Università degli Studi di Palermo

DiFC Dipartimento di Fisica e Chimica - Emilio Segrè

SUPERNOVA REMNANTS III
AN ODYSSEY IN SPACE AFTER STELLAR DEATH
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INAF ISTITUTO NAZIONALE DI ASTROFISICA

Collimated Fe-rich ejecta in the magnetar-hosting supernova remnant Kes 73

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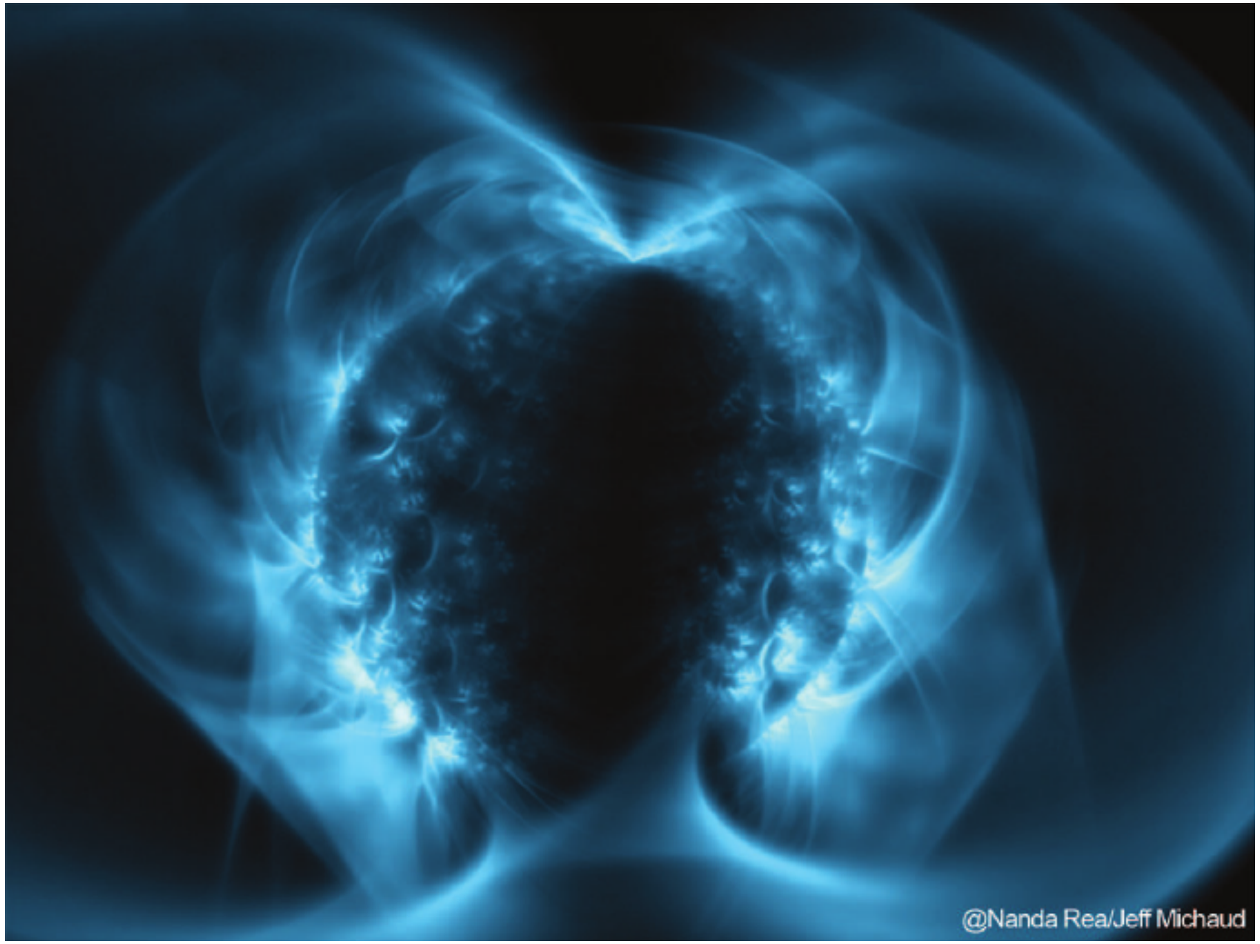
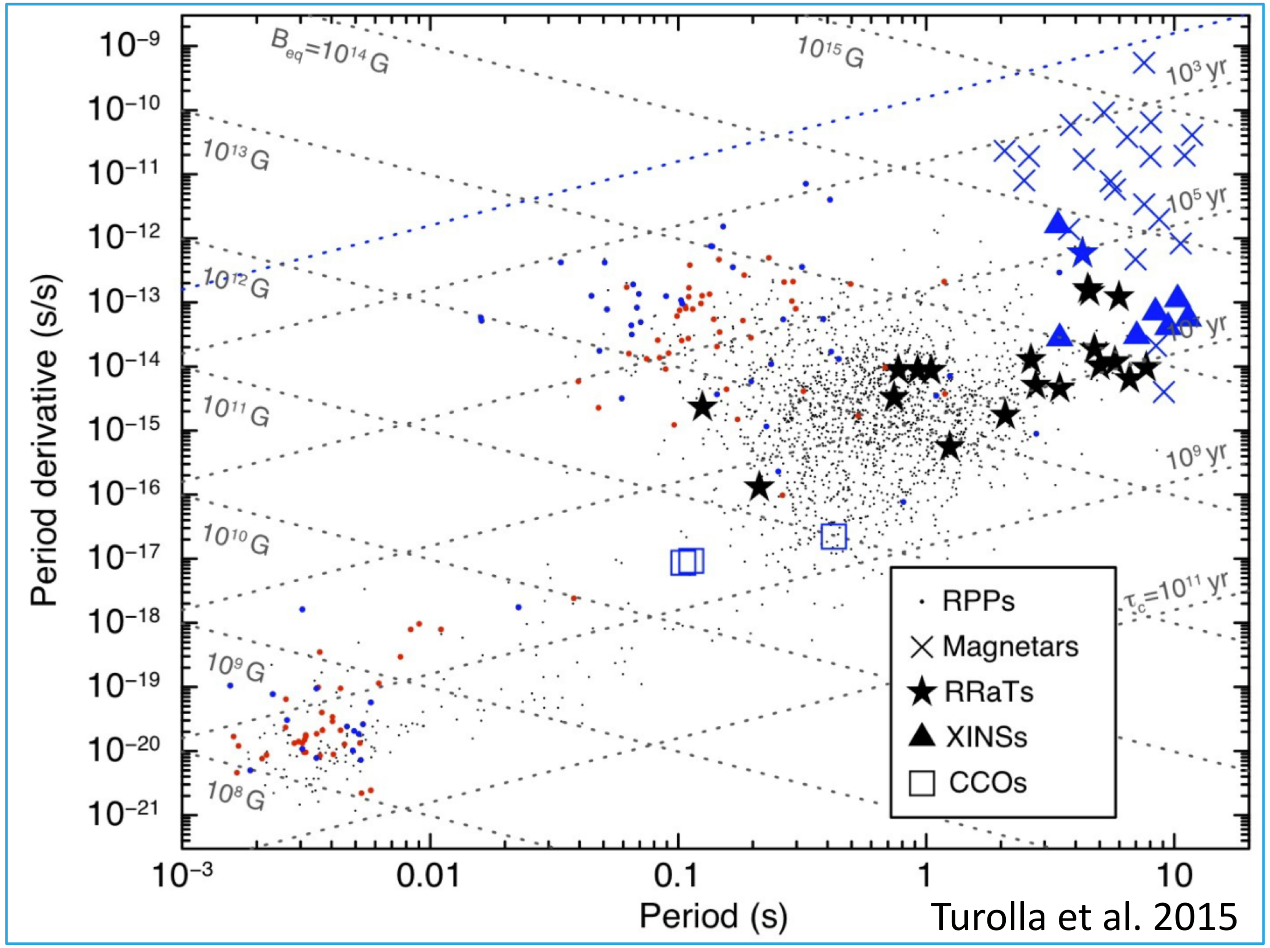
Magnetars

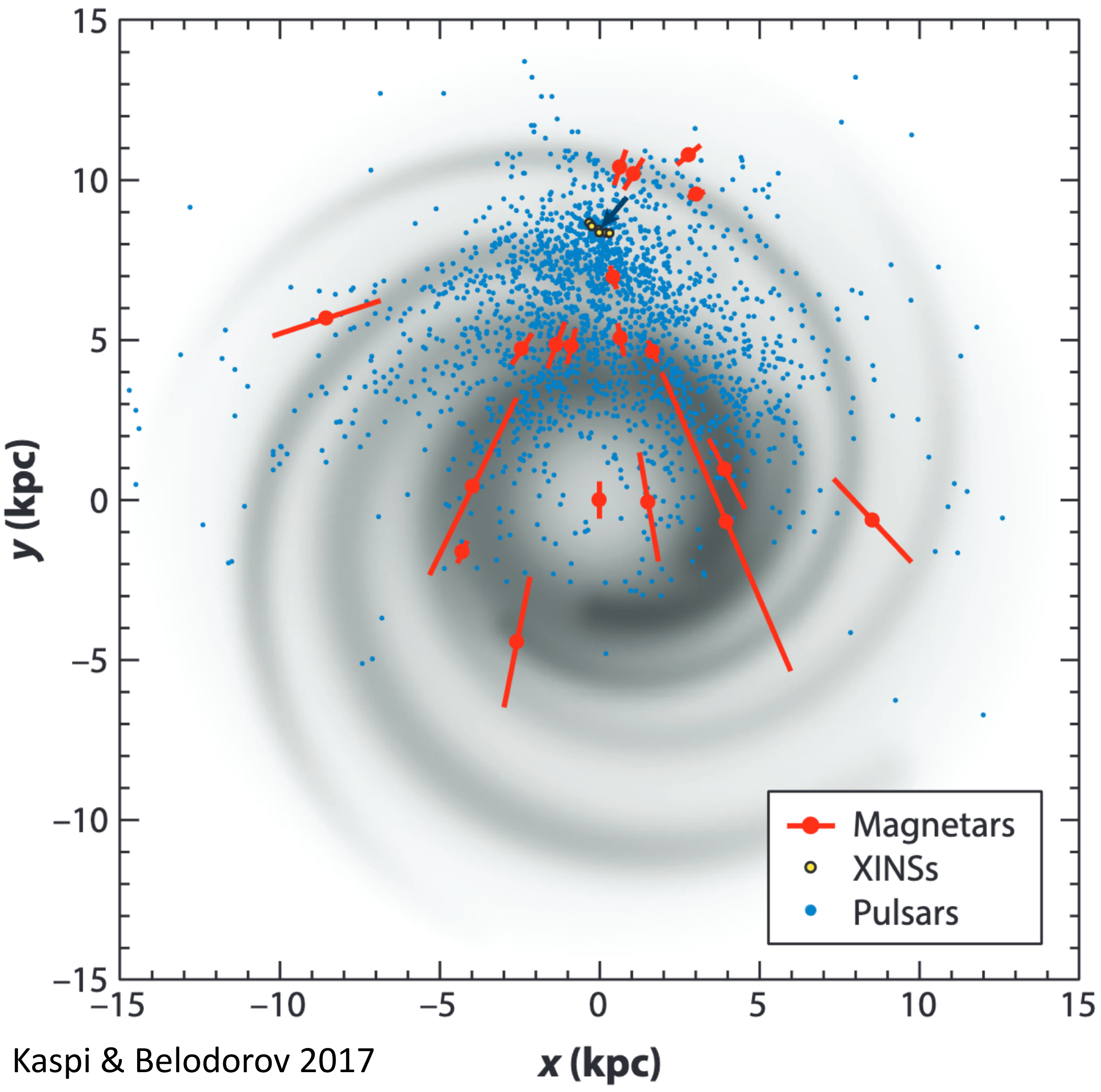




Isolated neutron stars characterized by strong activity and high variability, mainly powered by magnetic energy

Surface B≈10^{13}-10^{15}G (probably even higher in the interior): magnetars are *the strongest magnets in the present universe*

Magnetars – birth rate



Kaspi & Belodorov 2017

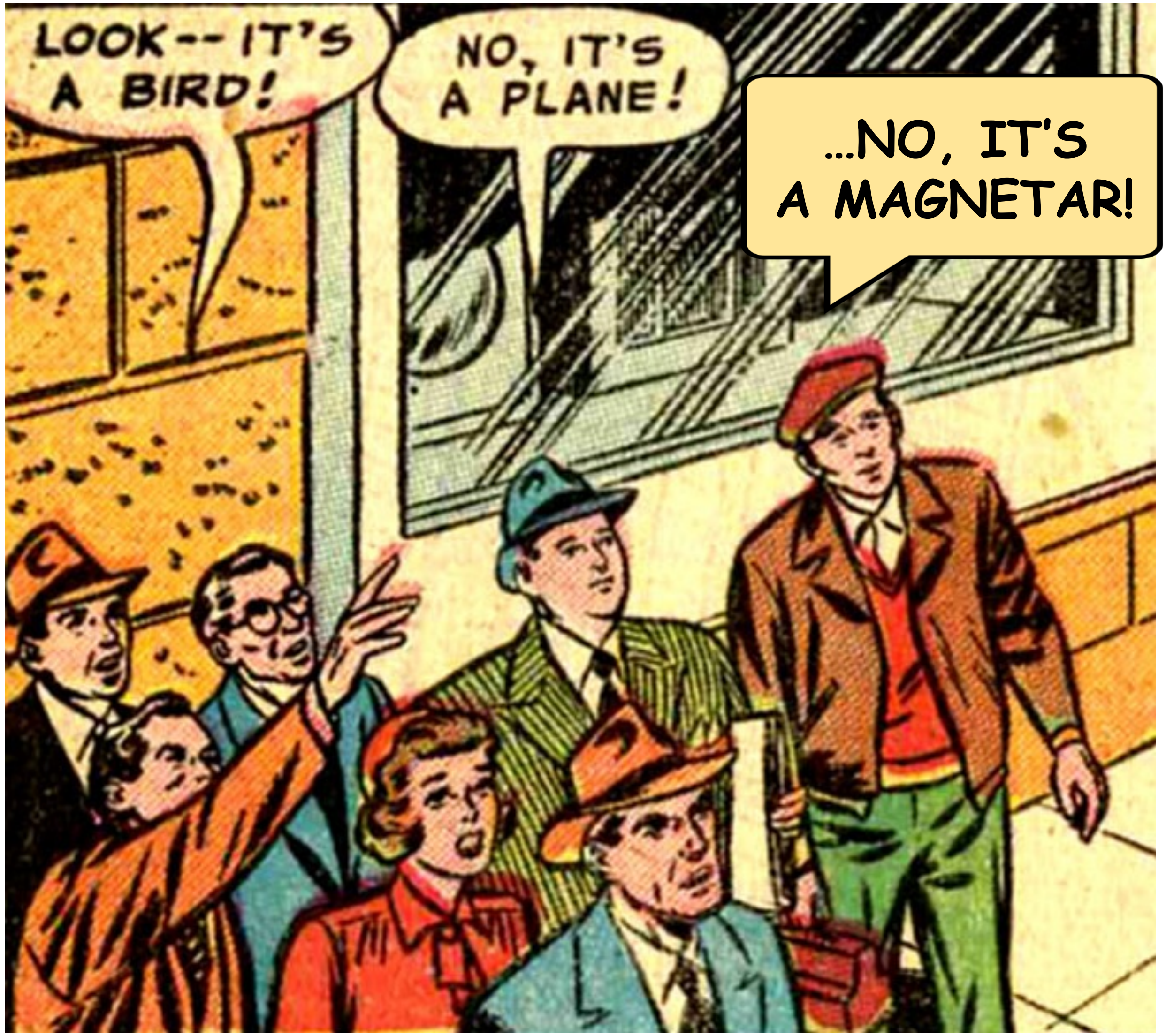
- About 30 Galactic magnetars
- ∼10% of young neutron stars (Kaspi & Belodorov 2017), but large uncertainties
- Birth-rate: ∼0.3 $(100\ \mathrm{yr})^{-1}$ (Turolla et al. 2015)
- Rate of CCSNe ∼1.6 ± 0.4 $(100\ \mathrm{yr})^{-1}$ (Rozwadowska et al. 2021)

