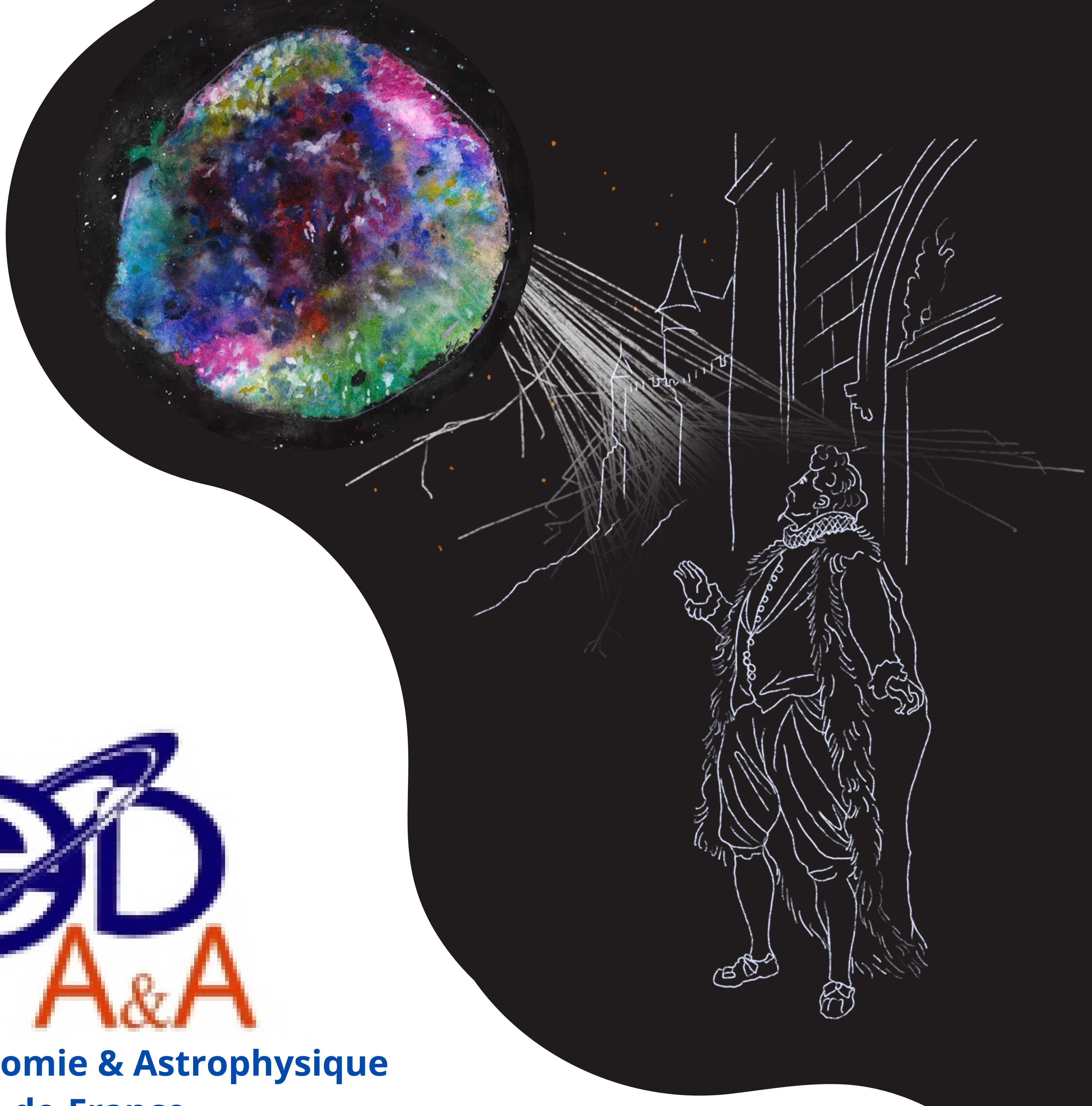
3D dynamic study *for the 450th anniversary of Tycho supernova remnant*



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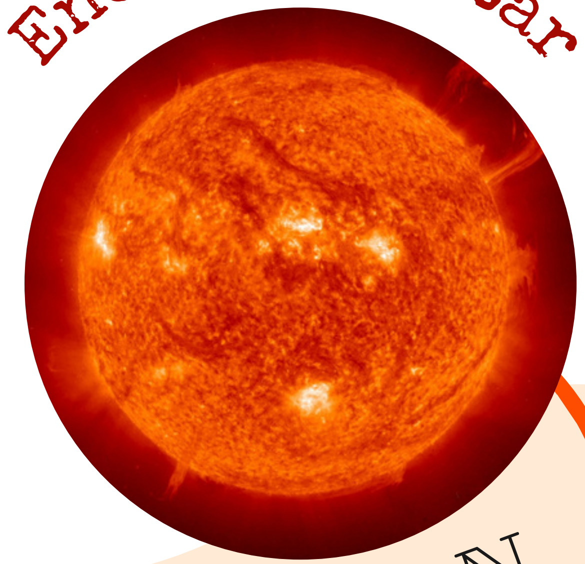
Rencontre Jeunes Physiciens
2 Novembre 2022

ED 127 d'Astronomie & Astrophysique d'île-de-France


End of life star


End of life star
EXPLOSION
Supernova

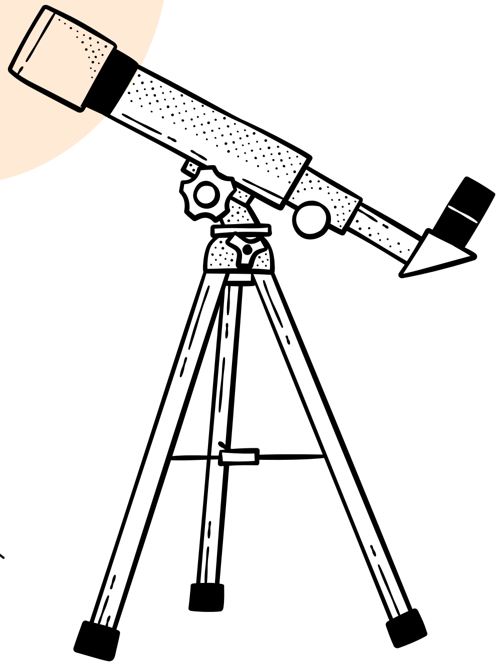
End of life star



EXPLOSION

Supernova

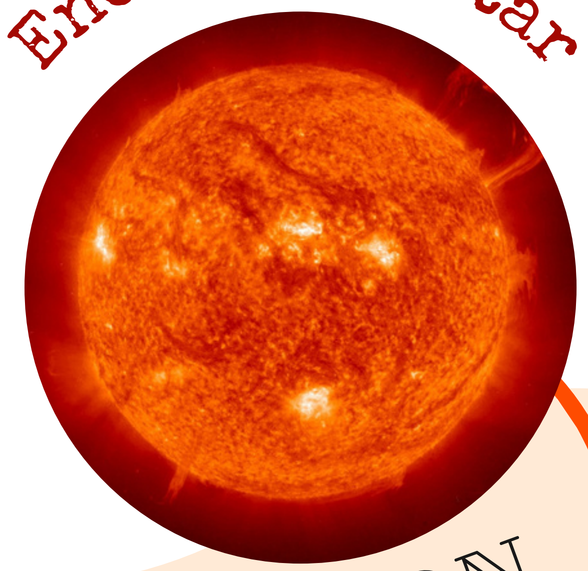
HISTORICAL OBSERVATION



Observed on November 11th 1572 !

