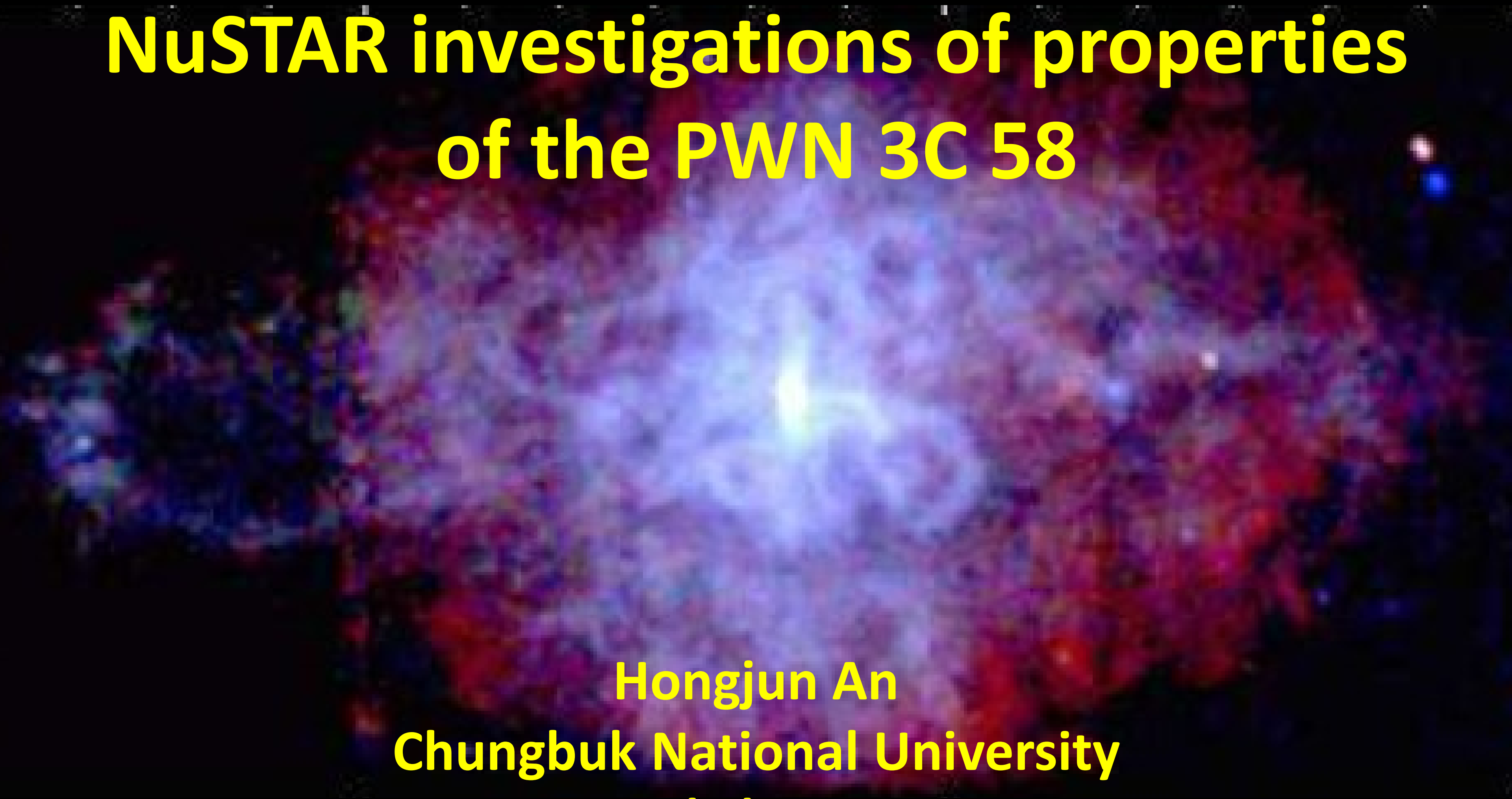
NuSTAR investigations of properties of the PWN 3C 58