Magnetars are not rare

Magnetars in extreme phenomena

Magnetars are invoked in several energetic astrophysical environment:

- GRBs (e.g., Zhang & Meszaros 2001 ; Troja et al. 2007; Rowlinson et al. 2013;…)
- FRBs (e.g., Beloborodov 2017; Mereghetti et al. 2020;…)
- Super-luminous SNe (e.g., Maeda et al. 2007; Woosley 2010; Margutti et al. 2018;…)



Origin of magnetars

Peculiar conditions at birth:

- **Dynamo model:** rapidly rotating proto-neutron star (T=1-3 ms) powering an energetic SN explosion (e.g. Duncan & Thompson 1992) ⟷ B amplification via turbulent dynamo triggered by magnetorotational instabilities

- **Fossil field scenario:** progenitor star with strong magnetic fields (e.g. Ferrario & Wickramasinghe 2006) ⟷ Magnetic flux conservation from very magnetized progenitors (O, B, A stars)

Origin of magnetars - issues

Both scenarios require some assumptions and have been severely challenged

- **Dynamo model:** rapidly rotating proto-neutron star (T=1-3 ms) powering an energetic SN explosion (e.g. Duncan & Thompson 1992)

No indications of particularly energetic explosions associated with magnetars (Vink & Kuiper 2006)

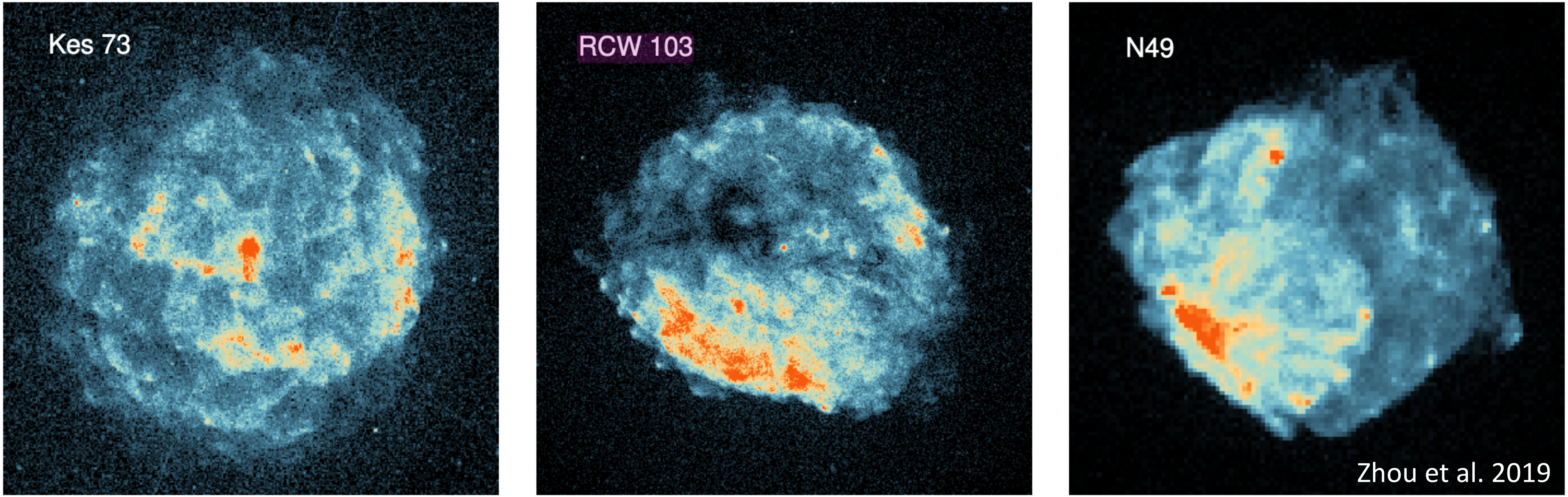
The two scenarios are not mutually exclusive

- **Fossil field scenario:** progenitor star with strong magnetic fields (e.g. Ferrario & Wickramasinghe 2006)

There are not enough strongly magnetized progenitors: fossil origin of the magnetic field is not viable (Makarenko et al. 2021)

Origin of magnetars: reverse engineering on their host SNRs

10 (over 30) magnetars are associated with SNRs: the study of the remnant can provide information on the explosion energy (and mechanisms) and on the progenitor



- Canonical explosion energy (Vink & Kuiper 2006)
- Canonical X-ray luminosities and spectra (Esposito et al. 2014)
- Relatively low mass progenitors (Zhou et al. 2019)

} **fossil field model**

Fossil field scenario? Some caveats

- Canonical explosion energy (Vink & Kuiper 2006)

Assuming the Sedov model, where $R \propto E^{0.2}$ (not sensitive to E)

- Canonical X-ray luminosities and spectra (Esposito et al. 2014)

Middle-aged SNRs, X-ray emission dominated by shocked ambient medium

- Relatively low mass progenitors (Zhou et al. 2019)

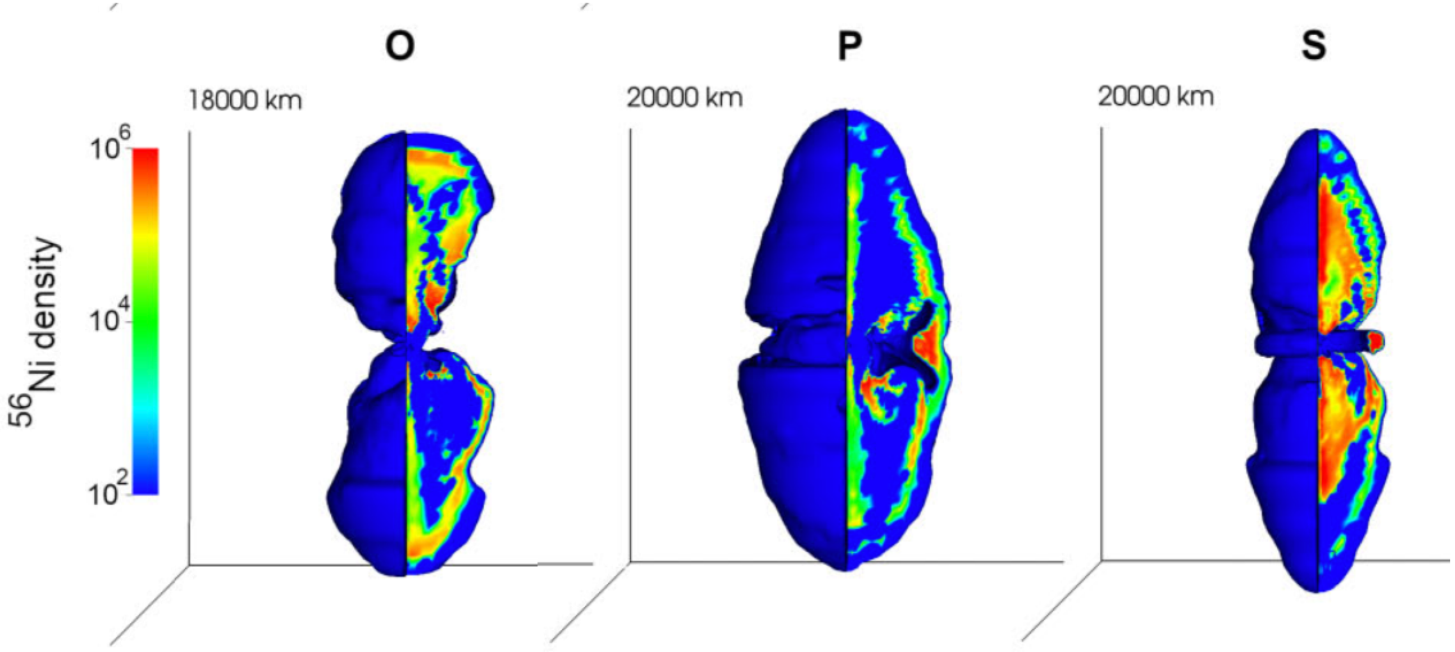
Derived from the chemical composition (no significant ejecta emission)

The dynamo scenario cannot be excluded

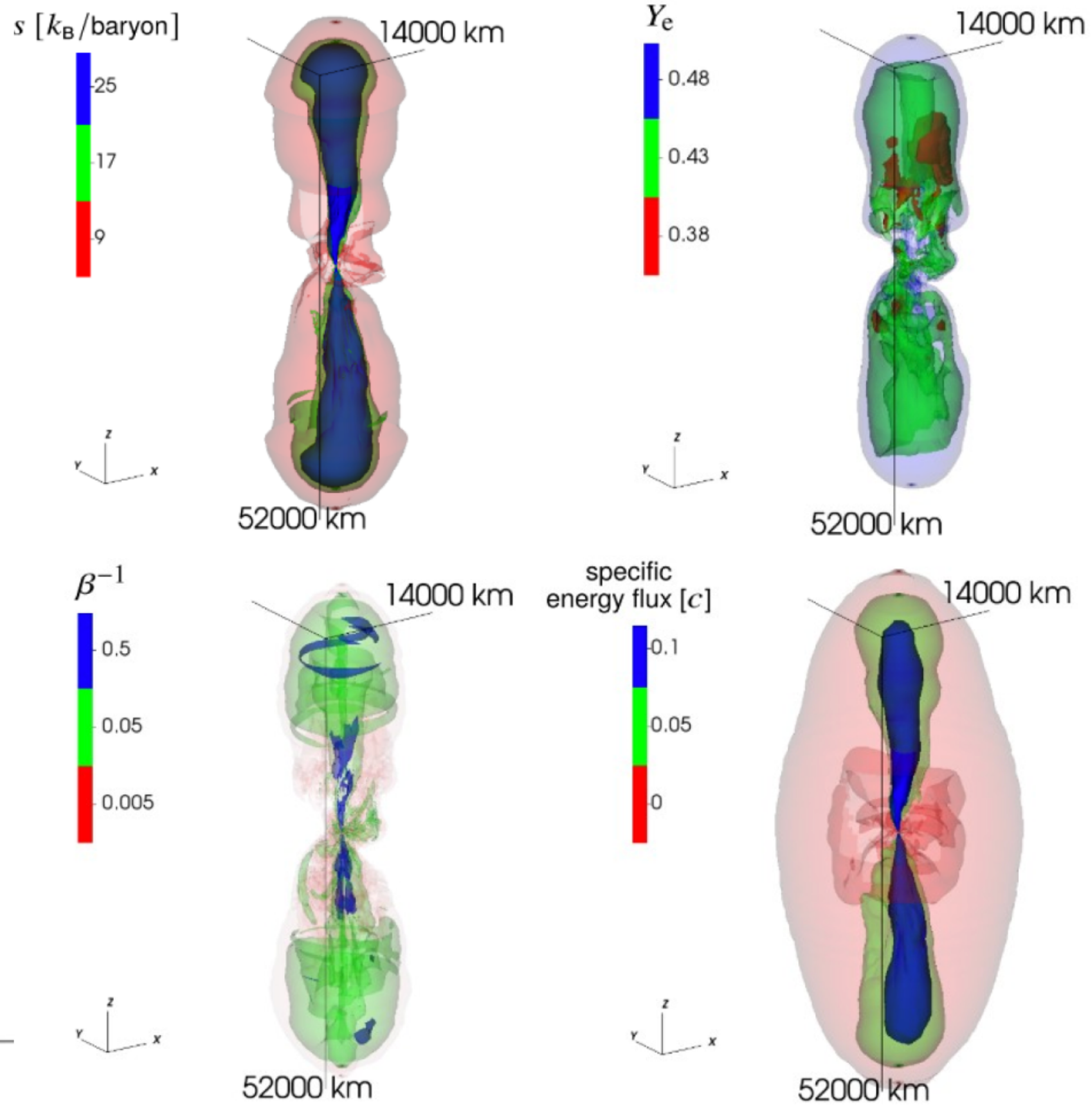
Imprint in the ejecta

Full 3D simulations of magnetorotational supernovae (also including ν–heating) show **highly anisotropic explosions** and the formation of a proto-magnetar with highly enhanced B (>10^{14} G)