Tycho Brahe (1546-1601)

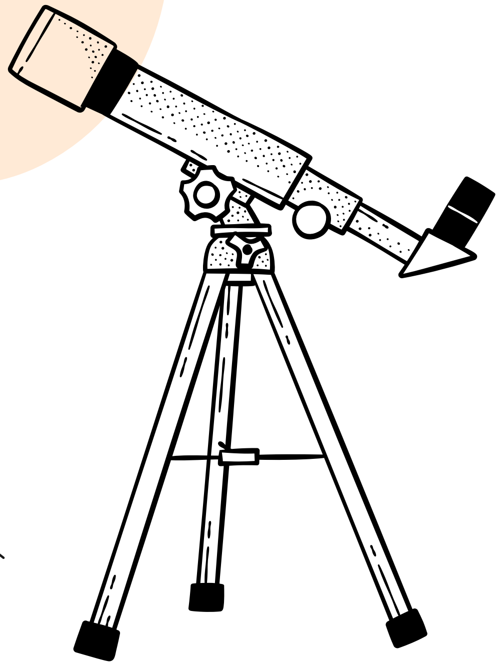
End of life star



EXPLOSION

Supernova

HISTORICAL OBSERVATION

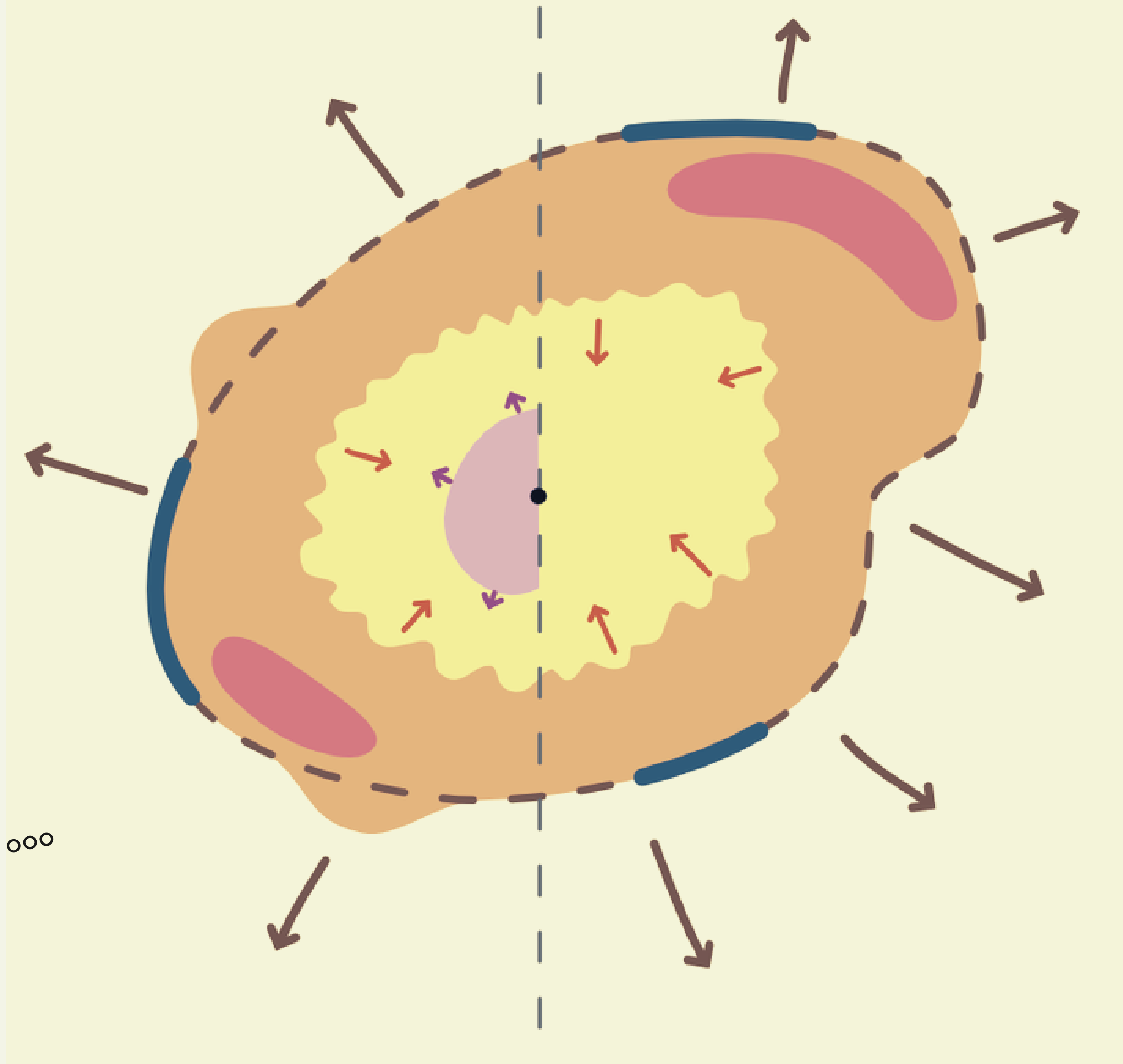


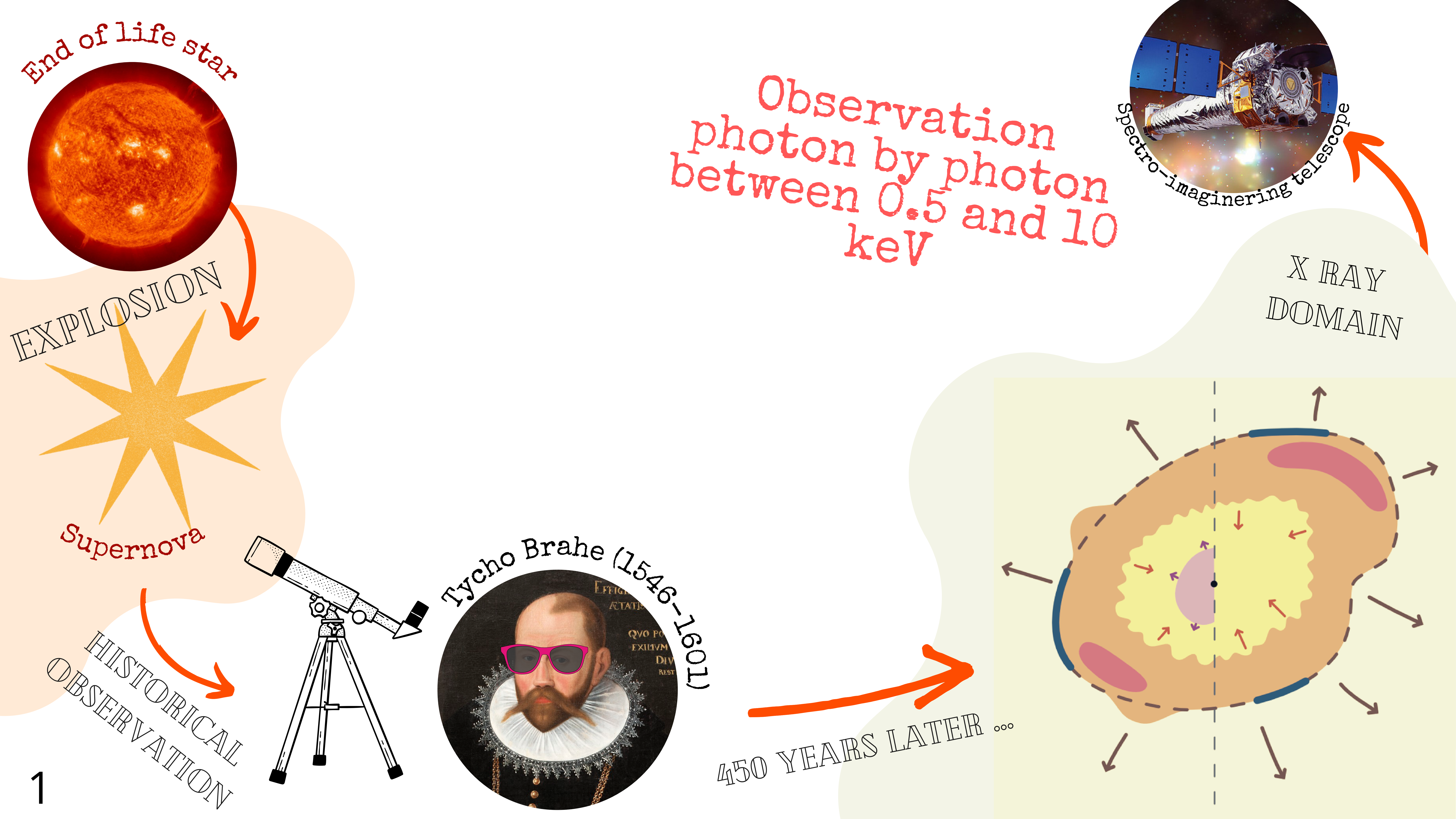
Tycho Brahe (1546-1601)

