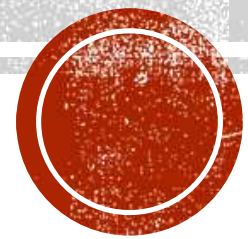
INVESTIGATING THE NATURE OF MAGNETIC TURBULENCE IN TYCHO'S SNR

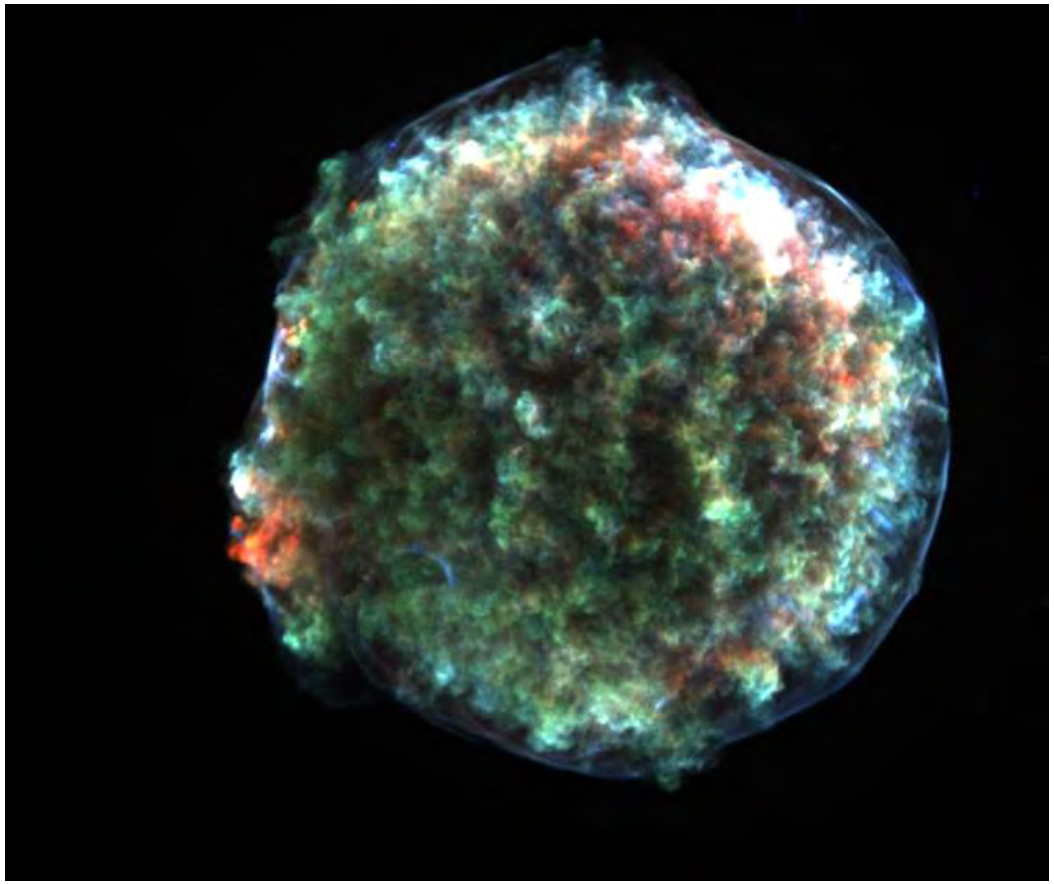


Ashwin Aravindaraj (1st Year PhD student)
National Tsing Hua University, Taiwan
Supervisor: Prof. Hsiang-Kuang Chang

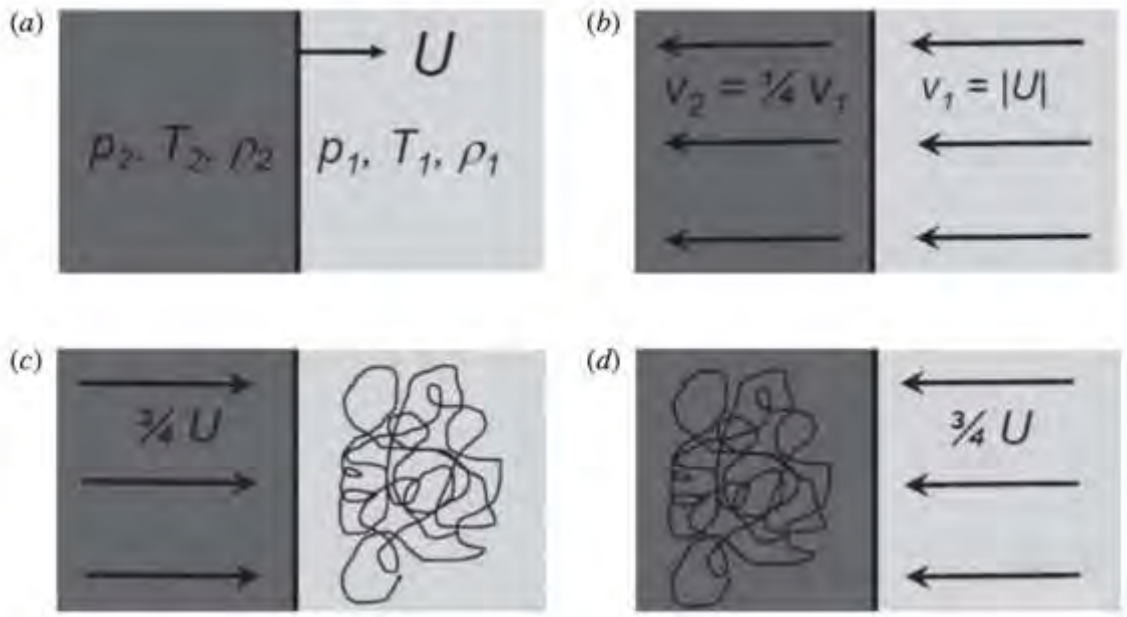
Ashwin Aravindaraj, Zhu Hui ,Adrien picquenot, Hsiang-Kuang Chang

INTRODUCTION

- Tycho's SNR was observed in 1572 by Tycho Brahe
- The remnant occurred from Type Ia Supernova.
- Chandra's Observation revealed the presence of thin X-ray filaments in the shock front.
- This filament is considered to be dominated by synchrotron energy losses.
- VERITAS reported detection upto 10 TeV photons.



