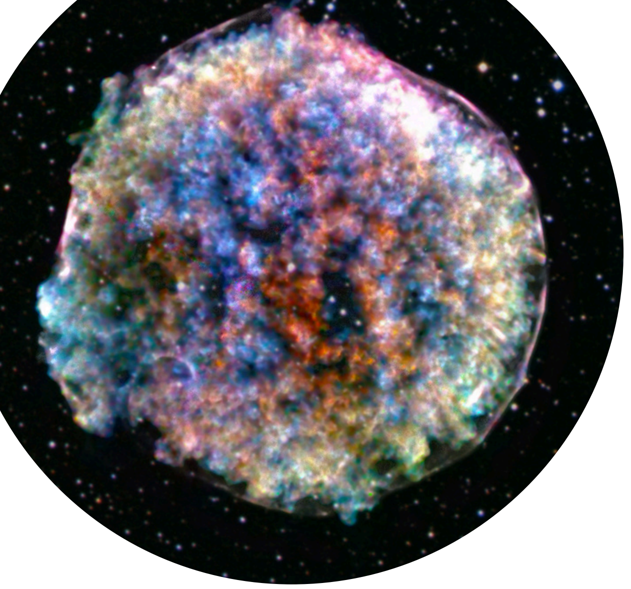
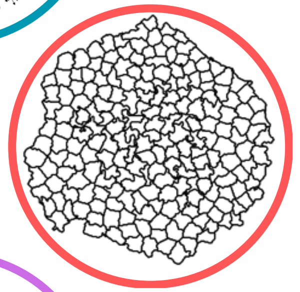
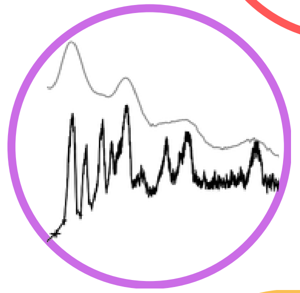


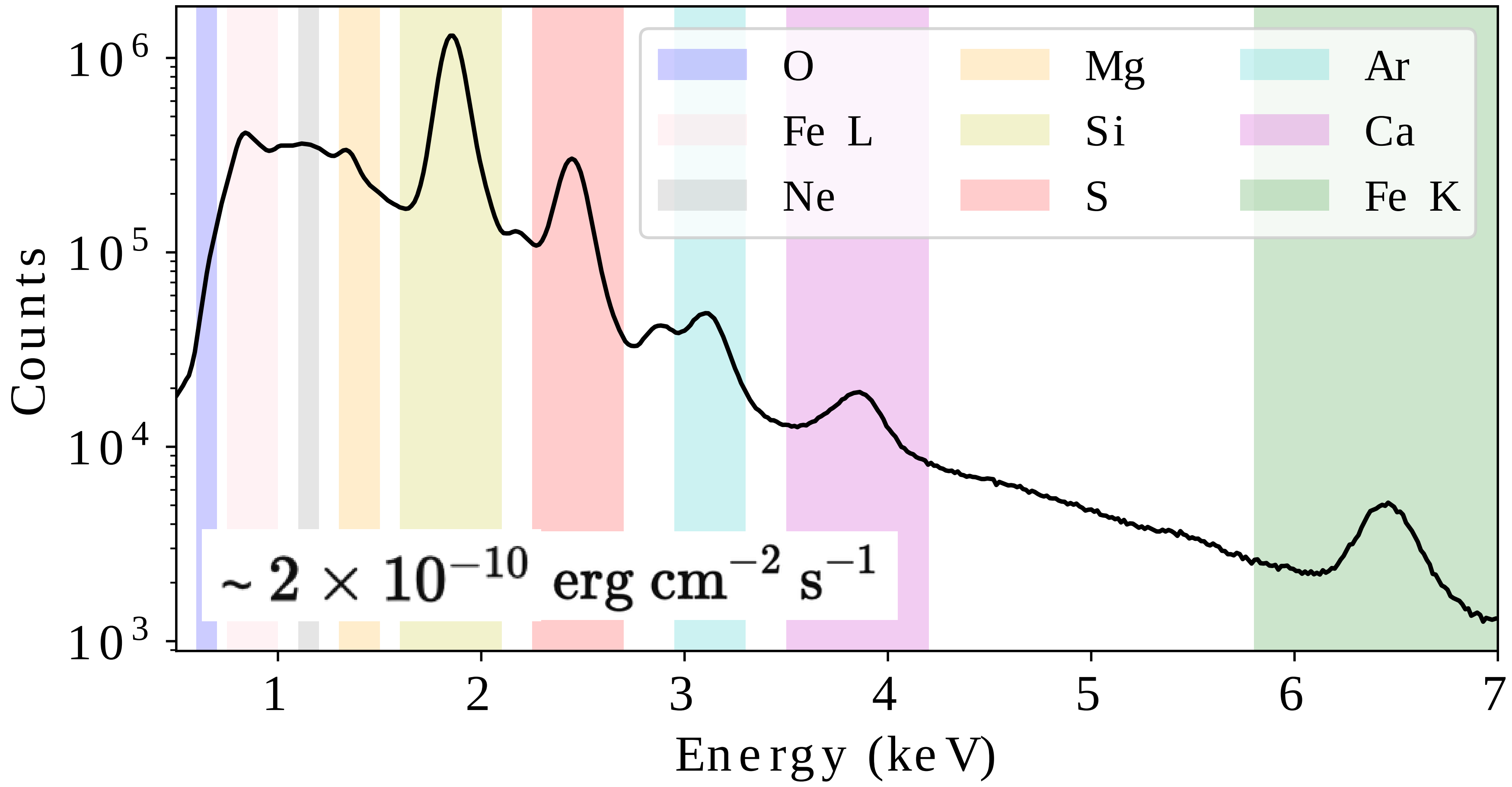

Tycho's SNR: Bayesian insights based on Chandra and XRISM Resolve data

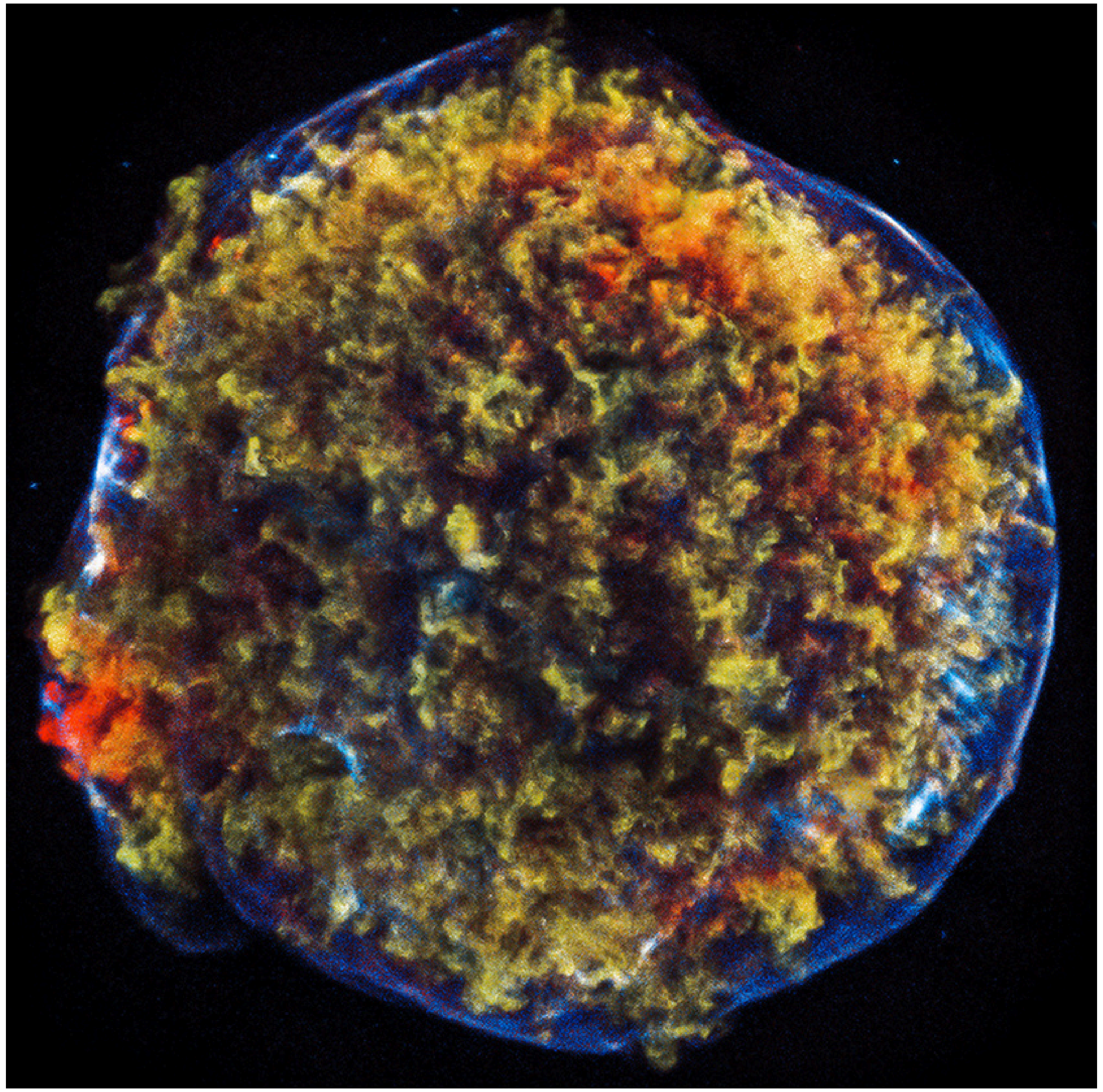
Leïla Godinaud *CEA Saclay - AIM*

Tycho's supernova remnant

- Explosion in 1572 observed and documented by Tycho Brahe
- Supernova thermonuclear (type Ia)
- Distance : ~ 3.5 kpc
- RA: 00h25m22.00s, Dec: +64d08'24.0"
- Size : 8 arcmin
- Observations with Chandra space telescope : more than 950 ks (~330 h) : 50 millions photons in the 2009 observations !

Chandra spectrum over the full extent of Tycho's SNR

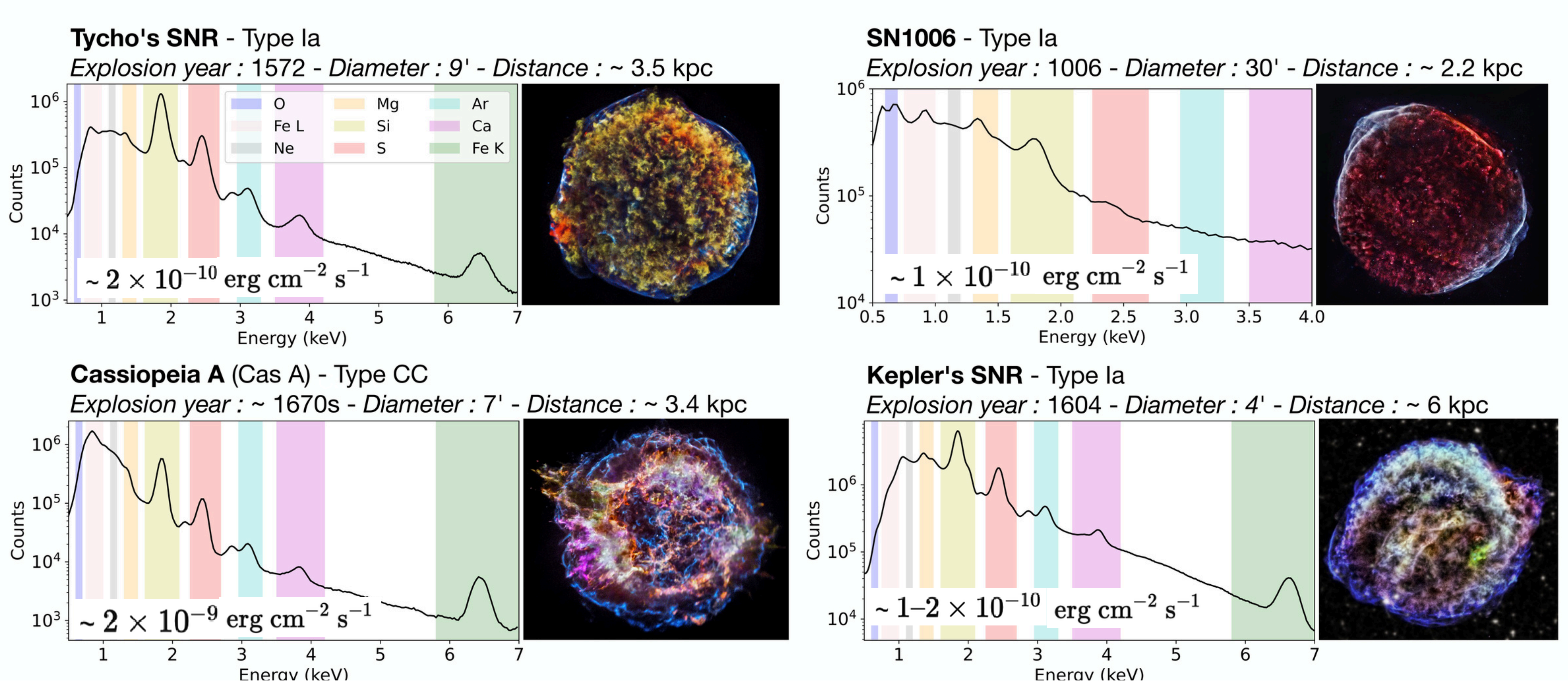




Credits: NASA/CXC

Composite image : synchrotron emission (*blue*), iron emission *(red)*, silicon and intermediate element emission *(green)*.

