<u>Spectrum</u> and <u>location</u> of <u>ongoing</u> particle acceleration in young supernova remnants

NuSTAR campaign of hard X-ray variability

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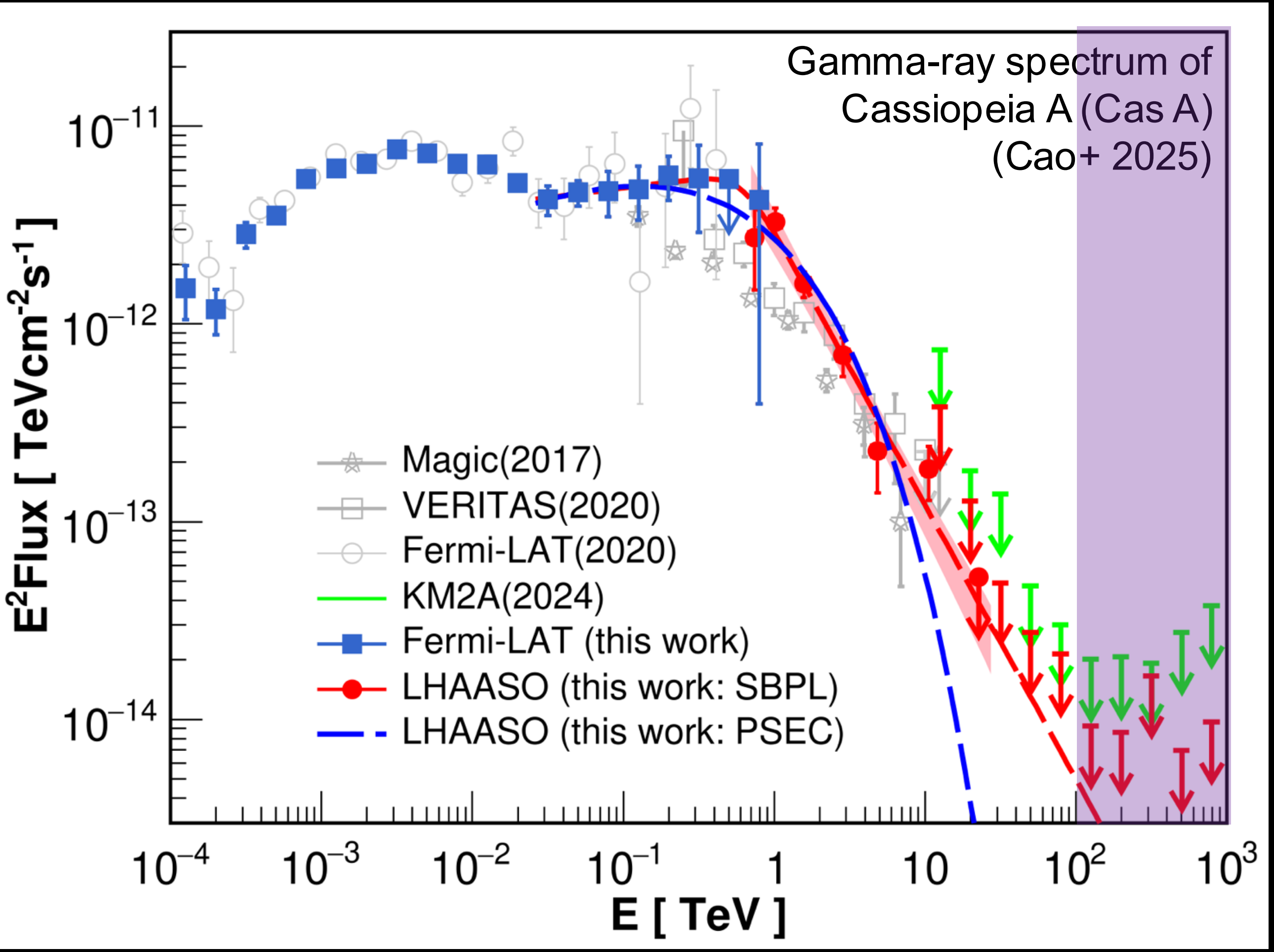
Young supernova remnants (SNRs) are NOT Ultru-high-energy (UHE > 100 TeV) γ ray sources.



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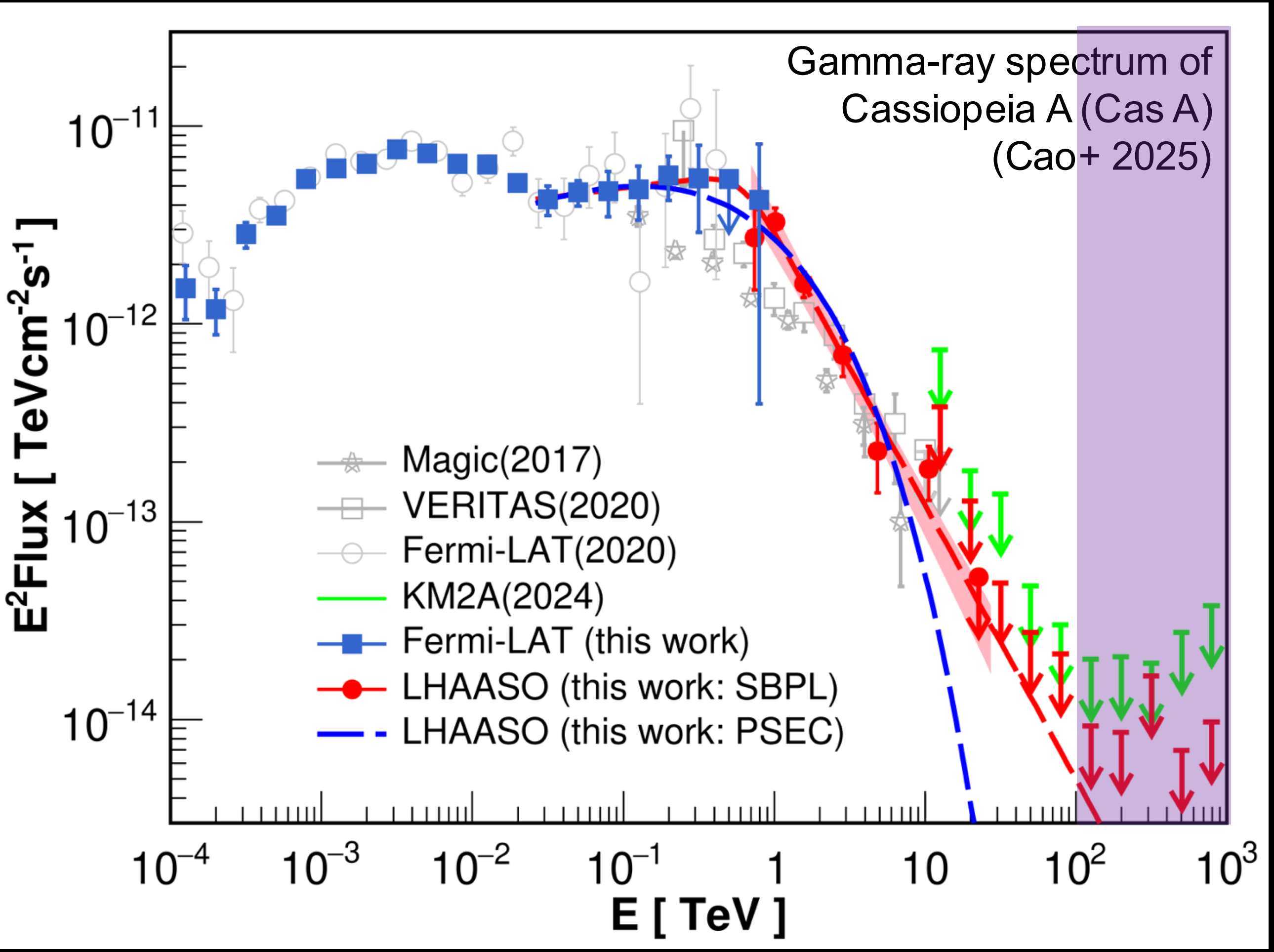
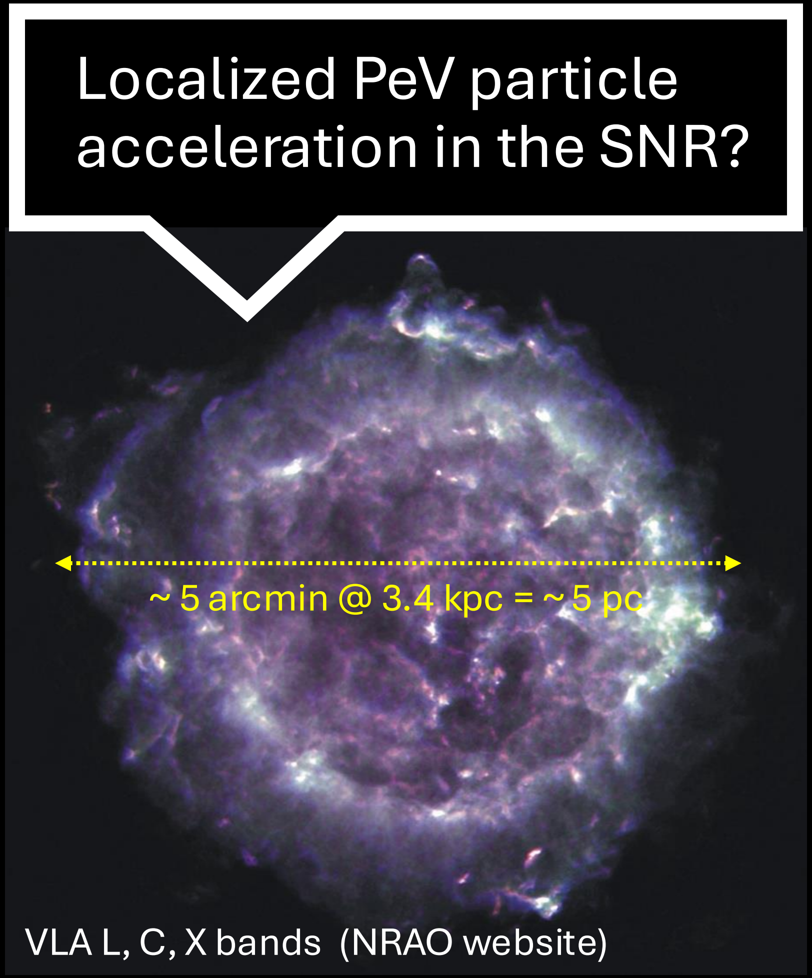
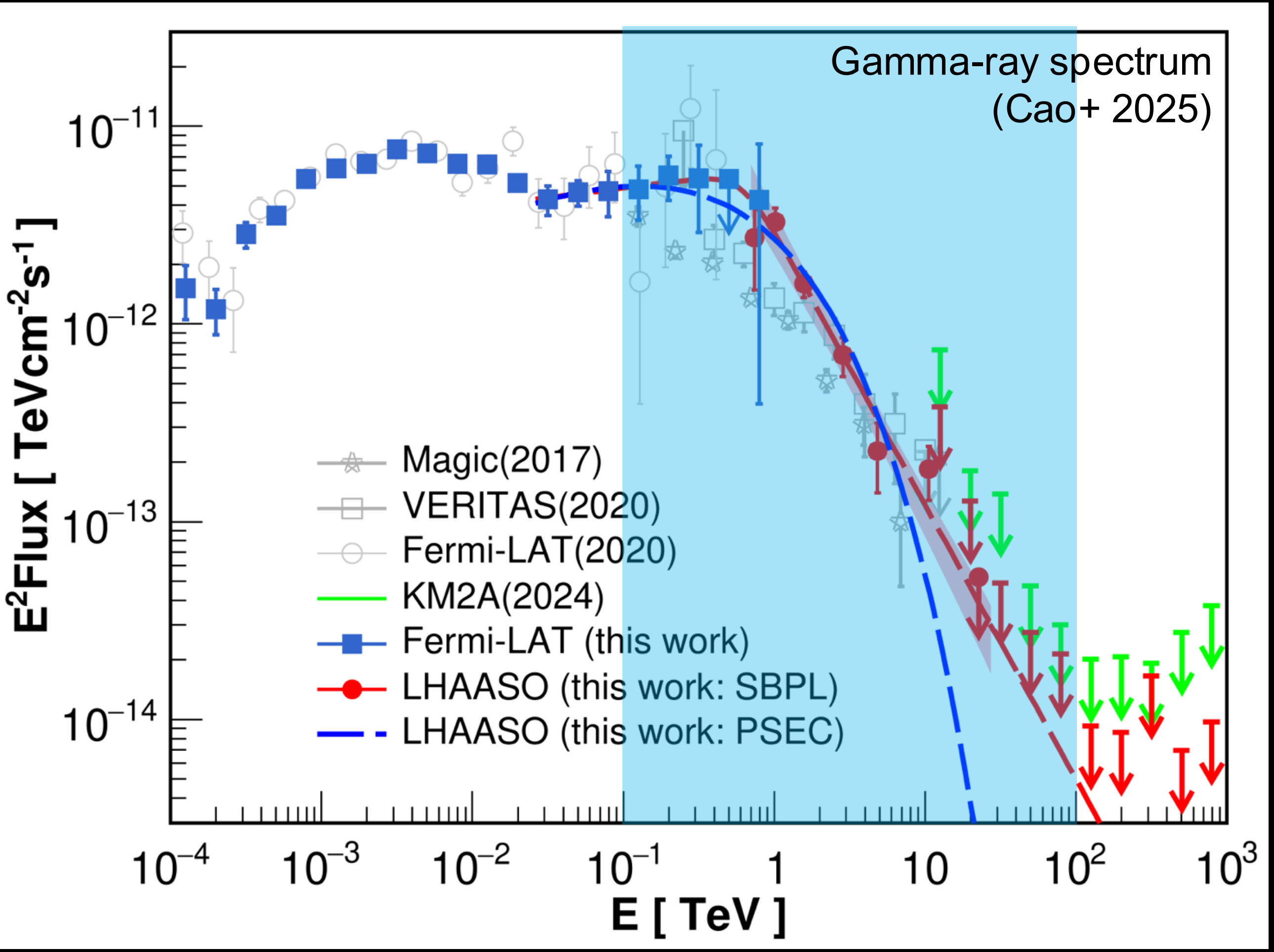
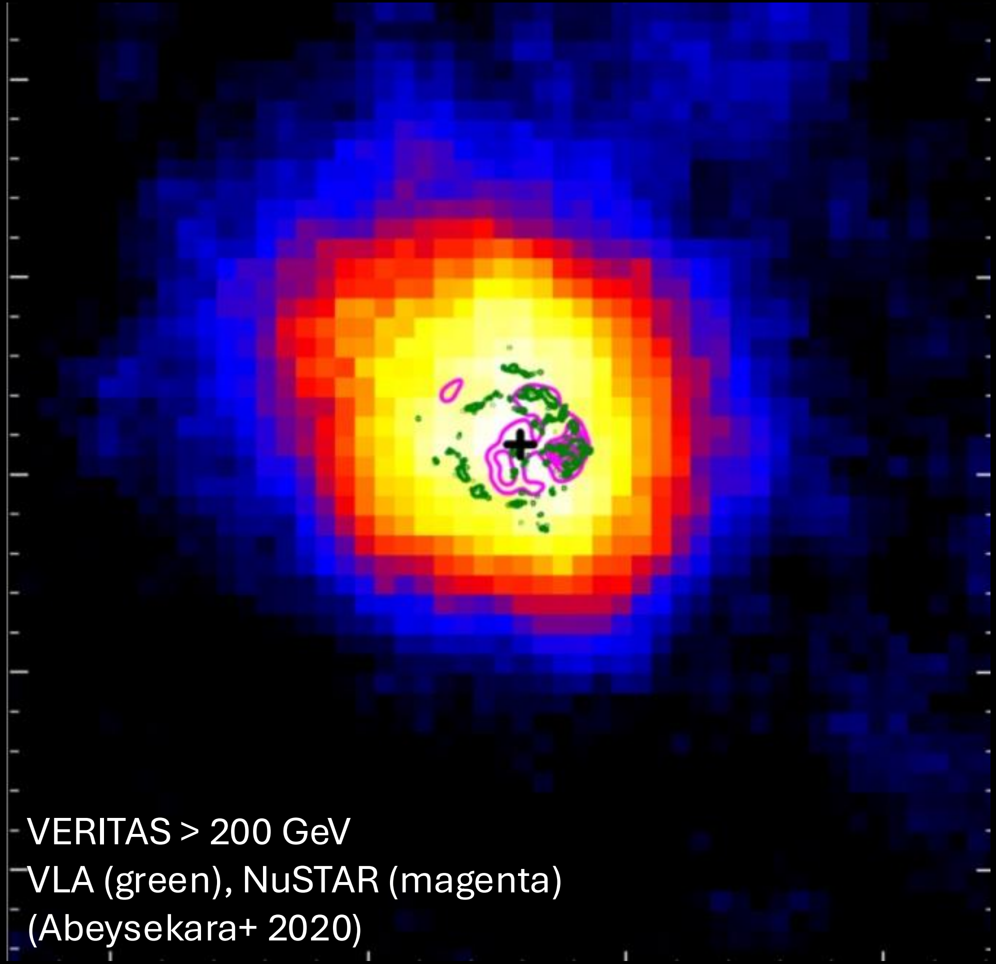