MOTIVATION



High energy astrophysics, M. Longair

- The particles gets scattered back and forth due to the turbulent magnetic field.
- The Energy gained by the particle per back-and-forth crossing

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \frac{V}{c} .$$

- SNR is considered one of the main sources of cosmic ray acceleration.
- Turbulence near the shock front plays an important role in particle acceleration.

Magnetic energy spectrum ➔ two-point correlation

Magnetic Energy Spectrum of Tycho SNR

Two-Point Correlation Function:

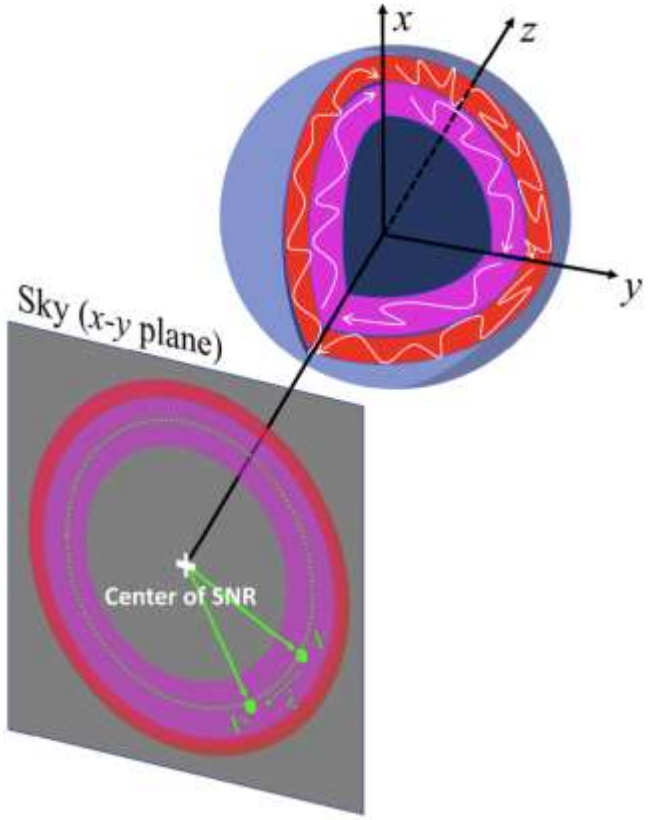
$$C^{(2)}_{I_\nu,S}(\boldsymbol{\lambda}) = \frac{\int_S I_\nu(\boldsymbol{X}) I_\nu(\boldsymbol{X}')\mathrm{d}^2\boldsymbol{X}}{\int_S \mathrm{d}^2\boldsymbol{X}} \equiv \langle I_\nu(\boldsymbol{X}) I_\nu(\boldsymbol{X}+\boldsymbol{\lambda})\rangle_{X,S},$$

$$i_\nu(\boldsymbol{r}) = K\nu^{-\alpha} B_n(\boldsymbol{r})^{1+\alpha}, = K\nu^{1-\gamma} B_n(\boldsymbol{r})^{\gamma},$$

I_ν – synchrotron radio specific intensity

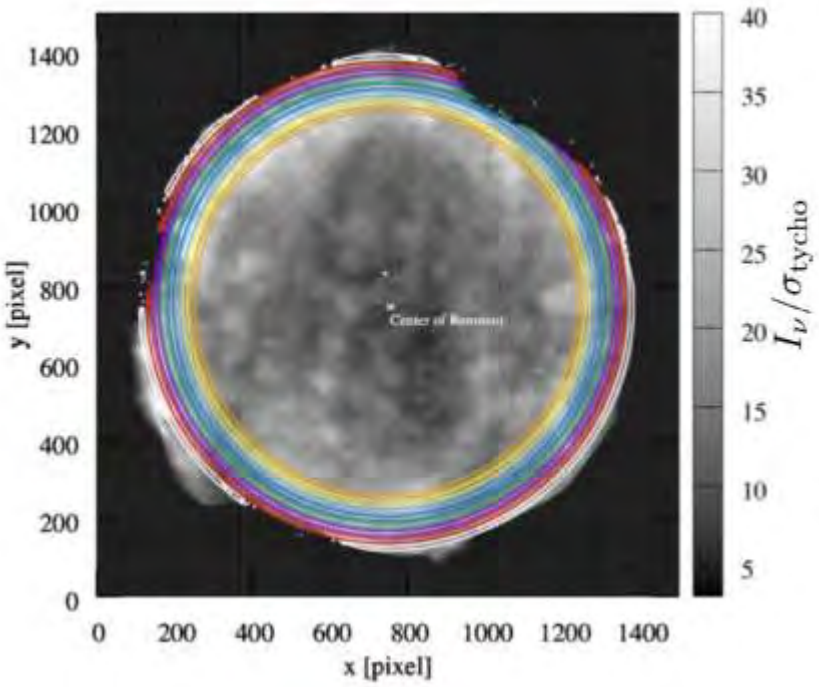
K – Function dependent on density of relativistic electrons.

