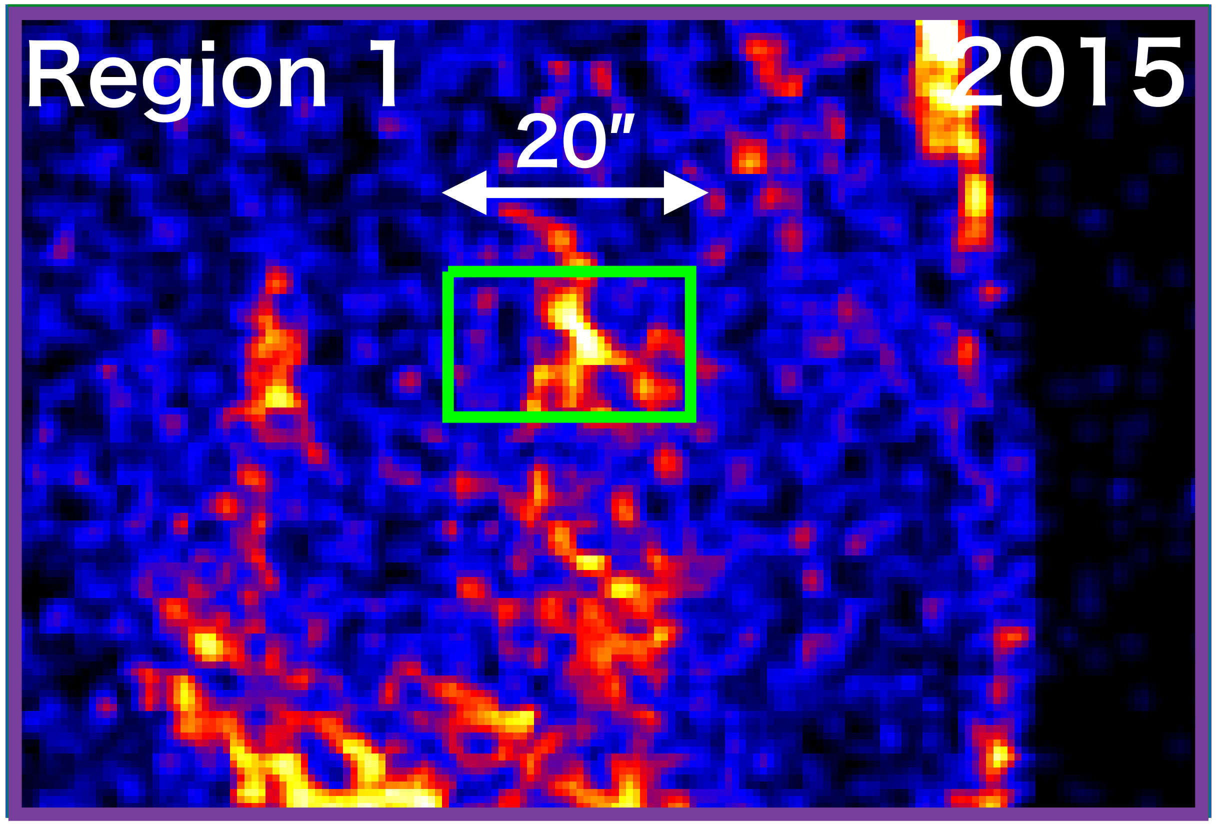


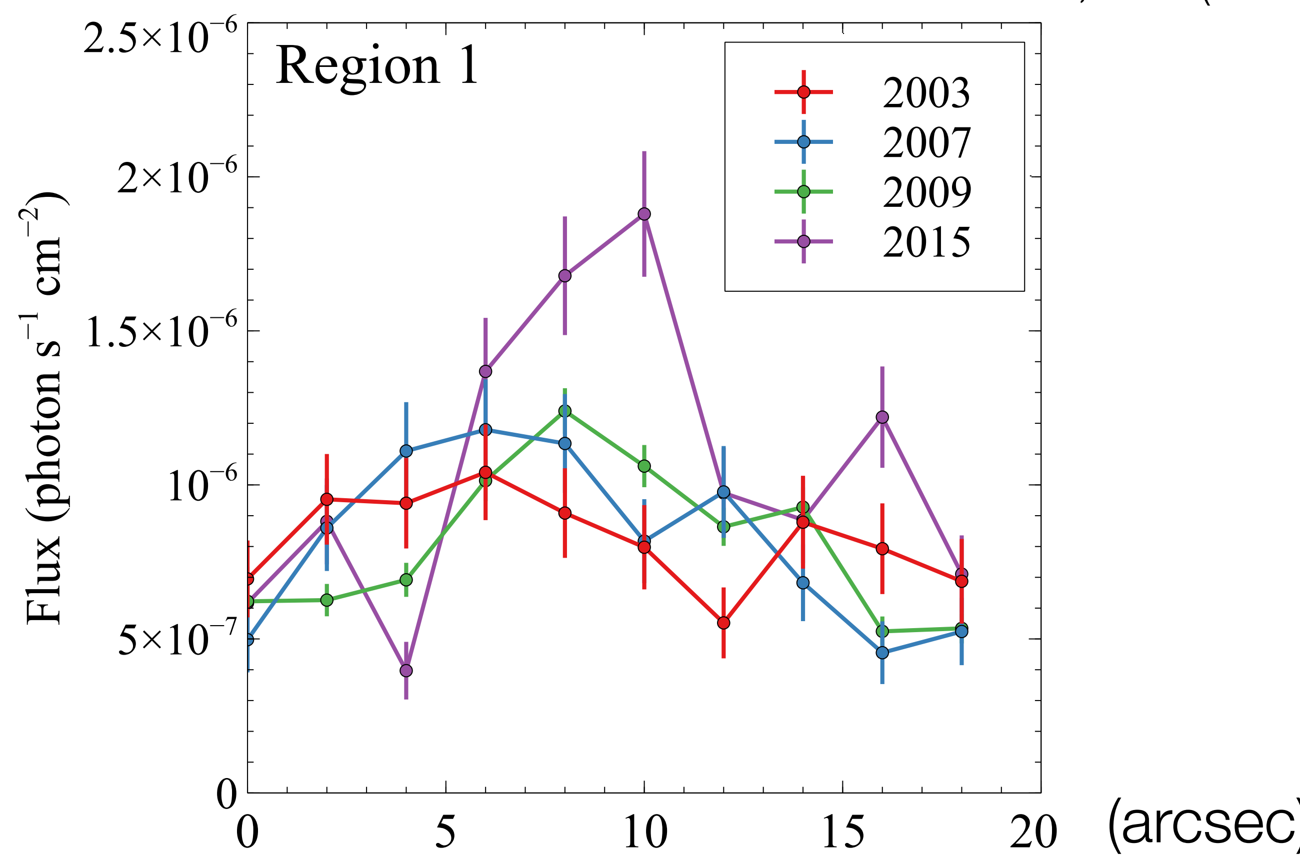


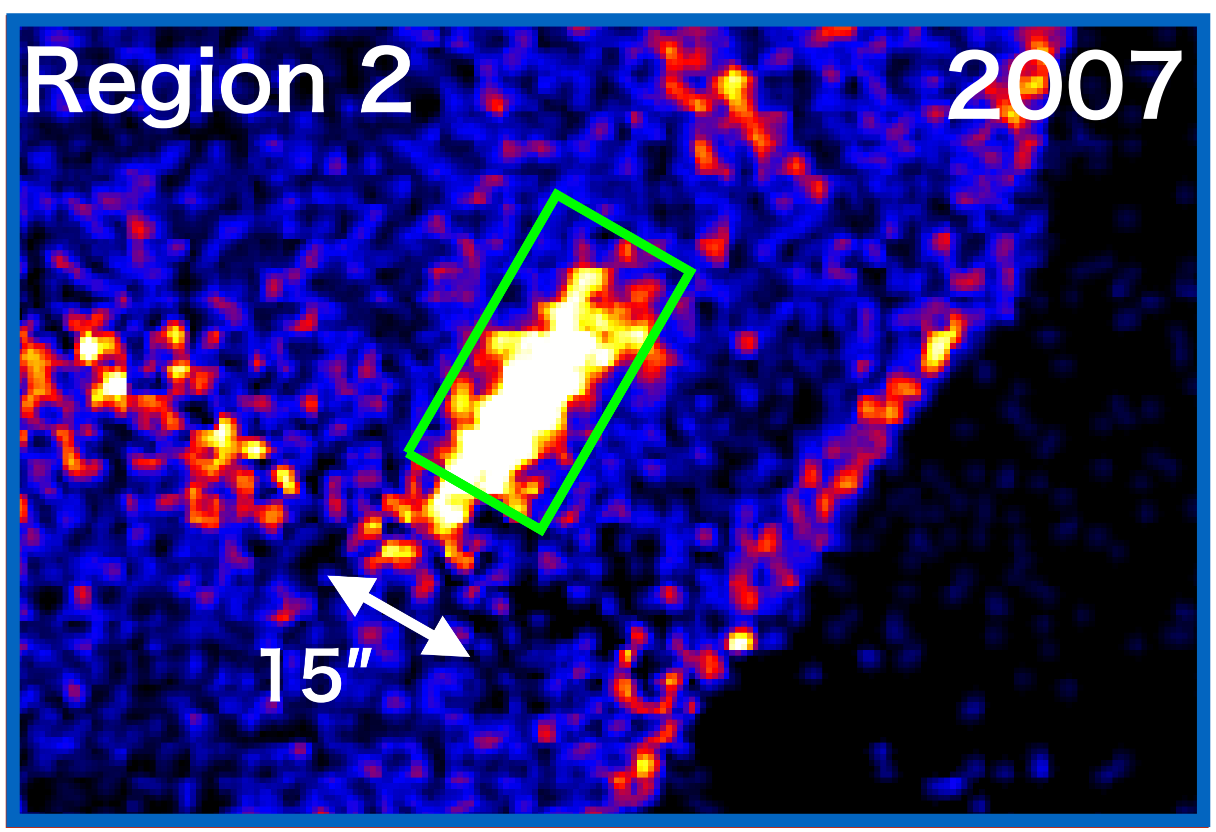