SNR panorama



Interest of Tycho's SNR as a Calibration Source

Pros:

- Bright source
- Prominent Si, S, and Fe emission lines
- No temporal variation
- Relatively homogeneous physical properties across the SNR

Cons:

- Extended source
- Relatively homogeneous physical properties across the SNR

3D dynamics

Related article for this section: Godinaud et al, 2023,

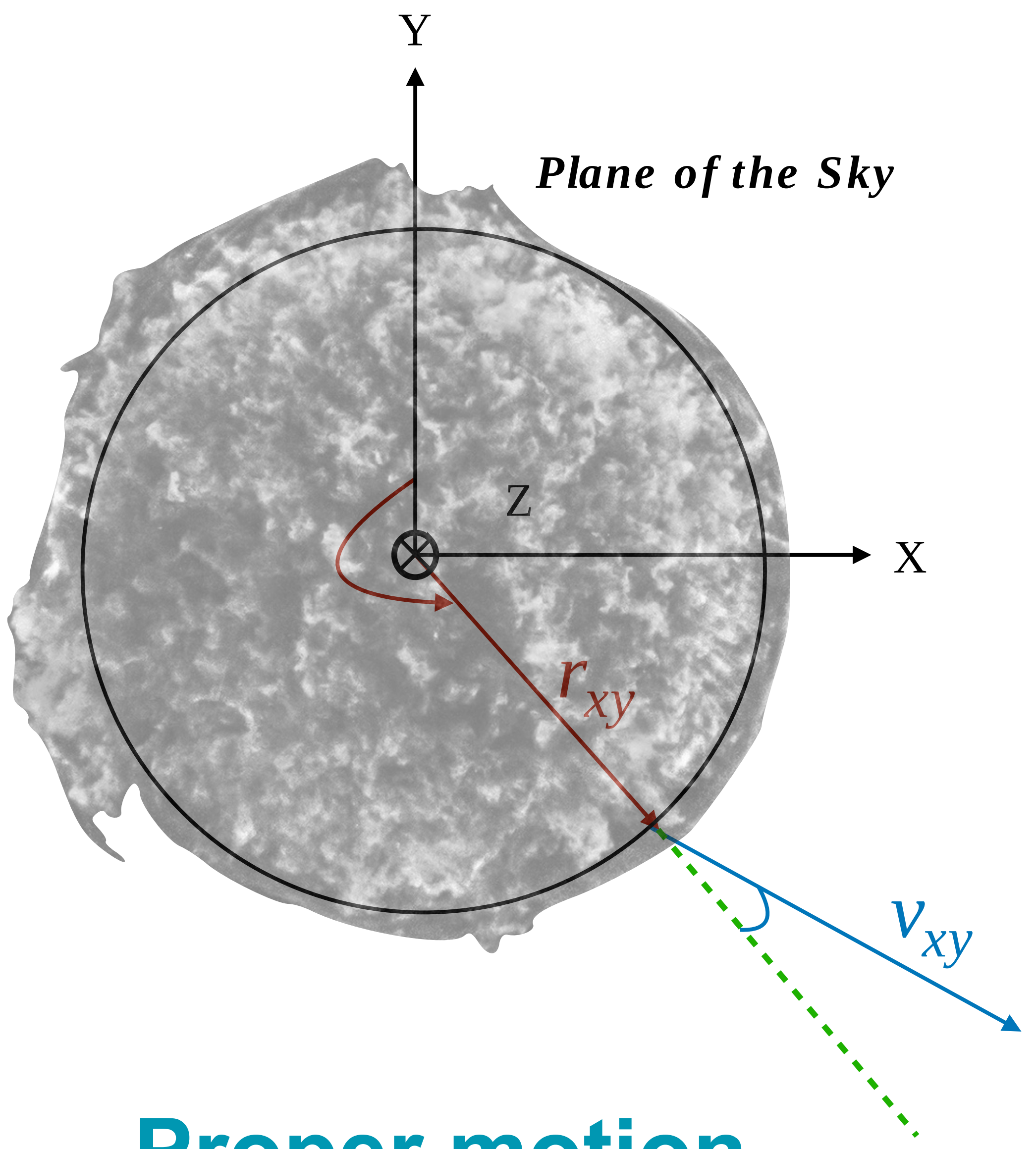
Astronomy & Astrophysics, Volume 680, id.A80, 18 pp.

3D dynamics principle

3D (x, y, z)

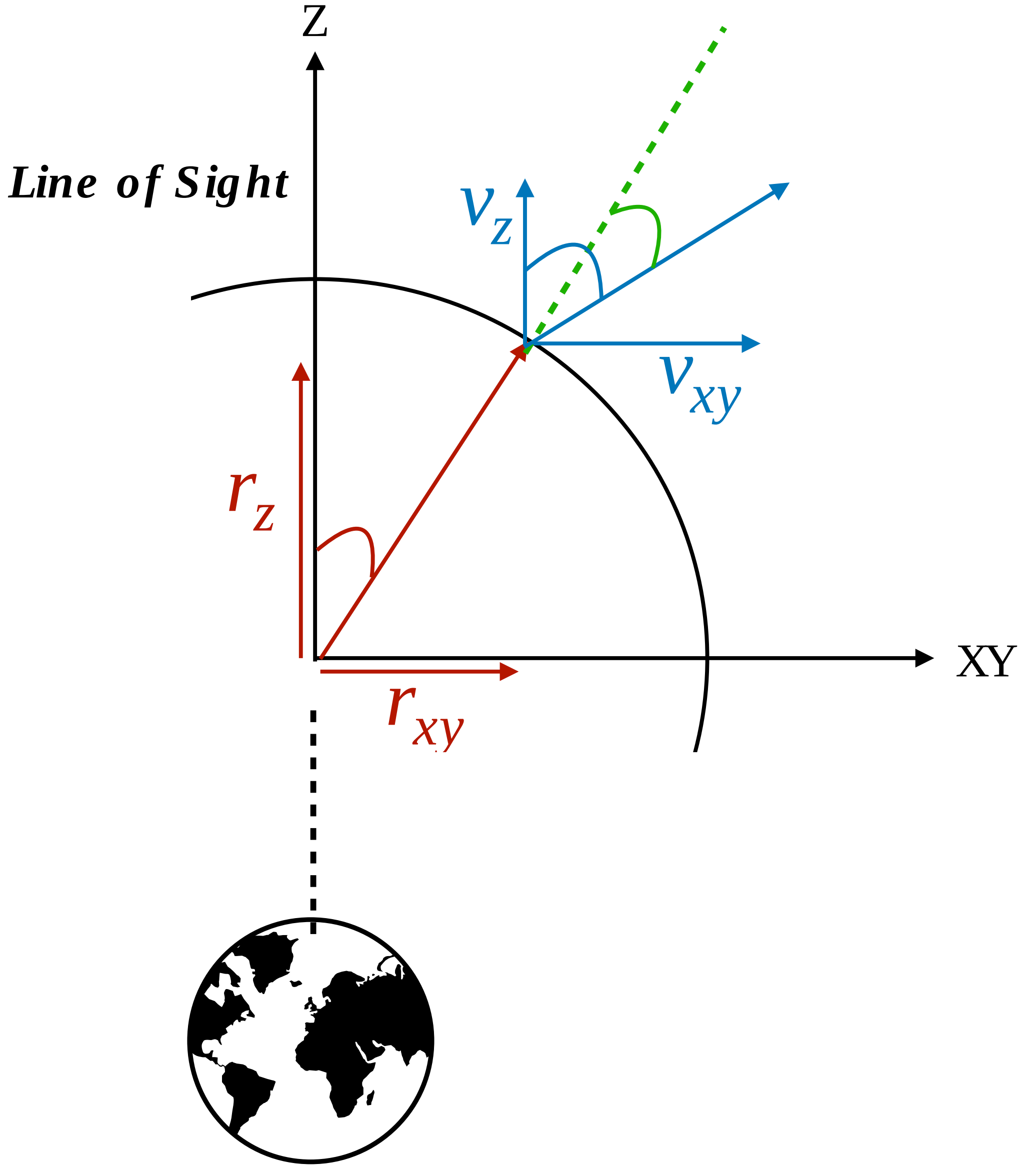
Plane of the Sky : Vxy

Line of Sight: Vz



Proper motion

Two separate studies

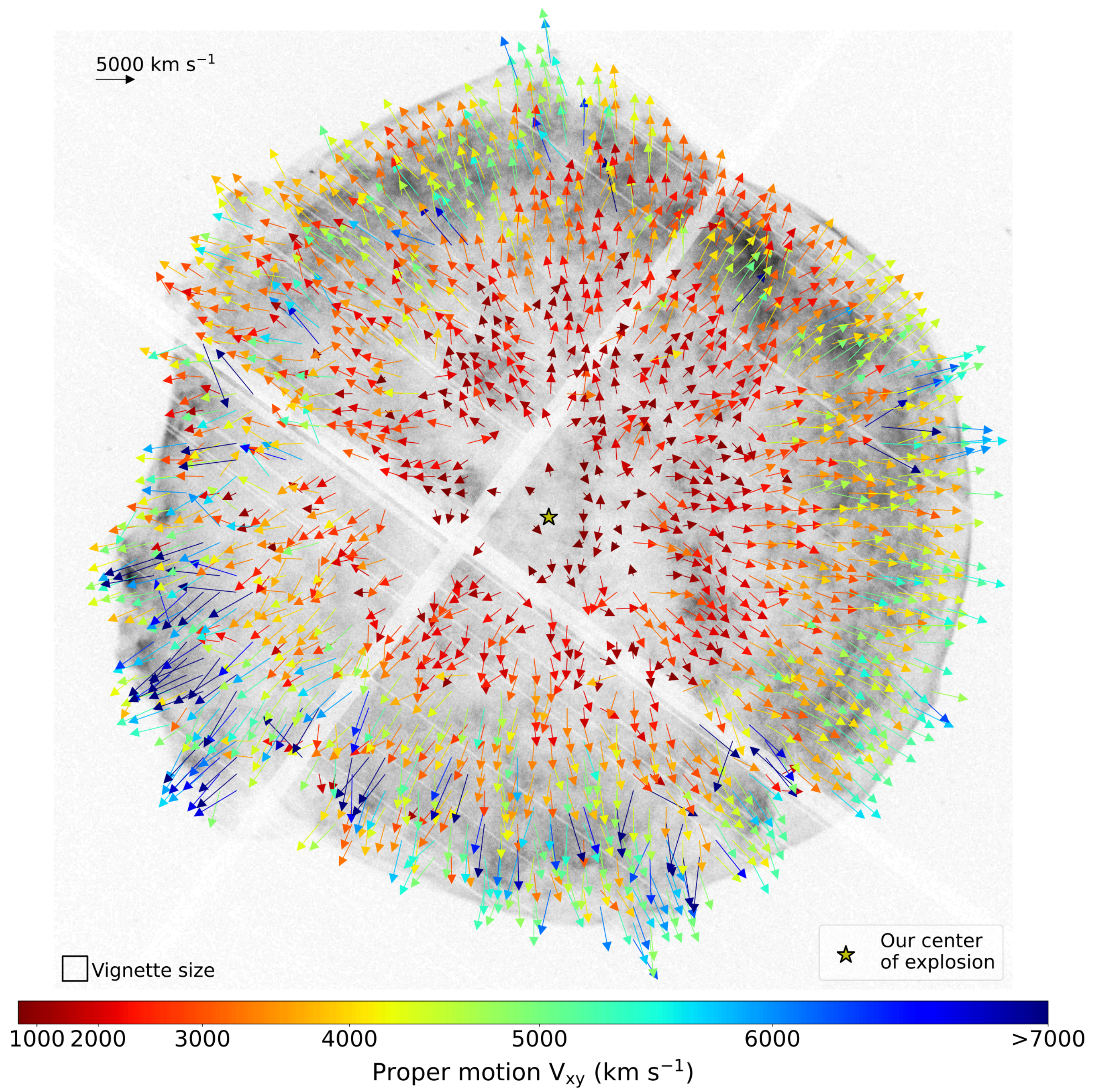


Doppler velocity

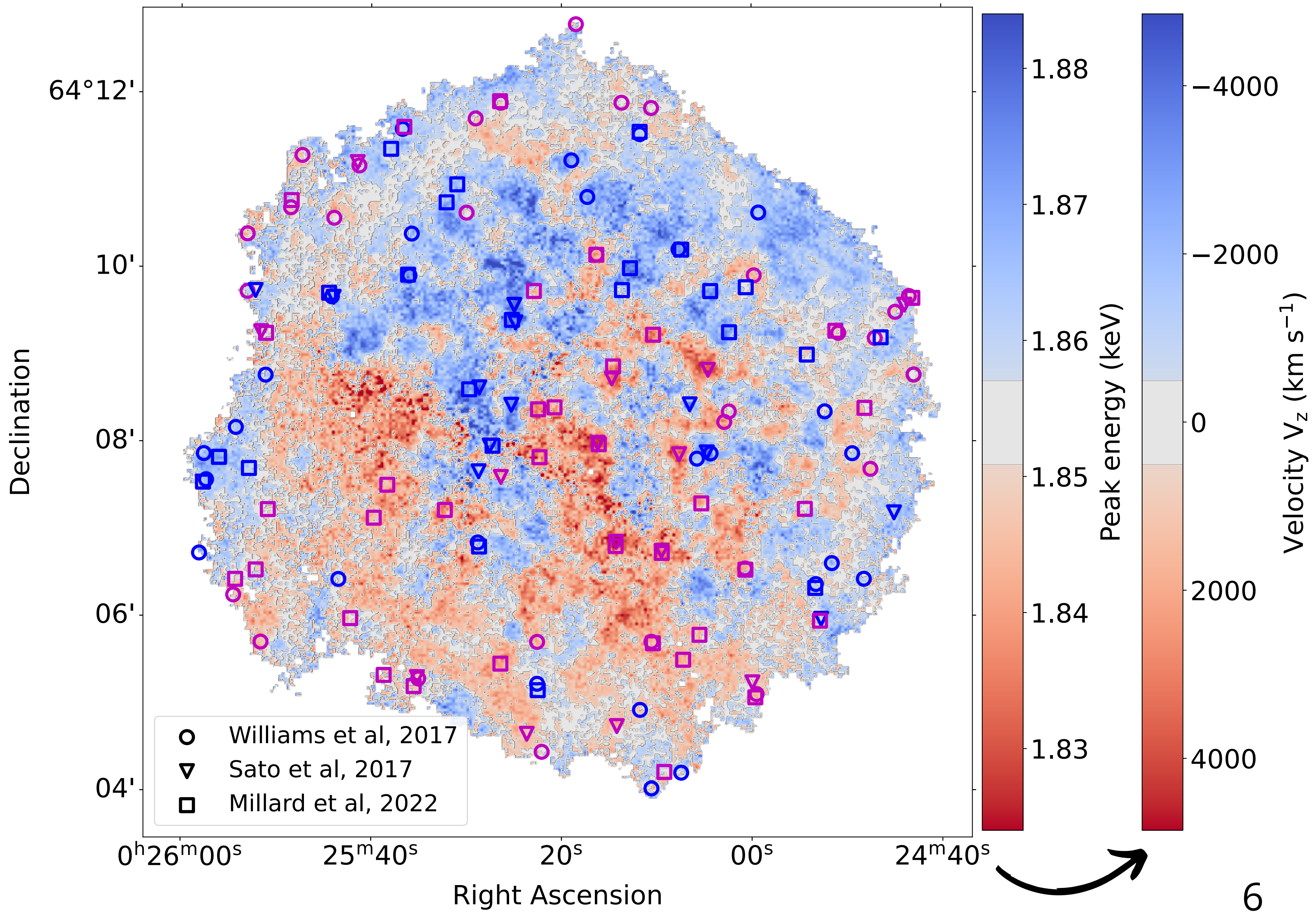
Tycho's SNR 3D dynamics

3D (x, y, z)