Strong **anisotropies in the inner ejecta** are expected

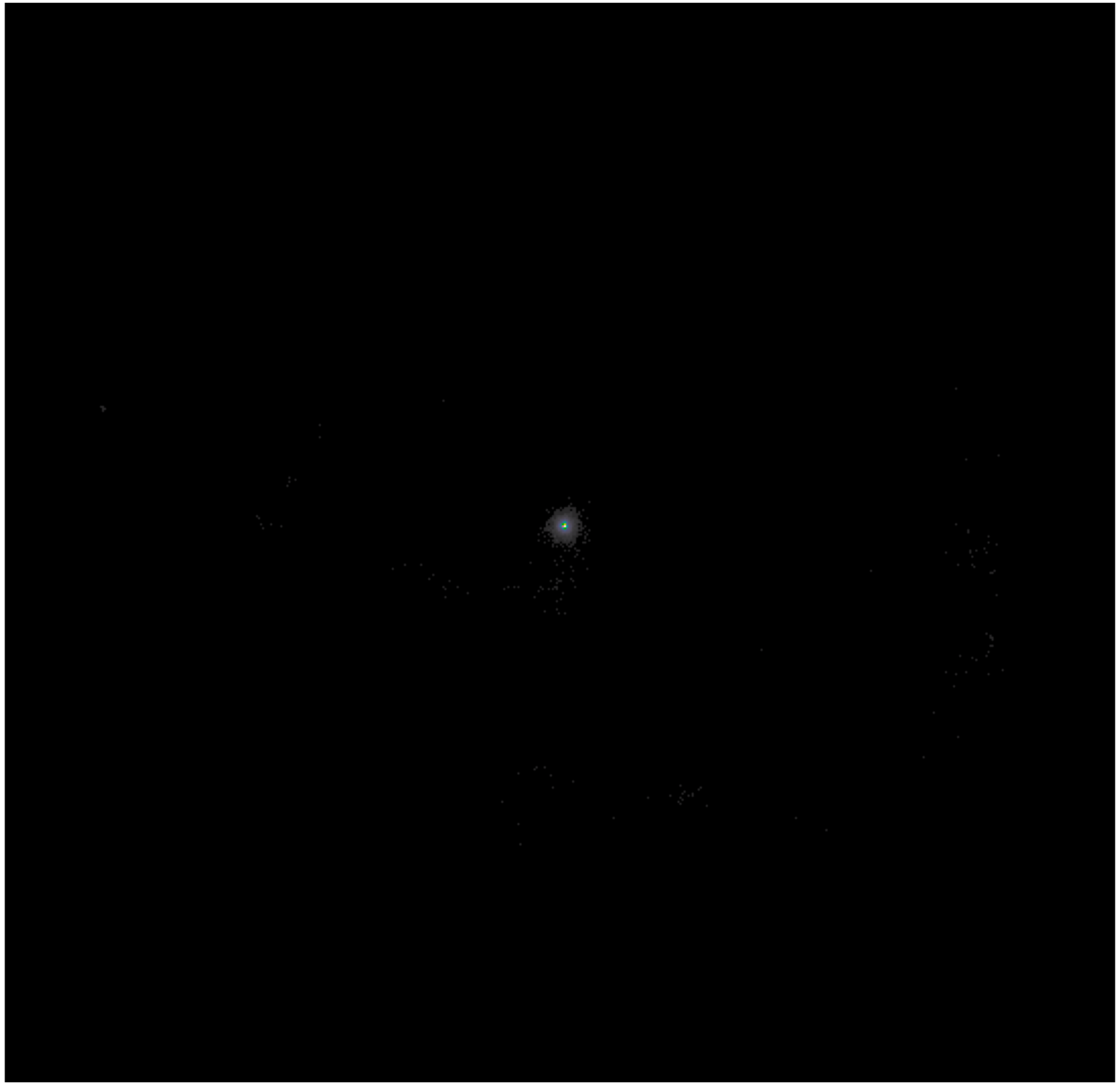


Reichert et al. 2022

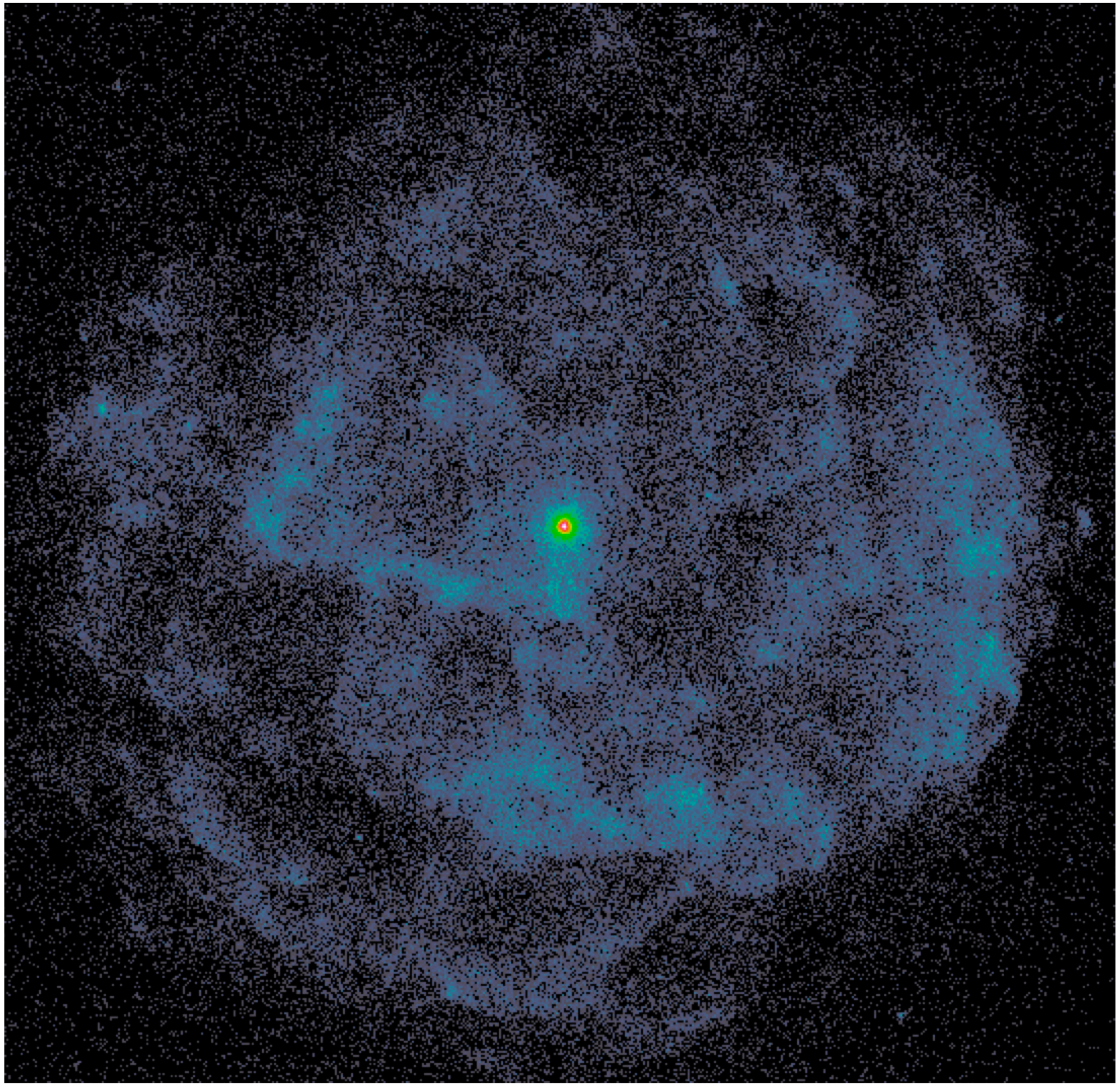


Obergaulinger & Aloy 2021

Kes 73 and its magnetar 1E 1841–045



Chandra map (linear color-scale)

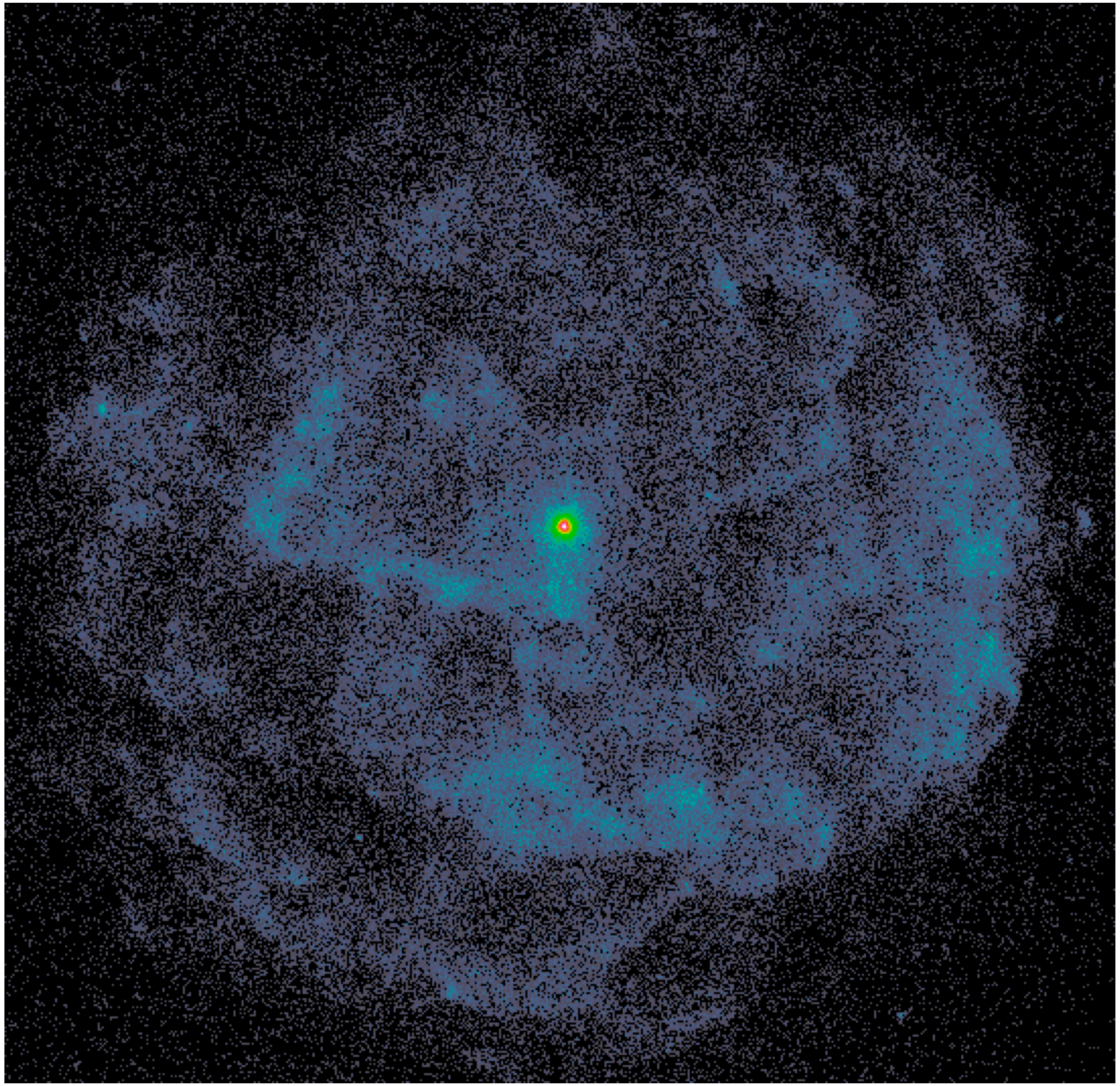


Chandra map (logarithmic color-scale)

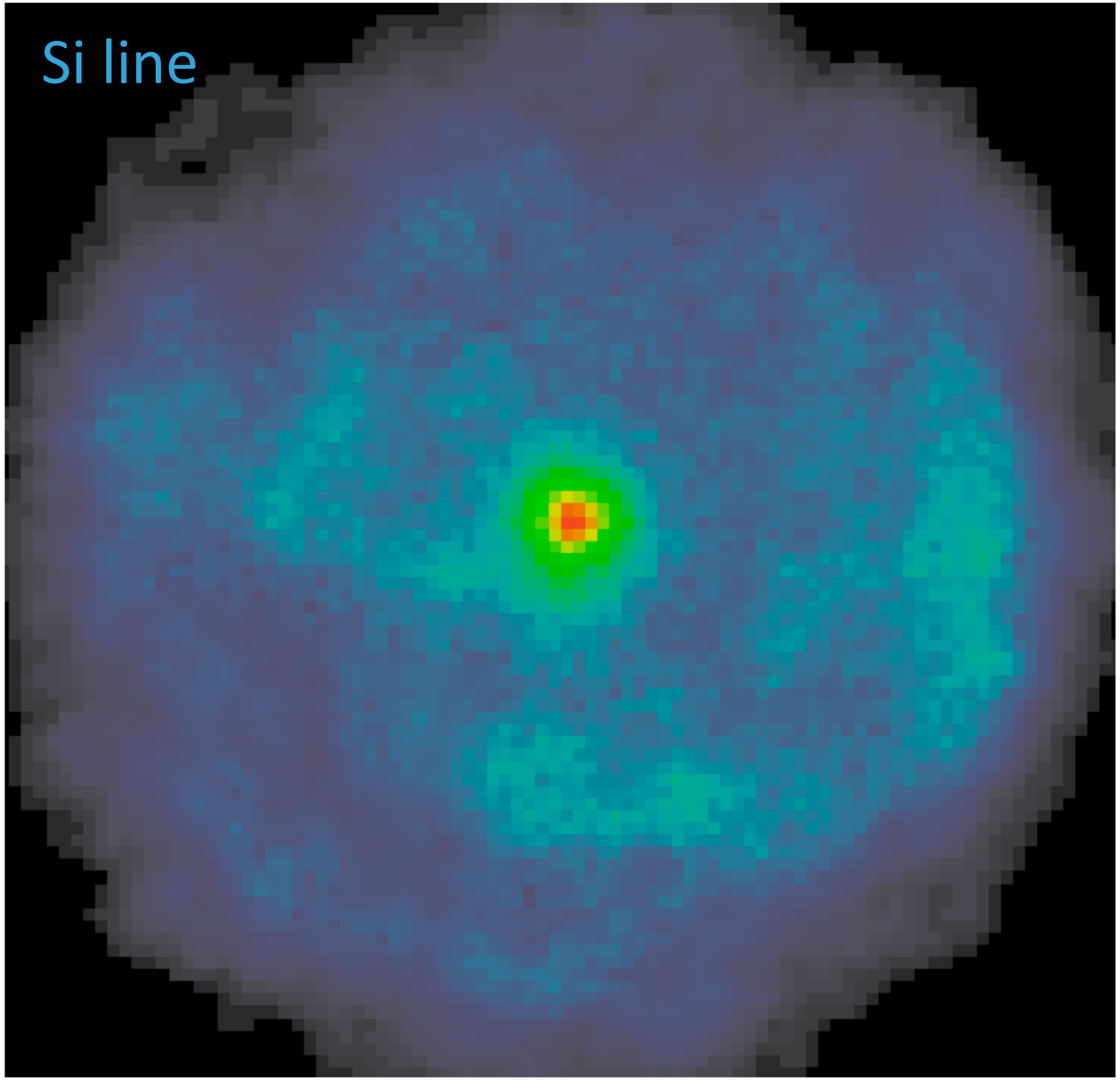
Kes 73

Middle-aged SNR (Borkowski & Reynolds 2017, Zhou et al. 2019)

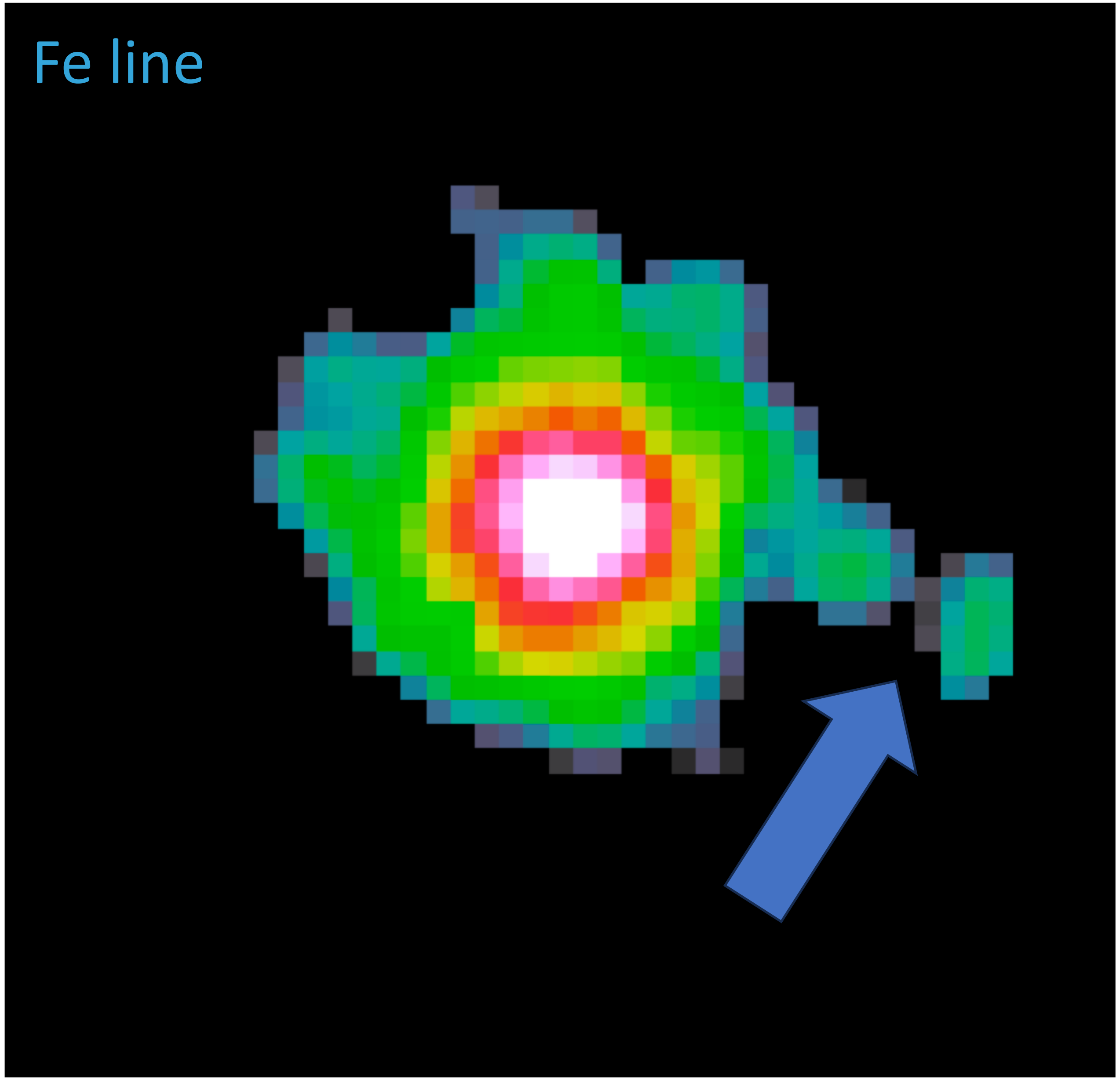
- Sedov age ~ 2000 yr
- Distance ~ 8.5 kpc
- X-ray emitting mass ~ 50±20 $M_\odot$ (emission dominated by the ISM/CSM)
- Likely interacting with a molecular cloud at East (Liu et al. 2017)



