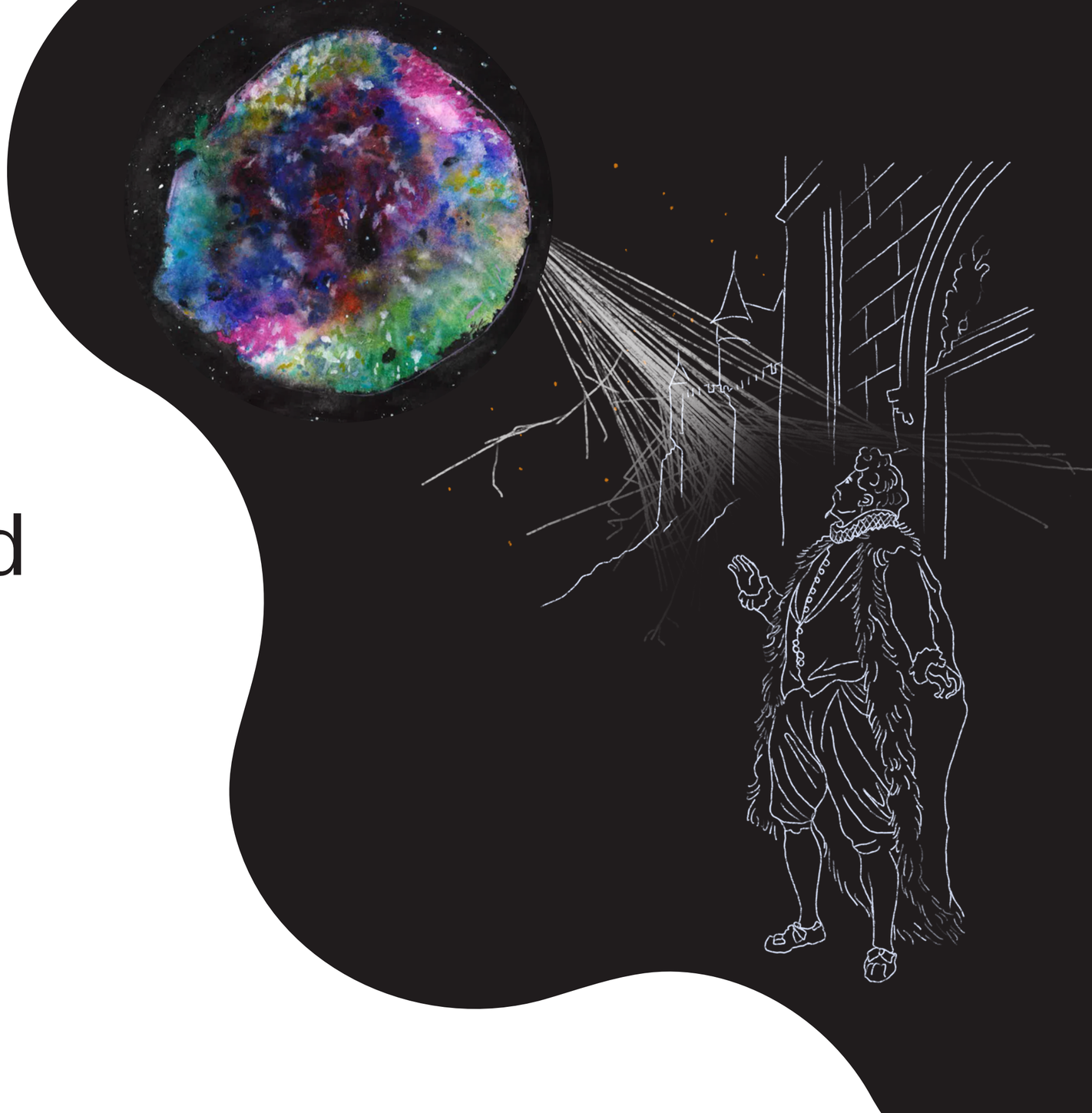
Study of Tycho SNR asymmetries with three dimensional velocity vector field



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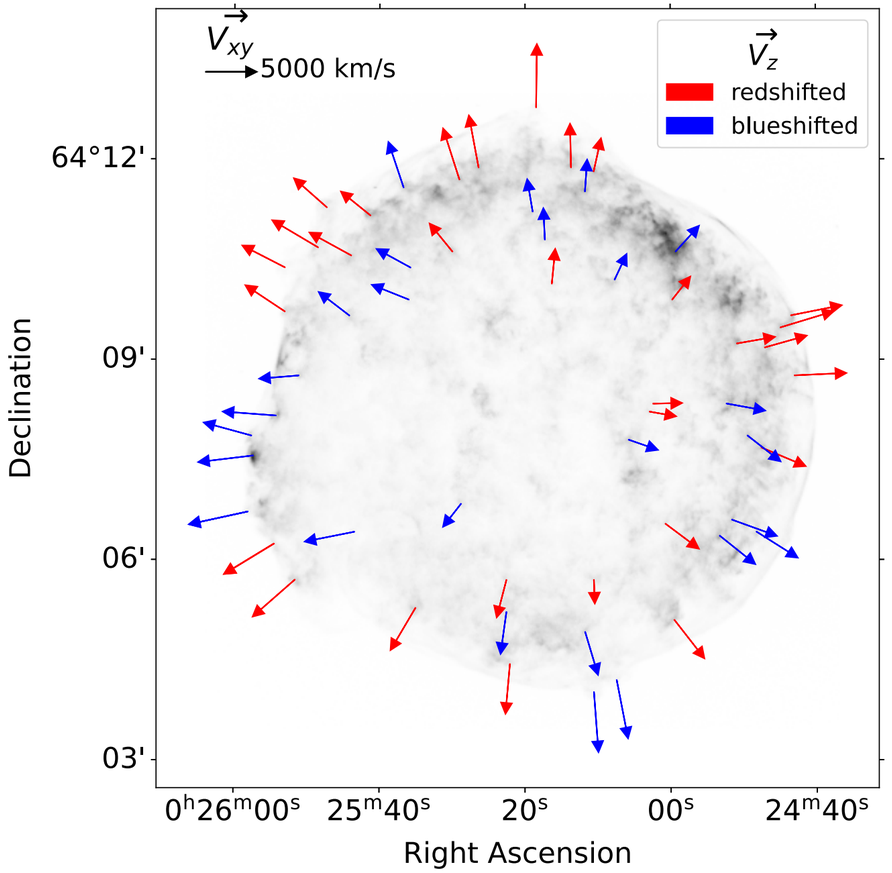
Why some new tools about the 3D ejectas dynamics ?



Plot with data from Williams et al, 2017

Origin of asymmetries ?

- Innate : asymmetries during the explosion
- Aquired : inhomegeneties in the CSM

Current methodology

- *Plane of sky* : two 1D profils to measure proper motion (Vxy) between two years
- *Line of sight* : measure of Doppler effect with spectrum fitting, deduce Vz

Limits

- Use only spectral OR spatial informations
- Limited spatial coverage (in the center)
- Not enough velocities vector to do statistics

The GMCA tool

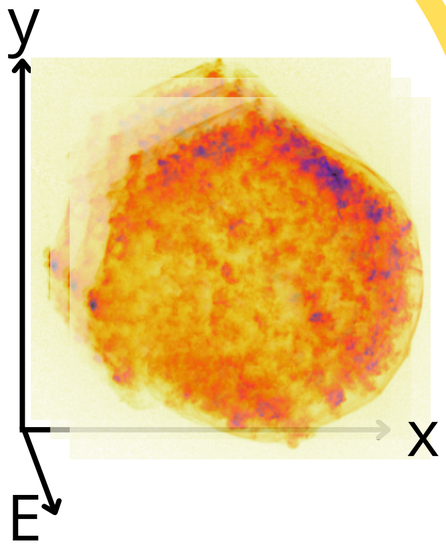
$$Cube = \sum_i Spectrum_i \; Image_i$$

General Morphological Components Analysis (GMCA) : Blind source separation in a linear combination of spectrums and images