Plane of the Sky : Vxy
Proper motion

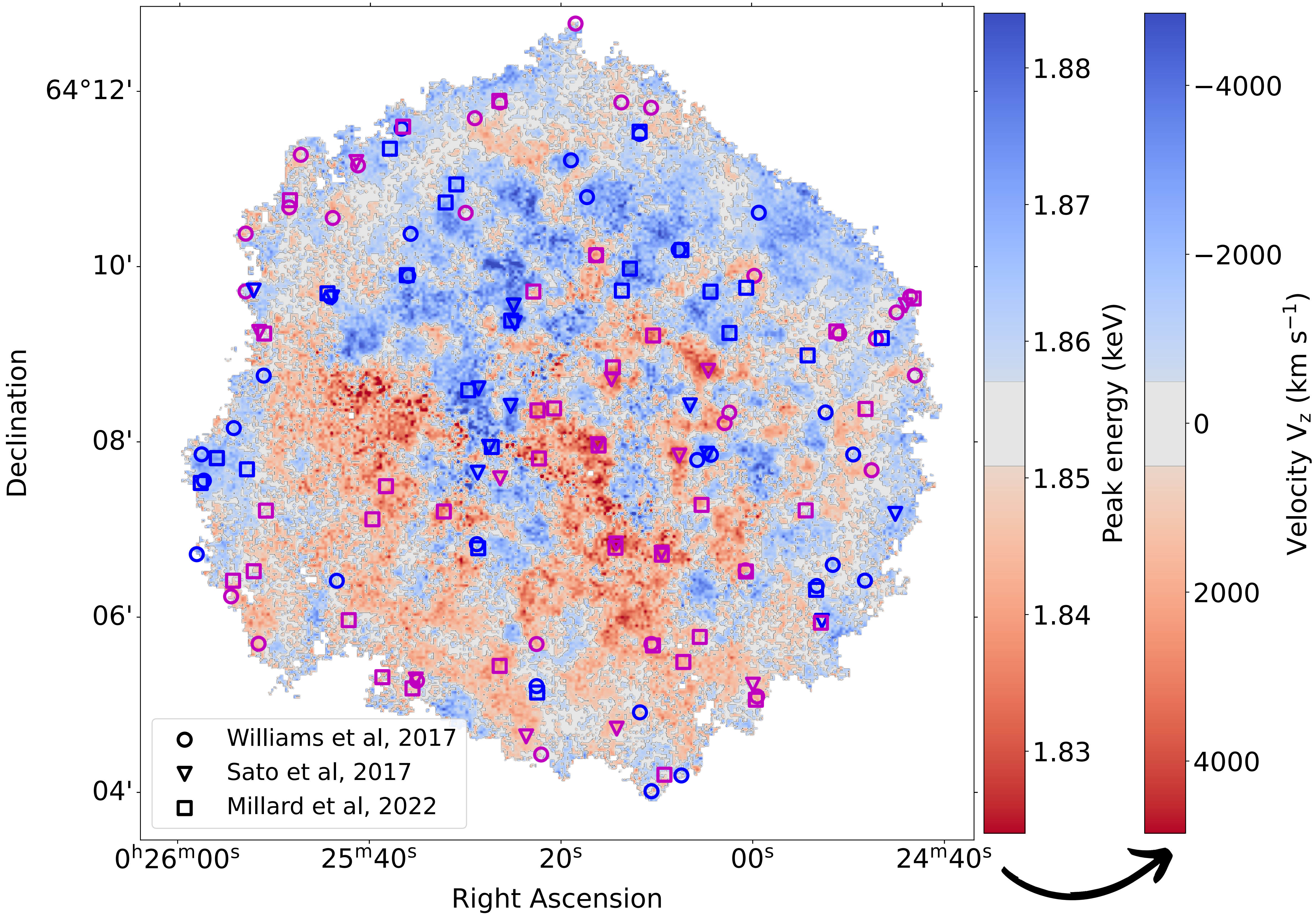


Line of Sight: Vz
Doppler velocity



$$v_z = \frac{E_c - E_{ref}}{E_{ref}} c$$

Position of the Si line

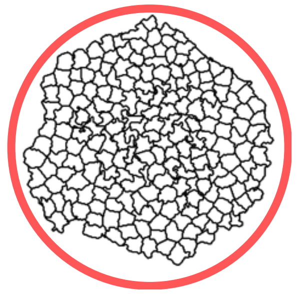


$$v_z = \frac{E_c - E_{ref}}{E_{ref}} c$$

- **Reconstruction of the Si peak energy map** using a decomposition + reconstruction of the data cube
- If we suppose one energy at rest, we can obtain Doppler velocity map

- Full coverage of the SNR at **2" resolution**
- Consistent with previous local studies

- **Clear North/South asymmetry** whose origin is unexplained



Physical mapping

Related article for this section: Godinaud et al, 2025

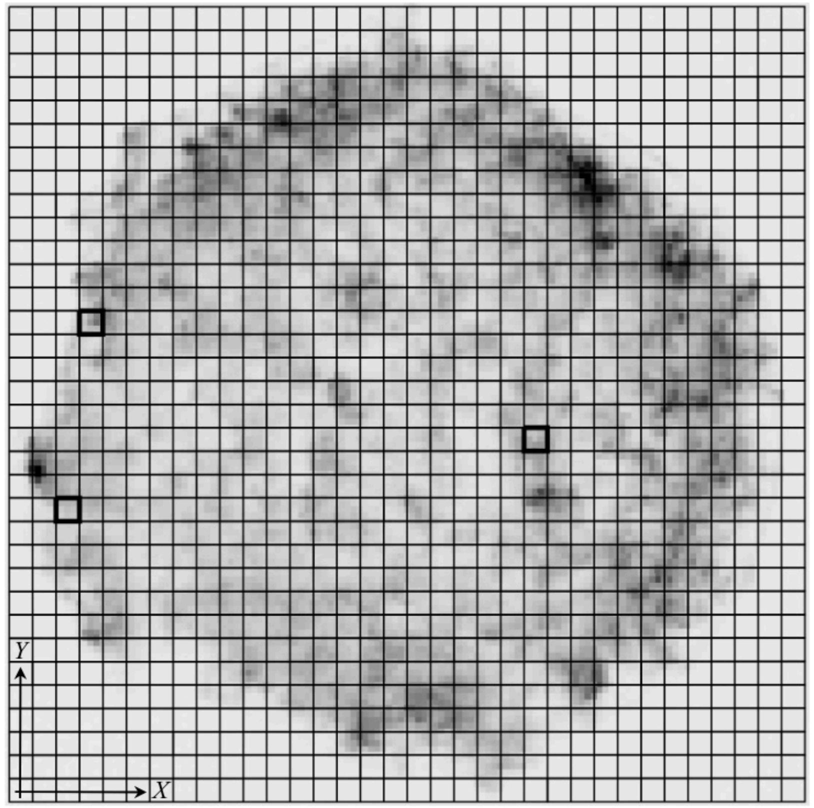
Astronomy & Astrophysics, Volume 693, id.A234, 20 pp.

Segmentation

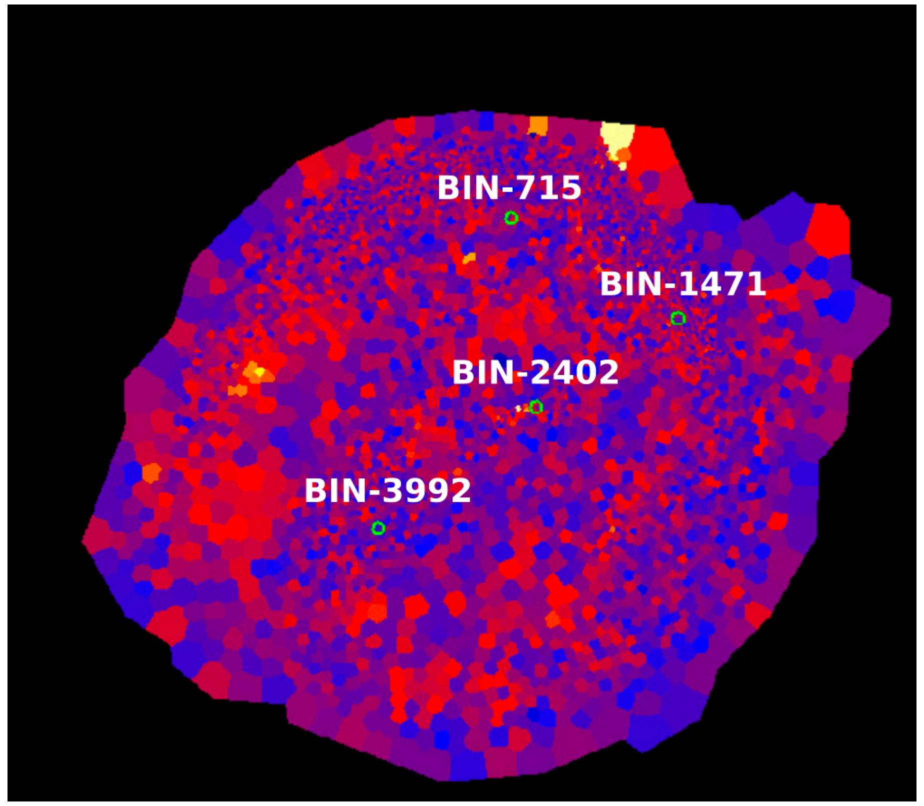
Two binning strategies used in the literature:

Cartesian grid

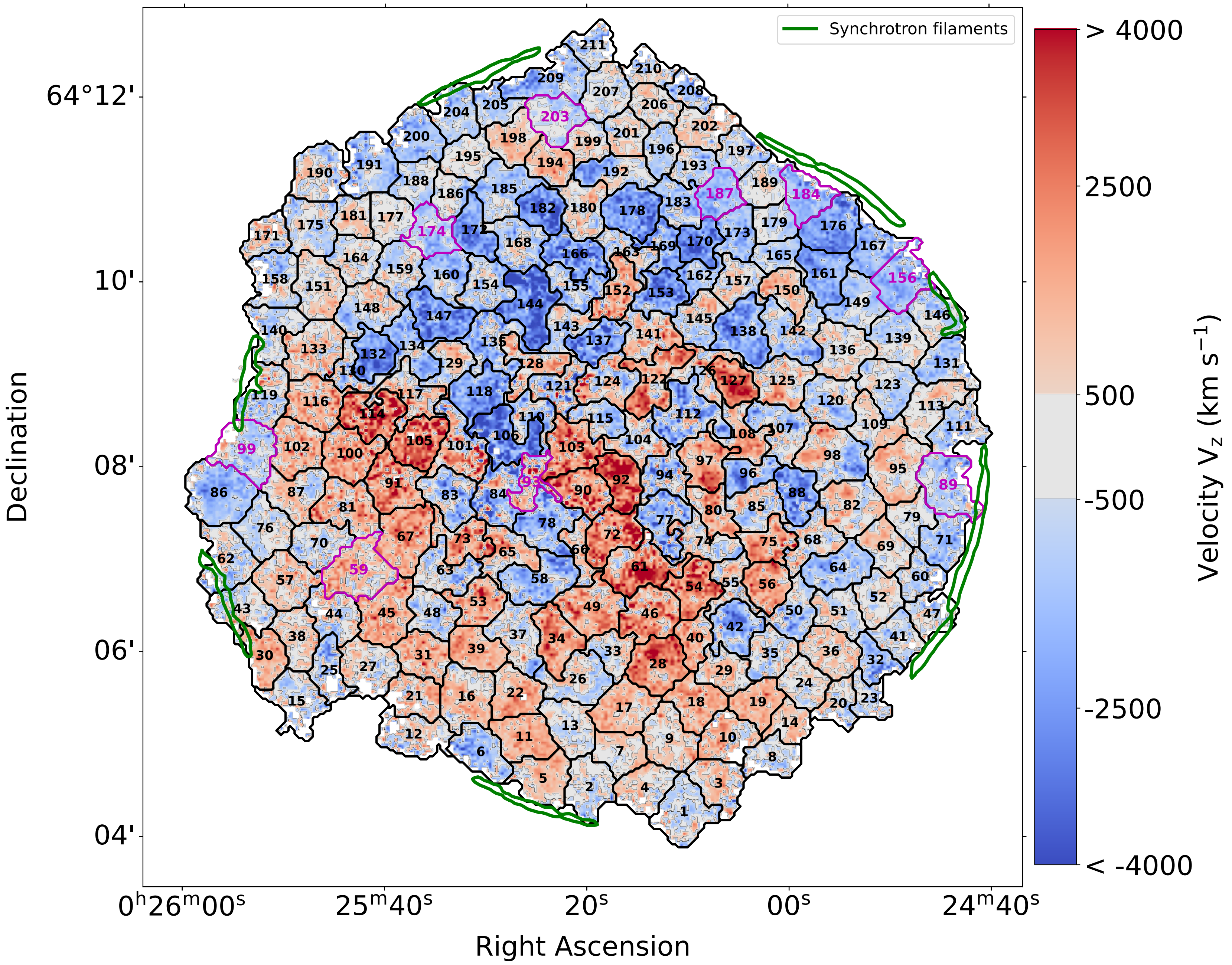
Adaptive binning to keep constant number of counts



Uchida et al, 2024

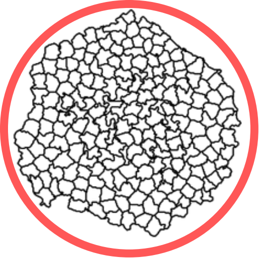


Sun et al, 2019



We choose an adaptive segmentation based on our Vz maps, to keep homogenous Vz values in each of the **211 regions**

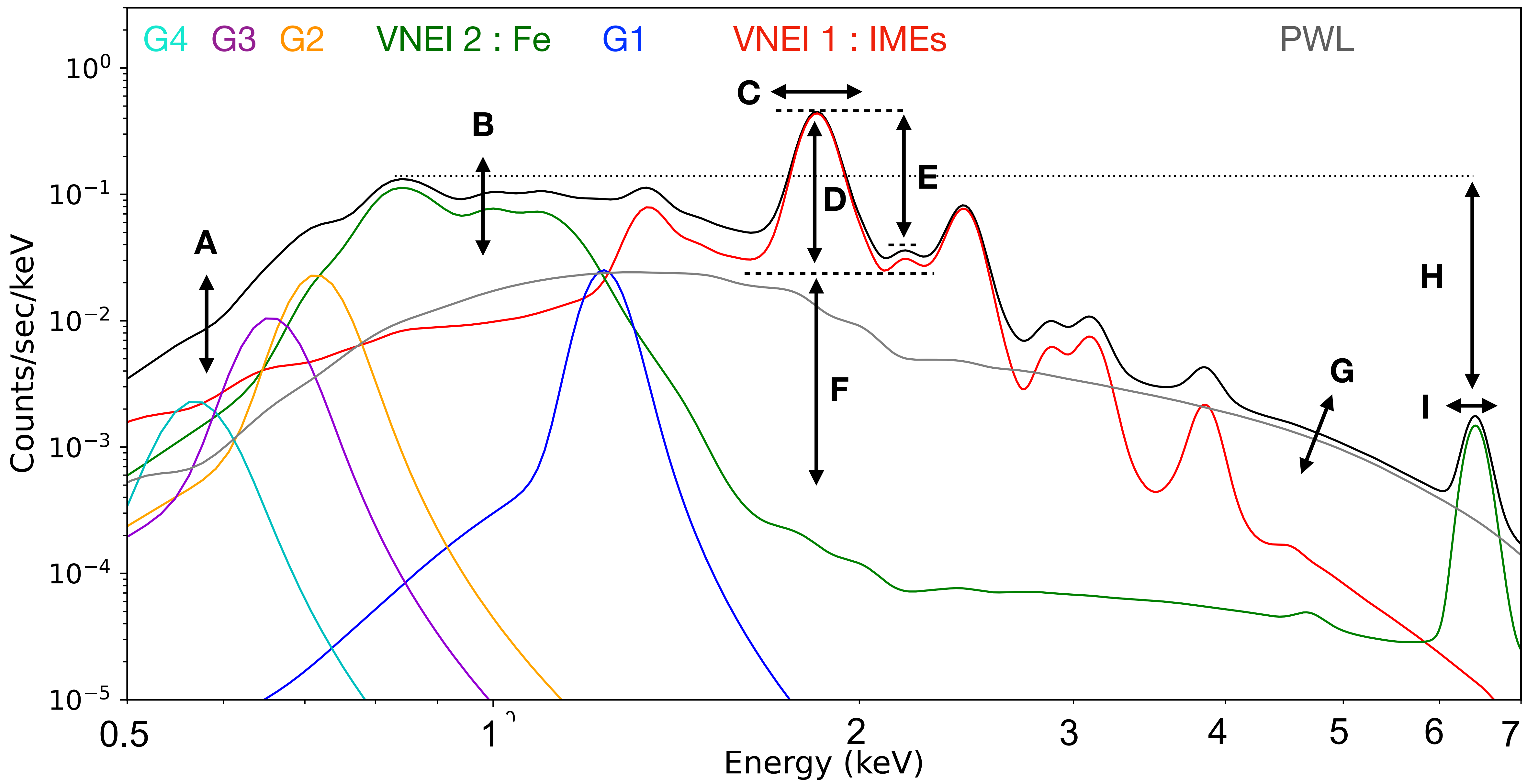
In average 2e+5 photons in each region



Model

- **One model to reproduce all the broadband properties across the full extent of the SNR**
- Challenge to constrain it then, there are a lot of degeneracies

→ 19 free parameters !

