Spectral Index Maps of PWNe

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X-ray Observations of PWNe

- Synchrotron sources $N(E) \propto E^{-\Gamma}$
- The emission spectrum relates directly to the emitting particle energy spectrum
- Short synchrotron lifetime for higher energy particles leads to a softening of the spectral index with distance
- Particles radiate close to where they are accelerated

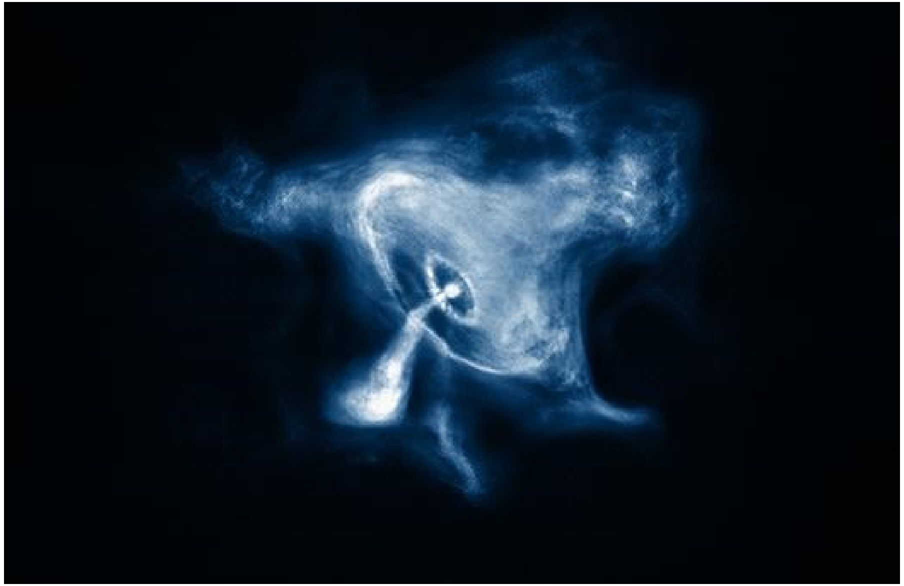
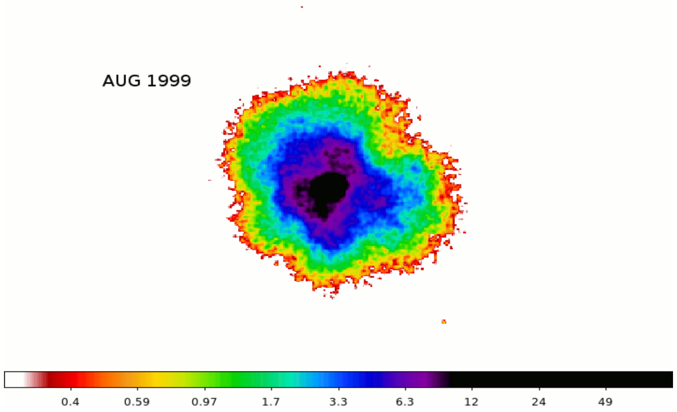


Image credit:
NASA/CXC/SAO

Variability in PWNe

- Variability has traditionally been found through the motion of persistent features
    - Eg. In Vela by Pavlov et al 2001
- The famous wisps observed in the crab nebula
    - Hester et al 1996
- Wisp like features seen in G21.5-0.9
    - Matheson & Safi-Harb 2010
- Outburst
    - Eg. Kes 75 by Ng et al 2008



ACIS observations of the PWN within G21.5-0.9
Guest et al 2019

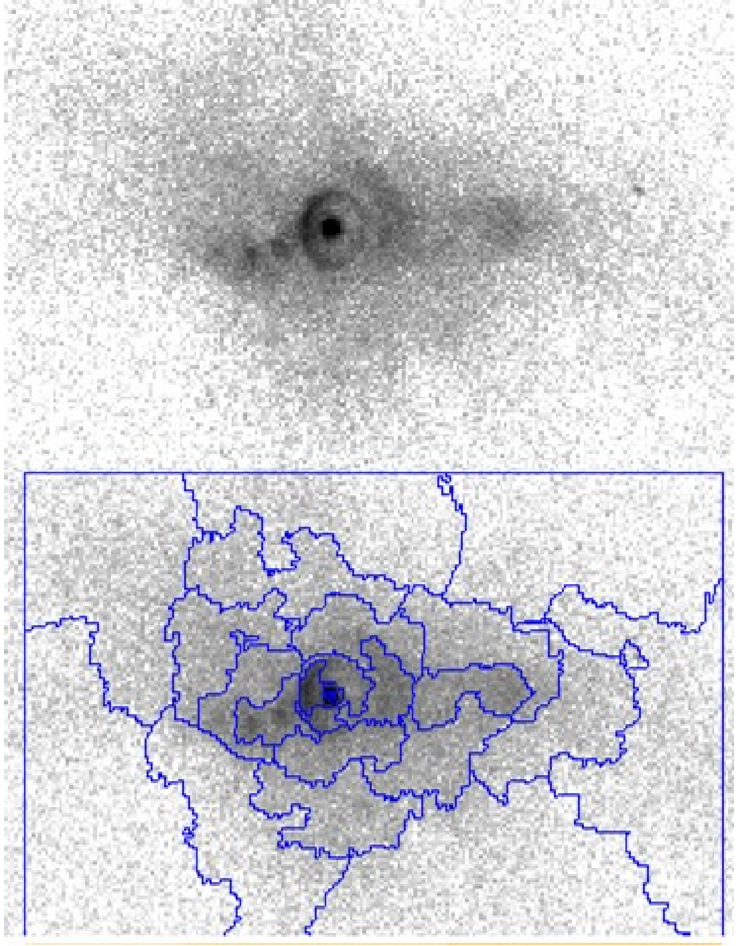
What is a spectral map?

- Map of the spectral index across the remnant
- Creating this from real data is challenging
- Fitting a spectrum requires a finite number of photon counts
- How to do this without losing all spatial information?