Bobin et al, 2015

Picquenot et al, 2021

Inputs

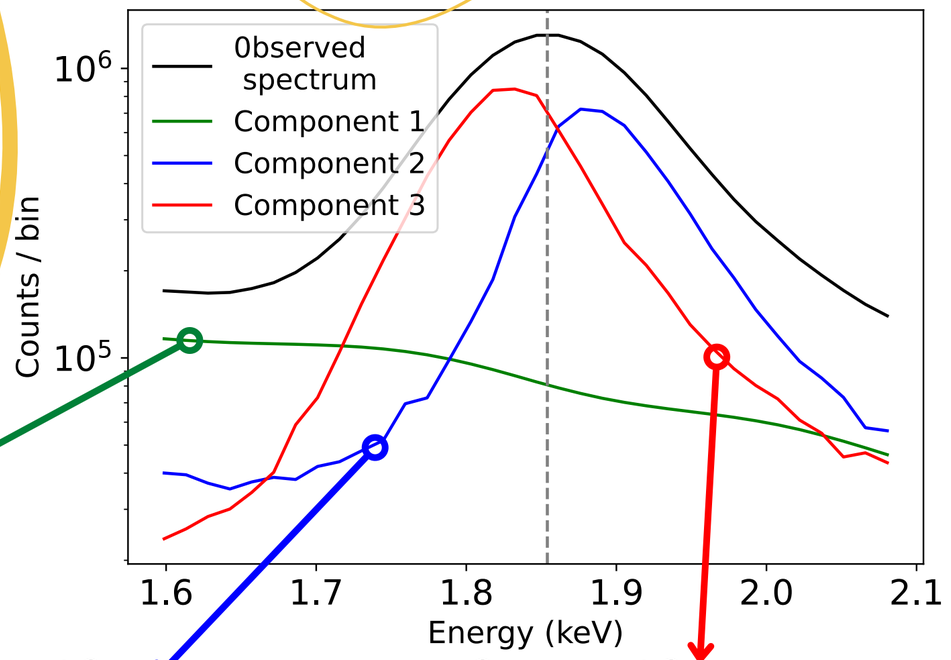


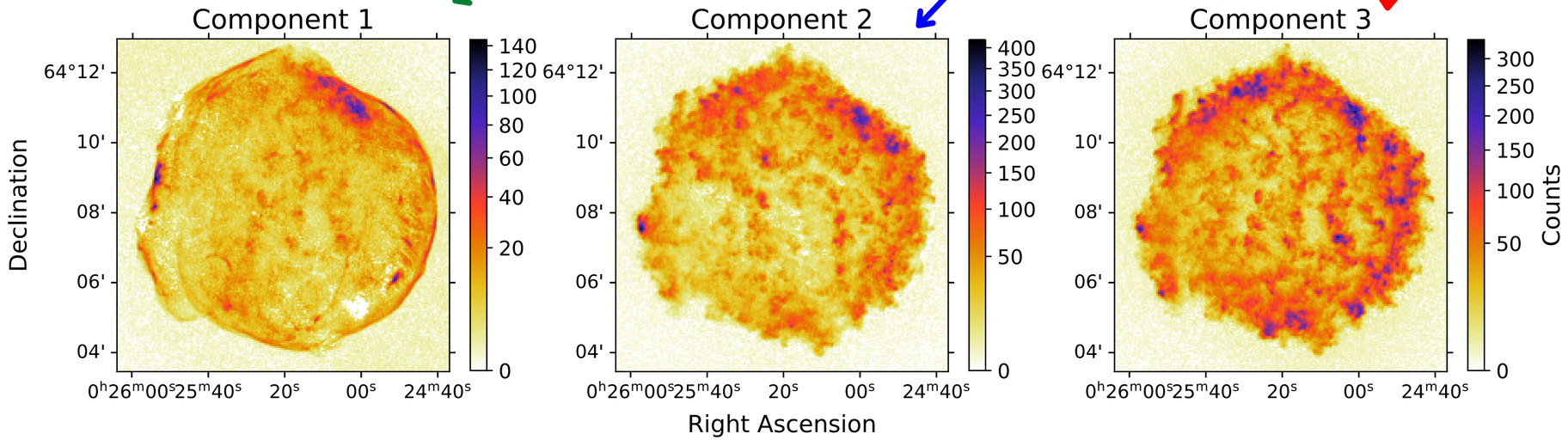
Cube of Tycho SNR, 2009

Si line (1.6 - 2.1 keV)

Chandra telescope

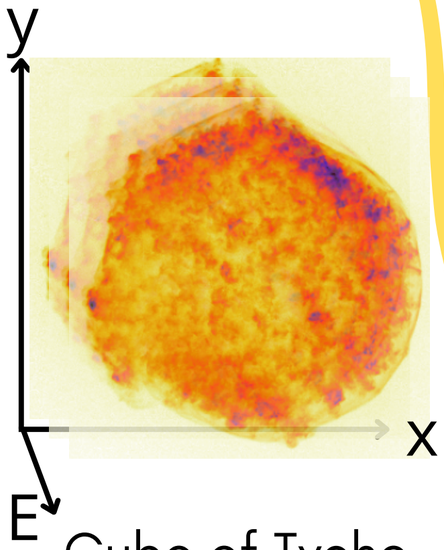
Results





The GMCA tool

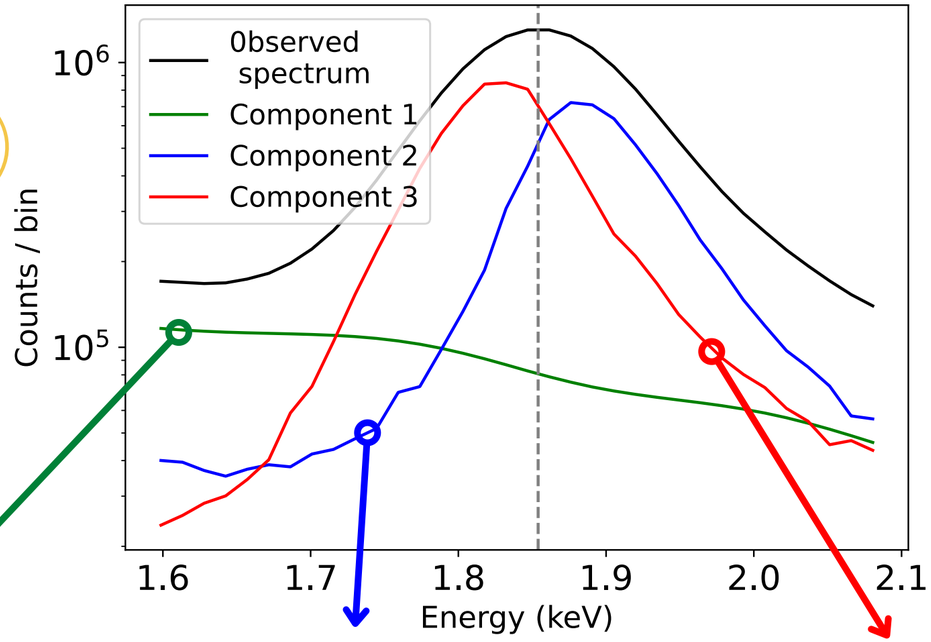
Inputs

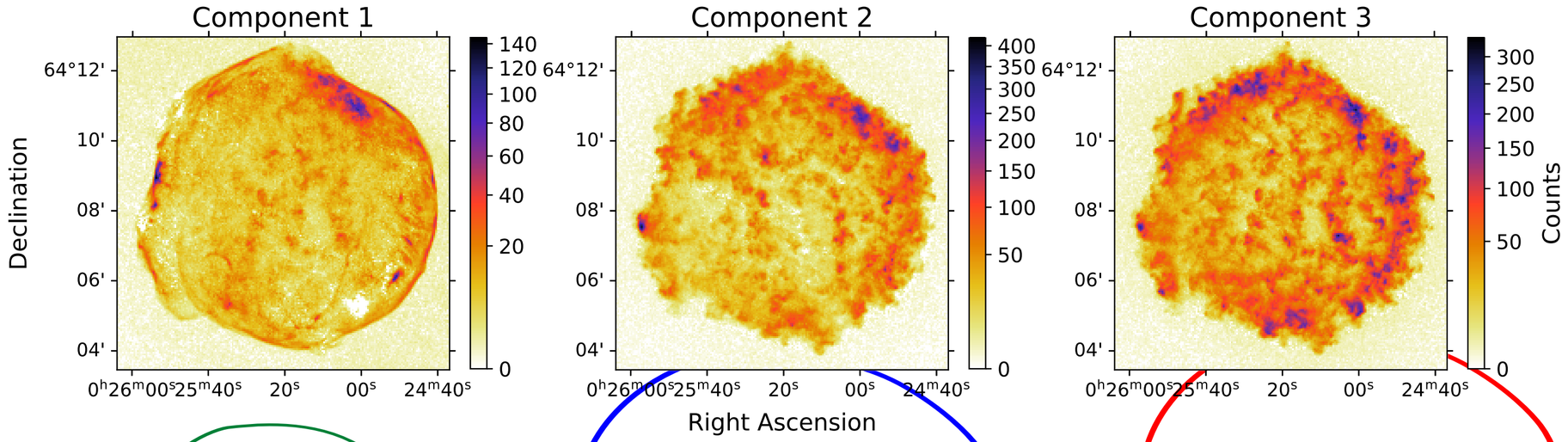


Cube of Tycho
2009
Si line

GMCA

Results





Interpretated as ...