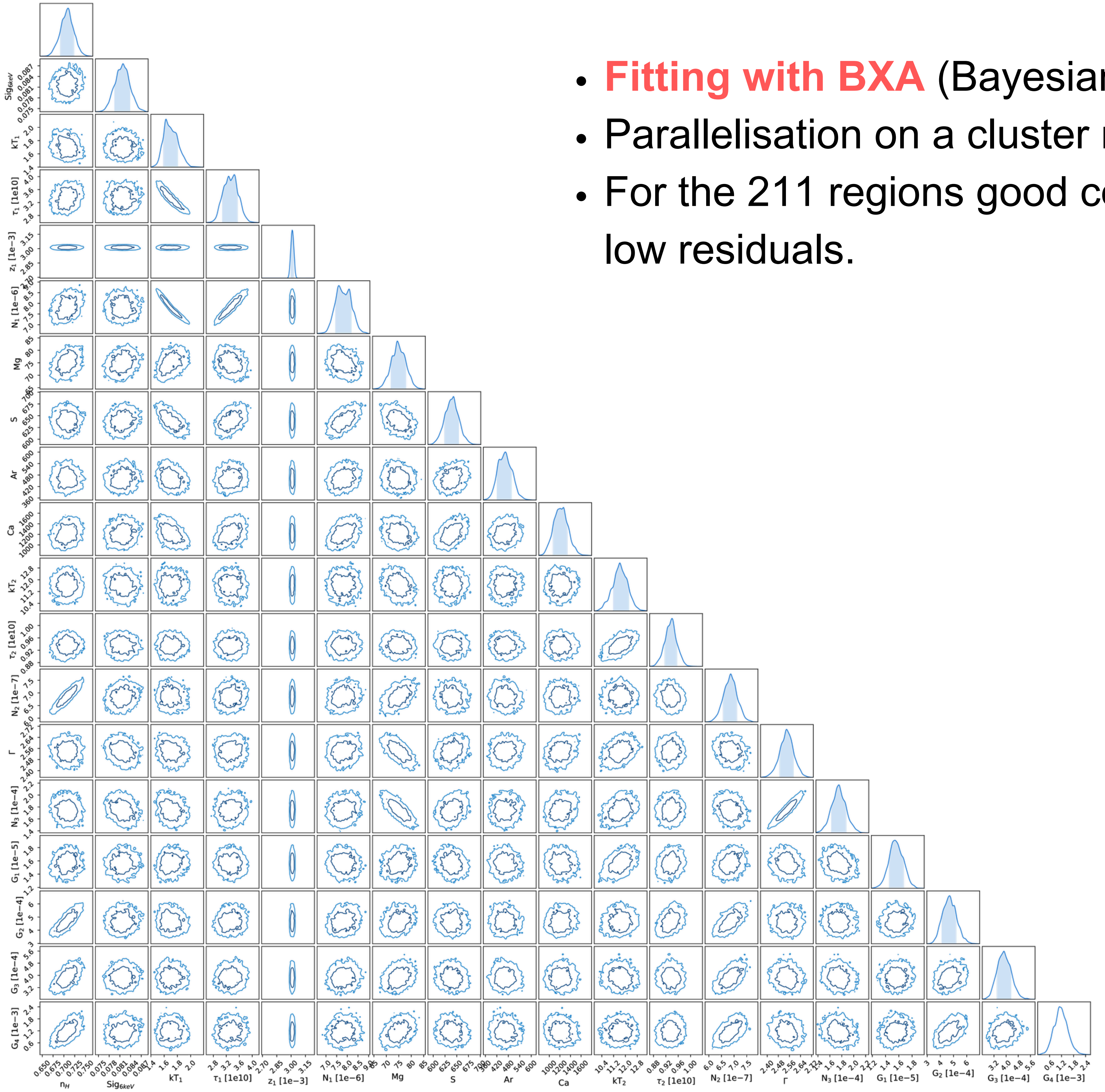


A : abs, norm G2, G3, G4 & VNEI 1
B : norm VNEI 2, pwl & VNEI 1
C : z1, kT1, tau1
D : abund Si
E : kT1, tau1
F : norm VNEI 1 & pwl, kT1, tau1
G : norm & index pwl
H : kT2, tau2, abund Fe
I : z2, kT2, tau2

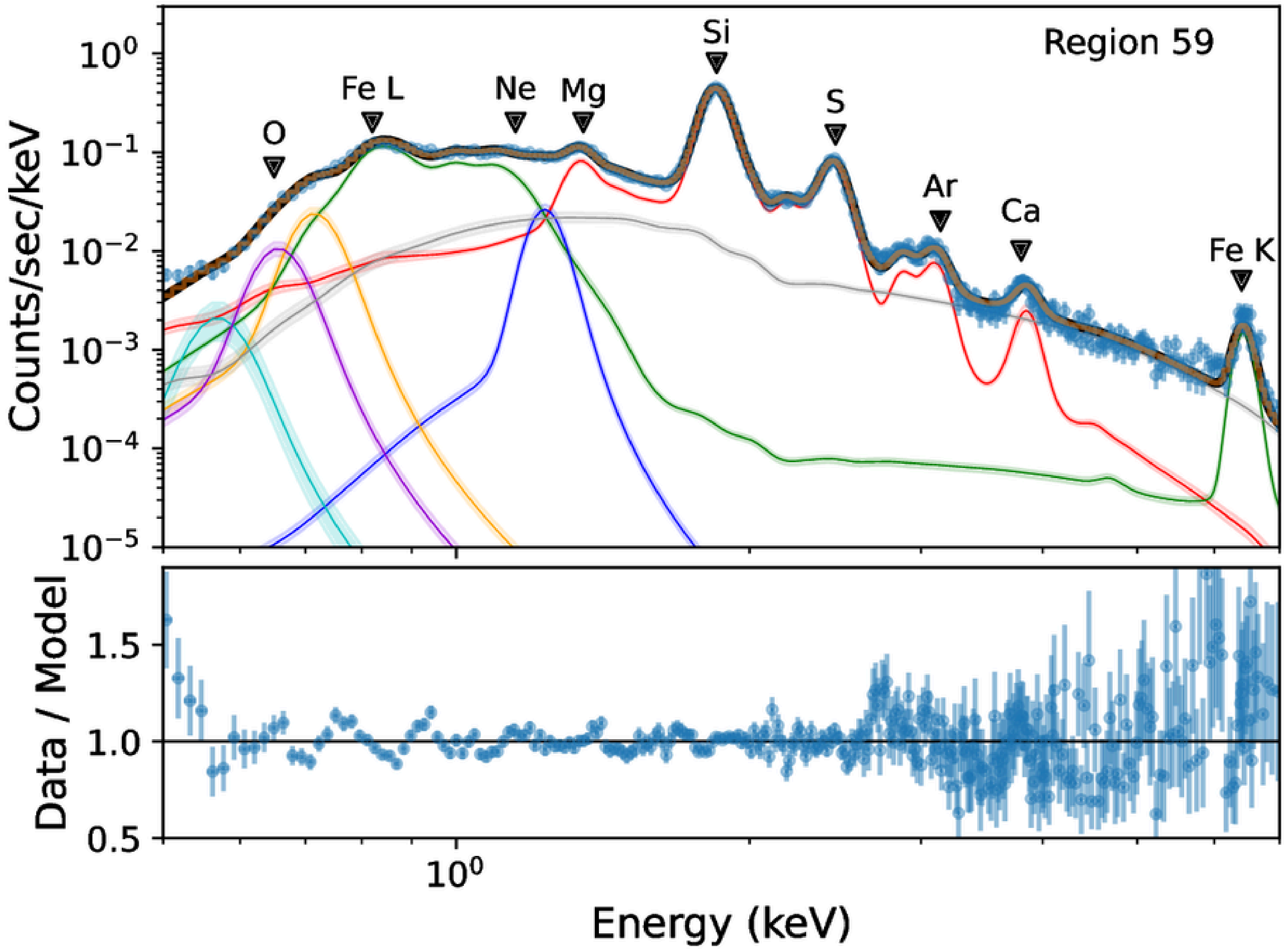
$$Tbabs\ [gsmooth\ [VNEI_{IMEs} + VNEI_{Fe} + zgauss_{G1} + zgauss_{G2} + zgauss_{G3} + zgauss_{G4}] + powerlaw]$$

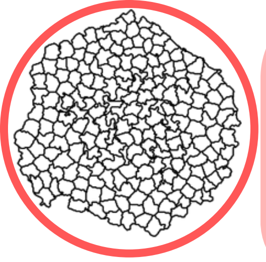
- *Tbabs*: External absorption
- *gsmooth*: Lines broadening
- $VNEI_{IMEs}$: **Thermal component for IMEs ejecta**
- $VNEI_{Fe}$: **Thermal component for Fe-rich ejecta**
- $zgauss_{G1}$ … $zgauss_{G4}$: 4 gaussian lines for residuals
- *powerlaw*: **Synchrotron continuum**

Fitting protocol



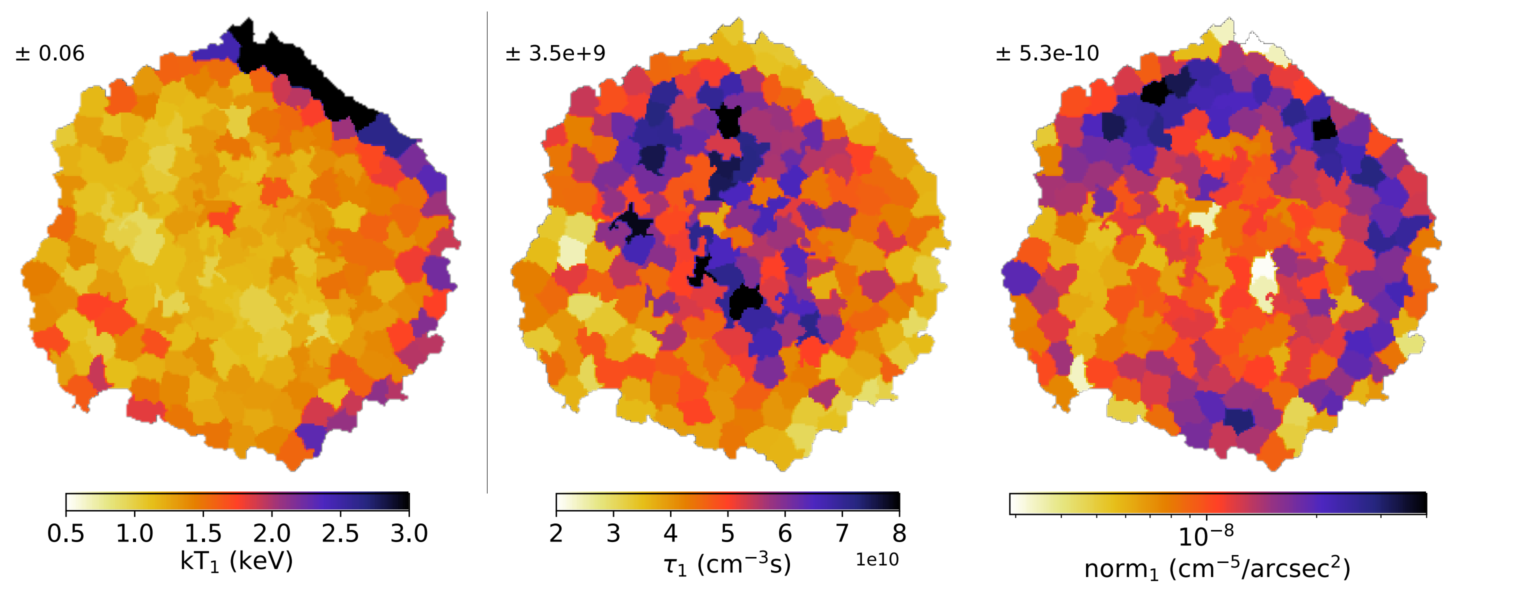
- **Fitting with BXA** (Bayesian X-rays Analysis using Nested Sampling).
- Parallelisation on a cluster necessary.
- For the 211 regions good constraints of the posterior distribution and low residuals.



