Component separation method application to young SNRs

Workshop LUMIèRE
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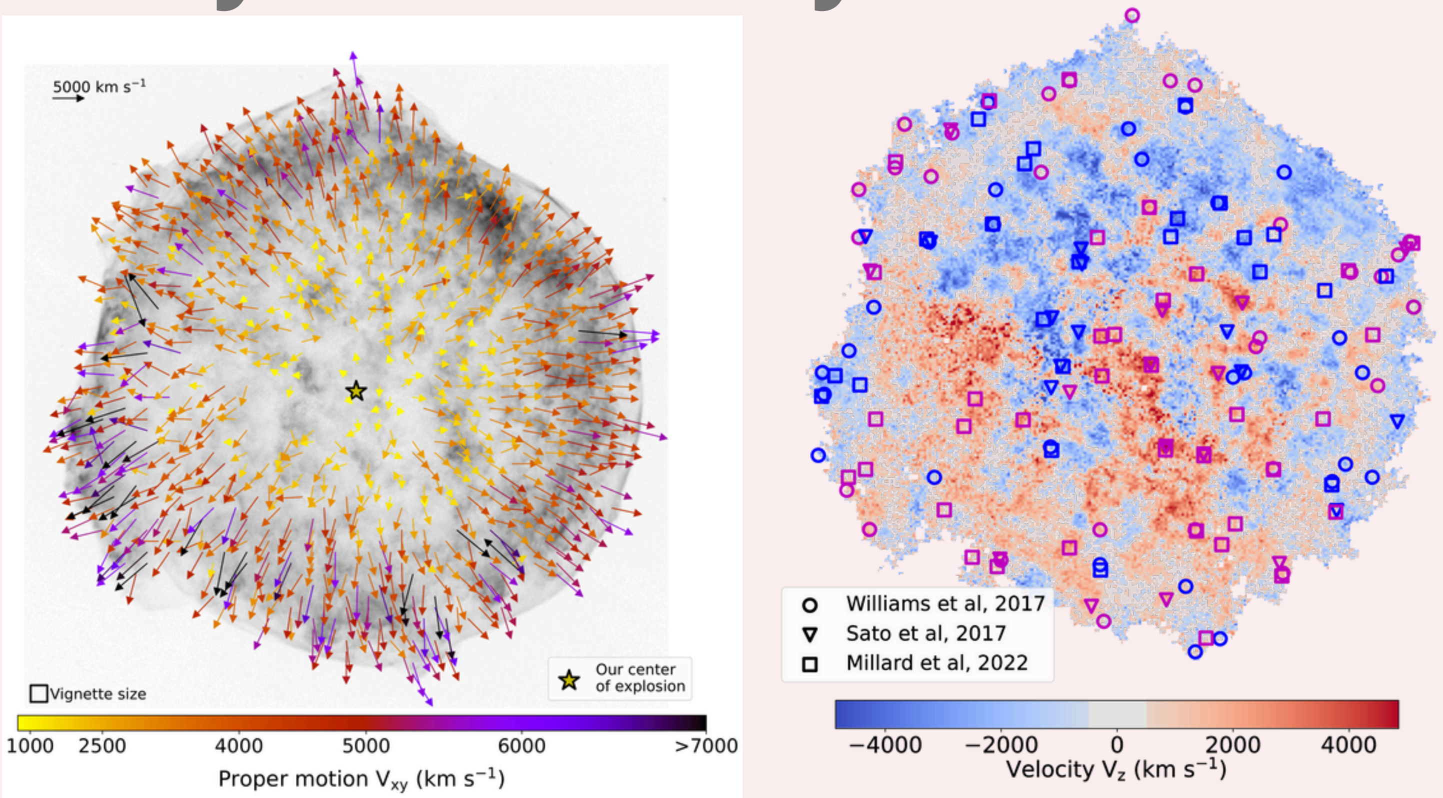
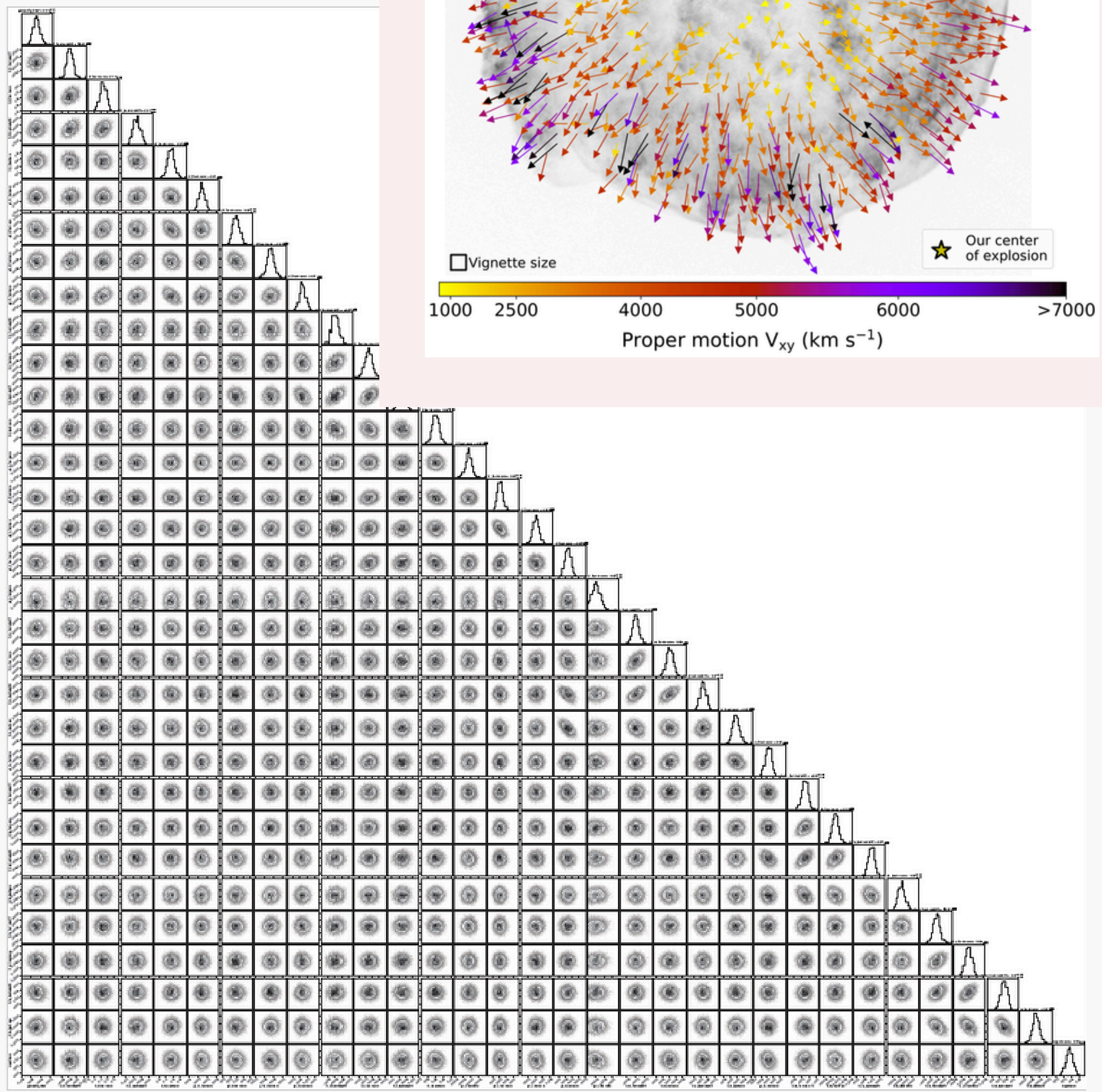
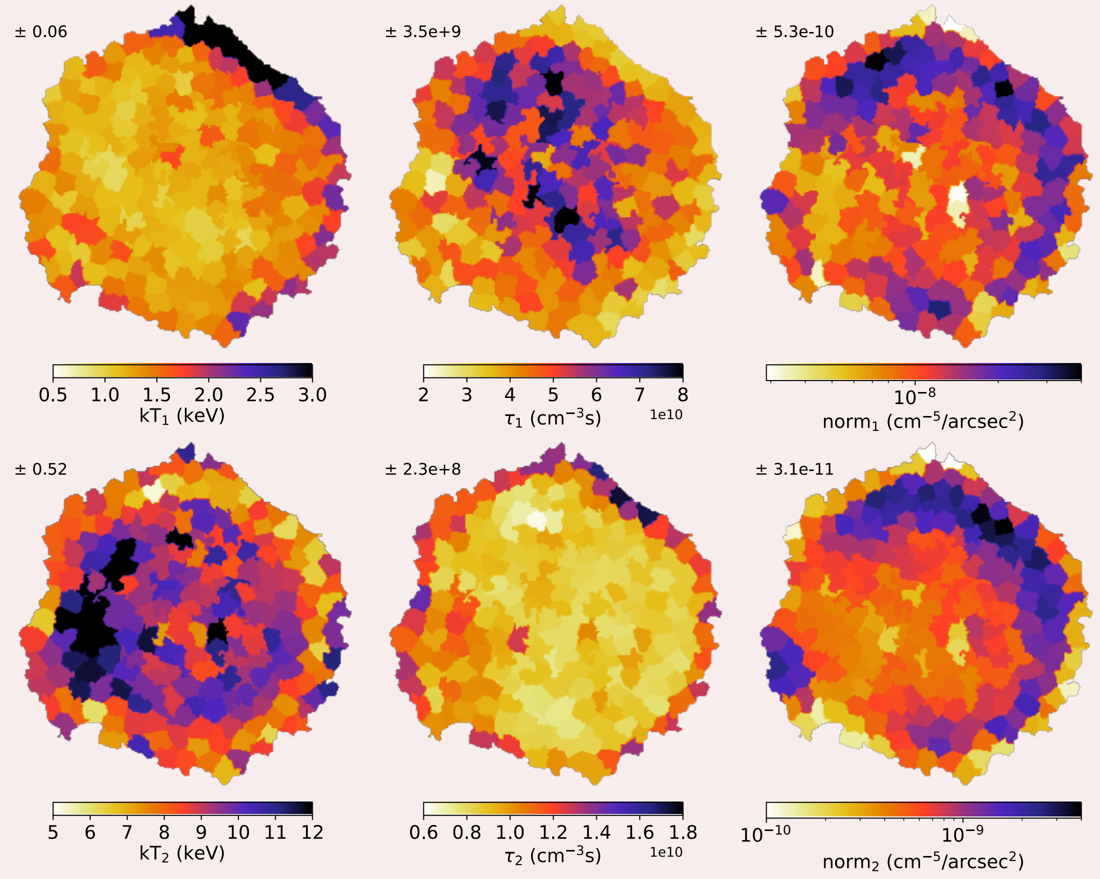
My work on SNRs