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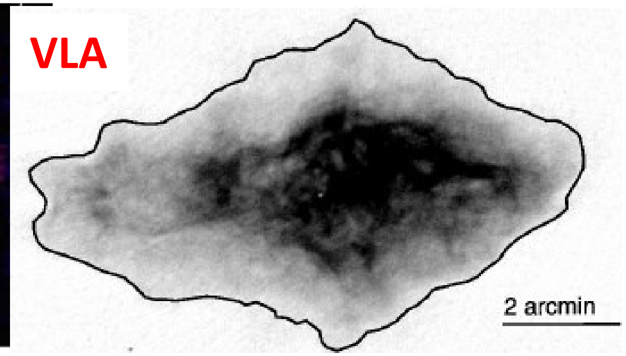
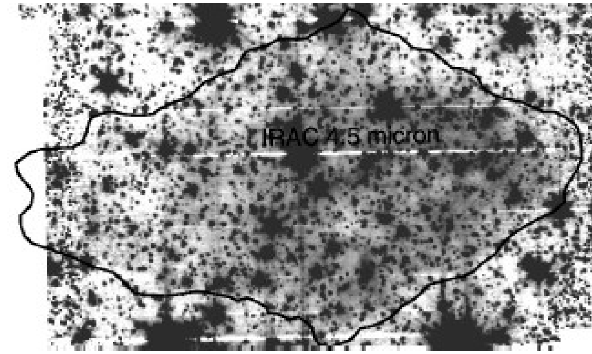
3C 58 is a bright X-ray PWN powered by an energetic pulsar

Chandra (Slane et al 2004)

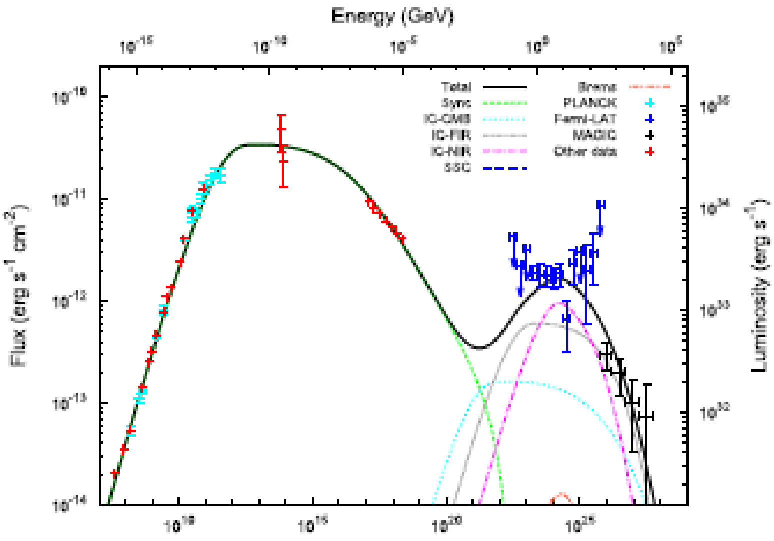




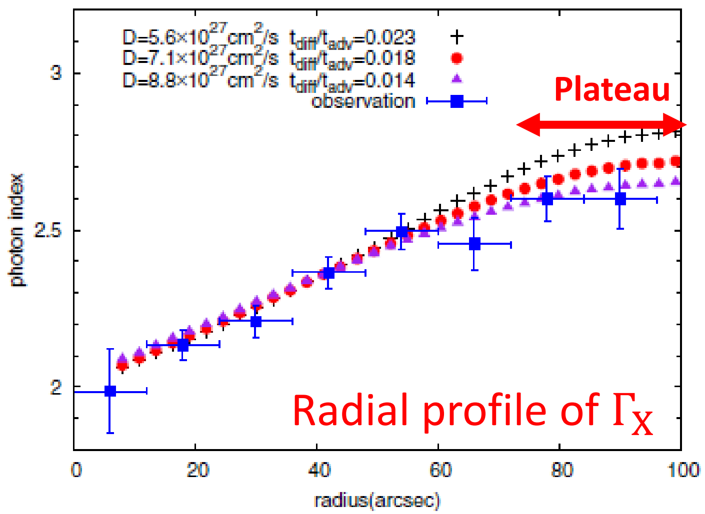
VLA/Spitzer; Slane et al. 2008

- The PWN is powered by an energetic 65 ms pulsar PSR J0205+6449
- A torus and a jet similar to those in the Crab nebula are clearly seen
- An extended radio/IR/X-ray source $\sim 6' \times 9'$
- GeV—TeV emission is also detected with Fermi/LAT and MAGIC
- X-ray spectrum becomes softer with distance from the pulsar (Chandra and XMM)
- XMM detected a thermal shell in the outer region (SNR 1181)