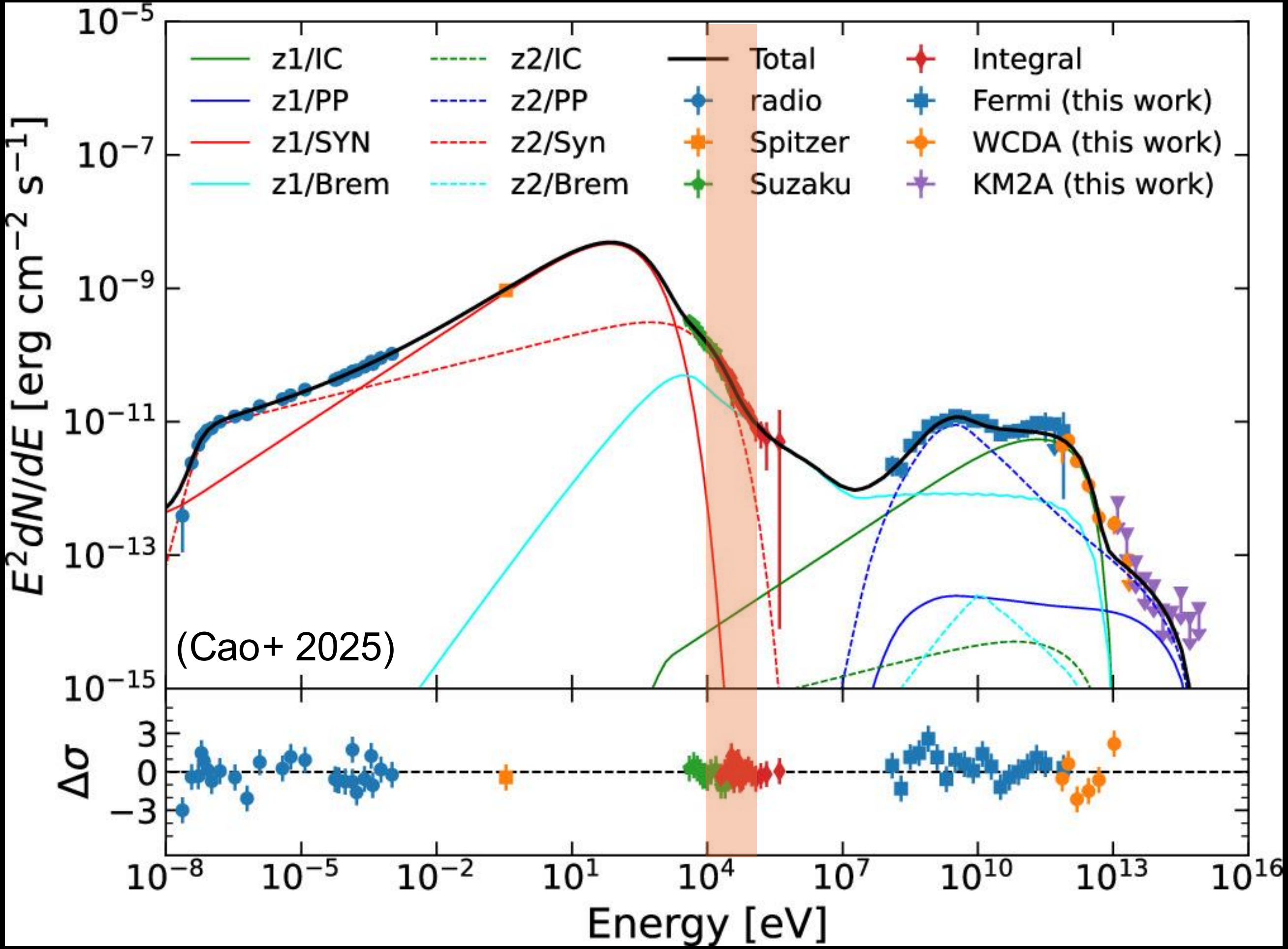


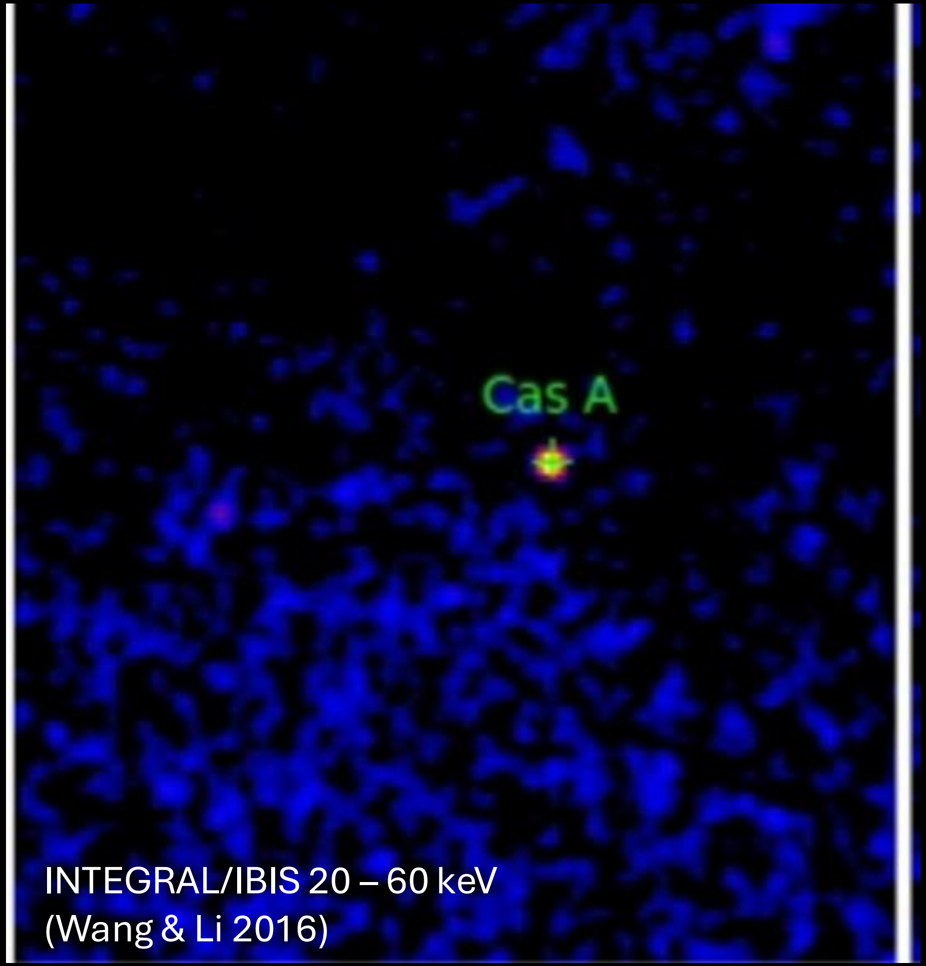
Very-high-energy (VHE > 100 GeV) telescopes cannot spatially resolve the SNRs.





Hard X-rays: the only probe for the spectrum & location of the most energetic particle acceleration





