Dublin Institute for Advanced Studies
School of Cosmic Physics

Magnetic field estimates in the 30 Dor C superbubble with *Chandra*

Patrick Kavanagh

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30 Doradus

Magellanic Cloud Emission Line Survey (Smith et al. 2006)

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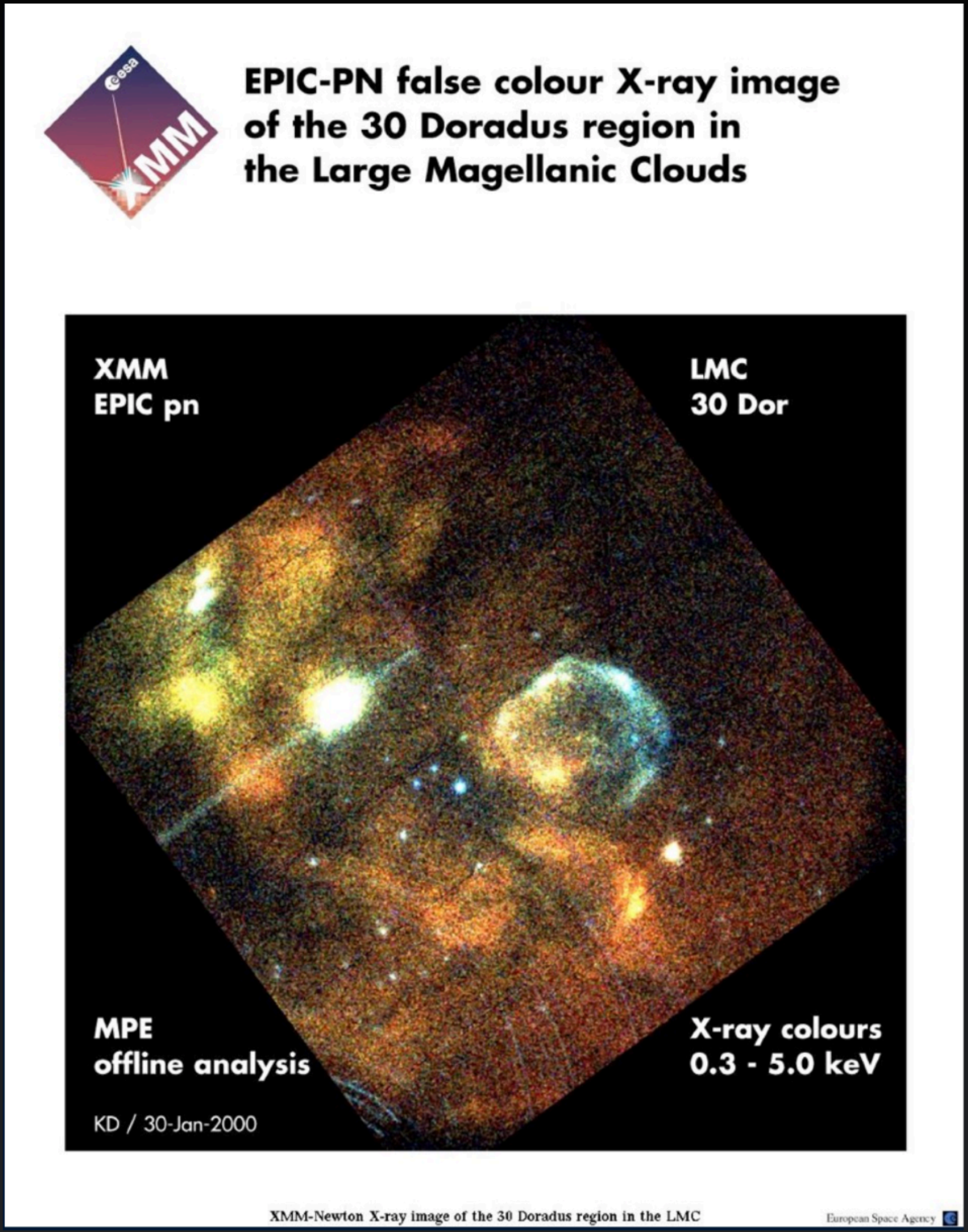
XMM-Newton first light

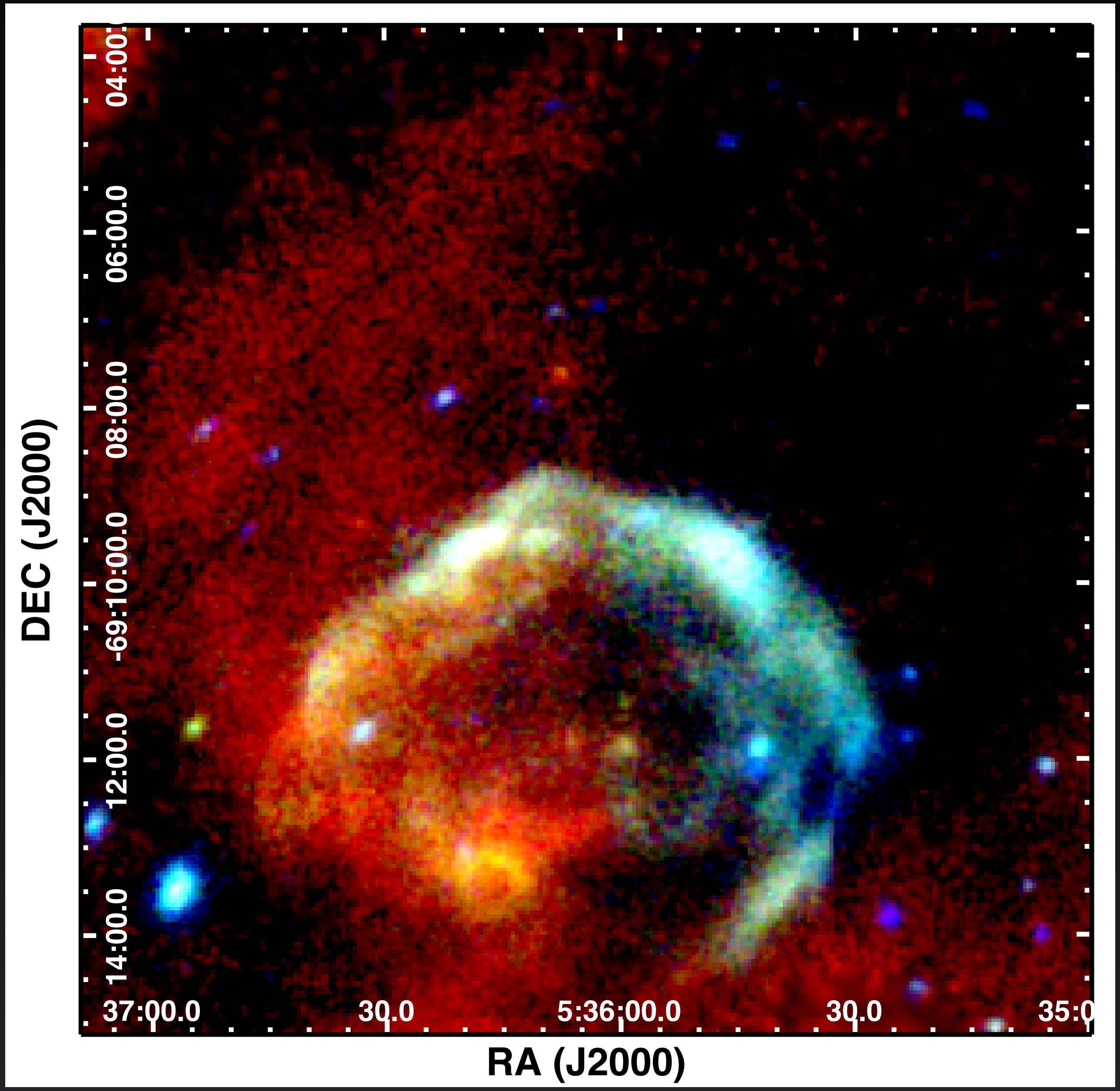


Dennerl et al. (2001)

30 Doradus C

- ***Chandra*** Bamba et al., 2004
- ***XMM-Newton*** Smith & Wang, 2004
- ***Suzaku*** Yamaguchi et al, 2009
- ***XMM-Newton*** Kavanagh et al., 2015

(pn = 420 ks; MOS1 = 556 ks; MOS2 = 614 ks)



RGB: 0.3-1 keV, 1-2 keV, 2-7 keV

X-ray characteristics

- Thermal emission with enhanced α-group elements
- Nearby SNR
- X-ray synchrotron shell
- ***shock speed*** $\gtrsim$ ***3000 km s***$^{-1}$