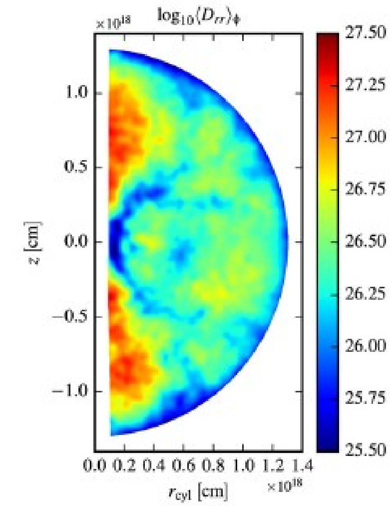
The X-ray bright source was studied well in the past



Li et al. 2018



Tang & Chevalier 2012



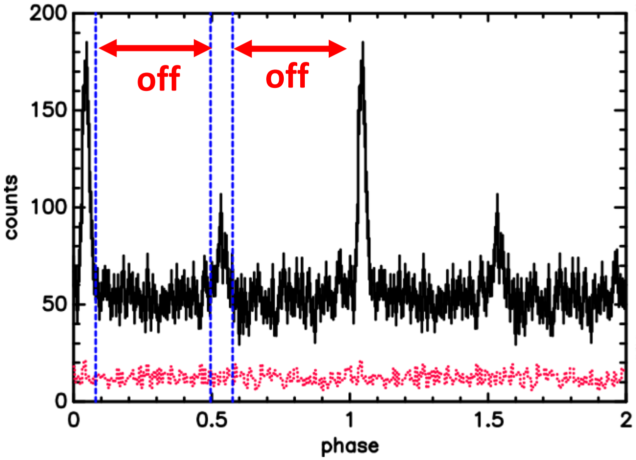
Porth et al. 2016

- Broadband SED models were applied to infer the particle energy distribution, magnetic field strength, and the age etc. (see also Tanaka et al. 2013, Bednarek & Bartosik 2003, Torres et al. 2013 and so on)

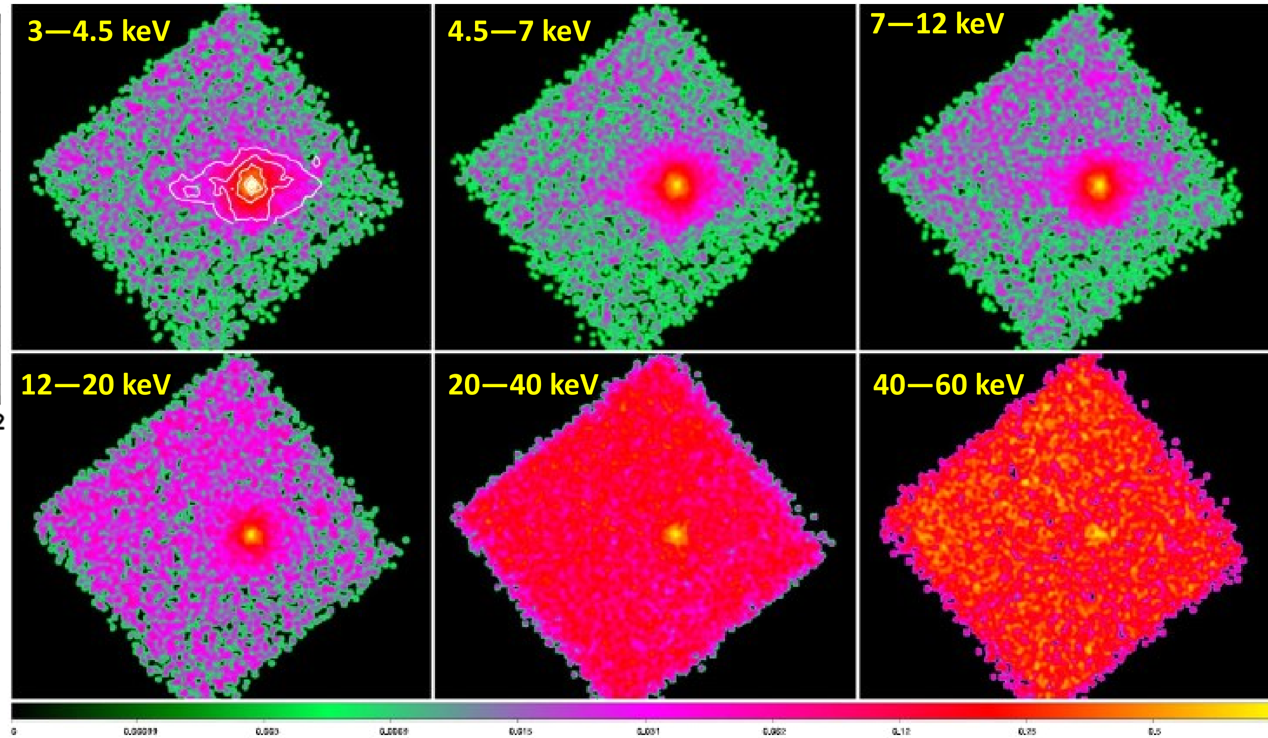
- Changes of the spectral index and size with the distance were explained with diffusion models (Tang & Chevalier 2012)