Contour Binning

Sanders J. S. 2006. MNRAS, 371, 2, 829

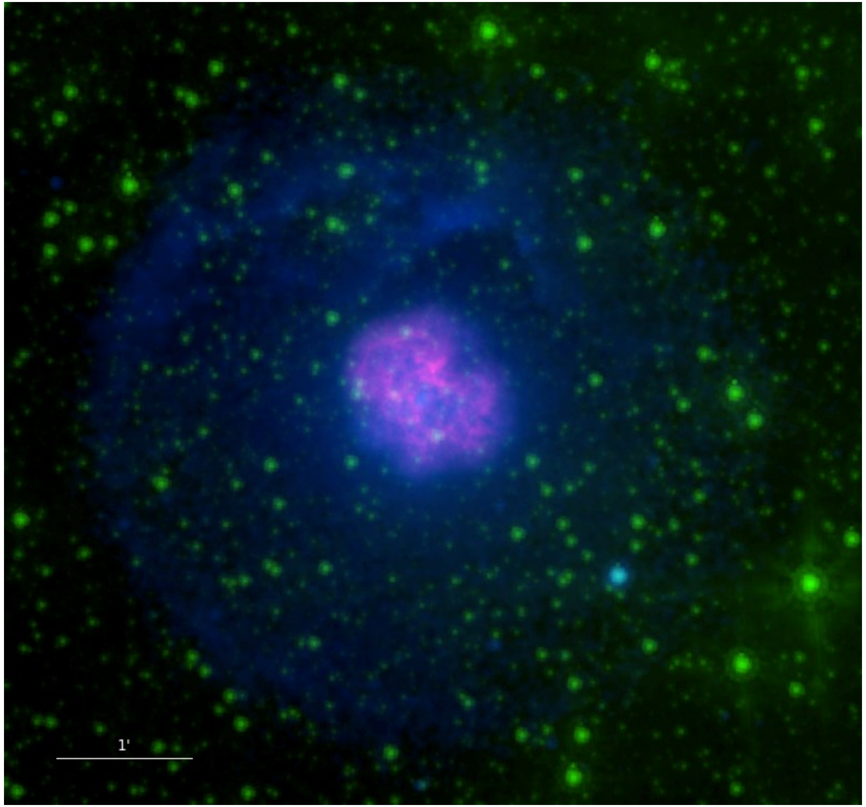
Adaptive algorithm which follows the surface brightness of an input image and generates regions which meet some signal limit



Example of the regions generated when applied to an observation of G54.1+0.3

G21.5-0.9

- Plerionic composite Supernova remnant
- Chandra calibration target
- Bright PWN
- Powered by 62 ms pulsar
  - Gupta et al 2005, Camilo et al 2006
- PWN expansion age of ~870 years
  - Bietenholz & Bartel 2008