A forward shock and a reverse shock which heats the ejecta

X RAY DOMAIN

450 YEARS LATER ...




End of life star
EXPLOSION
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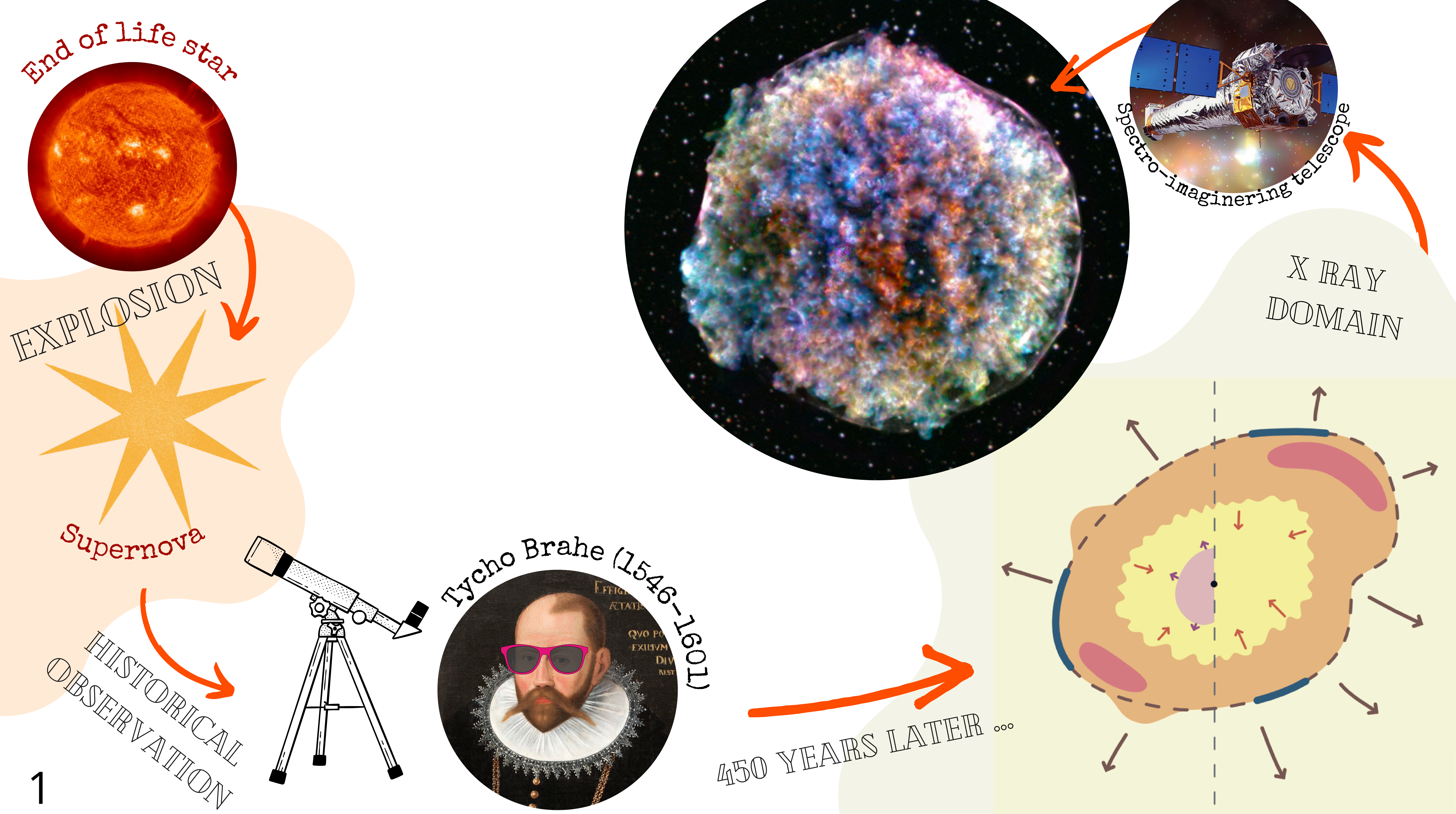
HISTORICAL OBSERVATION
Tycho Brahe (1546-1601)
450 YEARS LATER ...
X RAY DOMAIN
Spectro-imaginering telescope
Observation photon by photon between 0.5 and 10 keV
1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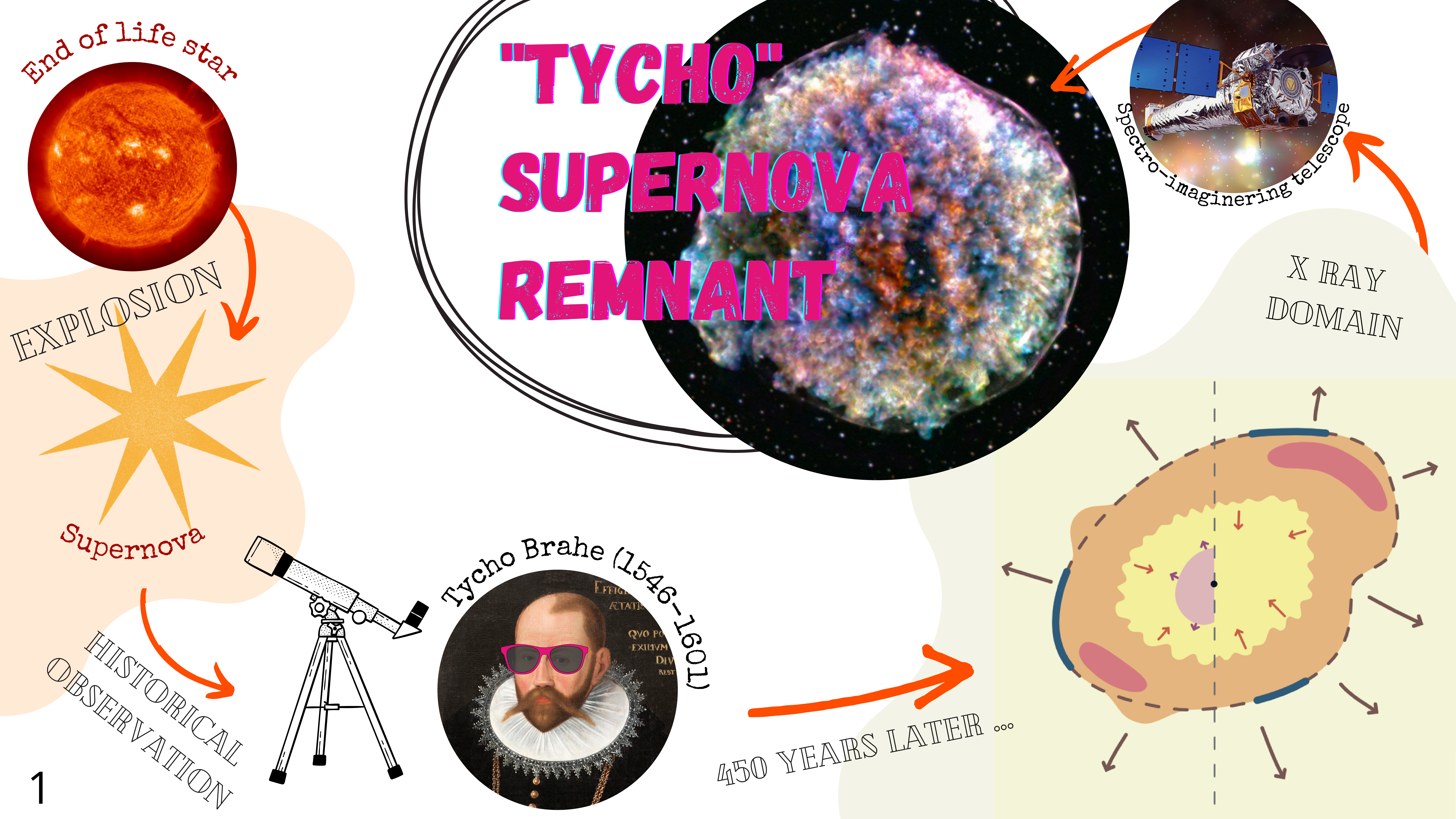
"TYCHO" SUPERNOVA REMNANT
End of life star
EXPLOSION
Supernova
HISTORICAL OBSERVATION
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450 YEARS LATER ...
X RAY DOMAIN
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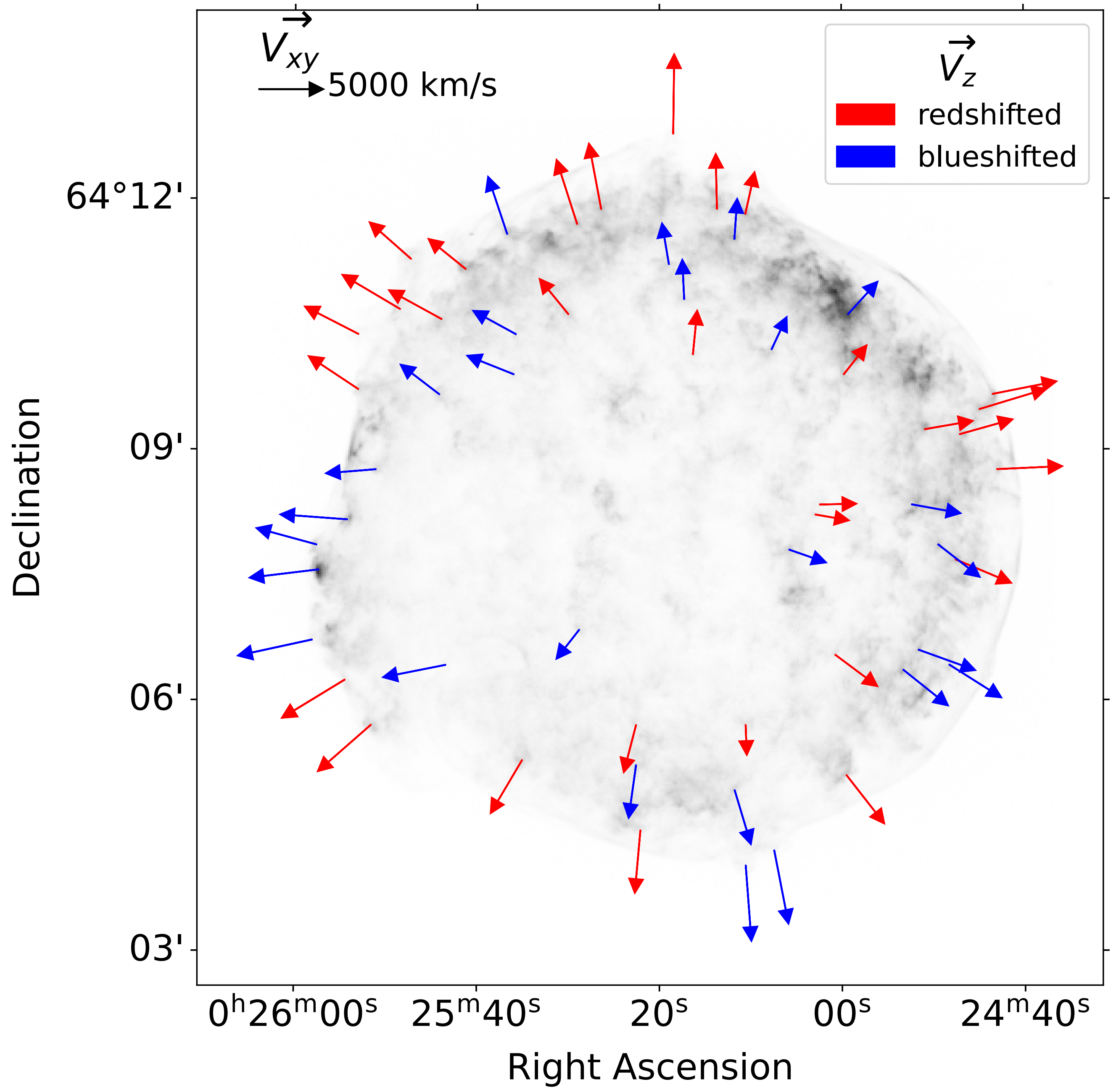
1