- The diffusion models can also be used to infer the maximum energy of electrons in the PNW (width of plateau in the radial profile of Γ)

We study 3C 58 at higher X-ray energies using NuSTAR



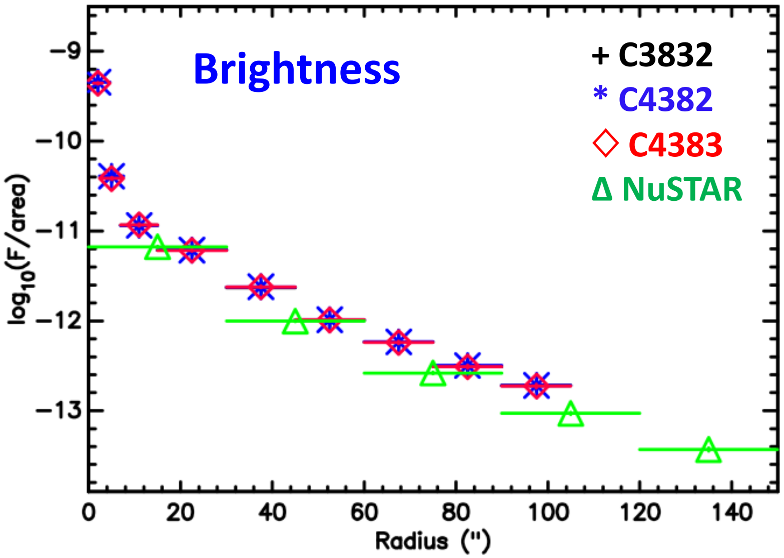
NuSTAR measured 3—79 keV
pulse profile
Two cycles are shown
An, H. (2019)

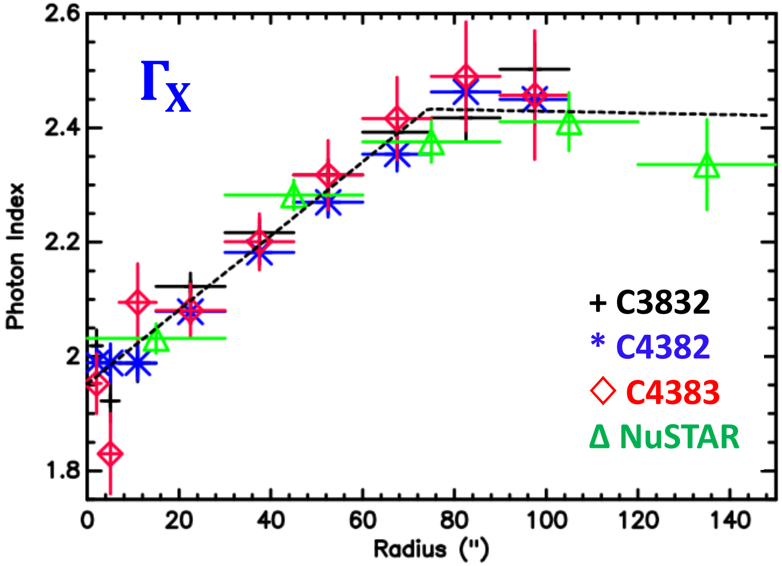


Off-pulse interval (normalized to 1 at the maximum)