B_n- magnetic field

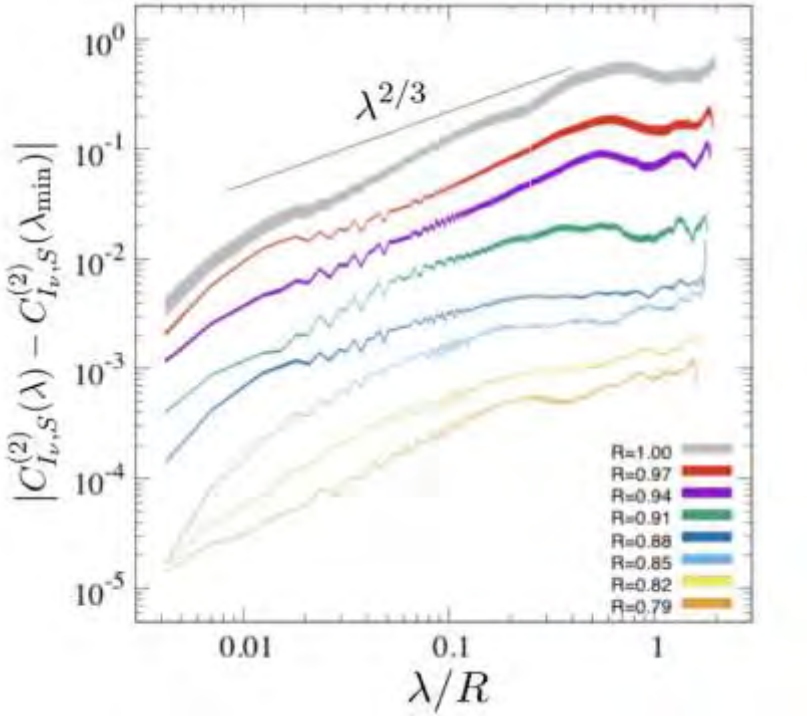


Shimoda et al. 2018

Previous results from radio observations



Radio specific intensity image of Tycho's SNR



Magnetic energy spectrum of Tycho's SNR

- For R>0.9 R_{SNR} (R_{SNR}=253 arcsec), the turbulence was developed upto $\lambda/R \leq 0.5$ and the spectrum follows a power-law (λ^m) of slope m=2/3 (kolmogrov-like turbulence)

- For R<0.9 R_{SNR} , the turbulence was developed upto $\lambda/R \leq 0.2$

Shimoda et al. 2018

Relation between diffusion coefficient and slope (m) of magnetic energy spectrum

Magnetic energy spectrum follows a power-law scale as:

$$\delta B^2(x) \propto x^m$$ **(m – slope of magnetic energy spectrum)**

Cosmic-rays resonate with magnetic fluctuations at a scale comparable to their gyro-radius (r_g)

$$x_{res} \sim r_g \propto \frac{E}{B}$$

Diffusion coefficient (D(E)):

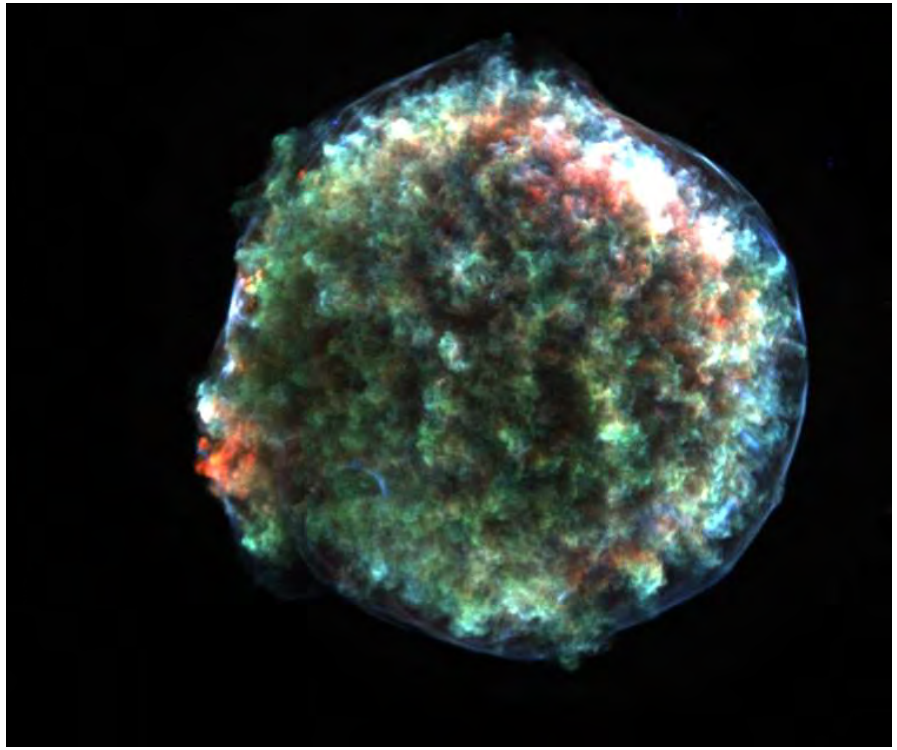
$$D(E) \propto \frac{r_g}{\nu}$$, **ν** – scattering frequency

$$\nu \propto \frac{\delta B^2}{B^2}$$

$$\boldsymbol{D(E) \propto E^{1-m}}$$

ANALYSIS:

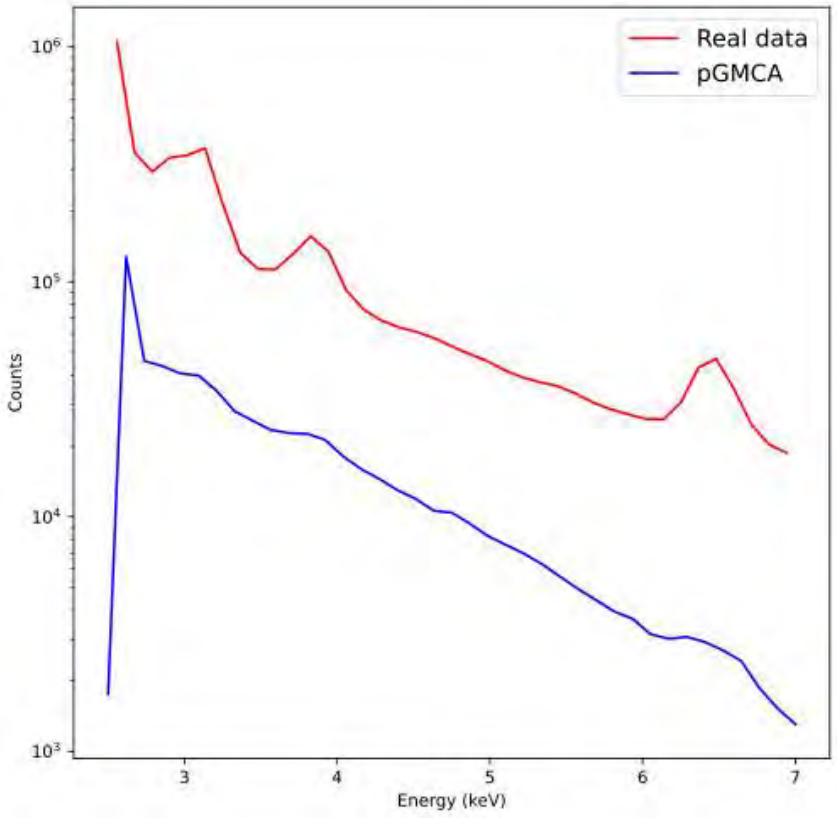
- Chandra data was used due to its spatial resolution (0.5 arcsec)
- Exposure corrected flux image was produced.



- Tycho's X-ray emission consists of thermal emission + non-thermal emission (synchrotron emission)
- Need isolated non-thermal X-ray flux image.
- Poisonnian based generalized component analysis (pGMCA) to separate thermal and non-thermal emission

Poissonian based generalized morphological component analysis

- 3D cube data (E, x, y) of Tycho's SNR is the input data.
- Separates the thermal and non-thermal image by returning the 3D cube data.
- Non-thermal X-ray count image is obtained by summing along the Energy axis and it is divided by chandra exposure map to obtain the non-thermal flux image (Photons cm^{-2} s^{-1})

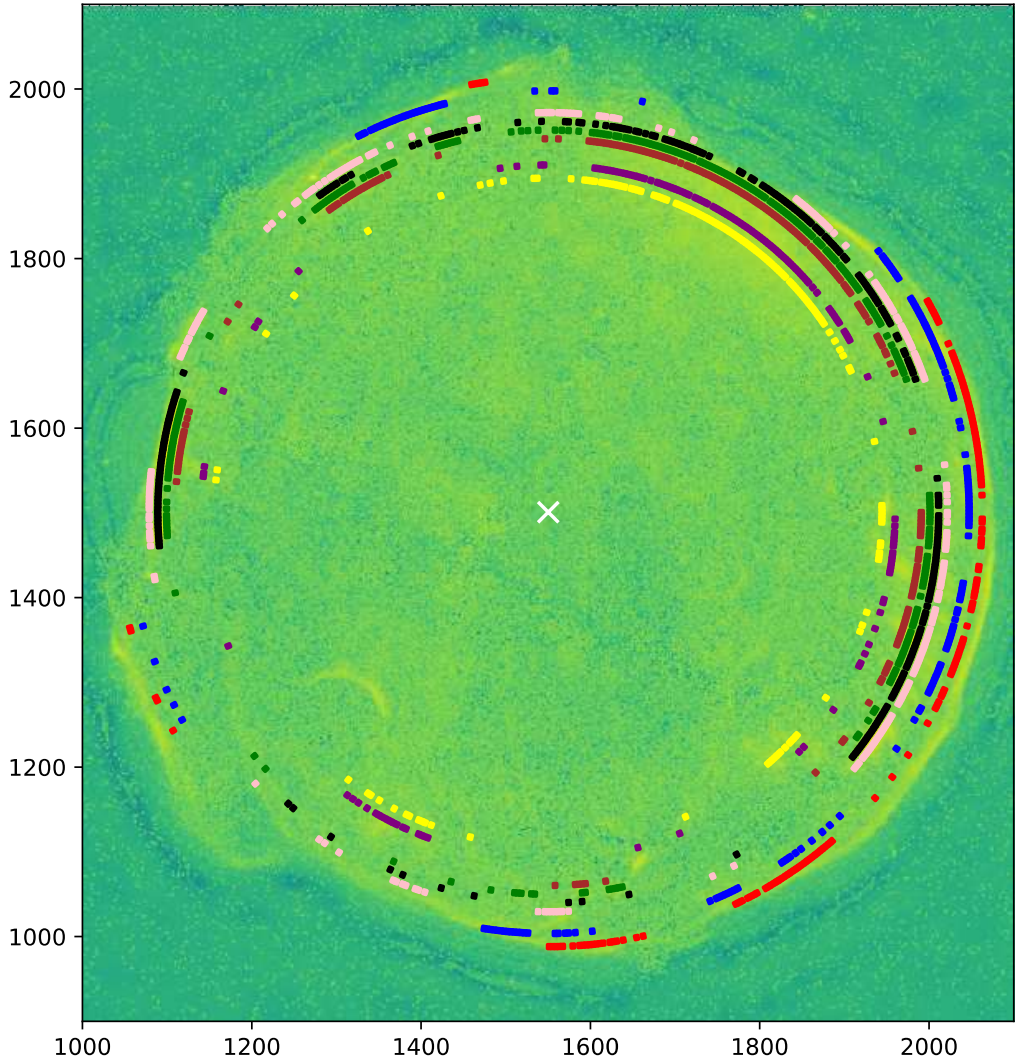


This part was carried out by our colloborator (Dr. Adrien Picquenot)