3D dynamics of Tycho's SNR

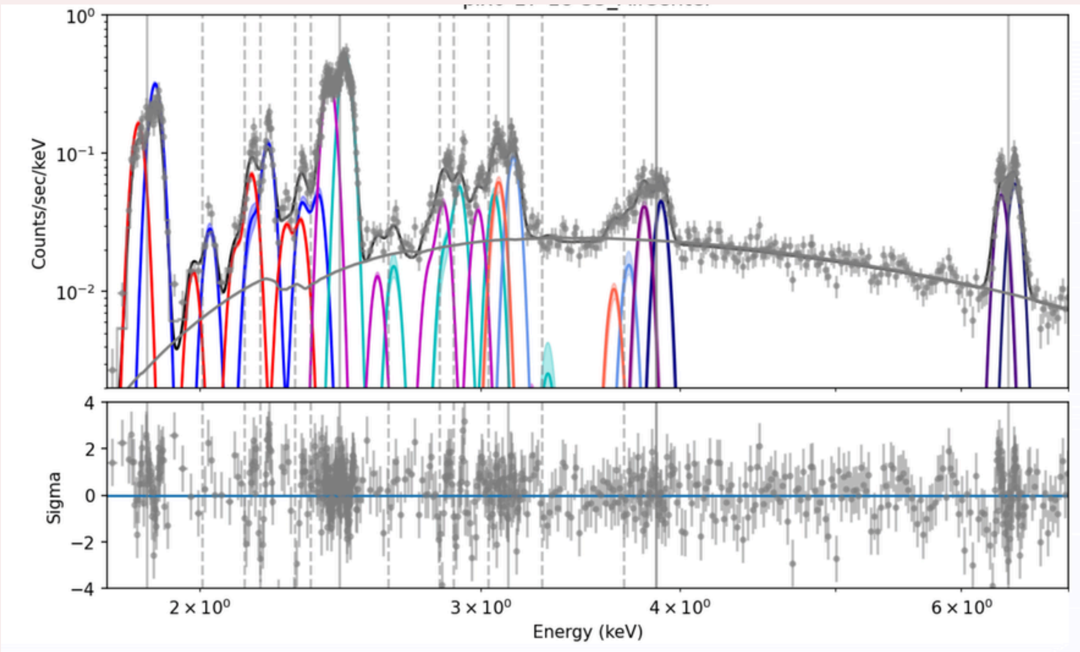




Parameter mapping of Tycho's SNR



XRISM fitting of Tycho's SNR to investigate 3D dynamics



GMCA

General Morphological Component Analysis

GMCA principle

- Data cube decomposition in a **linear combination of spectrum and image**

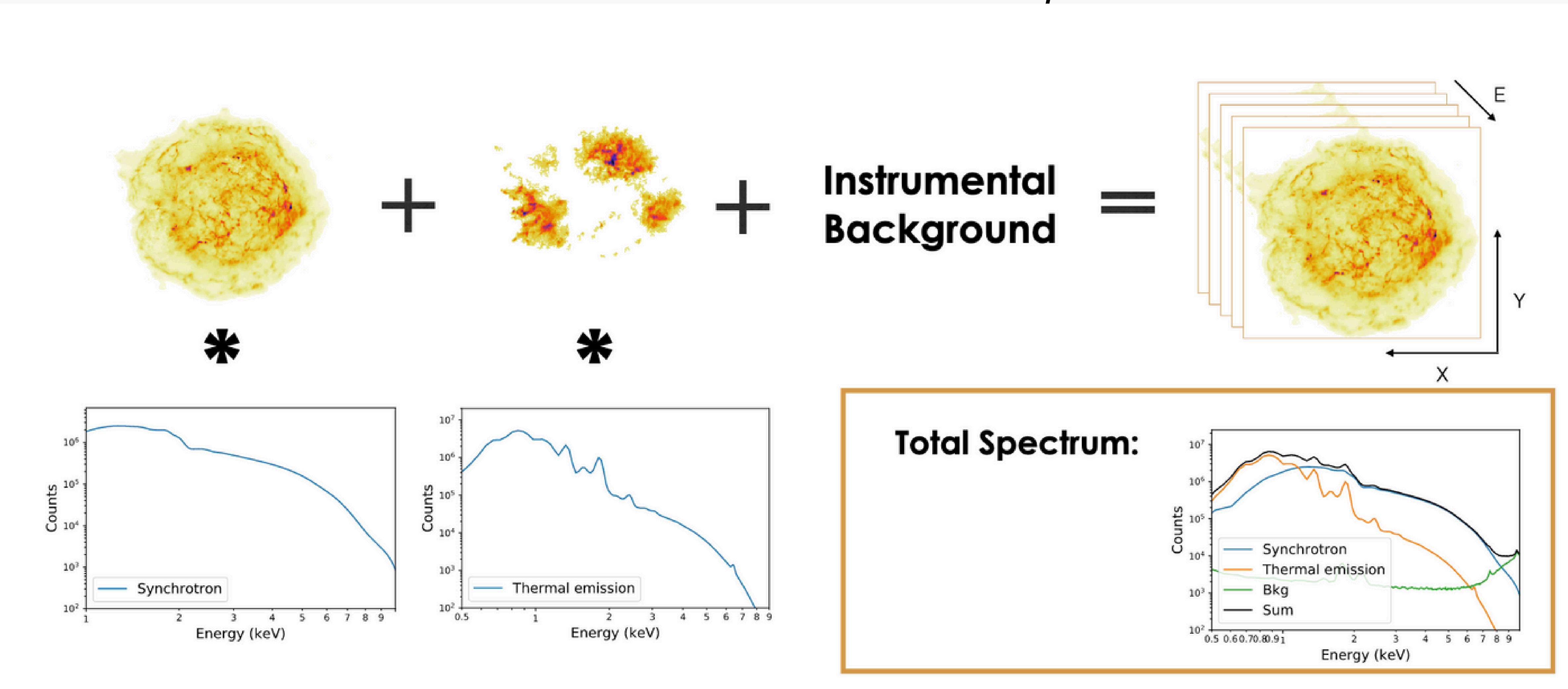
- Ill posed problem : sparsity regularisation based on wavelet transform

- Blind source process but possibility of initialisation

$$X = \sum_{i=1}^{n} A_i S_i + N$$

Cube (x, y, E) — *Spectra* — *Image* — *Noise*

Picquenot et al, 2019 - CasA



GMCA community

Technical articles :

- Bobin et al, 2015 : original method (GMCA)
- Picquenot et al, 2019 : pGMCA - Poisson noise
- Gertosio et al, 2023 : sGMCA - Semi blind
- Lascar et al, 2024 : SUSHI - Spatial variation of the output spectra

Science user articles:

- Picquenot et al, 2021 - Cas A, asymmetry per element
- Yamaguchi et al, 2021 - N103B
- Picquenot et al, 2023 - Cas A, synchrotron depending on energy
- Godinaud et al, 2023 - Tycho, Doppler velocity map
- Picquenot et al, 2024 - Separate thermal from non-thermal in 3 SNRs
- Picquenot et al, 2024 - Asymmetry per element, Tycho & Kepler
- Picquenot et al, 2025 - Perseus galxy cluster

pGMCA python script example

1) **Spatial and spectral rebining** to increase the stastistics, must be adapted to the goal of the study.

2) **Possible initialisation** of some spectra.

```
# choix Aref pour Kepler
nH = 0.6  # à vérifier
index = 2.6 # à vérifier
i1_pwl=np.abs(cube_data_nH - nH).argmin()
i2_pwl=np.abs(cube_data_index - index).argmin()
pwl_rebin = Rebin_template(E_template, cube_data_pwl[i2_pwl][i1_pwl], Eref )

test_Aref = np.array([pwl_rebin]).T
test_Aref.shape
```

3) Chose the **number of components** and the number of wavelet level.

4) **GMCA** (and then pGMCA, but longer)

```
# étape 1 : GMCA
Ncomp=3
nJ=3
cube_wav=pys.Starlet_Forward3D(cube_data,J=nJ)
Sources,g_A = GMCA(cube_wav,cube_data, Ncomp,0,UseP=0,L0=1,rL1=0,nmax=500, verb=1,mints=0.5)#, Aref = test_Aref)
spectrum, image_source = reconstruct_comp(Sources,g_A)
print(spectrum.shape, image_source.shape)

# étape 2 : enlever valeurs négatives
signs_gA = np.sign(g_A.sum(axis=0))
signs_S = np.sign(Sources.sum(axis=(1,2)))
Sources_inp=Sources.copy()
g_A_inp=g_A.copy()
for i in range(Sources_inp.shape[0]):
    im=Sources_inp[i,:,:]*signs_gA[i]
    mask = im > 0
    im_inpaint=pys.FBS_Inpainting(im*mask,mask,nmax=500,perscale=1,L0=0,kmad=0.1,J=2)
    Sources_inp[i,:,:]=im_inpaint
    g_A_=g_A[:,i]*signs_S[i]
    g_A_[g_A_<0]=0
    g_A_inp[:,i]=g_A_
X, S_gmca, A_gmca = cube_data, Sources_inp, g_A_inp

# étape 3 : pGMCA
A_pgmca,S_pgmca,_,_ = pGMCA2.BCD_Sparsity(X,A_gmca,S_gmca,np.mean(X),mu_k=100, CoVu=False,
                                  GFB = True,RwL1=False,J=nJ,s_thrd=1.,Starlet=False,Niter=3,verb=True,NiterIn=700)
                                       #,Aref = g_A_inp[:,0], Sref=None)

spectrum, image_source = reconstruct_comp(S_pgmca,A_pgmca)
```