Why some new tools about the 3D ejectas dynamics ?



Plot with data from Williams et al, 2017

Origin of asymmetries as a probe of the supernova

- 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

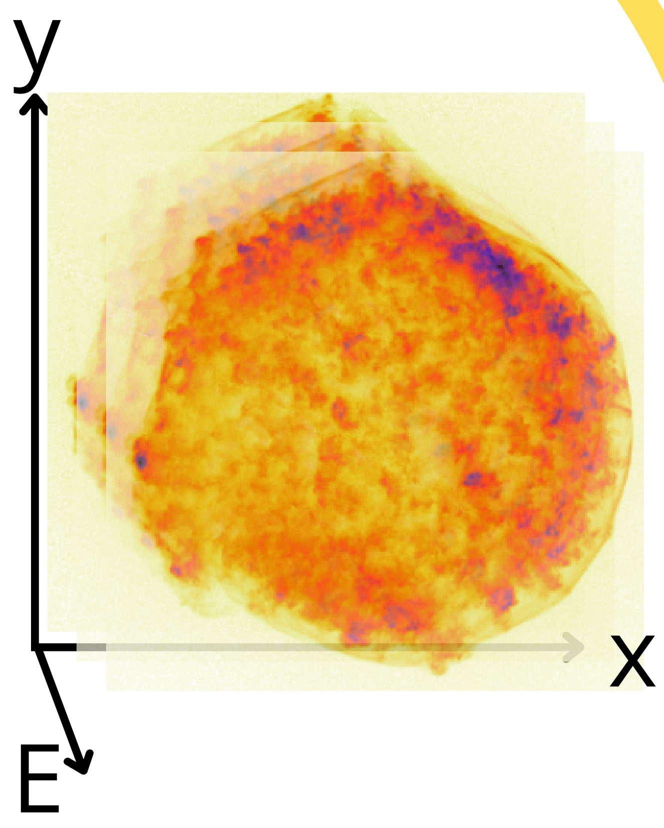
$$Cube = \sum_i Spectrum_i \ Image_i$$

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



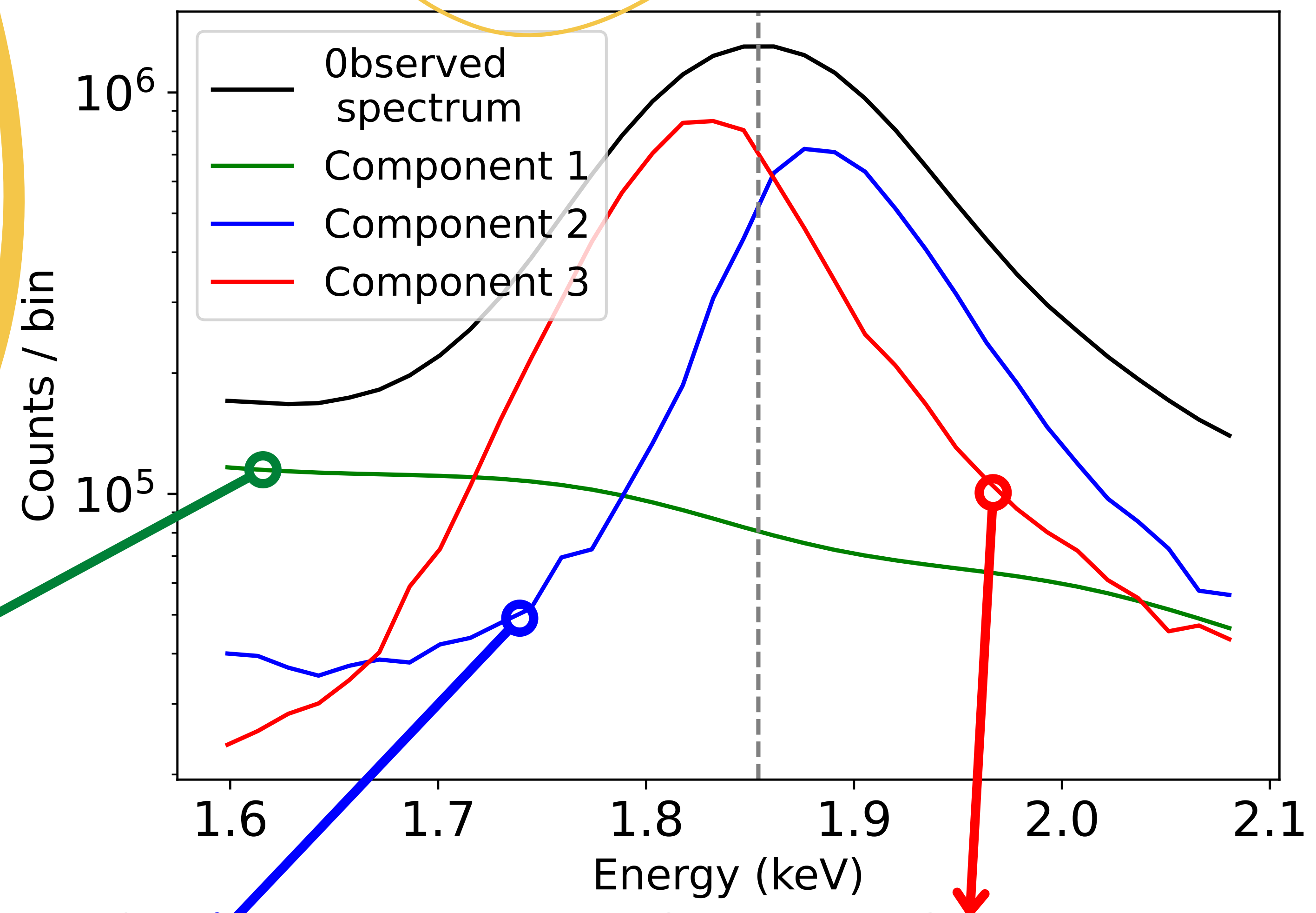
Cube of Tycho SNR, 2009

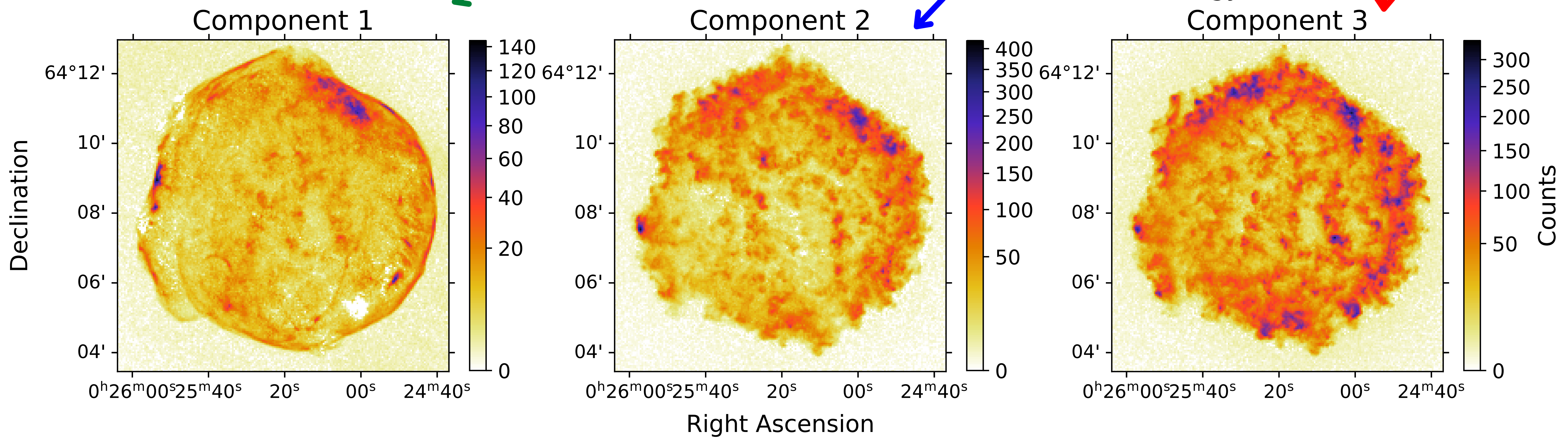
Si line

(1.6 - 2.1 keV)