REGION SELECTION

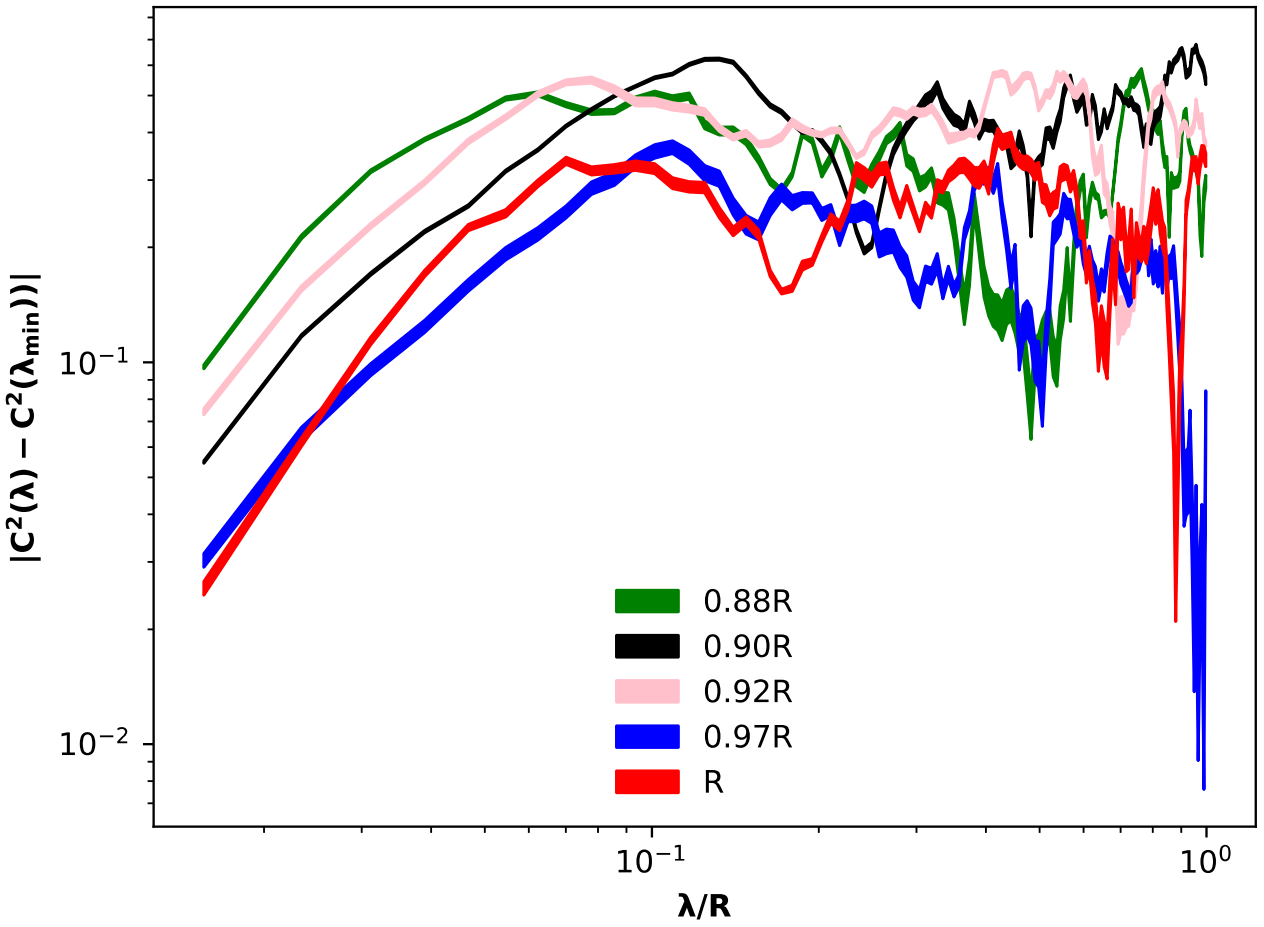
- Regions are binned with 1.968 arcsec
- Regions with median flux > $3\sigma_{noise}$ are selected
- Upper limit ➔ Pixel with values < $3\sigma_{noise}$ are replaced with $3\sigma_{noise}$
  Lower limit ➔ Pixel with values < $3\sigma_{noise}$ are replaced with 0

$$C_F^{(2)}(\lambda) = \frac{\int F(X)F(X')\mathrm{d}^2\mathrm{X}}{\sqrt{\int F^2(X)\mathrm{d}^2\mathrm{X}}\sqrt{\int F^2(X')\mathrm{d}^2\mathrm{X}}}$$



Non-thermal X-ray flux (2.5 – 7.0 keV)