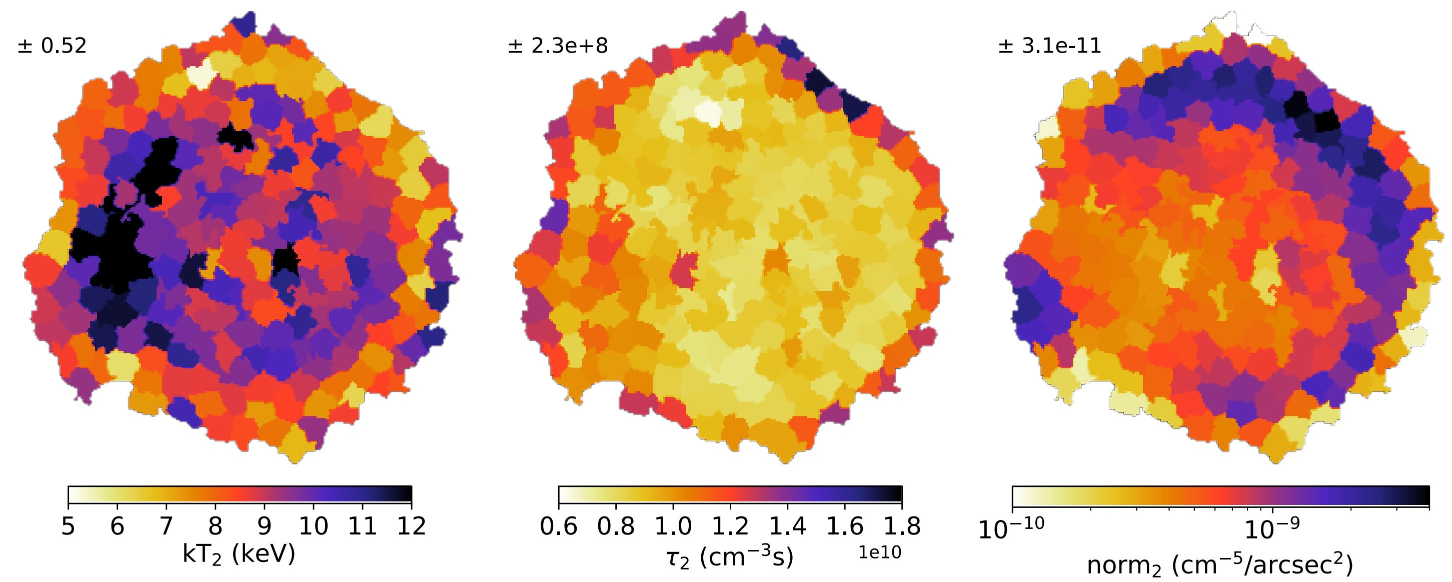


The 19 maps

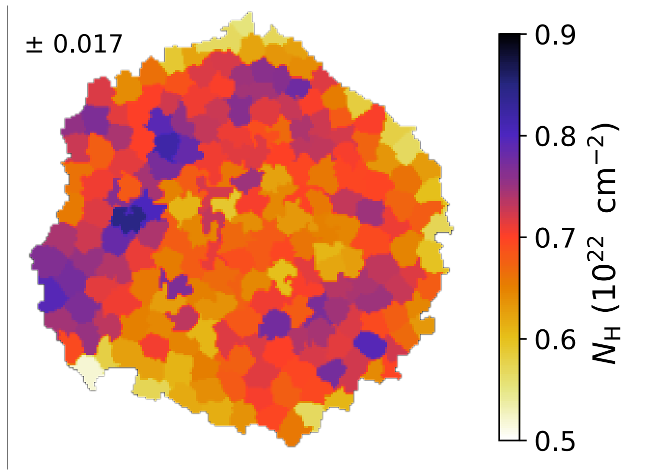
Thermal component for IMEs



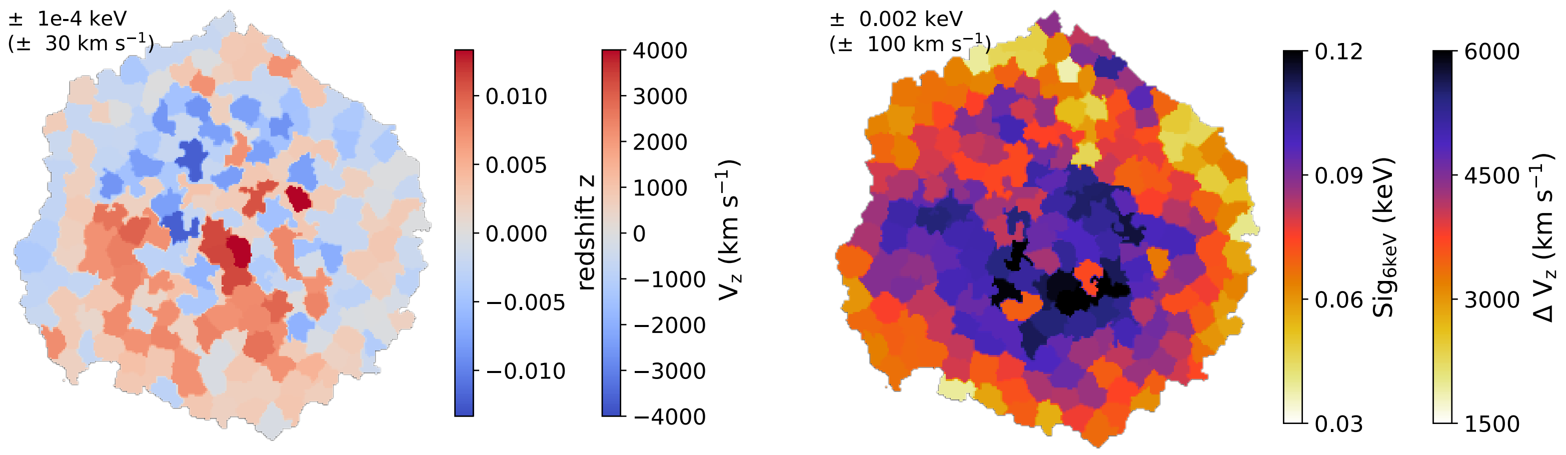
Thermal component for Fe



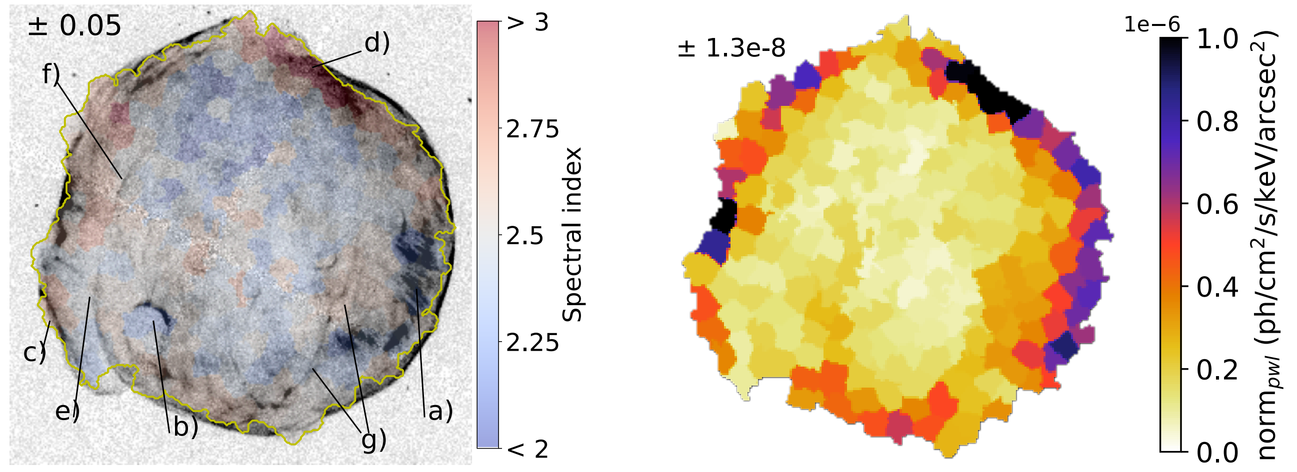
Absorption



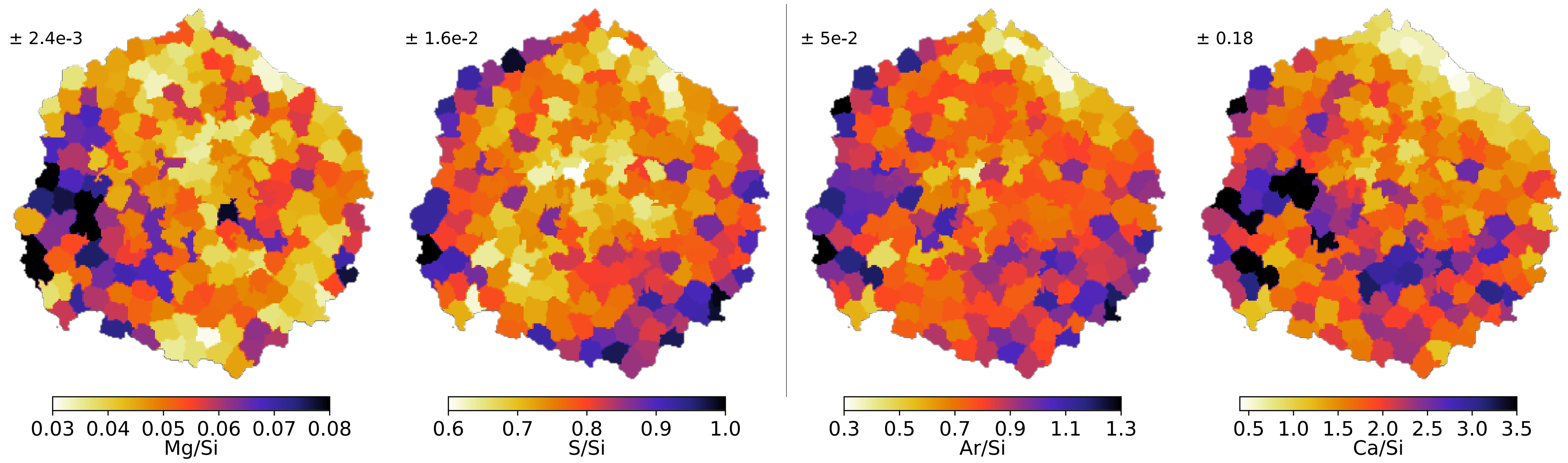
Dynamics : redshift and broadening



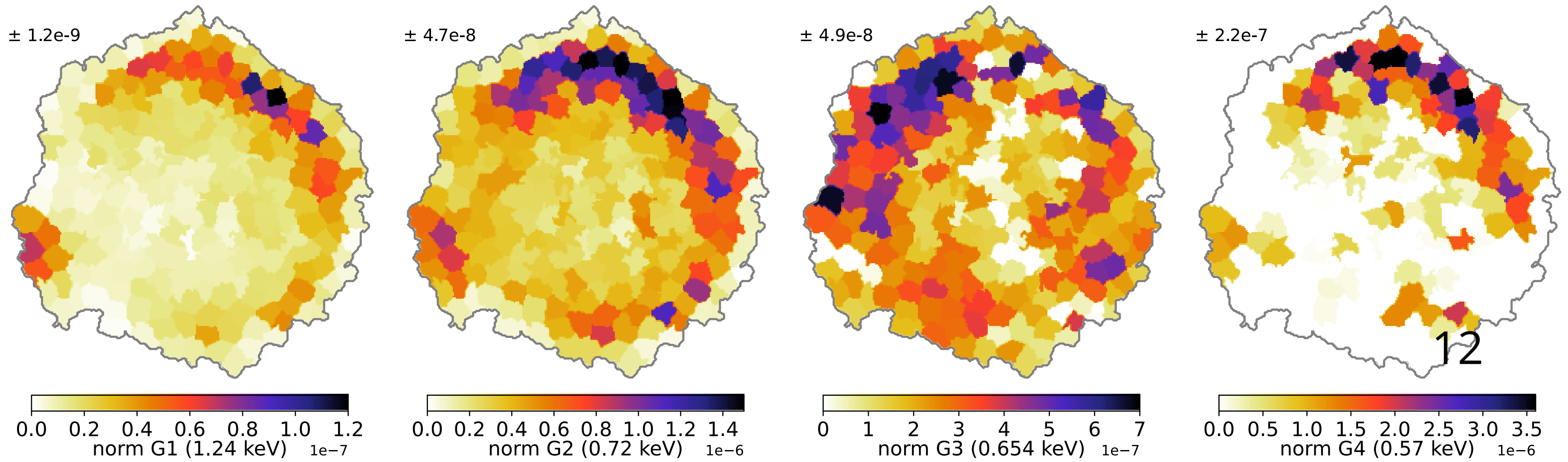
Power law for synchrotron emission



Abundances : Mg/Si, S/Si, Ca/Si & Ar/Si

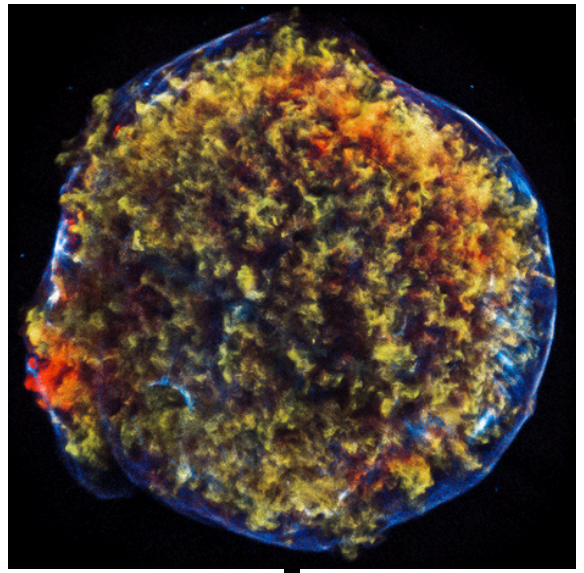


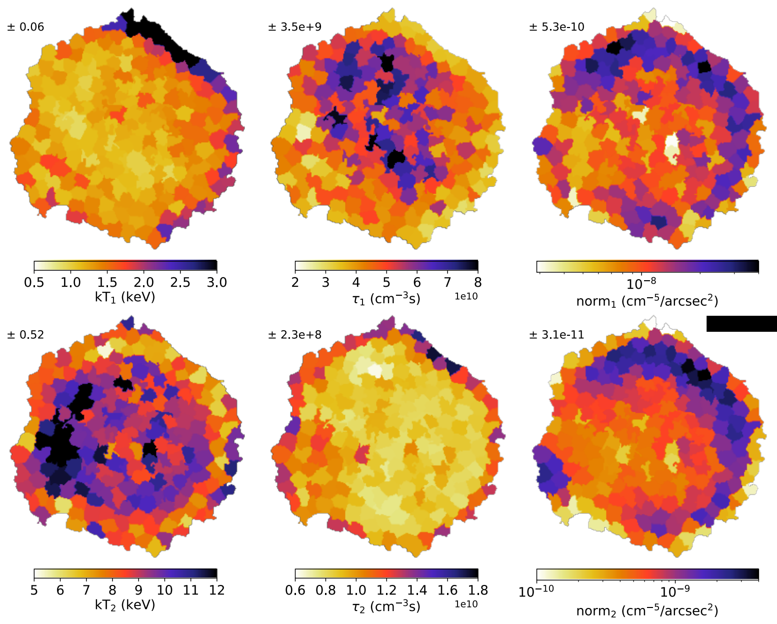
Gaussians : G1, G2, G3 & G4



SIXTE observations simulations

Chandra flux image of Tycho's SNR



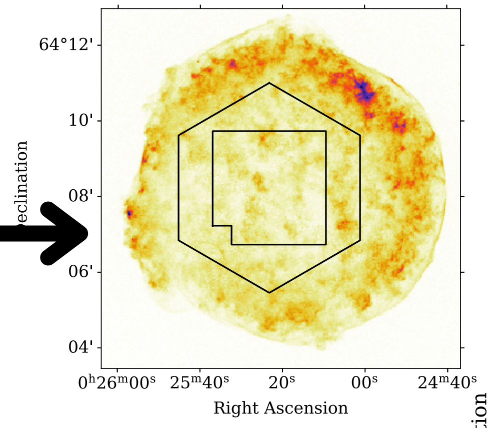


The 19 maps and a more advanced model

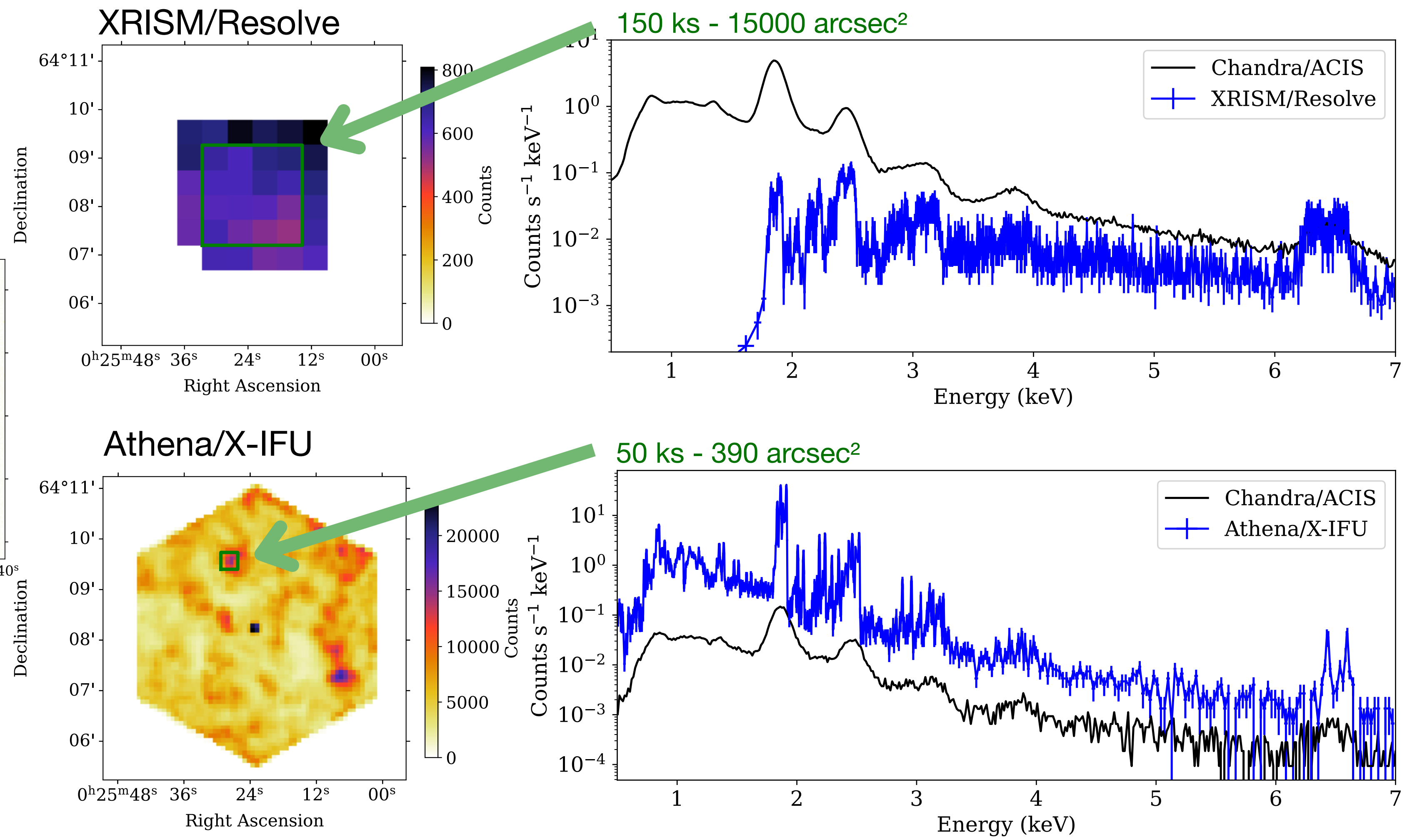
SIXTE (Simulation X-rays Telescope) software

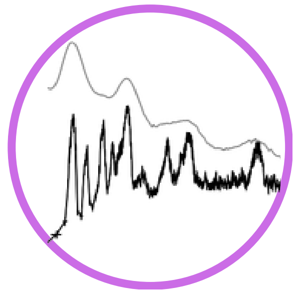
Dauser et al, 2019

Equivalent to 211 Xspec models !