H.E.S.S. **detection - first TeV superbubble**

H.E.S.S. Collaboration, 2015

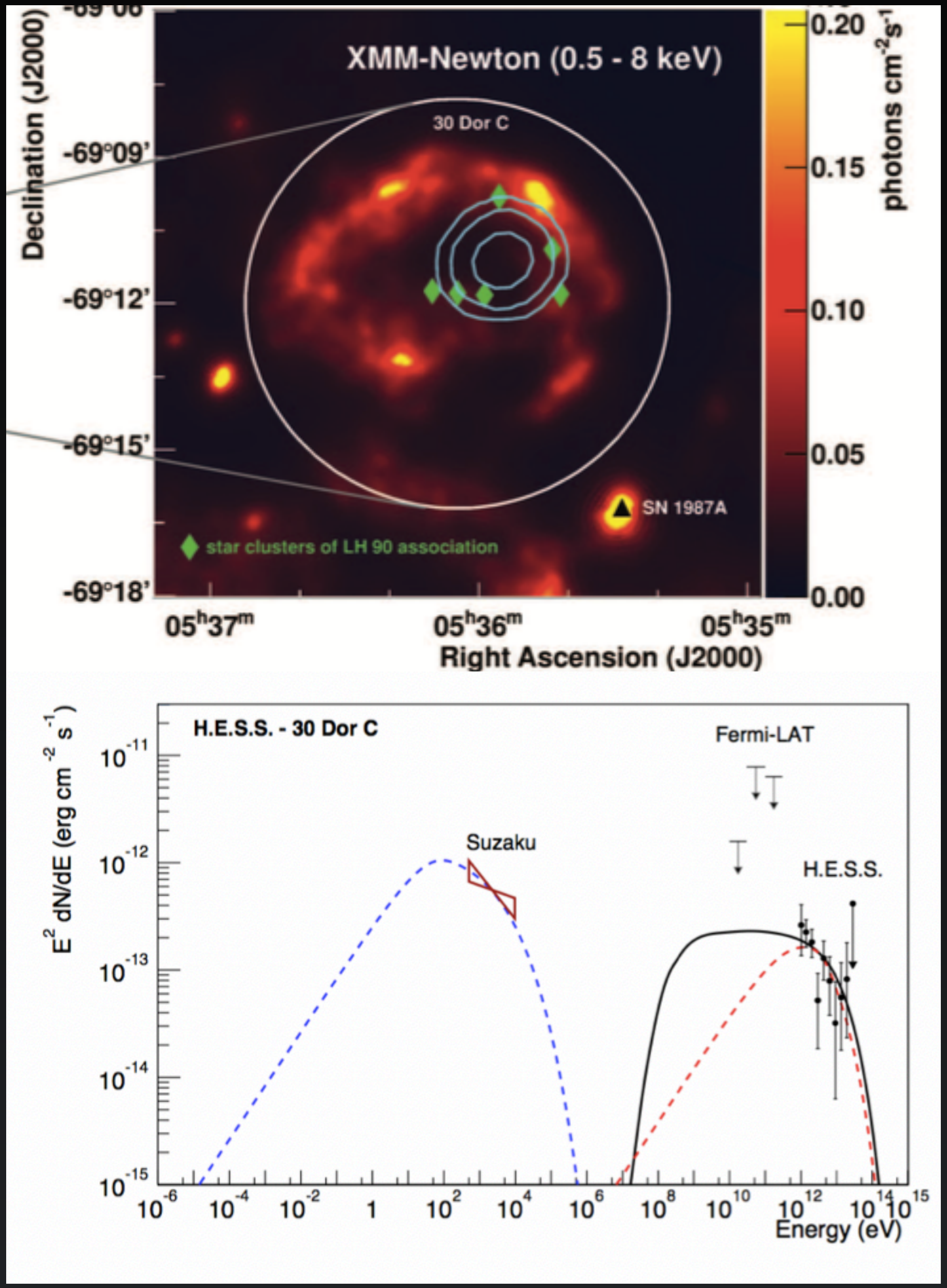
Dominant TeV emission mechanism?

Hadronic (pp):

- requires high target densities (> 20 cm^{-3}, possible)
- high (amplified) magnetic fields

Leptonic (IC):

- same particles responsible for synchrotron shell
- requires high shock velocities, low interior densities ($\sim 10^{-4}$ cm^{-3})
- average magnetic field ~ 15 μG



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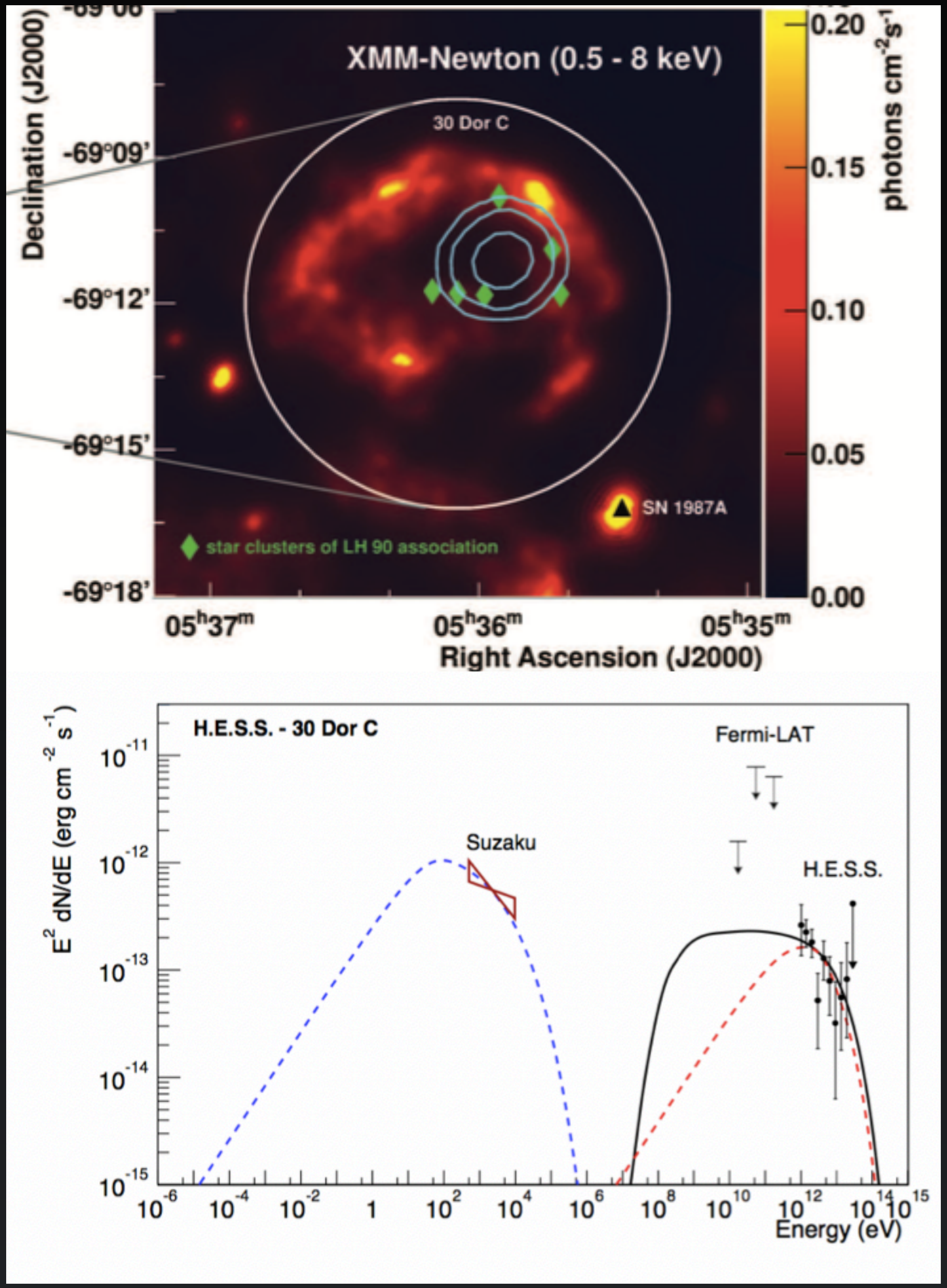
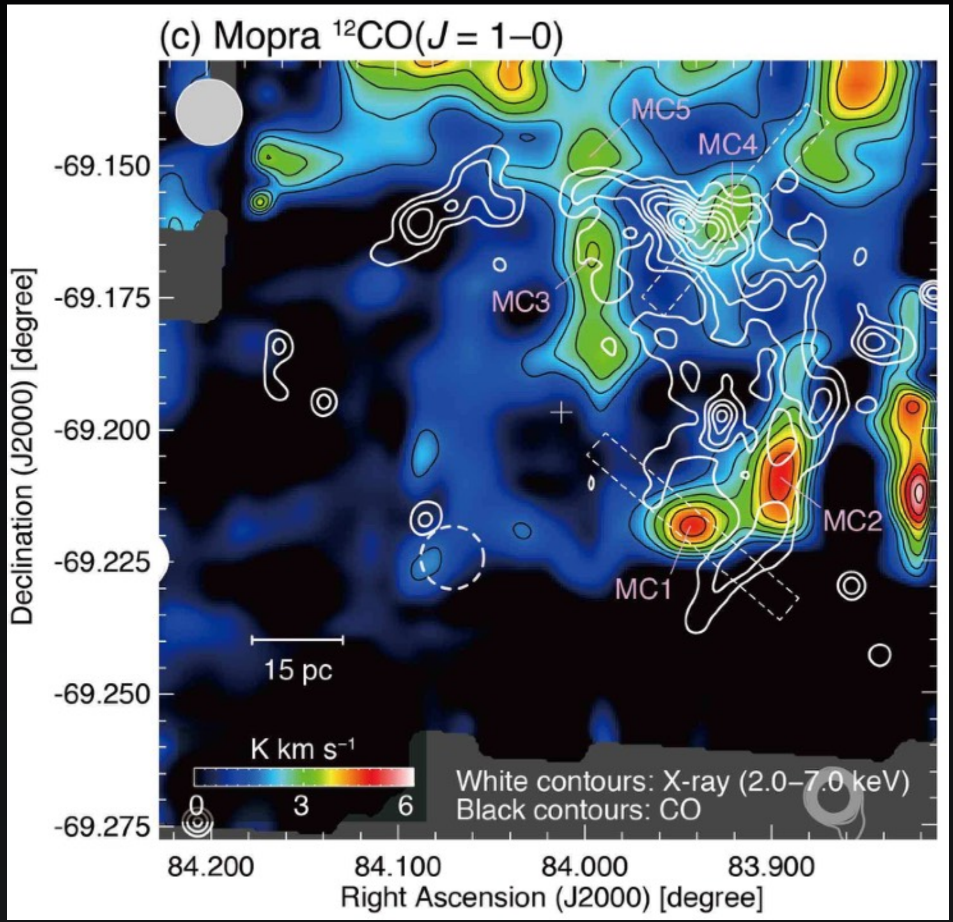