Guest et al 2019

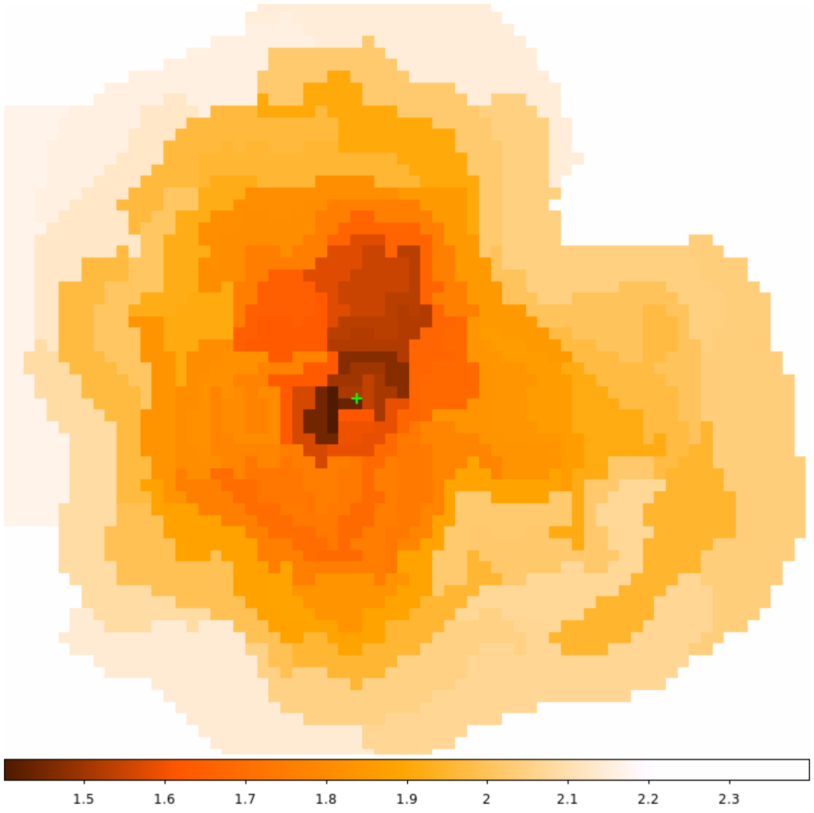
G21.5-0.9

Simultaneously fit observations from 1999-2014

Colour regions with the best fit value of the photon index

Reveals a plume of hard emission to the north of the pulsar

Hard emission close to the pulsar identified as a termination shock



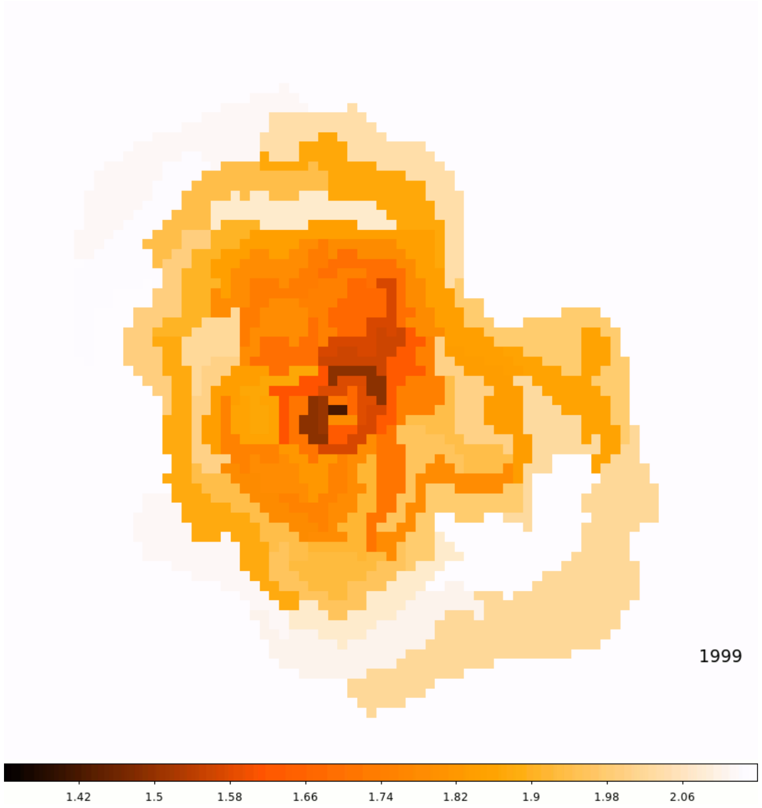
Guest et al 2019

G21.5-0.9

Observations are grouped by year to look for variability

Appears to show multiple outbursts

Significant variability in the northern plume



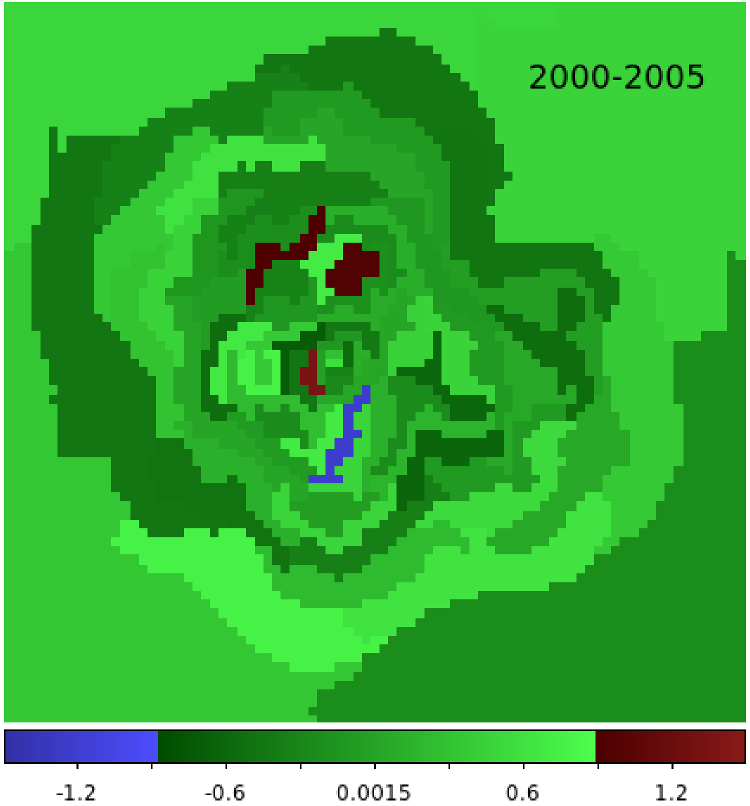
Significance Images

Are the results real?

Take the difference between two maps and divide by the sum of the errors

Any region approaching or exceeding

|1| is deemed significant



3C58

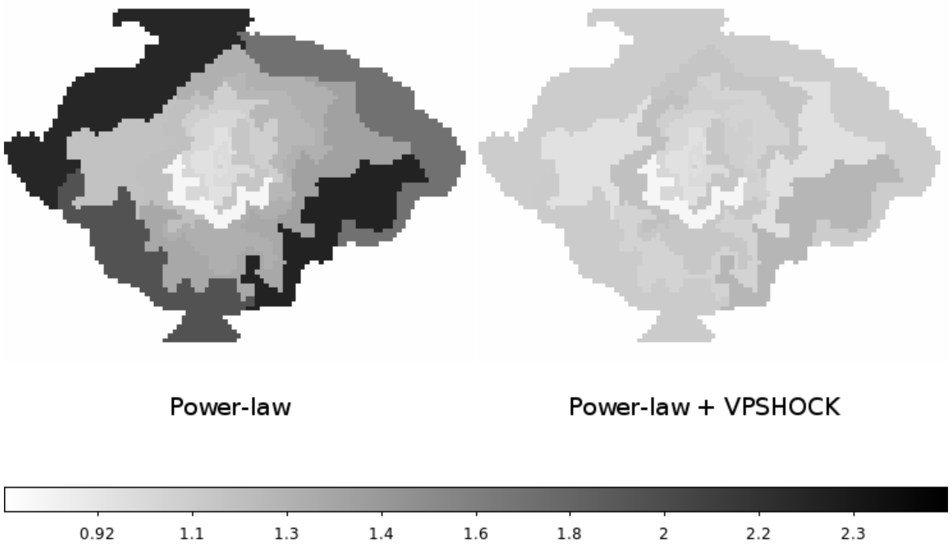
- PWN powered by 65 ms pulsar
  - Murray et al 2001
- Embedded in thermal emission
  - Slane et al 2004
  - Gotthelf et al 2004
- Jet & torus morphology seen with complex twists and loops
  - Slane et al 2002

3C58

The presence of thermal emission complicates the analysis

Generate a reduced chi-squared map

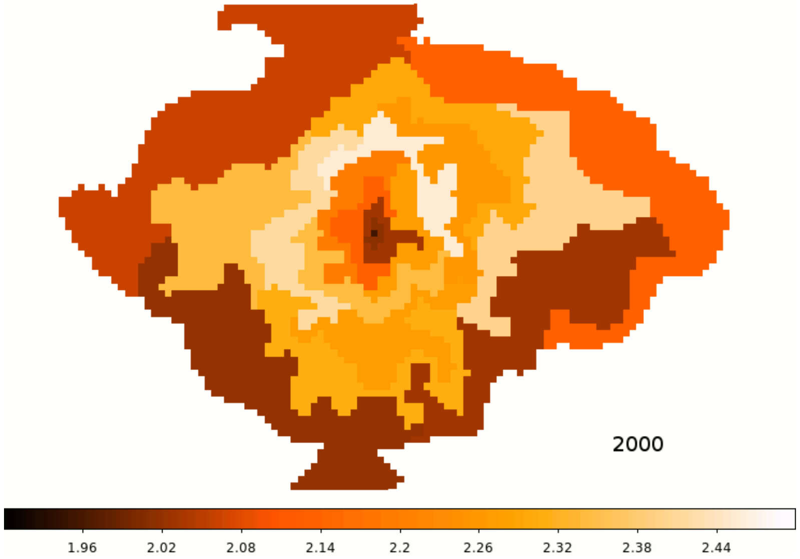
Add a thermal component to the regions which exceed some value

