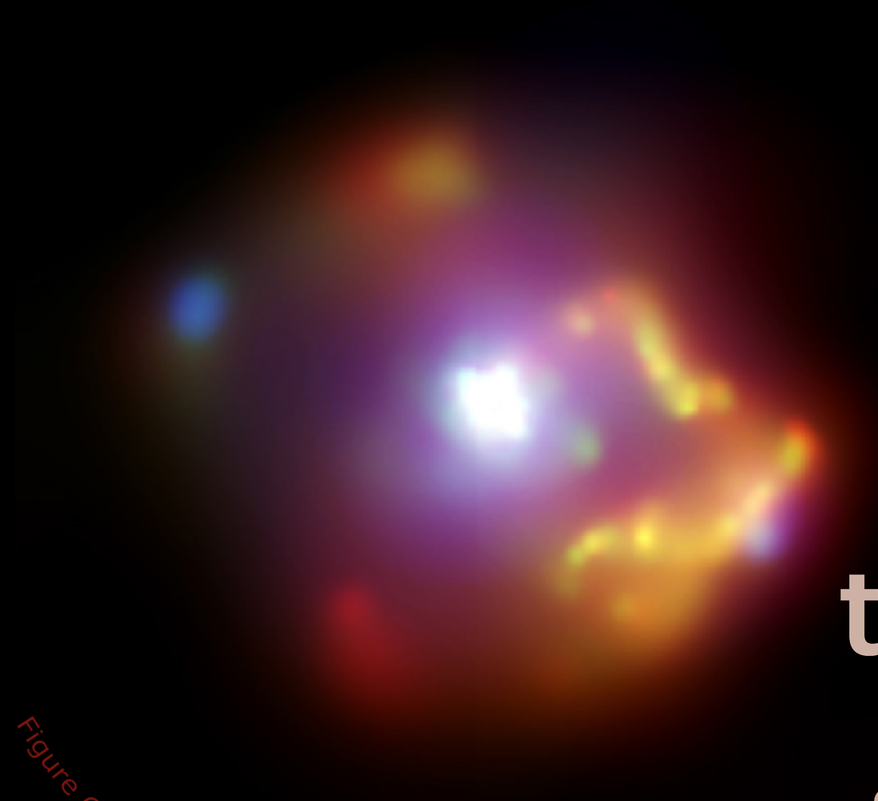


Figure Credit: NASA/CXC/SAO

Spatial Variations and Breaks in the Optical-NIR Spectra

of the Pulsar and Pulsar-wind Nebula in SNR 0540-69.3

Linda Tenhu, PhD Student at KTH Sweden

+ Collaborators J. Larsson, J. Sollerman, P. Lundqvist, J.Spyromilio, J. D. Lyman, and G. Olofsson

SNR 0540 ("Crab twin") ?

+ orientation on the sky

Located ~50 kpc away at the LMC

1100-1200 yr old

Oxygen rich

Massive star progenitor

Type II SN explosion

Forward Shock ~30'' (7 pc) from centre

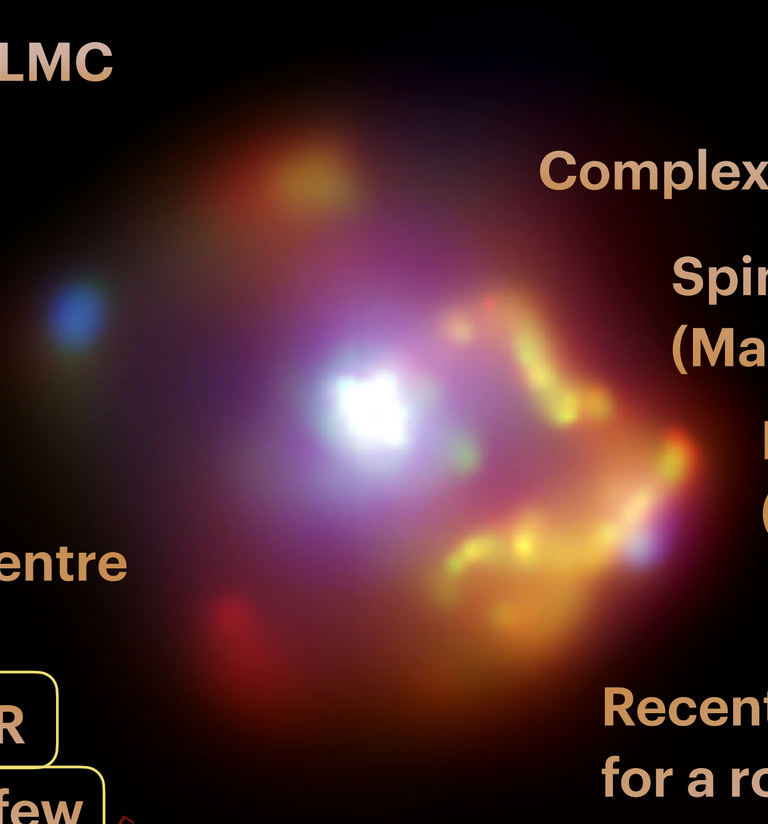


Figure Credit: NASA/CXC/SAO

Complex PSR and PWN in SNR 0540:

Spin-down rate change early 2010 (Marshall+15)

PWN X-ray luminosity increase (Ge+19)

Recently: first ever anti-glitch observed for a rotationally powered-pulsar (Tuo+24)

PWN and PSR

PSR and PWN amongst those few that are bright in optical

PSR has a fast spin period ~50 ms

PSR AND PWN 0540: THIS TALK

Optical synchrotron emission from PSR and PWN

Model this emission with a Power Law (or broken Power Law):

$F_\nu \propto \nu^{-\alpha}$ spectral index

(broken Power Law with 2 separate spectral indices)

Question:

What is the spectral index that best describes the PSR and PWN of SNR 0540?

Answer:

Learn more about the conditions at the emission sites

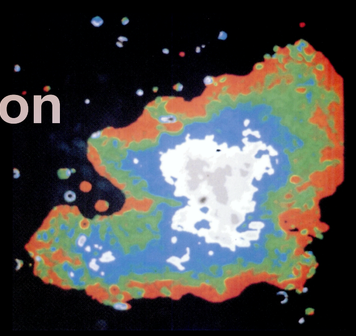
Figure Credit: NASA/CXC/SAO

Previous studies on 0540: conflicting results for both PSR and PWN spectral index

Optical studies on other PWNe:

Photometry on the Crab Nebula by Véron-Cetty+93

Canonical synchrotron cooling picture



Other wavelength ranges:

Similar results in X-rays (e.g Mori+04, Hu+22)

MUSE and X-Shooter Observations @ VLT

X-rays, 1.7′ across

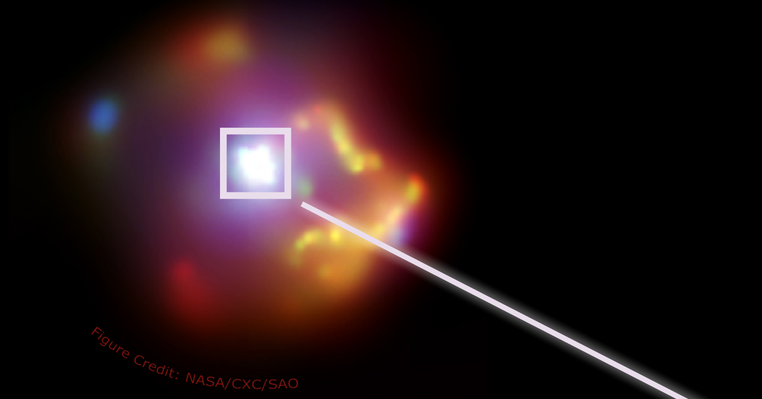
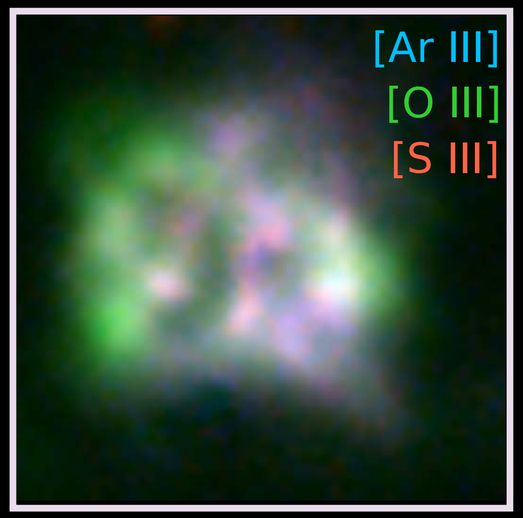
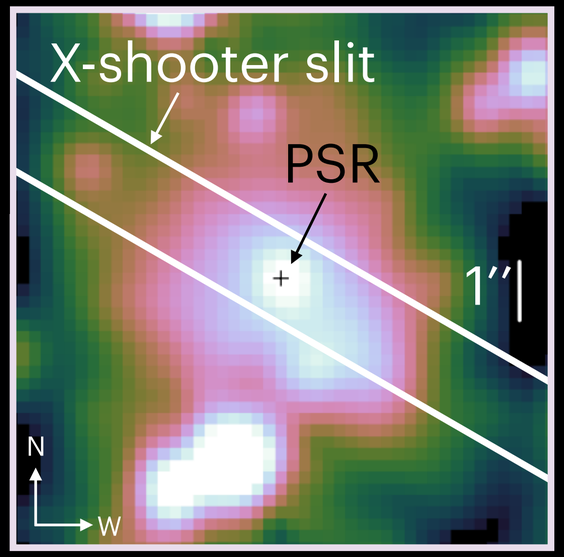


Figure Credit: NASA/CXC/SAO



Larsson+21

Optical, 14″ across



MUSE

IFU data: 4650—9300 Å

Entire FoV: 1′.0 x 1′.0

Observed: Jan & Mar 2019

X-shooter

Slit-spectroscopy: 3000—25 000 Å

Slit dimensions: 1″.2—1″.6 x 11″

Observed: Oct & Nov 2019

First NIR spectrum of the source!