Synchrotron emission

Blueshifted ejecta emission

Redshifted ejecta emission

Line of sight velocity from the energy centroid

Methodology

Combine red/blue GMCA images ponderated by GMCA spectral parameters

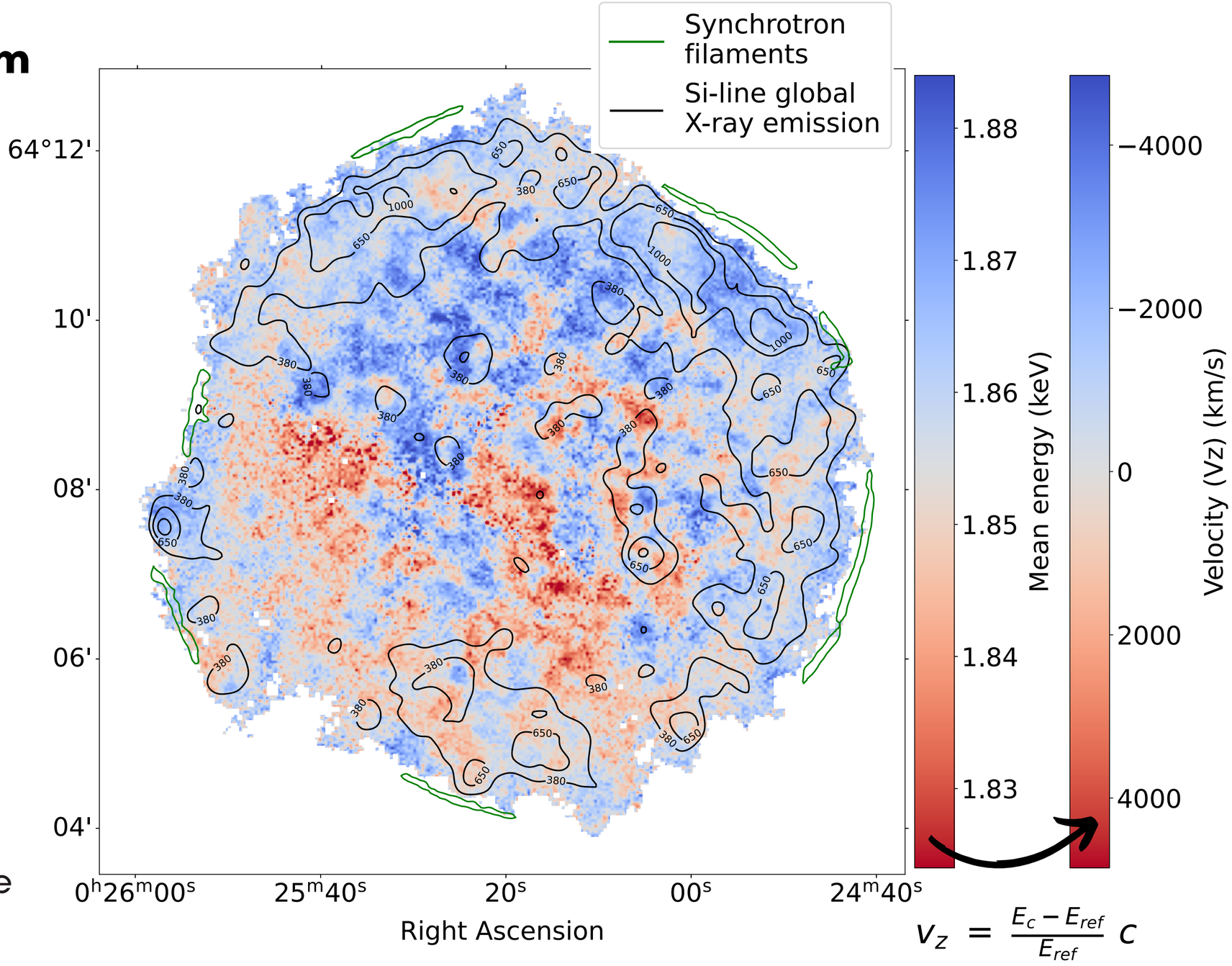
Results

NW/SE clear asymmetry

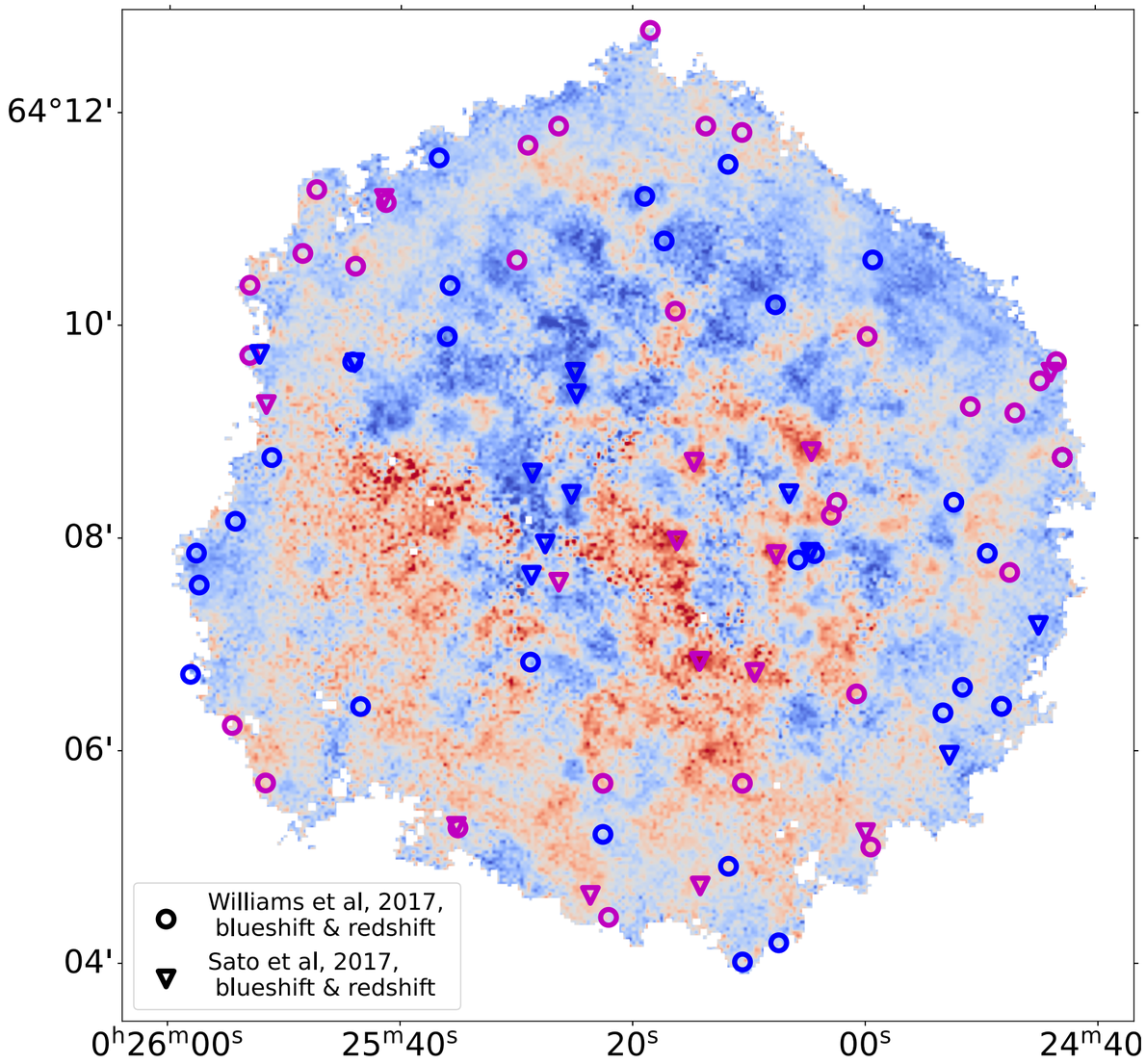
Total coverage of the SNR

Limits

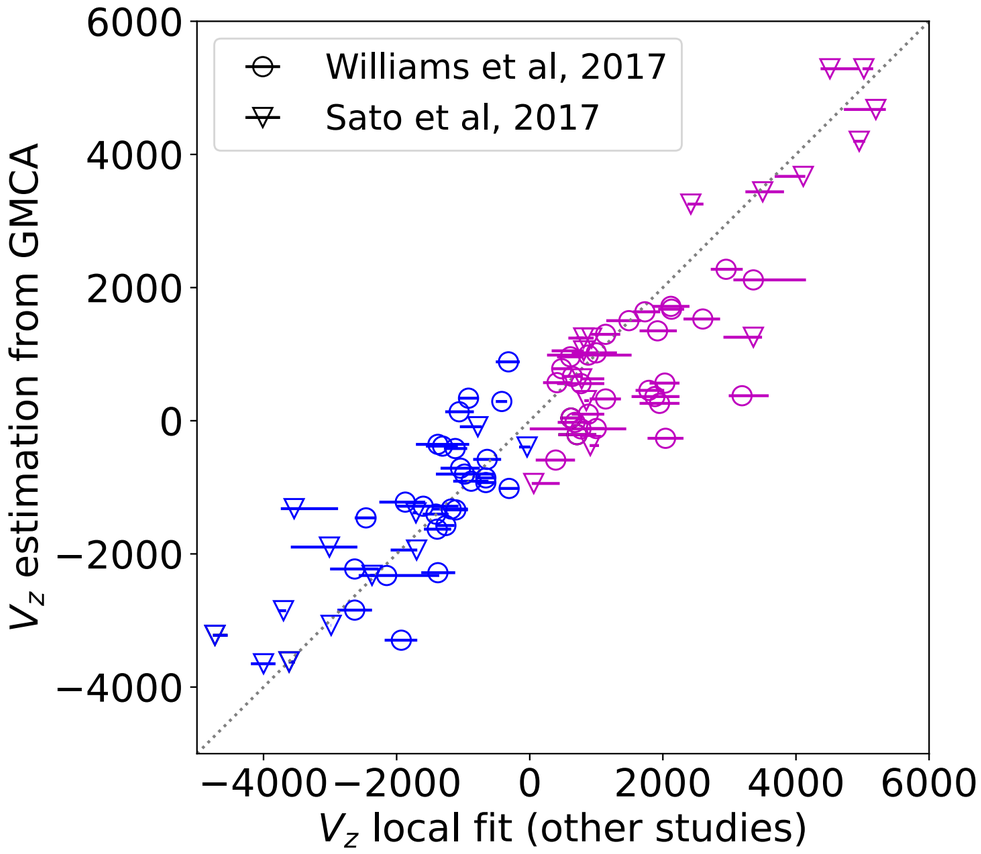
- Integrated values on the line of sight
- No uncertainties
- Only one energy of reference to obtain the velocity map



Cross checking our method



Comparing the velocity from Sato and Williams with our values at same position.

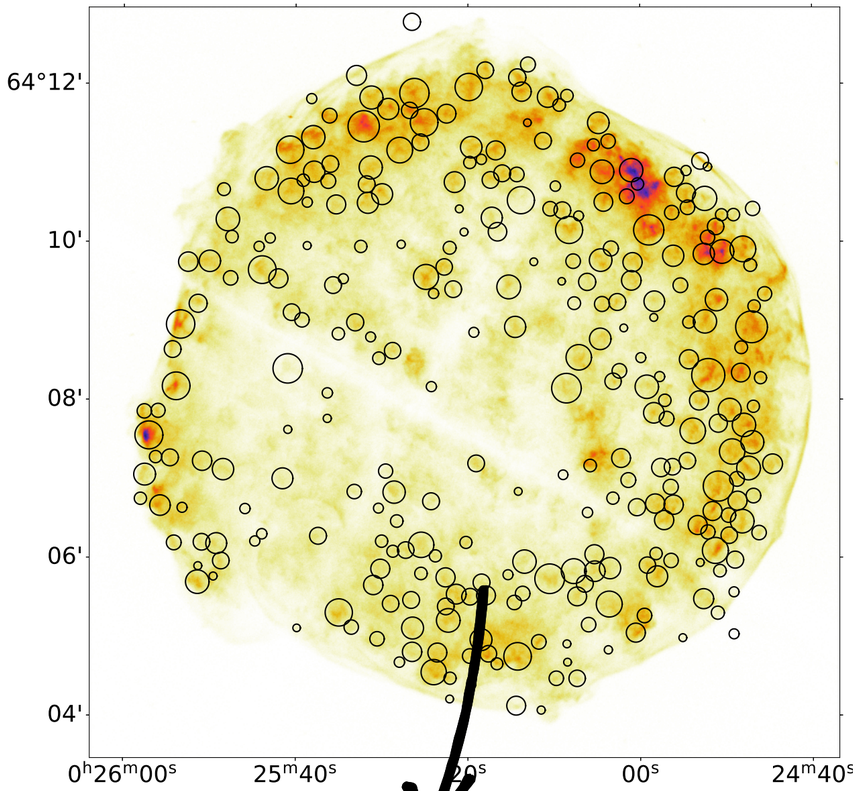


Very good agreement between our global method and other local studies.