- **The sharp pulses allow us to select broad off-pulse (PWN-dominated) intervals**
- **The size of the PWN gets smaller with energy (also seen in other PWNe): $100''$@ ~3 keV and $70''$ @ ~14 keV**

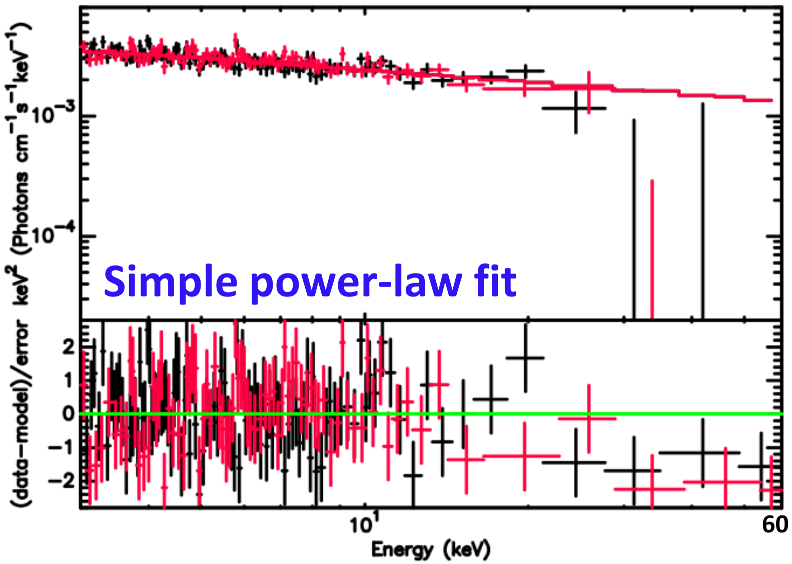
Brightness and photon index trends continue to higher energies

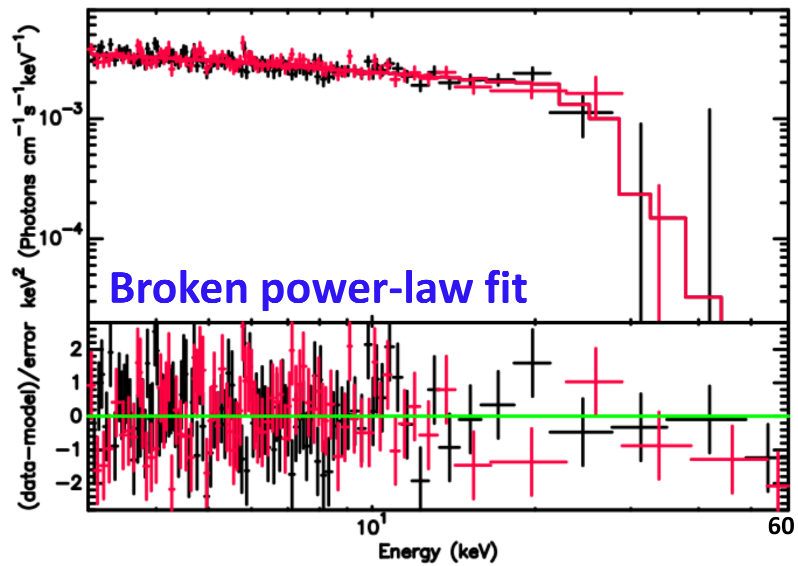




- The brightness and photon-index profiles measured with NuSTAR are similar to those measured with Chandra: the spectrum is a single power law up to $\sim 20\ keV$
- The $0.5 - 20\ keV$ photon-index trend shows a break at $R \sim 75''$, implying a maximum particle energy of $\sim 40\ TeV$ $(\gamma_{max} \approx 8 \times 10^7)$ in a diffusion model (tc12)
- These can provide the overall flow properties better when compared with MHD simulations of PWNe (e.g., Porth et al. 2014, 2016)