Data Preparation: Main Steps

Obtain uniform spatial resolution:

- MUSE PSF varies with wavelength
- → convolve each wavelength to the same resolution

Isolating the continuum spectrum

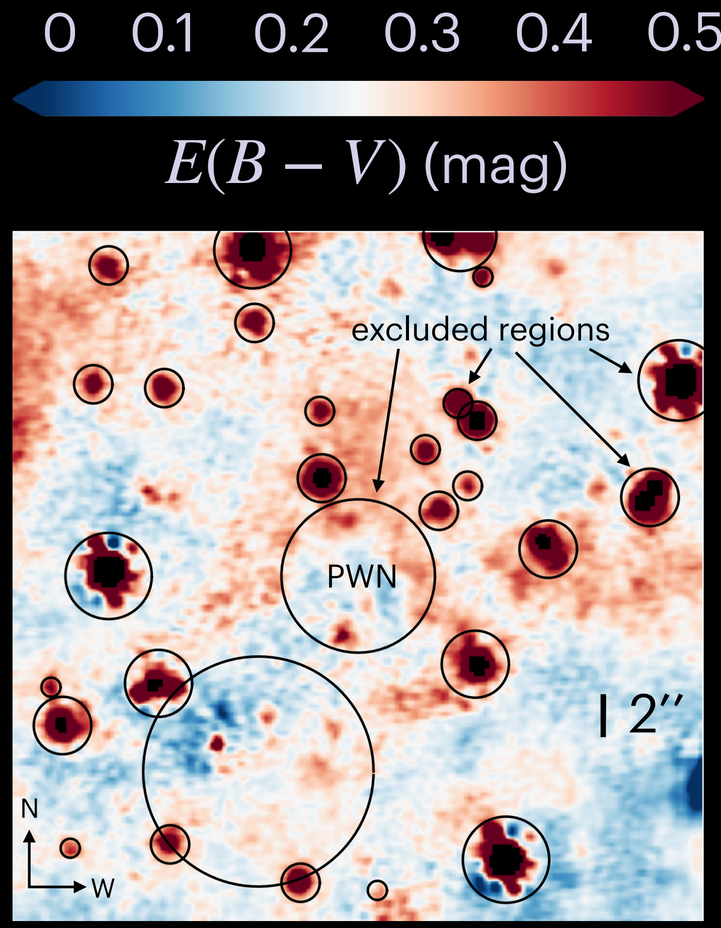
- Remove emission lines and other non-continuum features

Correct for extinction

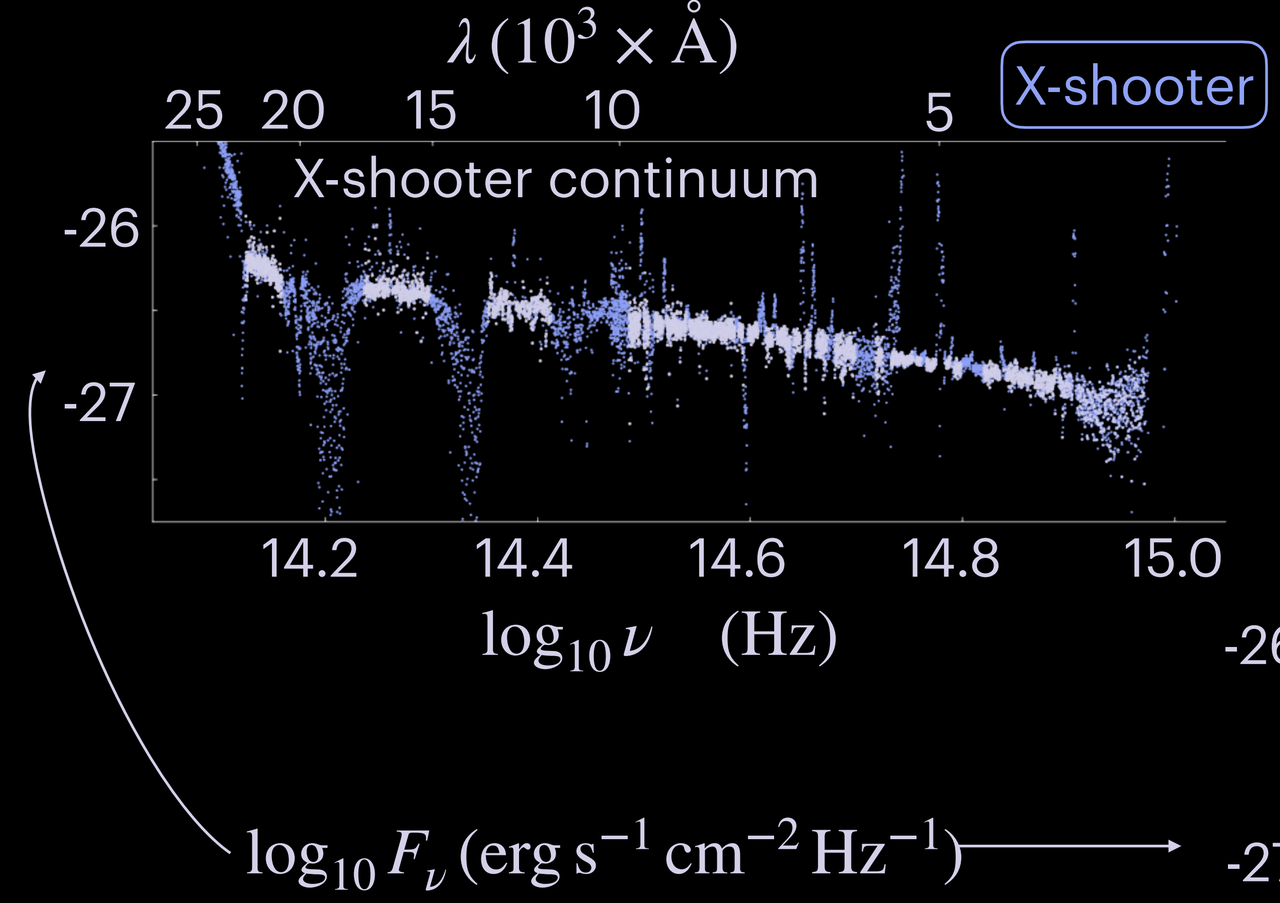
- Measure the Balmer decrement around the PWN:

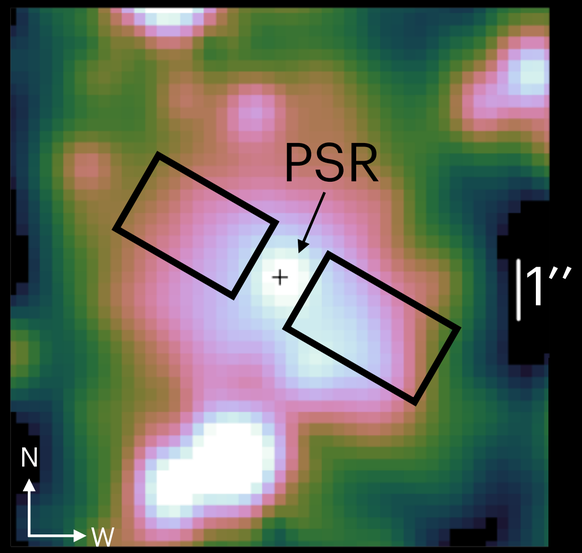
$$E(B-V) = 0.27 \pm 0.07.$$

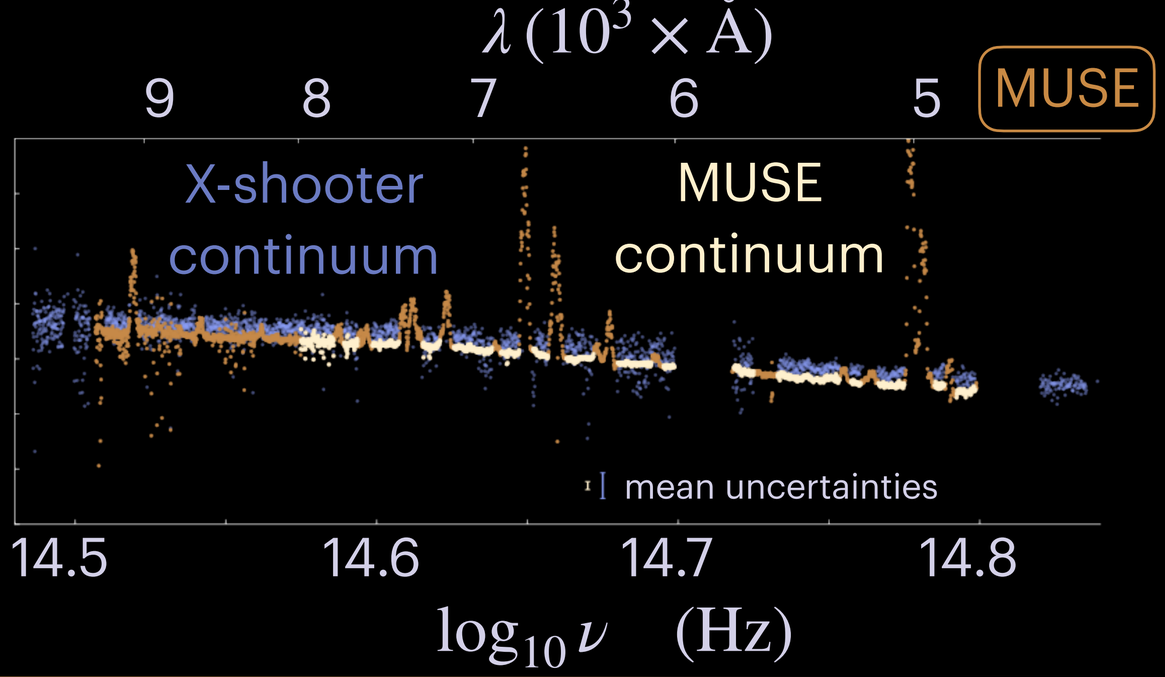
- Larger by ~0.07 compared to previous measurements (Kirshner+89, Serafimovich+04)