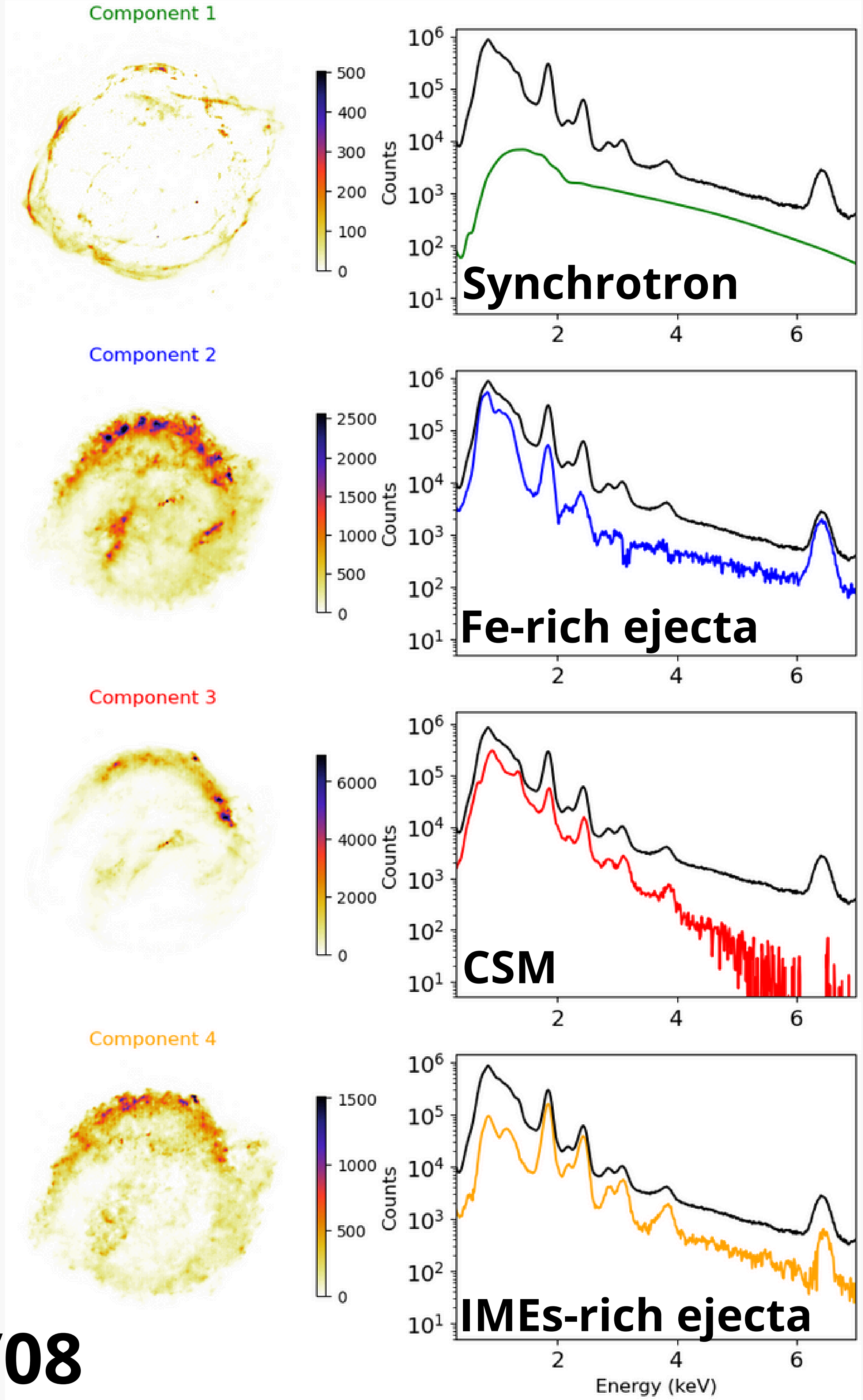
5) **Interpretation** of the outputs, check for any **leakage** between them

Applications

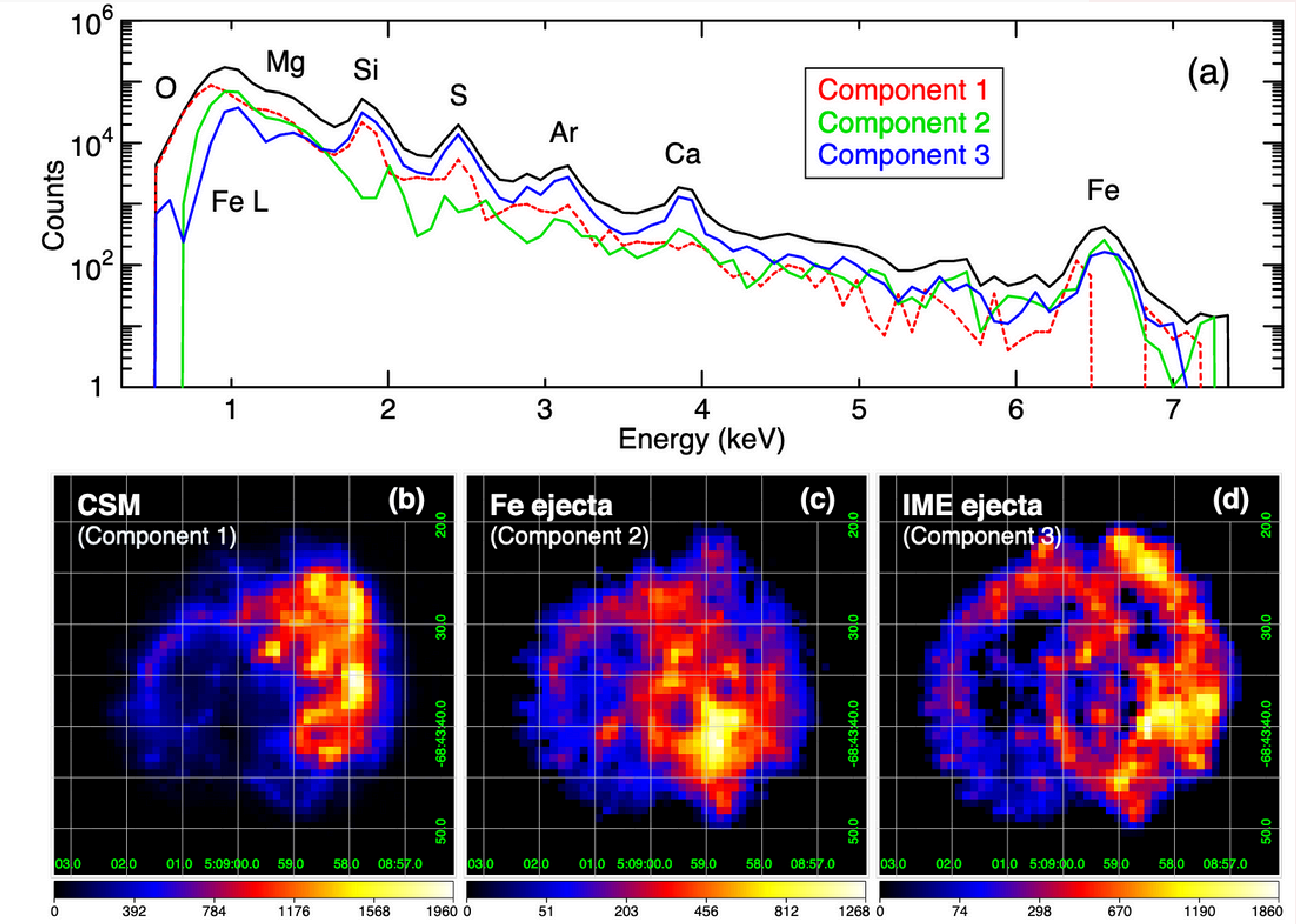
Broad band decomposition

- Perfect for **first view** of what we can hope from the tool.
- Components with **high spectro-morphological differences**.
- Power of the crowd : information at large and small scale but not to believe in the smallest details.