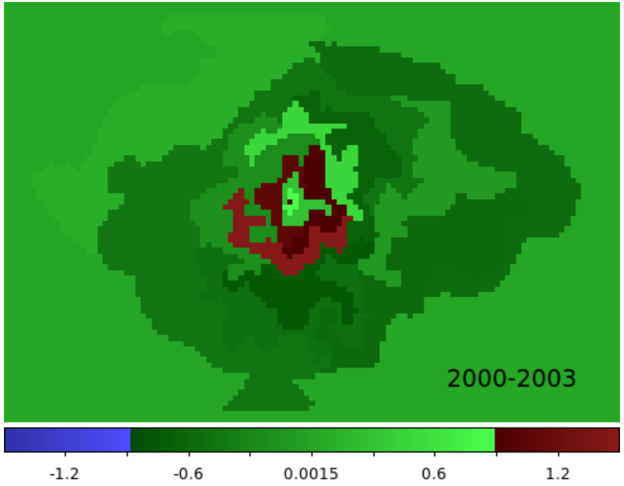


Reduced chi-squared map

3C58

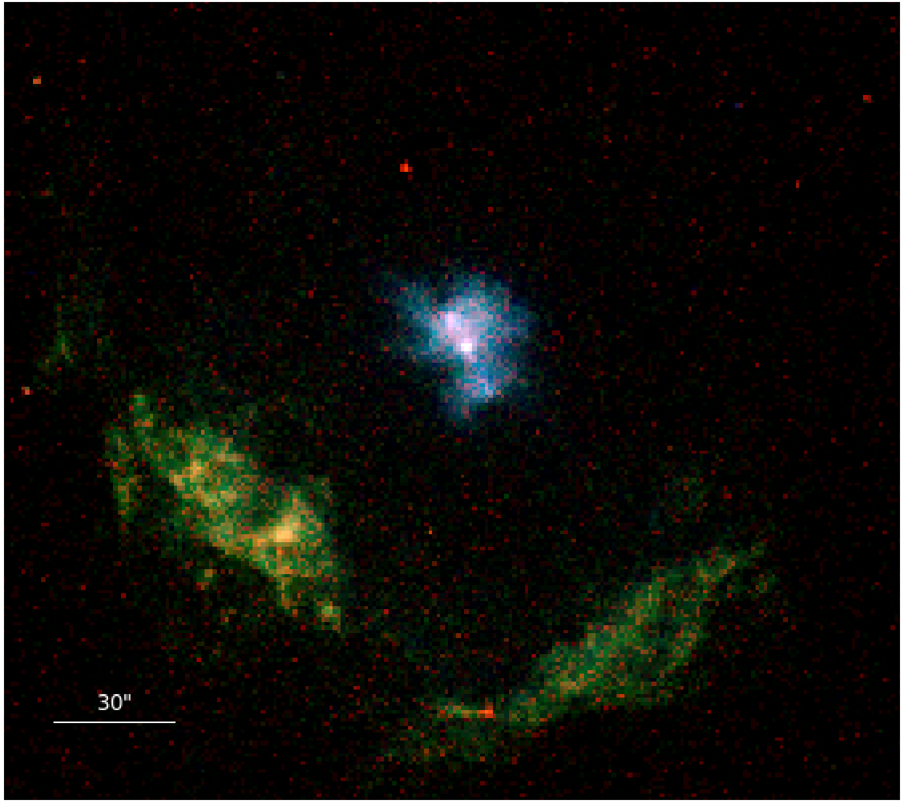
Differencing maps generated from Observations in 2000 and 2003 reveals a ring of hardened emission in the latter observation





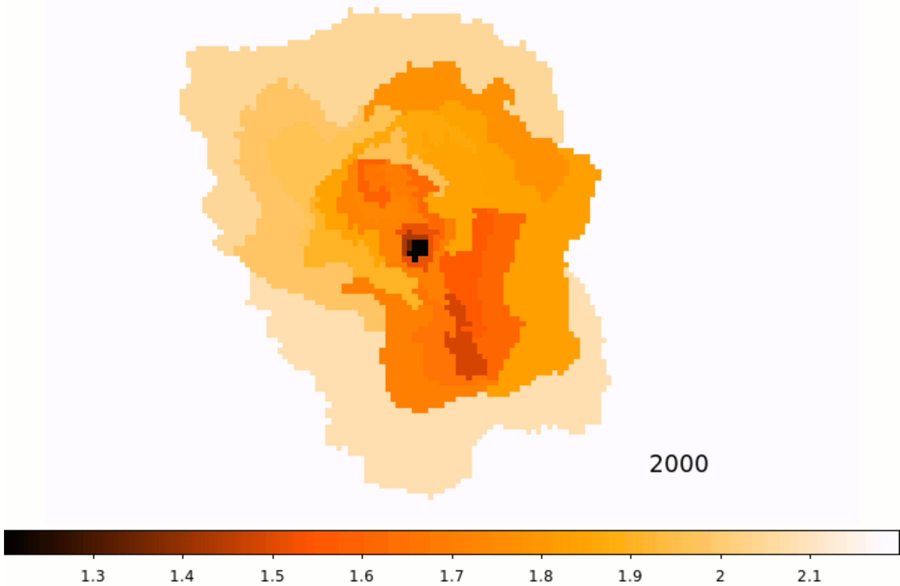
Kes 75

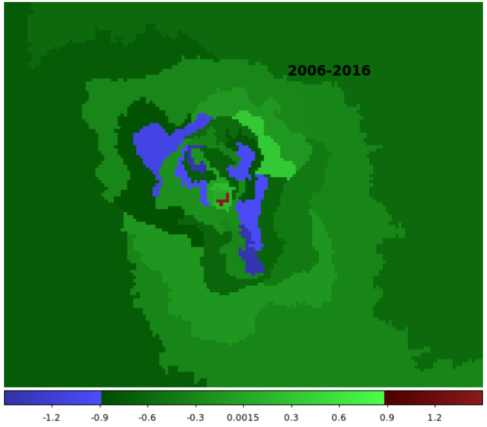
- Plerionic composite remnant
  - Helfand et al 2003
- PWN powered by 324 ms pulsar
  - Livingston et al 2006
- Magnetar outburst caught in 2006 - Brightening and softening of the pulsar
  - Kumar, H. S., Safi-Harb, S. 2008
  - Gavriil et al 2008
- Brightening of the jet post outburst
  - Ng et al 2008
- PWN expansion age 400 yr
  - Reynolds et al 2018