Kes 73: the XMM-Newton view

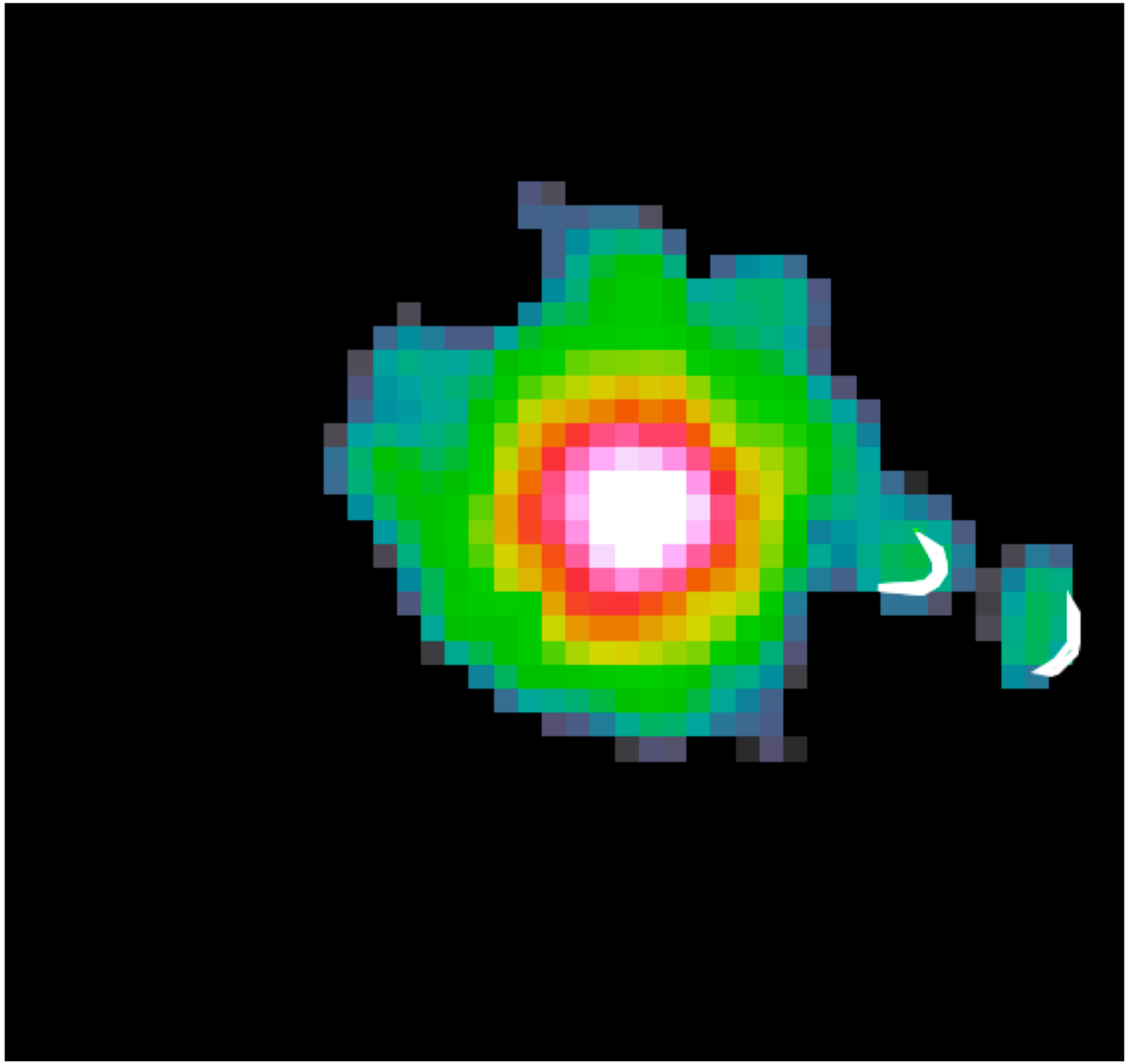


XMM (1.7-2 keV)

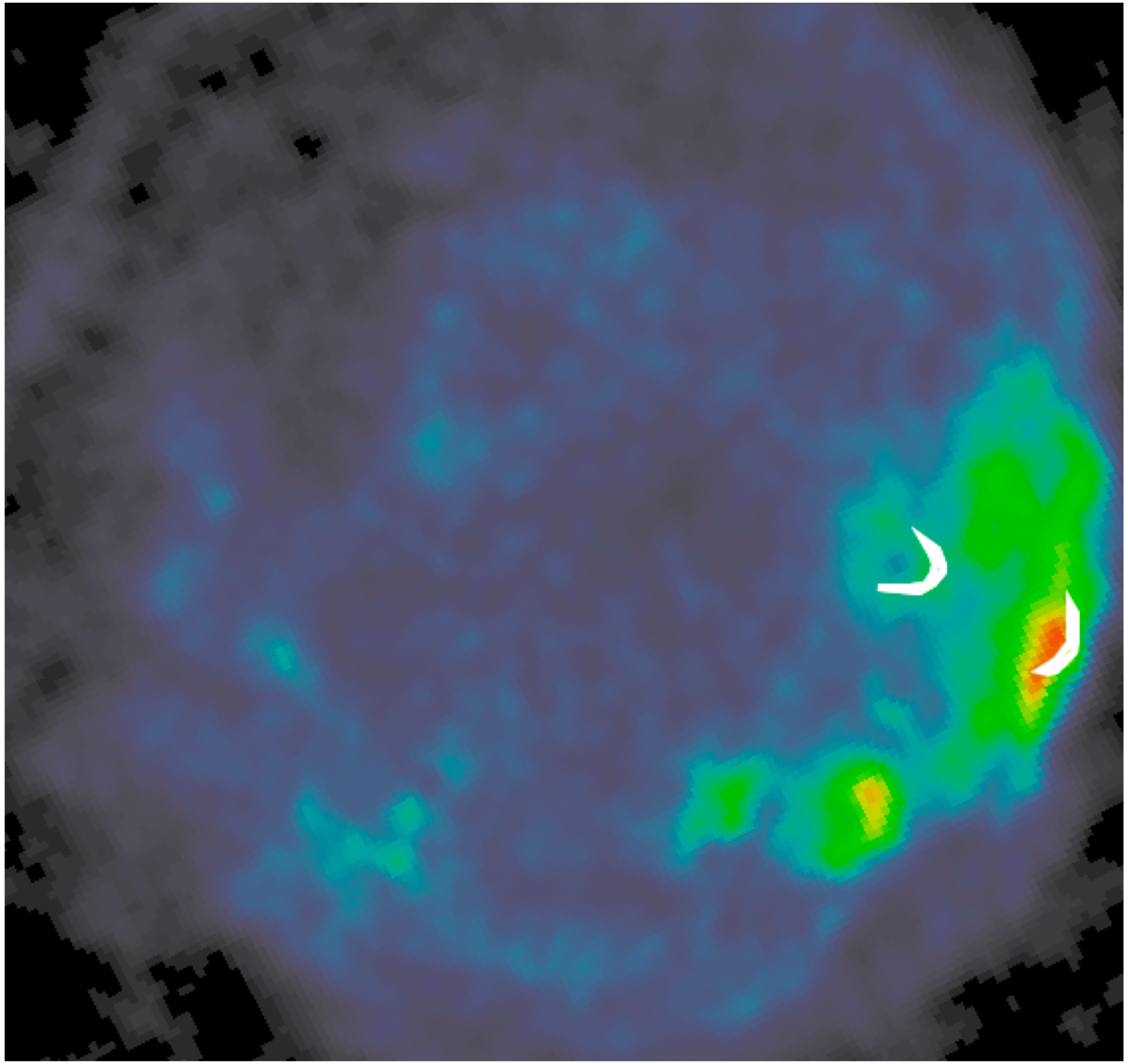


XMM (6.3-6.8 keV)

Kes 73: the XMM-Newton view

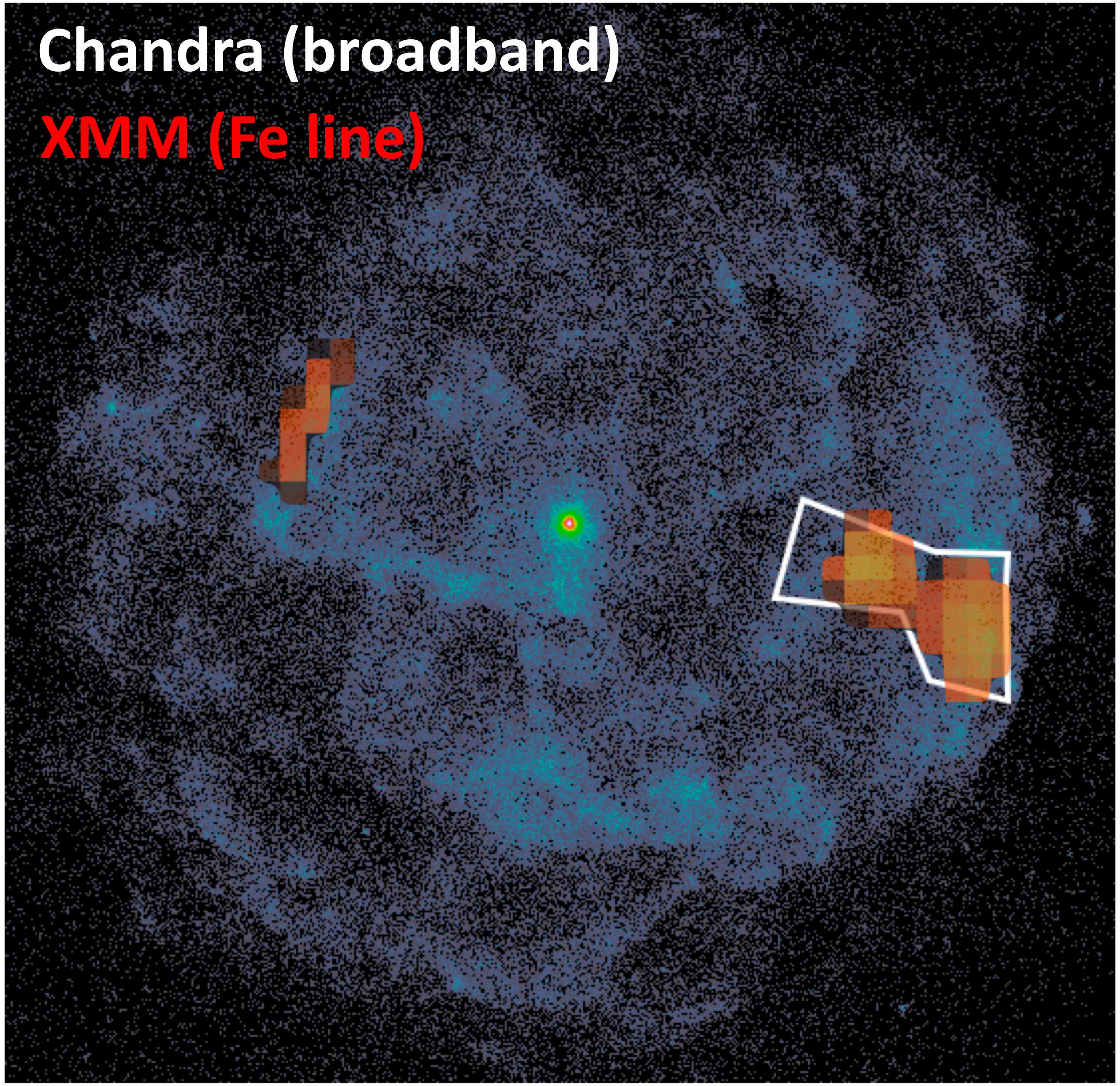


XMM (6.3-6.8 keV)

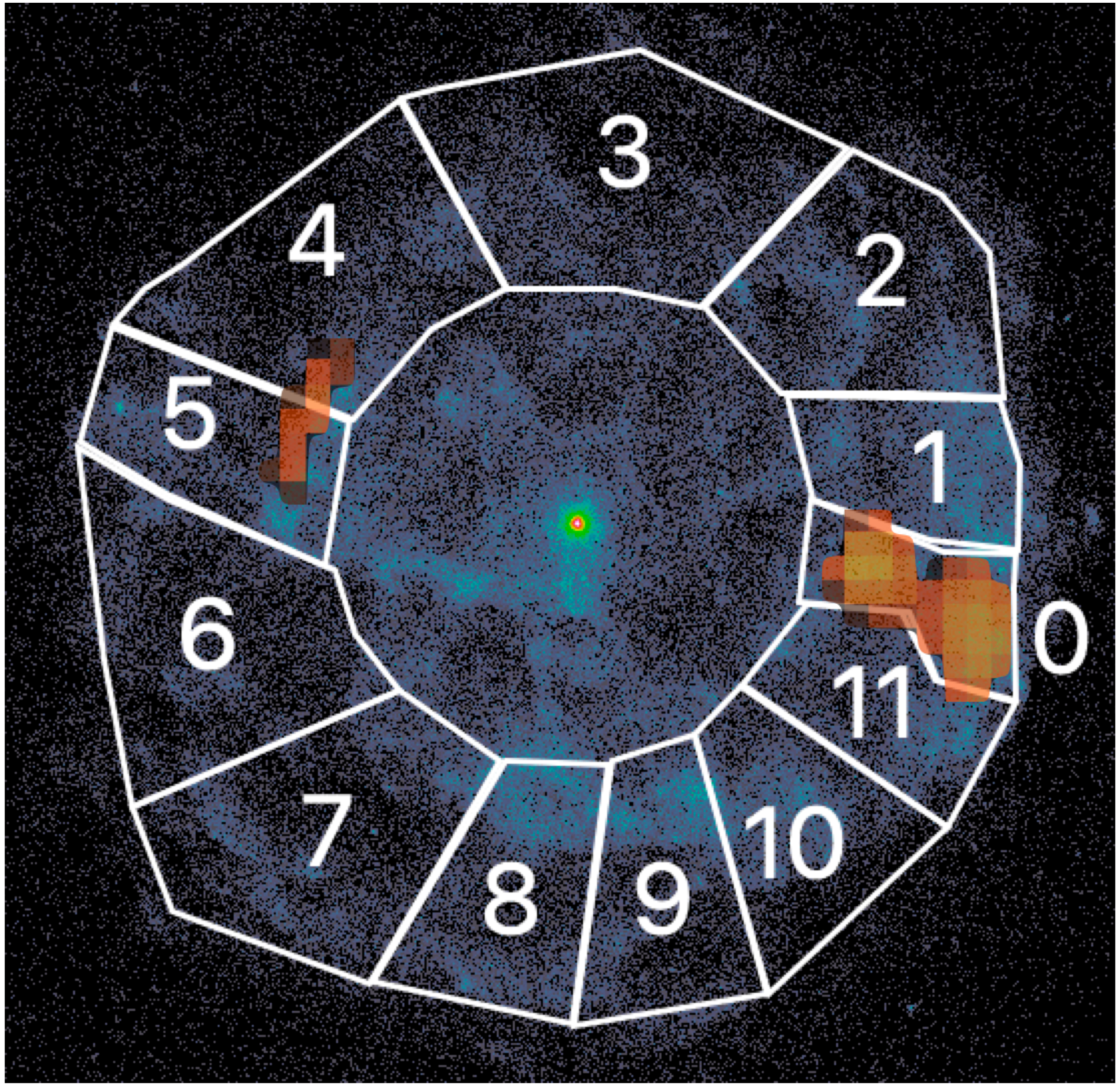


radio (20 cm)

An Fe-rich feature?