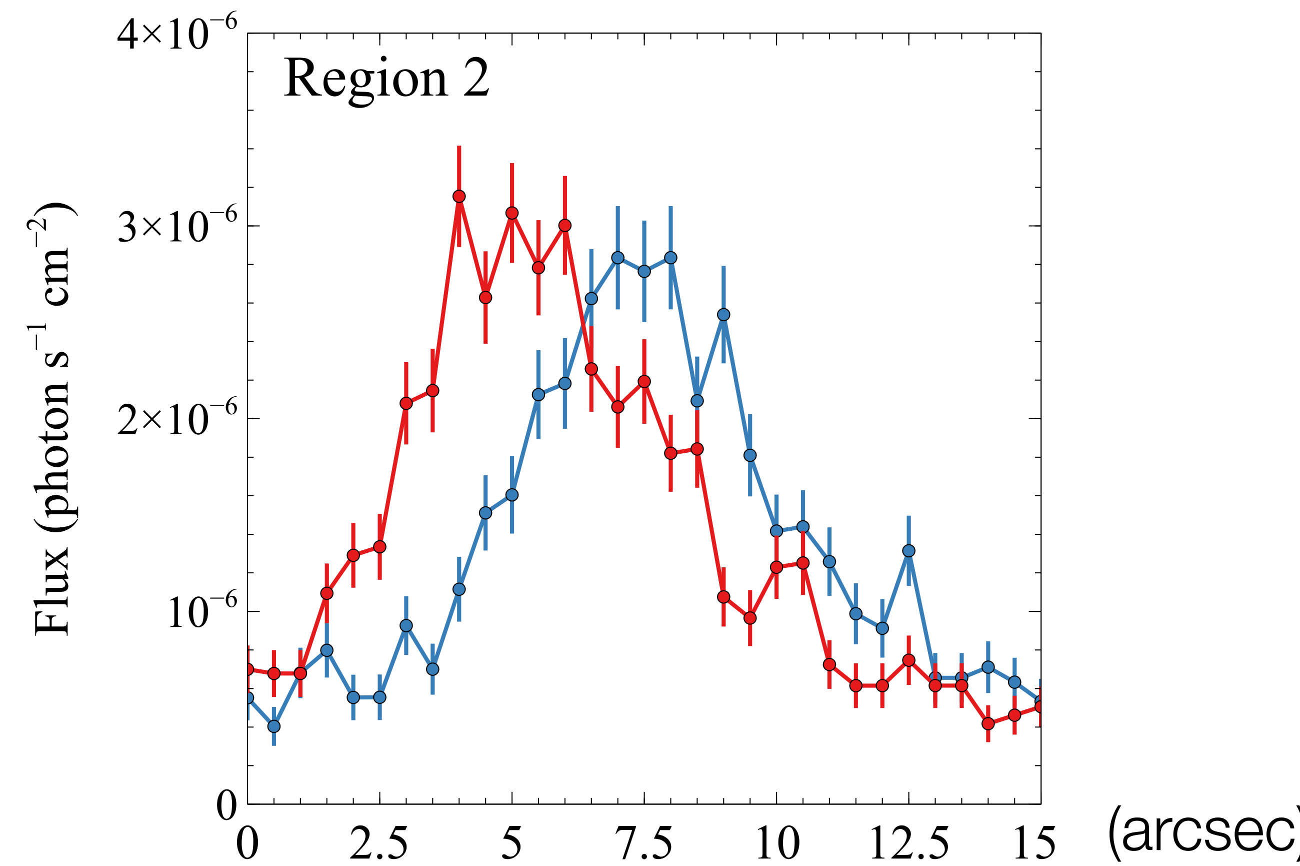

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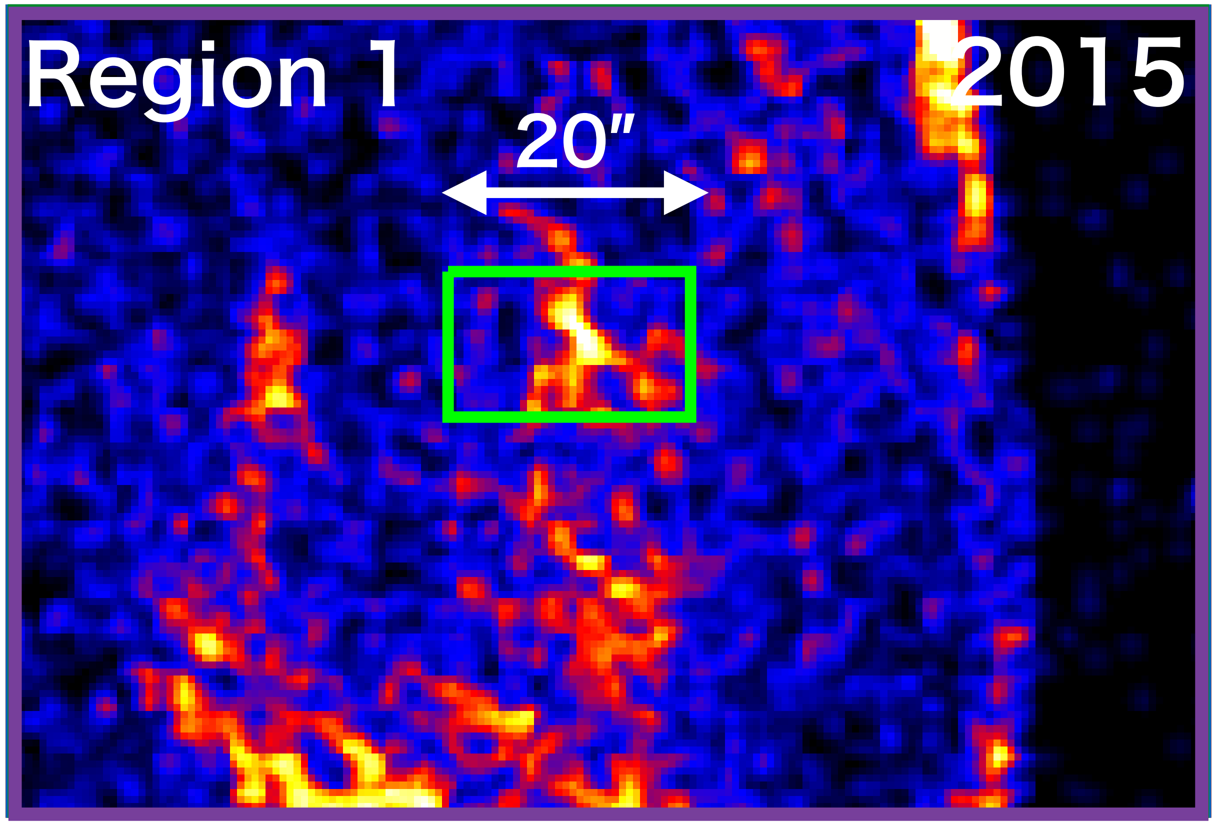