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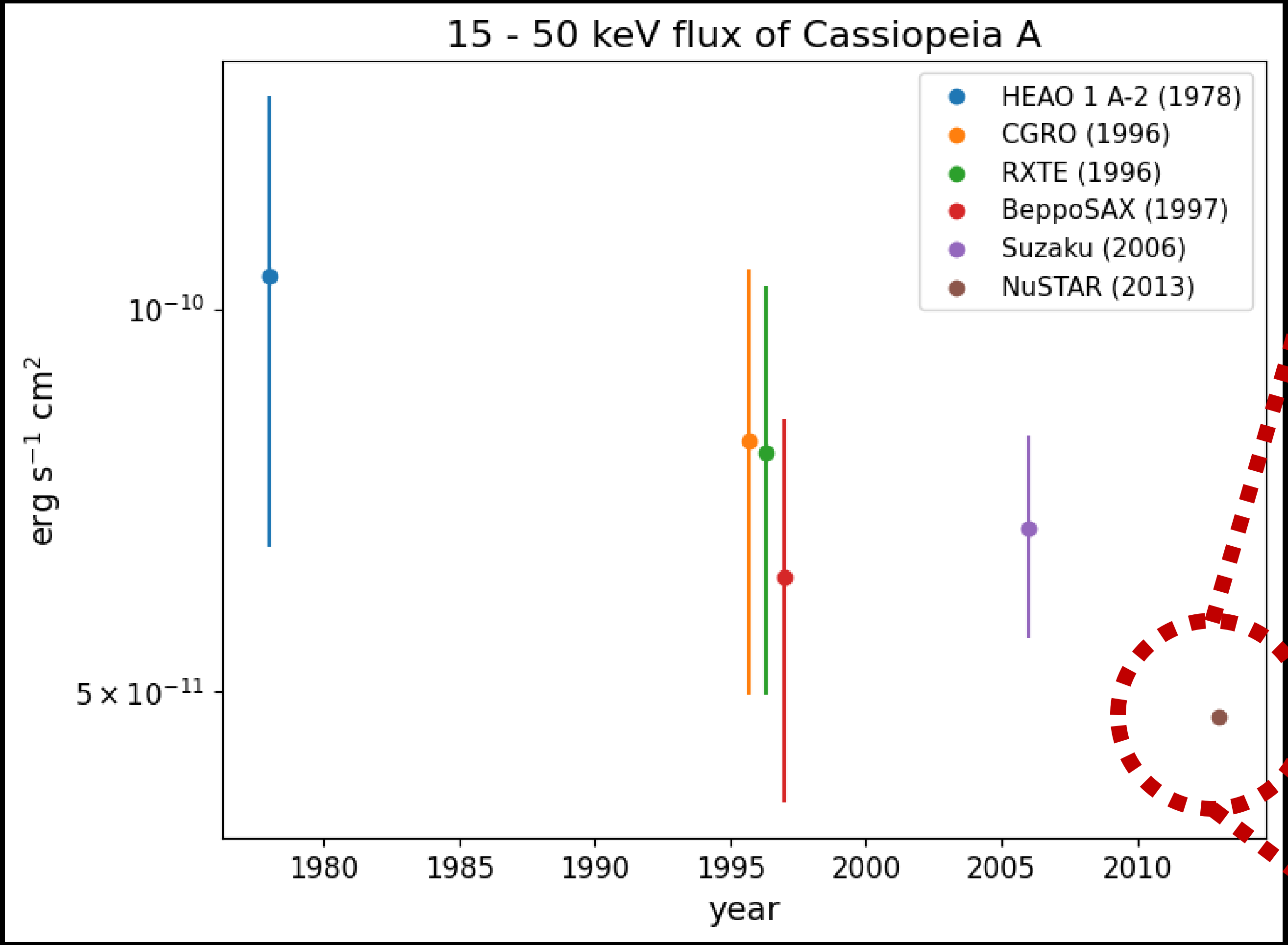
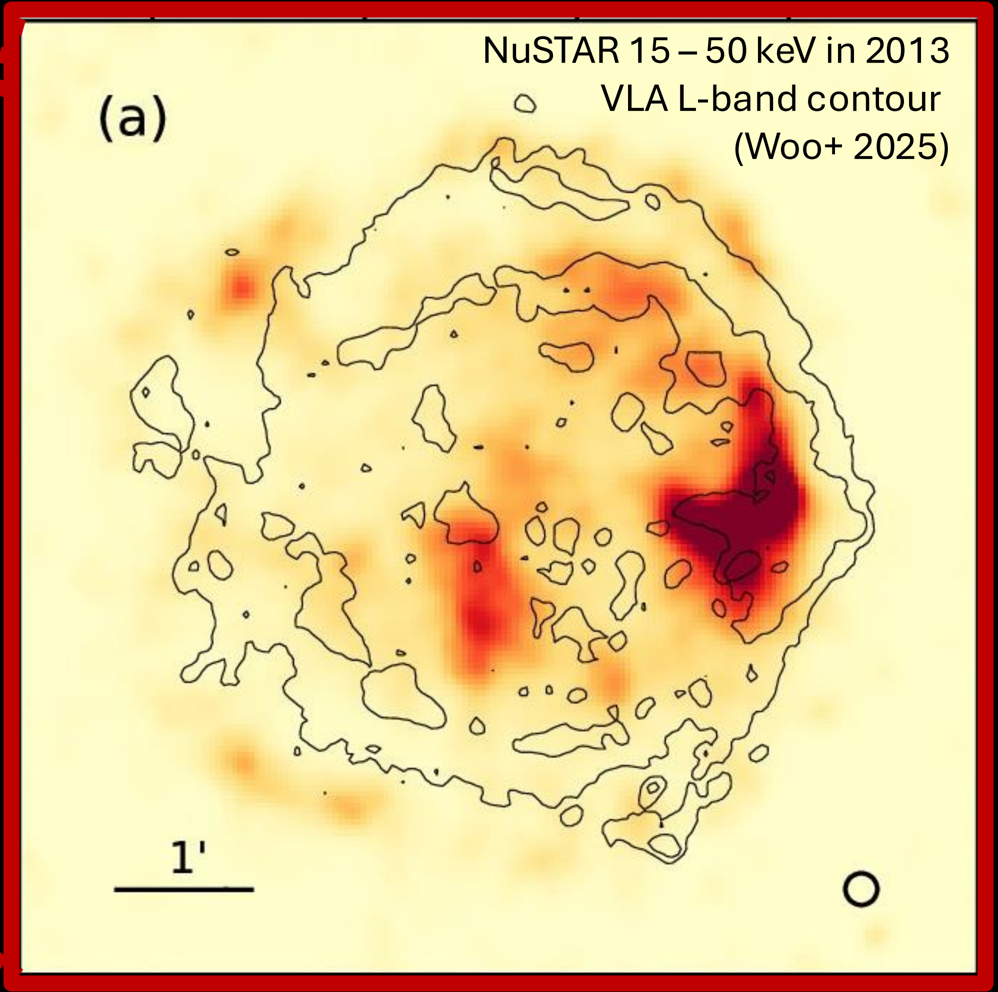
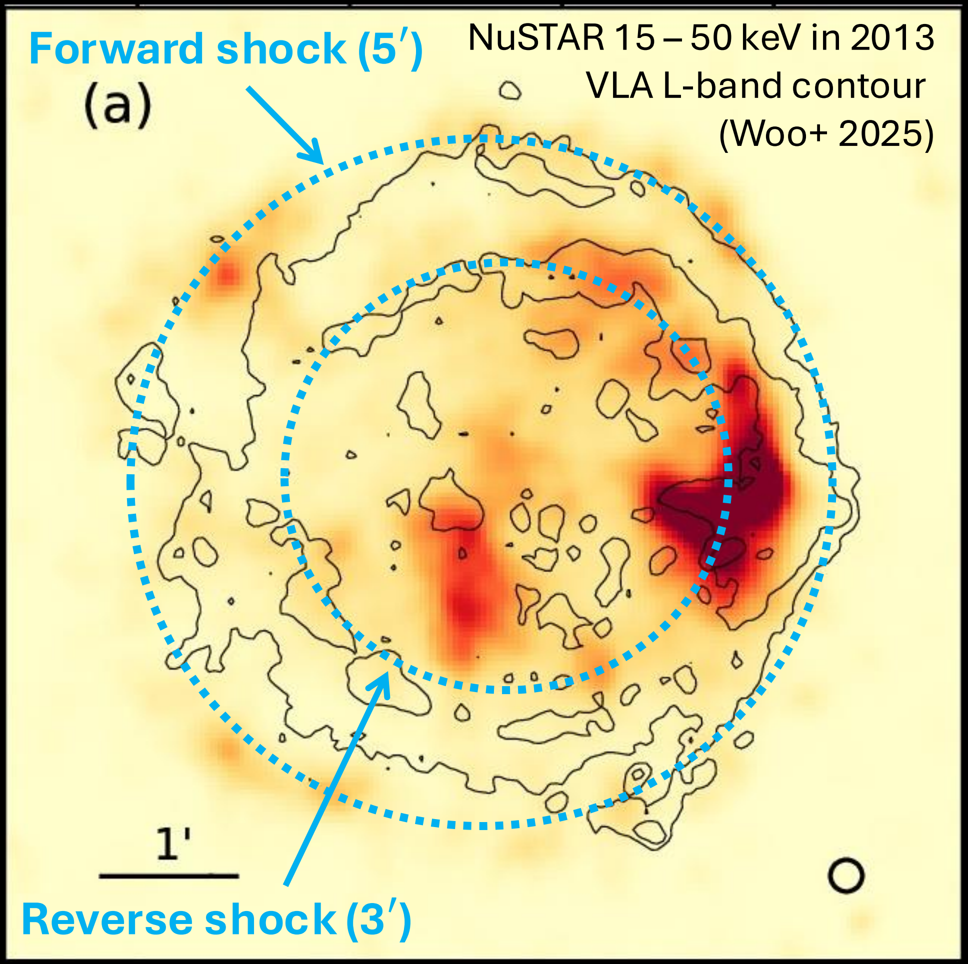
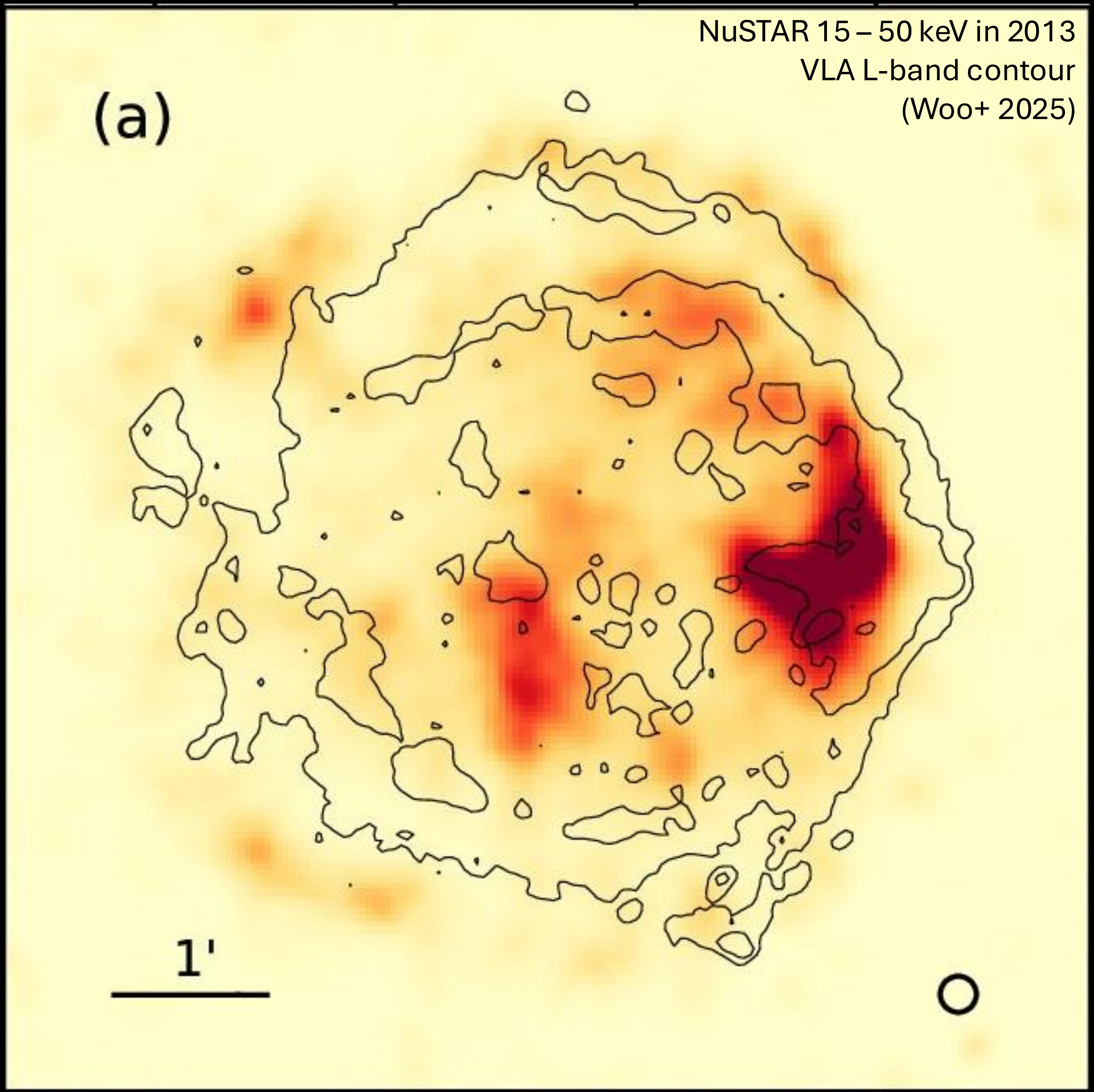