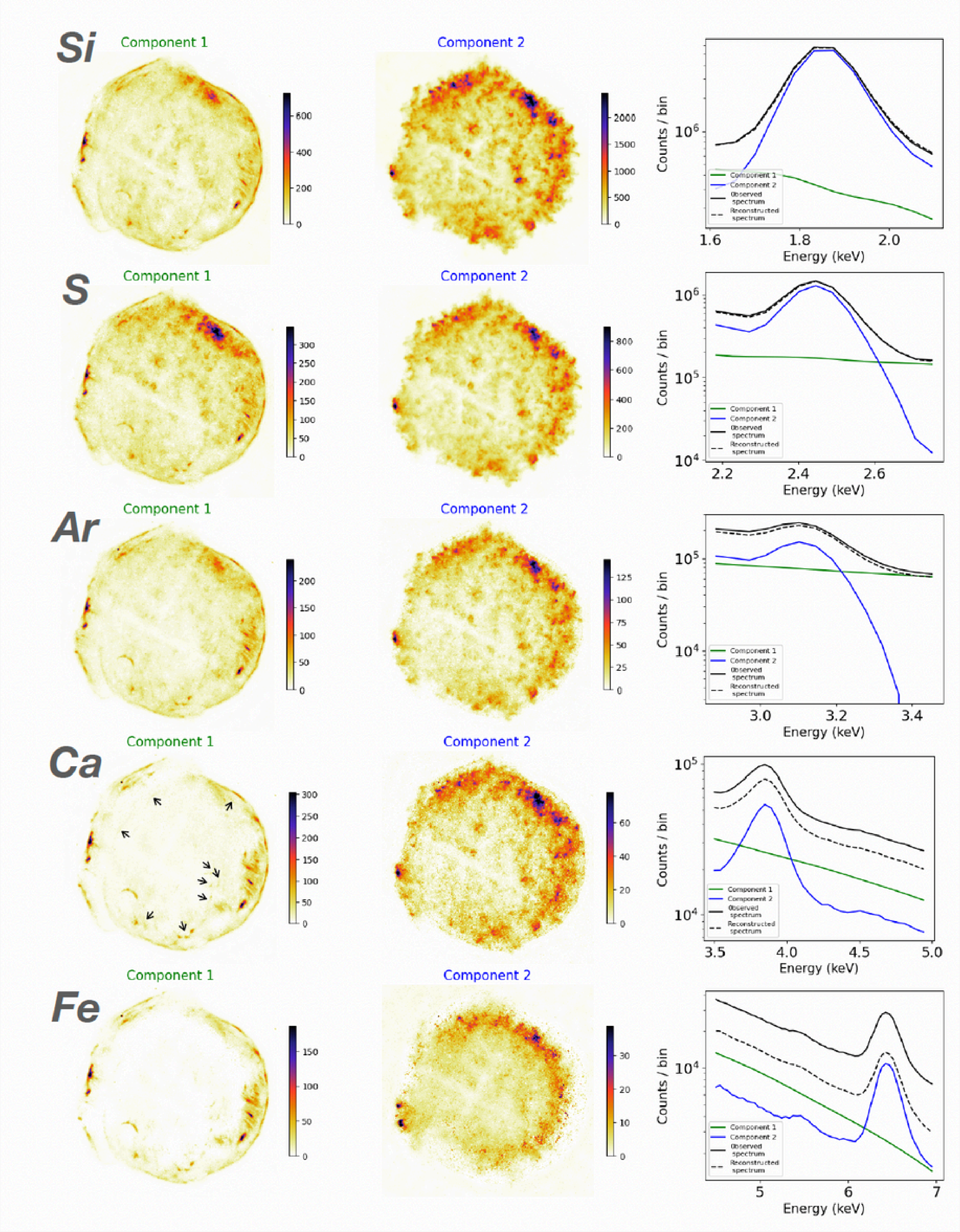
Kepler



Yamaguchi et al, 2021 - N103B



Tycho

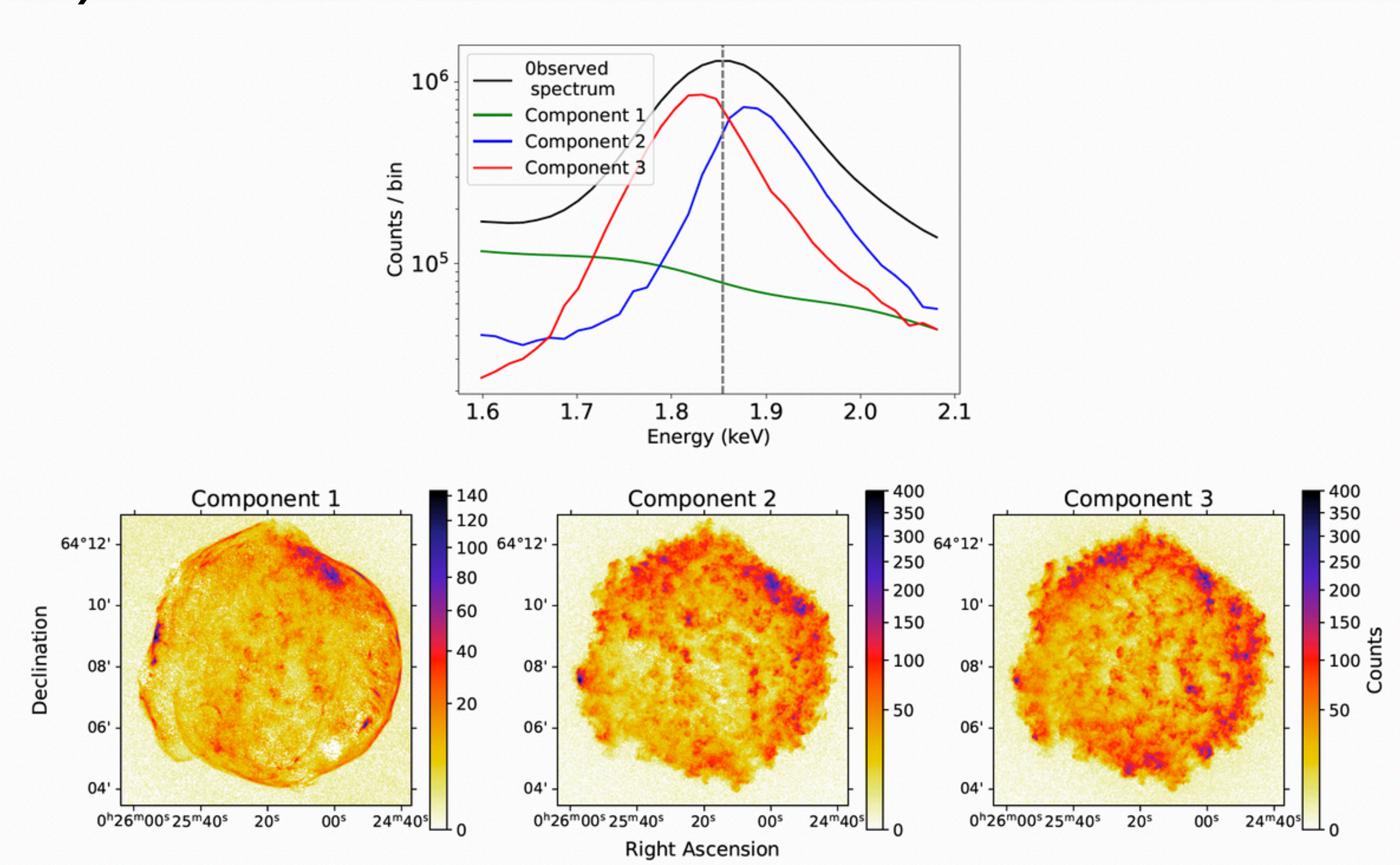


Decomposition per energy bands

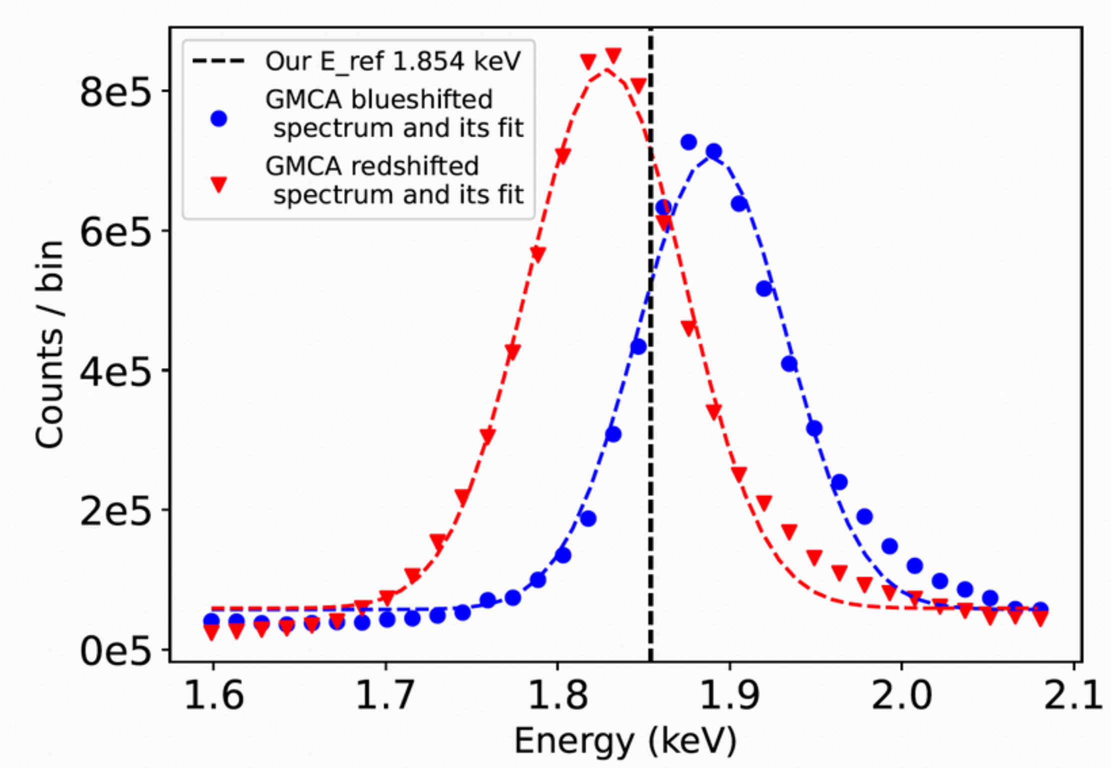
- A way to clean images in a little energy band and **reveal entangle components.**
- Thermal emission per element : study their morphology (ie. Picquenot et al, 2024), their stratification …
- Non thermal emission : synchrotron filament in different energy band (Picquenot et al, 2023)

Line position reconstruction

1) GMCA on the Si band



2) Fit the GMCA spectra with Gaussians



3) Reconstruct the position of the line in every pixels

$$Spectre_{ij,\mathrm{tot}}(E) = \sum_{k}^{GMCA} Im_{ij,\,k}\; Spectre_{k,\mathrm{GMCA}}(E)$$

$$Spectre_{k,\,\mathrm{GMCA}}(E) = \beta_k + \alpha_k \exp\left(-\left(\frac{E-\bar{E}_k}{\sigma_k}\right)^2\right)$$

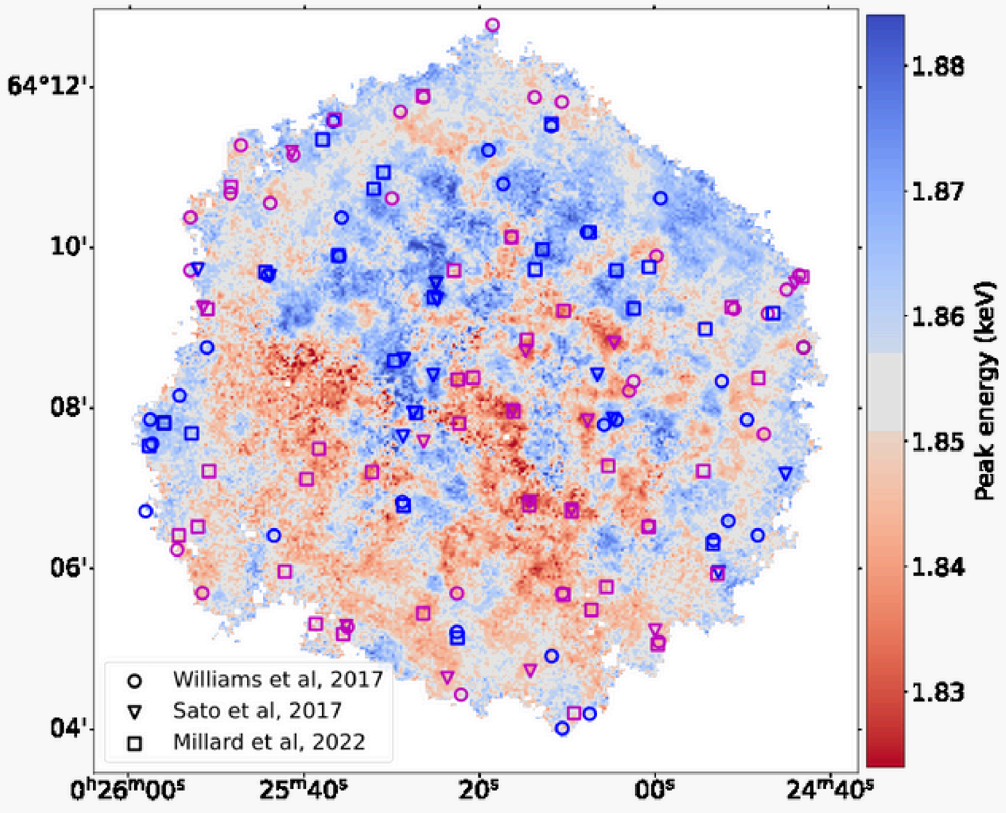
$$\left.\frac{\mathrm{d}A_{ij,\mathrm{tot}}}{\mathrm{d}E}\right|_{E_{p,\,ij}} = 0 \Leftrightarrow$$

$$\sum_{k=2,3} S_{ij,\,k}\,\alpha_k \frac{-2\,(E_{p,\,ij}-\bar{E}_k)}{\sigma_k^2} \exp\left(-\left(\frac{E_{p,\,ij}-\bar{E}_k}{\sigma_k}\right)^2\right) = 0$$