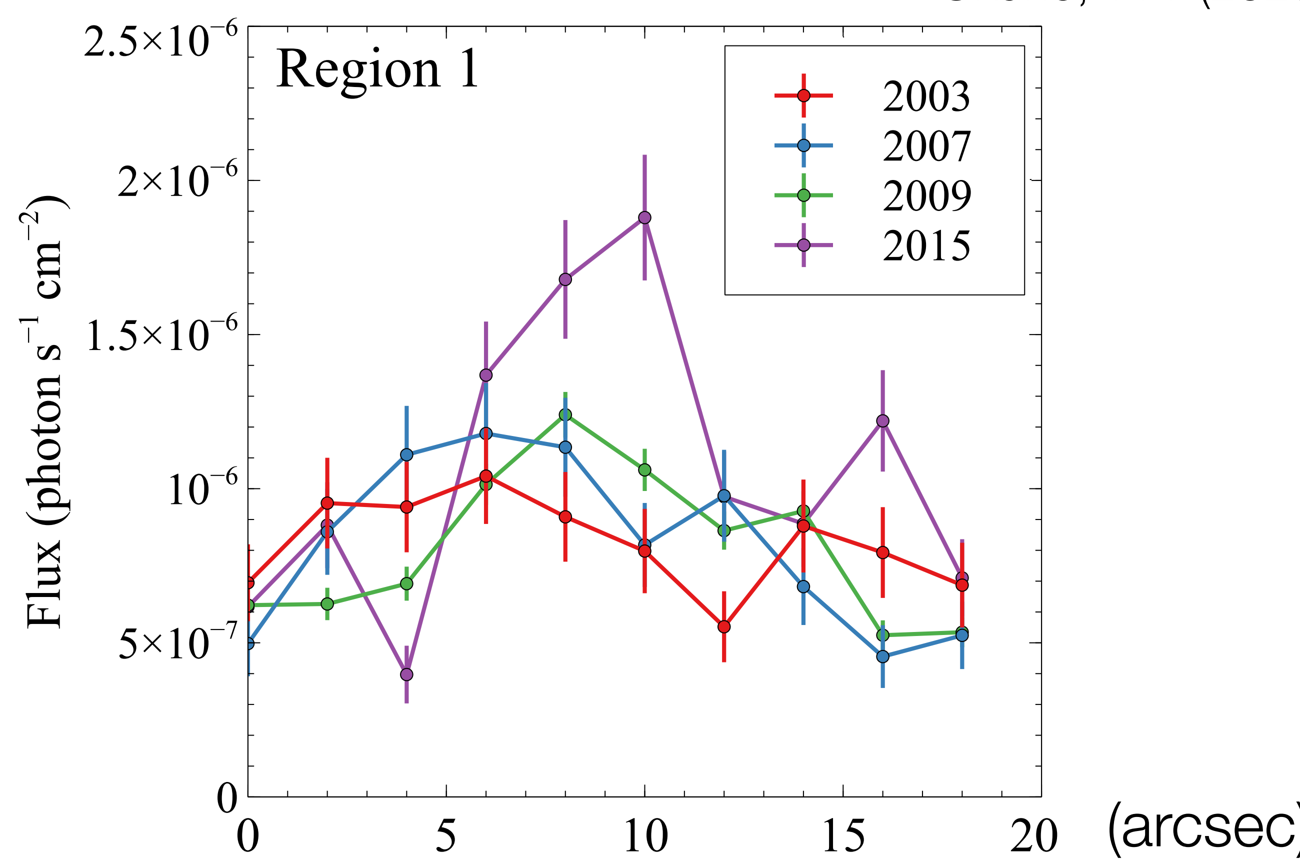


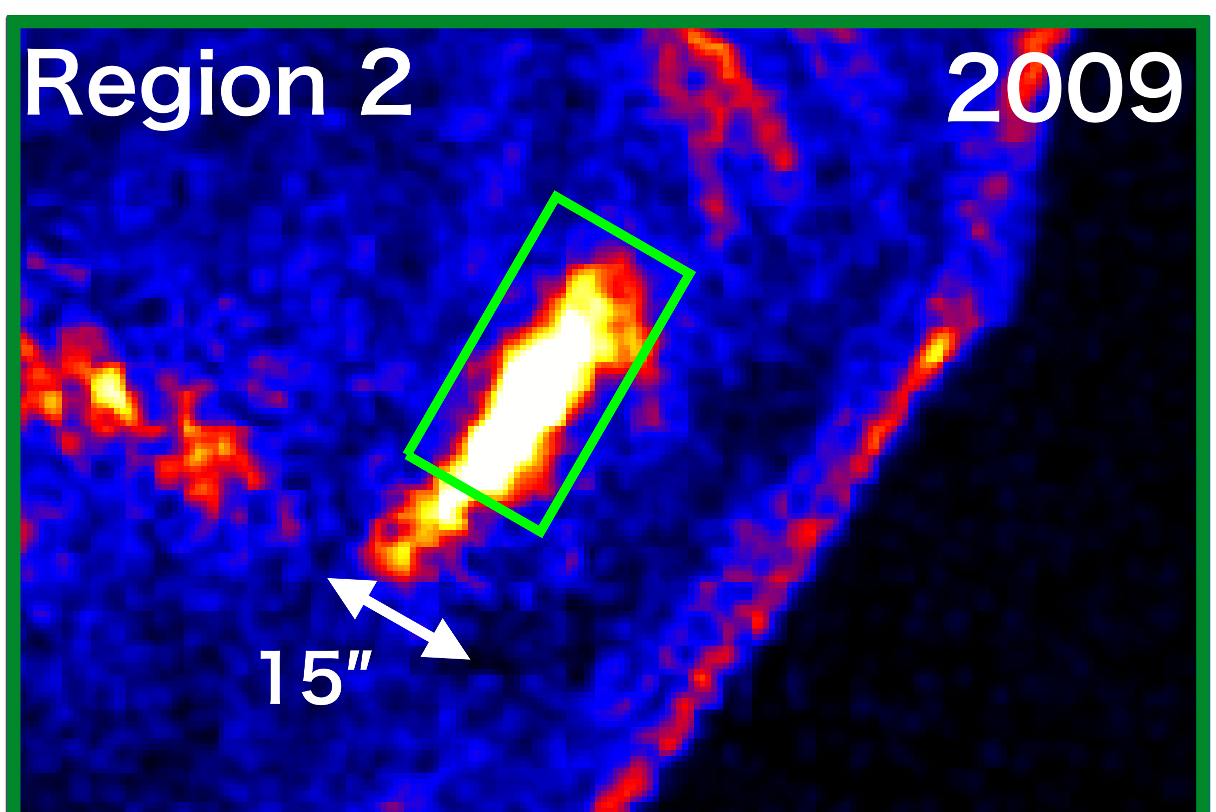


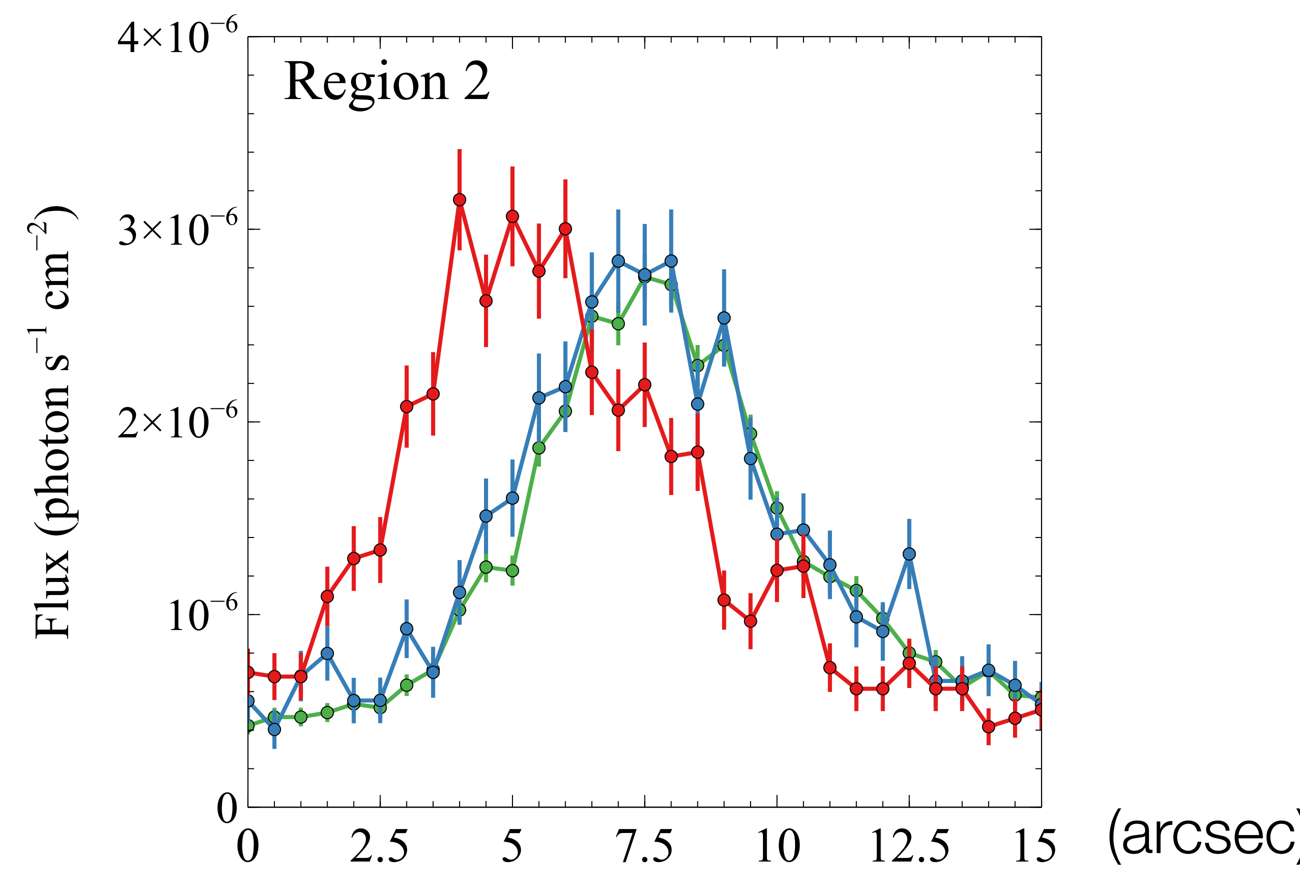