Example Continuum Spectra

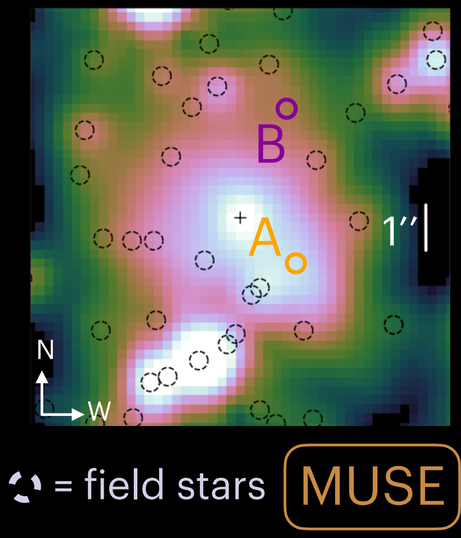




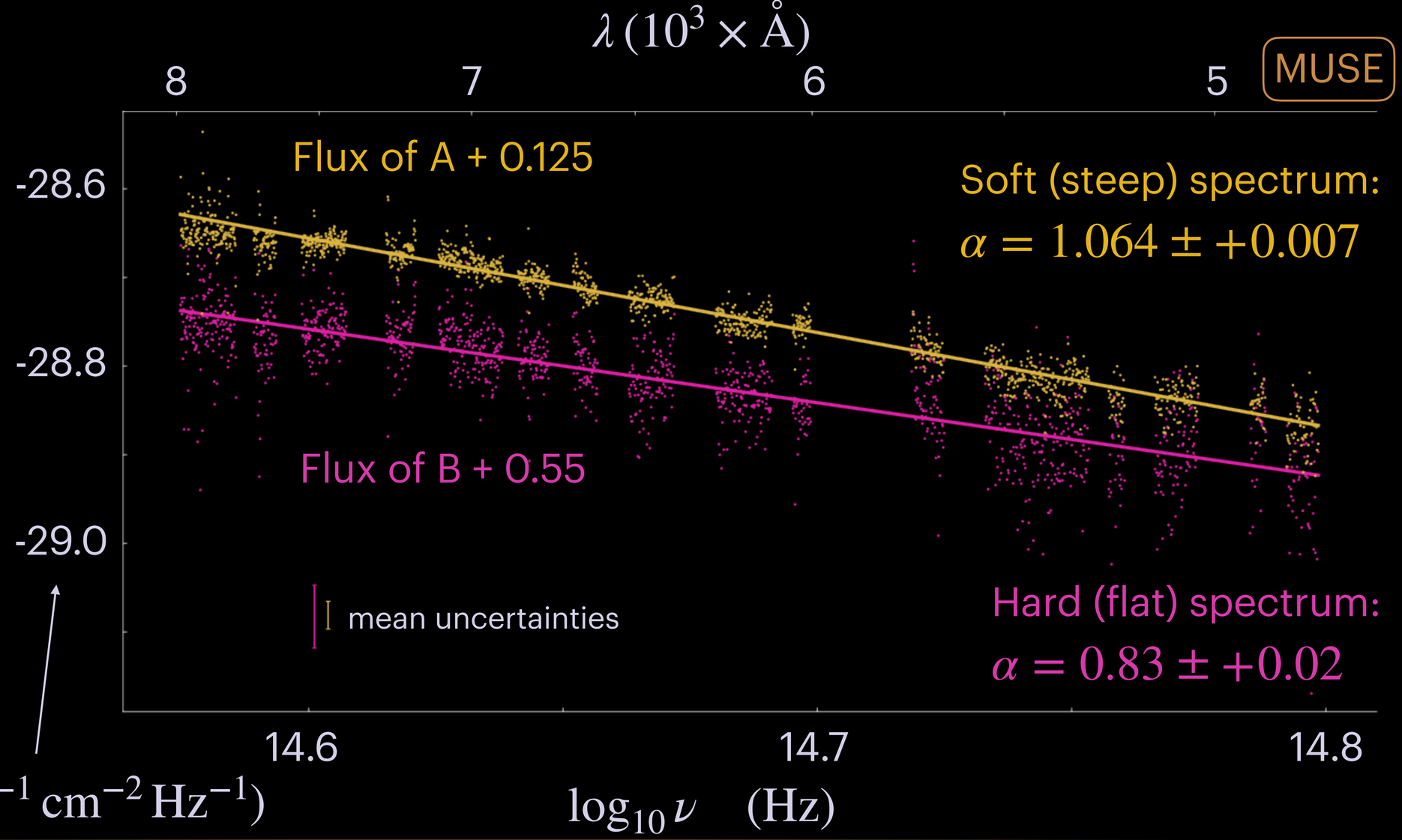


PWN: Fit Continuum Spectrum

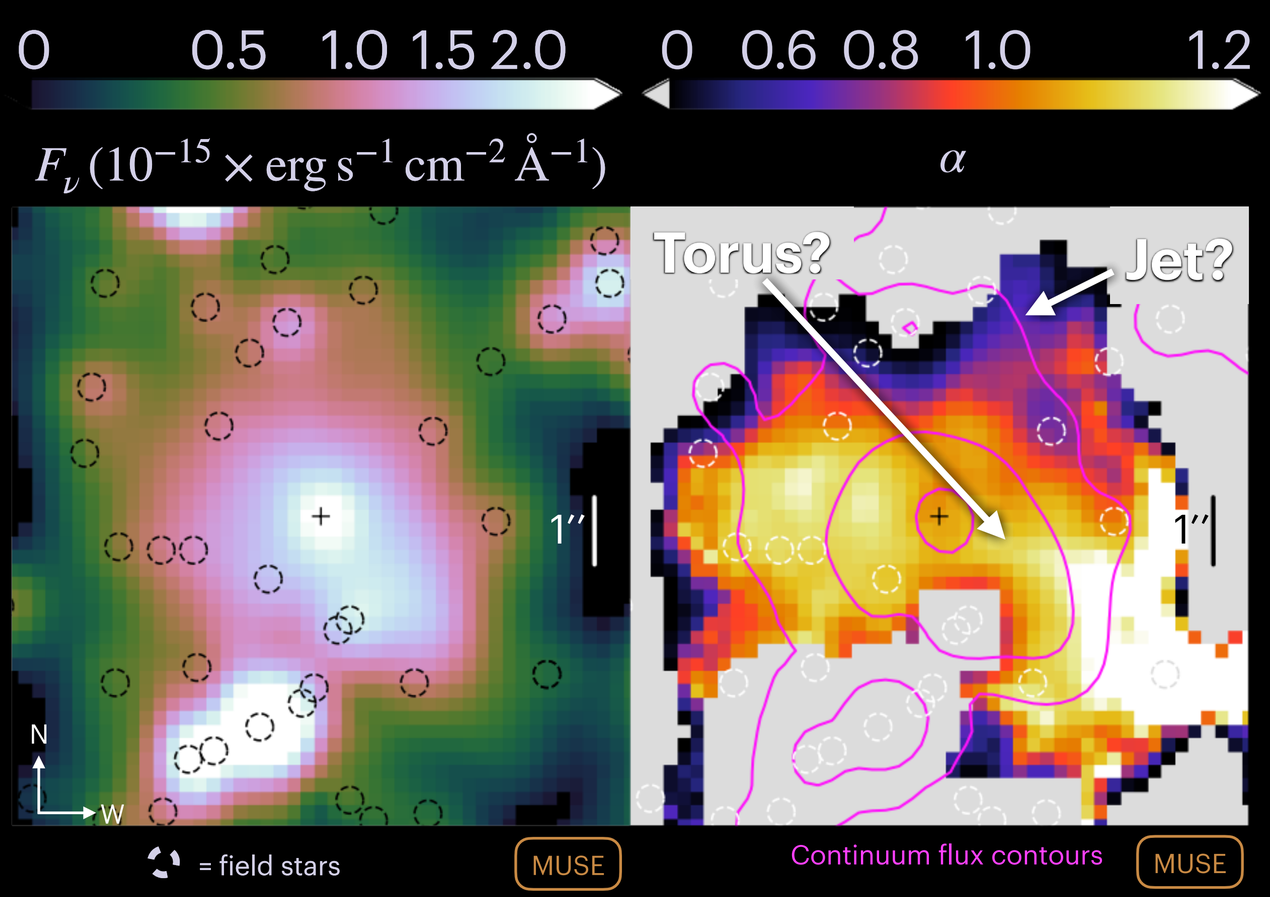
$F_\nu \propto \nu^{-\alpha}$



= field stars MUSE

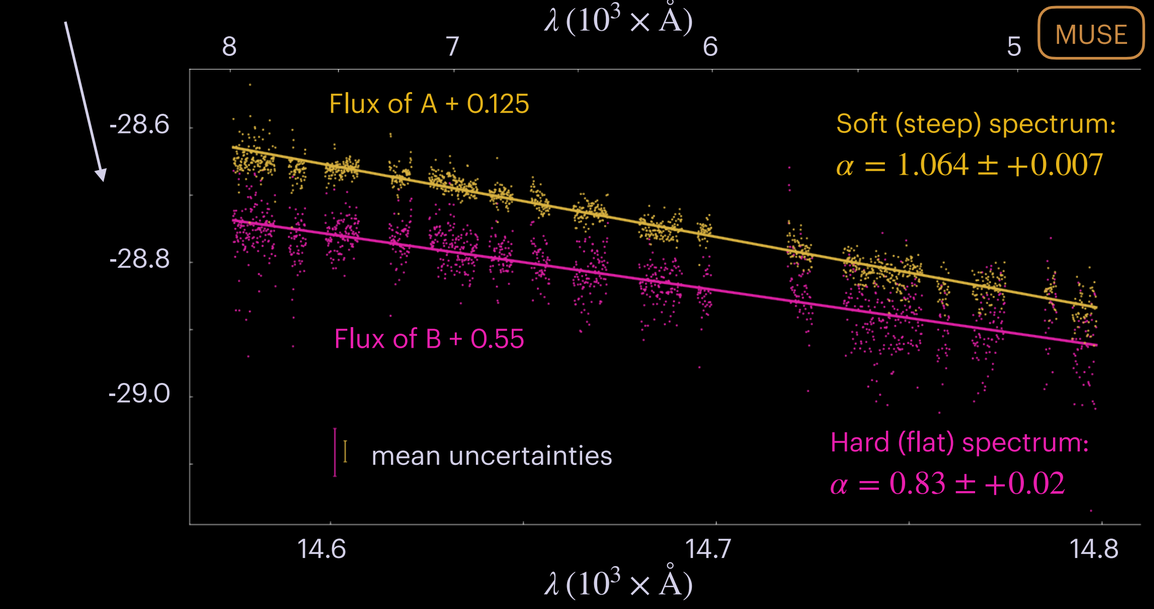


Spatial Variation of the Spectral Index α



Spatial spectral hardening towards PWN outer edge: from $\alpha \sim 1.1$ to $\alpha \sim 0.1$

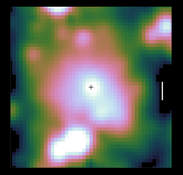
Power-law Model: $F_\nu \propto \nu^{-\alpha}$

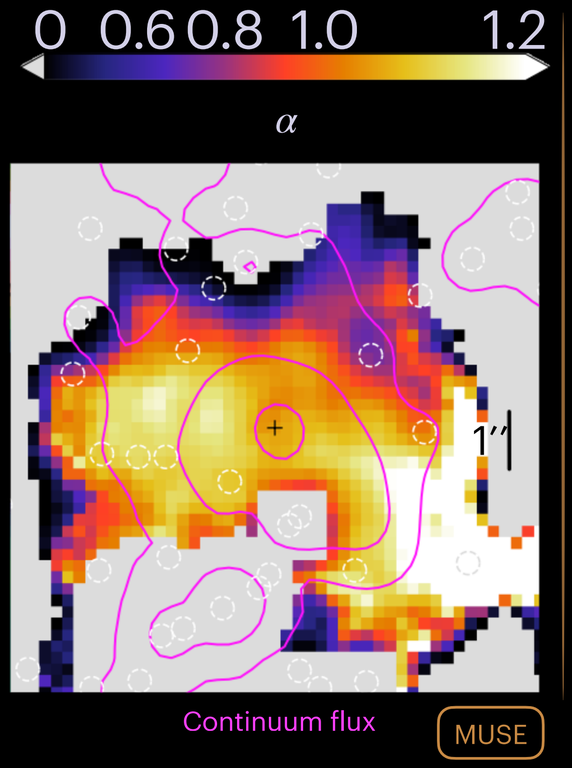


Serafimovich+04 : hints of similar variation along the torus in the optical

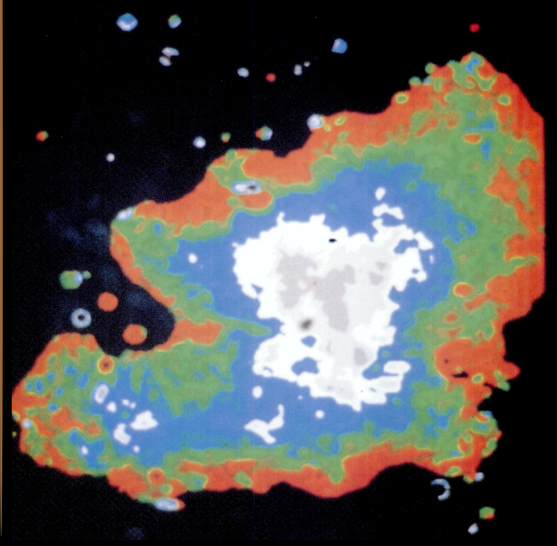
Opposite to what is expected from the canonical synchrotron cooling picture (e.g PWN observations in X-rays Hu+22)

Spatial Spectral Index Variation: SNR 0540 vs Crab





Véron-Cetty+93



Spatial spectral hardening towards PWN outer edge:

$$\alpha \sim 1.1 \rightarrow \alpha \sim 0.1$$

Spatial spectral softening towards PWN outer edge:

$$\alpha \sim 0.6 \rightarrow \alpha \sim 1$$

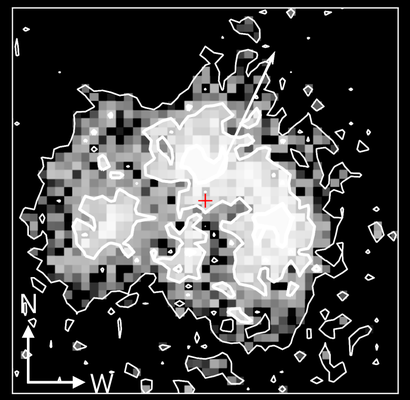
= canonical synchrotron cooling

Other non-synchrotron components in the continuum like Balmer recombination continuum or two-photon emission?