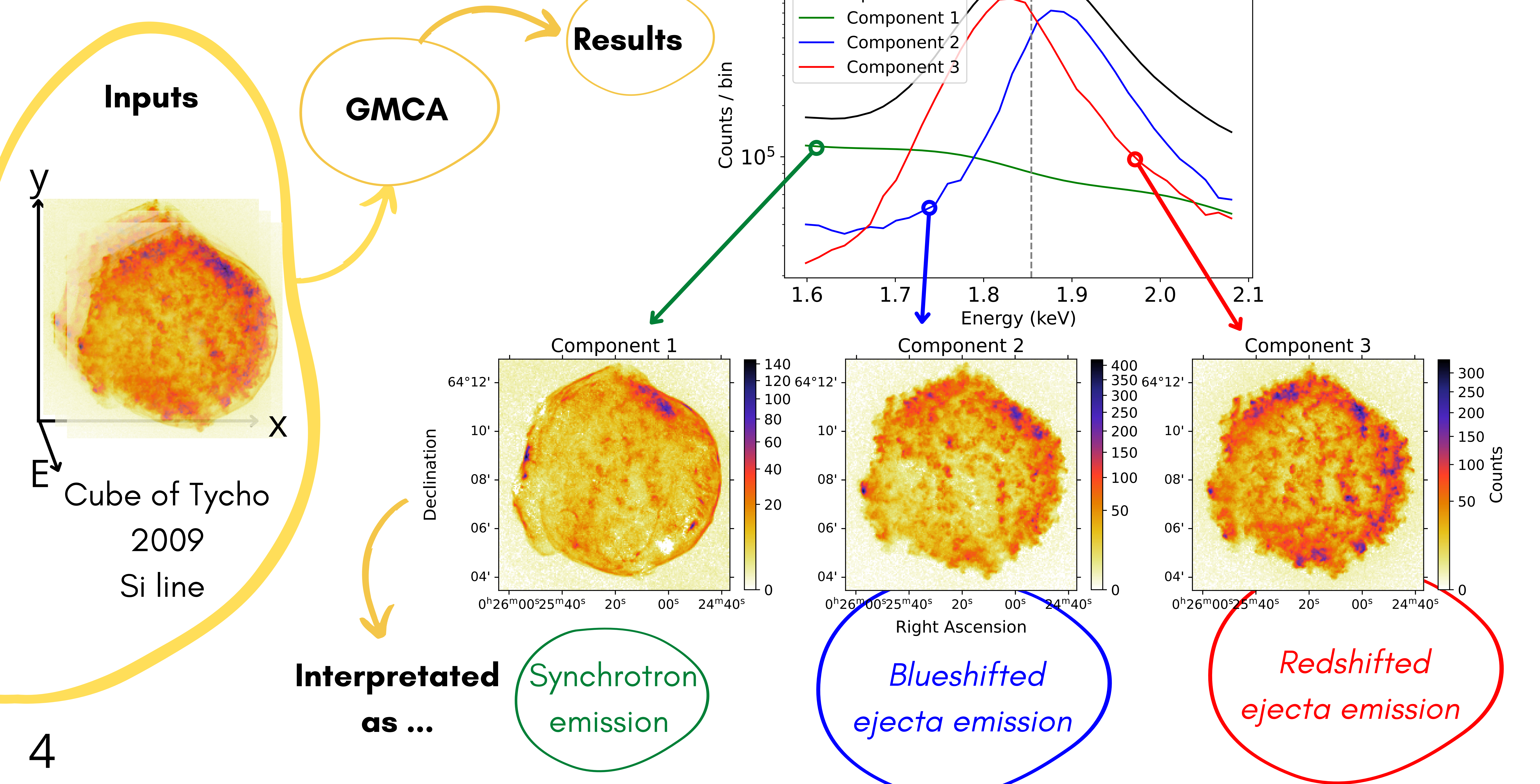
Chandra telescope

Results





The GMCA tool



Line of sight velocity from the energy centroid

Methodology

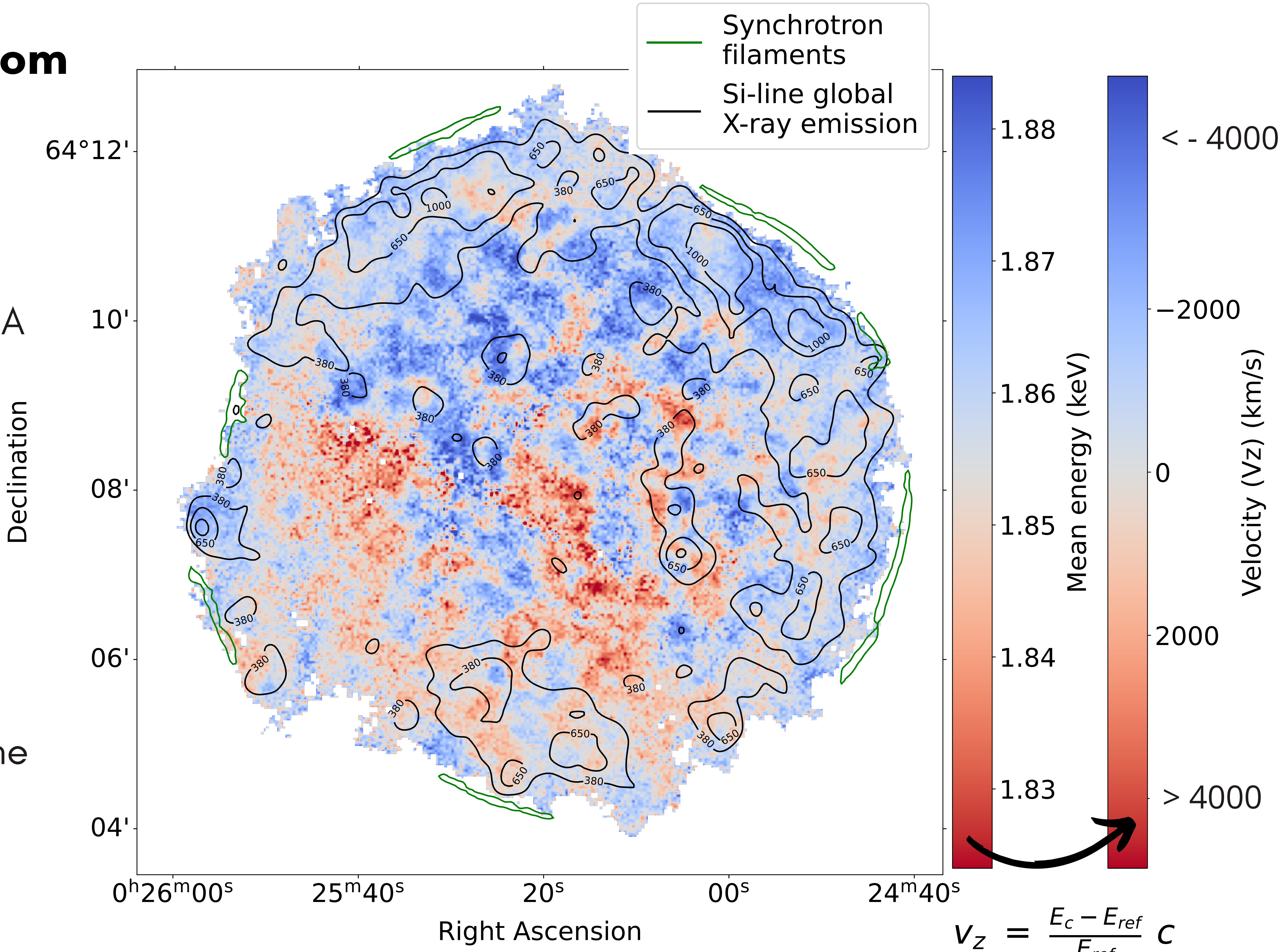
Combine red/blue GMCA images ponderated by GMCA spectral parameters