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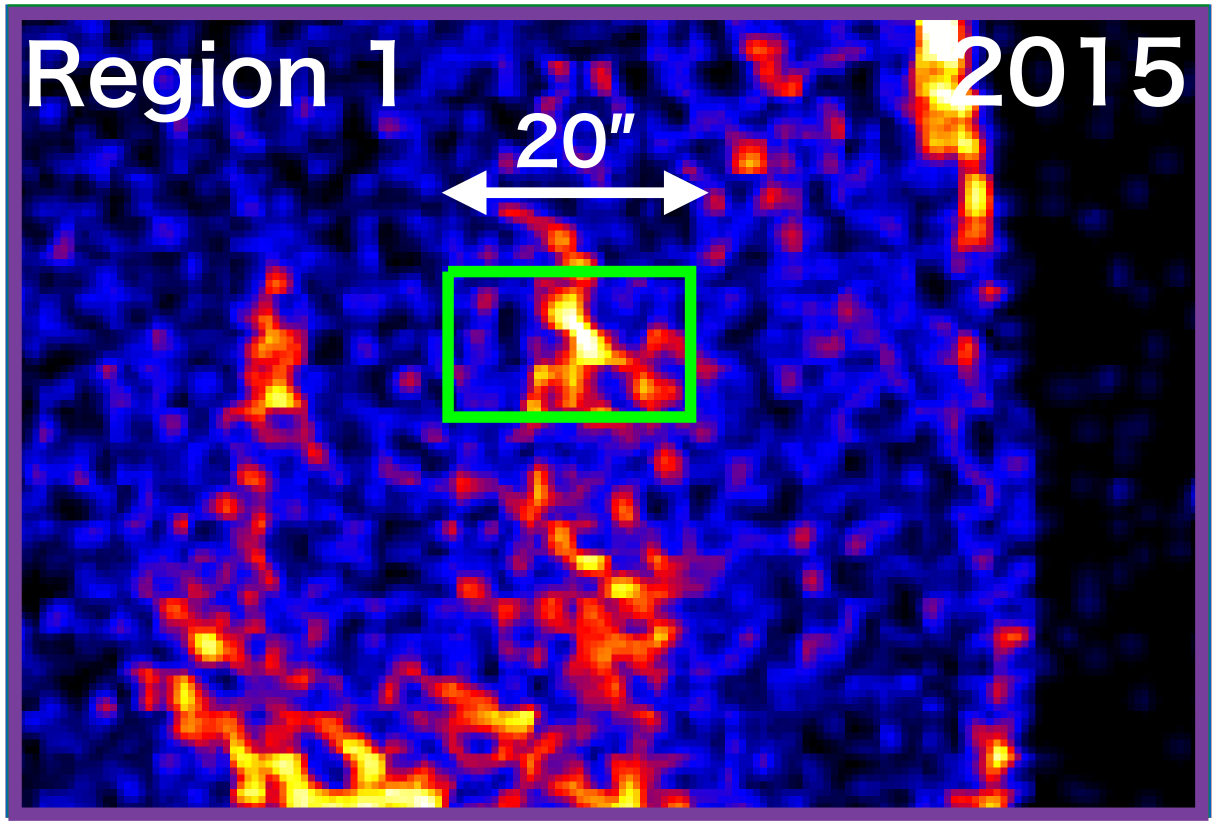