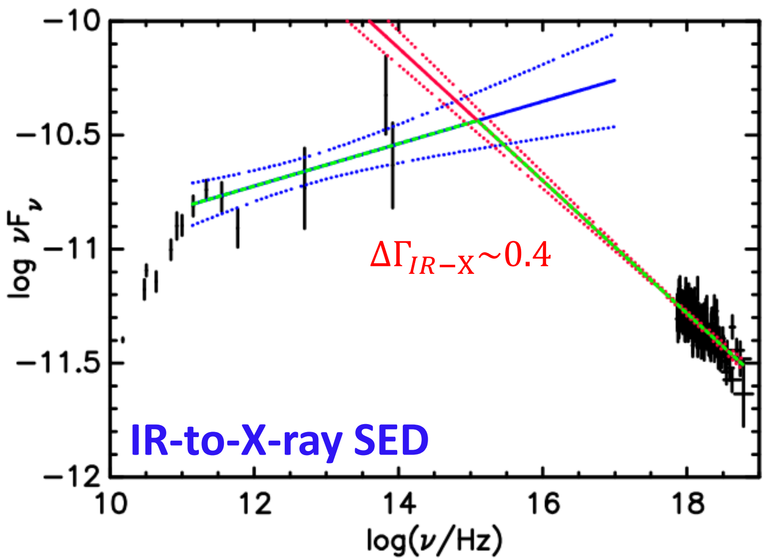
The spatially-integrated spectrum shows a hint of a spectral cutoff

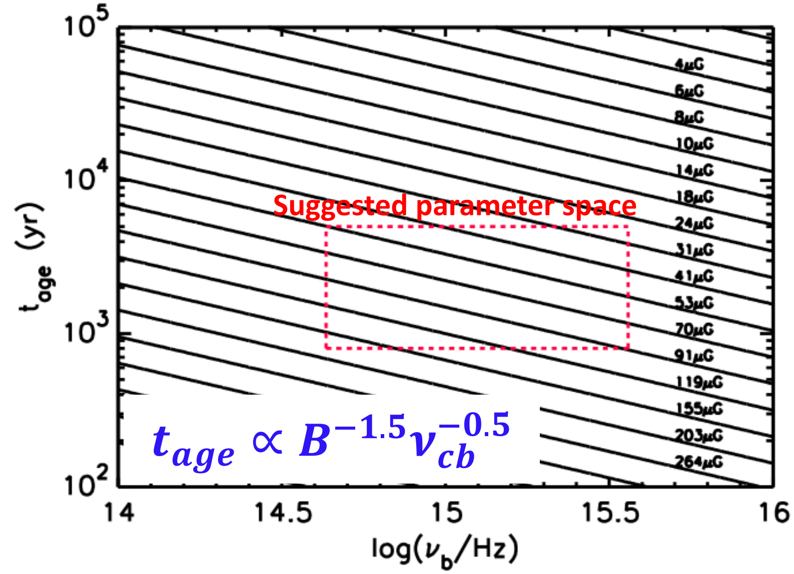




- **A simple power-law fit to the $3 - 60\ keV$ spectrum $(R < 3')$ shows deficit of counts at high energies**
- **A broken power-law model improves the fit (f-test $p \approx 4 \times 10^{-5}$ at $E_{cut} = 23 \pm 2\ keV$)**
- **The significance for the cutoff varies depending on the background selection (non-uniform), so further confirmation is needed**
- **If real, the cutoff suggests that $E_{max} \approx 140\ TeV$ $(\gamma_{max} \approx 3 \times 10^8)$**