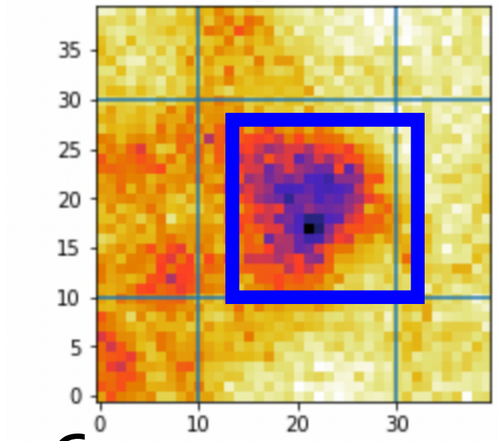
Velocity in the plane of sky : a new method

Tracking 2D features between epochs

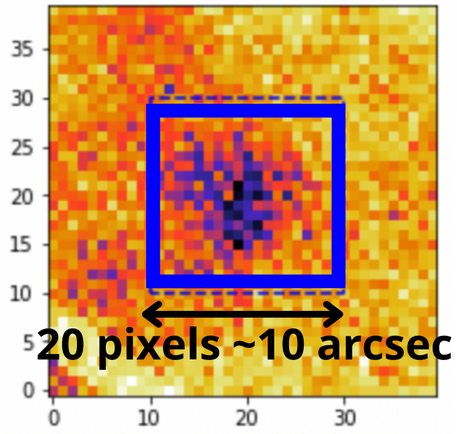
- Inspired from optical flow
- Adapted to the Poisson statistic
- 3D interpolation for sub-pixel precision
- Complete uncertainties ellipse
- Algorithm transparency

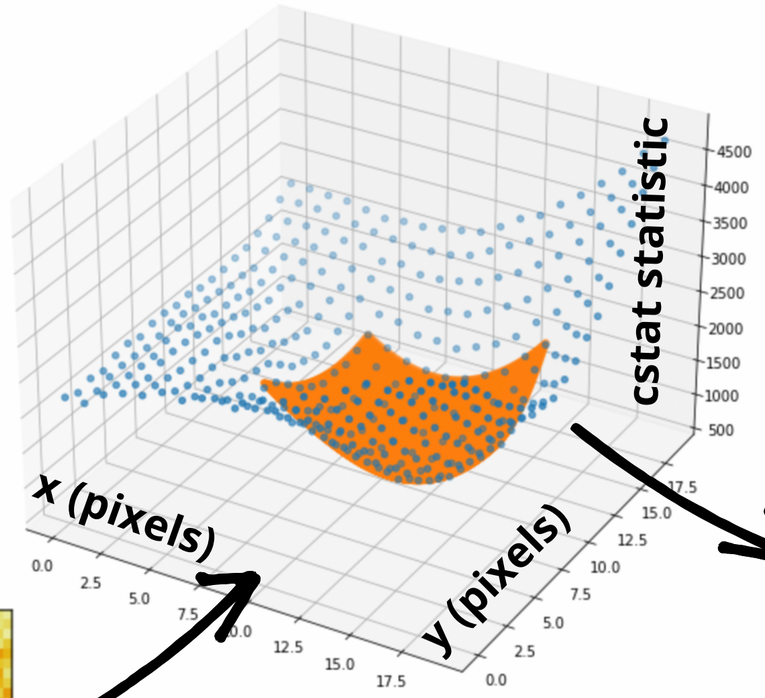


Model 2003

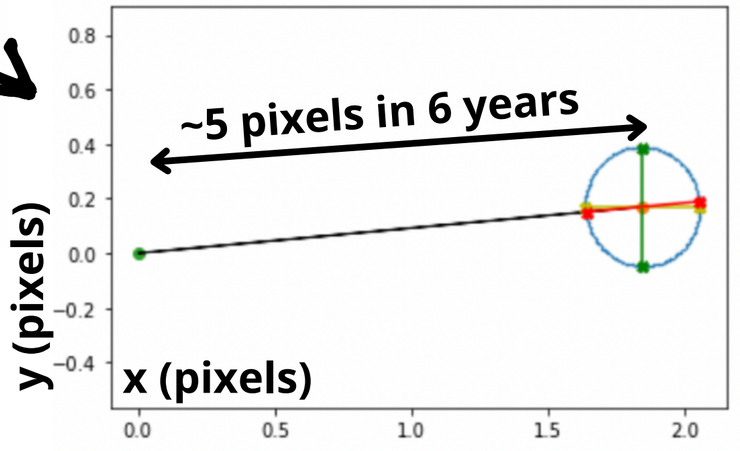


Observation 2015





Statistical landscape (cstat function)



Shift vector and uncertainties

Vector field Vxy in plane of sky

Results

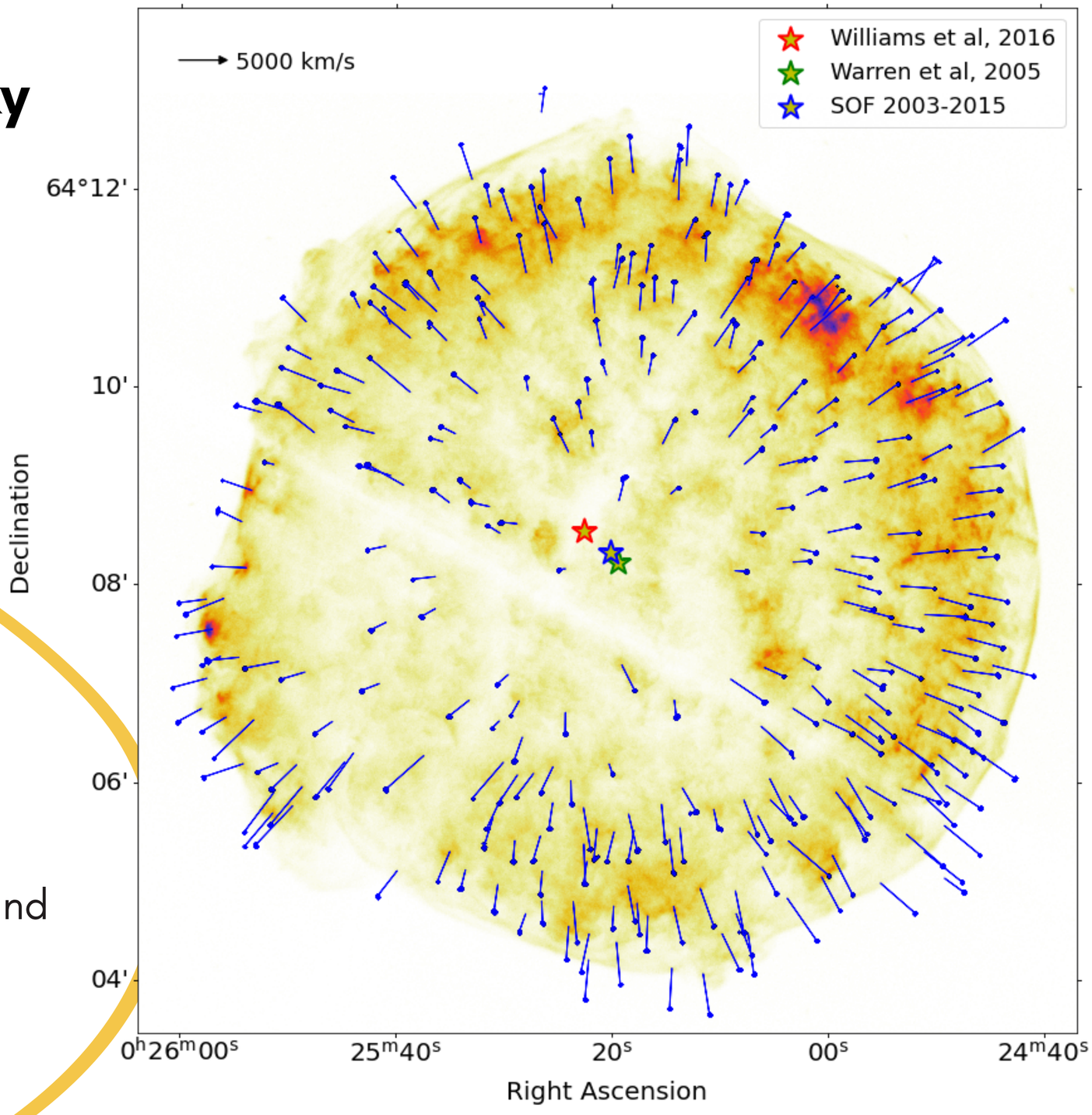
- **Hundreds of vector** (300), allowing a statistical study
- Full ellipse uncertainty (1 sigma)

Applications

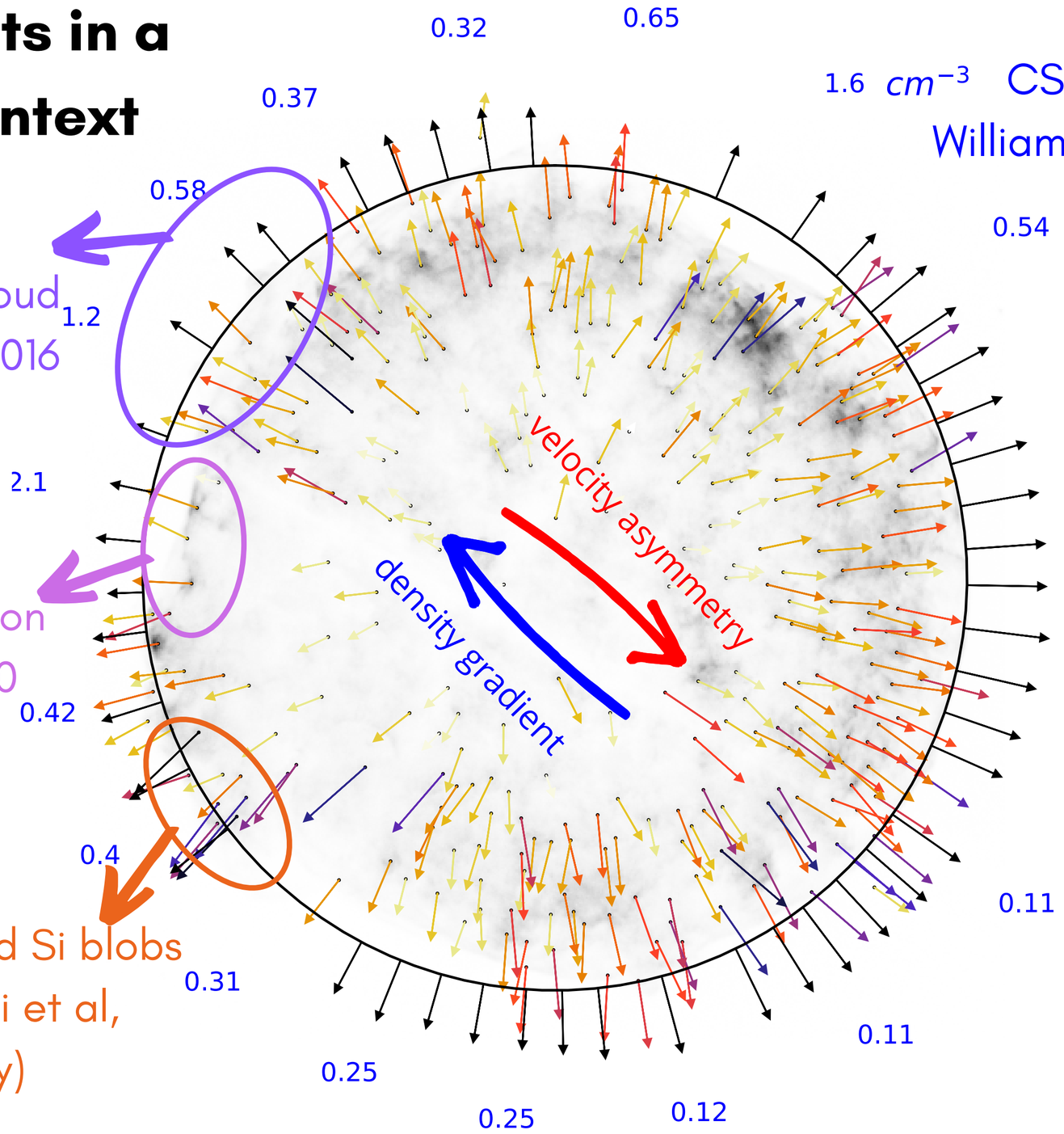
Finding a **center of explosion** using the ejecta as tracer and comparison with :