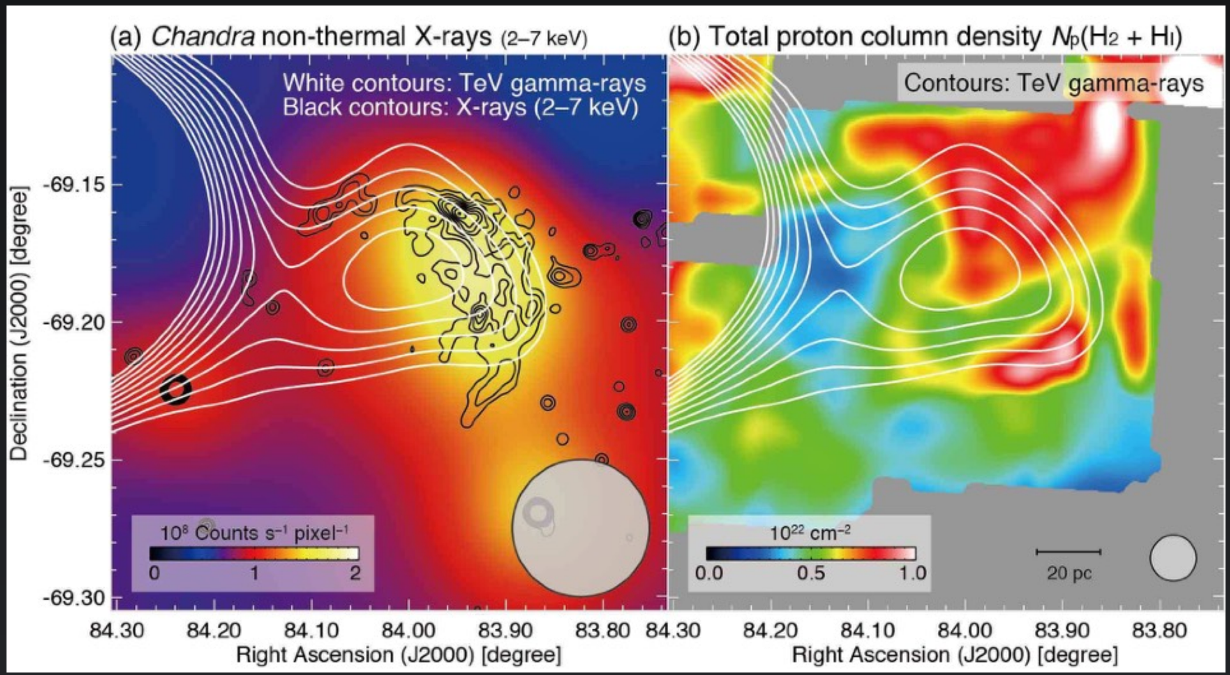
Evidence for shock-cloud interaction

Sano et al. 2017

- Non-thermal X-rays enhanced around CO clouds at ~1 pc scale
- TeV peaks around the total interstellar proton density and non-thermal X-rays
- Shock-cloud interaction could amplify B-field up to ~mG
- Both hadronic and leptonic scenarios possible

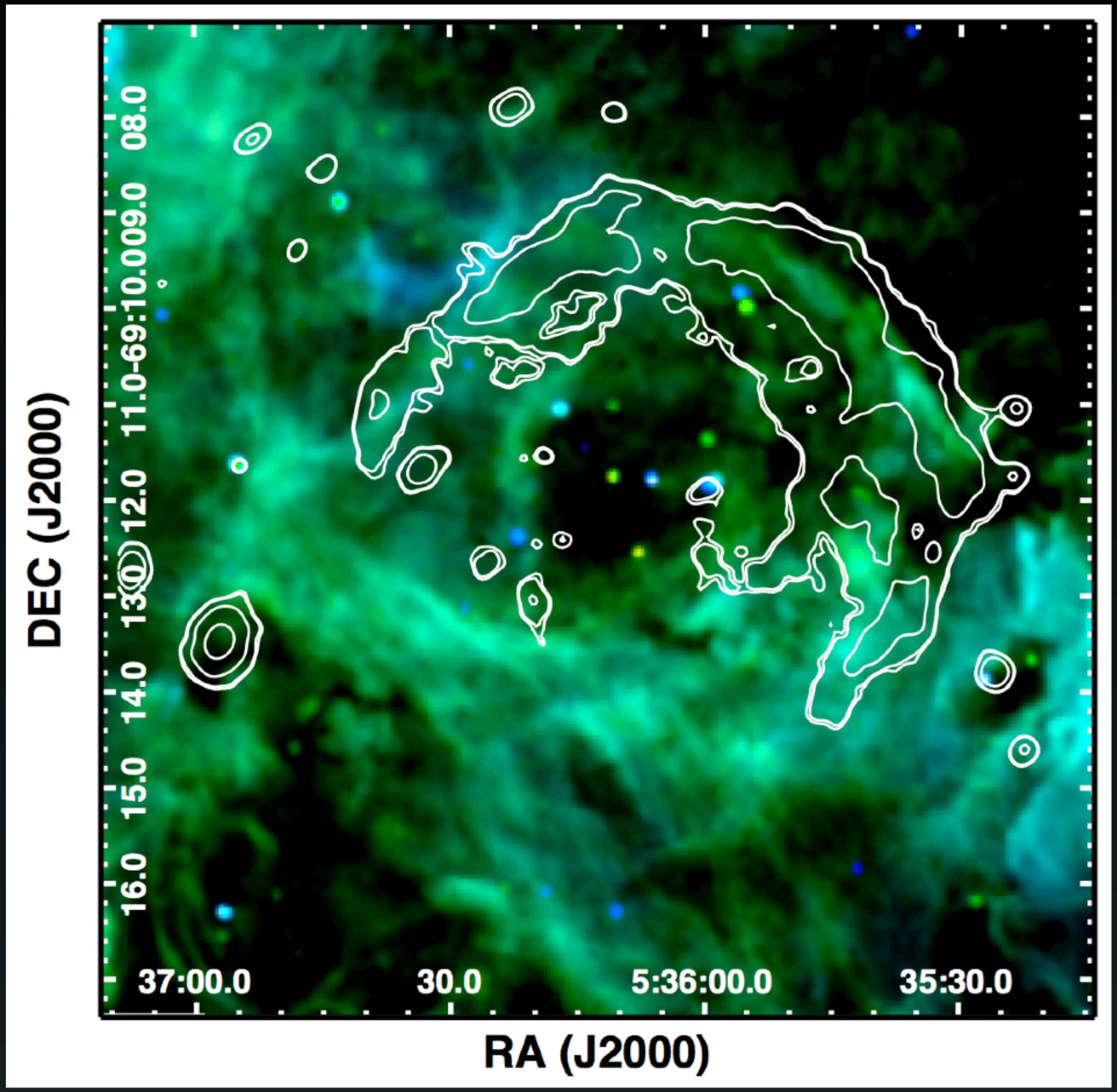
See talk of H. Sano





Hα and synchrotron shells correlated?

2-8 keV contours



RGB = [SII], Hα, [OIII] from MCELS

BUT!

Synchrotron shell must be expanding >3000 km s^{-1}

No evidence for anything > ~50 km s^{-1}

Aims:

We want to:

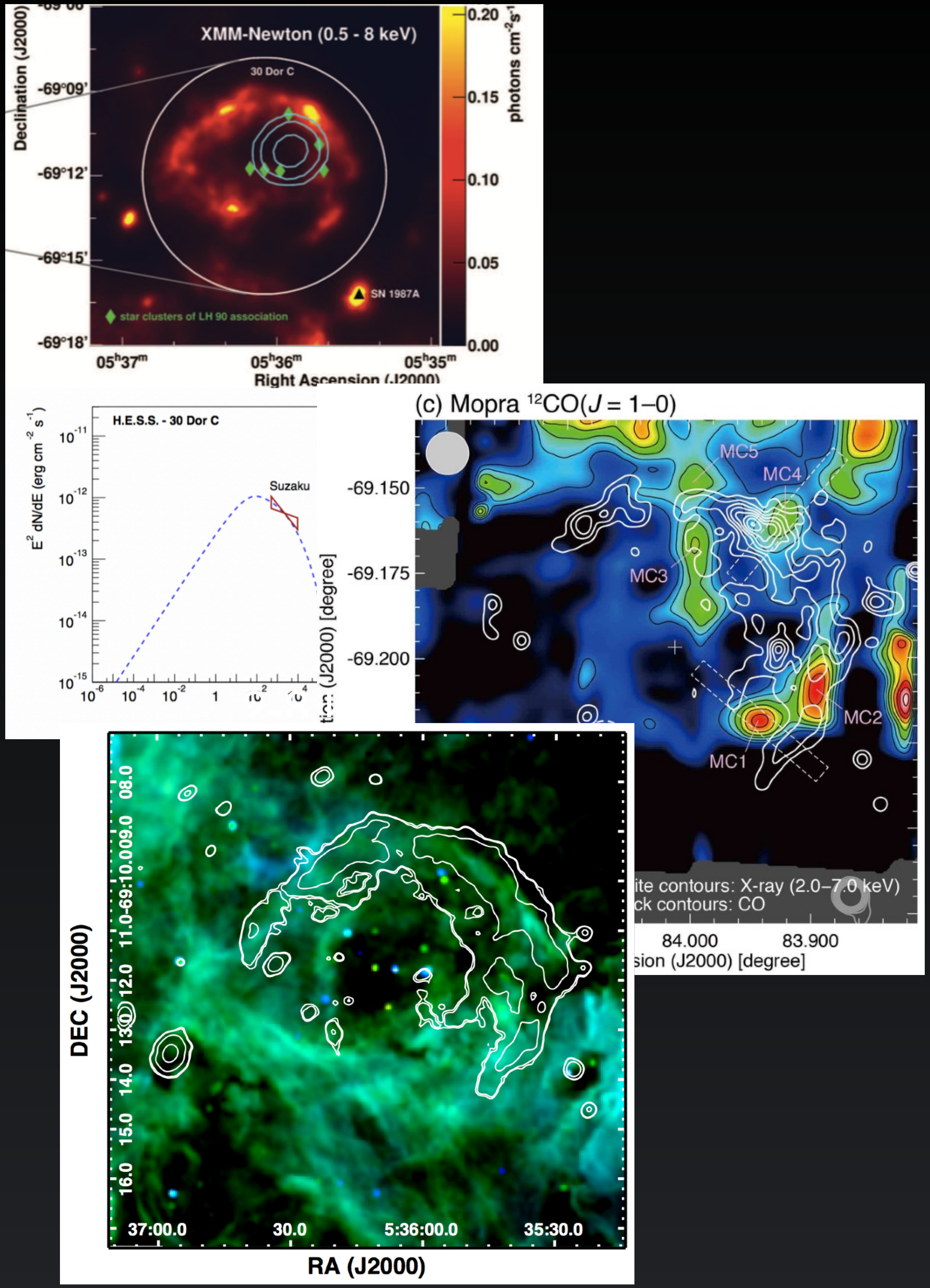
- measure the magnetic field to assess dominant TeV mechanism
- determine if the Ha and synchrotron shells are really correlated
- better correlated shell/cloud interaction?