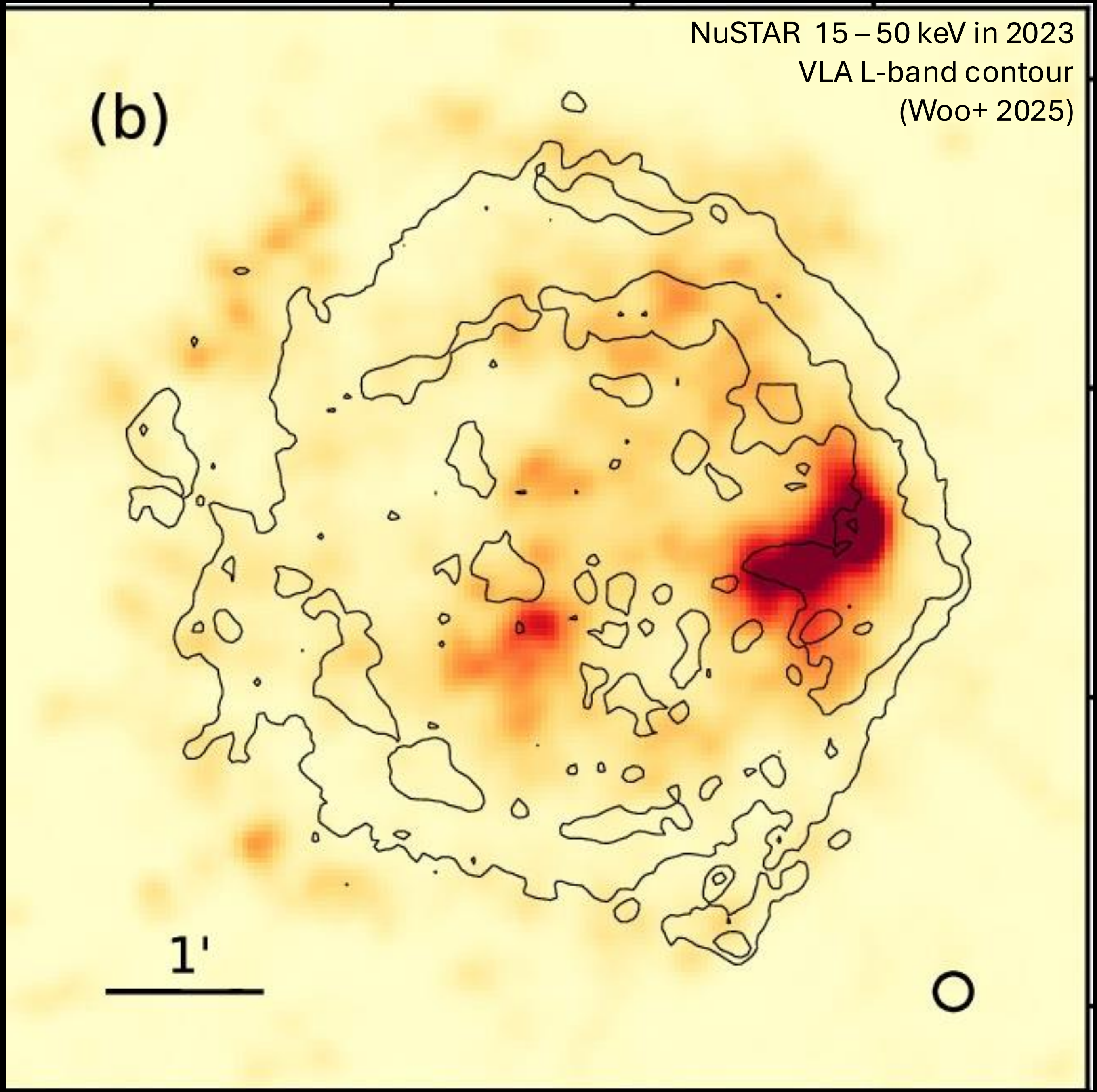


Most energetic location: reverse shock. Ongoing acceleration spectrum? Observe variability!

- Synchrotron cooling time scale
  $\sim 12 \left(\frac{E_\gamma}{10\ \mathrm{keV}}\right)^{-1/2} \left(\frac{B}{100\ \mu\mathrm{G}}\right)^{-3/2}$ yr
- **~ 10 years** is a good interval for probing the **interplay between fast cooling and acceleration** in the hard X-ray band.
- Archival NuSTAR data (2012 – 2013): 14 observations, 2.2 Ms
- **New NuSTAR data (2023): 2 observations, 200 ks**