OUR RESULTS: Magnetic Energy spectrum

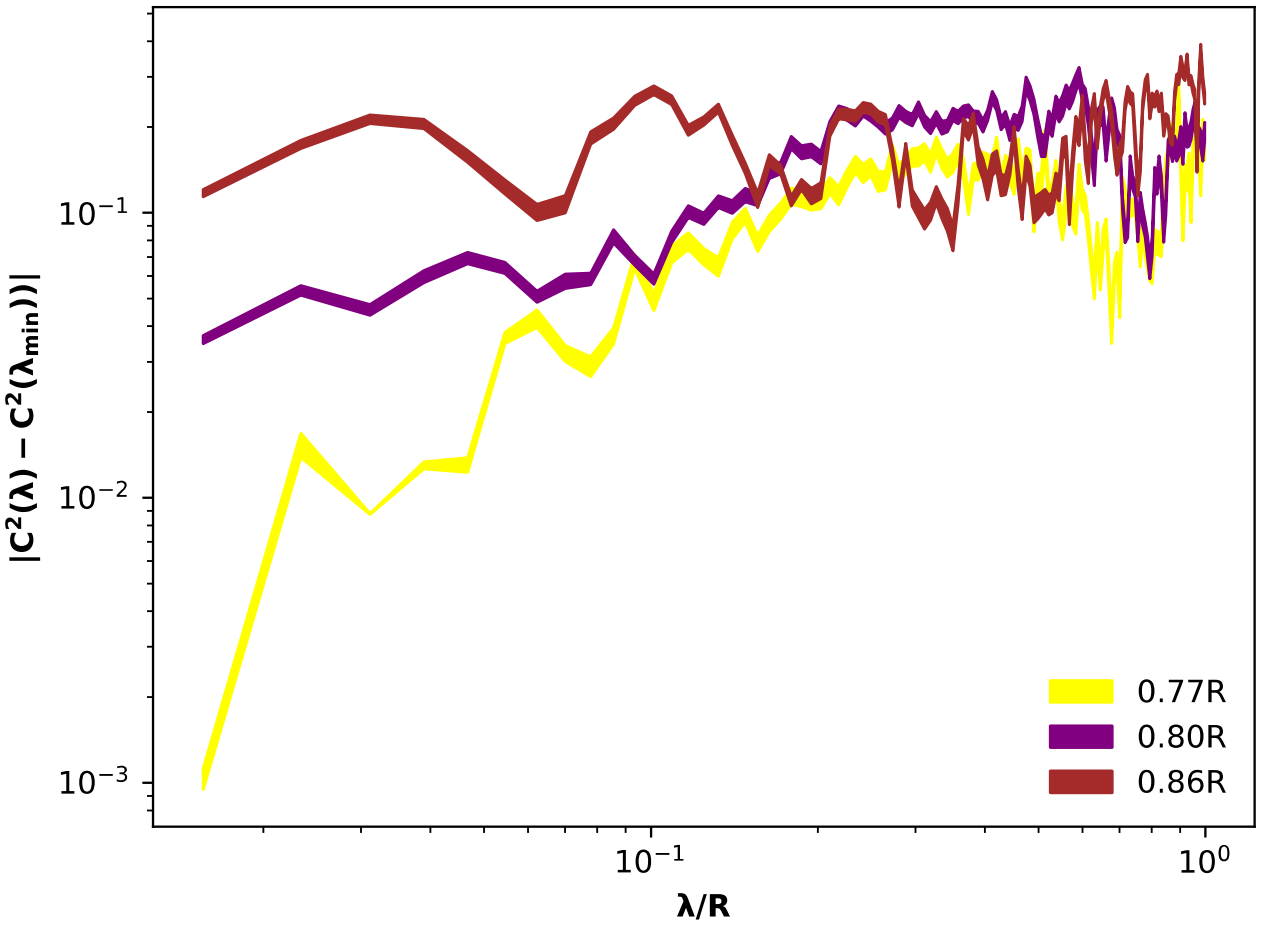


- For region r > 0.88 R turbulence is developed upto $\lambda \leq 0.1$
- The slope of the spectrum

Region	slope (m)
R	1.29 ± 0.08
0.97R	1.05 ± 0.05
0.92R	1.08 ± 0.07
0.9R	1.16 ± 0.06

- For radio image in the region r>0.9 R turbulence was developed upto $\lambda \leq 0.5$ with a slope of 0.66

Magnetic Energy spectrum



- For region r < 0.88 R turbulence is developed upto $\lambda \leq 0.2$
- The spectrum is chaotic.
- For radio image, in region r<0.9R turbulence was developed upto $\lambda \leq 0.2$.

Reasons for steepended slope:

- Synchrotron intensity depends on density (K) of electrons and magnetic field (B)

$$i_\nu = K\nu^{1-\gamma} B_n(r)^\gamma$$

I_ν – synchrotron radio specific intensity

K – Function dependent on density of relativistic electrons.

B_n- magnetic field

- Influence of number density of electrons on the magnetic energy spectrum could steepen the slope.

Alternate way to calculate magnetic energy spectrum → thickness of X-ray rim (Δx)

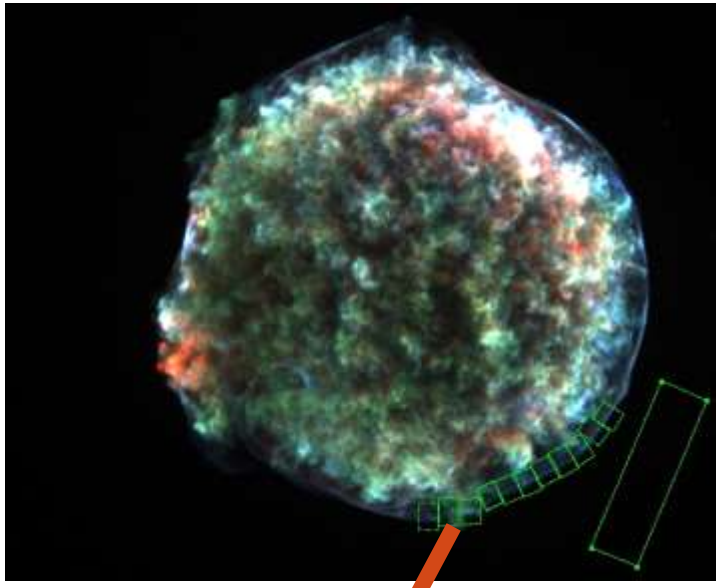
X-ray filament

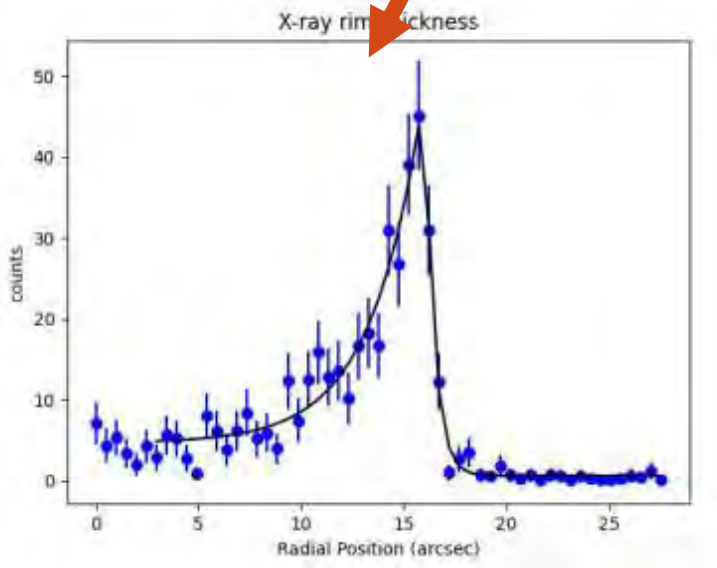
- X-ray rim dominated by synchrotron energy losses