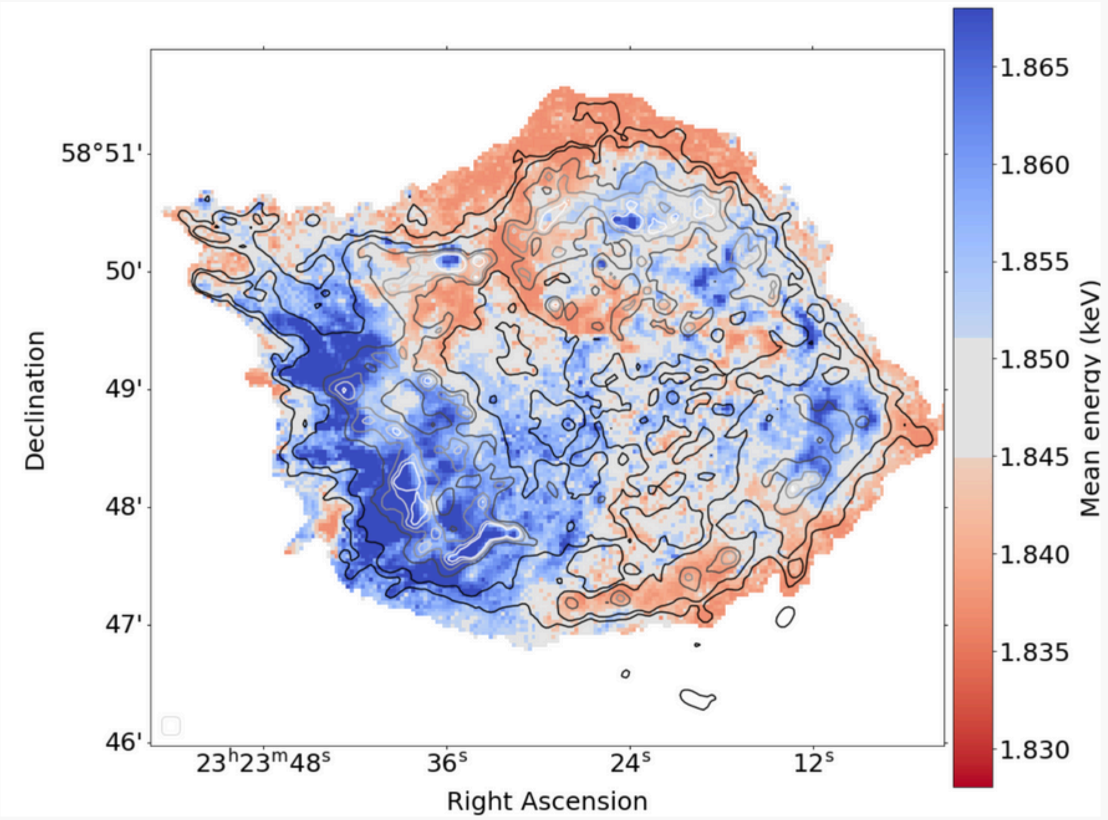
$$\sum_{k=2,3} S_{ij,\,k}\,\alpha_k \frac{(E_{\mathrm{p},\,ij}-\bar{E}_k)}{\sigma_k^2} = 0 \Leftrightarrow E_{\mathrm{p},\,ij} = \frac{S_{ij,\mathrm{r}}\frac{\alpha_\mathrm{r}}{\sigma_\mathrm{r}^2}\bar{E}_\mathrm{r} + S_{ij,\mathrm{b}}\frac{\alpha_\mathrm{b}}{\sigma_\mathrm{b}^2}\bar{E}_\mathrm{b}}{S_{ij,\mathrm{r}}\frac{\alpha_\mathrm{r}}{\sigma_\mathrm{r}^2} + S_{ij,\mathrm{b}}\frac{\alpha_\mathrm{b}}{\sigma_\mathrm{b}^2}}$$

Line position reconstruction

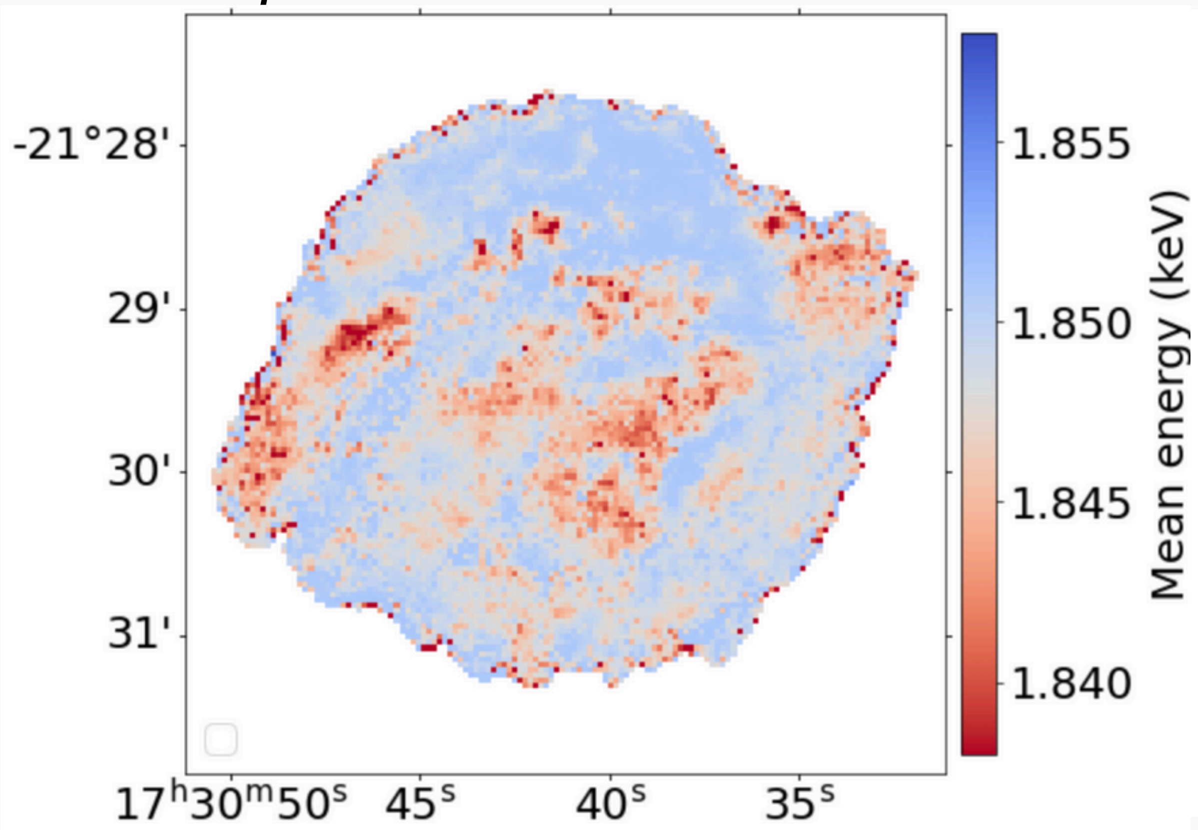
Tycho - Si (Godinaud et al, 2023)