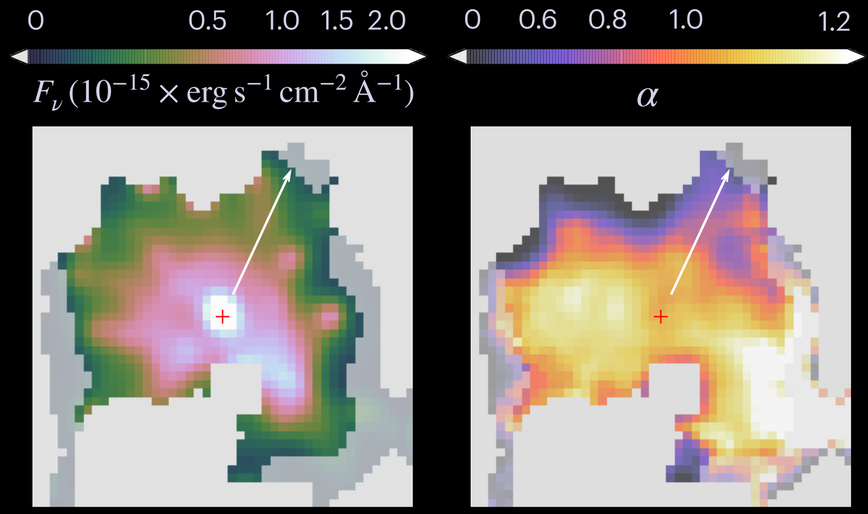
Continuum dominated by
balmer recombination or two-photon emission

→ spatial correlation between hard continuum
and Balmer emission lines

Hβ

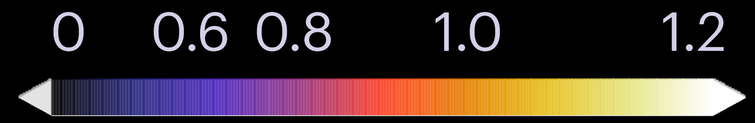


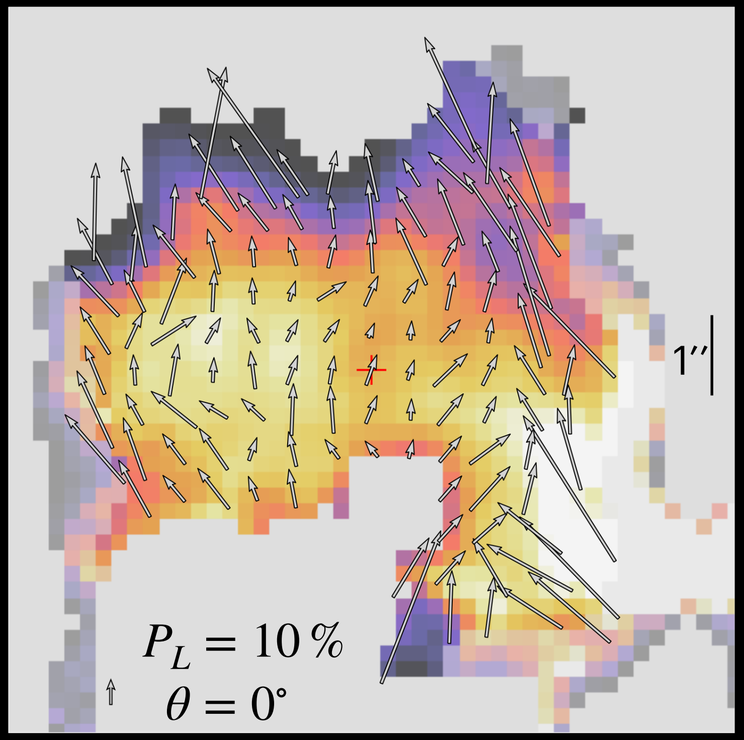
Larsson+21



No spatial correlation

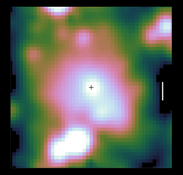
But similar variation in
optical polarisation degree!





Polarisation data: Lundqvist+11

[S III] [S III] + continuum [S III] + α



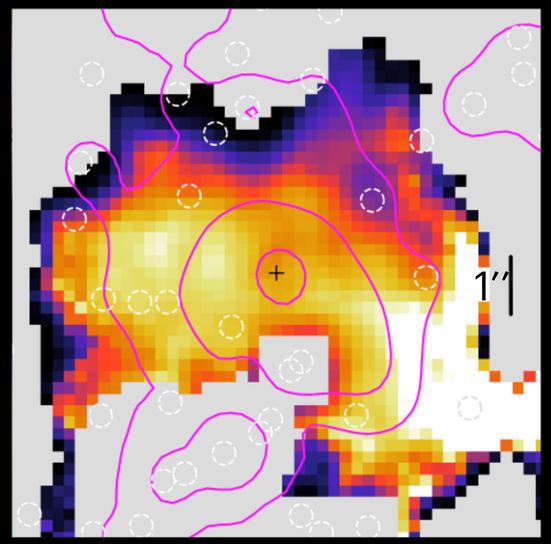
Spatial Spectral Index Variation: SNR 0540 vs Crab

0 0.6 0.8 1.0 1.2

α

Spatial spectral hardening towards PWN outer edge:

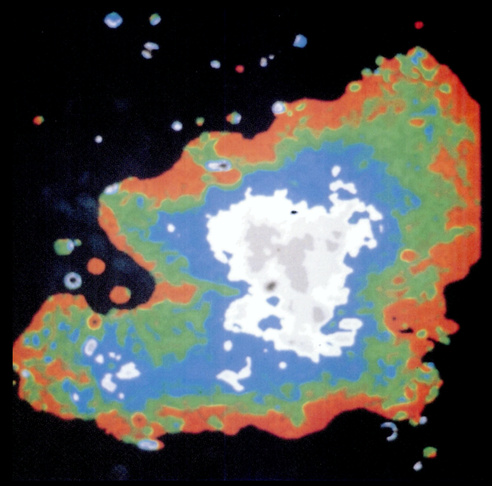
$$\alpha \sim 1.1 \rightarrow \alpha \sim 0.1$$



Continuum flux

MUSE

Véron-Cetty+93



Spatial spectral softening towards PWN outer edge:

$$\alpha \sim 0.6 \rightarrow \alpha \sim 1$$

= canonical synchrotron cooling

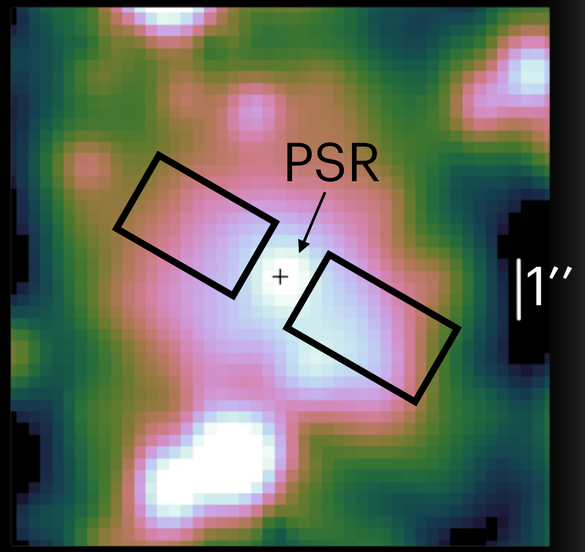
Other non-synchrotron components in the continuum like Balmer recombination continuum or two-photon emission?

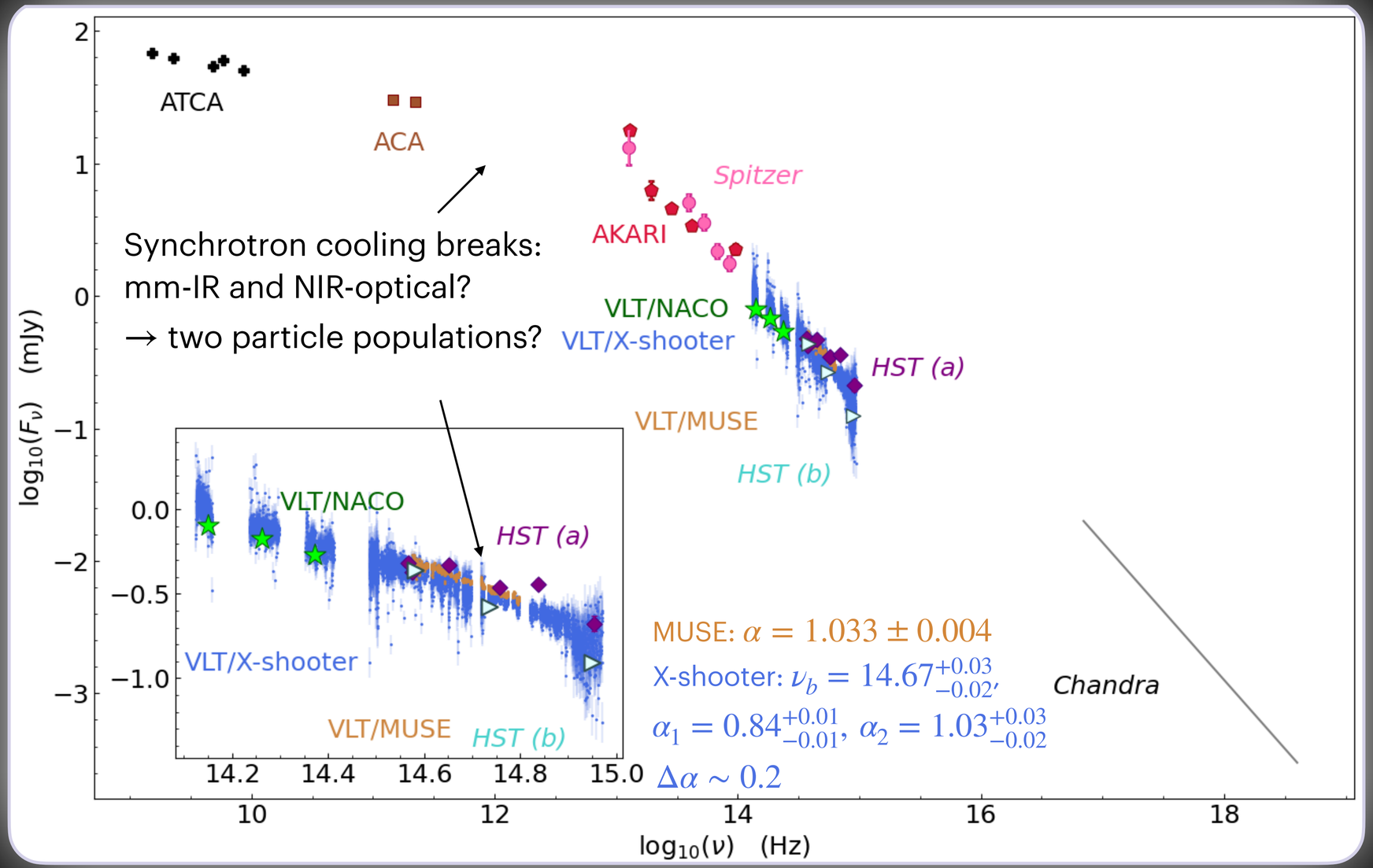
What can cause this unexpected result?