Results

- **N/S clear asymmetry**
- Total coverage of the SNR

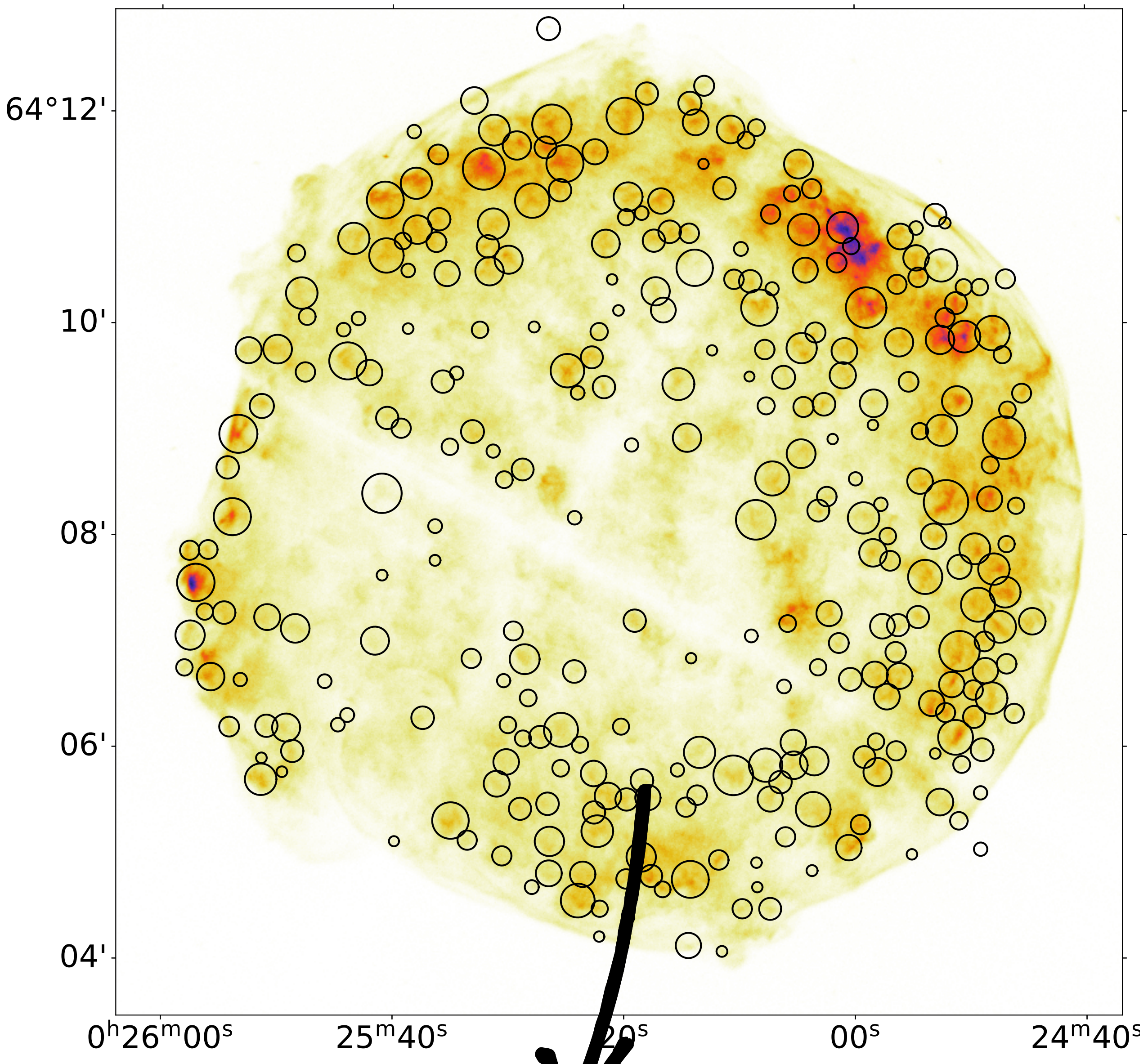
Limits

- Integrated values on the line of sight
- No uncertainties



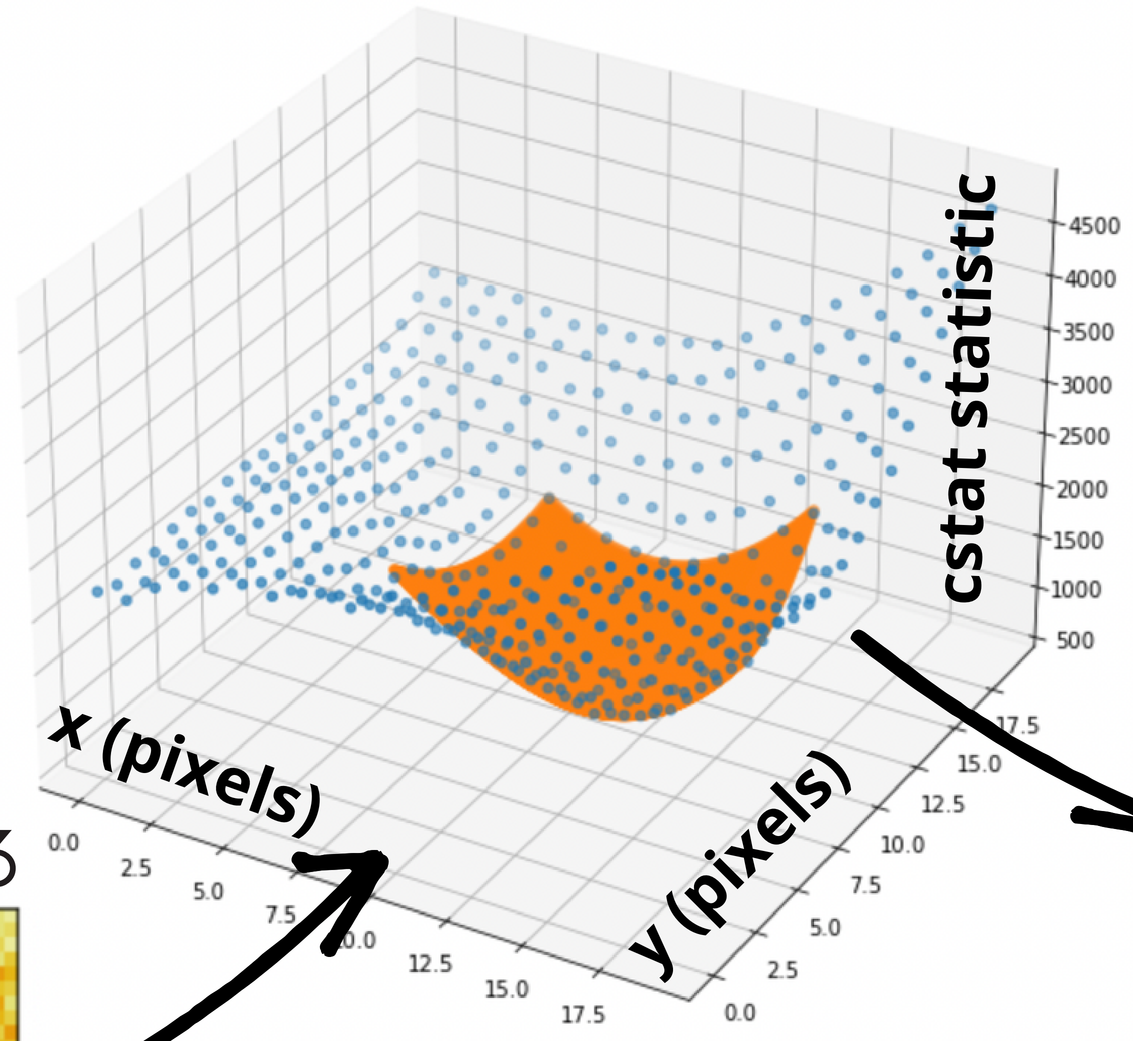
$$v_z = \frac{E_c - E_{ref}}{E_{ref}} c$$

Velocity in the plane of sky : a new method