-Warren et al, 2005 : geometrical method

- Williams et al, 2016 : based on simulation and forward shock expansion



Our results in a MWL context



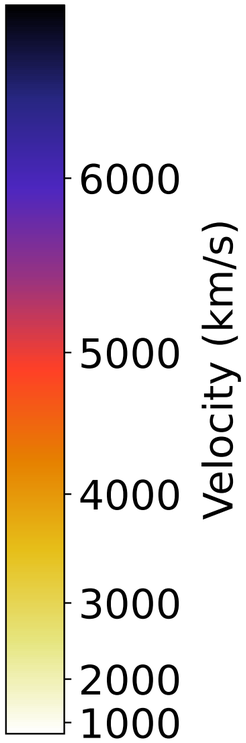
1.6 cm^{-3} CSM density gradient
Williams et al, 2013 (Infrared)

Potential molecular cloud
Zhou et al, 2016 (Radio)

Forward shock velocity : Katsuda et al, 2010 (X-ray)

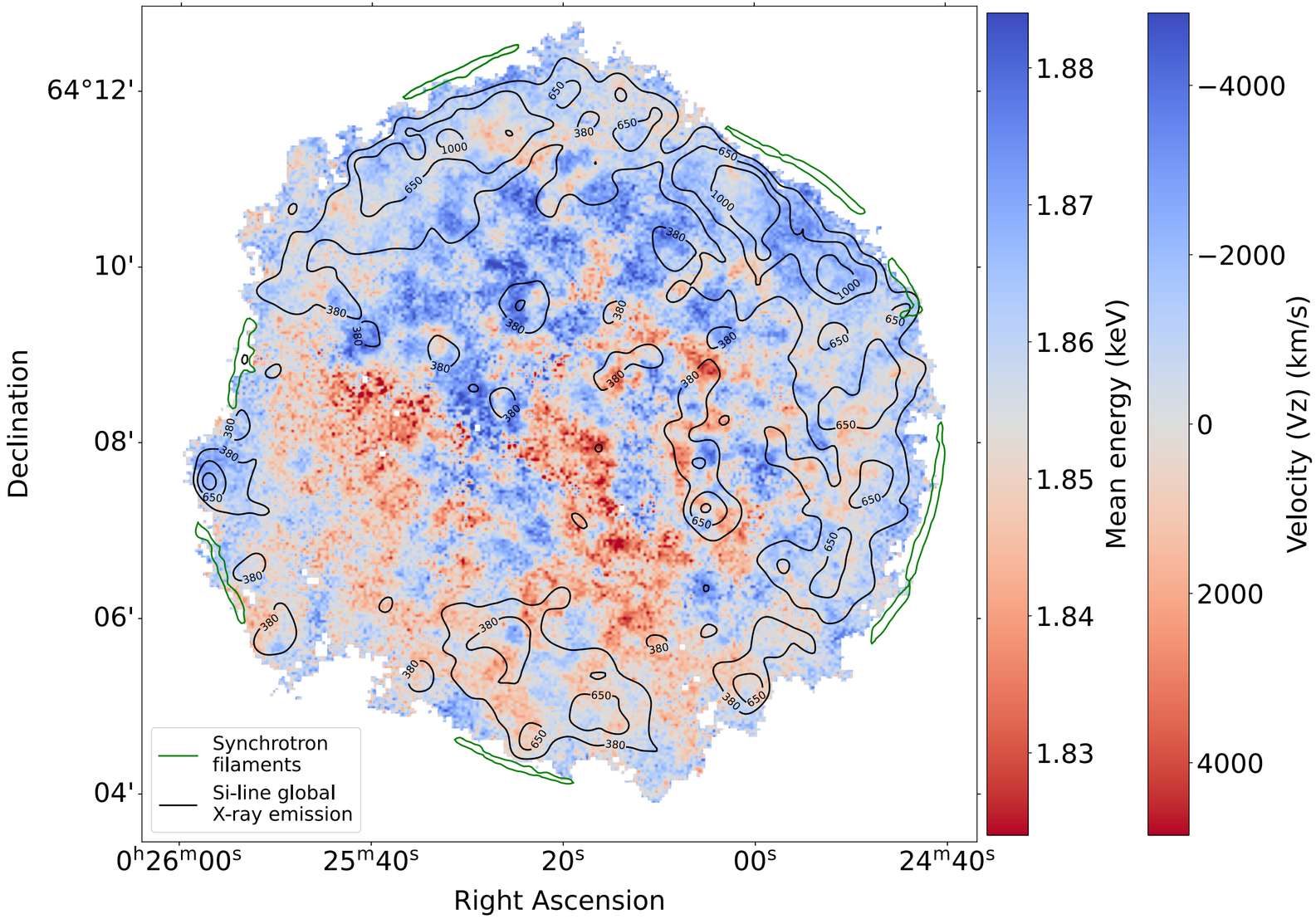
Balmer emission
Lee et al, 2010 (Optical)

Ejecta velocity field



Fast Fe and Si blobs
Yamaguchi et al, 2018 (X-ray)

Summary in the line of sight (Vz)



Methodology

- Cube decomposition with GMCA
- With the GMCA outputs, map of the energy centroid and integrated velocity in the line of sight

Results

- Asymmetries north south
- Agreement with other studies

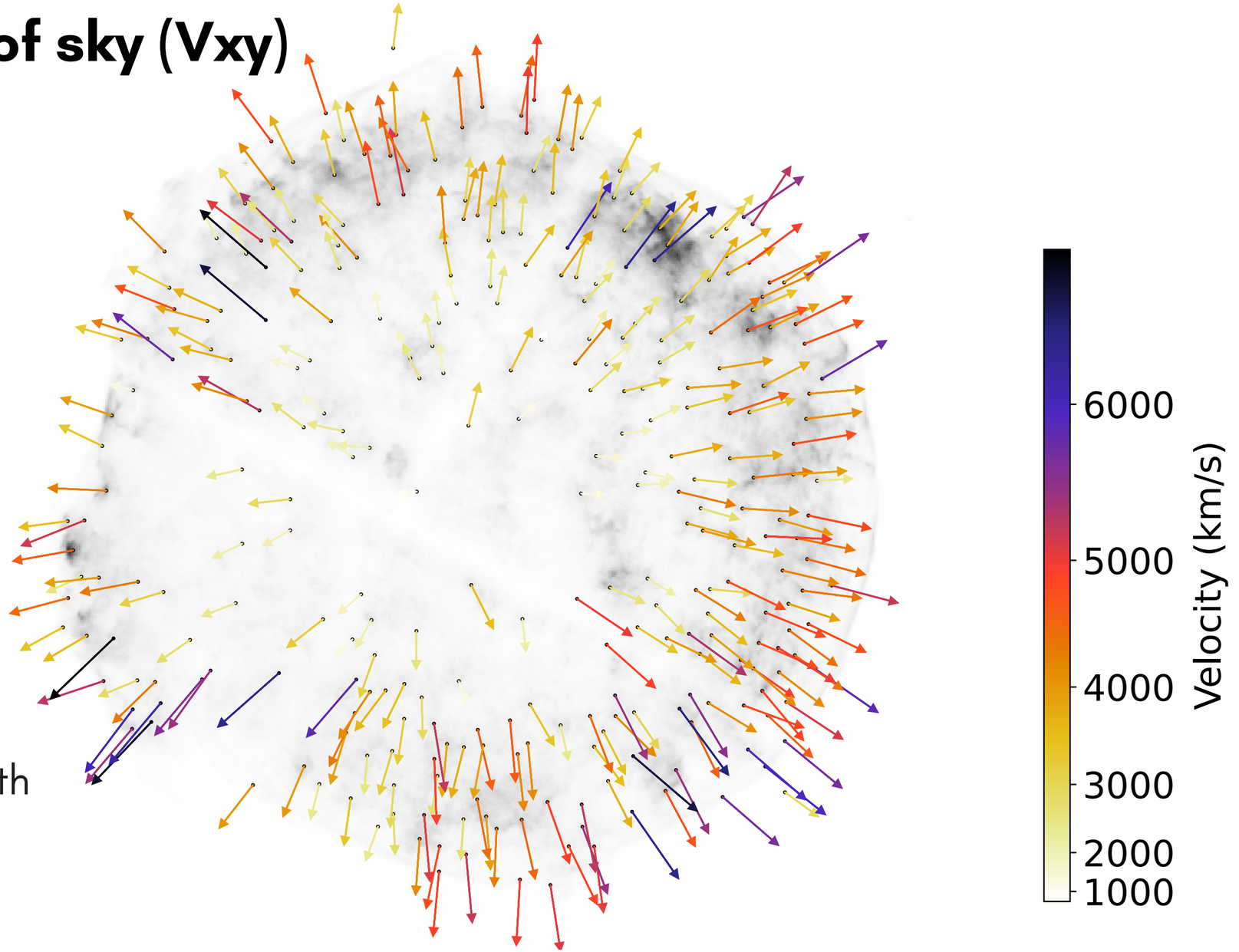
Summary in the plane of sky (Vxy)