Realistic simulations of observations with XRISM/Resolve and NewAthena/X-IFU

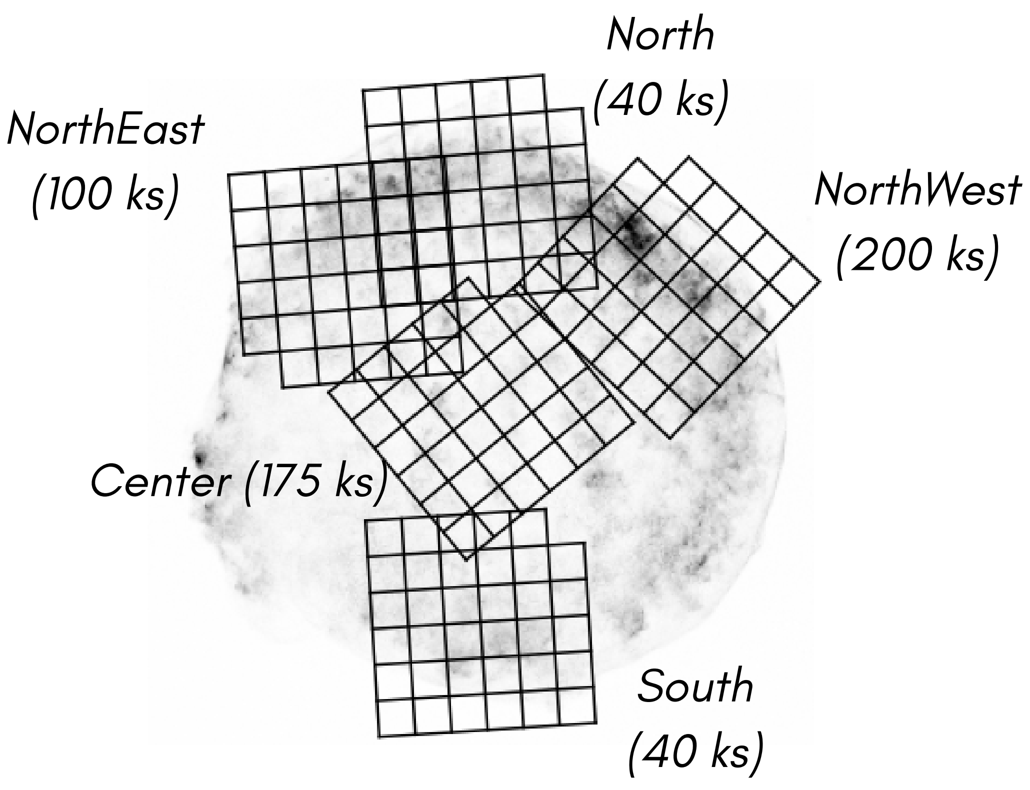




High resolution spectroscopy

Related article for this section: Godinaud et al, 2026 (to be submitted soon)

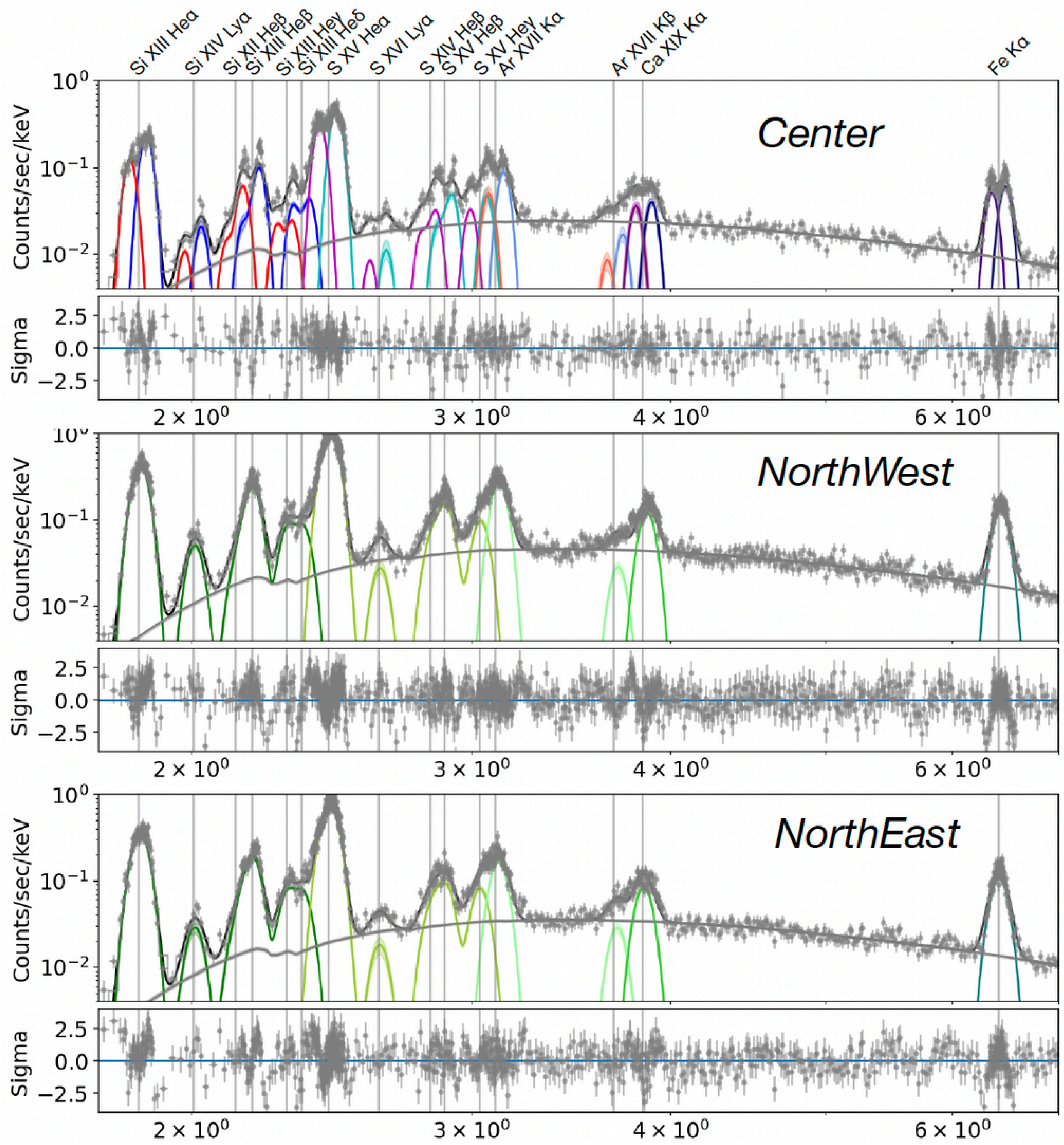
XRISM/Resolve data for Tycho's SNR



- 5 pointings from PV and AO1.
- Clear separation of the front and back emission toward the center of the SNR.

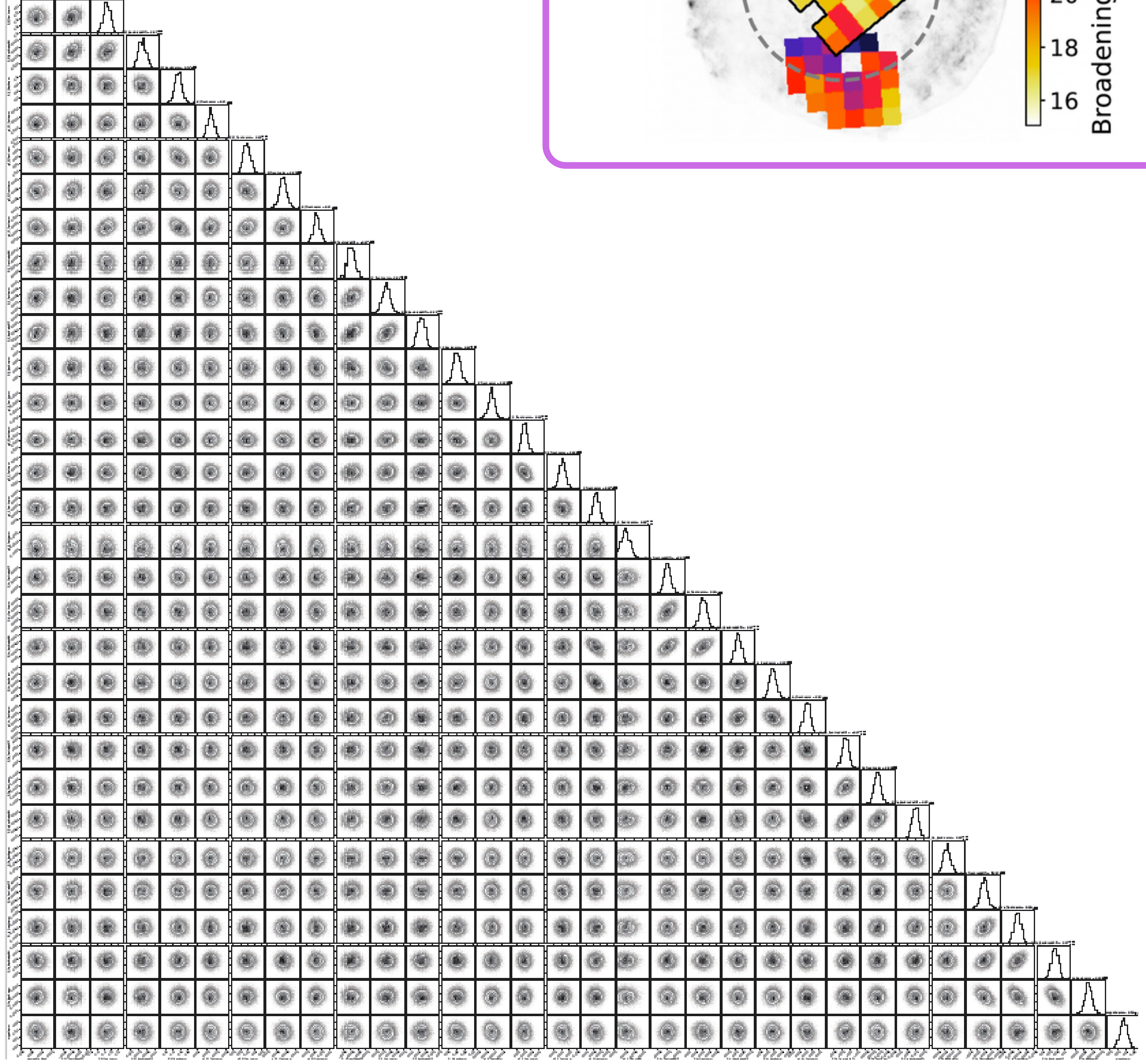
My work:

- Pixel level analysis: 150 high resolution spectra fitted !
- A Gaussian line model to reduce the computing time (still 1 week is needed for the analysis to run).