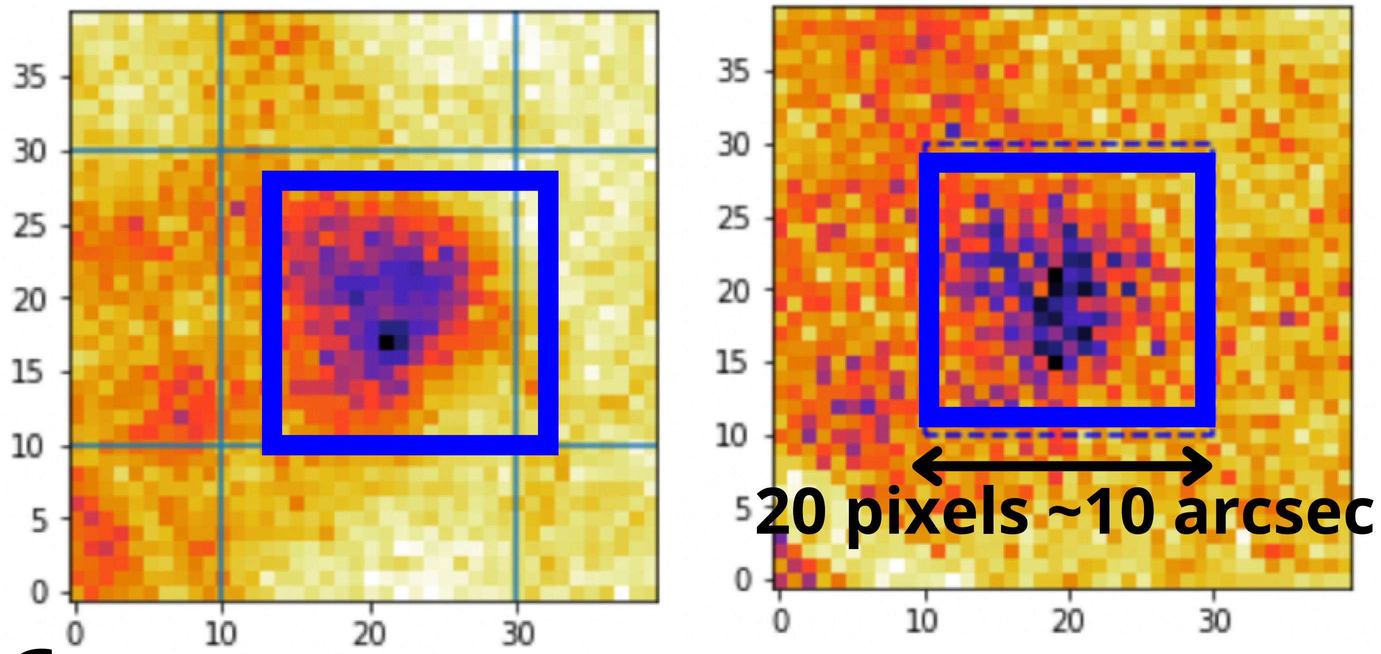
Tracking 2D features between epochs

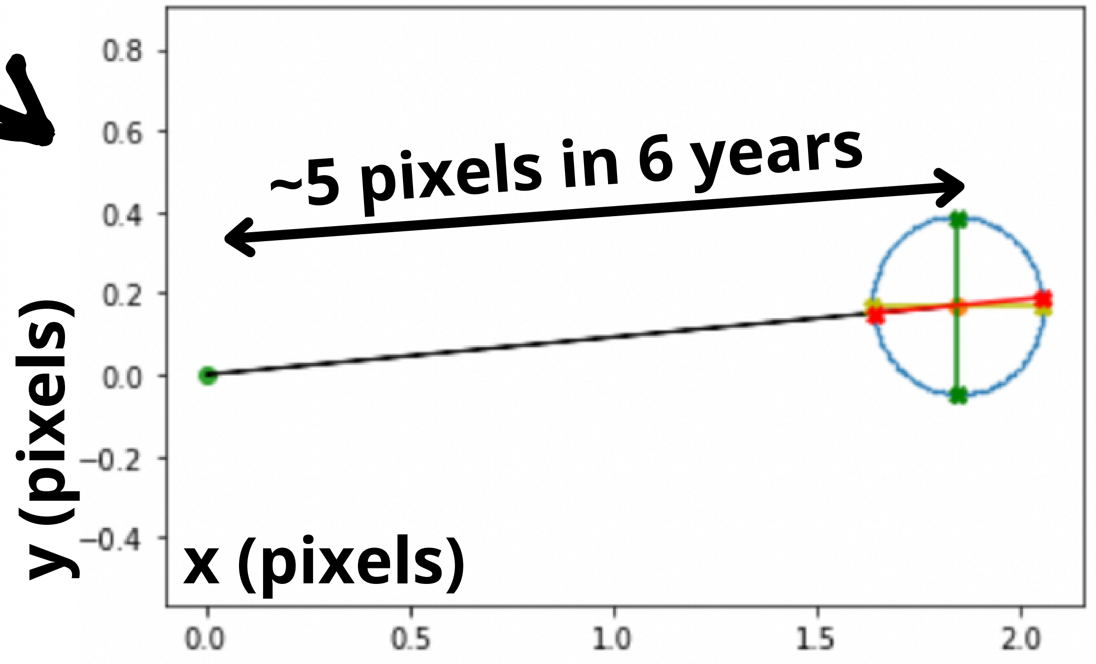
- Inspired from optical flow
- Adapted to the Poisson statistic
- 3D interpolation for sub-pixel precision
- Complete uncertainties ellipse
- Algorithm transparency



