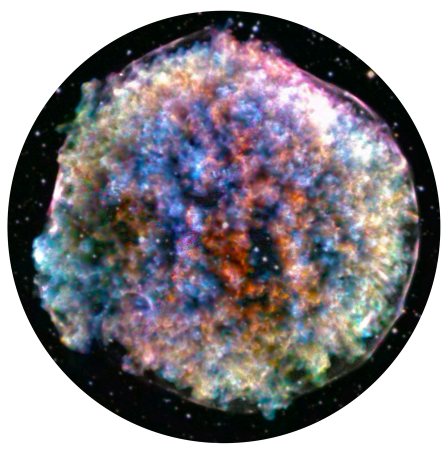

Mapping the 3D dynamics and spectral properties of Tycho's SNR in X-rays

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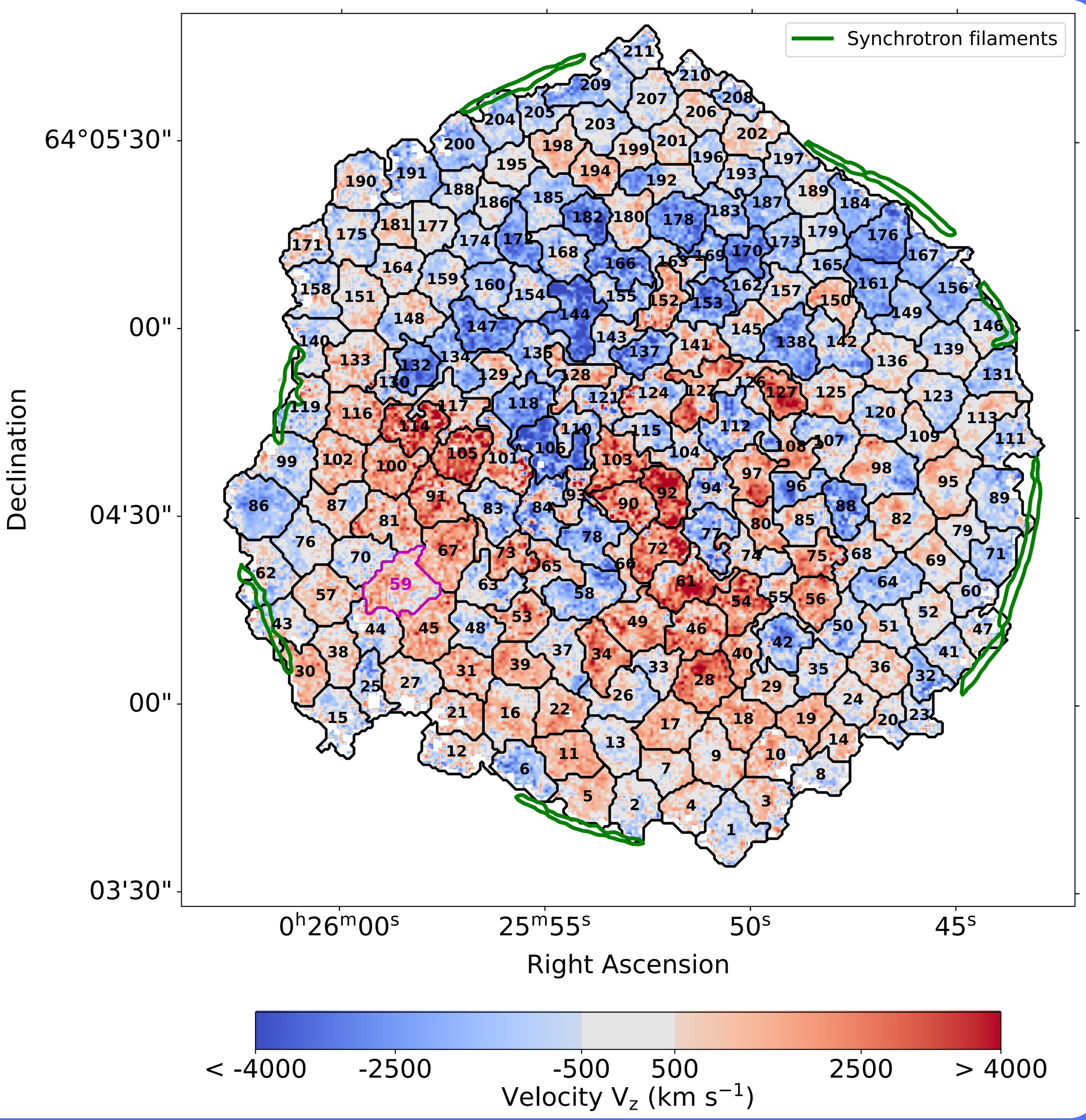
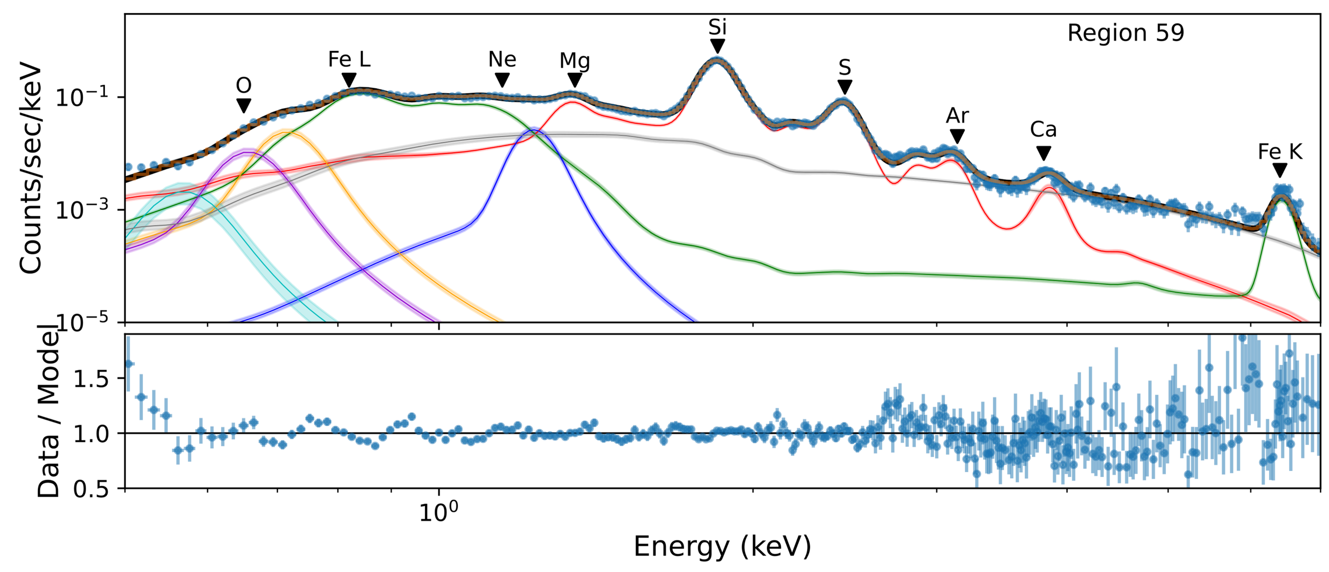
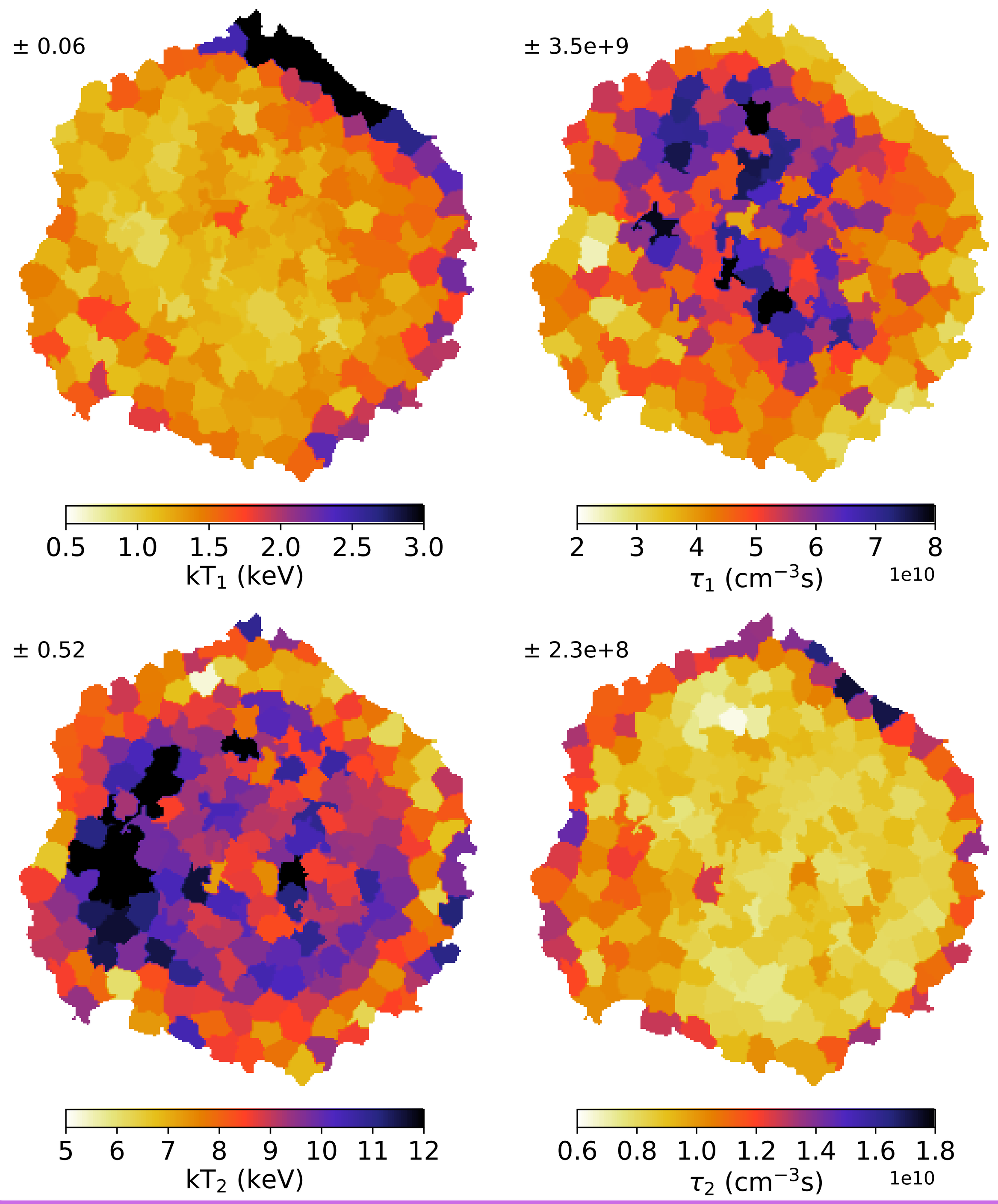
While Tycho's supernova remnant is one of the most studied type Ia Galactic supernova remnants, a global view of the physical properties of its ejecta is lacking, to understand its mysteries. In particular, the spatial distribution of the Si-rich ejecta line-of-sight velocity presents a large-scale unexplained asymmetry, with the north dominantly blueshifted and the south redshifted [1, 2, 3].