Time variability of the pulsar wind?

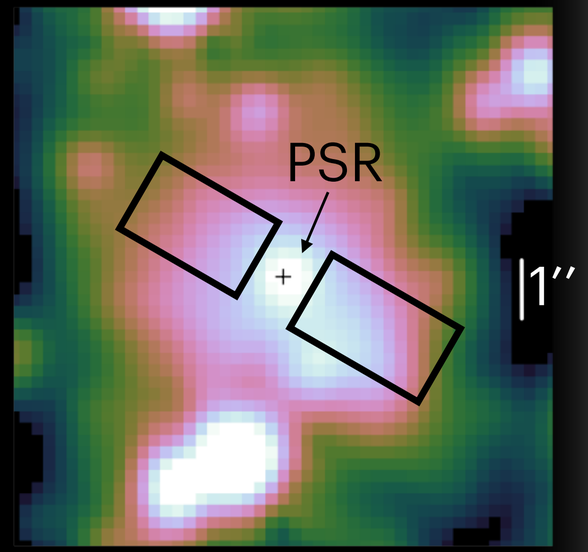
Re-acceleration of particles further out in the system?

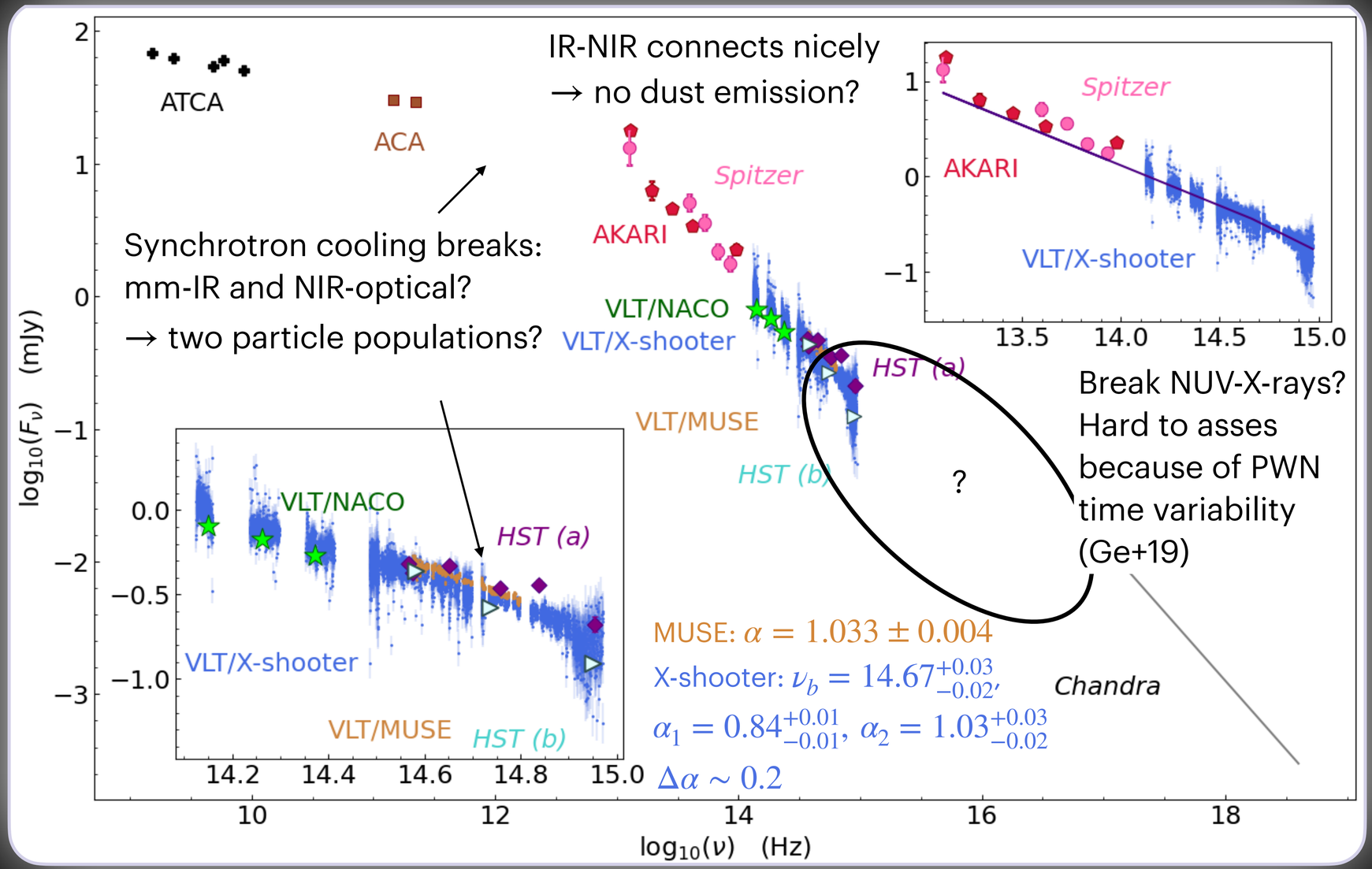
PWN 0540 Spectrum from the Radio to X-rays





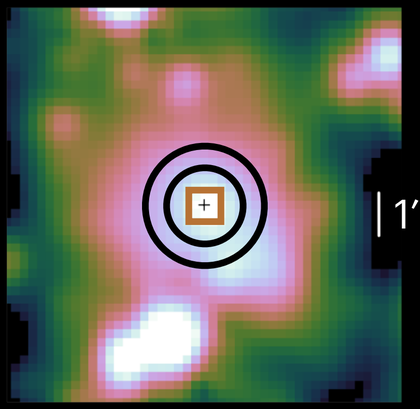
PWN 0540 Spectrum from the Radio to X-rays





PSR: Fit Continuum Spectrum

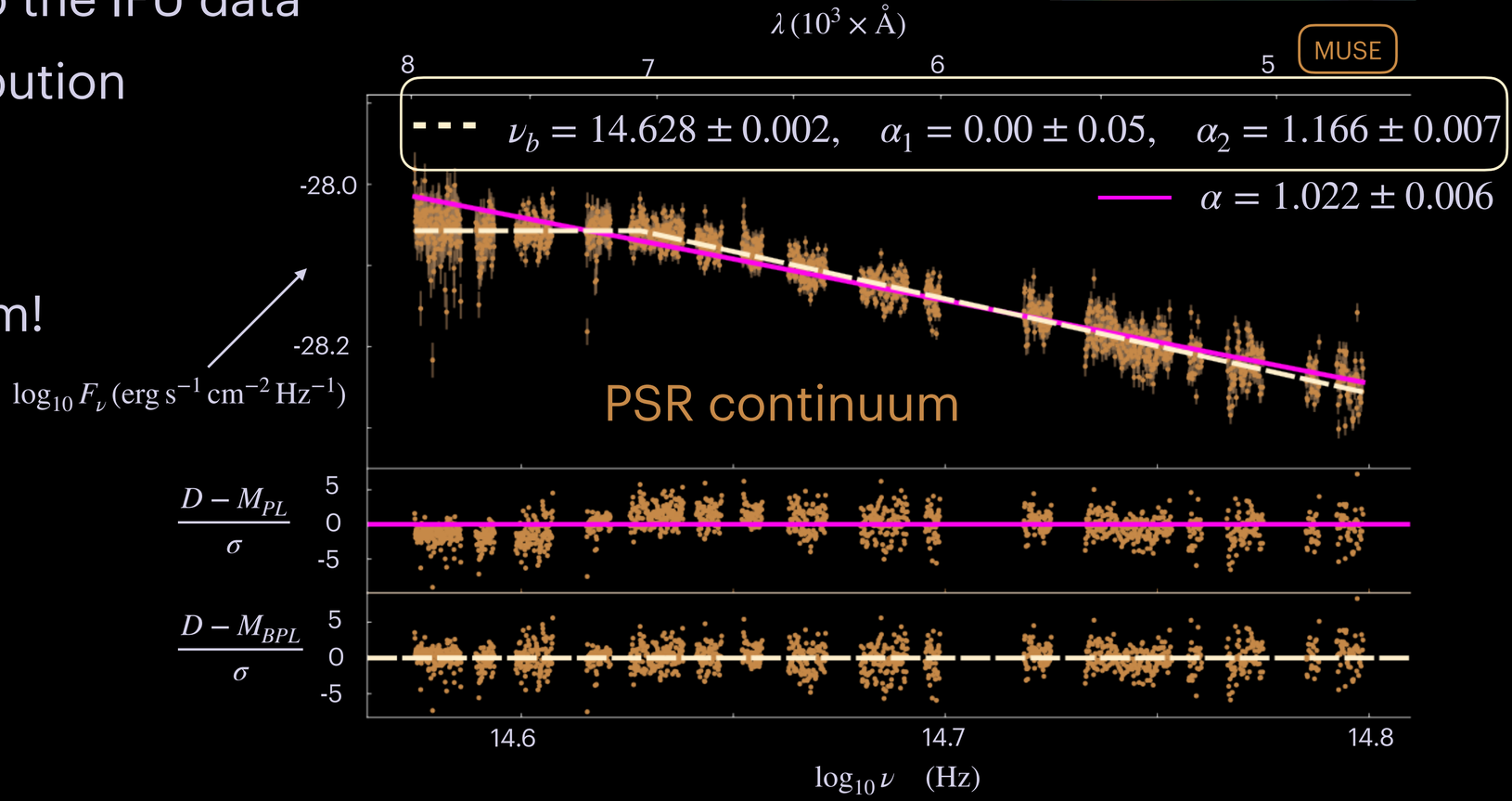
One of the pulsars that can be observed in the optical