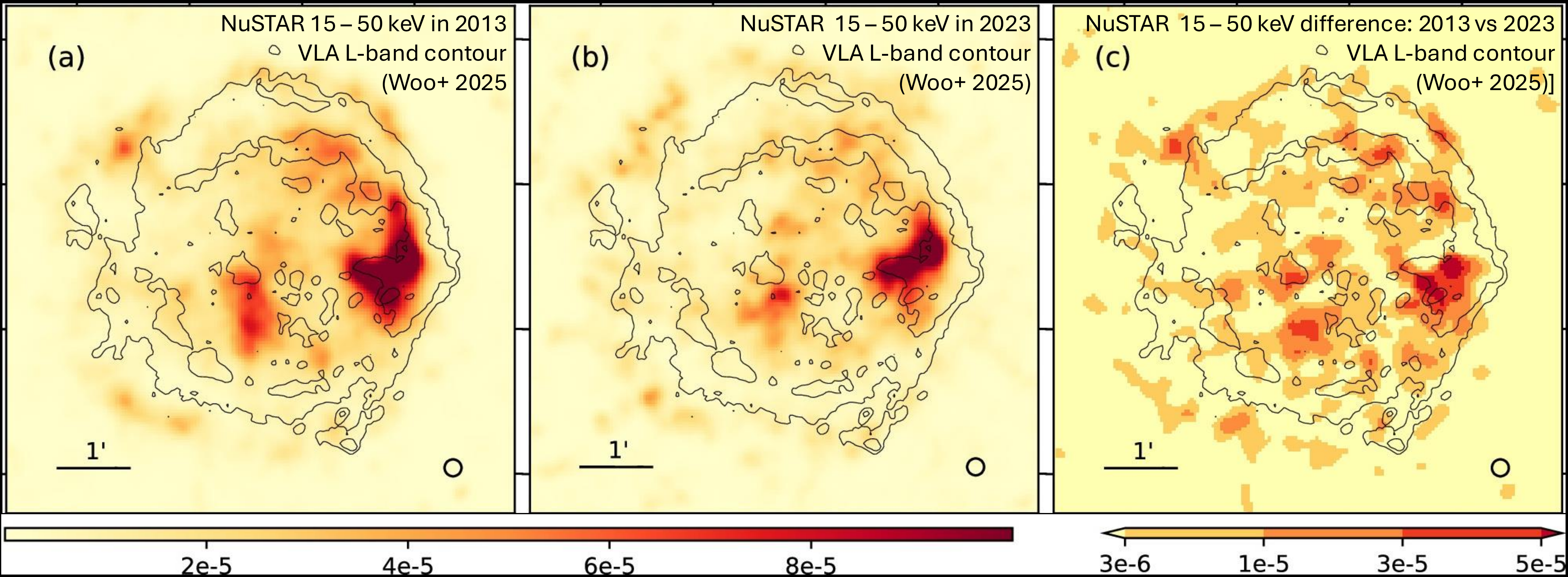



NuSTAR 15 – 50 keV in 2013
VLA L-band contour
(Woo+ 2025)
(a)
1'

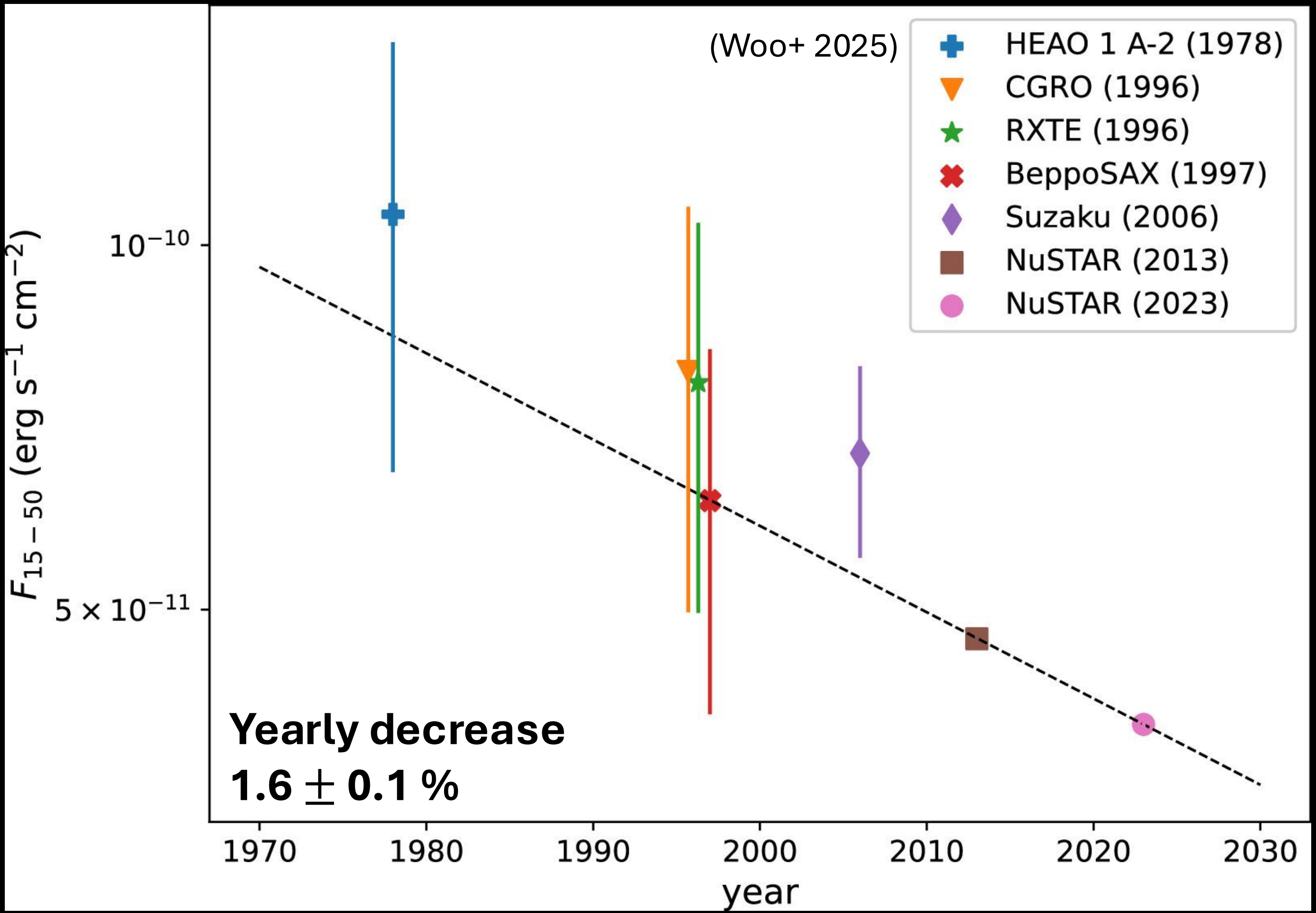


NuSTAR 15 – 50 keV in 2023
VLA L-band contour
(Woo+ 2025)
(b)
1'

First detection of hard X-ray variability in Cas A! Reverse shock is most energetic and variable.



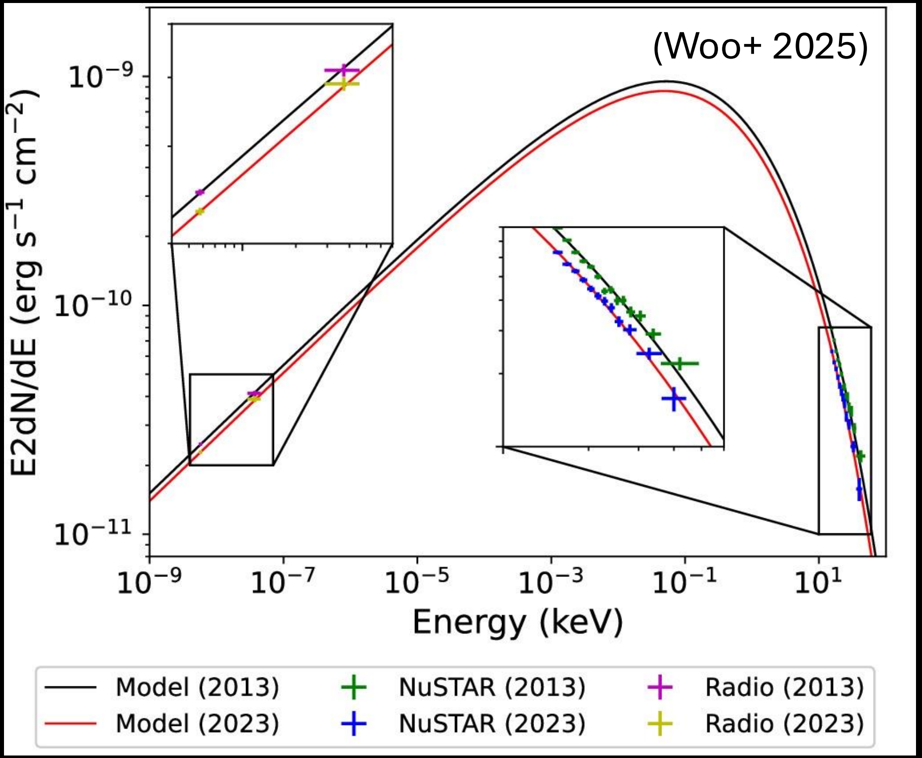
Most precise hard X-ray flux measurement with NuSTAR shows the whole remnant dimmed by 15% over 10 yrs.



Sycnrhotron cooling alone cannot explain the observed 15% NuSTAR flux decrease.

- For the observed NuSTAR flux decrease, **<u>magnetic field (B) = 6 μG</u>**
- **Contradicting**
  - Other independent estimations: **B $\sim 100\mu$G – few mG**

    (Longair 1994, Wright+ 1999, Berezhko+ 2003, Vink & Laming 2003, Uchiyama & Aharonian 2008, Patnaude & Fesen 2009, Abdo+ 2010, Sato+ 2018, Abeysekara+ 2020…)



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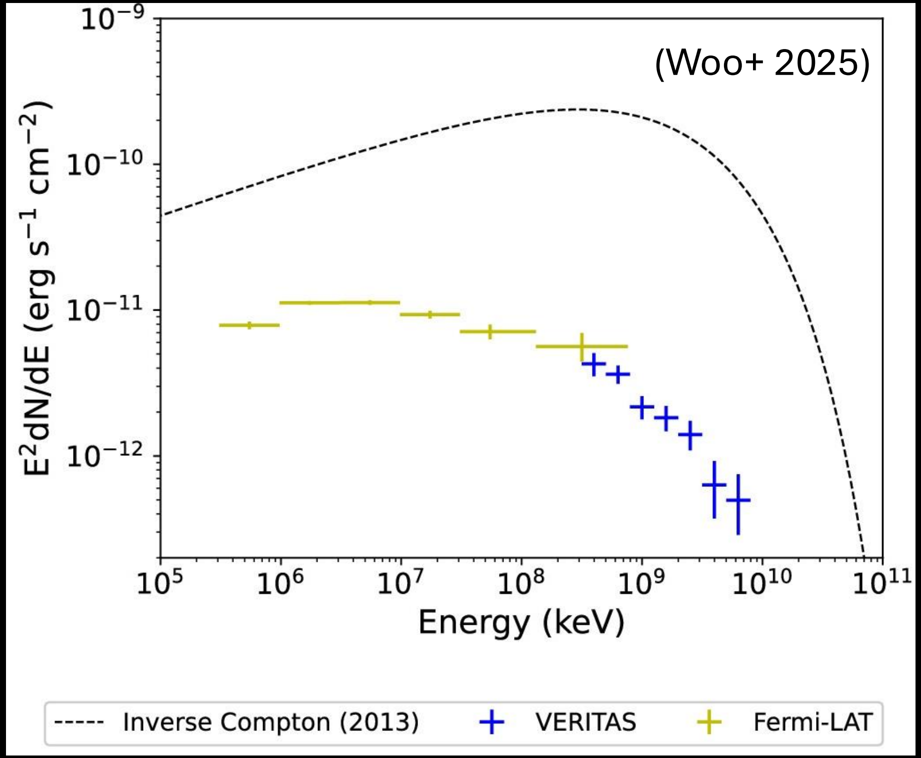
  - **Leptonic (inverse Compton) gamma-rays >>>>> observed gamma-ray flux**