To investigate the origin of this line-of-sight velocity asymmetry in the ejecta and its current dynamics, we carry out a detailed X-ray spatially-resolved spectral analysis of the entire shocked ejecta in Tycho's SNR to determine the physical properties of its various components. This study is based on the archival deep X-ray 2009 observations from the Chandra space telescope.



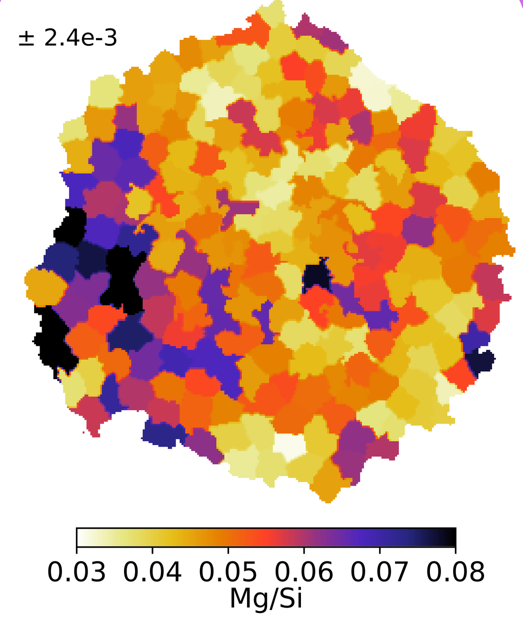


The selection of 211 regions over the entire SNR is based on a tesselation method applied to the line-of-sight velocity map. We model the ejecta emission with two thermal non-equilibrium ionisation (VNEI) components of different compositions for intermediate-mass elements (VNEI1) and iron-rich ejecta (VNEI2). We include Doppler shift and line broadening and add a power law for the synchrotron emission, and additional constraints. A Bayesian tool is used to conduct the fitting, using a nested sampling algorithm (BXA software [4]). It allows us to obtain a complete view of the statistical landscape.