Remove PWN contribution from the PSR spectrum

- Better than previously thanks to the IFU data
- Caveat: significant PWN contribution
- → difficult to remove perfectly

Now we have got optical spectrum!



Remove PWN contribution from the PSR spectrum

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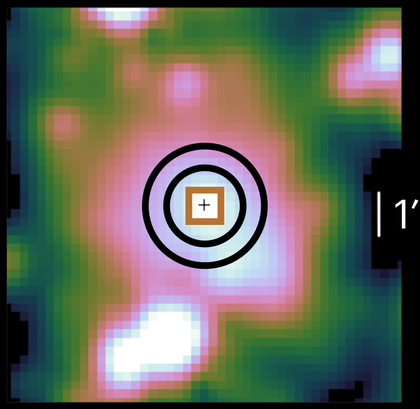


Previously in optical: no break!

Mignani+12 : $\alpha = 0.7 \pm 0.04$

Serafimovich+04: $\alpha = 1.07^{+0.20}_{-0.19}$

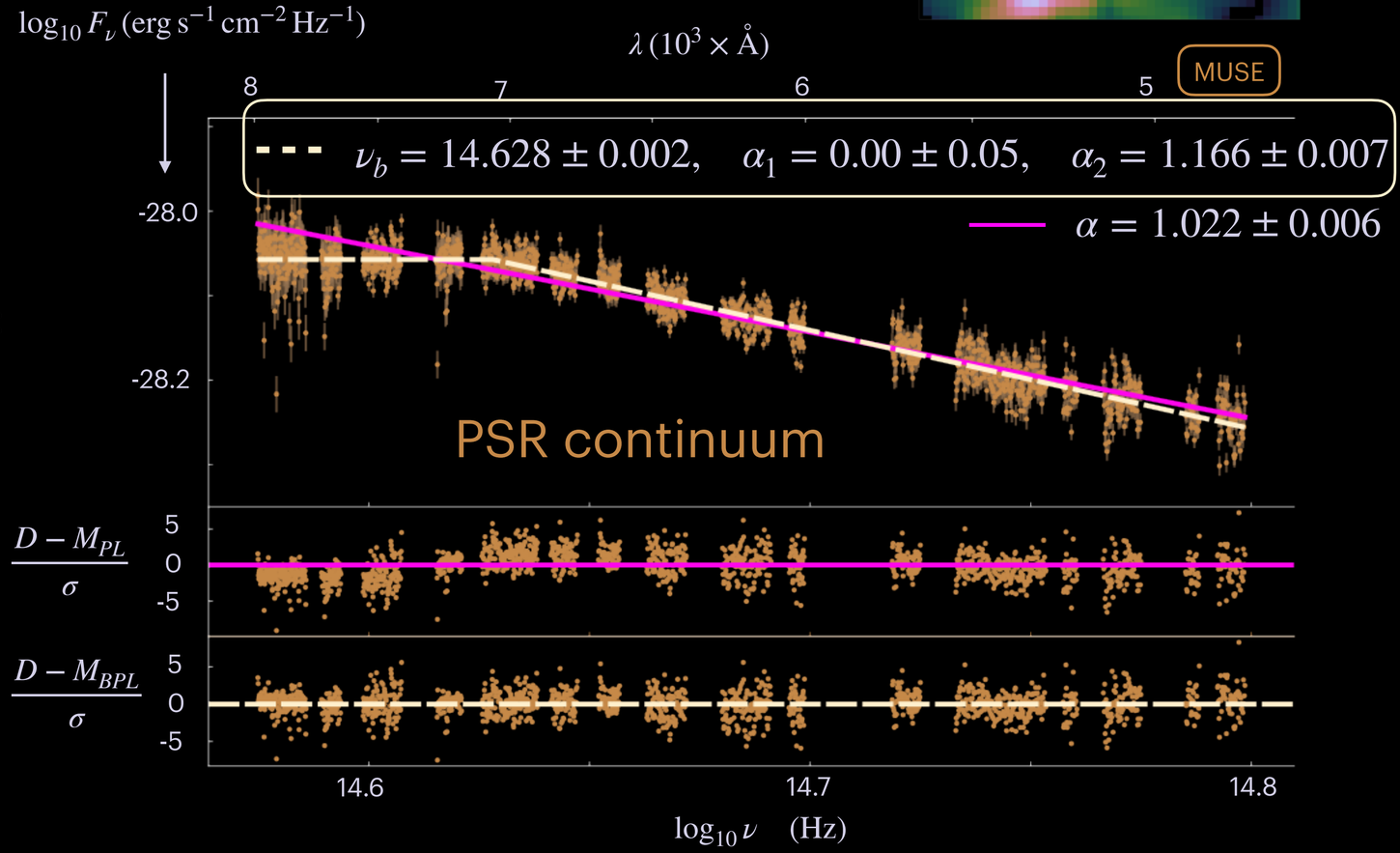
How this connects to other wavelengths:

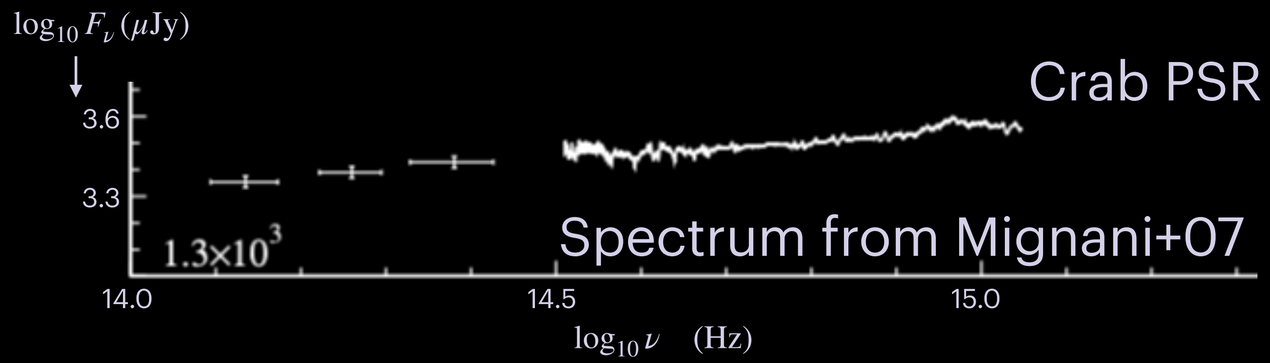
Mignani+19 UV: $\alpha \sim 3$!