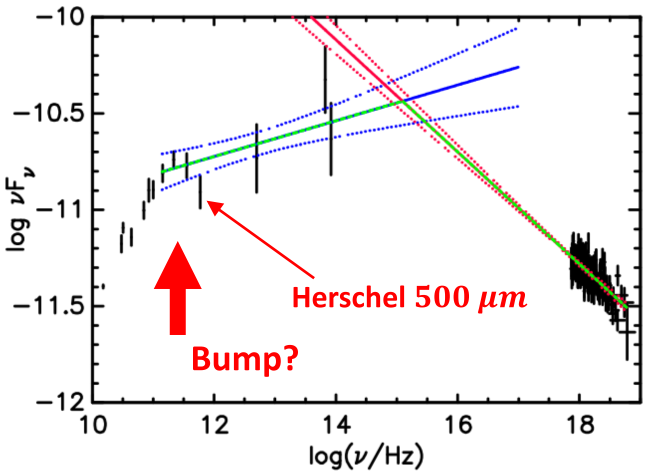
With the IR-to-X-ray SED, we can constrain $B = 30 - 200\mu G$

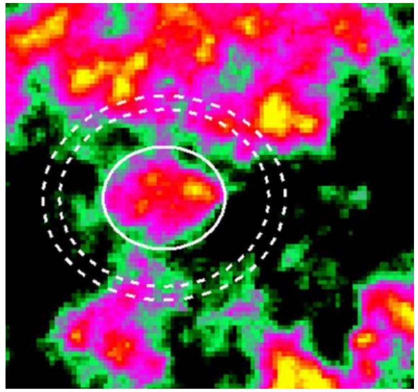




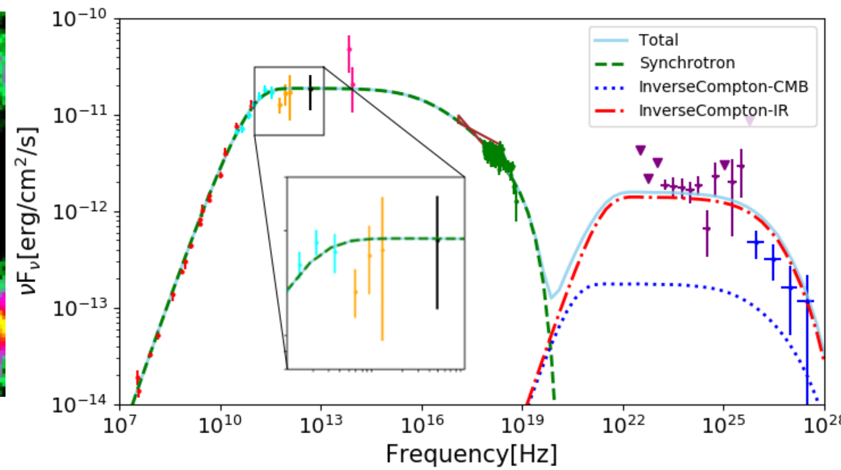
- We fit the IR-to-X-ray SED with a $\Delta\Gamma = 0.4$ broken power-law model to find the location of the cooling break $\nu_{cb} = 4 \times 10^{14} - 4 \times 10^{15}\ Hz$
- The degree of the break is slightly different from that of the ideal synchrotron cooling break $(\Delta\Gamma = 0.5)$
- Assuming ideal synchrotron cooling, we find that B is $30 - 200\mu G$ for an assumed age range of $1000 - 5000\ yr$