Kes 75

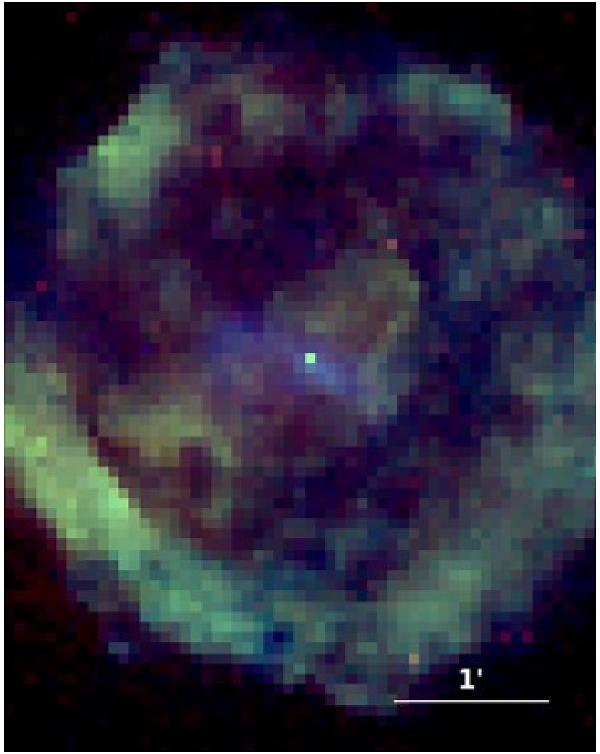
We find slight hardening of the southern jet from 2000-2006 followed by significant softening from 2006-2016





G11.2-0.3

- Plerionic composite remnant
  - Vasisht et al 1996
- PWN powered by 65 ms pulsar
  - Torii et al 1997
- The PWN is heavily obscured by thermal emission from the supernova remnant shell
  - Roberts et al 2003
- Observed in 2000, 2003, 2013
- Only deep observations are from 2013



G11.2-0.3

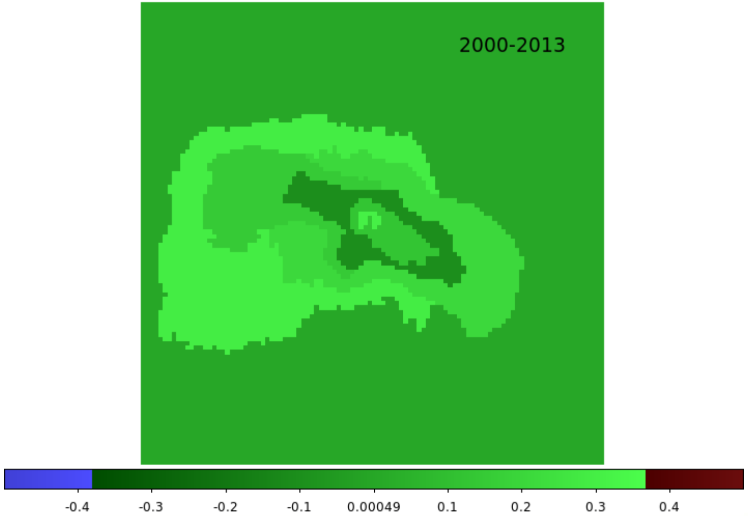
Filter image to 3.5-8 keV where the non-thermal emission is dominant

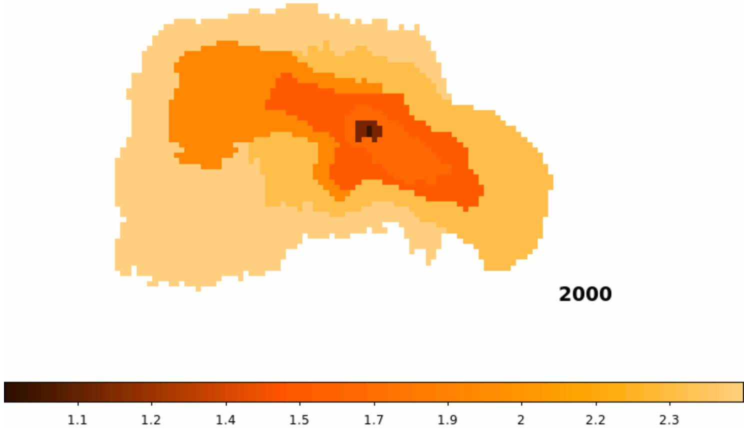
Fit spectra over this energy range

No significant variability observed

Truly stable?

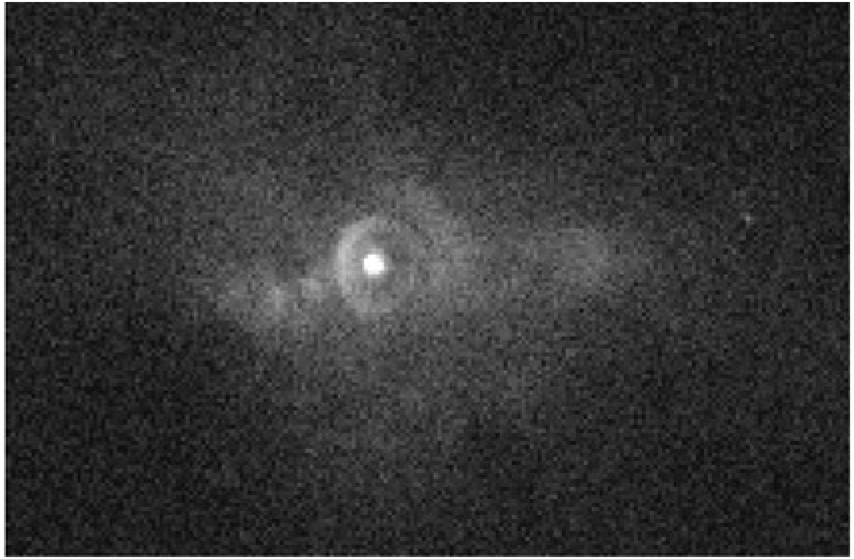
Consequence of large errors from short observations?