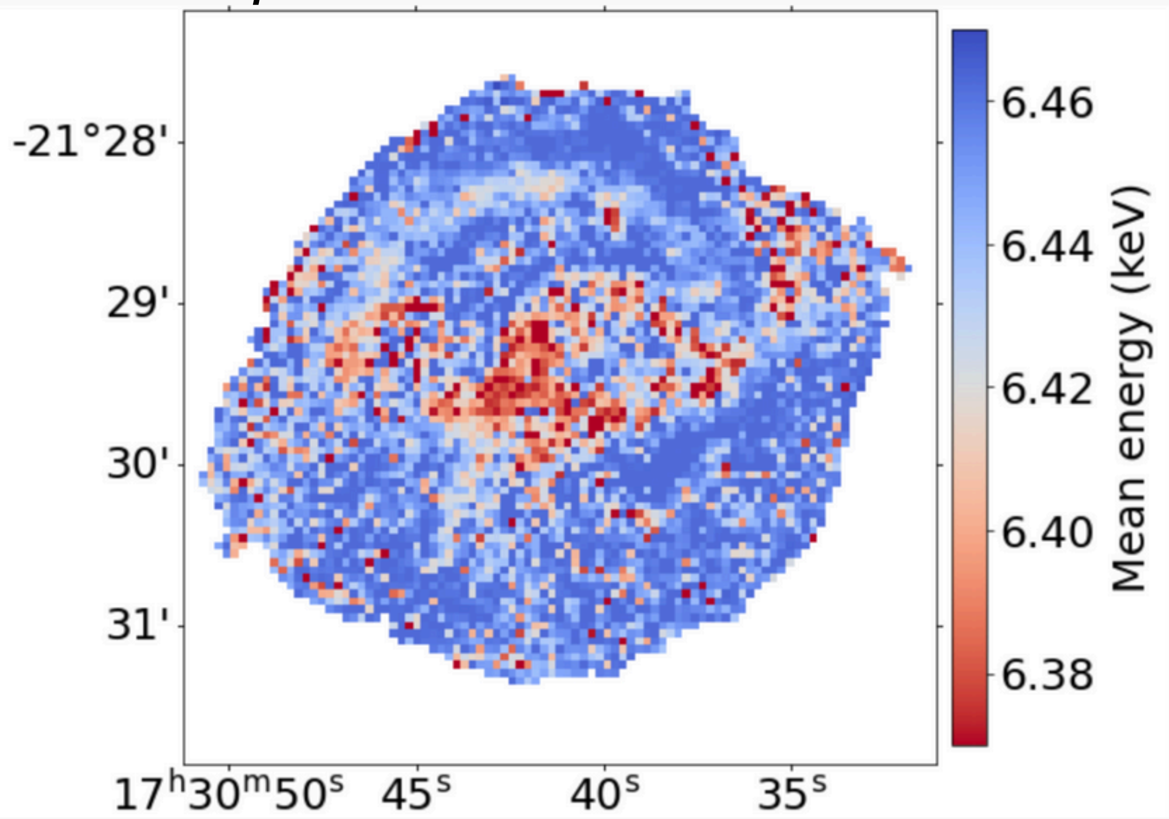
Cas A- Si



Kepler - Si

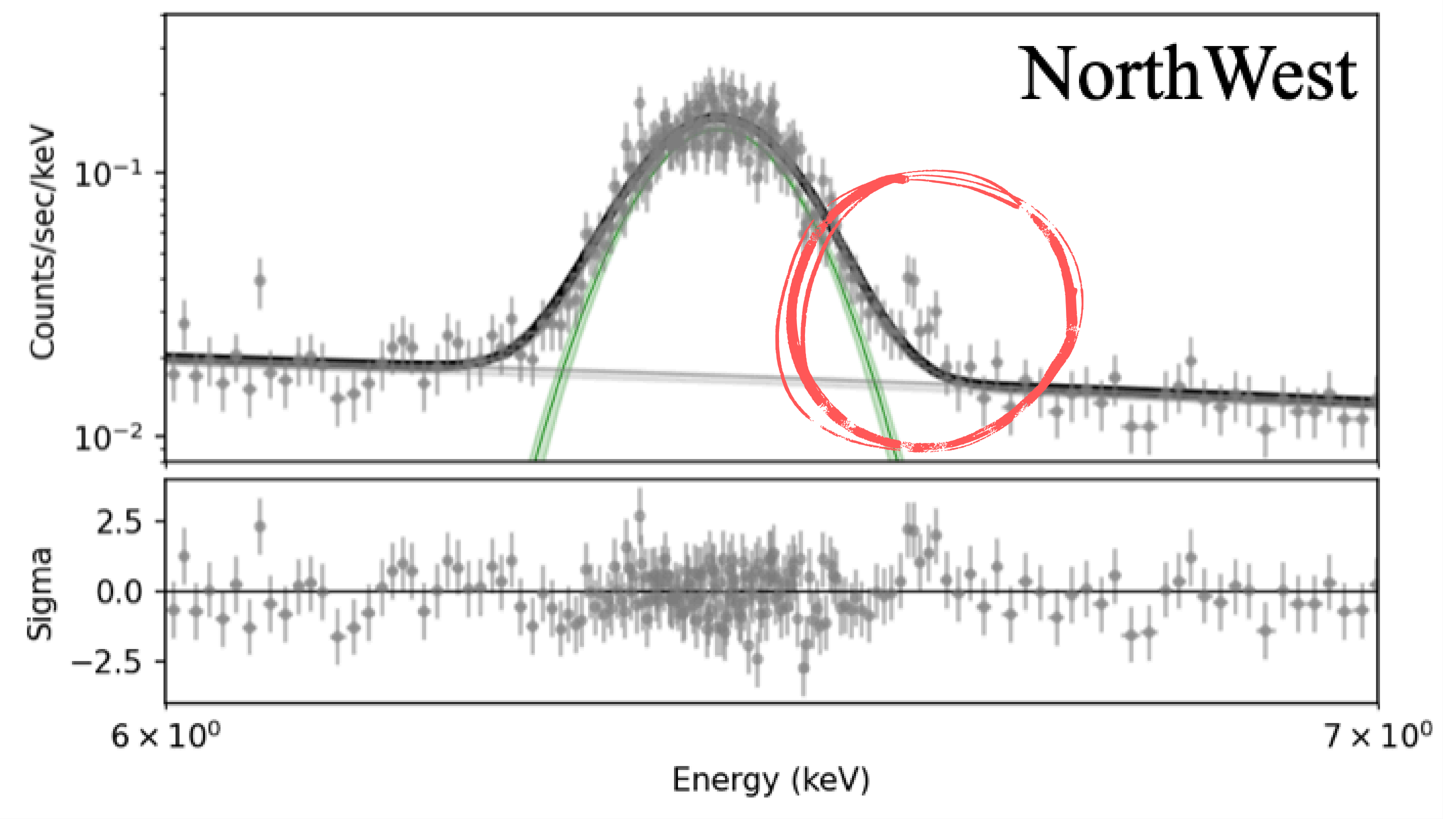


Kepler - Fe

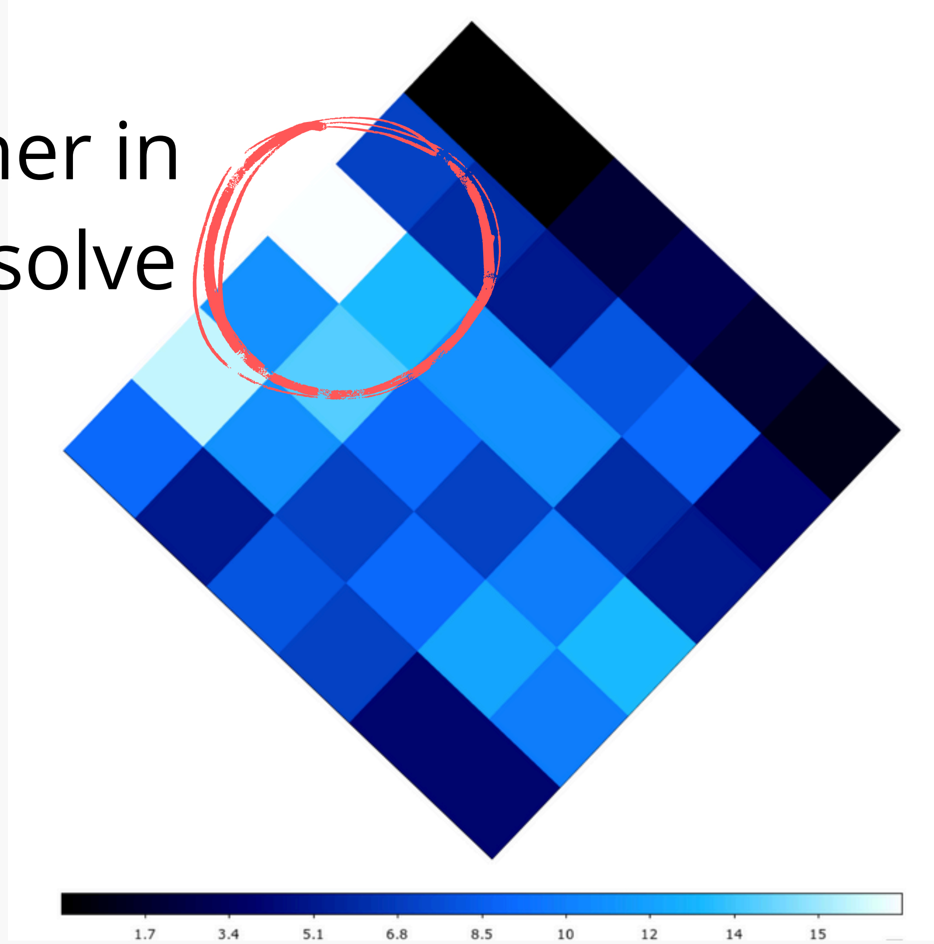


Hidden component

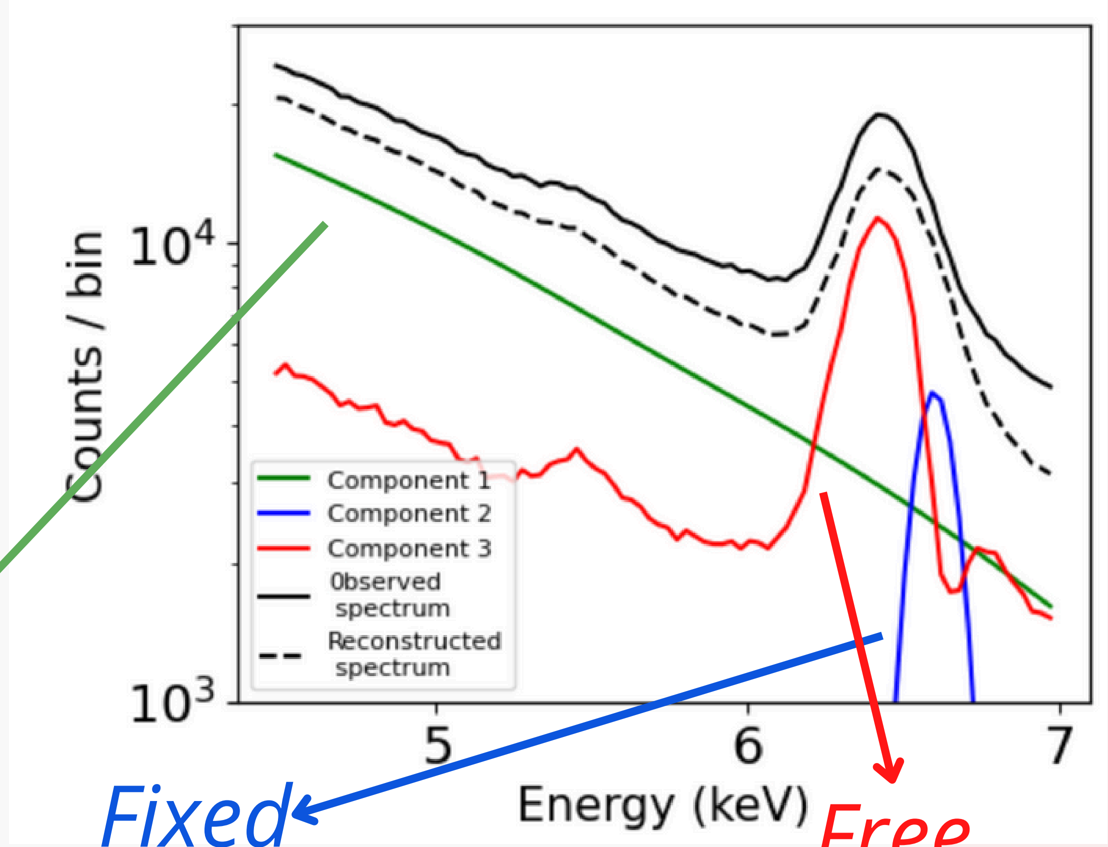
1) We observe a mysterious 2nd peak in the Fe-K complex in our XRISM data !