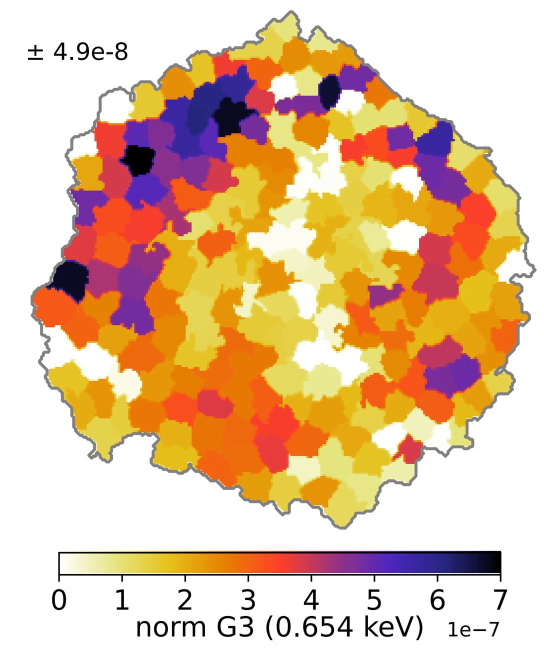
We provide 19 maps of the physical parameters of the various components across the SNR ejecta. The Doppler shift map (derived mainly from VNEI1) confirms spectrally the large-scale north-south asymmetry in the line-of-sight velocity.

We do not observe a similar dipole in our maps of temperature (kT1 & kT2) and ionization time (τ1 & τ2). Thus, this asymmetry can be innate (from an anisotropic explosion) or acquired (due to the interaction of the ejecta with some large structures in the ambient medium). In the second case, however, it is surprising that this potential interaction leaves no evidence in terms of temperature and ionization time.



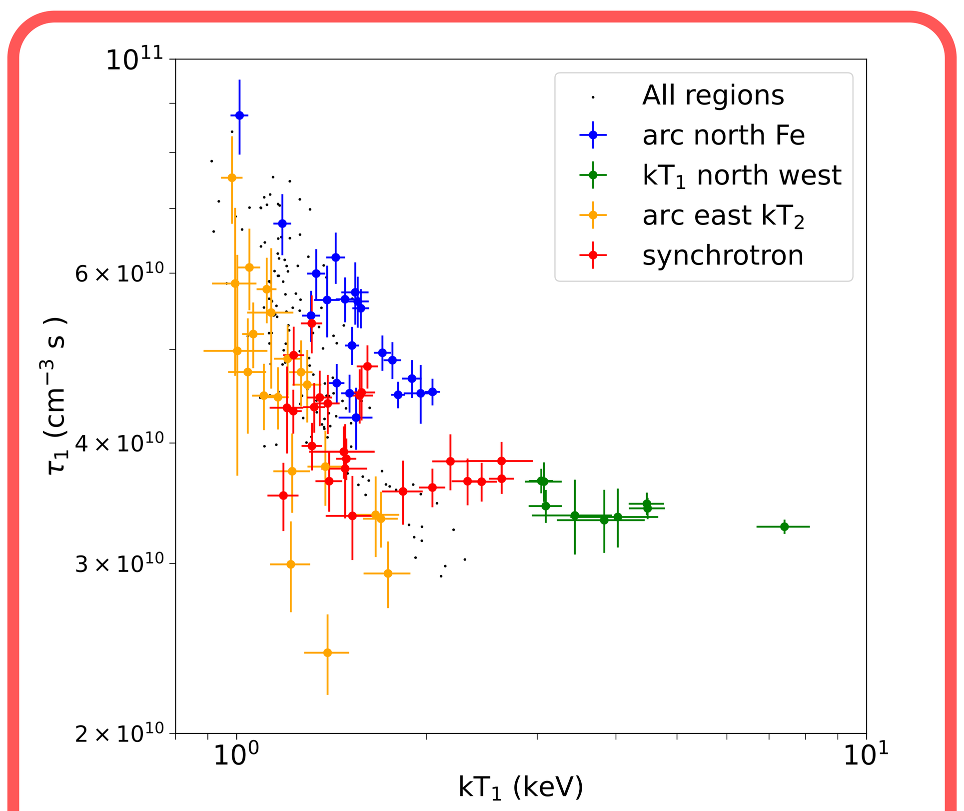
We also obtain abundance maps for Mg, S, Ar and Ca relative to Si. Their spatial distribution is rather homogeneous, with higher values in some areas.