$$\Delta x \approx E^{\frac{\mu-1}{2}} B^{-3/2}$$

Δx – X-ray rim thickness
E – Energy of the electron
B – Magnetic field

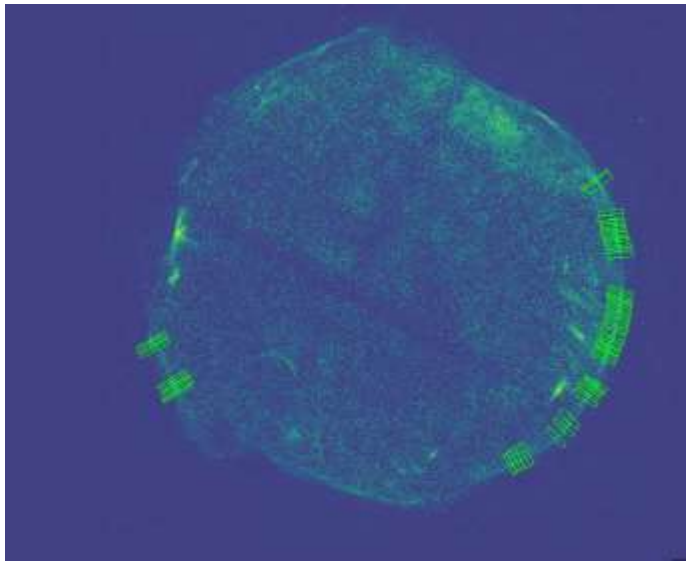
- X-ray Rim thickness not affected by number density of electrons



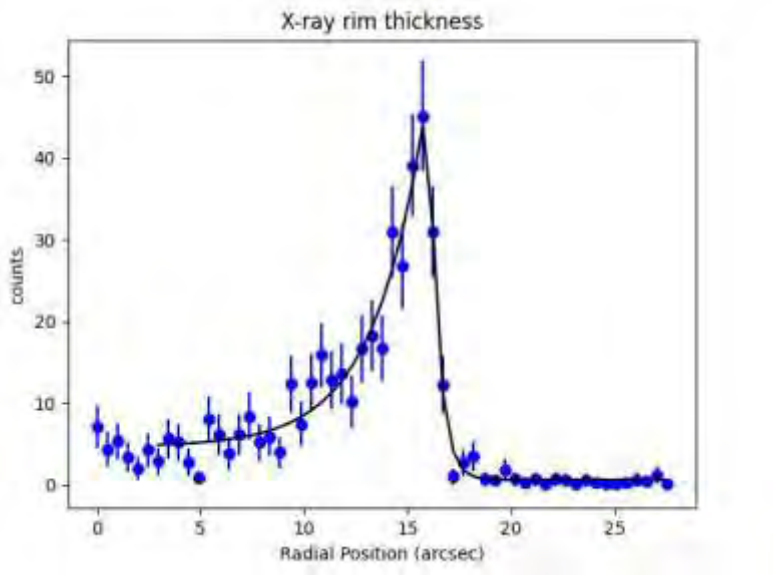


Region selection

- **The selected regions are 3 arcsec wide.**
- **62 selected regions.**
- **Thickness is calculated for (2.5-4.0 keV)**