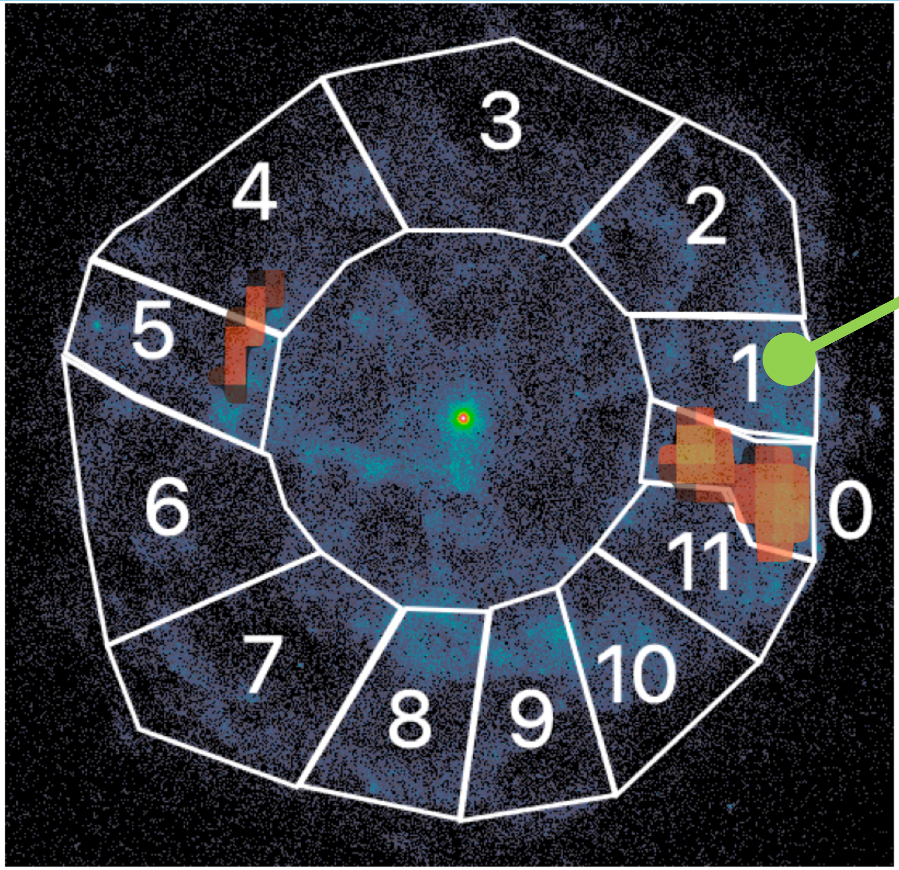


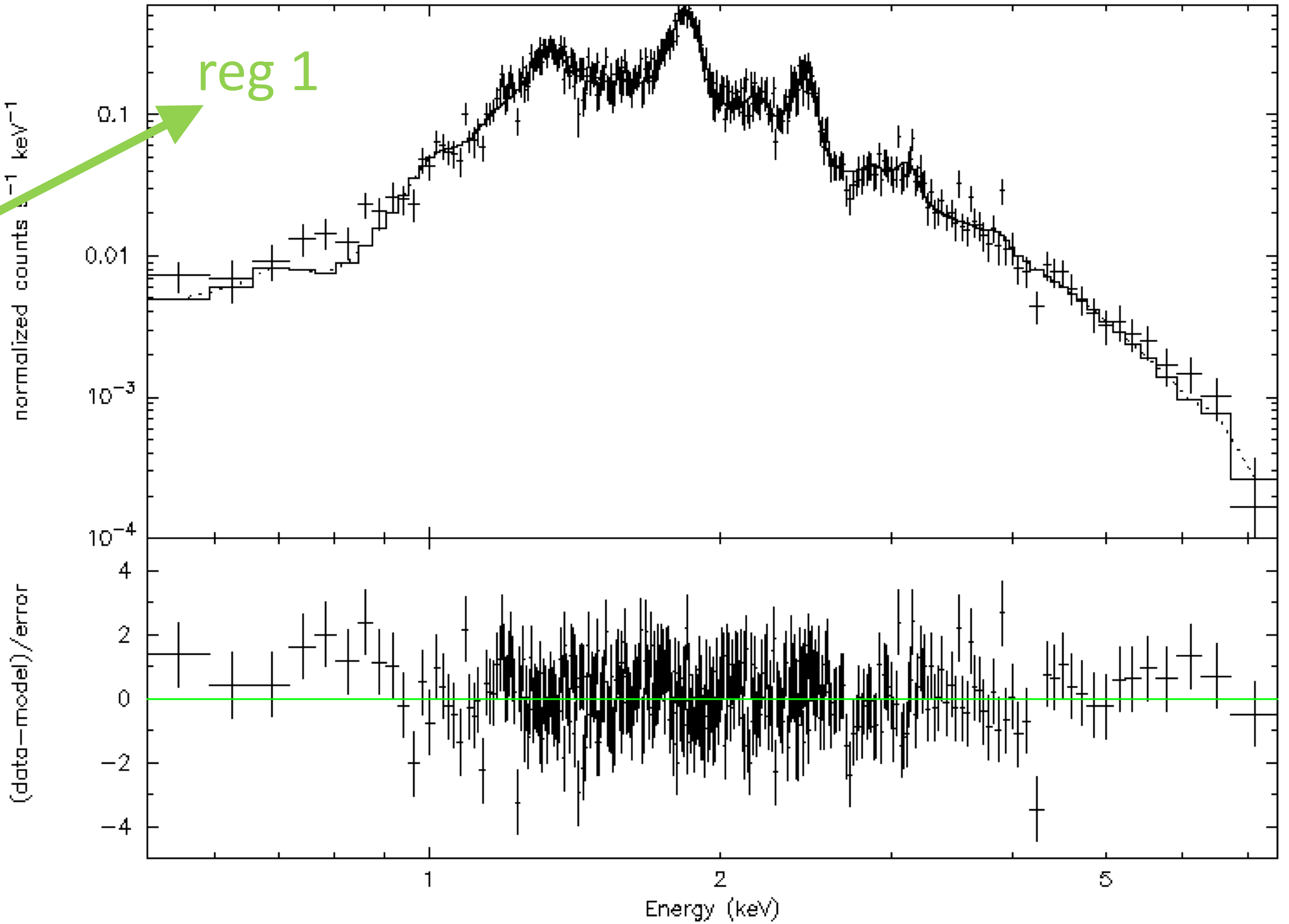
Spectral analysis



- Spatially resolved spectral analysis with EPIC-pn
- Approx. same number of counts (>12000 in the 0.5-8 keV band) in all regions
- One optically thin isothermal component in non-equilibrium of ionization (as in Zhou et al. 2019)

Spectral analysis – "normal" regions

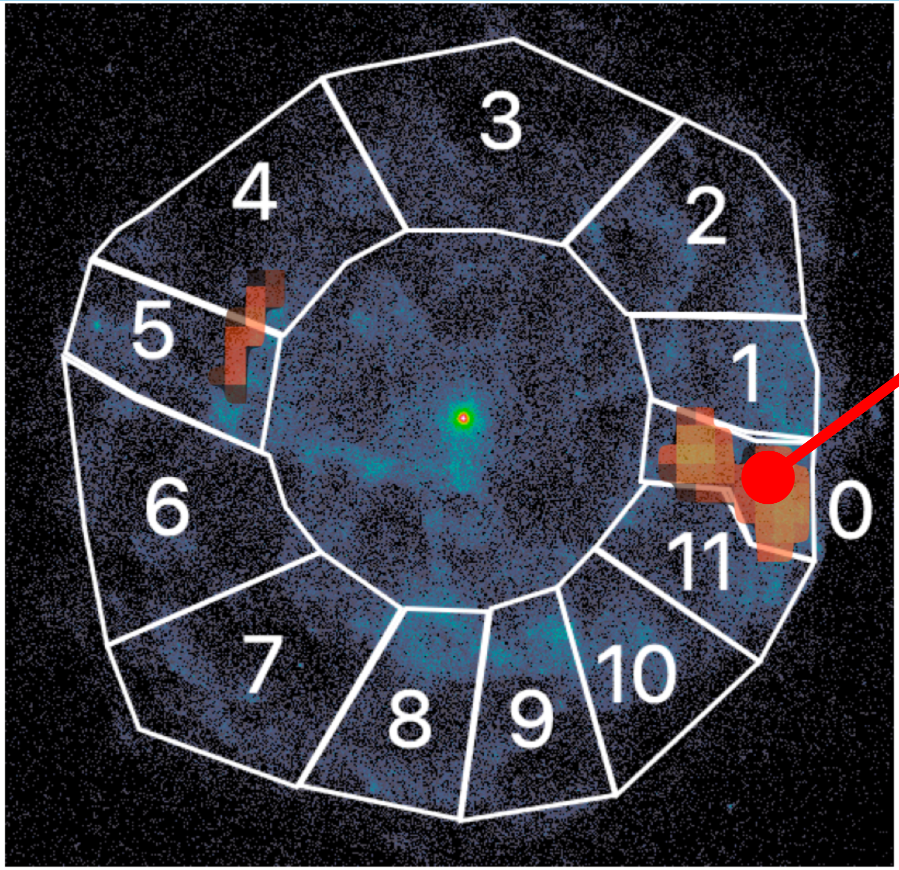




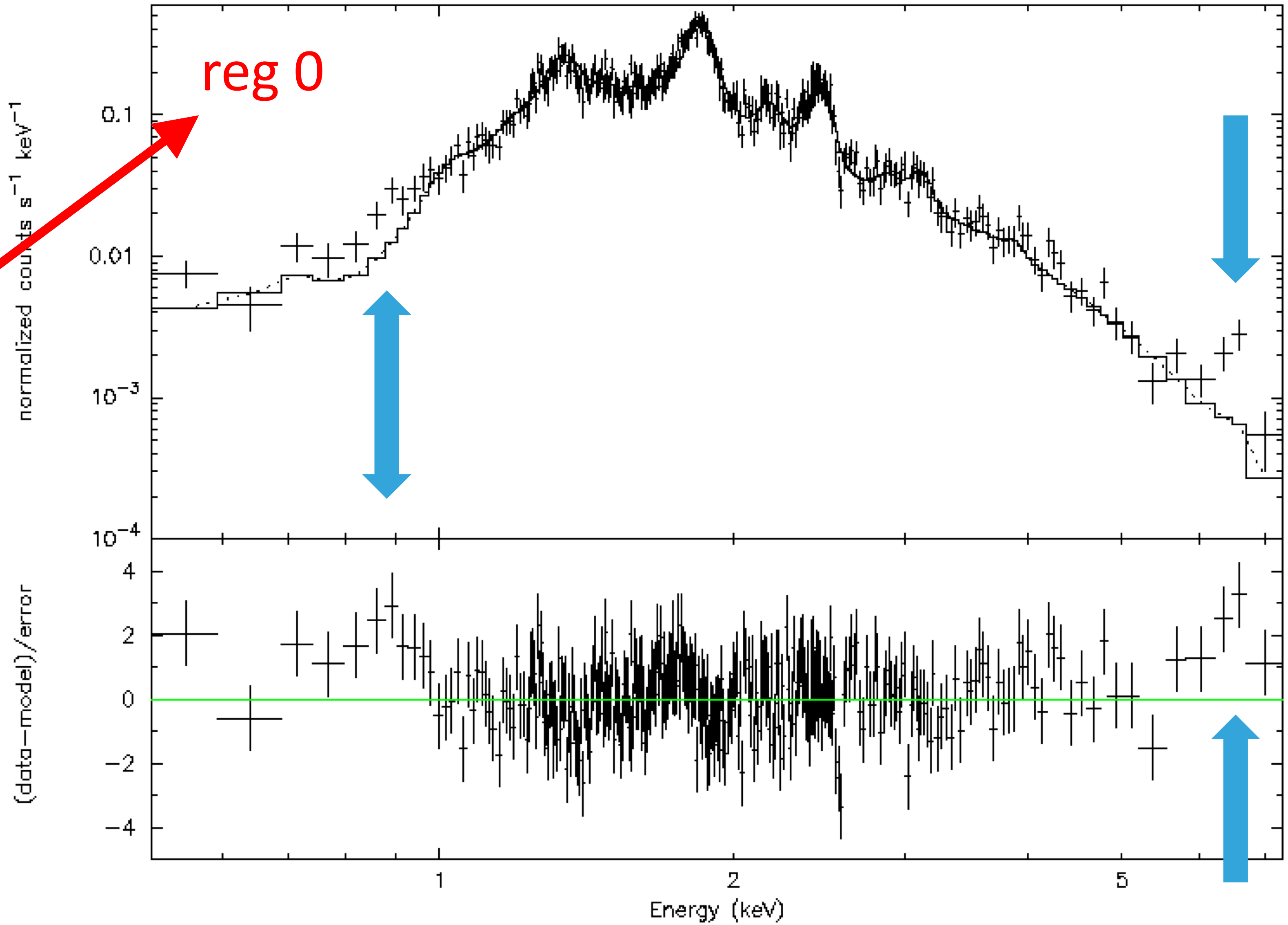
- $kT = 1.1 \pm 0.1$ keV
- $\tau = 6.7 \pm 1.1 \times 10^{10}$ s cm^{-3}
- $Ne = 1.6 \pm 0.6$
- $Mg = 1.2 \pm 0.4$
- $Si = 1.1 \pm 0.3$
- $Fe = 0.5 \pm 0.2$