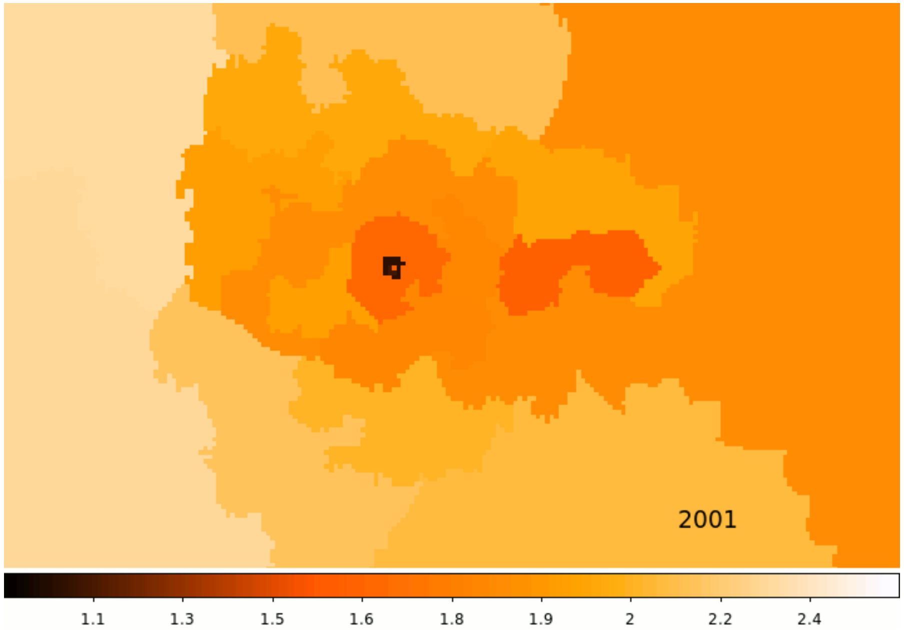


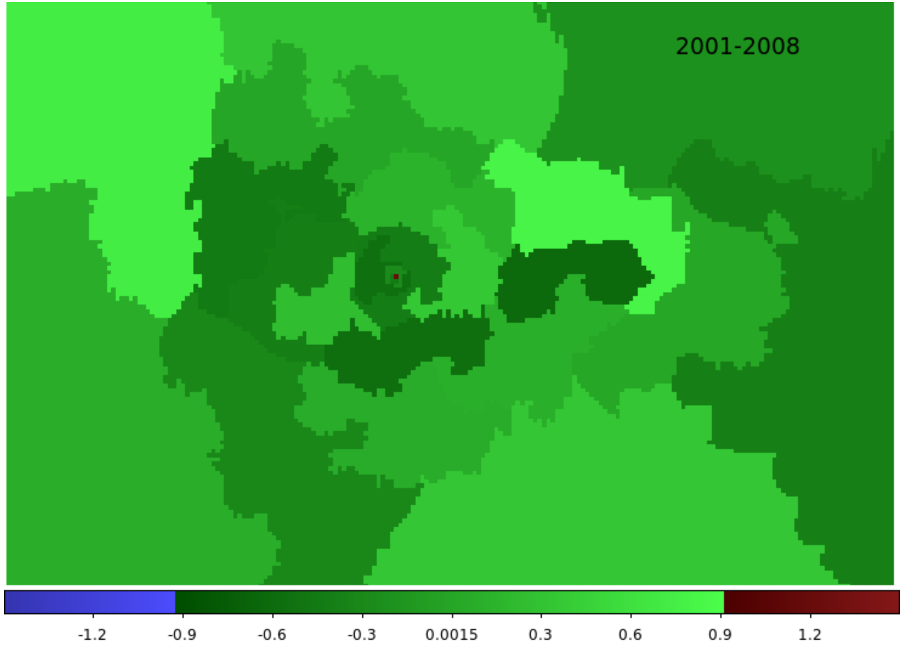
G54.1+0.3

- Plerionic composite remnant
- Discovery of Infrared shell
  - Temim et al 2010
- Prominant ring and jet features
  - Lu et al 2002
- Powered by 137 ms pulsar
  Characteristic age of 2900 years
  - Camilo et al 2002
- Progenitor 15-20$M_{\odot}$ isolated star
  - Gelfand et al 2015



G54.1+0.3





No significant changes are observed

Conclusions

Spectral maps are a powerful tool to study pulsar wind nebulae

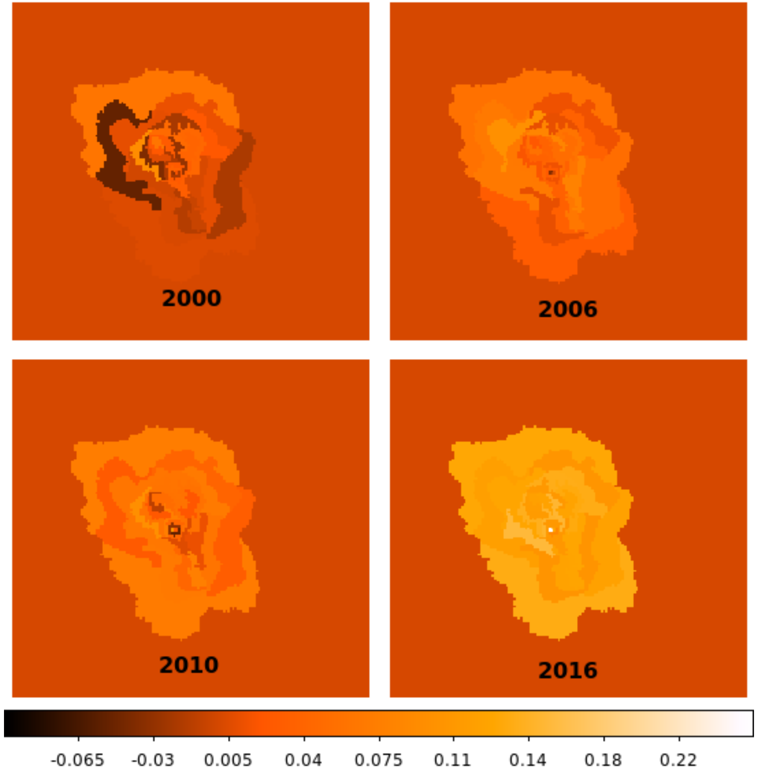
As a whole a PWN may be extremely stable in its emission