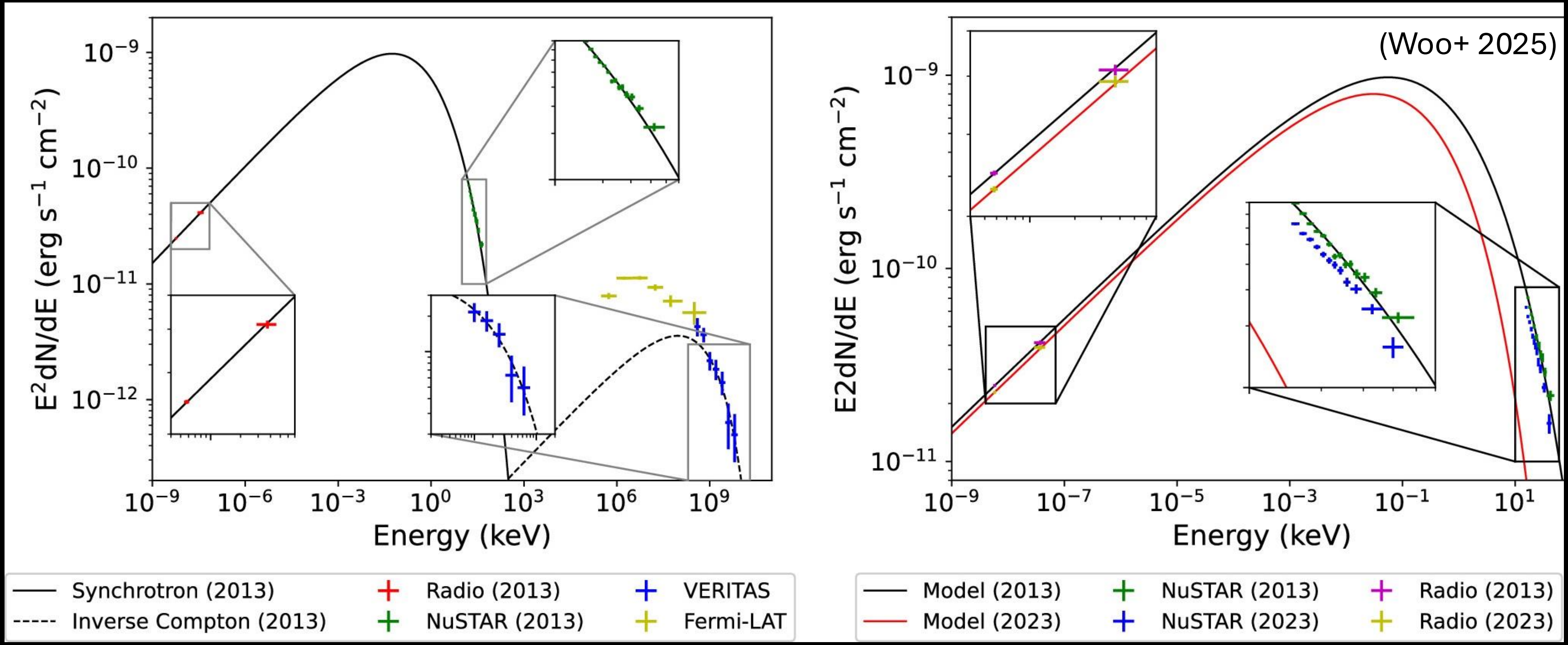
→ **B field must be >>>>> 6 μG.**



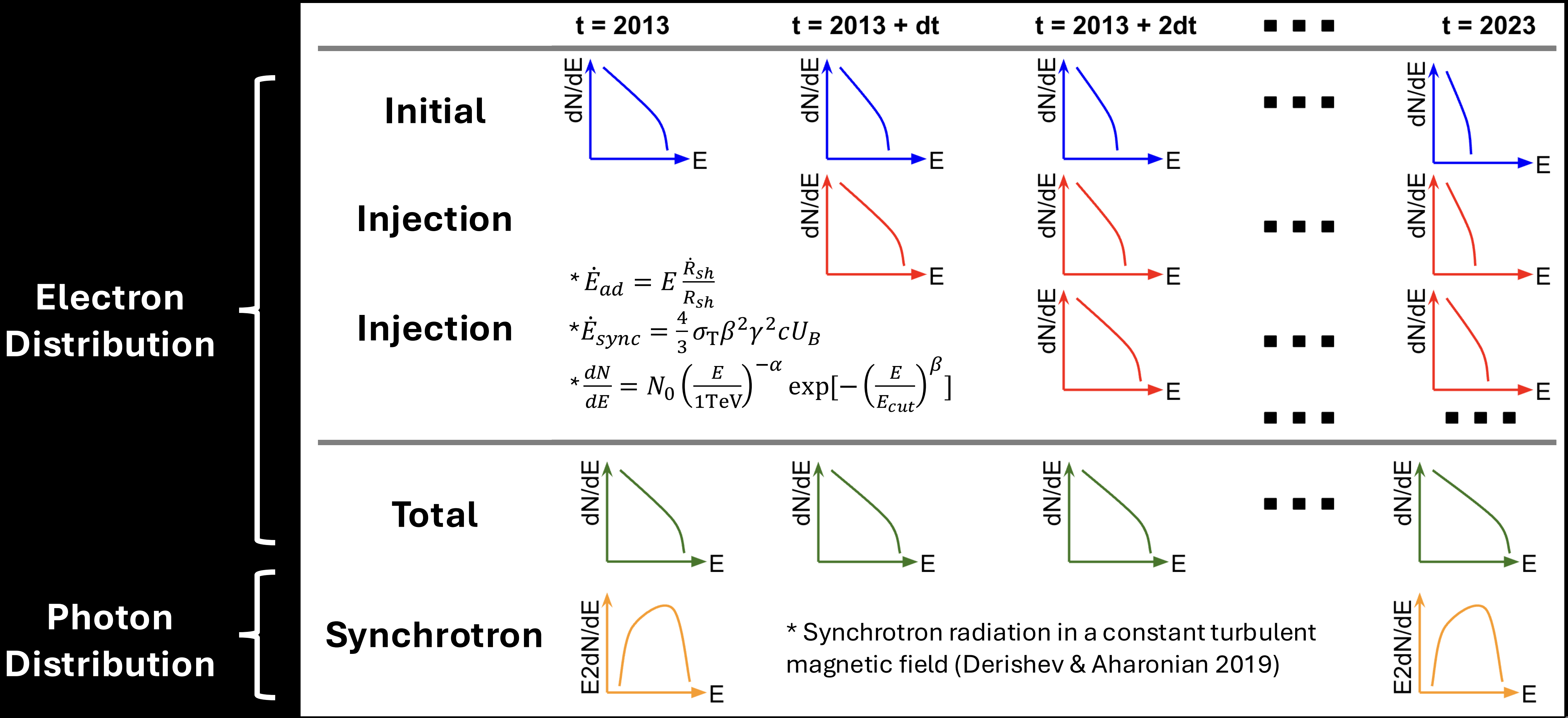
Lower-limit B overpredicts NuSTAR flux decrease. Ongoing electron acceleration is required.

- Not to overpredict observed gamma-ray flux, **lower limit B = $123 \pm 3\ \mu$G**
- Predicted NuSTAR flux decrease >>>>> observed flux decrease

→ **Ongoing electron injection is required to compensate fast cooling.**



Our cooling & injection model + NuSTAR variability constrain the current electron injection spectrum.



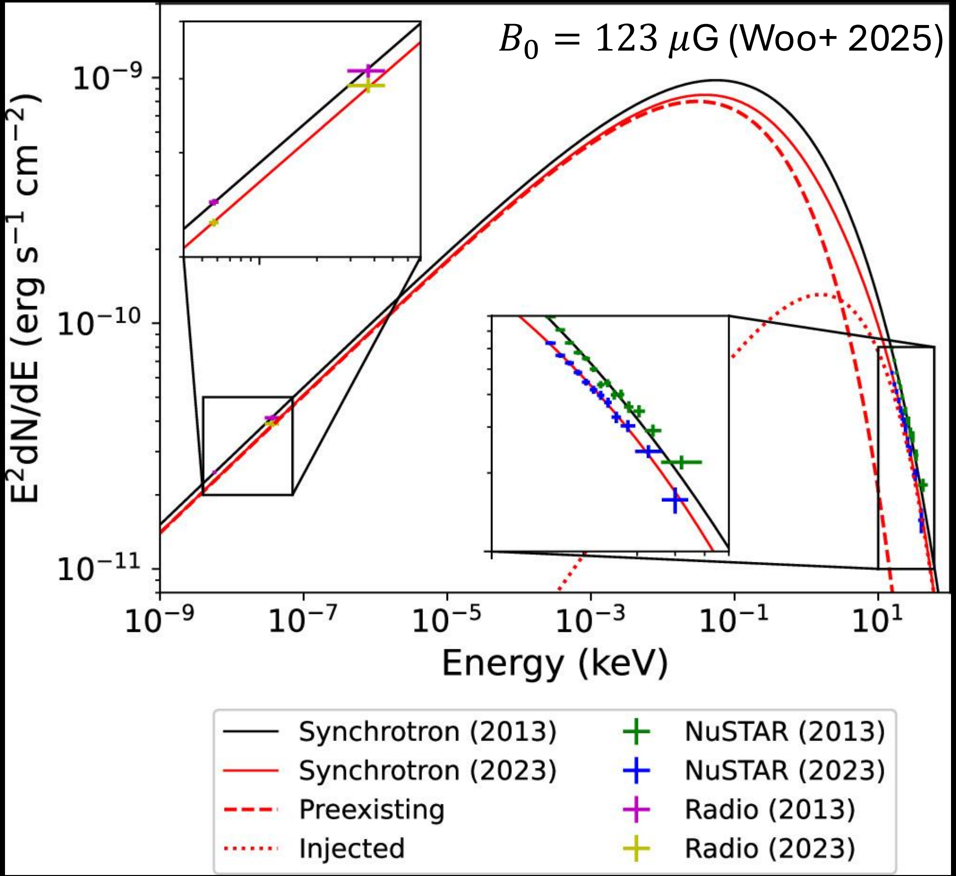
Current injection spectrum is harder than before. Ecut << 1 PeV confirms Cas A is not a PeVatron.