All parameters in agreement with the Chandra analysis by Zhou et al. 2019

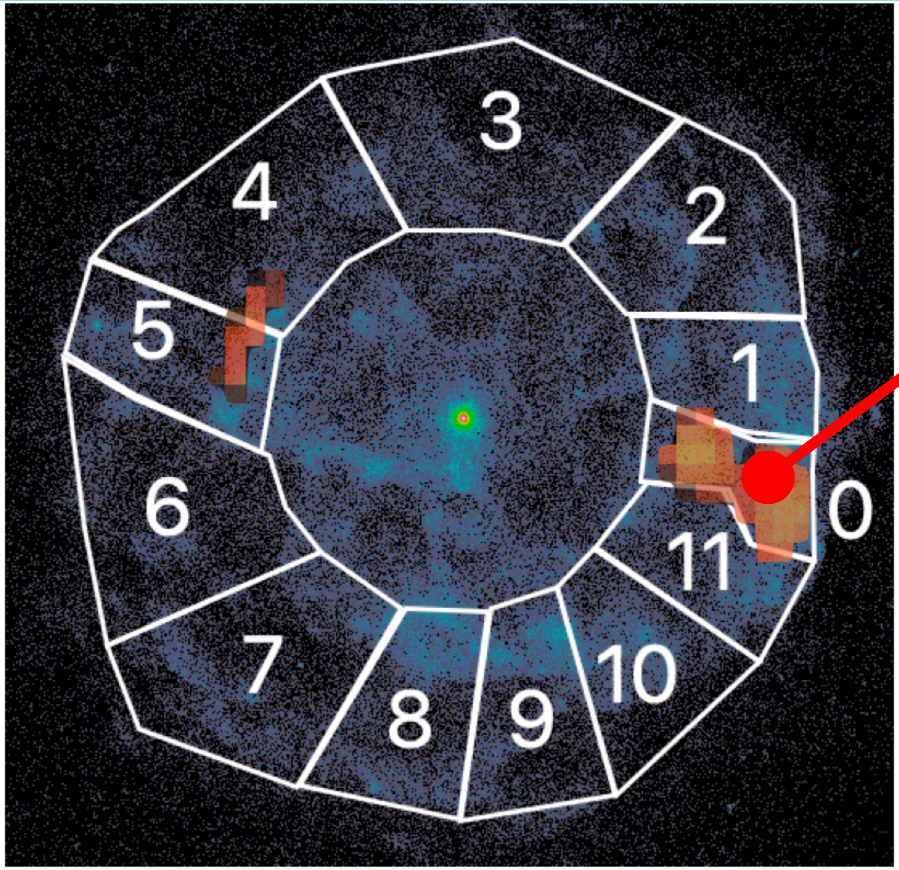
Spectral analysis – Fe regions

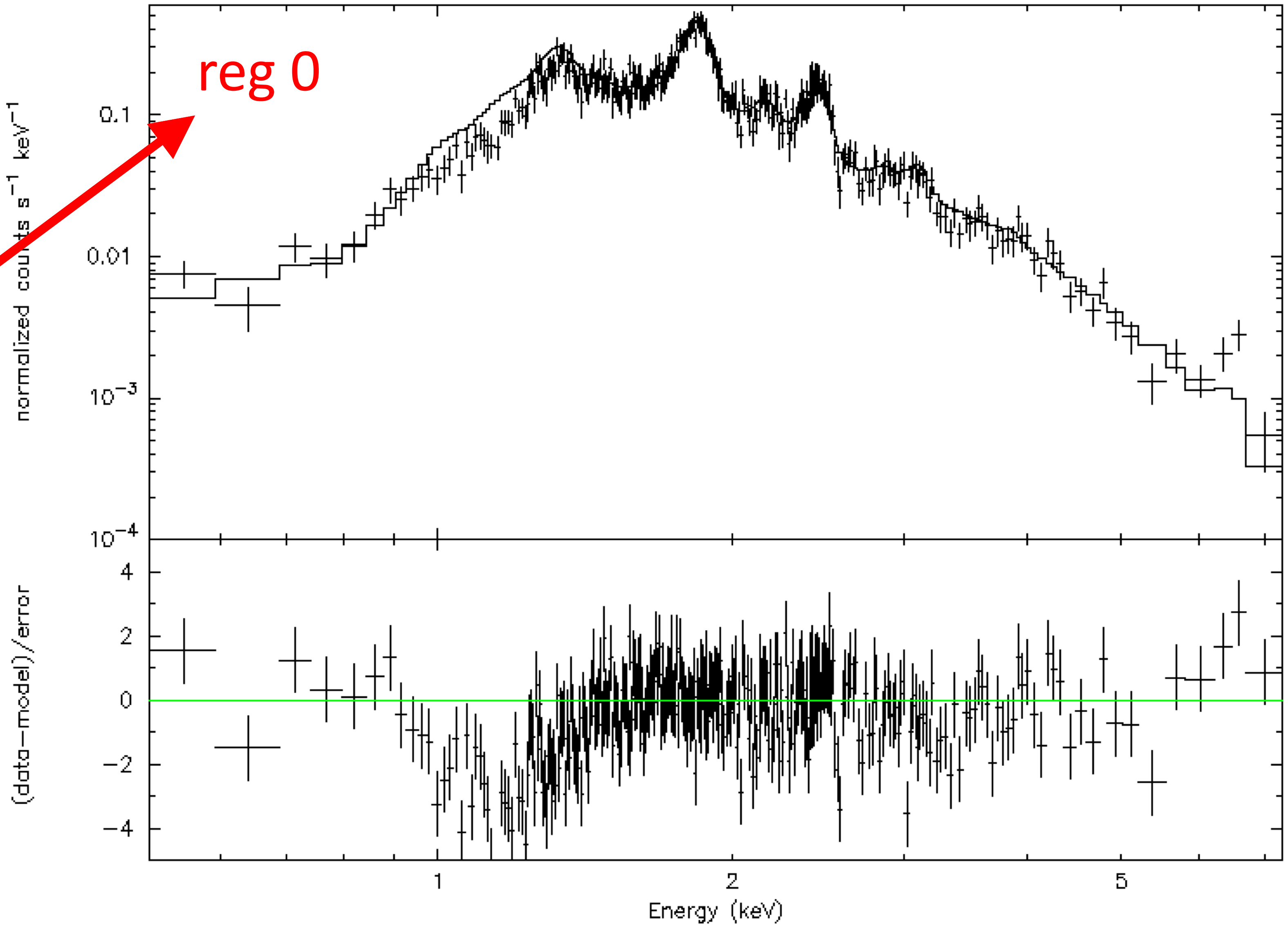


Same model as region 1: clear residuals at Fe lines!



Spectral analysis – Fe regions

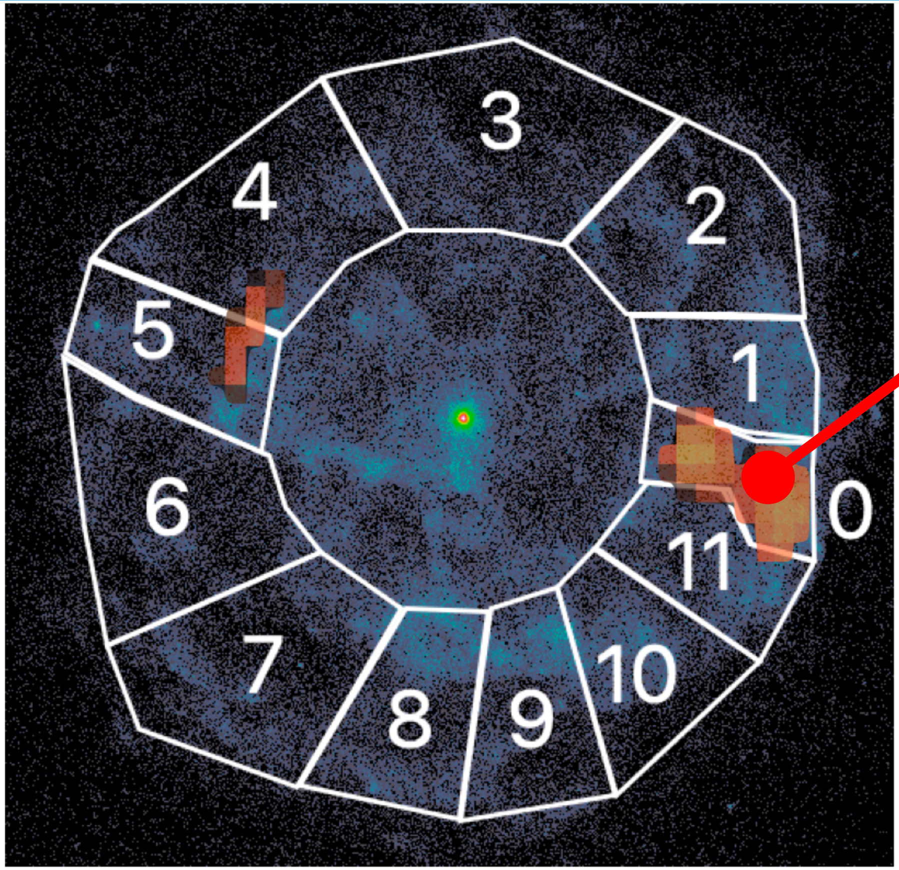


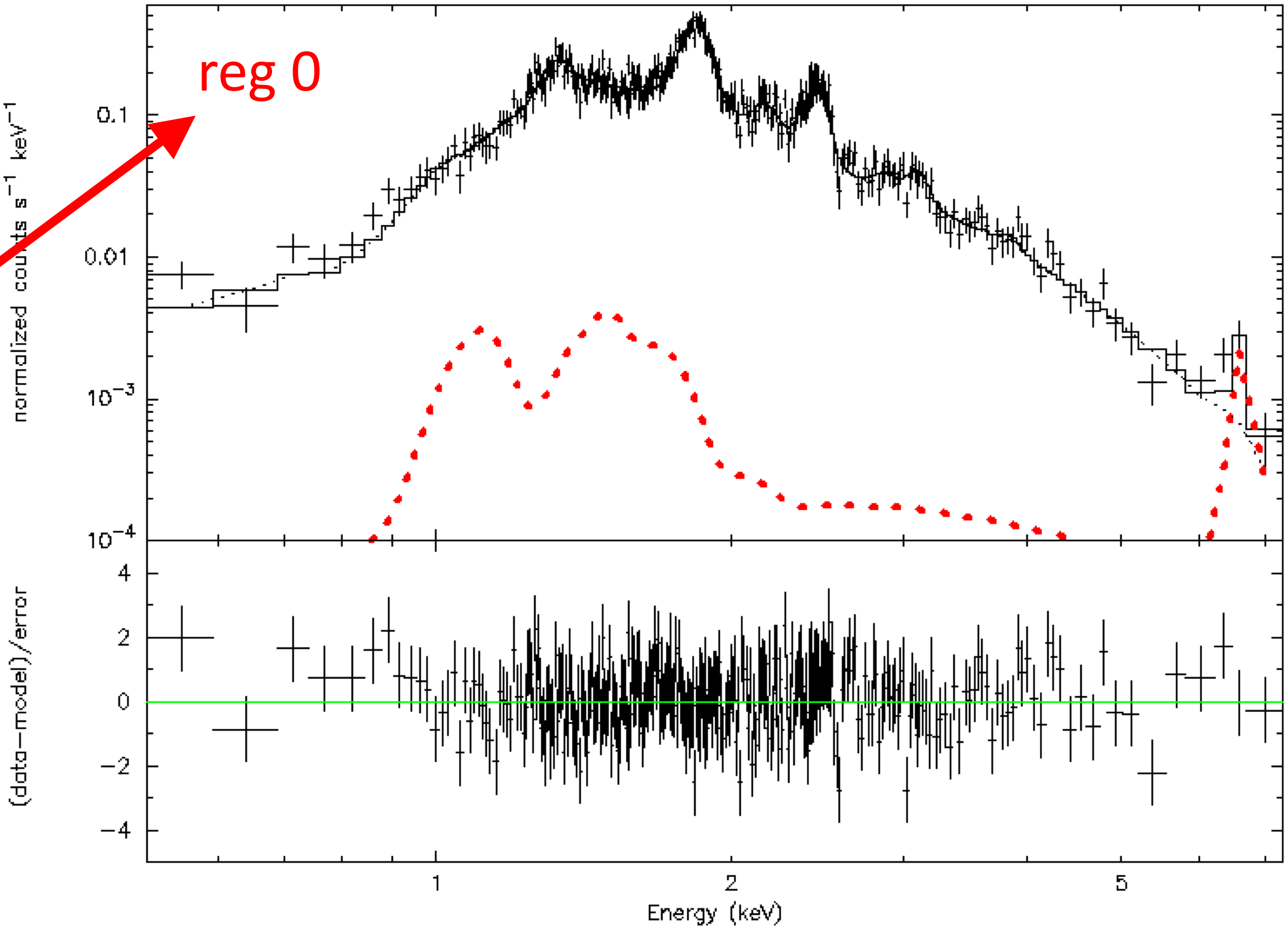


An additional Fe-rich component is necessary to explain the Fe lines

The issue cannot fixed by increasing the Fe abundance of the X-ray emitting component