S, Ar and Ca maps are well correlated, unlike Mg, which is probably produced in a different layer during the explosion.



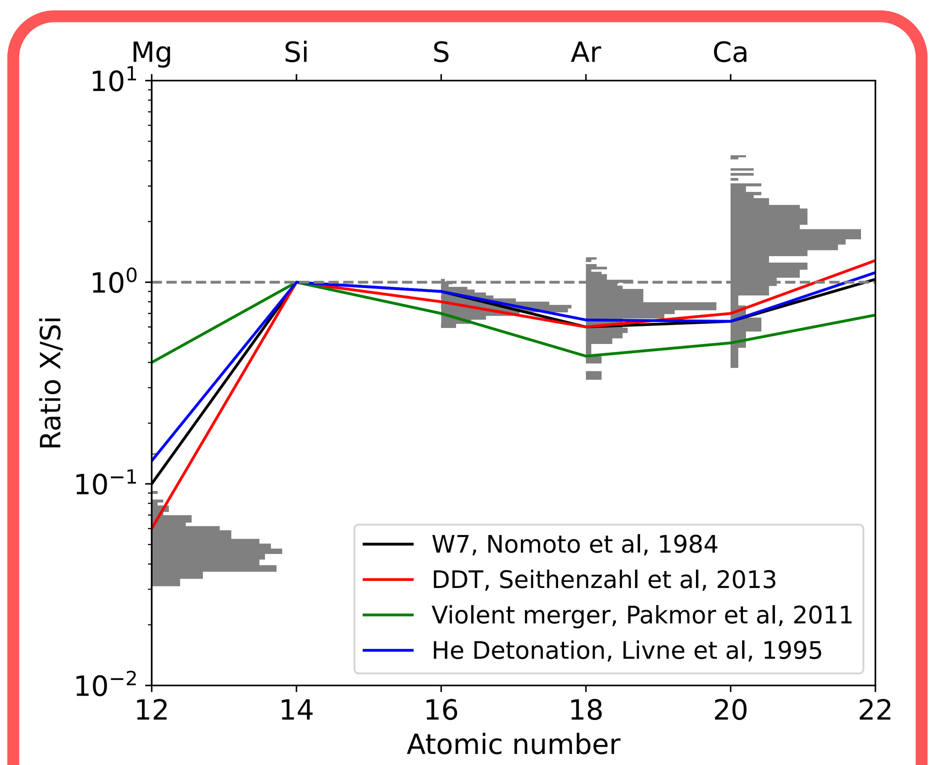
We detect and map for the first time the oxygen emission with a Gaussian component at 0.654 keV. It reveals an enhancement in the northeast.

This oxygen can be some ejecta heated by the reverse shock but coming from a different layer than the IMEs and iron group, hence their different morphology. Or it can be some surrounding medium heated by the forward shock, a feature whose presence in the Tycho's SNR has not yet found a consensus in the literature.