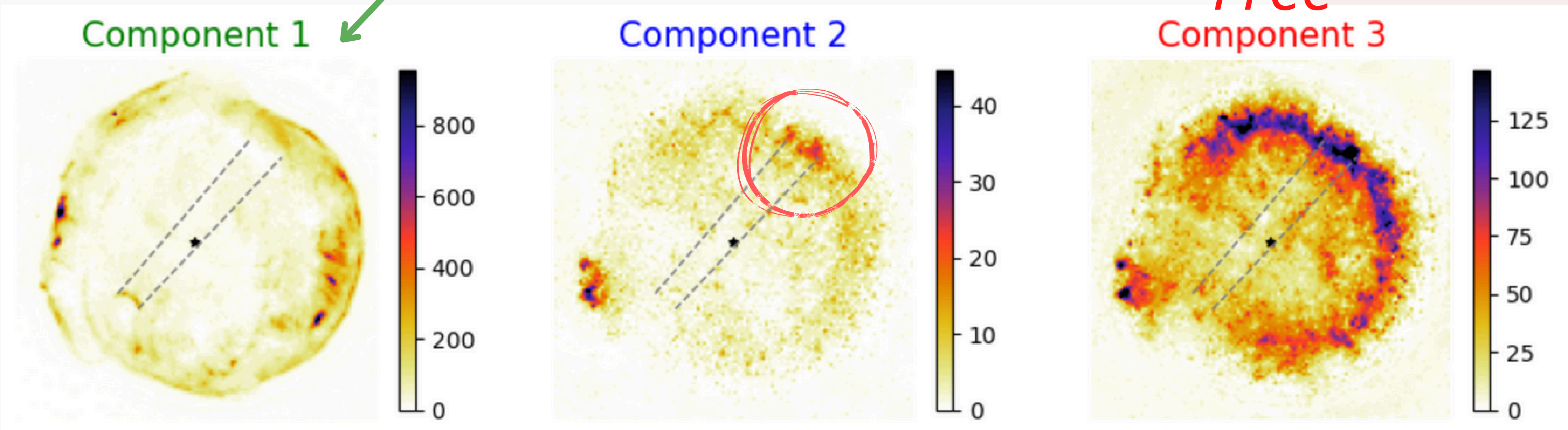
2) The line is higher in one of XRISM/Resolve pixel ...



3) With GMCA we can check the spatial origin of this additional line at Chandra resolution **by initialising the input spectra**.

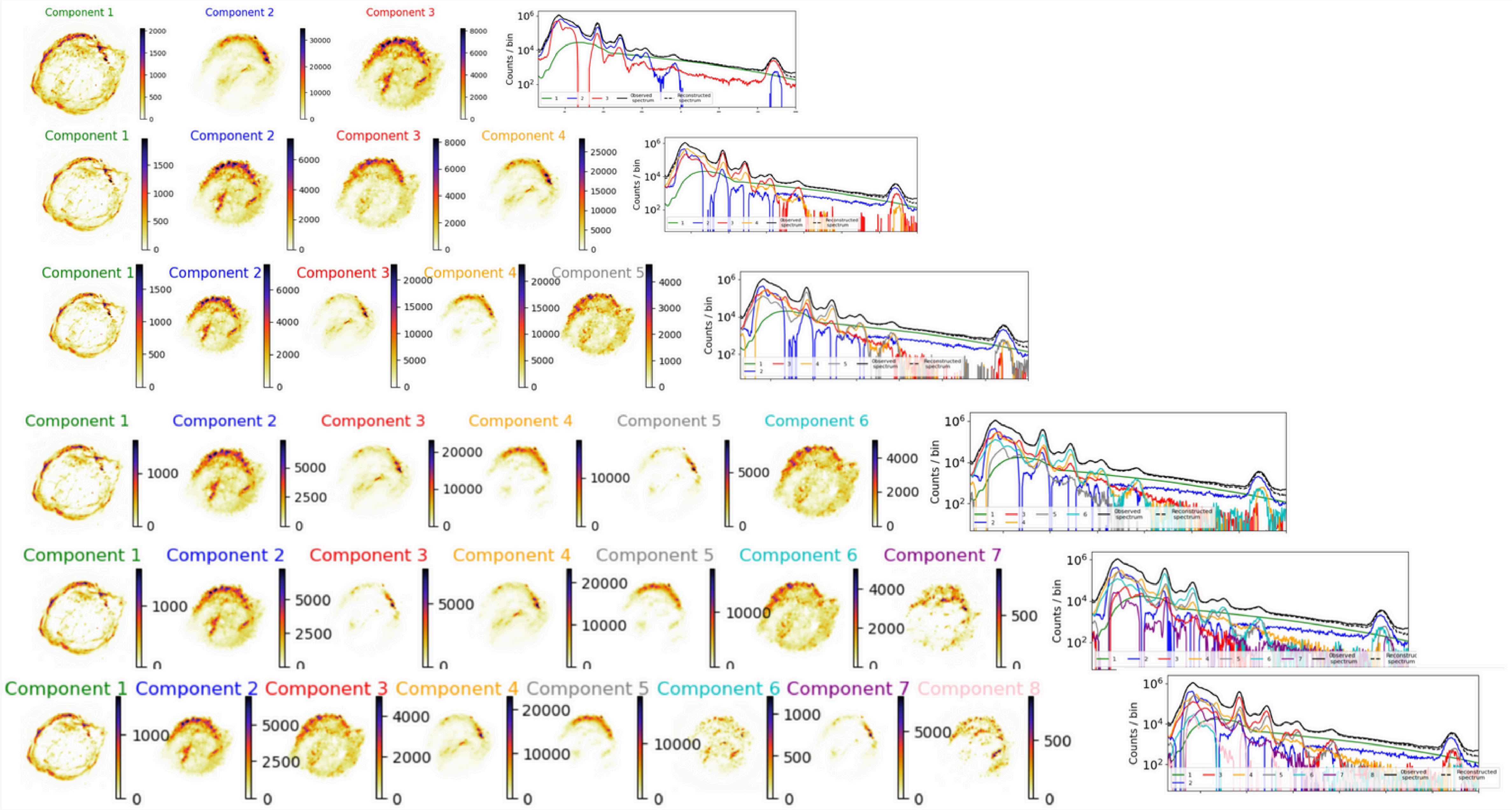


Fixed
Fixed
Free



— Limitations

Play with the user's inputs



Check on the input parameters :

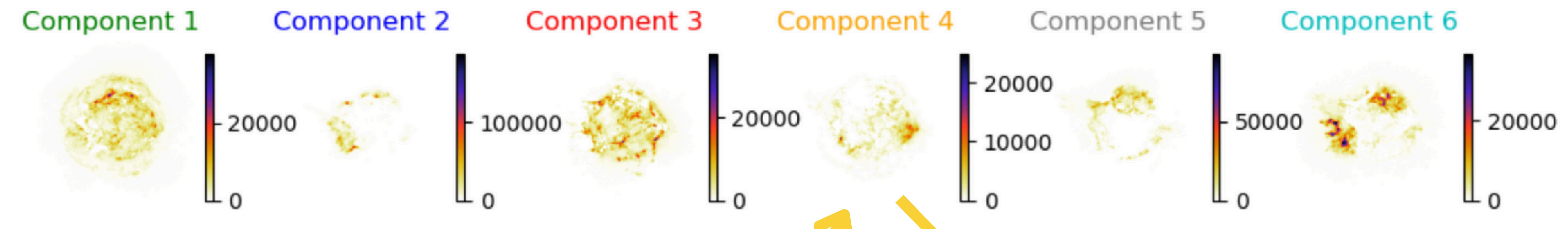
- The spatial and spectral binning
- The number of components *
- The energy band
- The parameter of the initialized

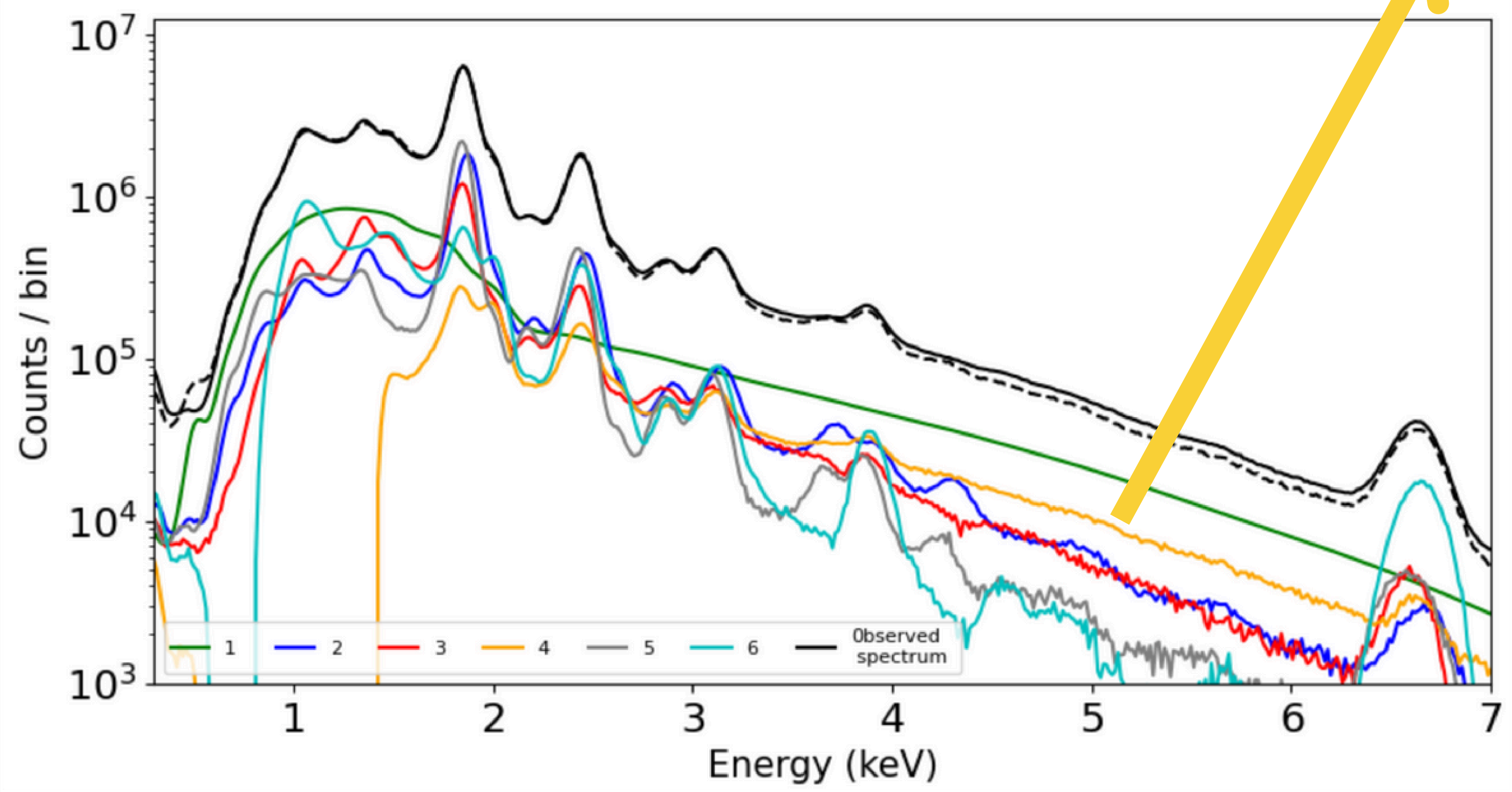
There are compromises to do depending of the aim of the study and to have enough counts in the outputs.