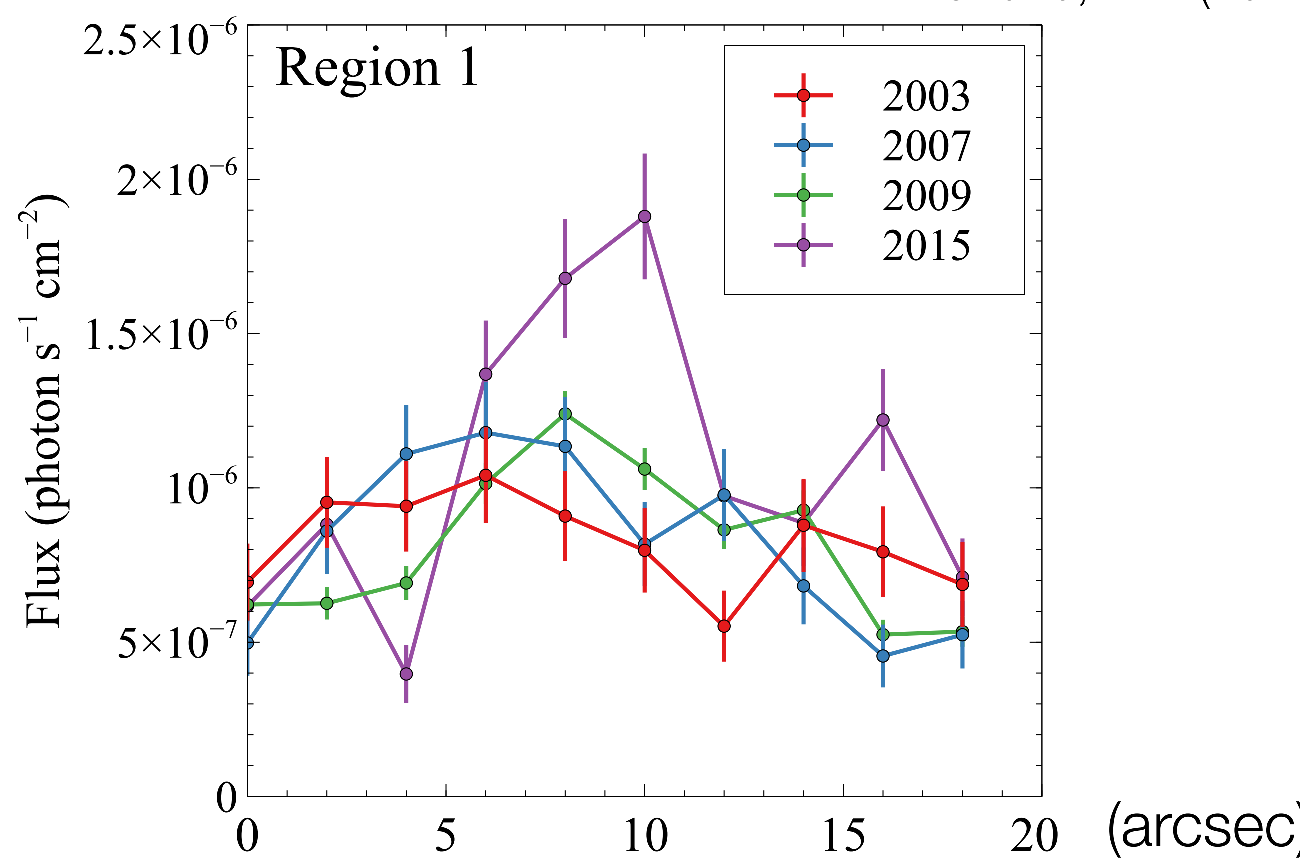


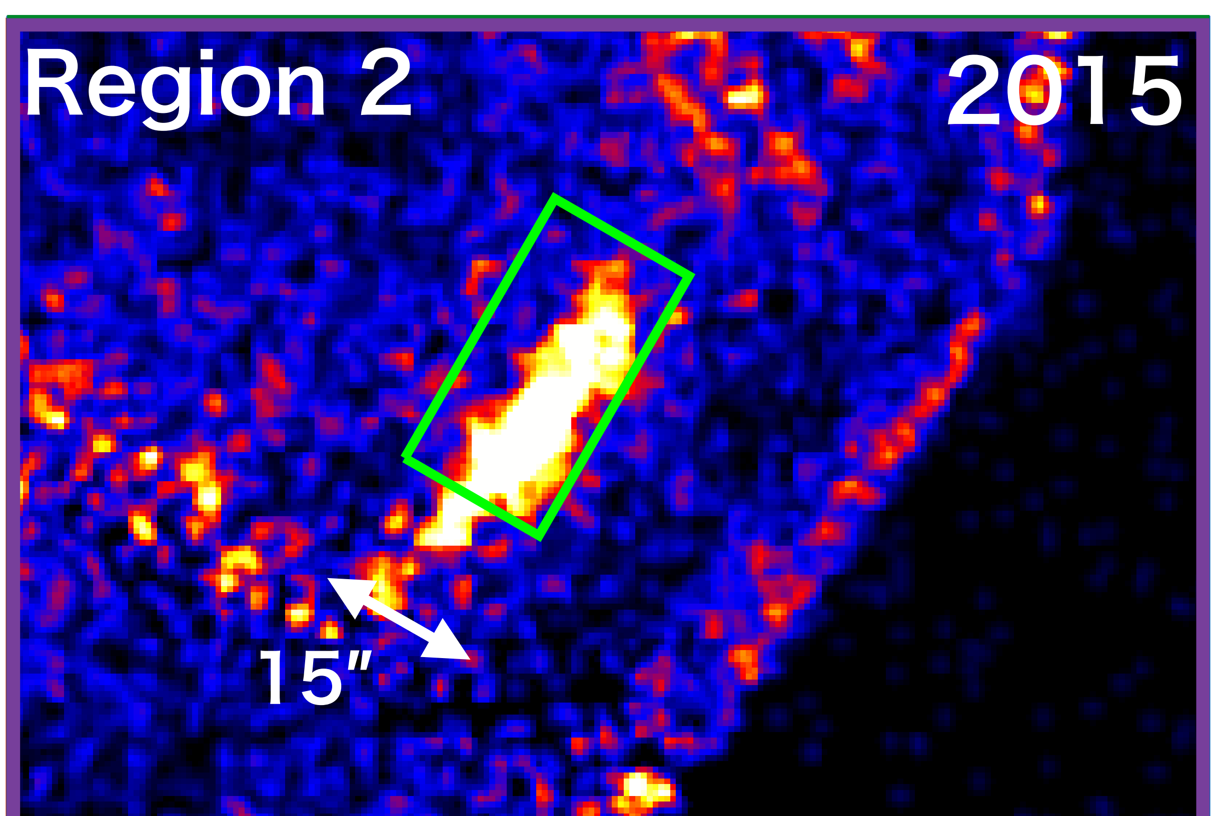