Methodology

- New method to mesure proper motion
- Obtention of hundreds vector

Results

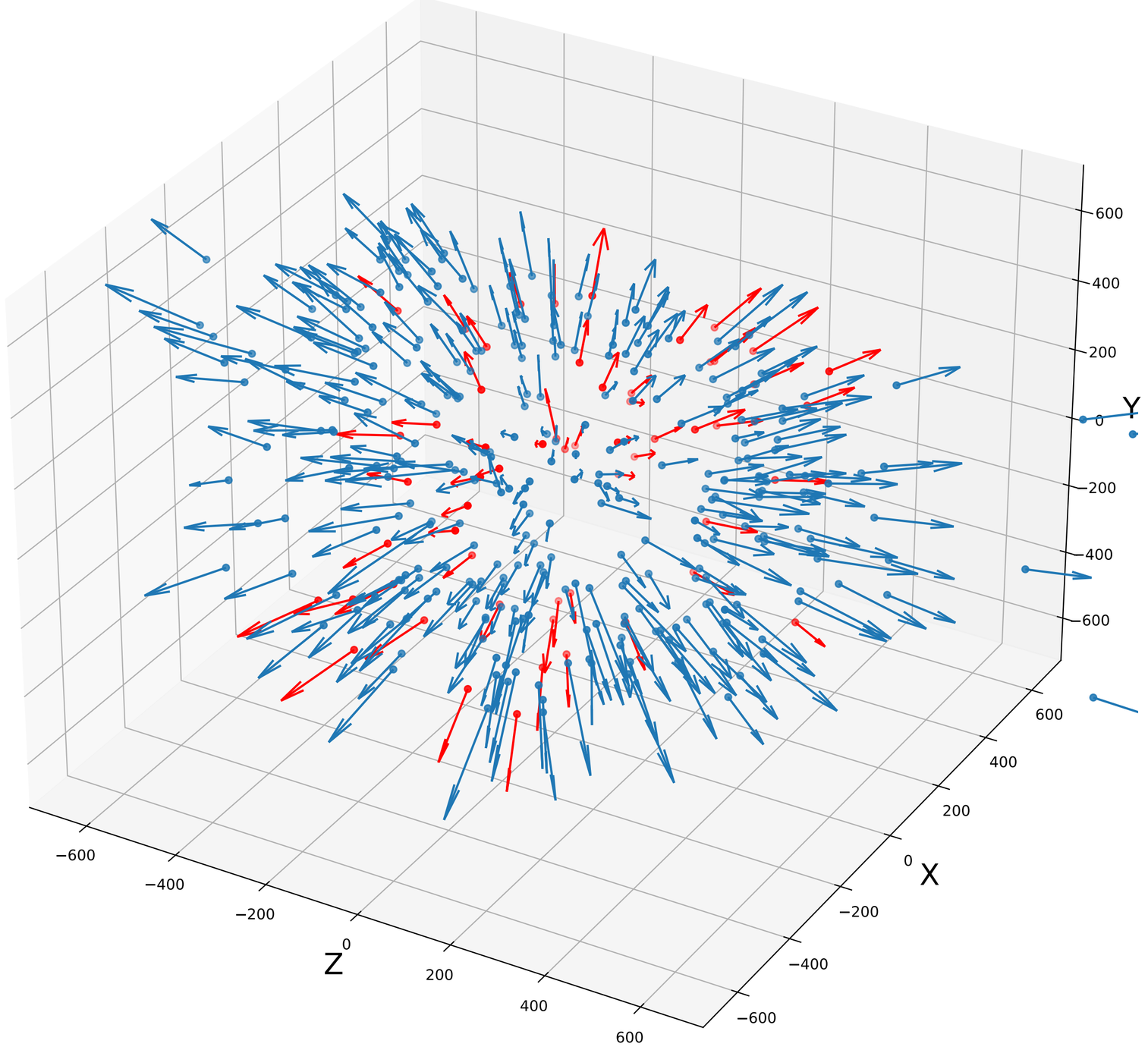
- Asymmetries north-east versus south-west
- Center of explosion deduce with this ejecta expansion



What's next ?

Toward a 3D reconstruction

- Localize the vector in the line of sight
- For now more hypothesis are needed



Thanks for your attention

And happy birthday Tycho SNR !

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Illustrations

- Gavin Leroy
- Julie Borgese

Data used in this presentation

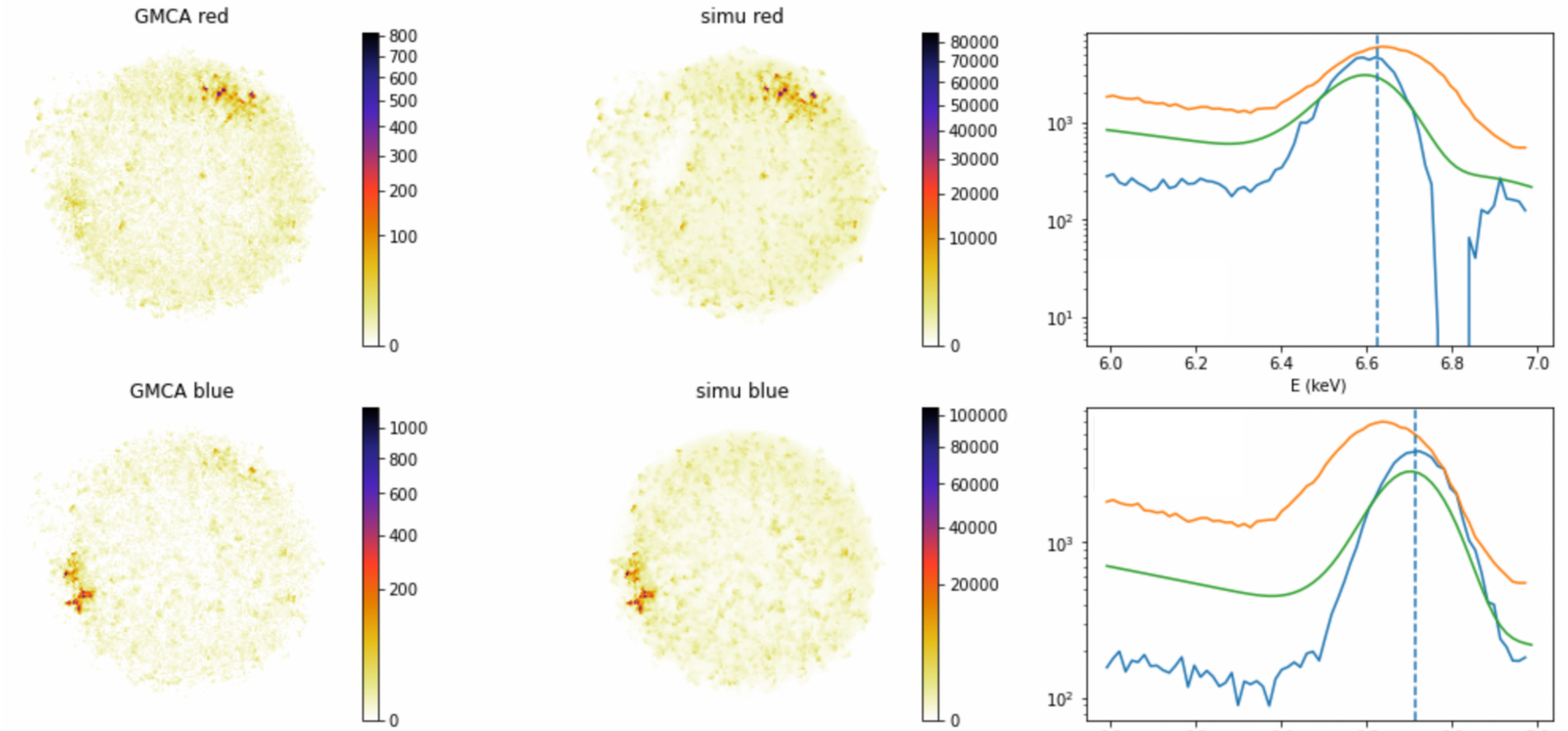
- Chandra telescope
- Williams et al, 2017
- Sato et al, 2017
- Katsuda et al, 2010
- Williams et al, 2013

Phew it's over ...

But there are some backups !

GMCA check with simulations

With the data (x,y,z,E) from S. Orlando simulation of CasA, we compare :



GMCA results with the simulated cube (x, y, E) centered on Fe line

The two images of the half shells with position z>0 or z<0 (Fe line)

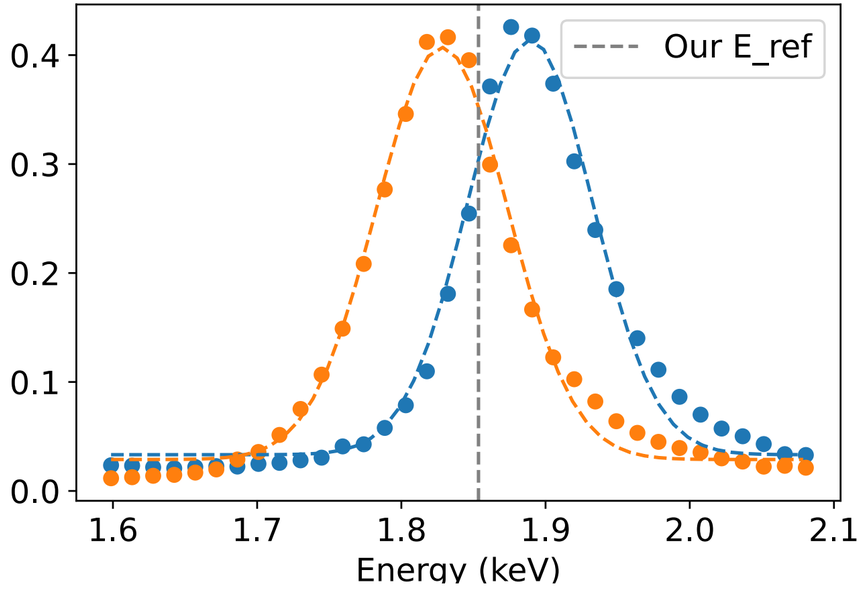
- Total spectrum
- GMCA ouput
- spectrum from half shell

Method to obtain Ec map

1) We use GMCA's definition to "reconstruct" the spetrum in each pixel (i,j)

$$Spectrum_{i,j} = \sum_{Component\ k} Image_{GMCA,k,i,j}\ Spectrum_{GMCA,k}$$

2) We fit the GMCA spectrum with a gaussian. We obtain an analytical expression of these spectra and so, of the spectrum in each pixel.