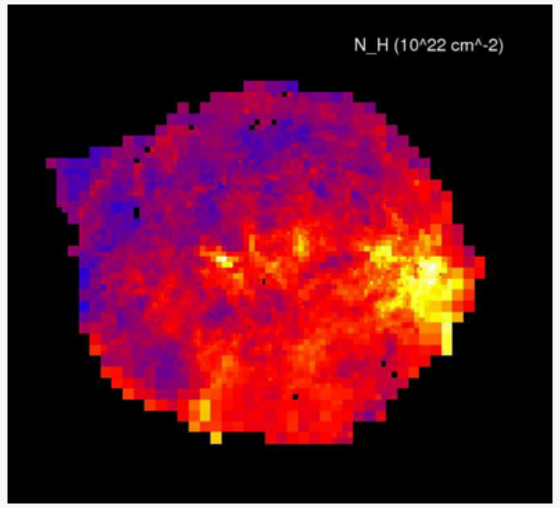
See Appendix B of Picquenot 2019 about AIC criteria to choose the number of components

Interpretation of the outputs

Non additive component : the example of Cas A



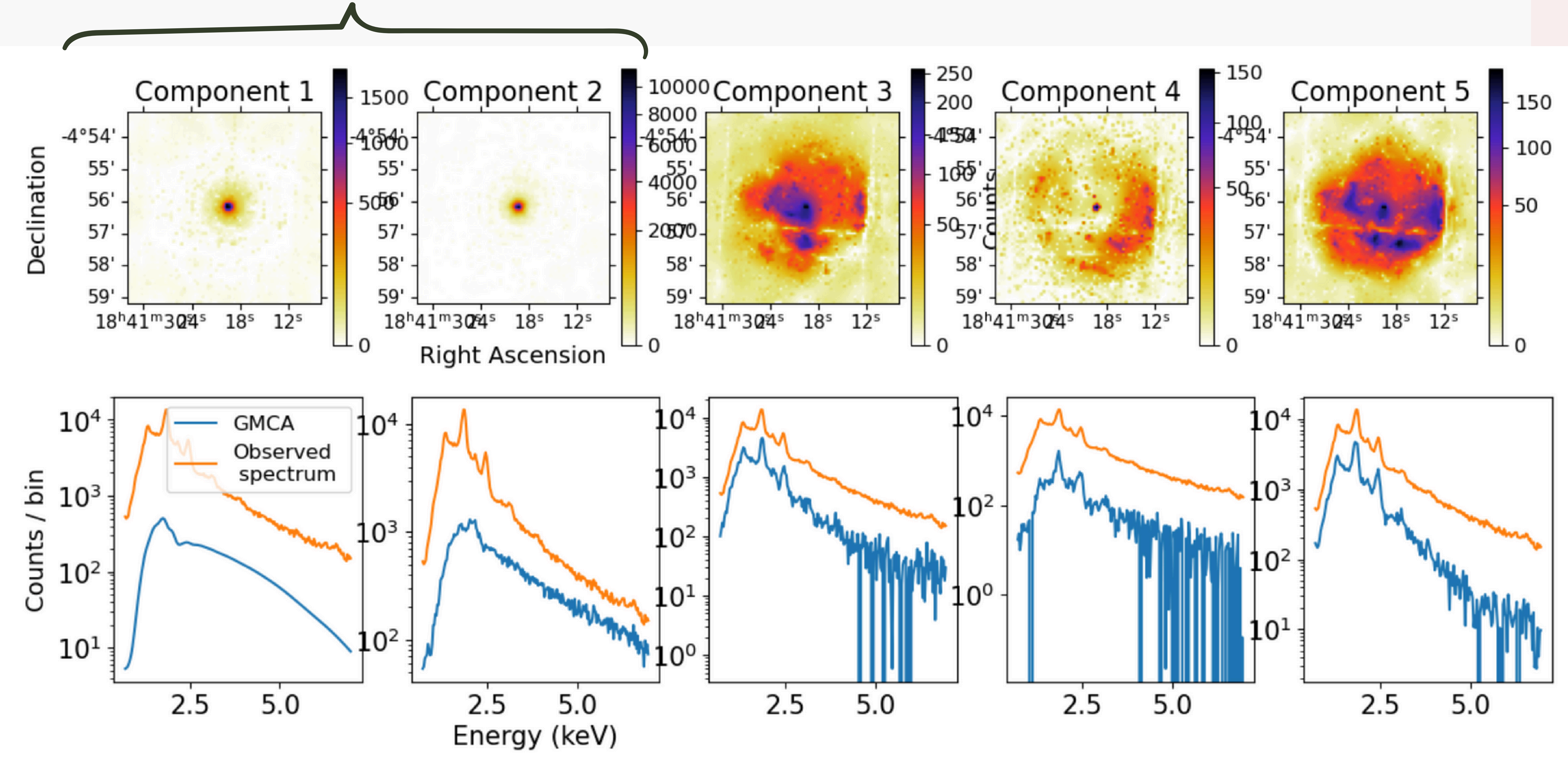




Absorption map
Parameter mapping of Cas A
Hwang et al, 2011

Interpretation of the outputs

Effect on the PSF on XMM data of Kes 73



Going further with the GMCA spectra

Problems if you want to fit a GMCA spectrum :

- By default **no uncertainties in GMCA**
  see Appendix of Picquenot et al, 2021 for a bootstrap resampling and its effect on Poisson noise

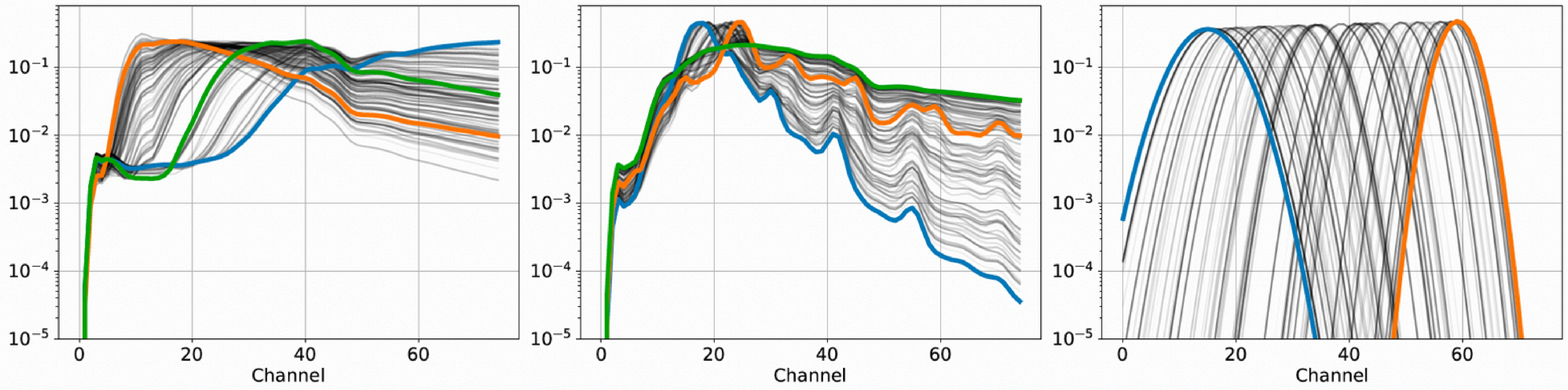
- Sometimes “holes” in the spectra and leakage between the components due to the **lack of statistics**
  A “template 3D fitting method” proposed in Picquenot 2025
  inspired by fitting in Gamma-rays
  Use the image of GMCA and fit the spectrum with simple physical model

Opportunities

sGMCA : semi-blind

- 1) Produce a library of spectra template
- 2) **Train the auto-encoder to learn the variations between these spectra**
- 3) Initialisation of sGMCA with these learned sepctral librairies
- 4) sGMCA (similar to GMCA but semi-blinnd)

Gertosio et al, 2023



(a) Absorbed synchrotron power-law models (b) Absorbed thermal models (c) Gaussian line models

Figure 2: Ensemble of three emission models. The colored thick lines are the chosen anchor points in the context of the IAE modeling.

SIXTE simulation

The options to do simulation of observations (increasing difficulities) :

- 1) "fakeit" based on **one spectral model**
  → no spatial information
- 2) SIXTE : **1 spectral model + 1 image** at high resolution
  → Same spectral information everywhere
- 3) SIXTE : **1 spectral model + 1 image per each component**
  → GMCA output ideal for this !
  → fast to simulate and a bit more precise for ARF or SSM test
- 4) SIXTE : Use a **spectral parameter mapping** of your source
  → More precise but long to do the preliminary study
  → I have done this for Tycho's SNR
- 5) Advanced SIXTE : Use a **3D numerical simulation** as input
  → Very computational intensive

Good intermediate solution

Summary

- GMCA is a tool for ***decomposing a data cube into a set of components, each with an associated image and spectrum***, using a blind source separation approach.
- Its use is straightforward: one must ***choose the spatial and spectral binning, the number of components***, and an optional initialization.
- The outputs must always be ***interpreted*** with prior knowledge of the object.
- The general philosophy is to extract global information to study properties on both large and small scales, but ***individual pixels should not be over-interpreted.***
- Finally, the tool requires a ***large amount of statistics*** to operate optimally.
- Application possible to ***every type of data cube.***

Thanks for your attention !

Don’t hesitate to contact me : leila.godinaud@cea.fr