We need:

- an image with the best possible resolution of the synchrotron shell

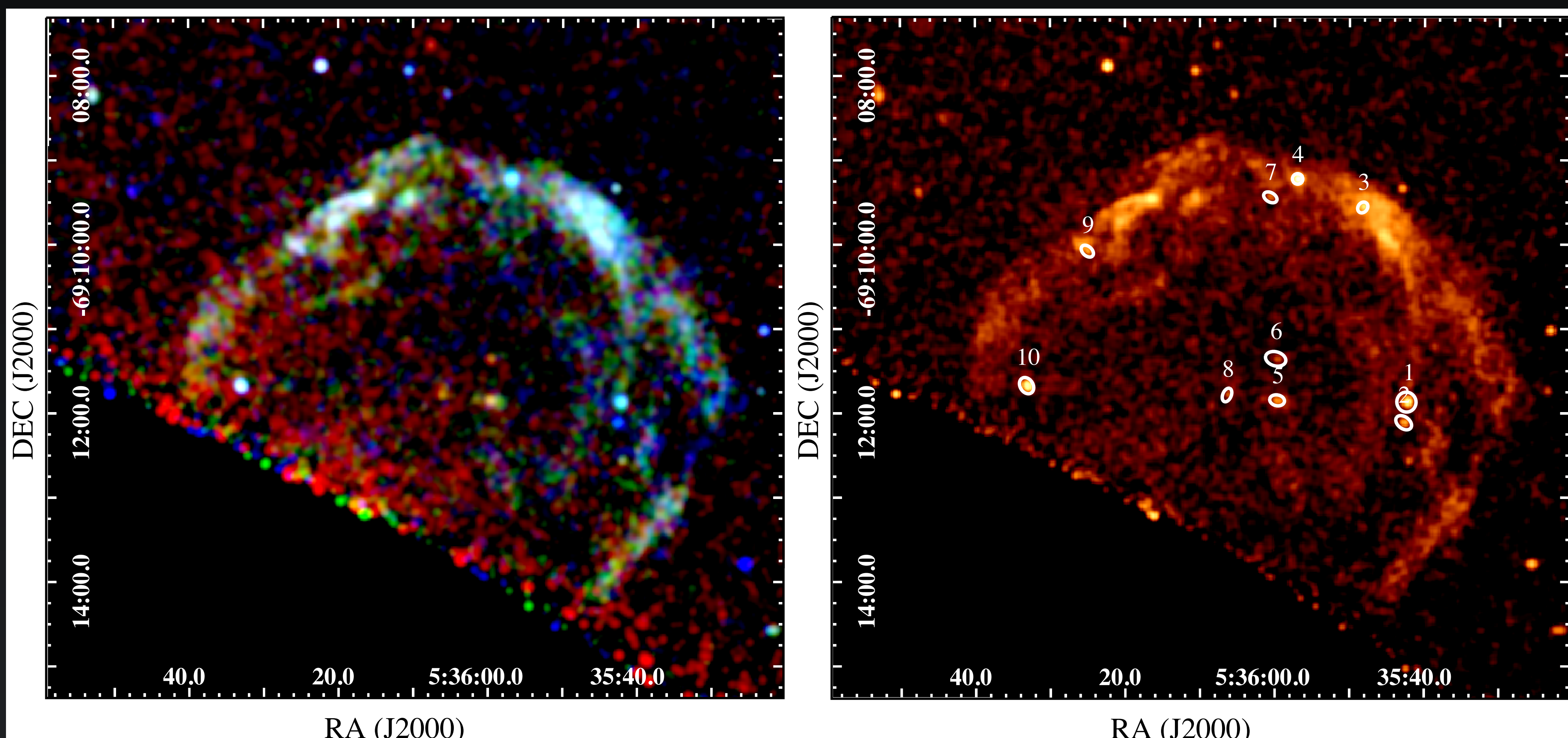
We used:

- the Chandra X-ray Observatory



Chandra observation

- observed May 2017 with ACIS-S
- centred on brightest region of synchrotron shell
- exposure time of ~81 ks



RGB = 0.3-1 keV, 1-2 keV, 2-8 keV

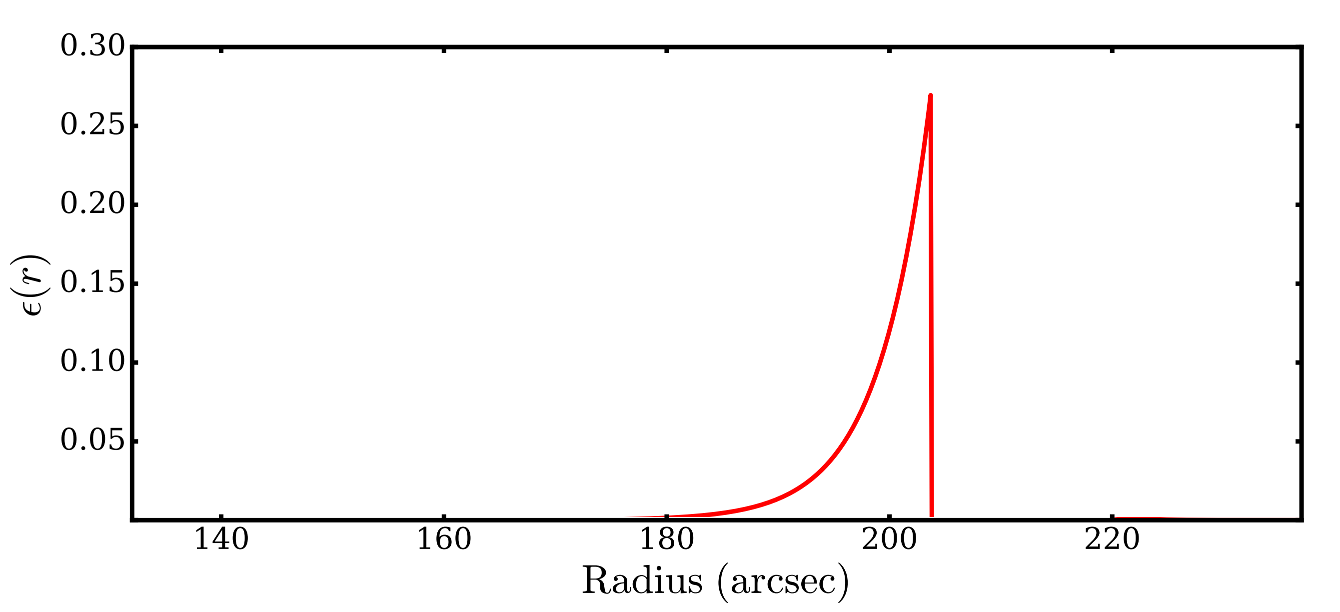
1.5-8 keV with sources

Magnetic field measurement

Synchrotron emissivity profile

$$\epsilon(r) \propto exp(-(r-R)/l_{obs}), \quad r < R$$

$$\epsilon(r) = 0, \quad r > R$$



B-field estimate

Helder et al., 2012

$$B_2 \approx 26 \left(\frac{l_{\rm adv}}{1.0 \times 10^{18}\ {\rm cm}} \right)^{-2/3} \eta_{\rm g}^{1/3} \left(r_4 - \frac{1}{4} \right)^{-1/3} \mu{\rm G}$$

$$l_{\rm obs} \approx \sqrt{2} l_{\rm adv}$$

Profile fitting

Assume model:

$$\epsilon(r) \propto exp(-(r-R)/l_{obs}), \quad r < R$$

$$\epsilon(r) = 0, \quad r > R$$

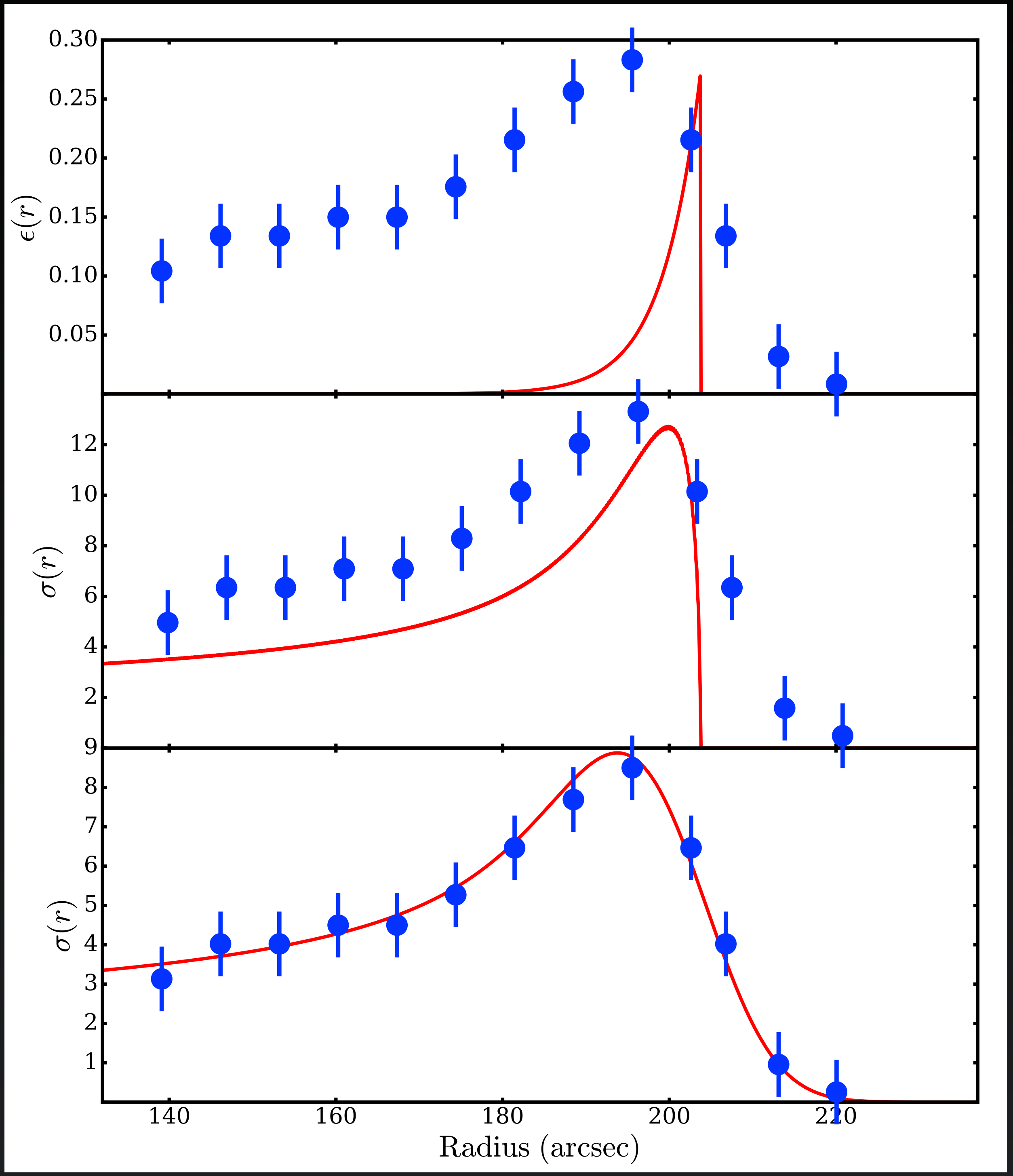
Assume spherical symmetry:
(Abel transform)

$$\sigma(r_p) = 2\int_{r_p}^{R} \frac{\epsilon(r) r}{(r^2 - r_p^2)^{1/2}} dr$$

Convolve with *Chandra* PSF:

- generated using MARX in each bin
- variable width convolution applied for varying PSF along profile

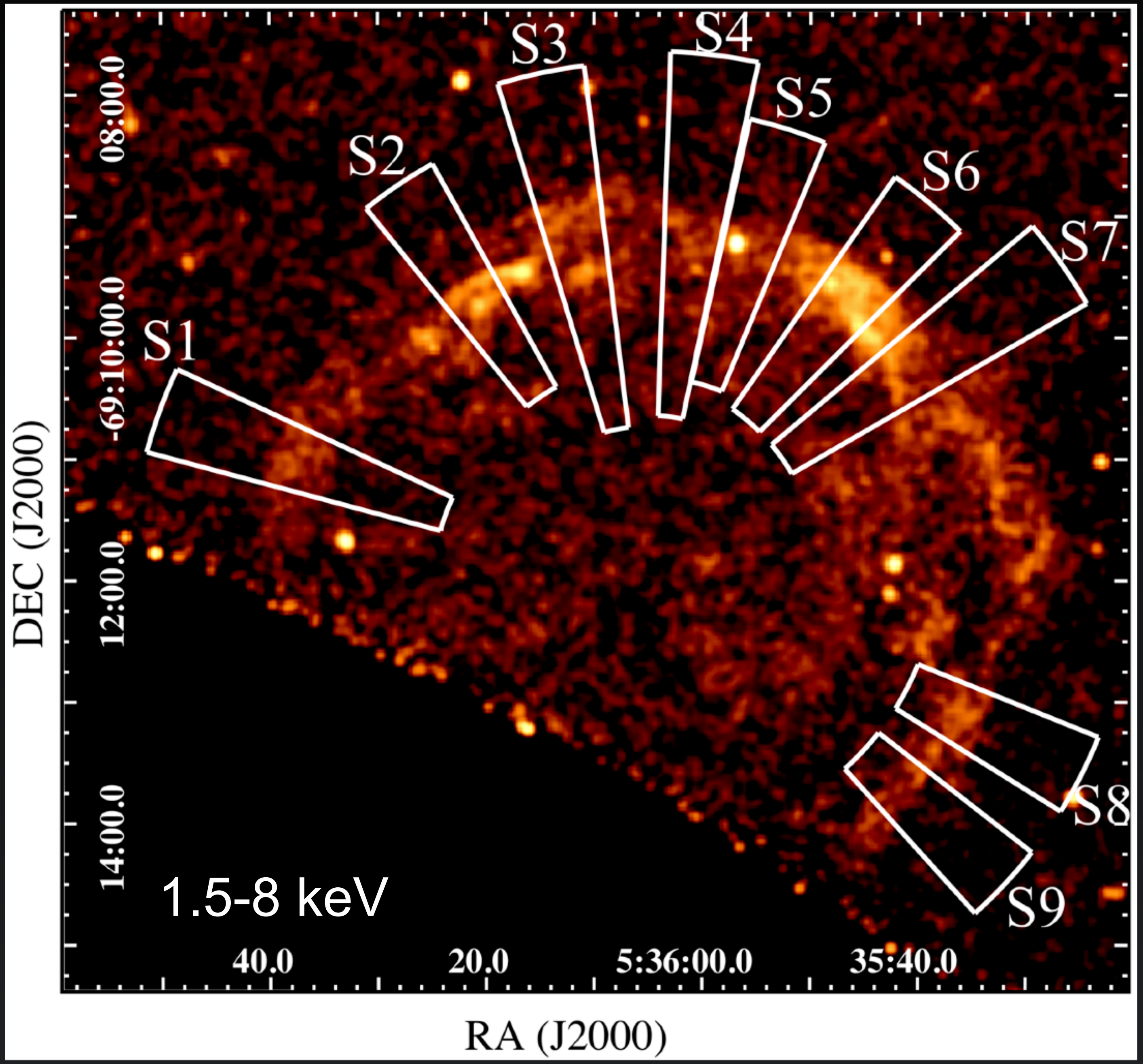
Determine best fit model



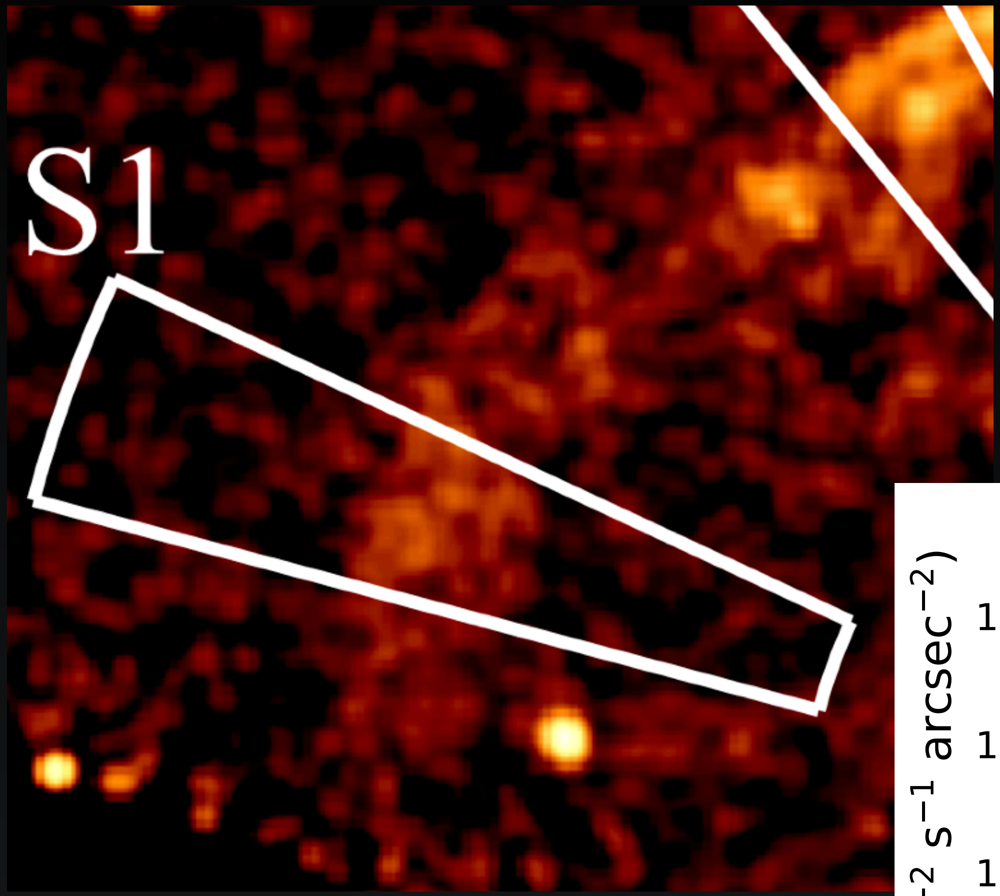
(Willingale et al.,1996)