High resolution Imaging combined with sensitivity and X-ray spectroscopy is required to observe variability in the wind

Additional Slides

Chandra Contamination

Difference between contamination corrected map and uncorrected map
The column density is frozen to the same value for each year of observation

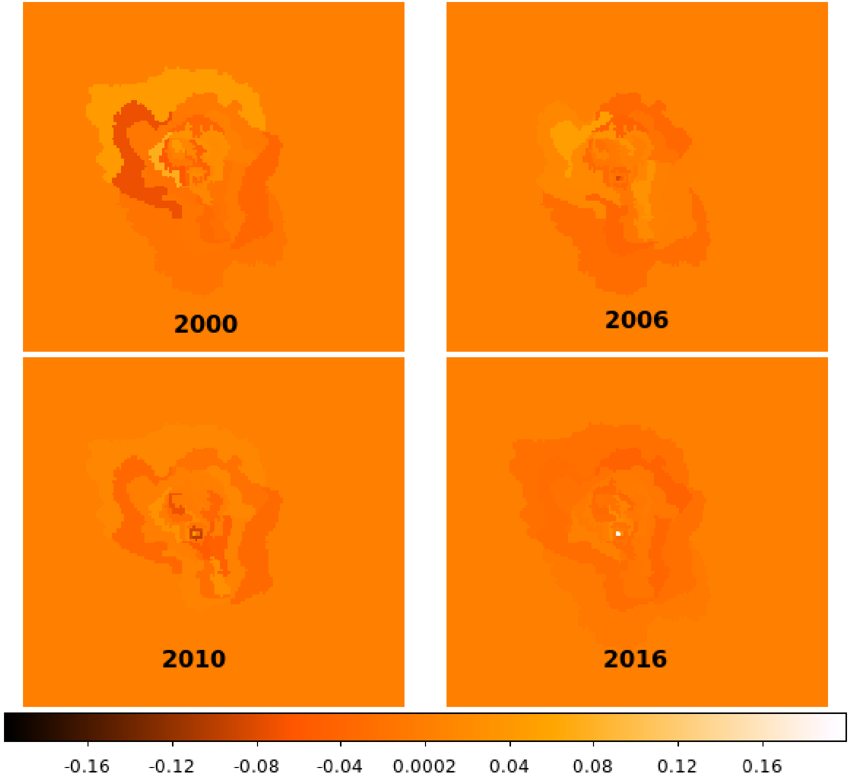


Chandra Contamination

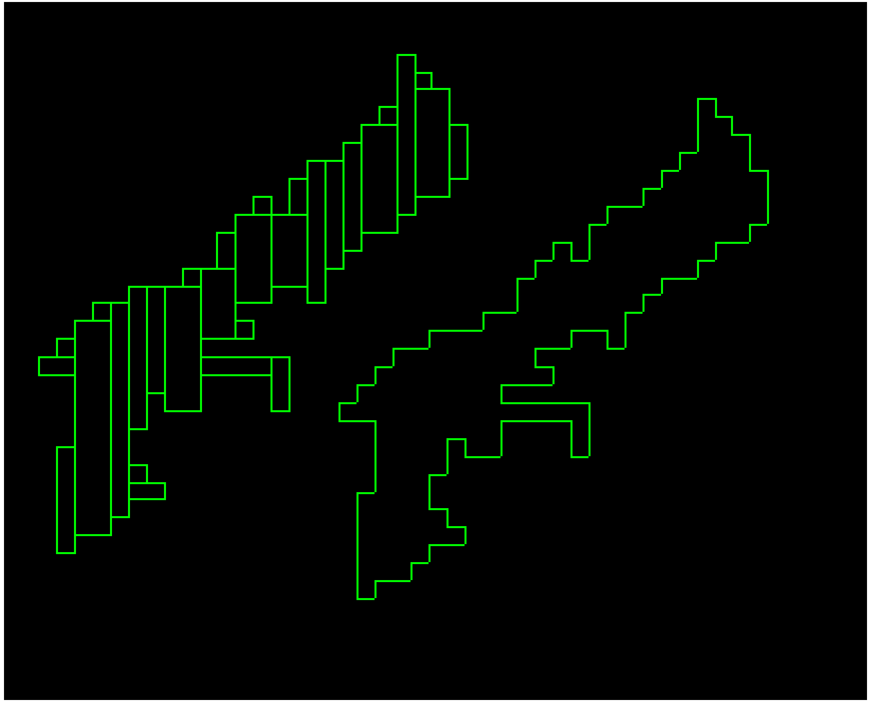
Difference between Contamination corrected maps and uncorrected maps