3) To find the maximum of the silicon line Ec in the spectrum of each pixel, we must to solve this equation :

$$\frac{d\ Spectrum_{i,j}\ (E_c)}{dE} = 0$$

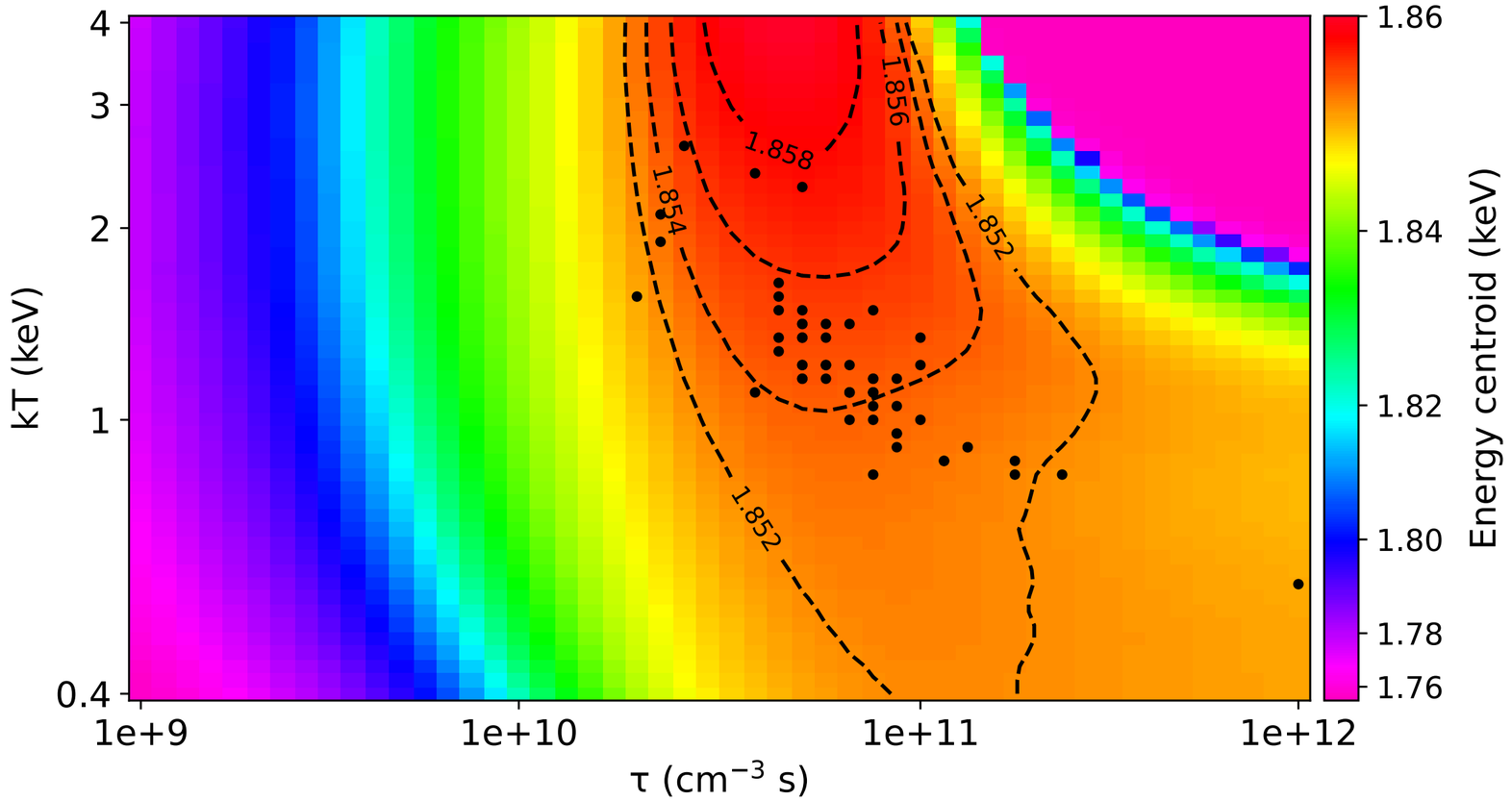
4) And an analytical proxi of the solution is :

fit parameters from GMCA's spectrum red and blueshifted

$$E_c = \frac{Image_{ij,r}\ \frac{\alpha_r}{\sigma_r^2}\ E_{r,mean} + Image_{ij,b}\ \frac{\alpha_b}{\sigma_b^2}\ E_{b,mean}}{Image_{ij,r}\ \frac{\alpha_r}{\sigma_r^2} + Image_{ij,b}\ \frac{\alpha_b}{\sigma_b^2}}$$

GMCA's image red and blueshifted

Energy at rest

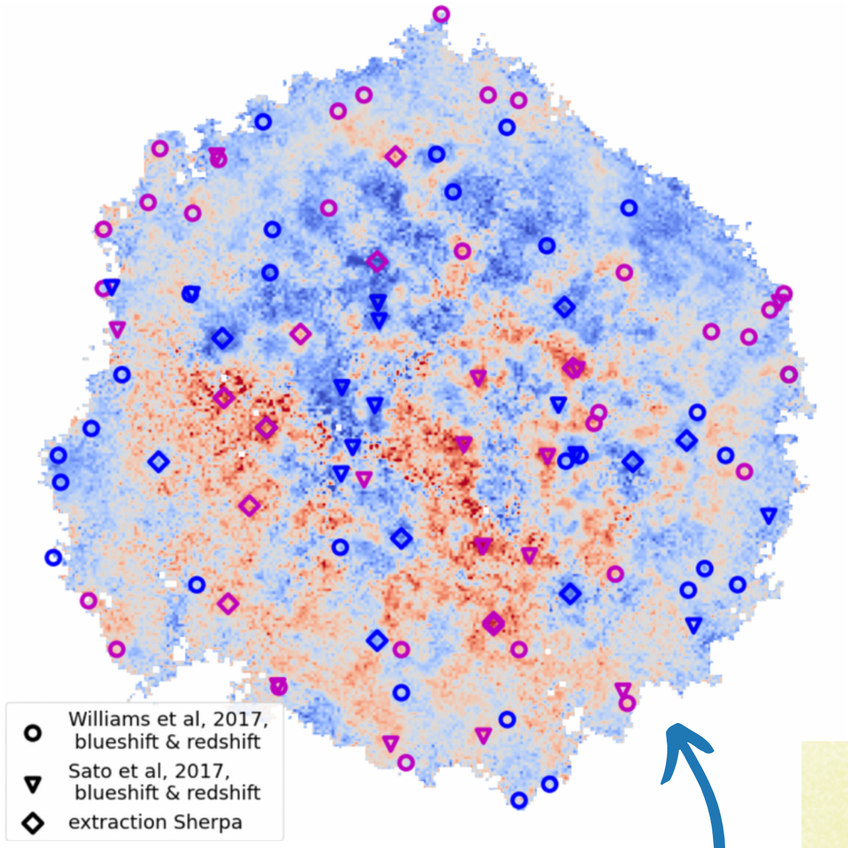


- Map : silicon energy centroid from vnei library with kT and tau variation but no redshift

- Points : (kT, tau) measurements from the article Williams et al, 2017

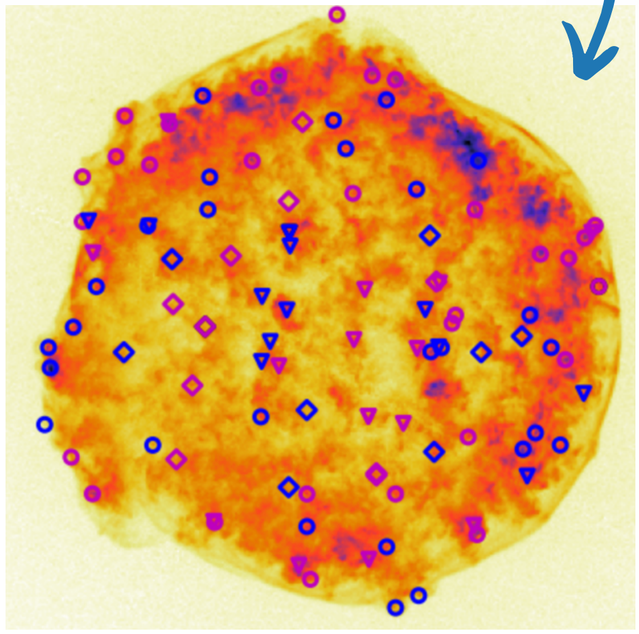
- We take the mean value with contour that seems to optimize the points