Caveats:

Early 2010s: Spin-down rate change + PWN X-ray luminosity change (Marshall+15, Ge+19)

Recent: anti-glitch (Tuo+2024)





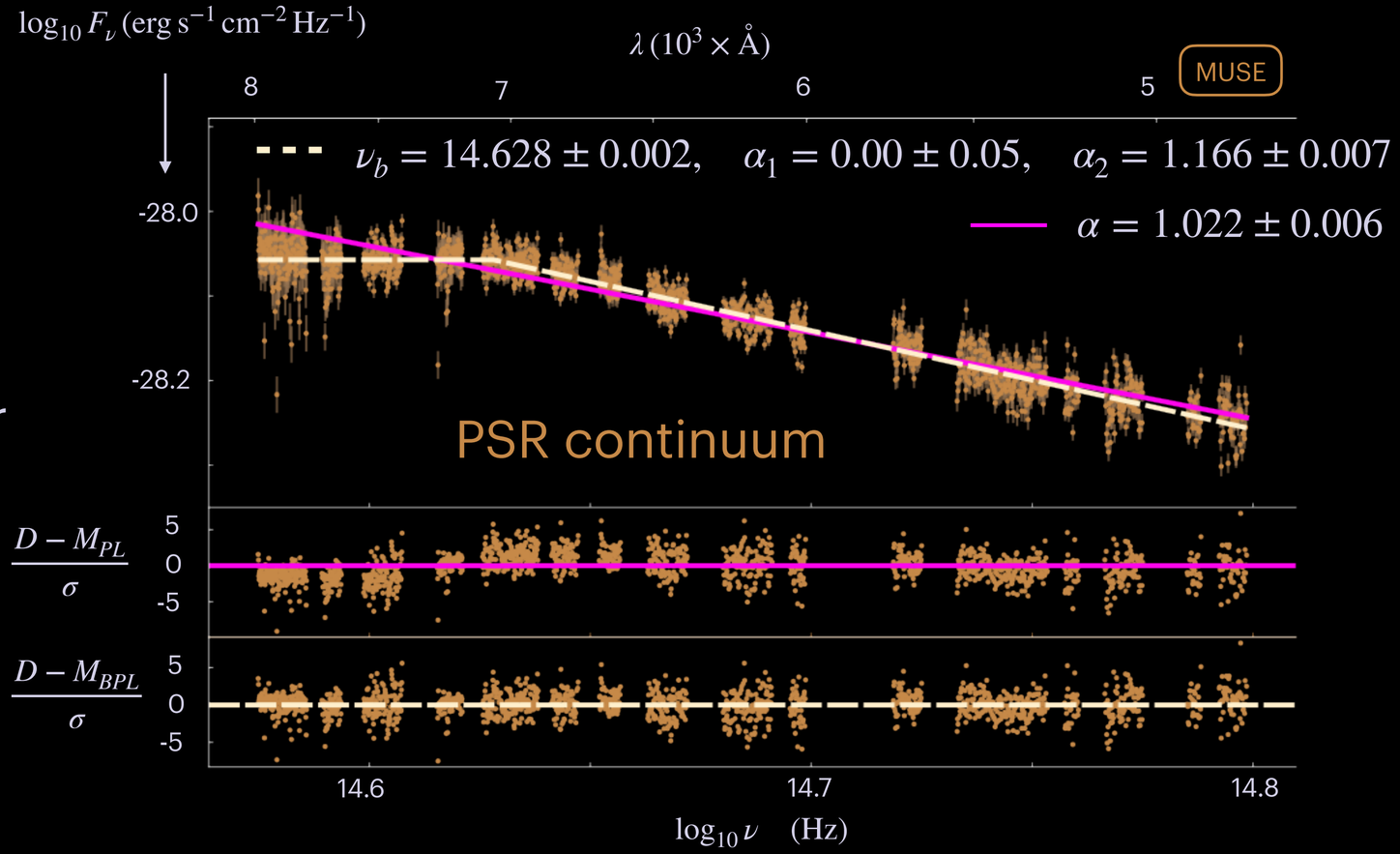
Crab PSR vs PSR 0540

Very different pulsar spectra!

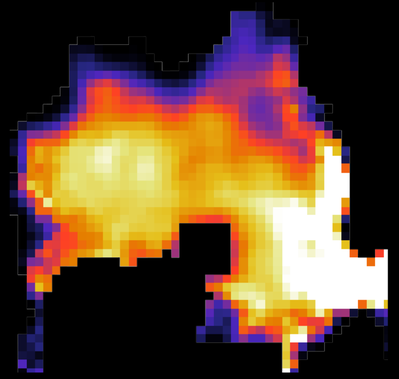
Fit: Sollerman+19, $\alpha = -0.16 \pm 0.07$

Perhaps these objects are not as similar as previously thought?

Differences in pulsars propagating to PWNe?

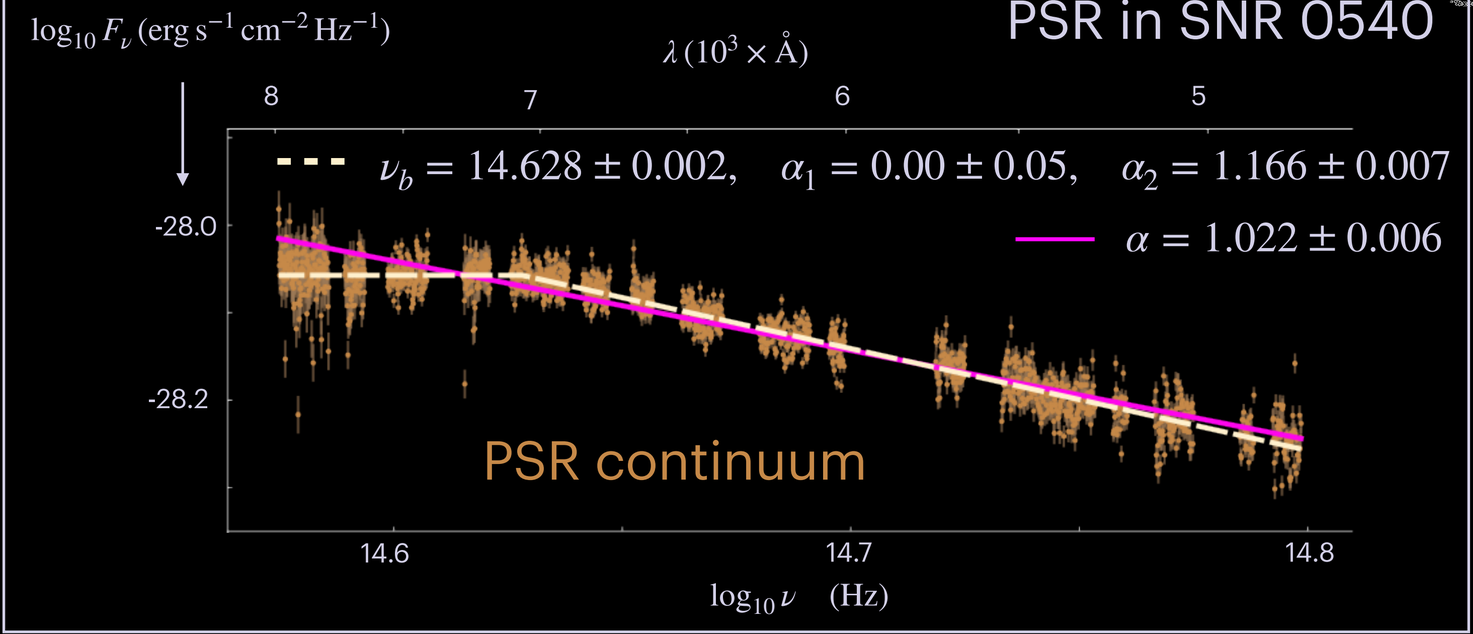


PWN in SNR 0540



Spatial spectral hardening towards PWN outer edge

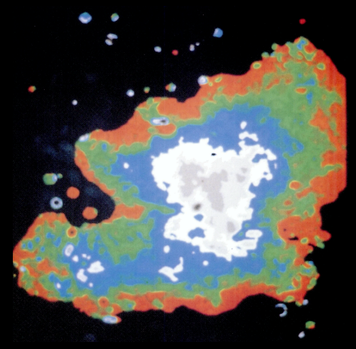
PSR in SNR 0540



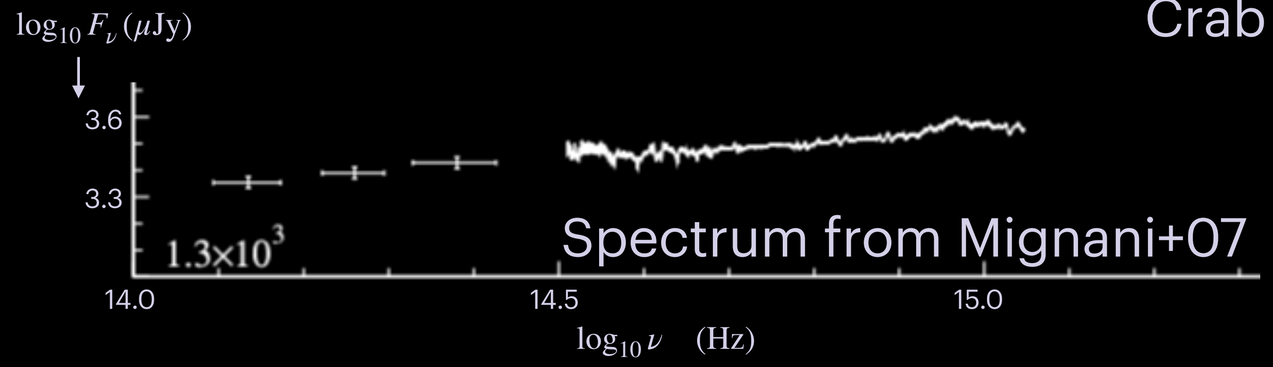
Opposite to the canonical synchrotron cooling picture

Véron-Cetty+93

Crab Nebula



Crab PSR



→ calls for more (optical) observations

Differences in pulsars propagating to PWNe?

See more information: Tenhu+24