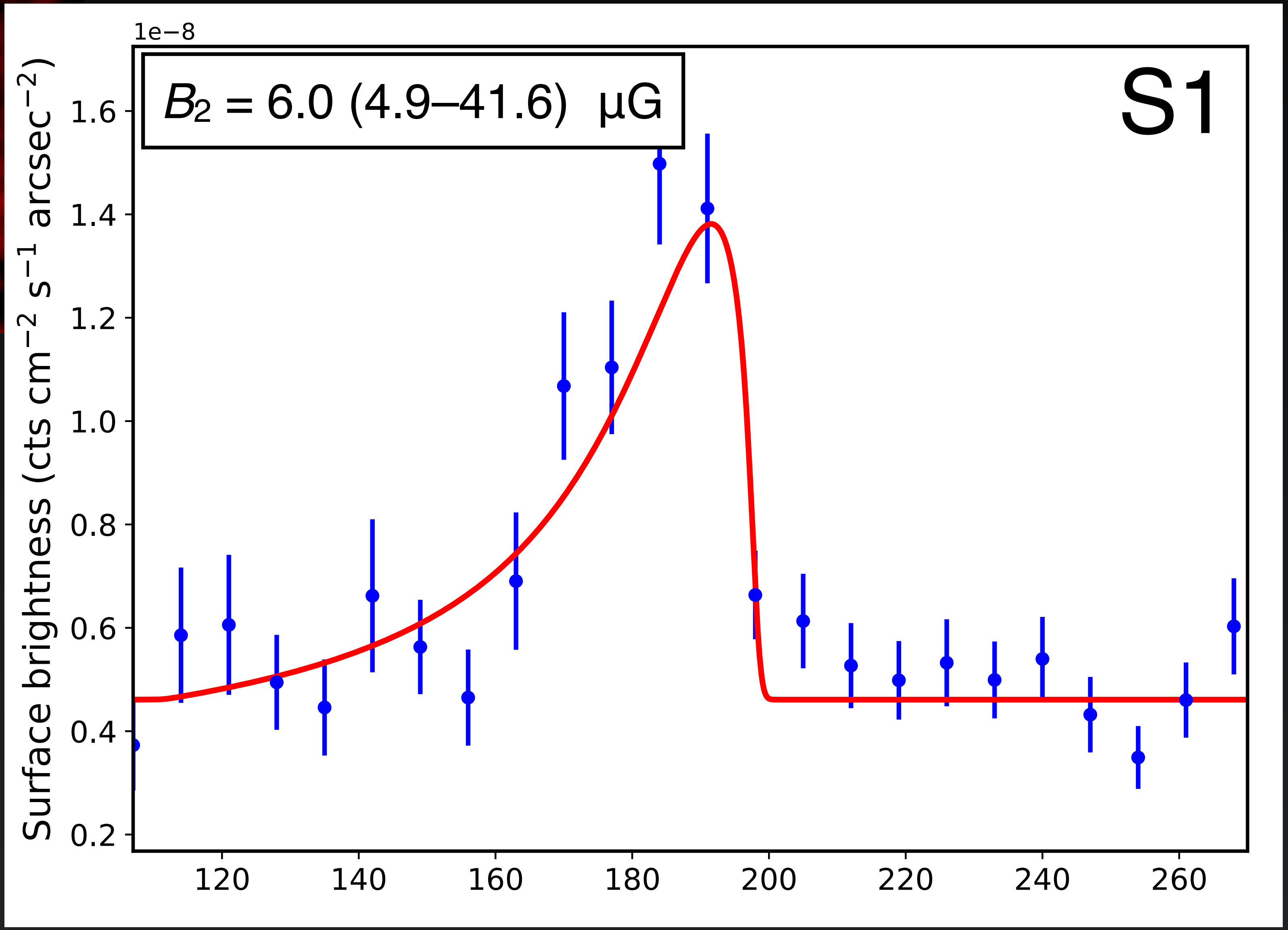
Segment definition

- Centred on 30 Dor C shell
- 1.5-8 keV energy band
- S/N > 5 per bin (omit bins close to centre)
- Point sources/contaminating interior emission masked
- S8 and S9 covers S3 and S4 chips, only consider S4