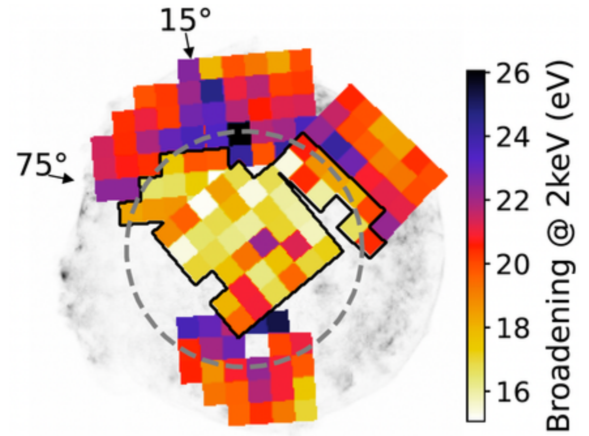


Front and back properties of Tycho's SNR per element

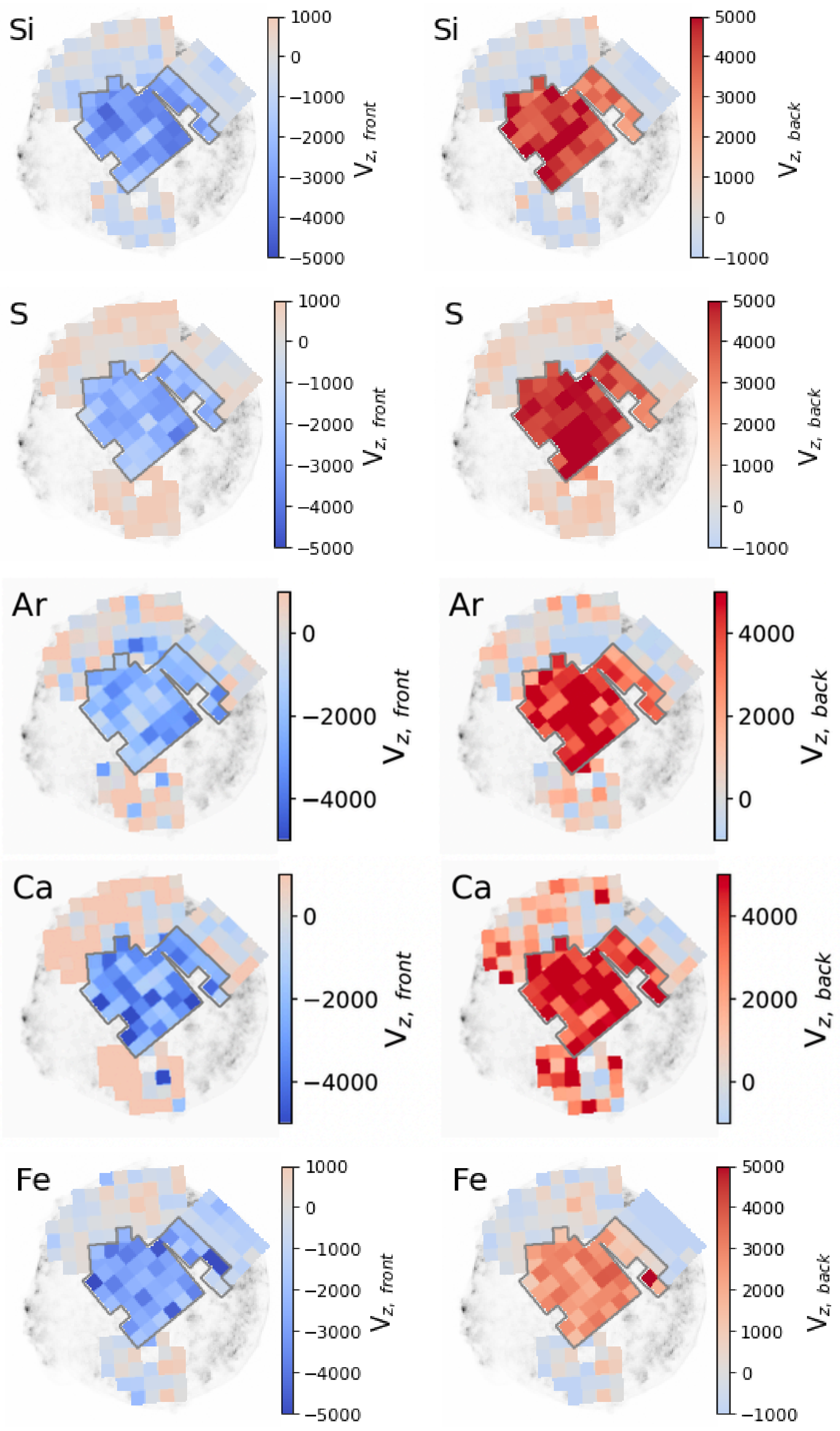
BXA fitting tool



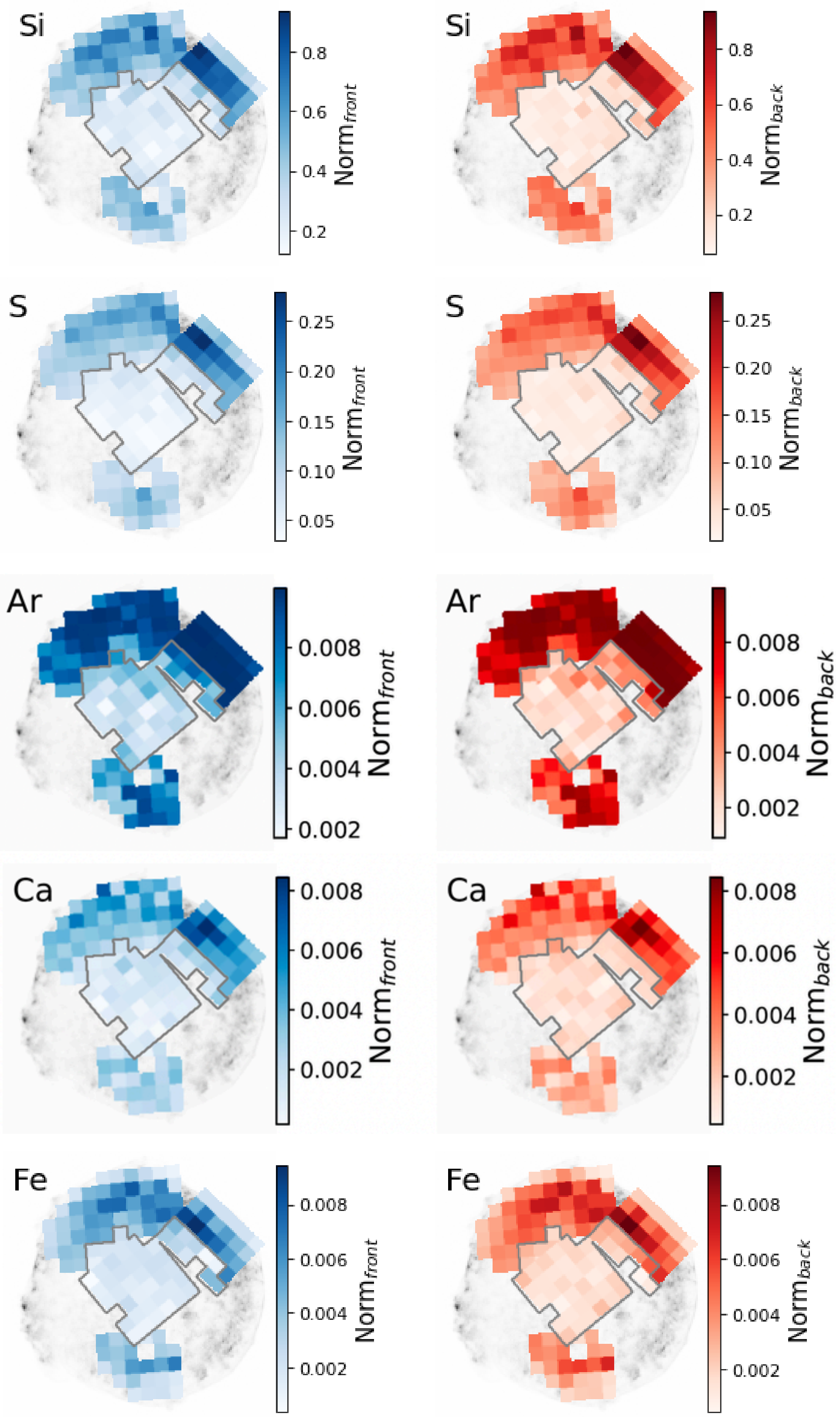
Global line broadening



Front and back velocity



Front and back flux



Si

S

Ar

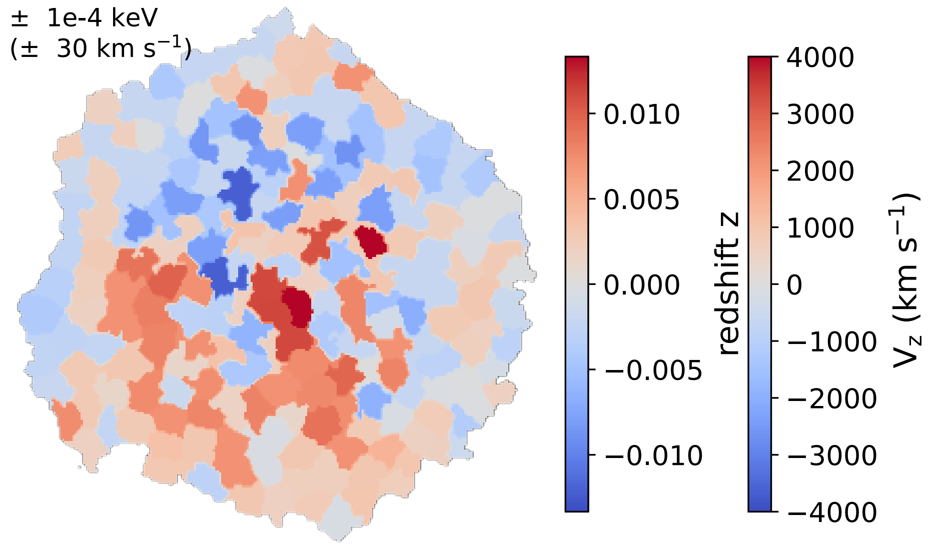
Ca

Fe

Tycho for calibration purpose

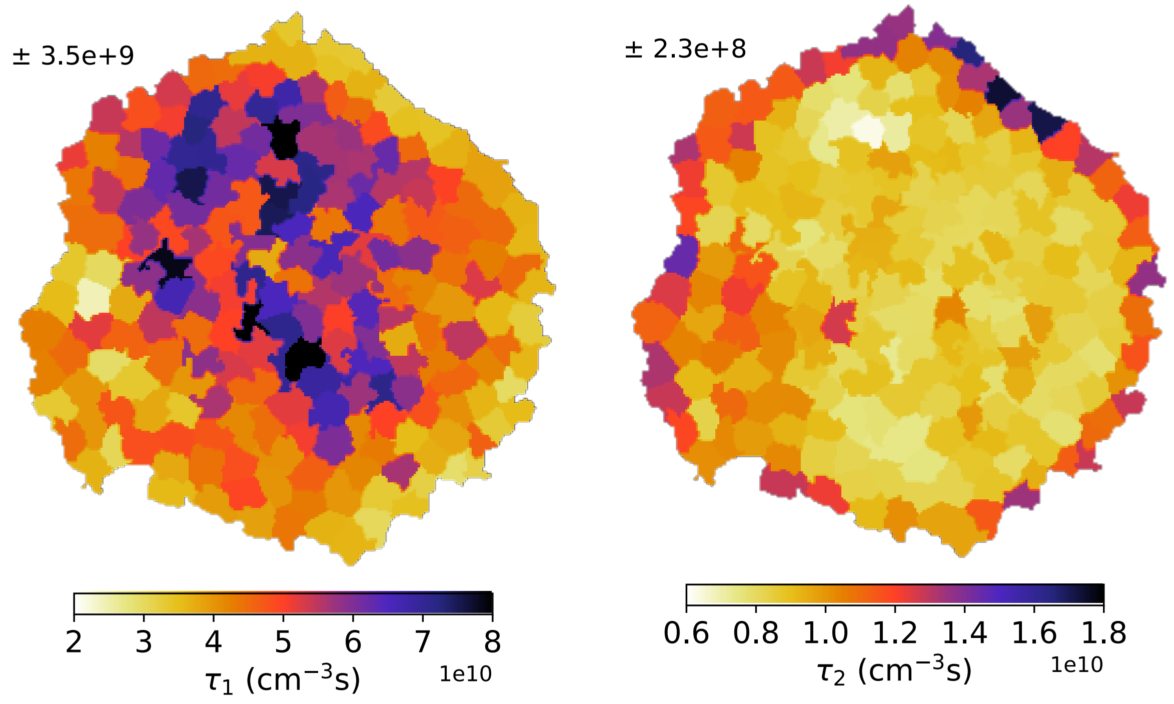
Position of the line at CCDs resolution

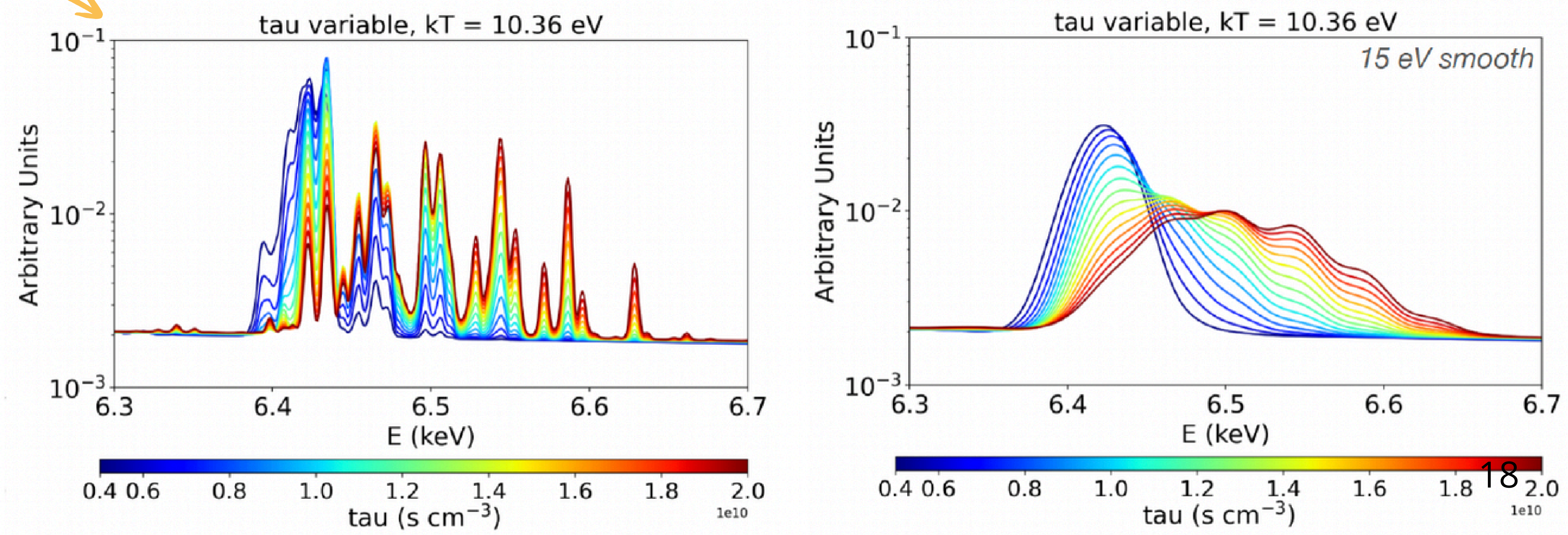
Redshift map



- The **position of the lines varies spatially** across Tycho's SNR.
- This is due to an **asymmetry in the mean velocity along the line of sight (Doppler shift)**,
- but also to **variations in ionization**, which affect the position of line complexes at CCD resolution.