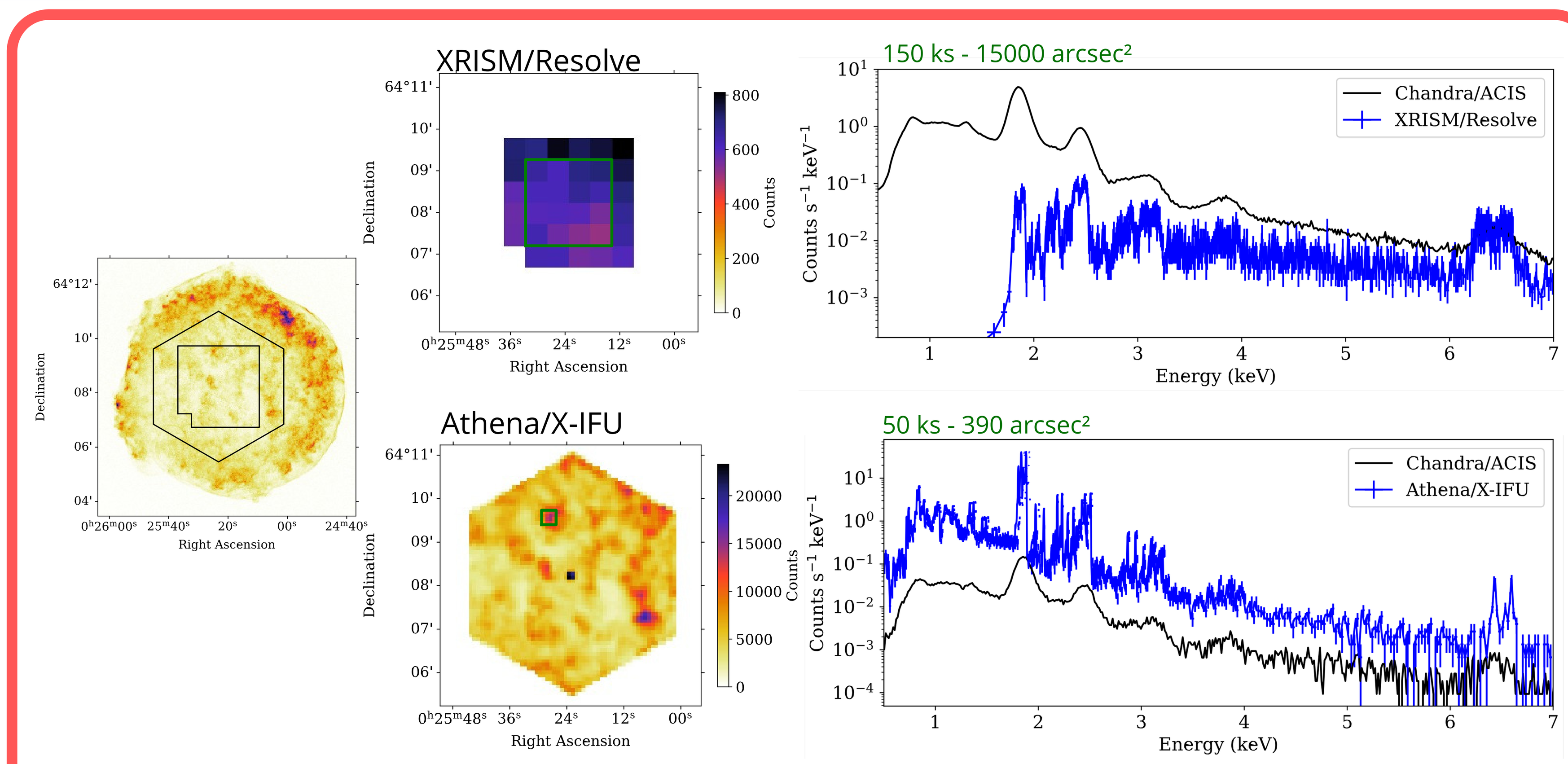


A banana- shaped anti-correlation between the temperature and ionization time was observed in several SNRs [5, 6]. Despite an intrinsic degeneracy between kT and τ, due to the limited spectral resolution of Chandra, our analysis reveals a clear anti-correlation which is statistically significant.

In addition, there is also a correlation with the position in the SNR. It seems to indicate a physical origin of this kT-τ relation associated to different plasma conditions and histories of the shocked ejecta.



We compare the abundances of Mg, S, Ar, and Ca with some Type Ia nucleosynthesis models. The values are consistent with the global yields expected for a thermonuclear supernova explosion. To discriminate the models, lighter and heavier element abundances would be useful. In the case of a delayed-detonation model [7], we favor an explosion with fewer than one hundred ignition points to reproduce the observed an-isotropic distribution of elements abundances.



This spatially resolved spectroscopic study will be very useful to prepare observations at high spectral resolution in the X-ray band with XRISM (X-Ray Imaging and Spectroscopy Mission, launched in 2023) and Athena (Advanced Telescope for High ENergy Astrophysics, scheduled for 2037). We used the SIXTE software [8] to simulate observations of Tycho's SNR as seen by XRISM/Resolve and Athena/X-IFU, revealing their amazing scientific potential. However, the spatial resolution of XRISM will not be as good as Chandra's, which will bring new challenges to the X-ray analysis, such as the spatial-spectral mixing (contamination of the spectra from neighboring regions). These simulations are essential to prepare the data analysis and disentagle this effect.

[1] Godinaud et al, 2023 ; [2] Millard et al, 2022 ; [3] Uchida et al, 2024 ; [4] Buchner et al, 2016 ; [5] Sun et al, 2019 ; [6] Williams et al, 2017 ; [7] Seitenzahl et al, 2013 ; [8] Dauser et al, 2019

Godinaud et al, 2023
Tycho's SNR 3D dynamics with innovative tools

Godinaud et al, 2024
Tycho's SNR spatially resolved spectroscopy