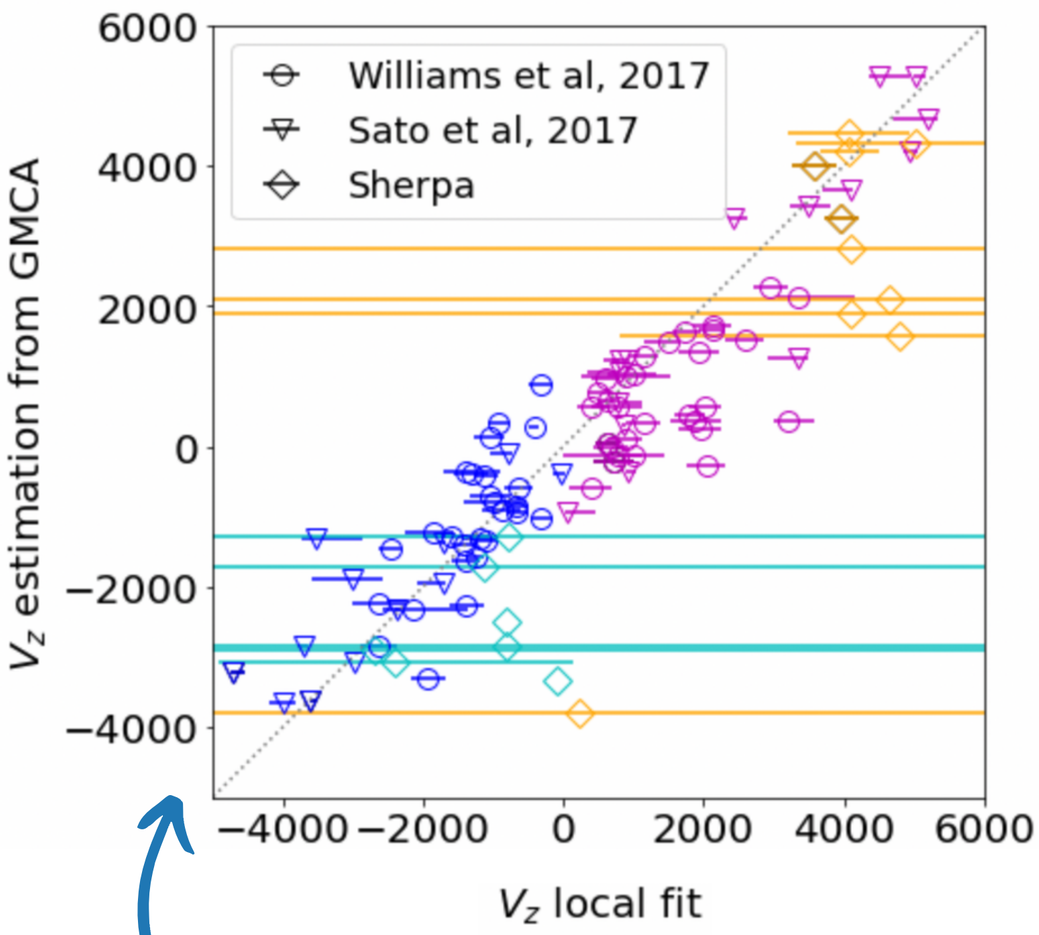
Spectrum extraction with Sherpa



Our silicon energy centroid reconstruction and points from :
- articles (Williams 2017 and Sato 2017)
- our first fast check

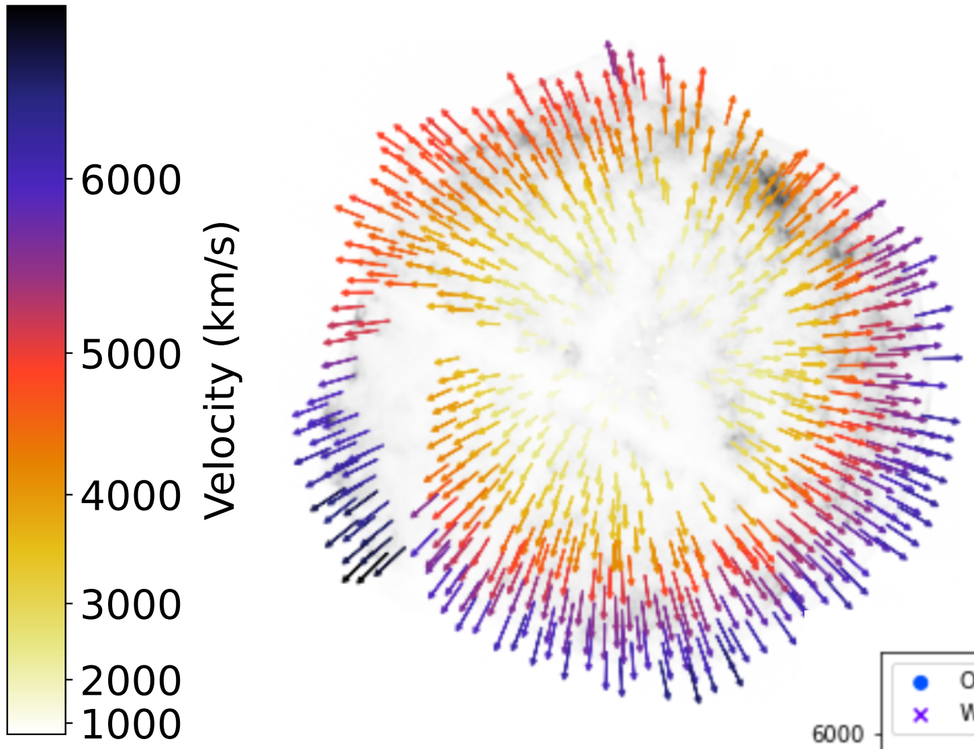
Total image in the Si-band and the same points.
Our points are not choosen to be bright blobs.





For now, our global method seems agree with local method but difficult to say because of uncertainties of the fit

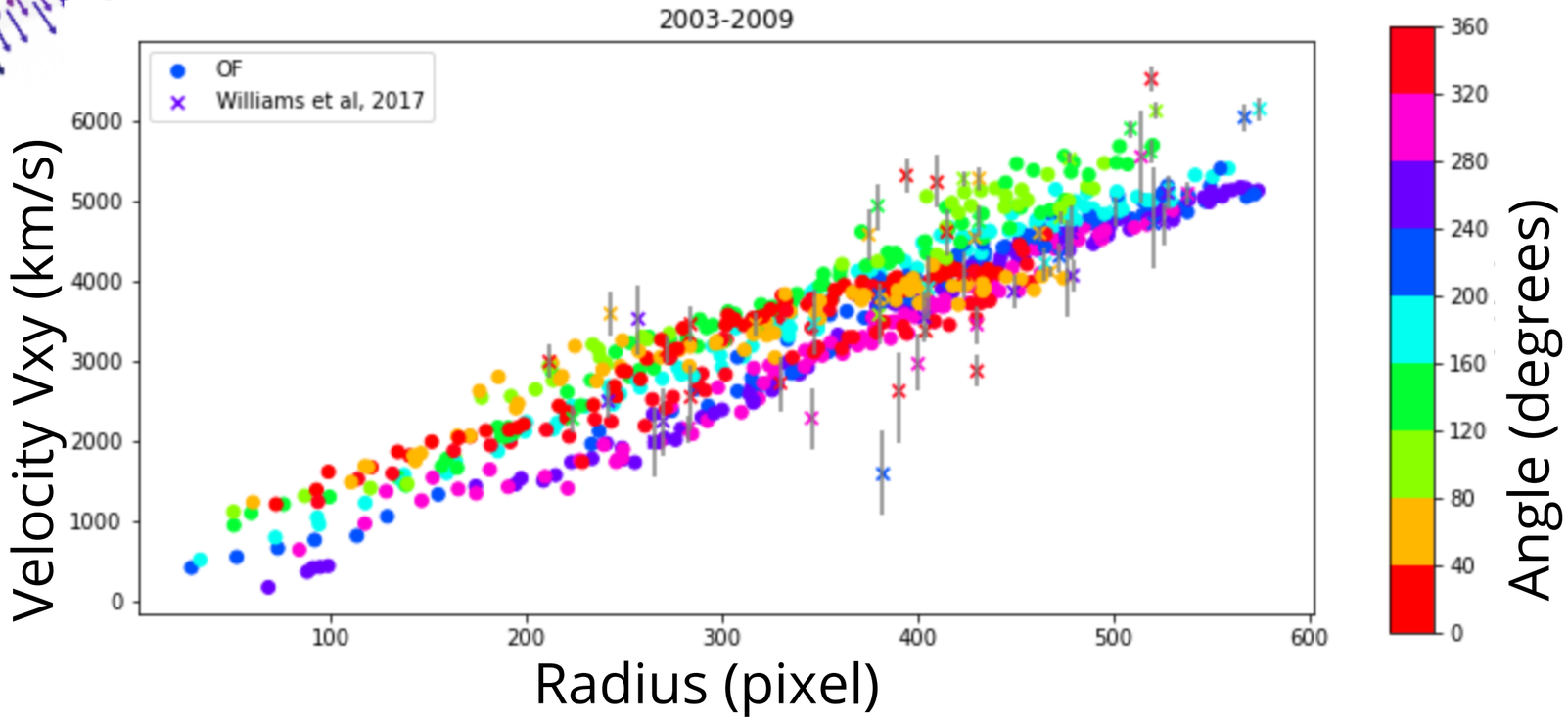
Optical Flow in the plane of sky



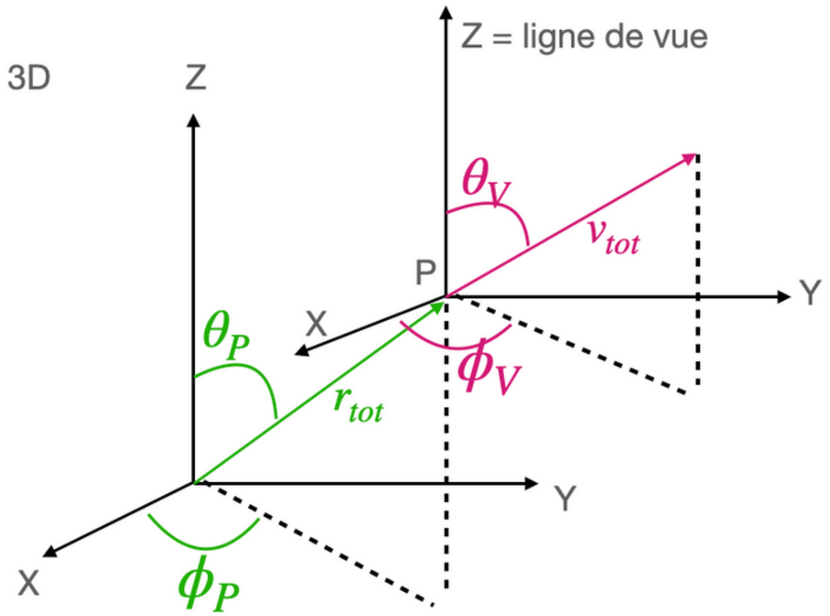
- Tool OpticalFlow from the library OpenCV
- Normaly for Computer Vision
- But results for SNR with big uncertainties on the fiability of the tool

Velocities asymetries map (above)

Relation between Vxy and radius with colors for angle ->



3D reconstruction



$$v_z = v_{tot} \cos\theta_V$$

$$v_{xy} = \sqrt{v_x^2 + v_y^2} = v_{tot} \sin\theta_V$$

$$r_z = r_{tot} \cos\theta_P$$

$$r_{xy} = \sqrt{r_x^2 + r_y^2} = r_{tot} \sin\theta_P$$

If we suppose that **radius and velocity vectors are colinear** $\theta_V = \theta_P$ we find :

$$r_z = \frac{V_z}{V_{xy}} r_{xy}$$