- **Current injection spectrum must be harder** than that of the earlier stage!
- Injection spectrum **(before cooling) has higher Ecut** than the preexisting spectrum (after cooling)

Table 2
Best-fit Parameters for the Synchrotron Cooling and Injection Model

Electron Population	Preexisting Electrons[a]	Injected Electrons		
B_0 (μG)	123 ± 8	123[b]	400[b]	1000[b]
q	2.44 ± 0.03	2.2	2.0	1.9
$E_{\rm cut}$ (TeV)	4 ± 1	36	19	12
β	0.74 ± 0.05	2[b]	2[b]	2[b]
Total electron energy (fraction)[c]	(1.09 ± 0.02) × 10^{49} erg	0.4%	0.9%	2.1%
Injection rate (10^{37} erg s^{-1})	…	14	4	2

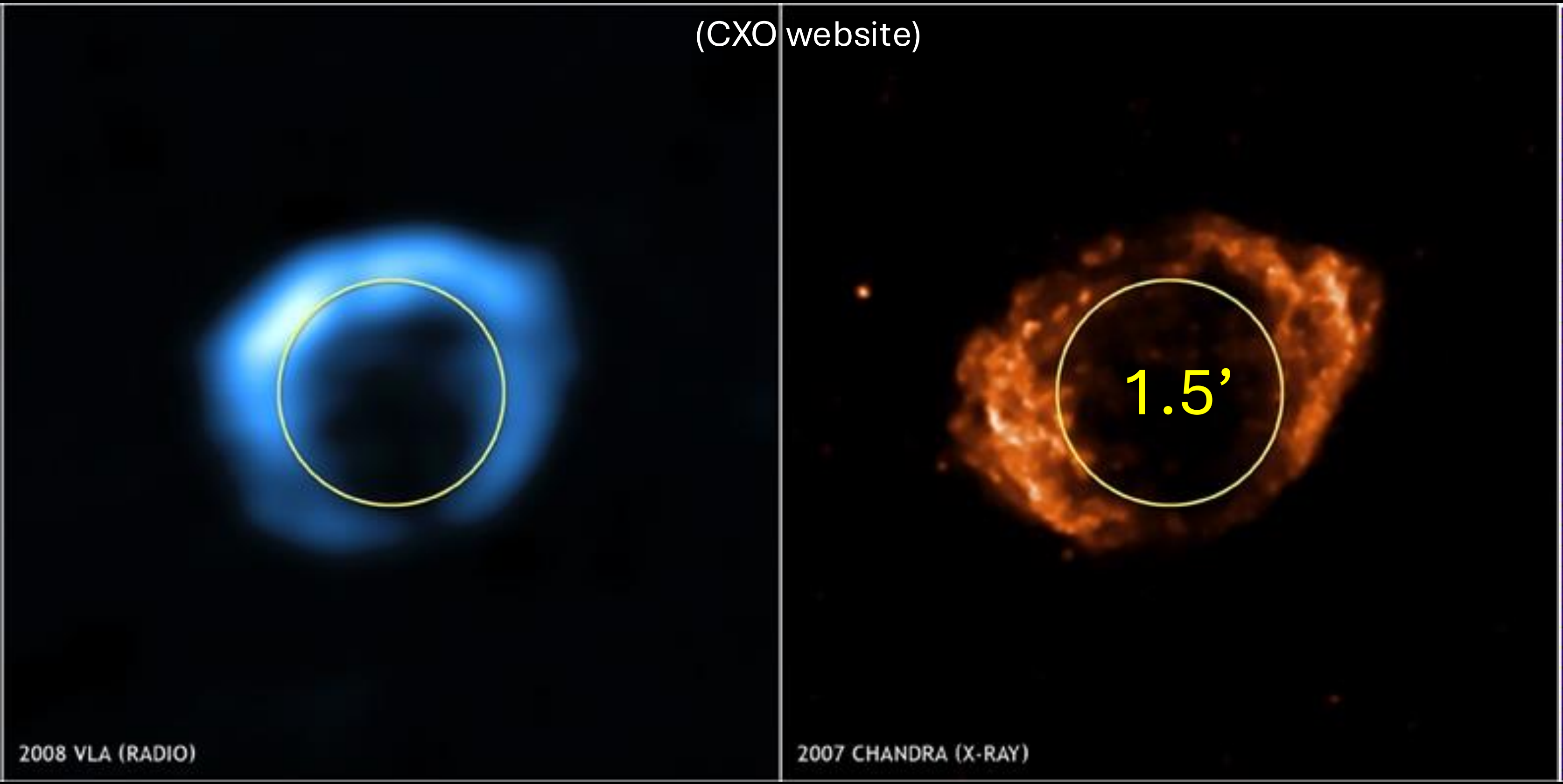
Notes.
[a] The parameters for preexisting electrons are given only for the lower-limit magnetic field $B_0 = 123 \pm 8$ μG. For higher magnetic fields, q and β do not change, while $E_{\rm cut}$ and total electron energy decrease.
[b] Parameters were held fixed.
[c] Total electron energy is reported for preexisting electrons. The fraction of the total energy of the preexisting electrons that were injected between 2012–2013 is reported for injected electrons.

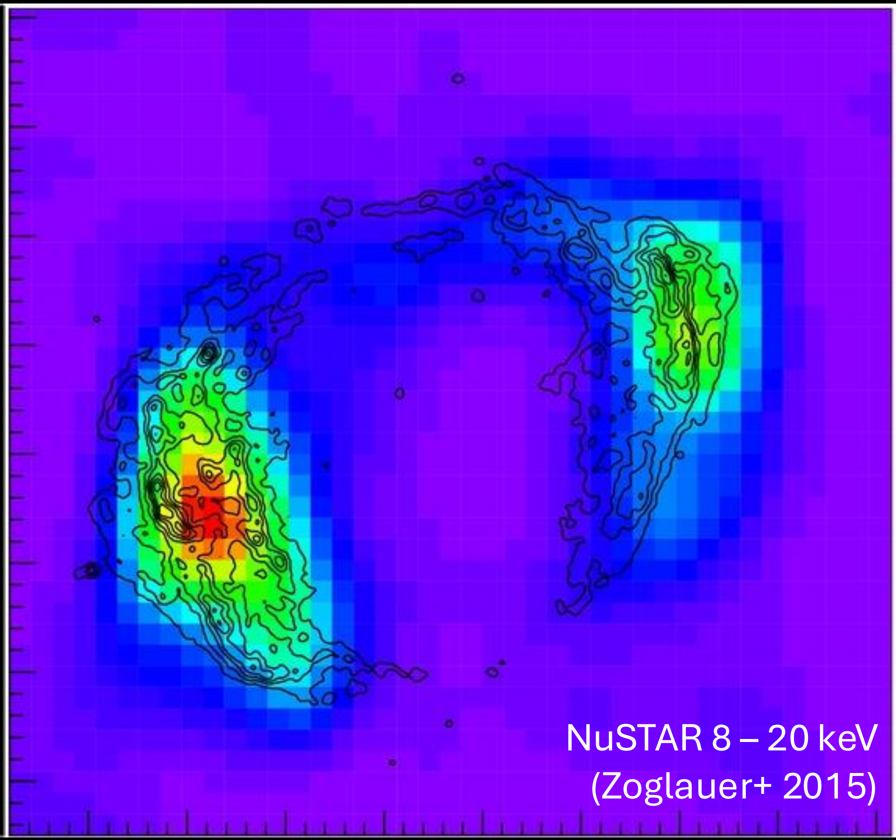


Younger SNR G1.9+0.3 has been brightening! Forward shock (EW) is most energetic.

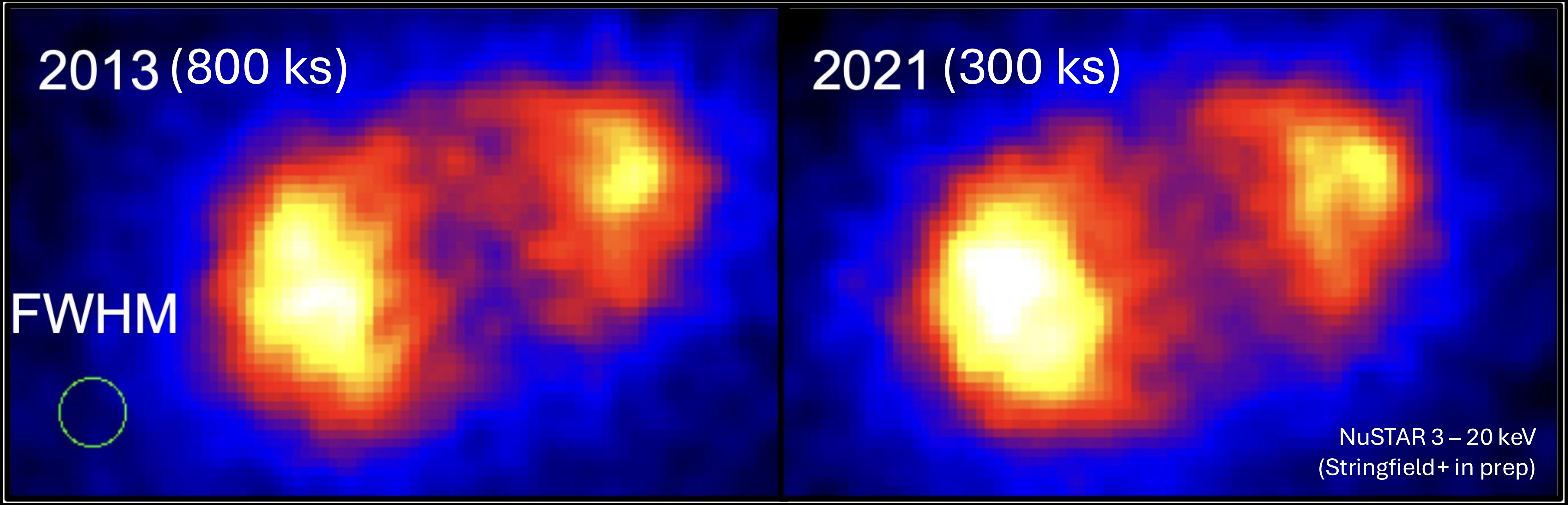
- **No gamma-ray emission detected by Fermi-LAT or H.E.S.S.**

(CXO website)





Multi-epoch NuSTAR observation detected hard X-ray brightening by 12% over 8 years.