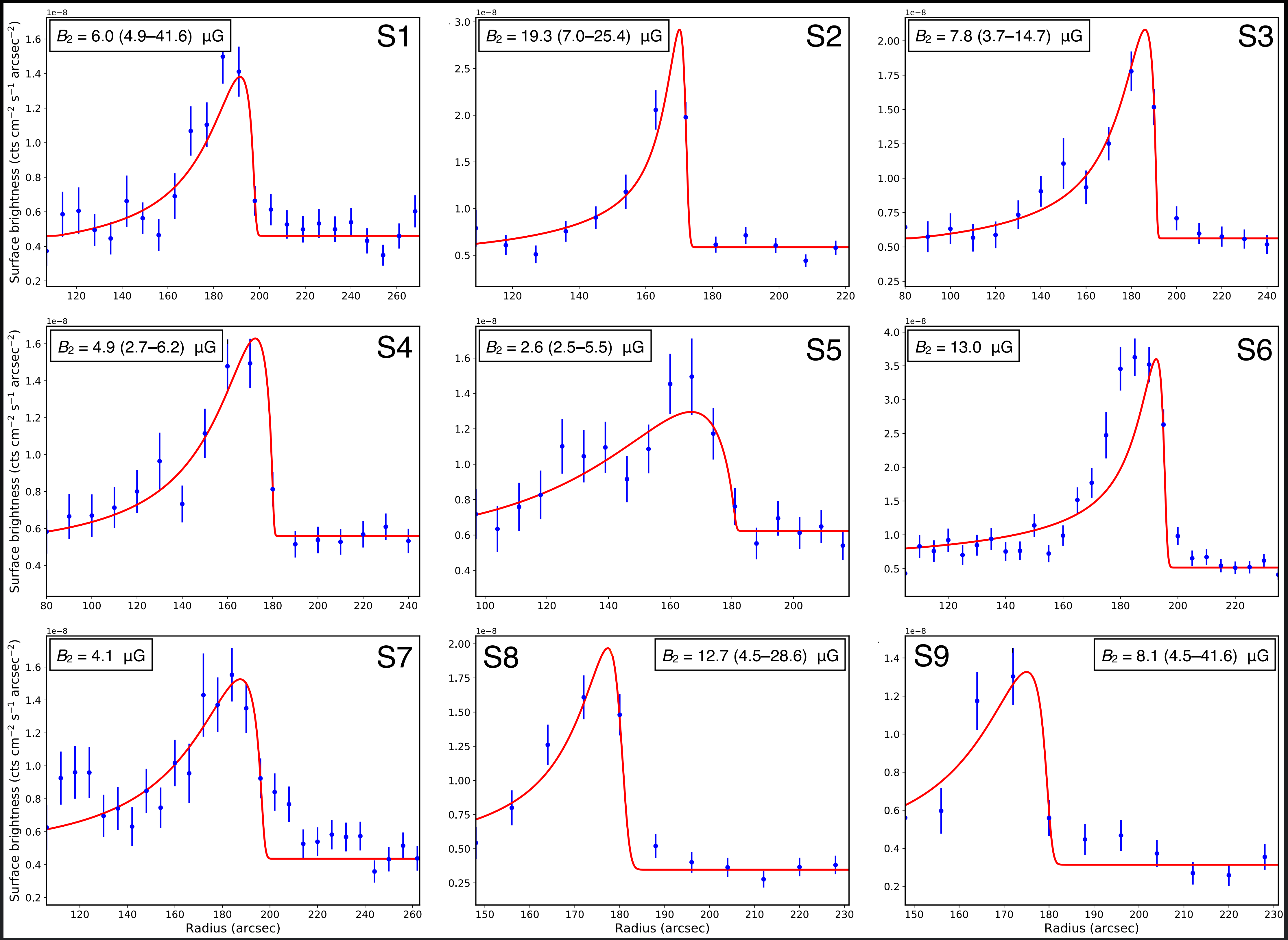


Fit results


S1

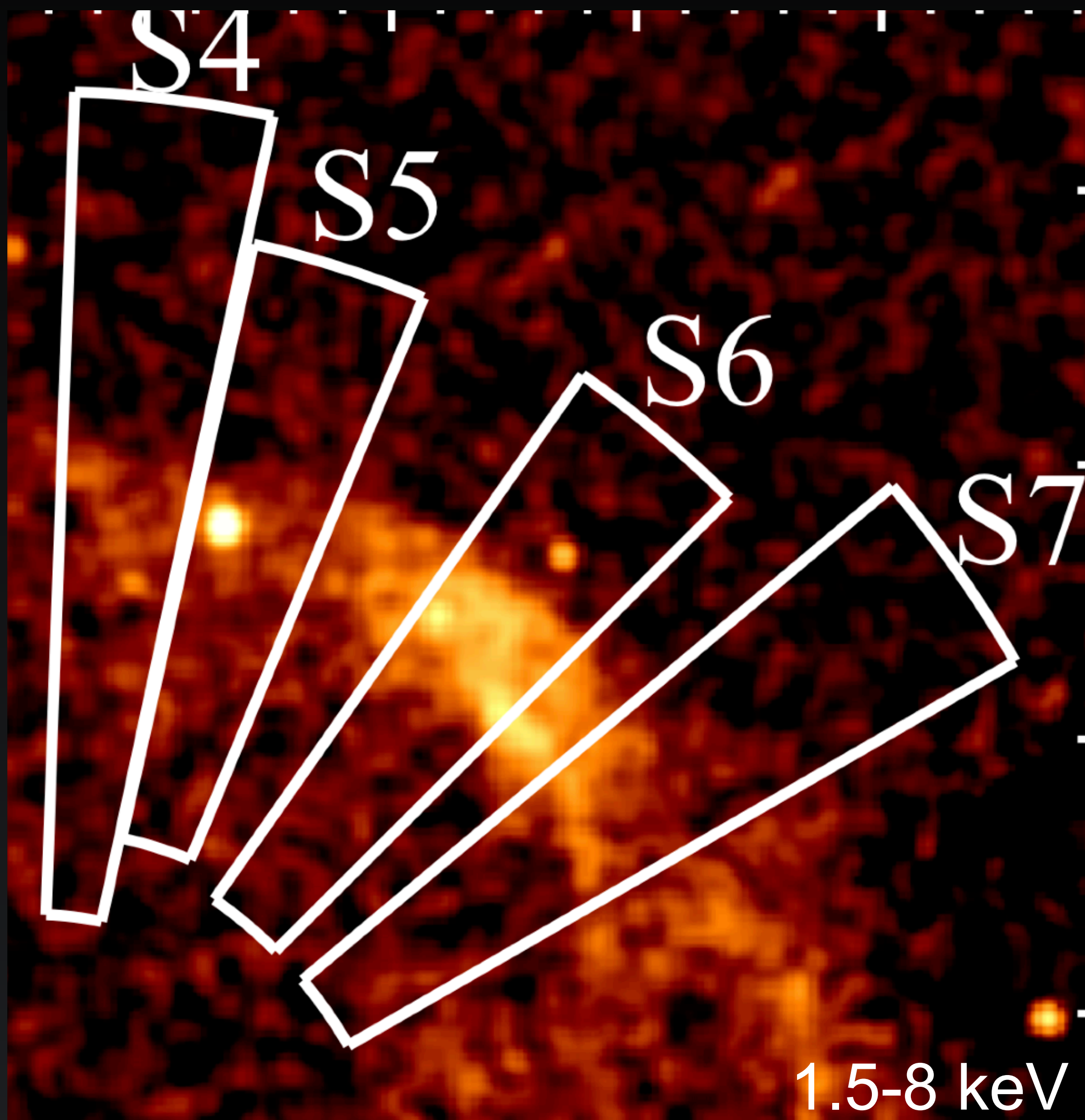

1e−8
B_2 = 6.0 (4.9–41.6) μG
S1
Surface brightness (cts cm^{-2} s^{-1} arcsec^{-2})
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
120
140
160
180
200
220
240
260

Fit results



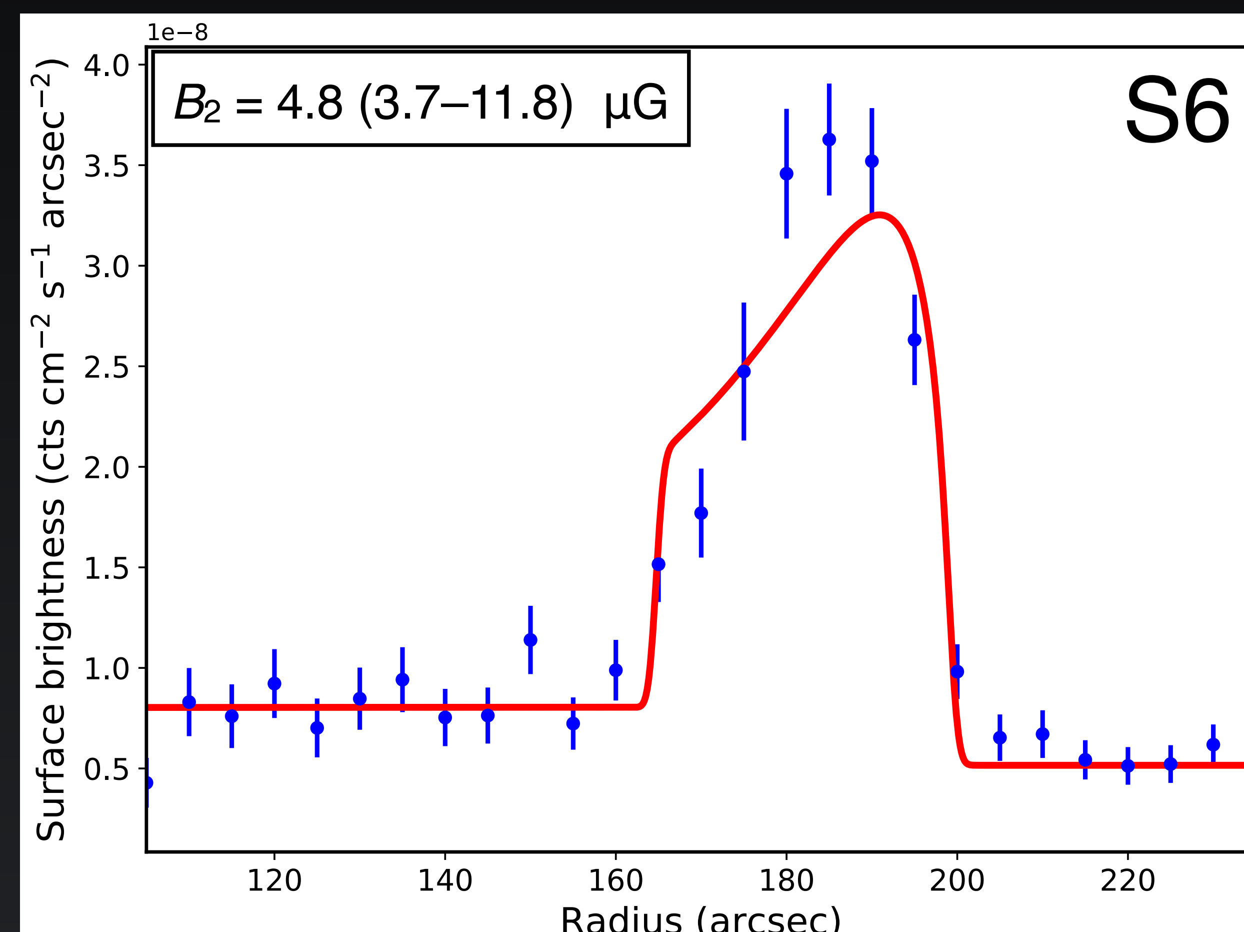
Average B_2 ~ 10 μG (3-42 μG)

Bad profile fits

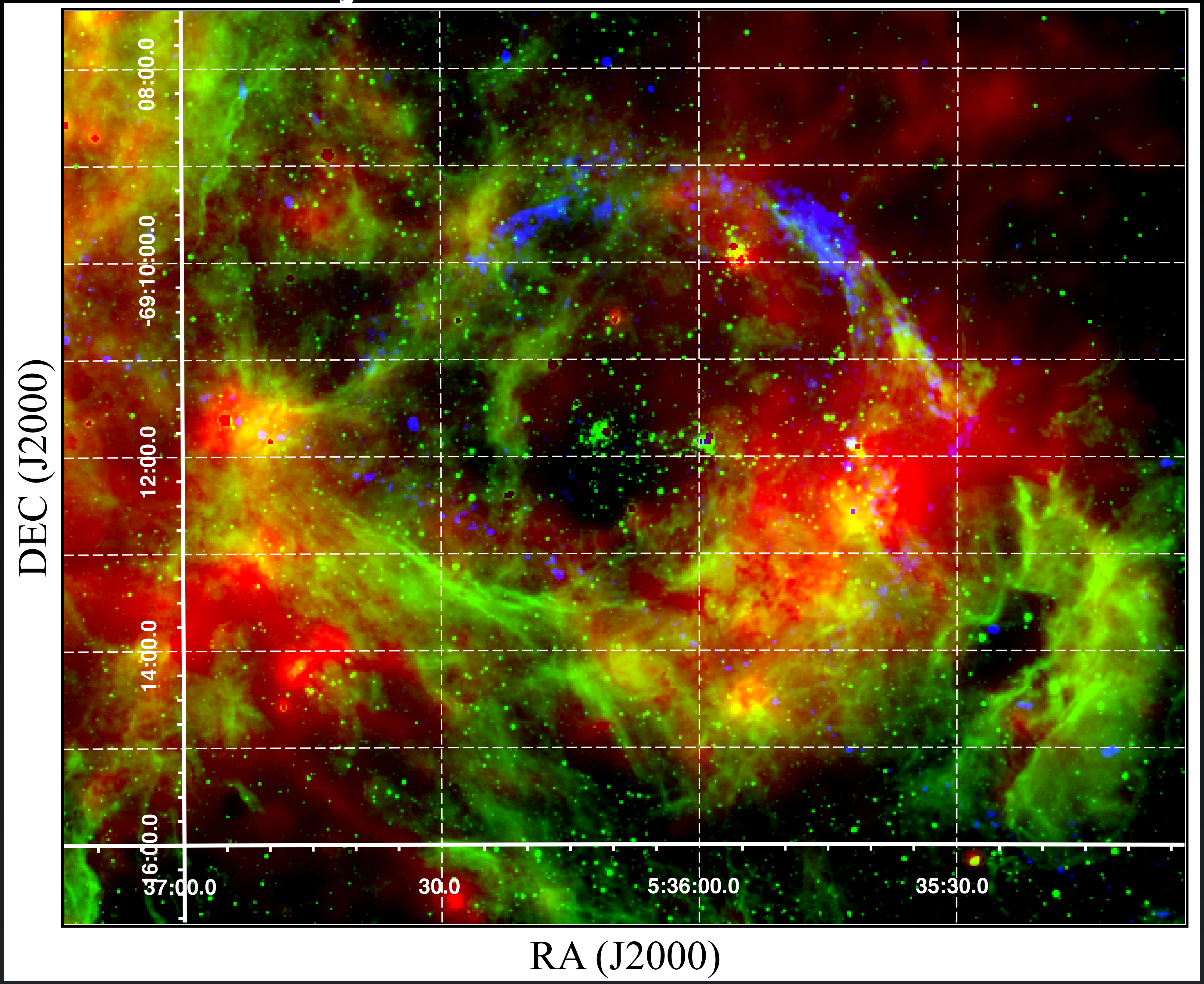


Change model assumption:

$$\epsilon(r) = \begin{cases} 0, & r < r_f = r_c R \\ A \exp(-(r-R)/l_{\rm obs}), & r < R \\ 0, & r > R \end{cases}$$



Hα and synchrotron shells correlated?



RGB = Spitzer 24 µm, MCELS2 Hα, Chandra 2-8 keV

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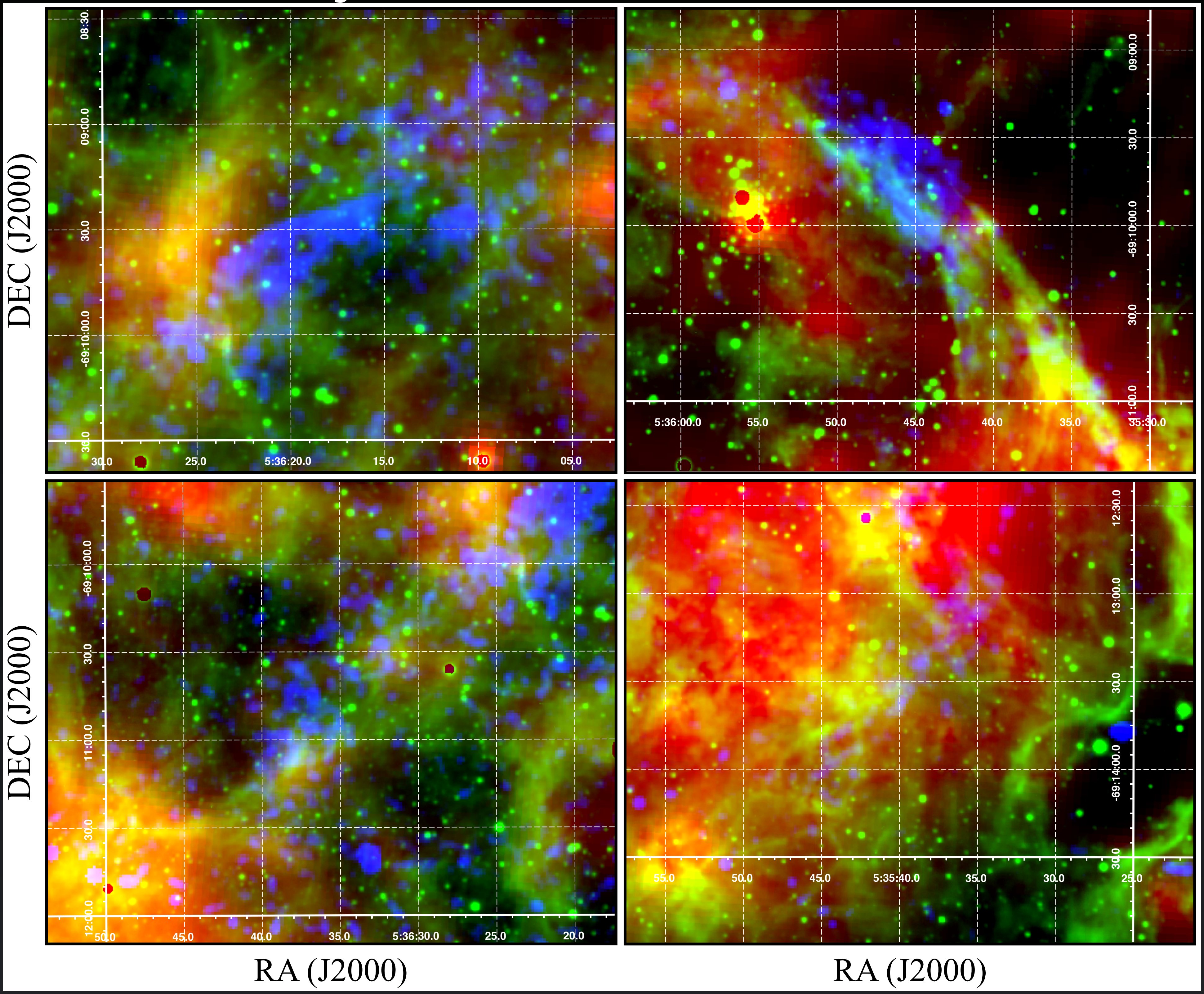

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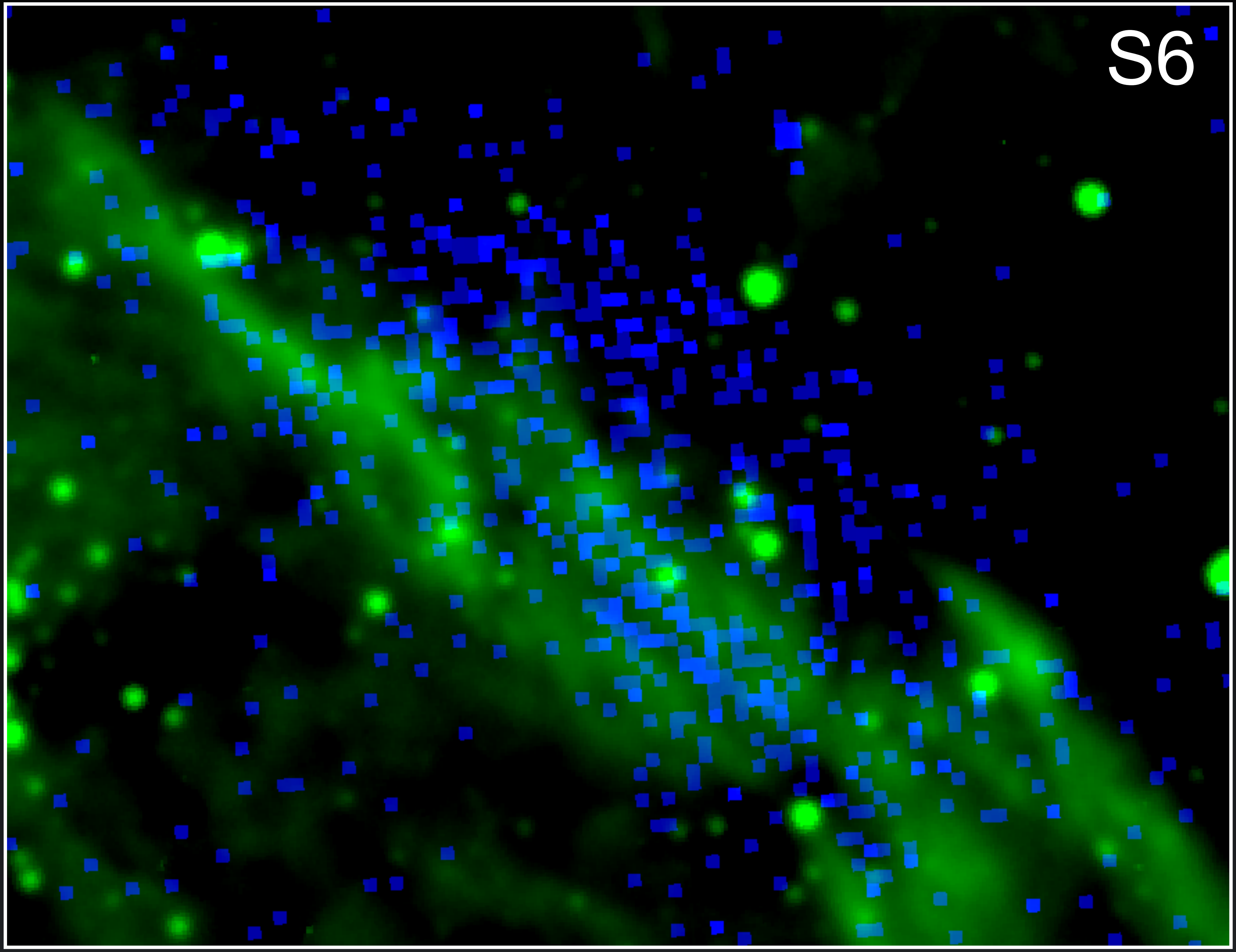

GB = Hα, 2-8 keV

Conclusions

- B-field in the downstream region is low and consistent with compressed ISM field
- Favours a leptonic origin for TeV gamma-rays
- Unexplained bright regions and knots present - evidence for shock cloud interaction?
- Hα and synchrotron shells not correlated on small spatial scales
- Supernova remnant expanding in bubble:
    - yet to encounter shell / appears to have pushed through gaps in shell