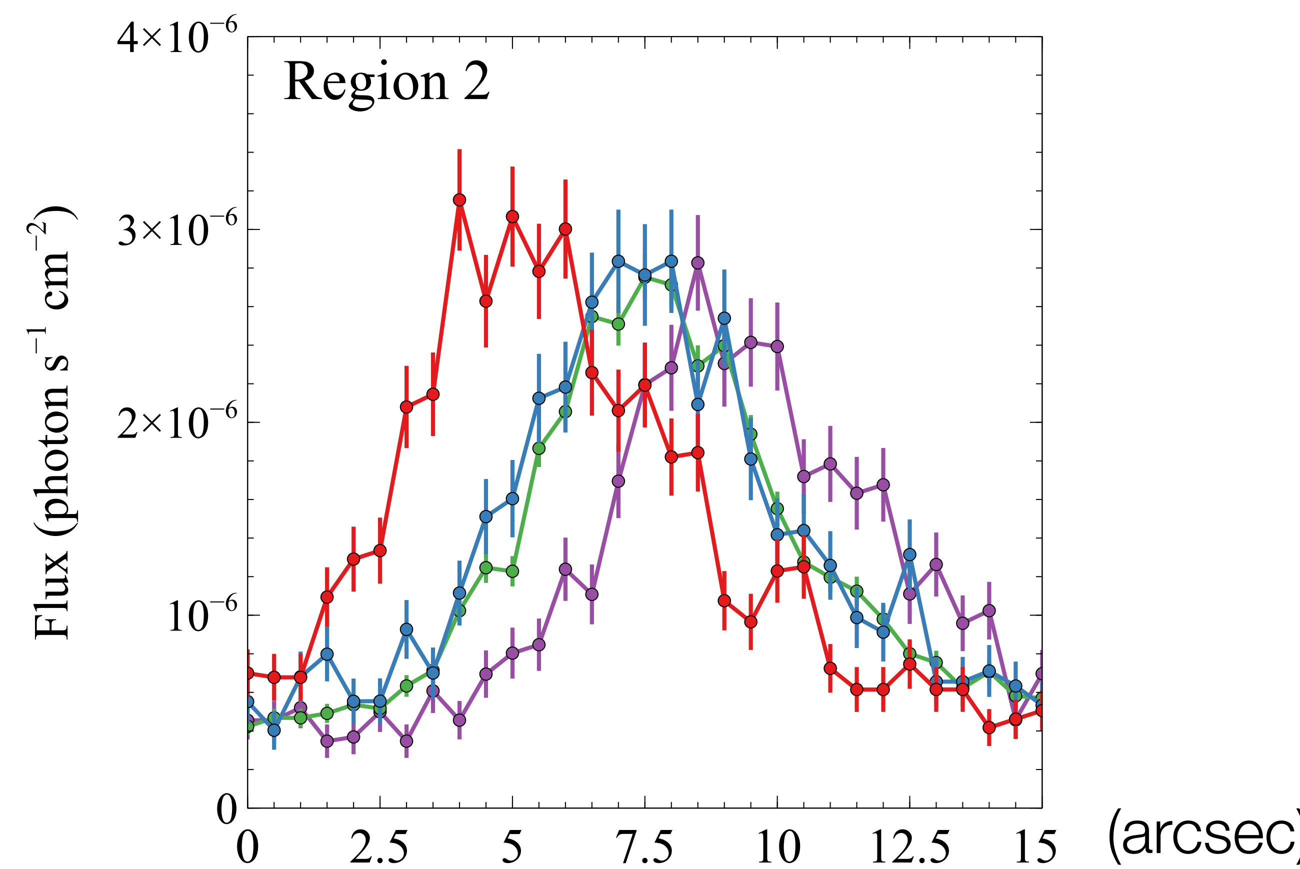

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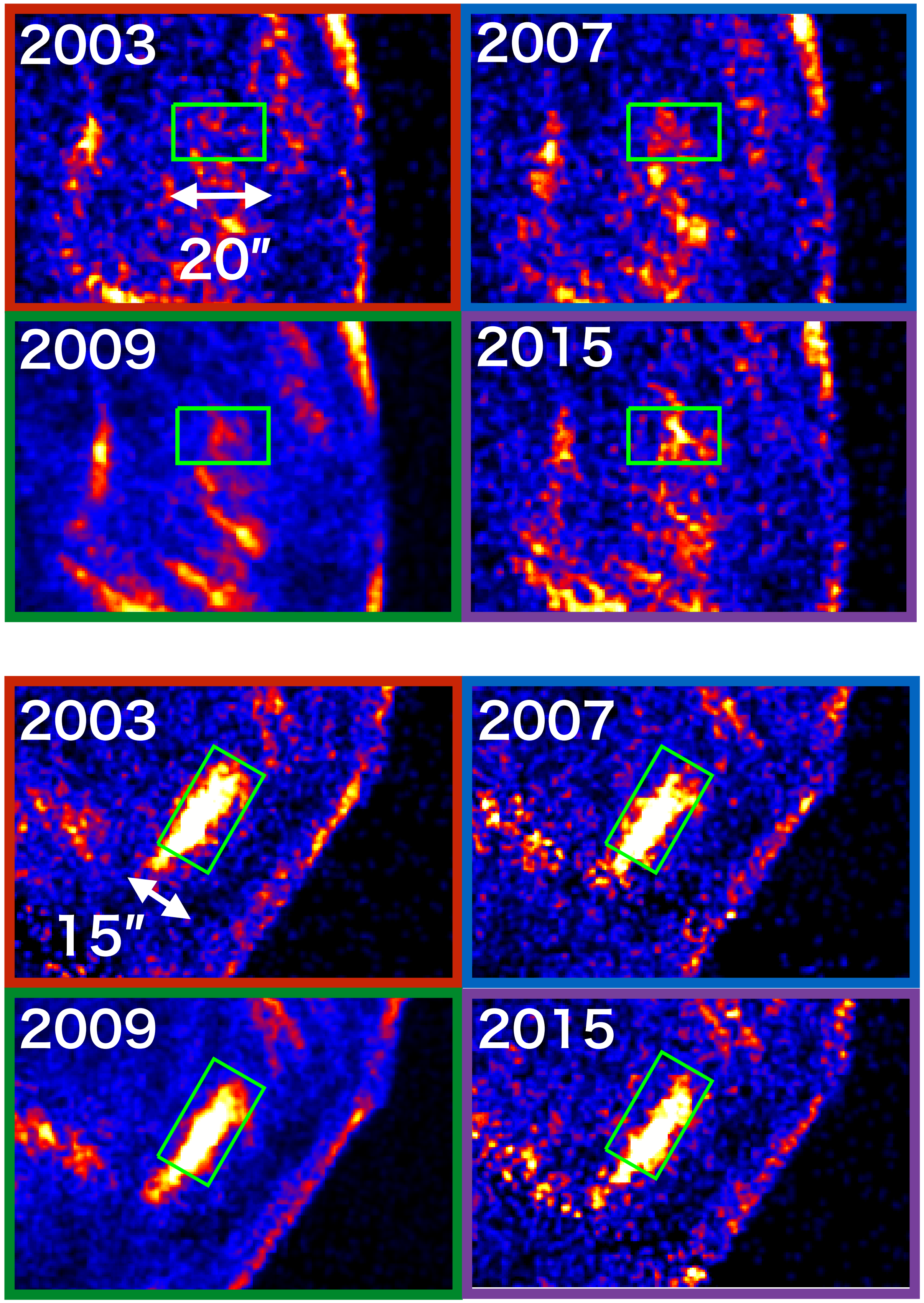