We construct a broadband SED of 3C 58





Herschel 500 μm

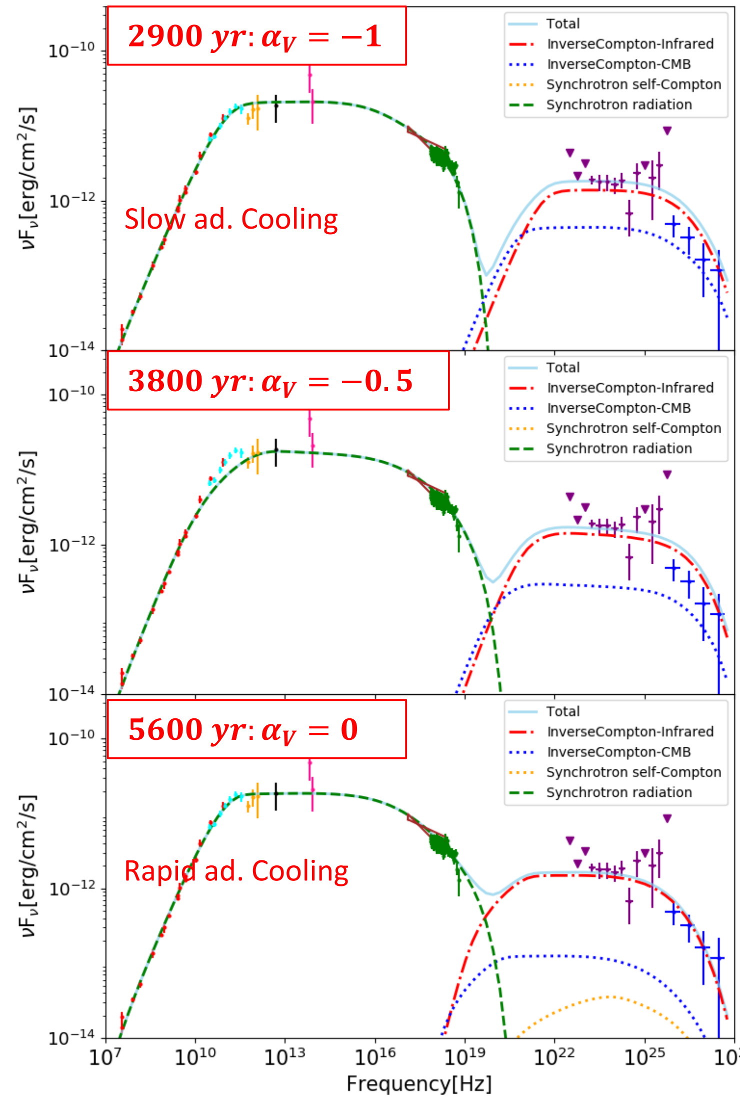


Kim, Park, and An, 2019

- **We generated a broadband SED. Notice that there appears to be a small bump at $\sim 10^{11}$ Hz (measurements of PLANCK and Herschel; The PLANCK collaboration 2016); we confirm this with a reanalysis of the Herschel data**
- **The significance of the Herschel measurements is low, so further study is needed**
- **A similar IR bump is seen in the Crab nebula (Macias & Perez, 2010) and is not significant either**

We model the broadband SED with a synchro-Compton model

- **For modeling, we use power-law prescriptions for the flow speed and magnetic field strength: $V(r) \propto V_0 r^{\alpha_V}$ and $B(r) \propto B_0 r^{\alpha_B}$, and used Bohm diffusion $D \propto B^{-1}E_e$ (spherically symmetric) (e.g., Reynolds 2009)**
- **For a measured PWN size $(3.7\ pc, d = 3.2\ kpc)$ and a radio expansion speed $(V_0 R^{\alpha_V} = 600\ km/s)$, the age is constrained**
- **Assuming the flow speed and B is not increasing with r $(-1 < \alpha_V < 0)$, we infer $2900\ yr < t_{age} < 5600\ yr$ for 3C 58**
- **We model the SED assuming three different ages (different adiabatic cooling time scales)**
- **The large- and small-age models explain the SED well, but noticeably, the middle-age model shows a hump (excess) at $\sim 10^{11}\ Hz$**



Kim, Park, and An, 2019

Summary

- With a 80-ks NuSTAR observation, we find that a $\Gamma_X \approx 2.2$ simple power-law X-ray spectrum extends to hard X-ray band $(20\ keV)$

- The radial profile of X-ray photon indices has a break at $\mathrm{r} \approx 75''$, implying a maximum electron energy of $40\ TeV$ in a diffusion model

- The high-energy X-ray spectrum shows a hint of spectral cutoff at $\sim 23\ keV$ which suggests that there are $140\ TeV$ electrons in the PWN

- The measurement of the cooling break (IR-to-X-ray) suggests that the average B is $30 - 200\mu G$ for assumed ages of $1 - 5\ kyr$

- At $\sim 10^{11}\ Hz$, excess in the SED is seen; this may be due to external dust-contamination or another population of electrons (internal)

- Power-law prescriptions of the flow properties and the PWN size are used to constrain the age of the PWN $(2.9 - 5.6\ kyr)$; models for the age range can explain the observed broadband SED