Spectral analysis – Fe regions

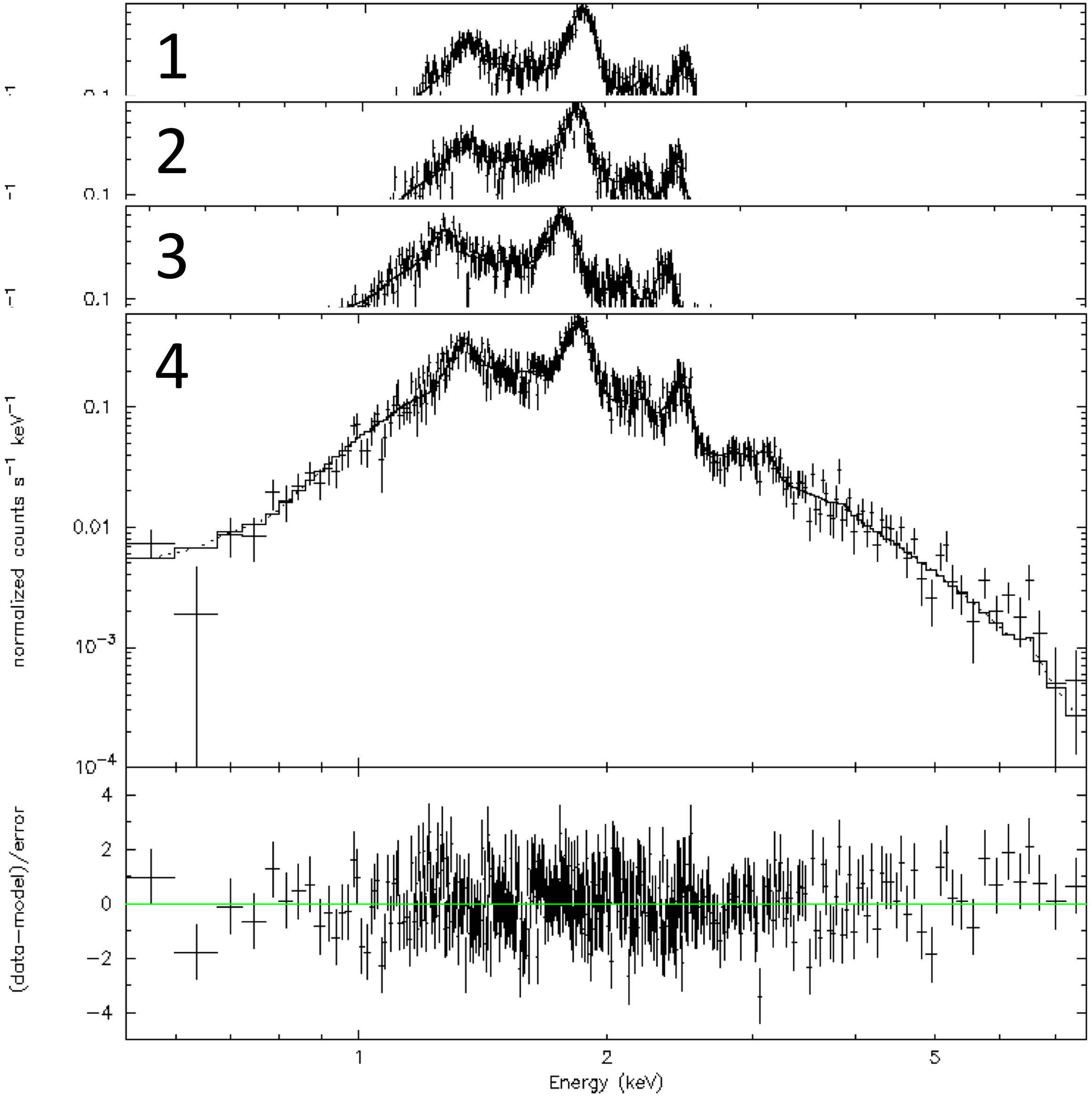


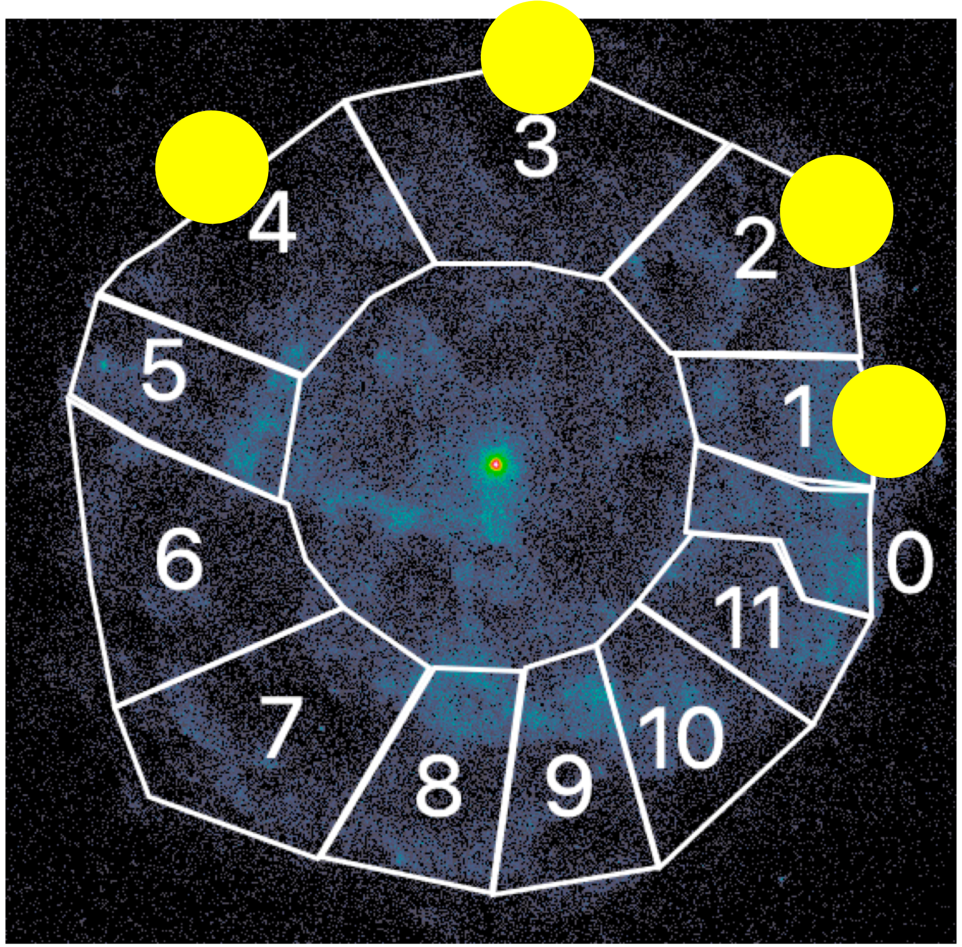


An additional Fe-rich component is necessary to explain the Fe lines

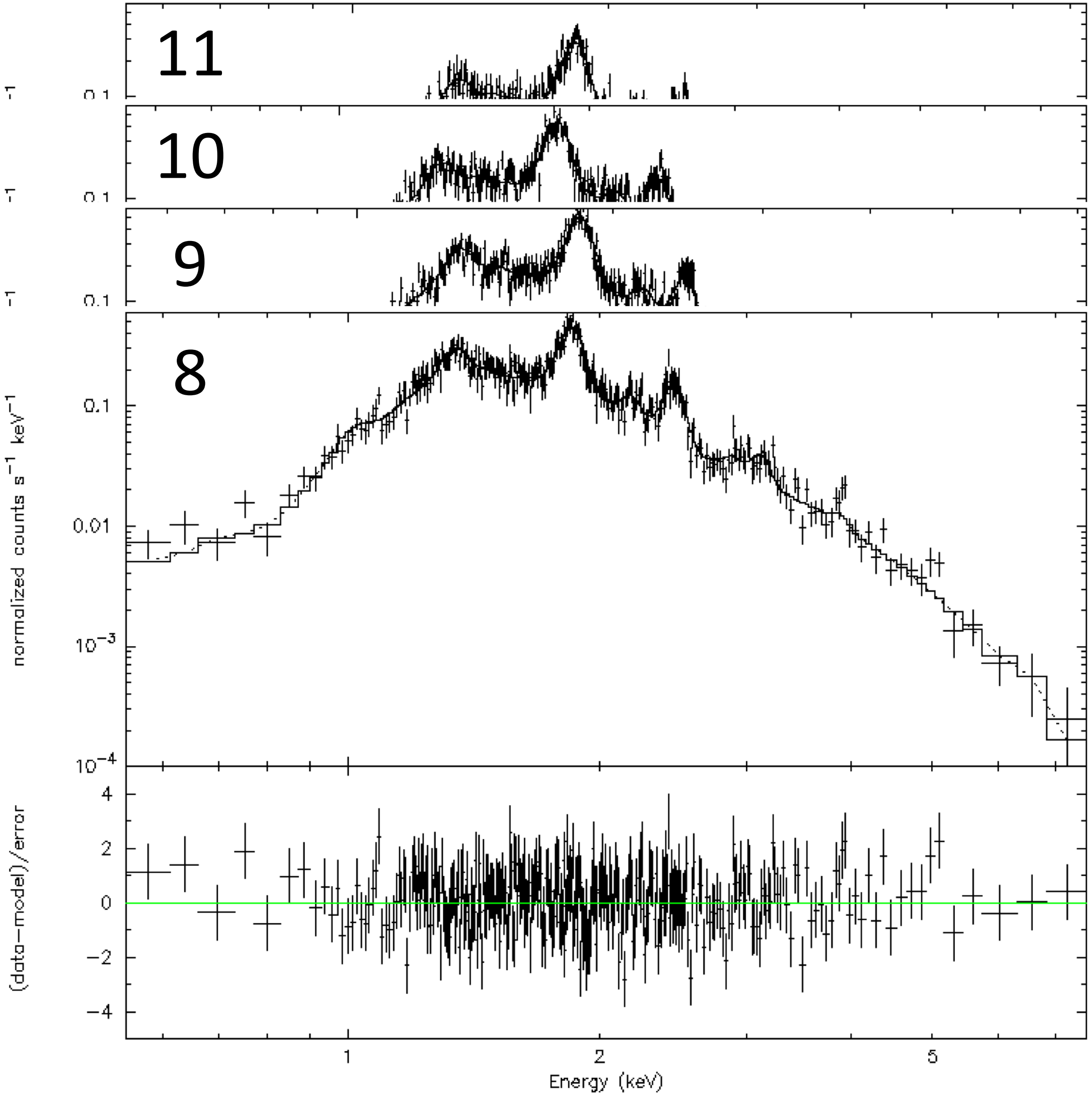
The emission measure of the additional pure-Fe component is >0 at >3σ confidence level