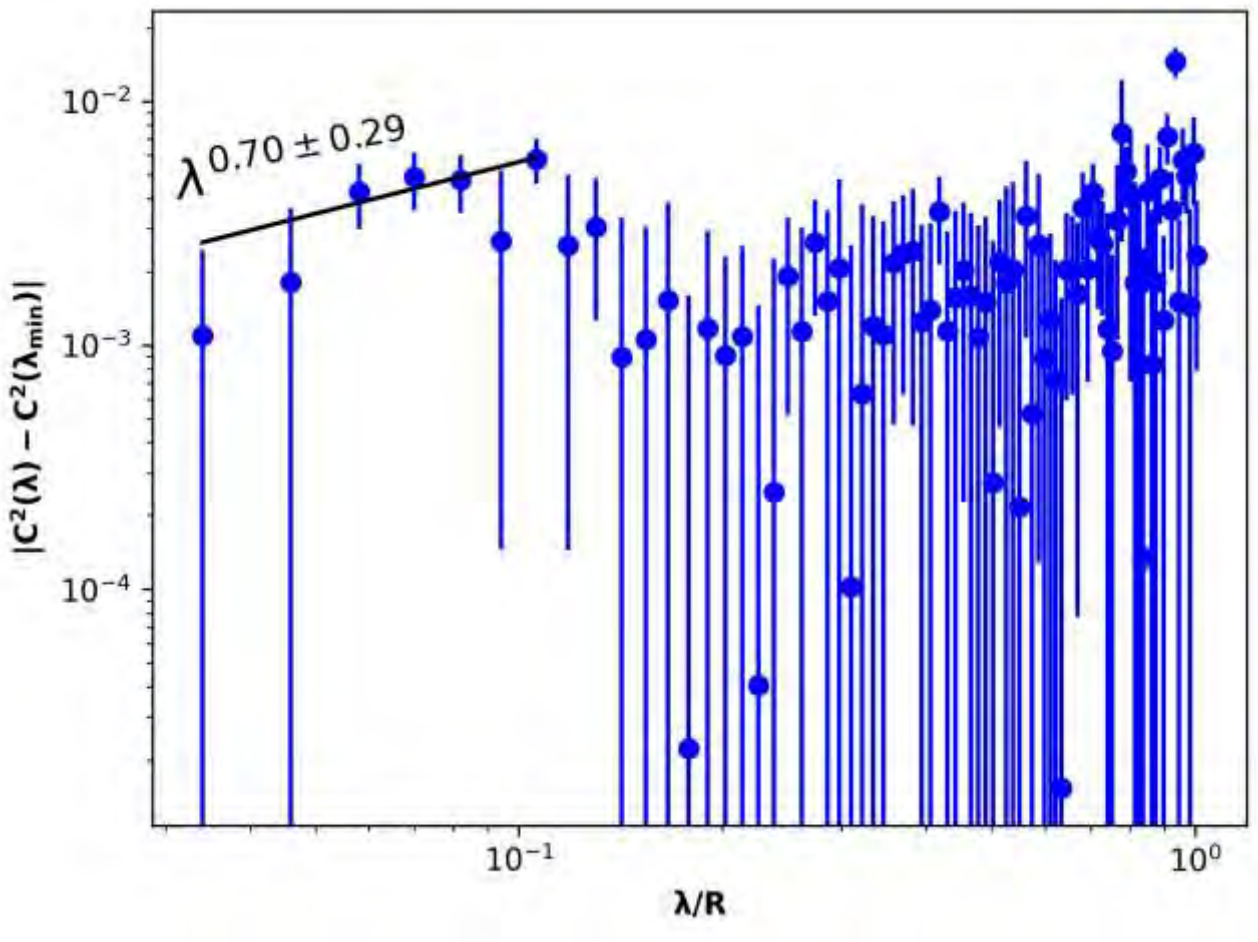
Non-thermal
X-ray image of Tycho (2.5 – 4.0 keV)



$$h(r) = \begin{cases} A_u \exp\left(\dfrac{r_0 - r}{w_u}\right) + C_u, & r \geqslant r_0 \\ A_d \exp\left(\dfrac{r - r_0}{w_d}\right) + C_d, & r < r_0 \end{cases}$$

R.A	Dec	FWHM (arcsec)	Reduced chi-square (χ^2_ν)
6.2460627	64.0794862	1.84 ± 0.15	1.22
6.243246	64.0803043	1.313 ± 0.082	1.1
6.2404299	64.080986	1.9 ± 0.23	1.55
6.2376138	64.0816675	1.62 ± 0.28	1.6
6.2347969	64.0824858	2.16 ± 0.48	1.69
6.2144512	64.0875278	2.94 ± 0.68	1.44
6.2091233	64.0902567	2.05 ± 0.14	1.09
6.2072412	64.0914852	1.86 ± 0.07	1.52
6.2053575	64.0929869	4.09 ± 2.72	1.1
6.194379	64.0992638	2.91 ± 0.34	1.16
6.1931221	64.1003559	1.7 ± 0.05	1.2
6.1921795	64.101175	2.5 ± 0.17	1.29
6.1909247	64.1018572	2.6 ± 0.28	1.1
6.1896694	64.1025394	2.58 ± 0.28	1.03
6.1874775	64.1028106	0.996 ± 0.004	0.95
6.1871599	64.103767	1.56 ± 0.06	1.34
6.1818031	64.1107317	2.86 ± 0.36	1.59
6.1811726	64.111551	2.4 ± 0.2	1.44
6.1805424	64.1123704	2.16 ± 0.06	1.25
6.1802244	64.1133266	2.22 ± 0.13	1.37
6.1792808	64.1141458	2.05 ± 0.03	1.37
6.1783371	64.1149647	1.35 ± 0.01	0.96
6.1777065	64.115784	1.43 ± 0.04	1.15
6.1764505	64.1164662	1.74 ± 0.05	1.66
6.1758198	64.1172855	1.28 ± 0.08	1.55
6.1755009	64.1183784	1.396 ± 0.006	1.42
6.1748686	64.1194713	1.41 ± 0.02	1.44
6.1729861	64.1201526	1.71 ± 0.05	1.42
6.1732938	64.1211093	1.38 ± 0.01	1.02
6.172976	64.1219291	1.45 ± 0.03	1.37
6.1723451	64.1227484	1.54 ± 0.05	1.66

Magnetic Energy spectrum using X-ray rim thickness



- Turbulence is developed upto $\lambda \leq 0.1$
- Turbulence scale is similar to the magnetic energy spectrum calculated from non-thermal X-ray photon flux.

Reasons for different turbulence scale traced by Radio and X-ray emitting electrons:

Turbulence scale near shock front : X-ray emitting electrons ($\lambda \approx 25.3\, arcsec \approx 10^{18} cm$)
Radio emitting electrons ($\lambda \approx 126.5\, arcsec \approx 8 \times 10^{18} cm$)

- **X-ray emitting electrons can trace small-scale turbulence if gyro-radius (r_g) is larger than the turbulence scale ($r_g \geq \lambda$)**

  Magnetic field strength and electron energy estimated from the thickness of X-ray rim width (Parizot et al 2006)

  $B > 100\, \mu G, \quad E = 10\, TeV$ and their respective gyro-radius ($r_g \approx 10^{14} cm$)

- **Due to shorter lifetimes of X-ray emitting electrons, these might trace the turbulence present near the acceleration sites.**

SUMMARY

- The magnetic energy spectrum from non-thermal X-ray image showed a turbulence scale upto $\lambda \leq 0.1$ for region r>0.88R and $\lambda \leq 0.2$ for region r<0.88R.

- Magnetic energy spectrum derived from X-ray rim thickness showed a turbulence scale upto $\lambda \leq 0.1$.