Ionisation time map for the IMEs (Si) and Fe

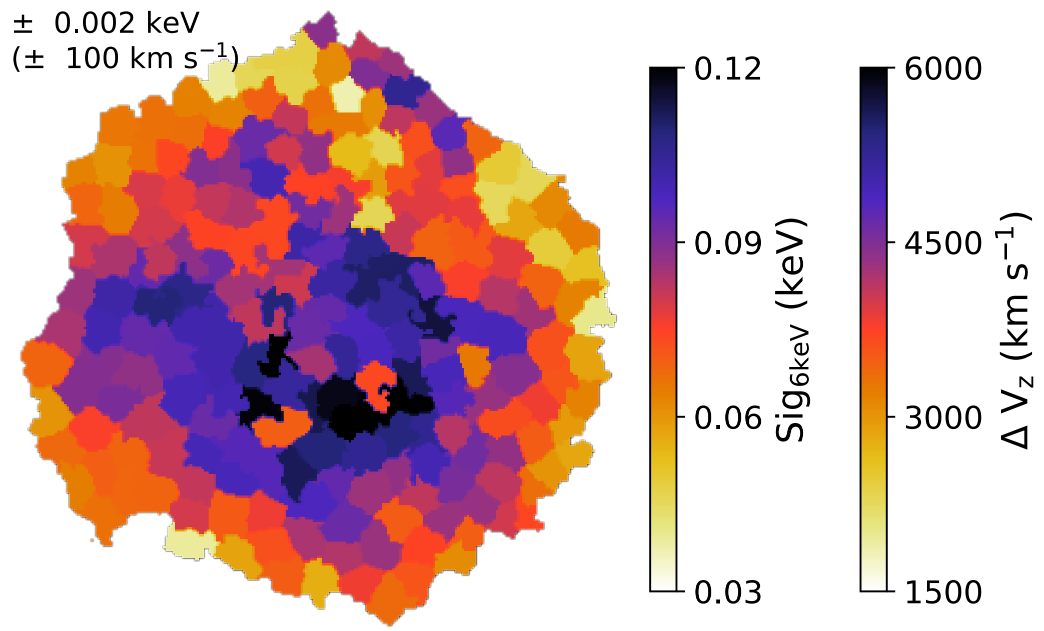


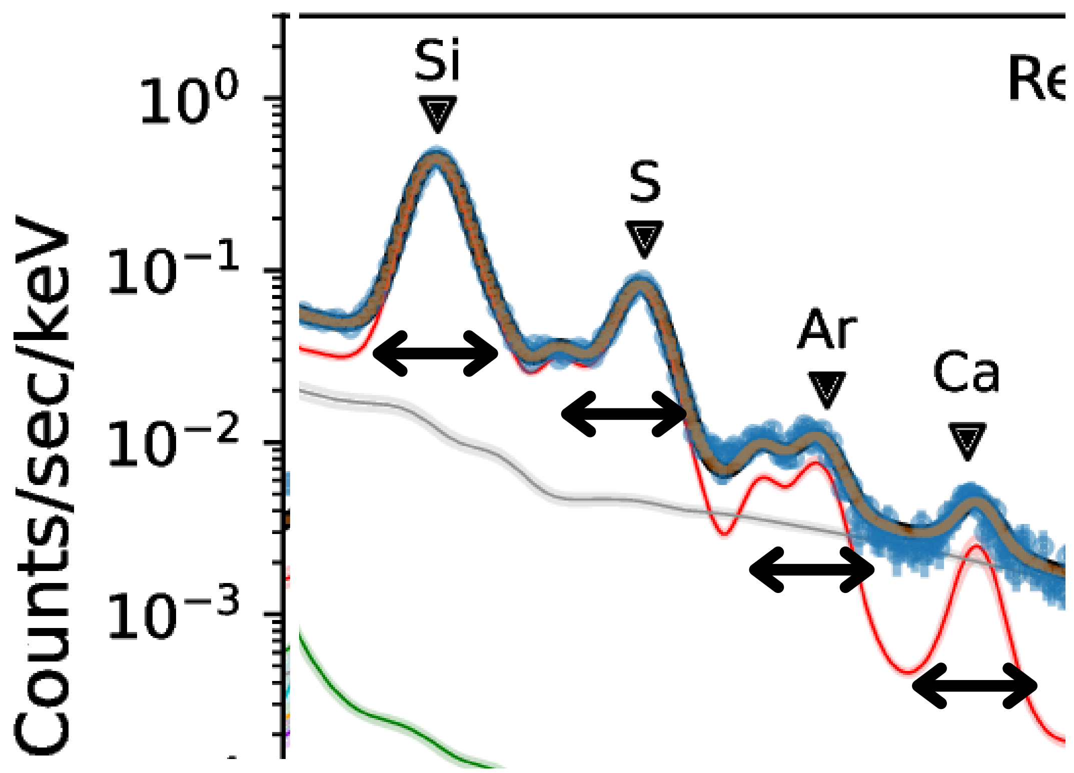


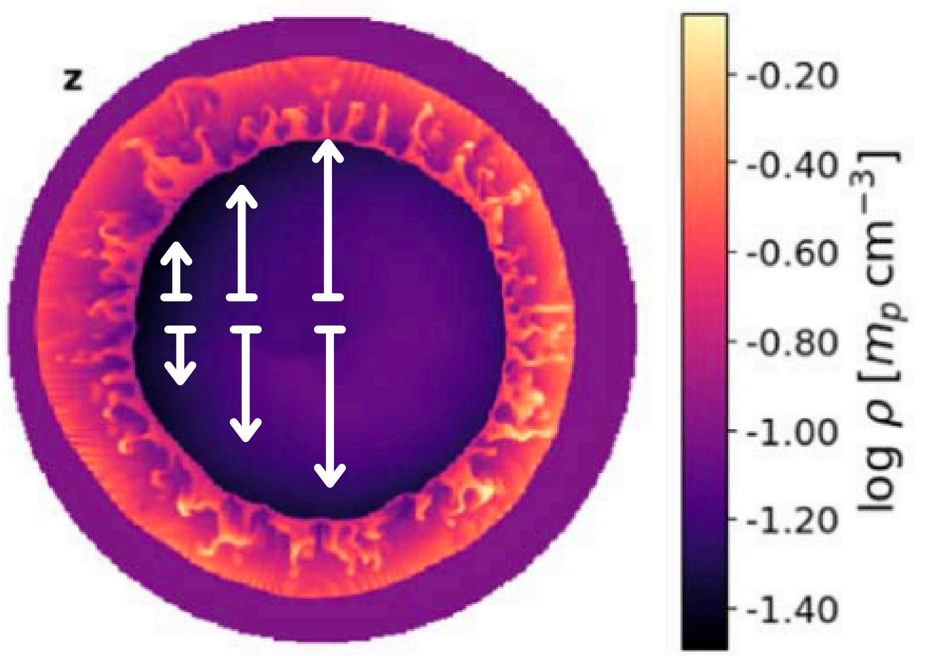
**Measured with Chandra/ACIS*

Line Broadening from velocity dispersion

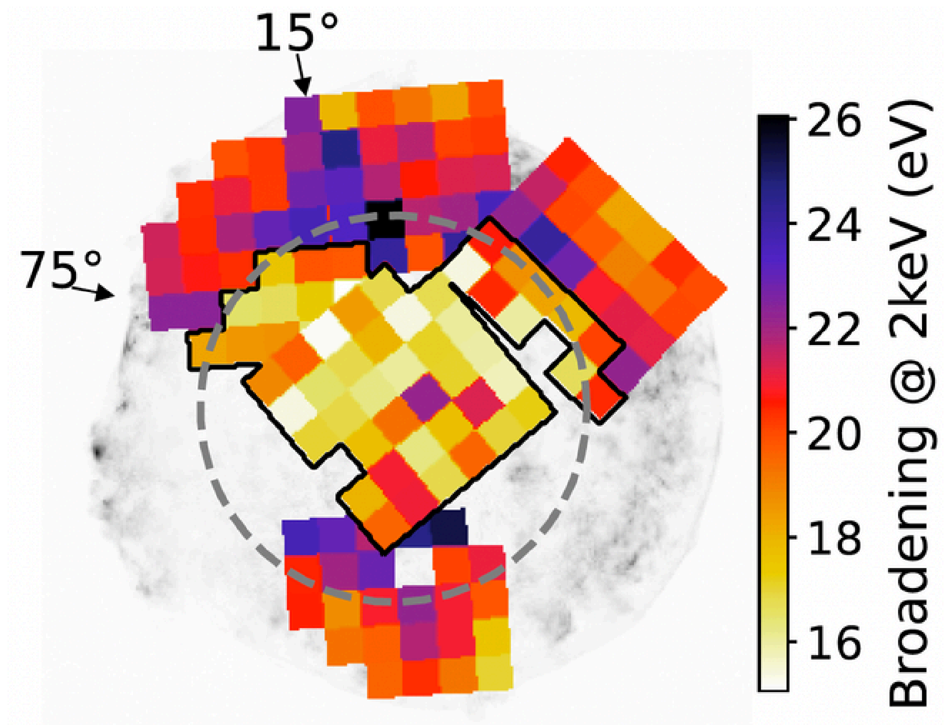
Measured with Chandra/ACIS

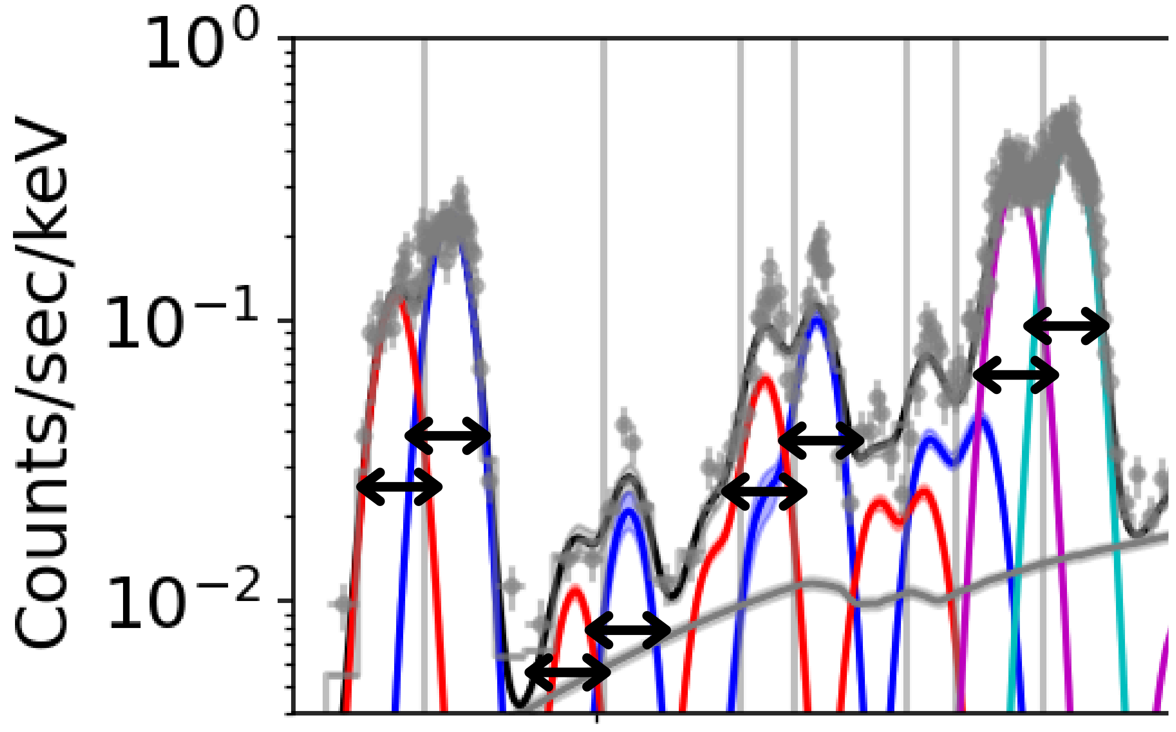


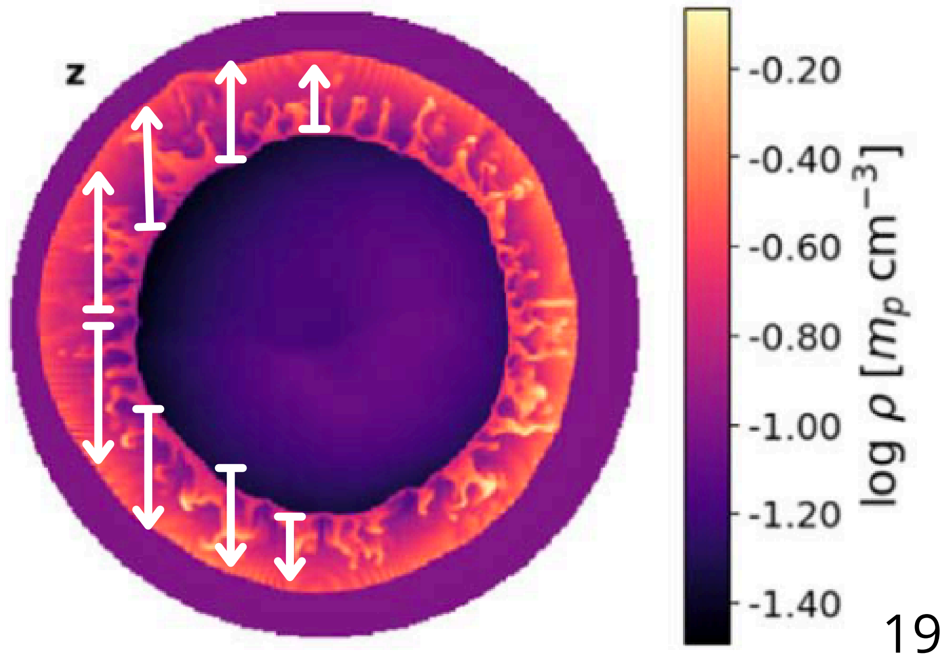




Measured with XRISM/Resolve

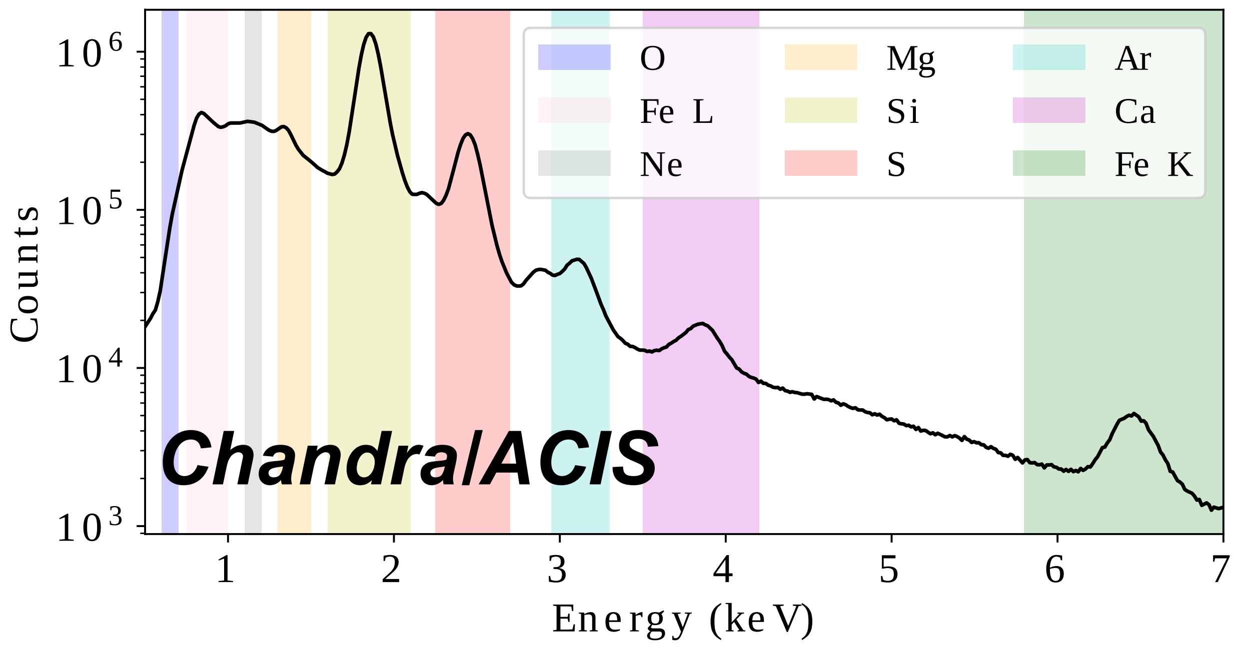


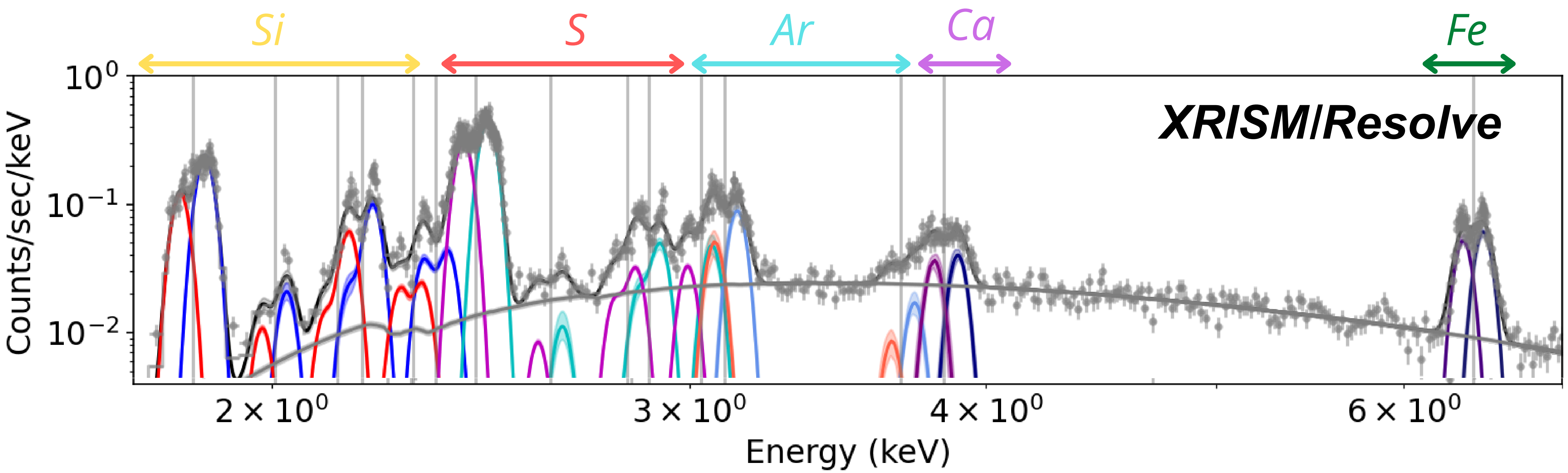




Simulations from Ferrand et al, 2011

Summary





Pros to use Tycho as calibration source:

- Bright source
- Prominent Si, S, and Fe emission lines
- No temporal variation

But keep in mind that:

- Spatial variation of the line position.
- Spatiale variation of the broadening of the line.

But we have good models!

- All the Chandra parameter mapping is included in a SIXTE model (or use directly the 211 Xspec fit).
- Model fitted on XRISM observations.
- Gaussians-style models also possible.