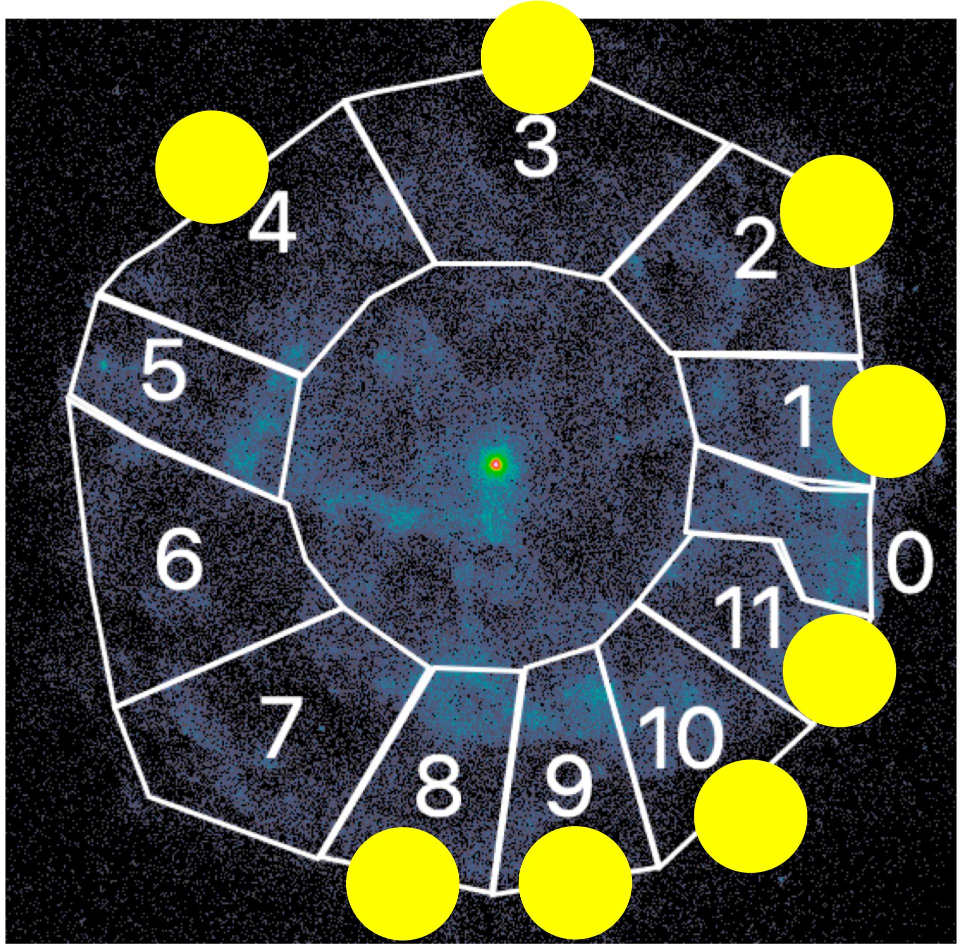
Spatially resolved spectral analysis



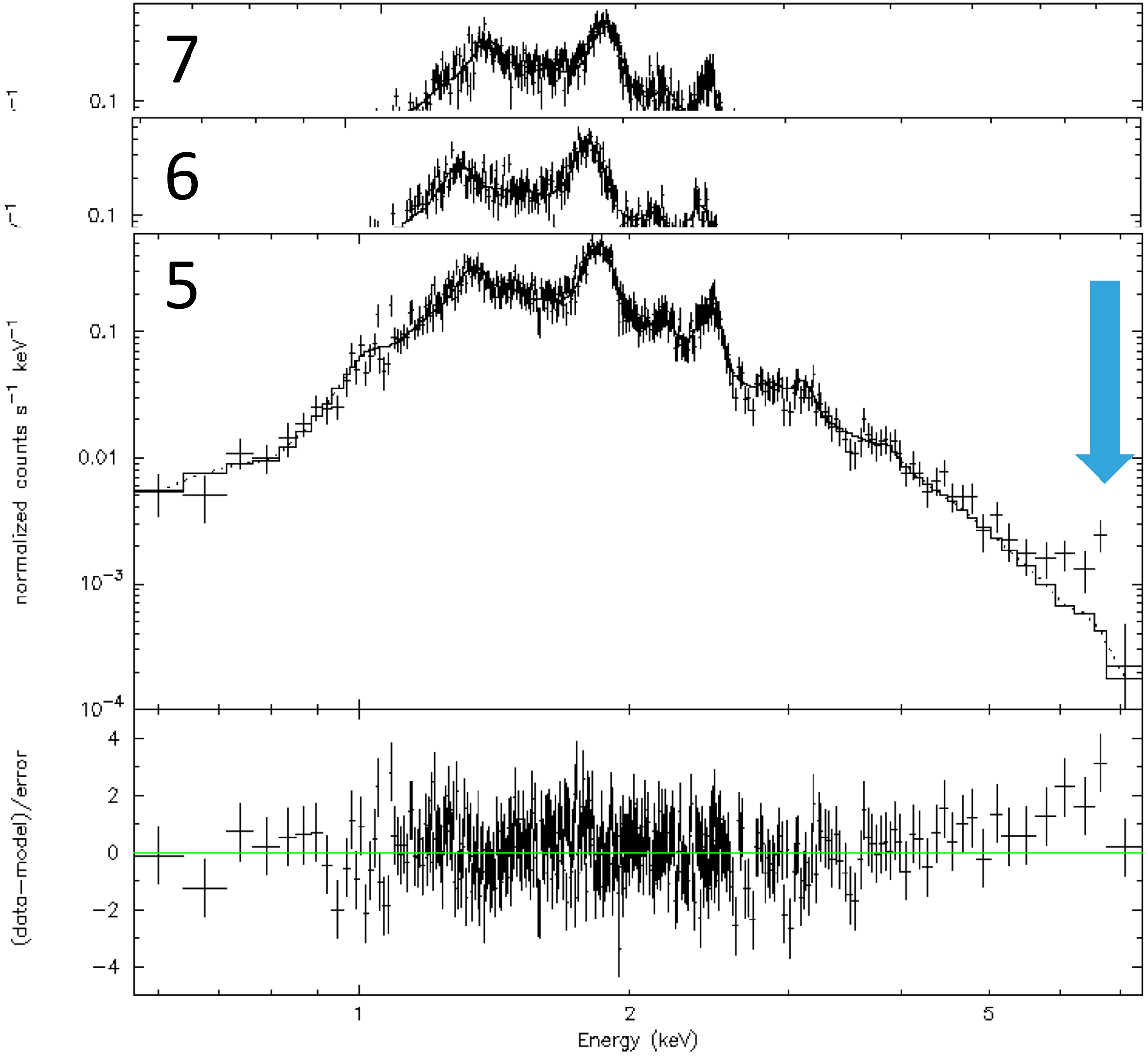


Spatially resolved spectral analysis

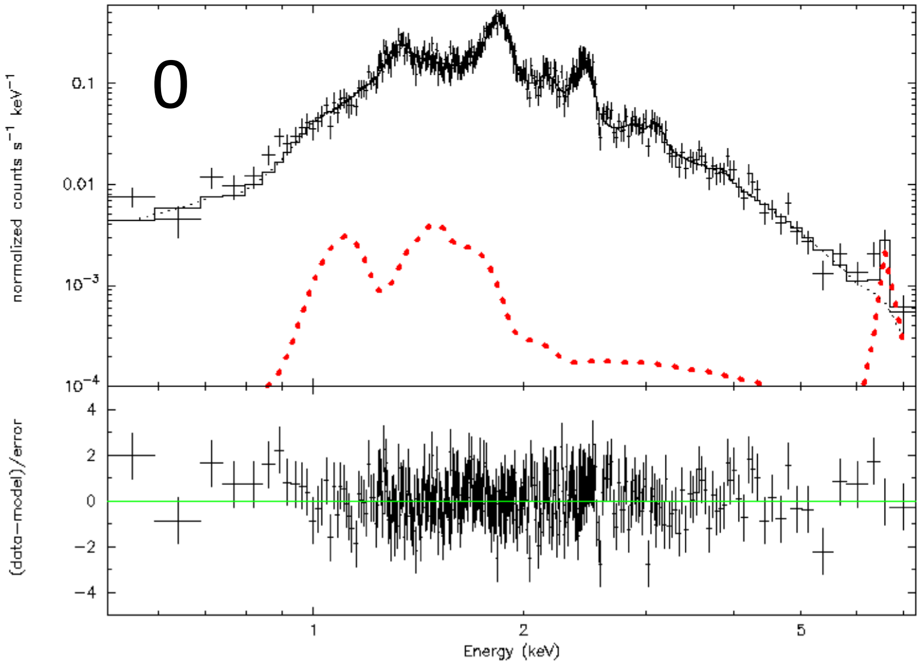


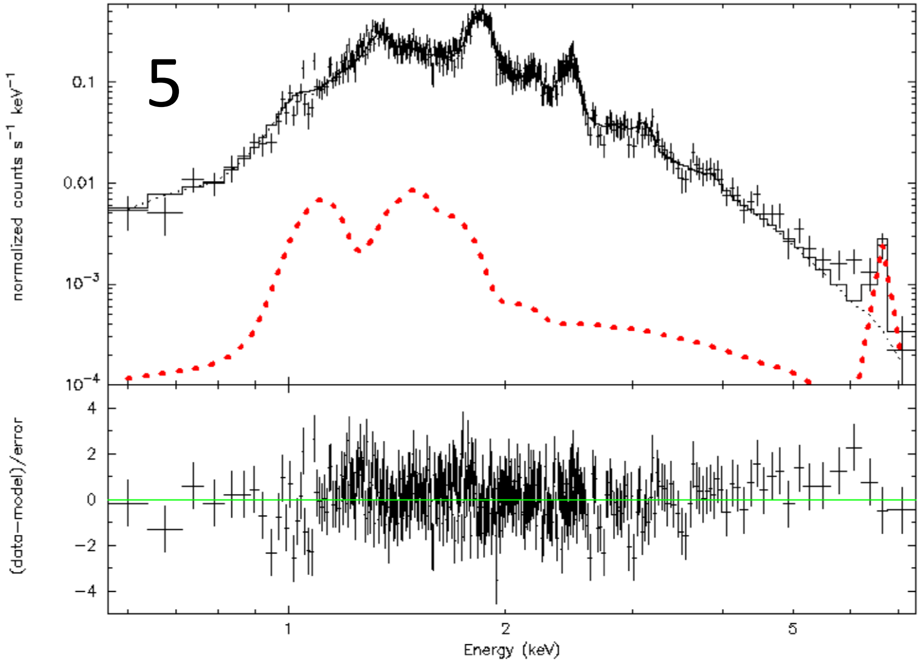


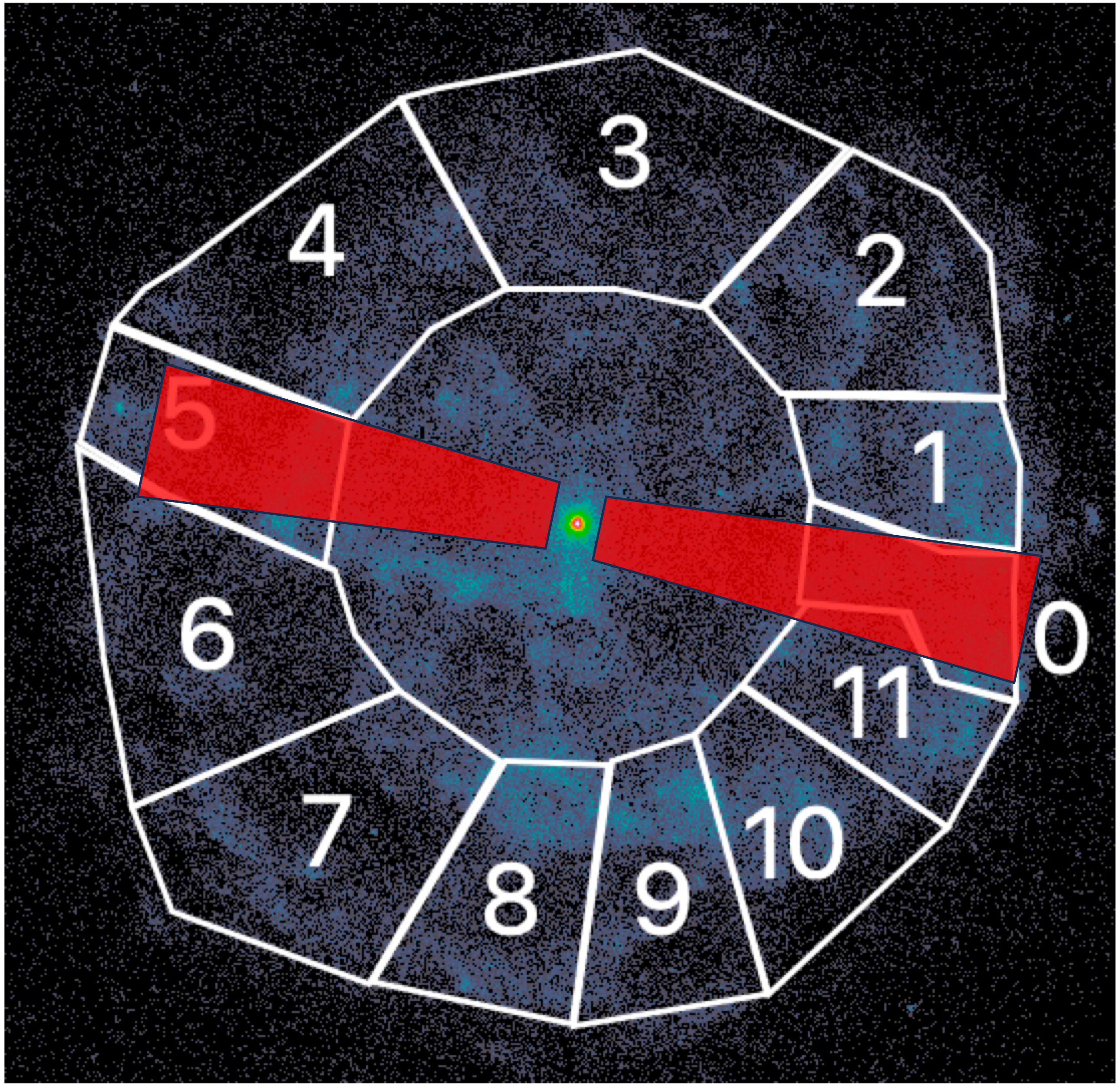
Spatially resolved spectral analysis



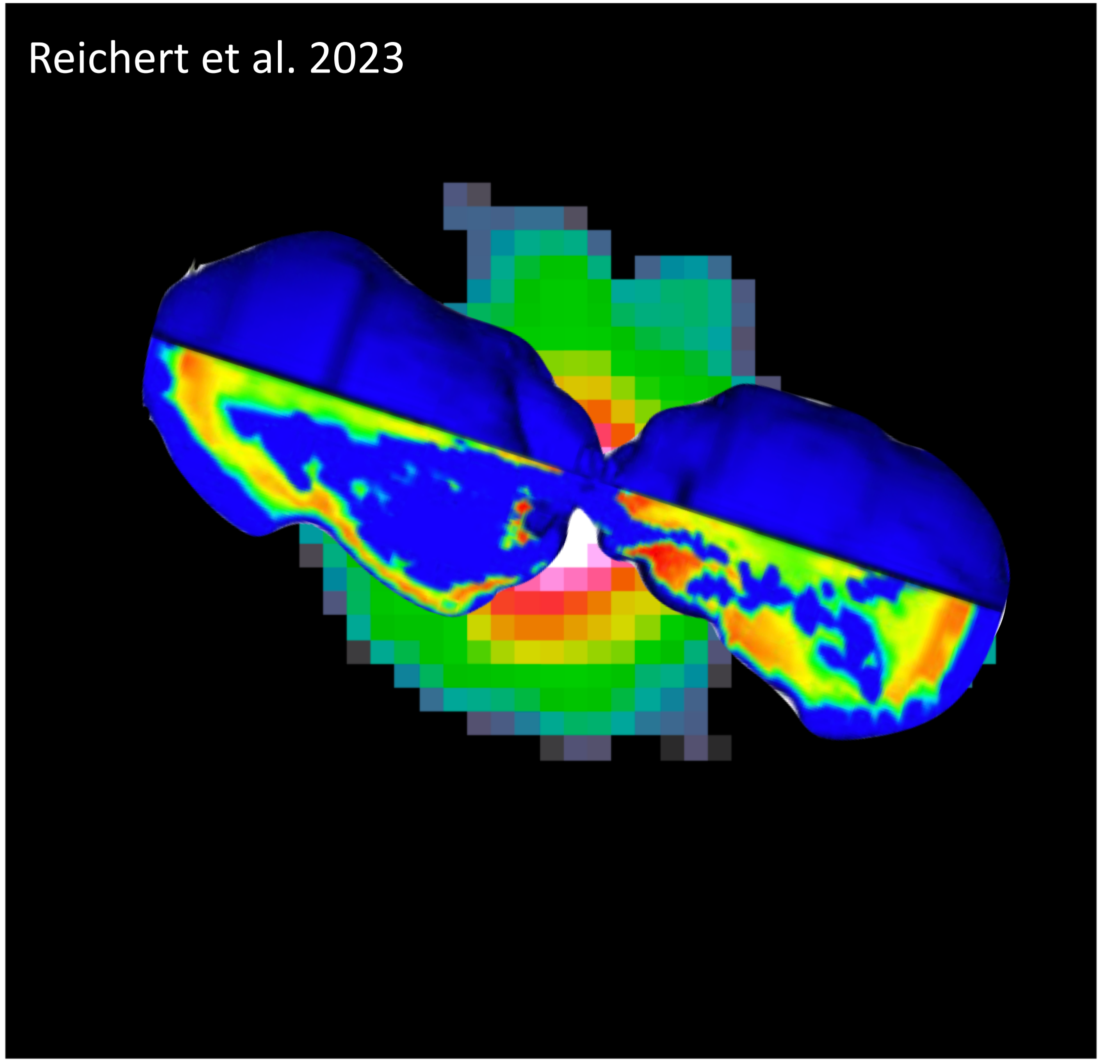
An Fe-rich collimated structure





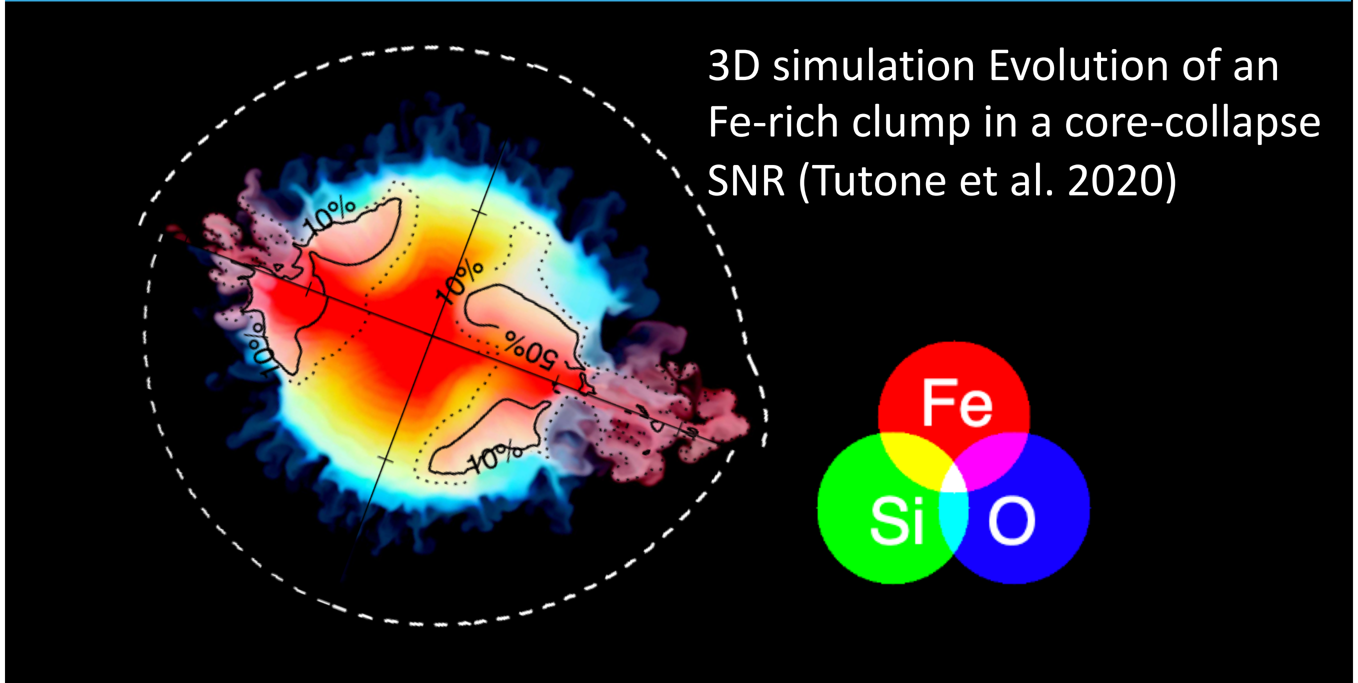


Physical properties of the southeastern feature



- $n_{Fe} \approx 1$ cm^{-3}
- $M_{Fe} \approx 0.3\, M_{\odot}$
- $K_{Fe} \approx 10^{49}$ erg

3-D simulations of magnetorotational SNe show collimated Fe-rich jets, with the Fe mass ranging between 0.1-1 $M_{\odot}$ (Reichert et al. 2023). *Do these structures survive in the SNR?*



3D simulation Evolution of an Fe-rich clump in a core-collapse SNR (Tutone et al. 2020)

- Pure-Fe plasma
- Localized in two ellipsoidal knots
- Density derived from the best-fit value of EM
- Velocity = distance/age

Conclusions

- We detected a collimated Fe-rich structure in Kes 73
- The structure can be associated with pure-ejecta
- The collimated Fe-rich ejecta show a high mass and kinetic energies
- The results *support a magnetorotational origin for the magnetar in Kes 73*
- Detailed comparison with MHD simulations is in progress