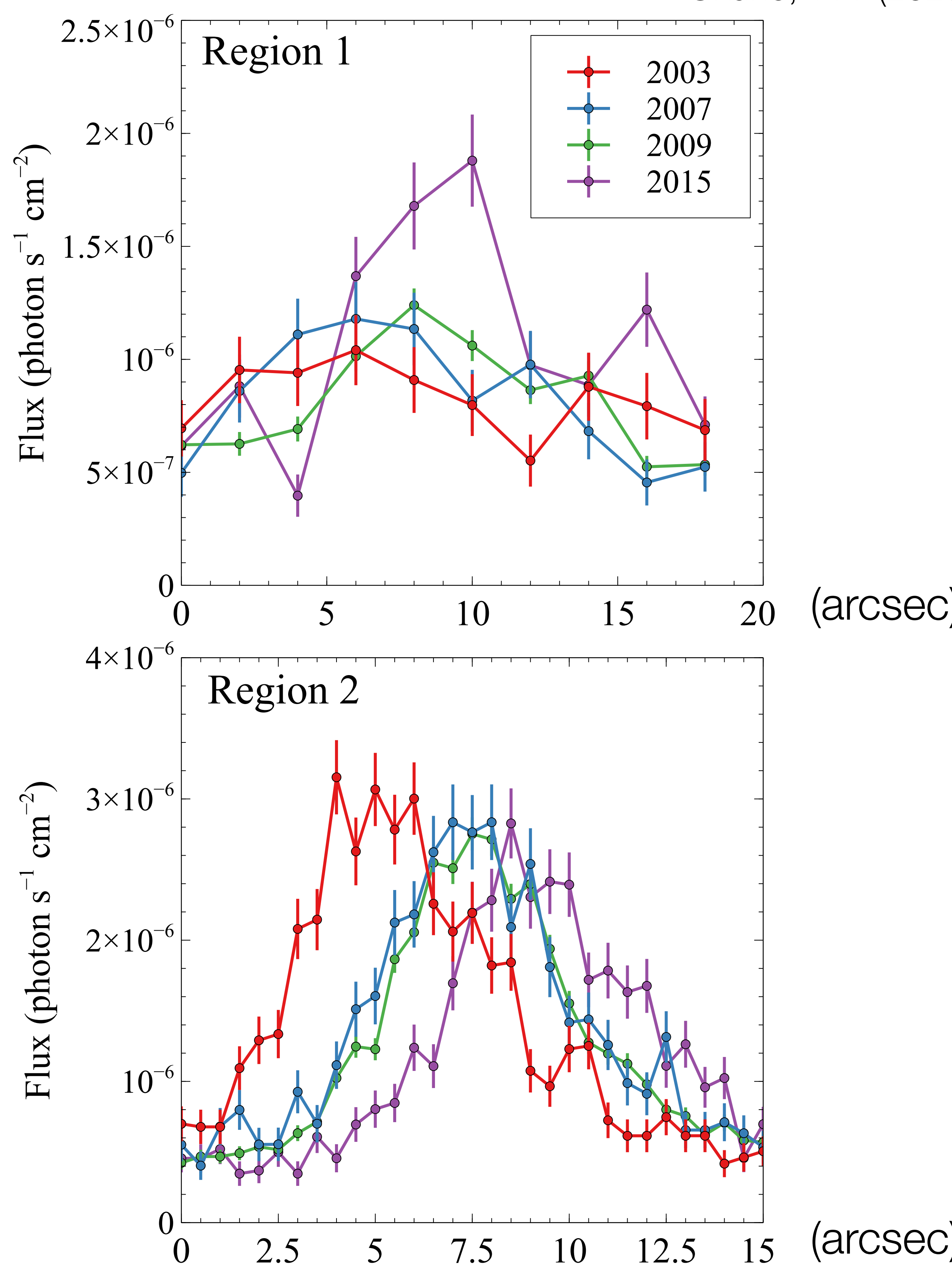
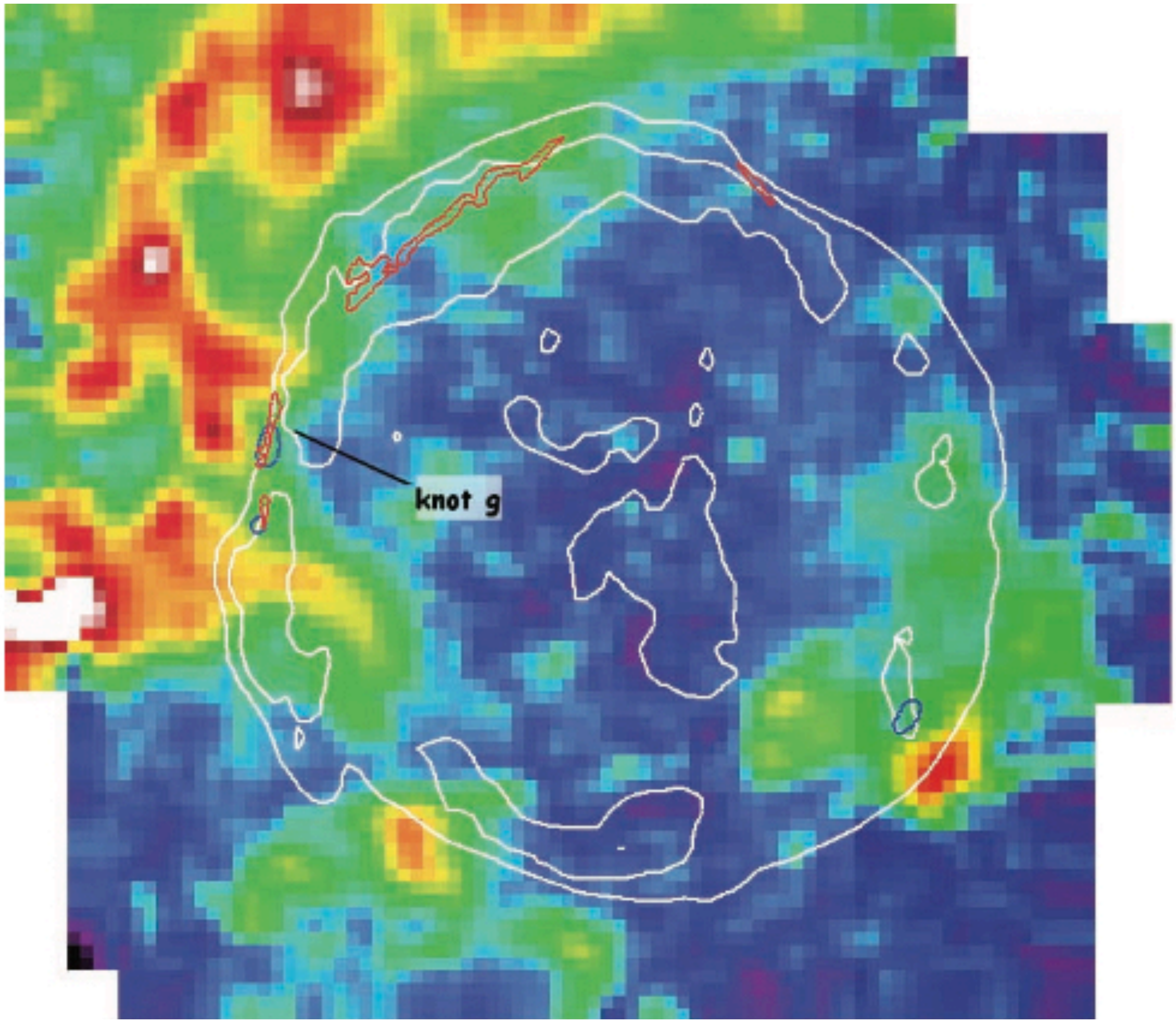