Different values of the column density were used

These were found from fitting the whole pwn spectrum

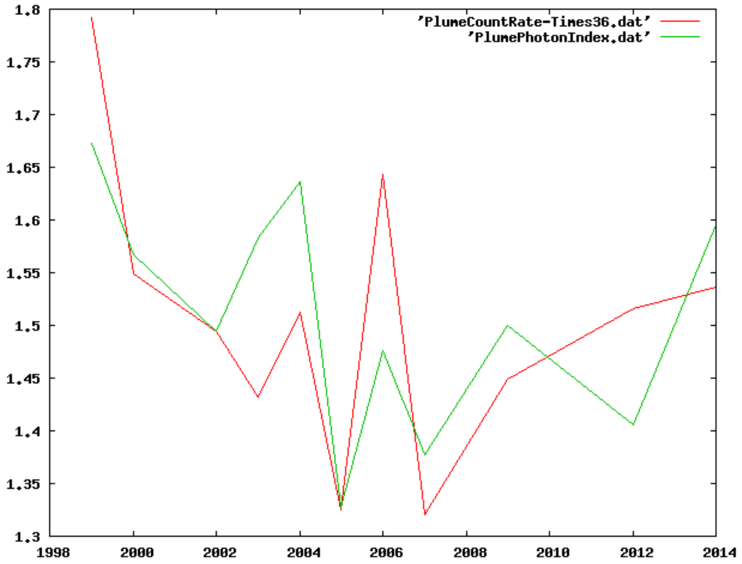


Generated Regions

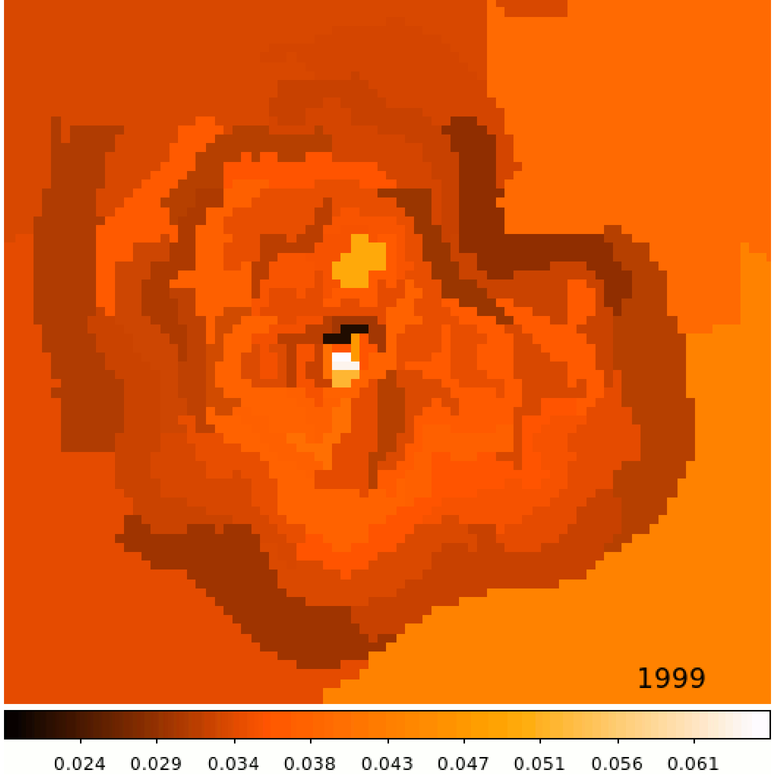


G21.5-0.9

Count rate Map

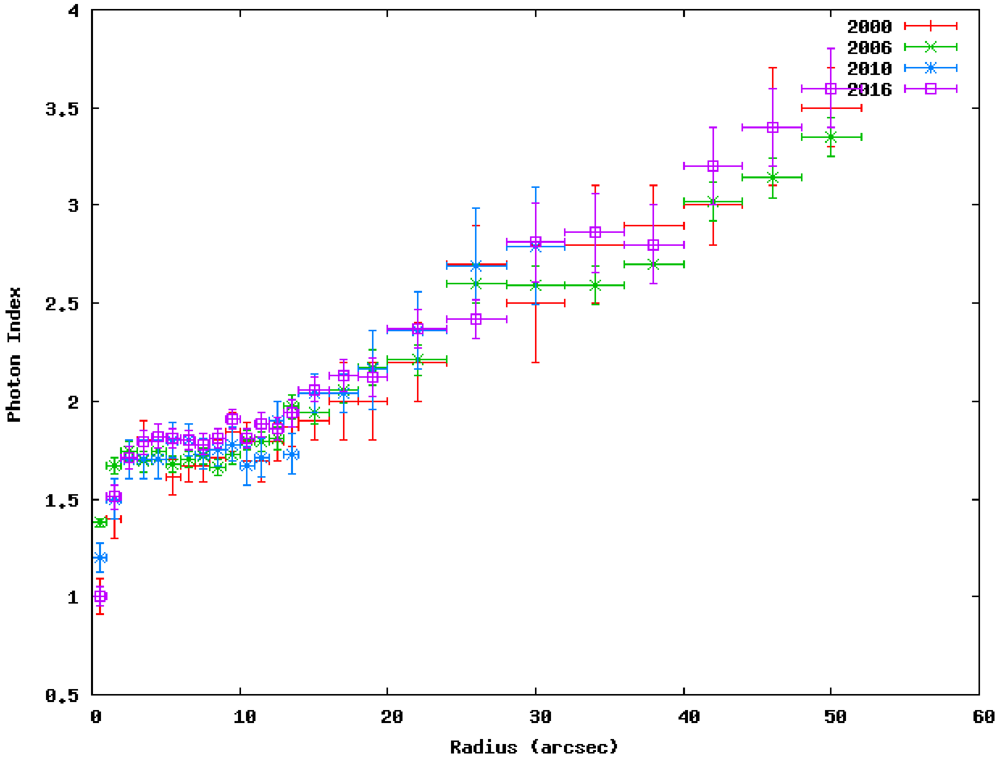


Count rate (red) and Photon index (green) for the plume region

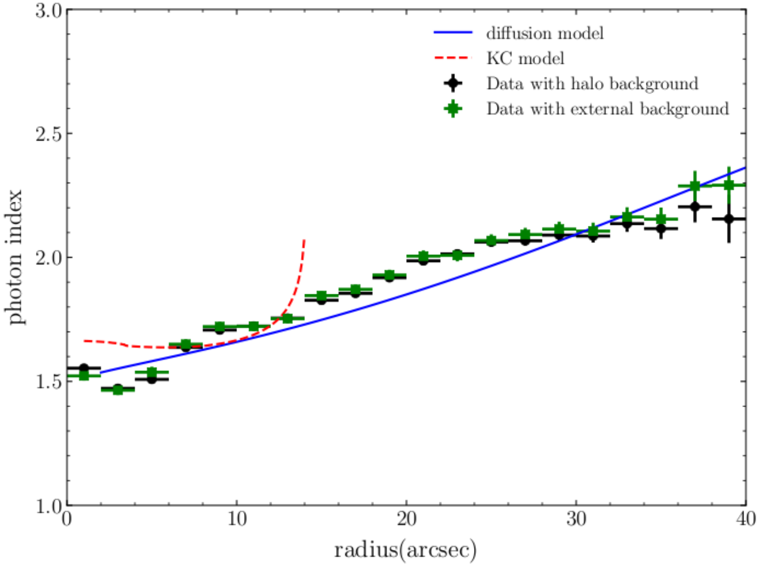


Average count rates for the spectral map regions

Radial Profiles



Kes 75 Radial Profile



G21.5-0.9 Radial Profile
Guest et al 2019