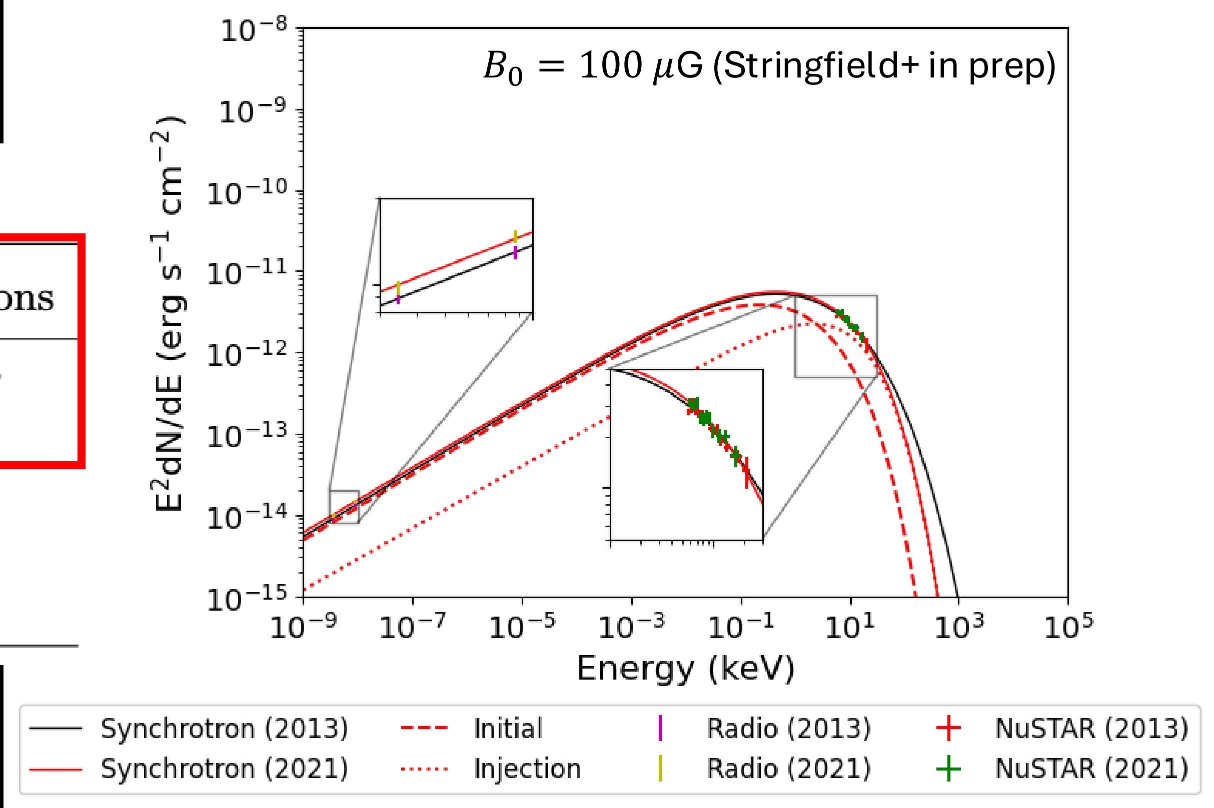


Injection spectral index remains constant. G1.9+0.3 is not a PeVatron.

- 22% of the total electron energy was injected over the past 8 years.

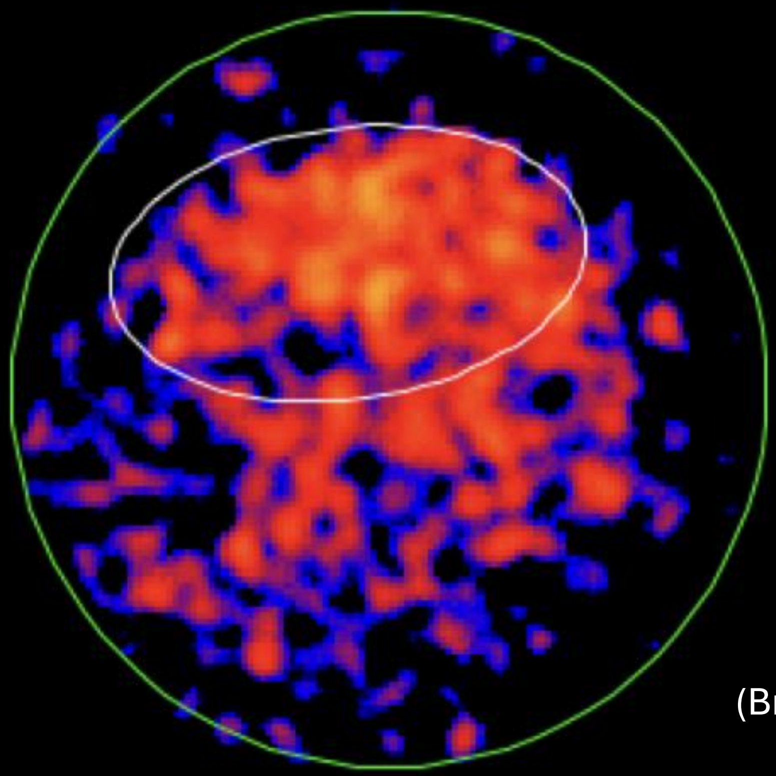
Table 7. Best-fit parameters for the G1.9+0.3 SED

	Preexisting electrons	Injected electrons
q	2.2	2.16 ± 0.026
E_{cut} (TeV)	10.1 ± 0.9	31.6 ± 5
β	0.82 ± 0.06	2^*
Electron energy	5.0×10^{46} erg	22 %
Injection rate $(10^{37}$ erg s$^{-1})$		2.8



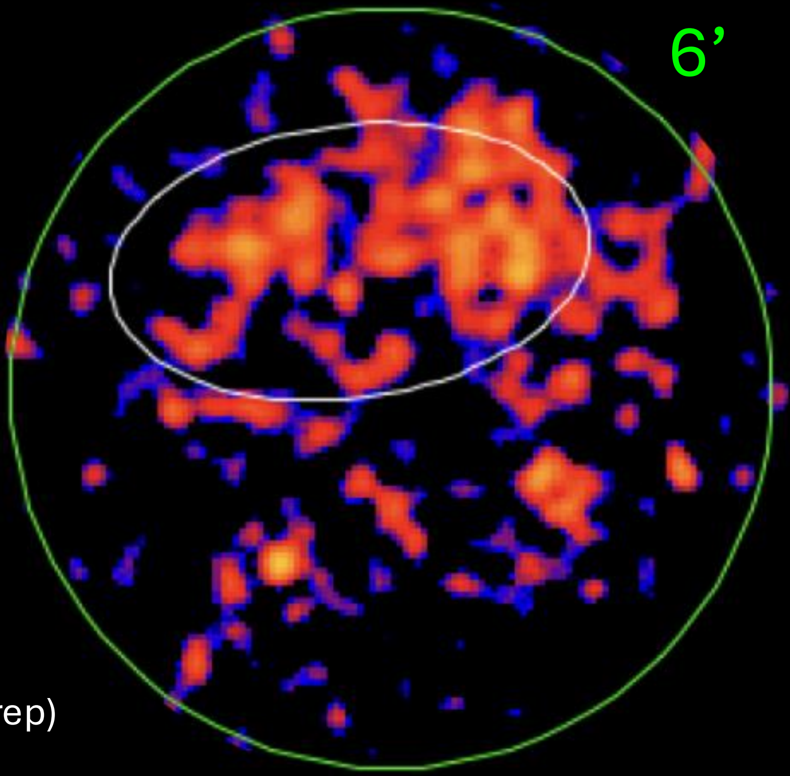
Kepler’s hard X-ray flux and spectrum remains unchanged over 10 years.

- Gamma-ray detection up to 20 TeV by Fermi-LAT and H.E.S.S.



NuSTAR 15 – 25 keV in 2014 (250 ks)

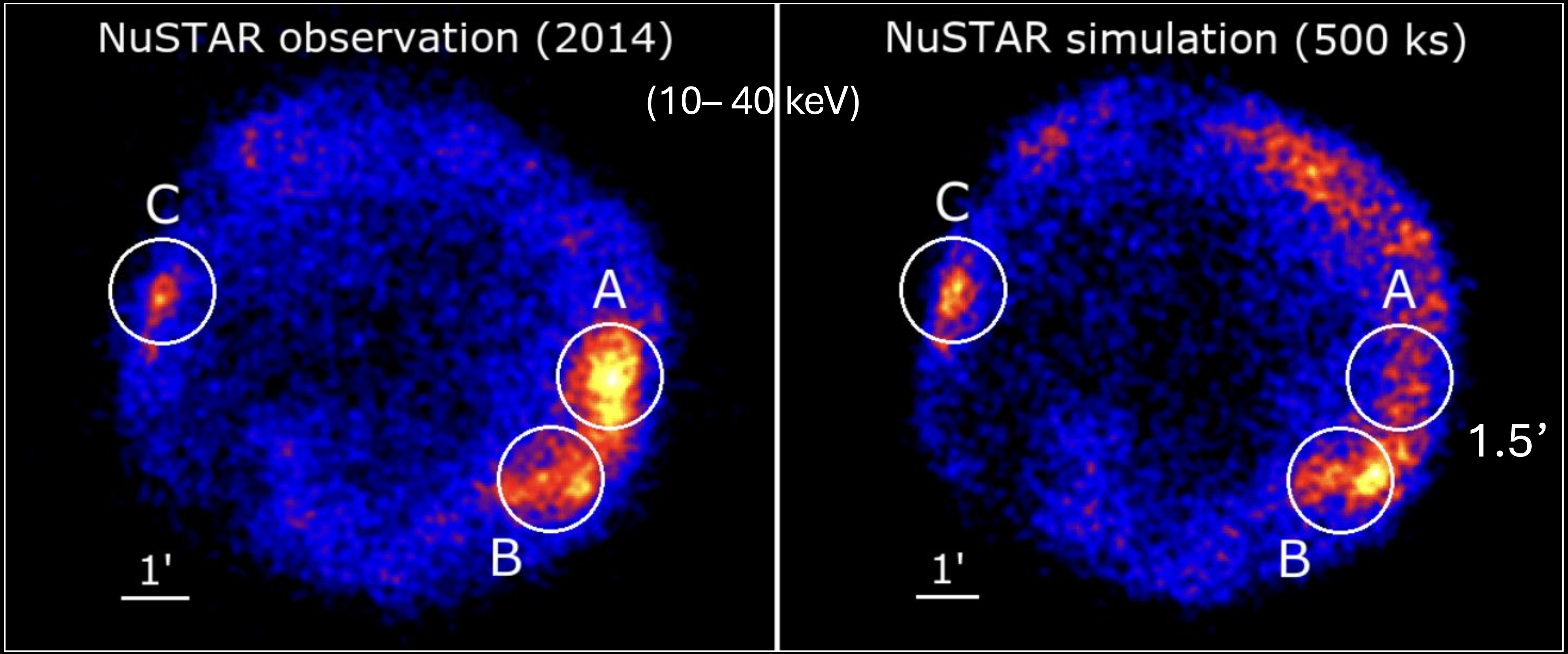
(Brewer+ in prep)



NuSTAR 15 – 25 keV in 2024 (200 ks)

Tycho will allow to spatially resolve particle acceleration thanks to the close distance < 3 kpc.

- Gamma-ray detection up to 10 TeV by Fermi-LAT and VERITAS
- Simulation of different flux variability for different regions based on Chandra observation



Uniquely constraints on ongoing acceleration provides observational ingredients for DSA theories.

	Cas A	G1.9+0.3	Kepler	Tycho
Supernova type	IIb	Ia	Ia	Ia
Age (yr)	350	100	420	450
Distance (kpc)	3.4	8.5	6	2.5
Flux change	–15% / 10 yr (15 – 50 keV)	+12% / 8 yr (3 – 20 keV)	0% / 10 yr (15 – 25 keV)	
Preexisting Electron spectrum	$\Gamma = 2.4$ $E_{cut} < 4$ TeV	$\Gamma = 2.2$ $E_{cut} < 10$ TeV		
Injection spectrum	$\Gamma < 2.2$ $E_{cut} < 36$ TeV	$\Gamma < 2.2$ $E_{cut} < 32$ TeV		