# Shock-Cloud Interaction?




Lee+ (2004)

Color: $^{12}$CO(J=1–0) Hα X-ray (4–6 keV)
Contour: 1420 MHz radio continuum

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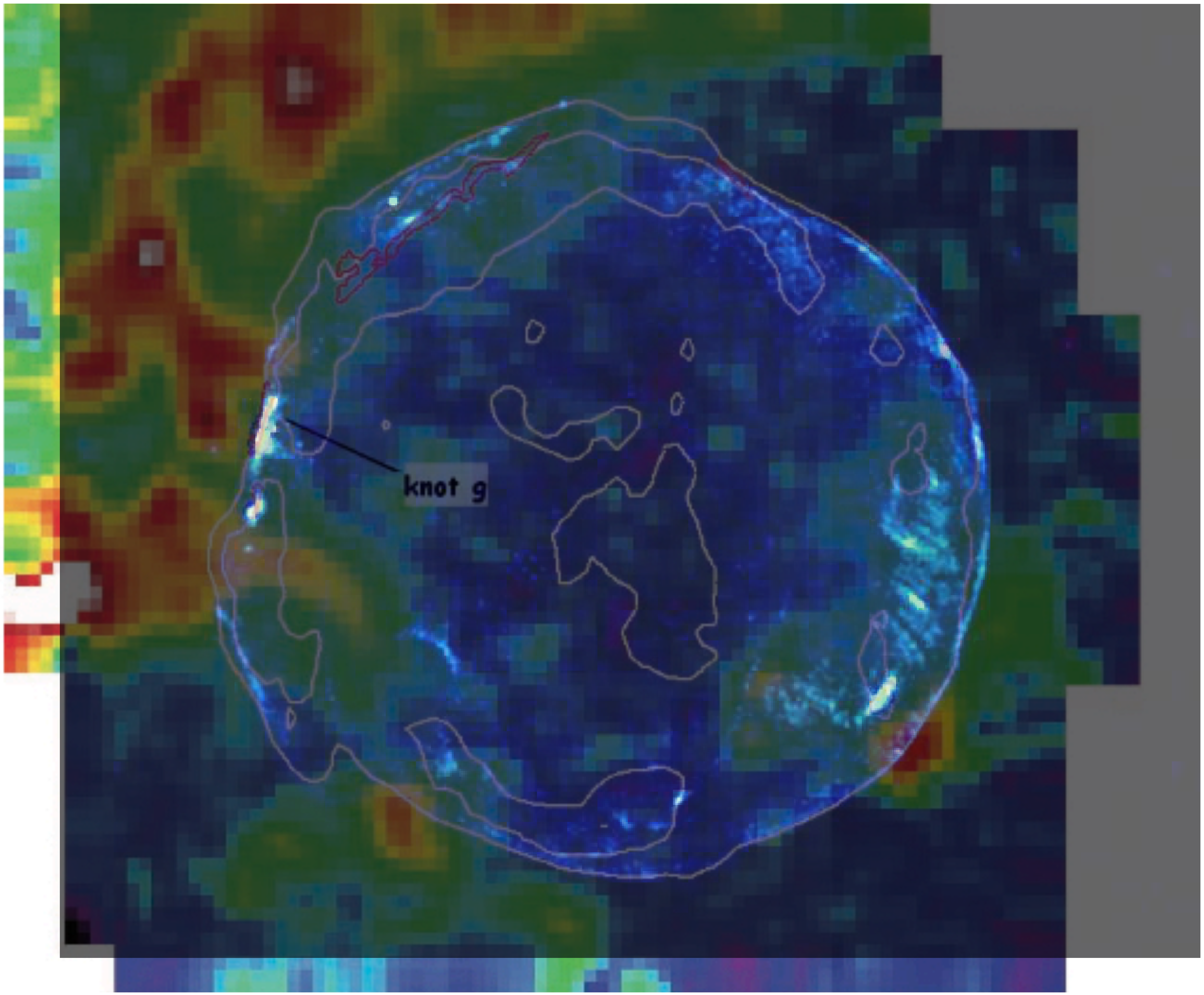


Lee+ (2004)

Color: $^{12}$CO(J=1–0) Hα X-ray (4–6 keV)
Contour: 1420 MHz radio continuum

# Summary

- Particle acceleration in SNRs extensively studied through observations in X-rays and gamma rays.
- Although gamma-ray emissions from some SNRs are firmly identified as $\pi^0$ decay, none of them extends up to ~ 100 TeV.
- PeVatrons search is currently one of the hottest topics in the field.
- Observations of interacting SNRs would be important for this purpose since highest-energy particles may have escaped in the past.
- LHAASO J1908 and G106.3 may be such examples.
- Multi-wavelength studies are important to reveal the nature of those sources.
- Synchrotron X-ray variability can provide indirect evidence that SNRs has ability to accelerate particles up to ~ PeV.
- Shock-cloud interactions seem to work as another mechanism to amplify magnetic fields.