Statistical landscape (cstat function)

Model 2009 Observation 2003





Shift vector and uncertainties

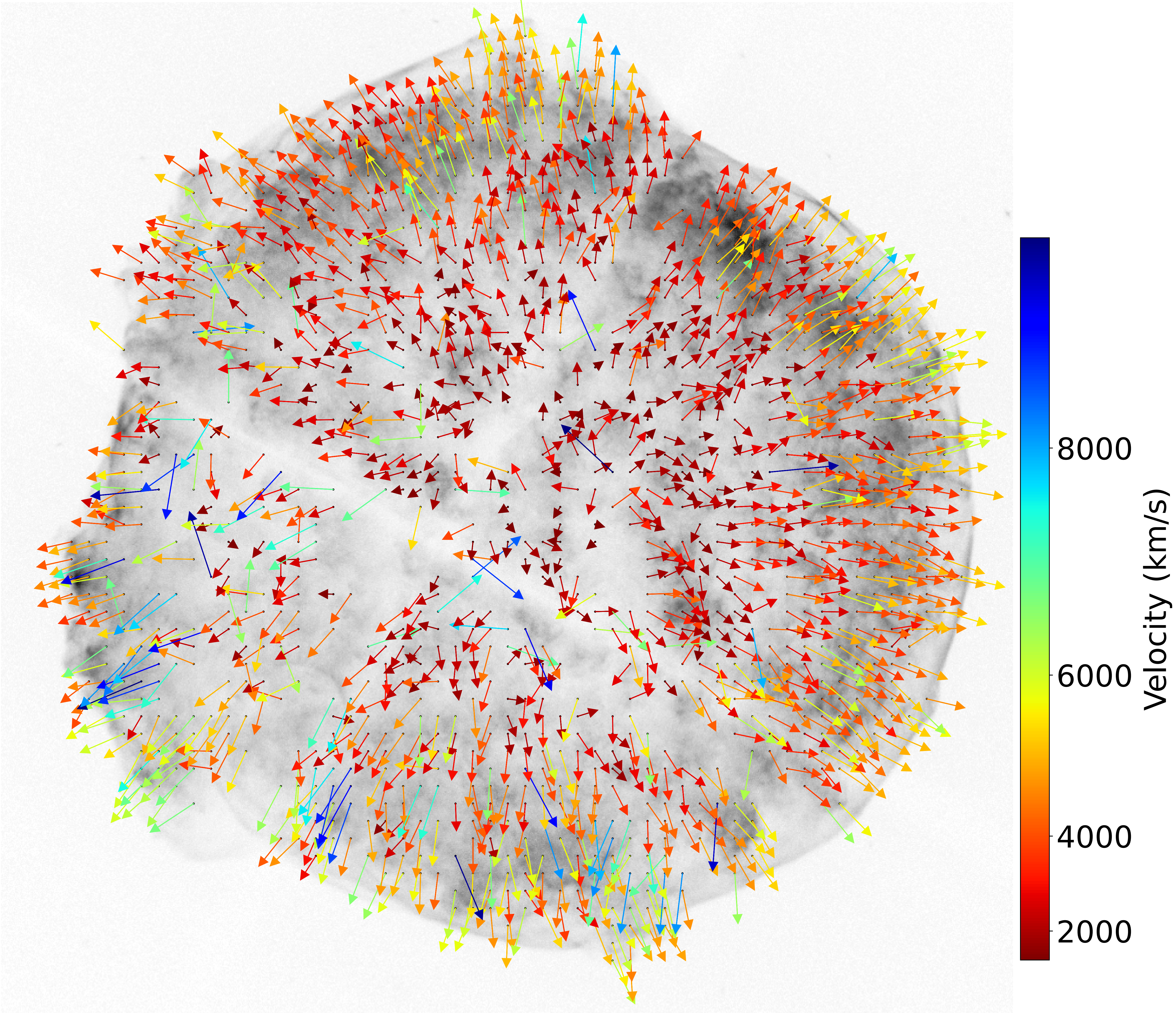
Vector field Vxy in plane of sky

Results

- **Hundreds of vector** (1350), allowing a statistical study

- Full ellipse uncertainty (1 sigma, not shown here)

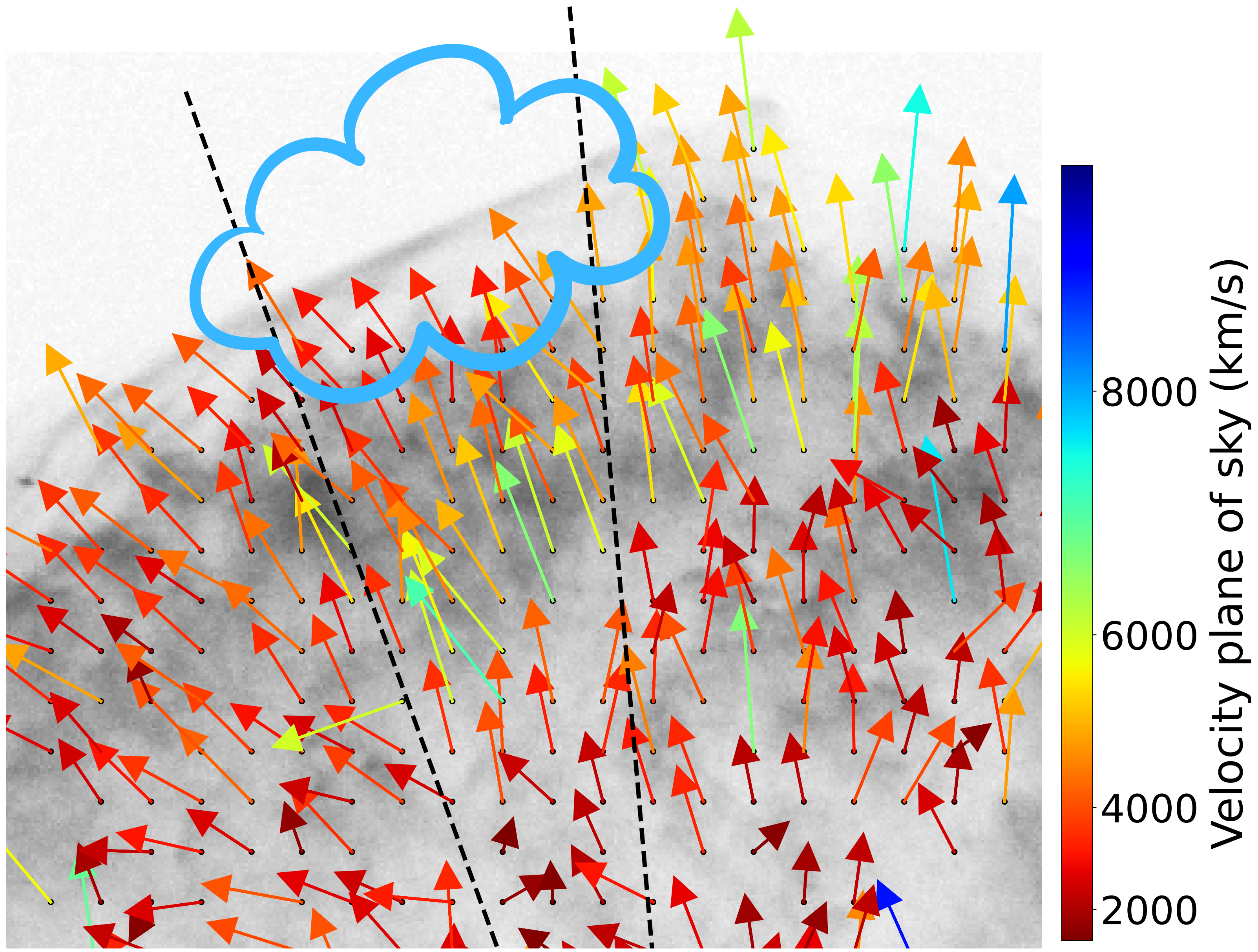
- local behaviour, no large scale regularisation

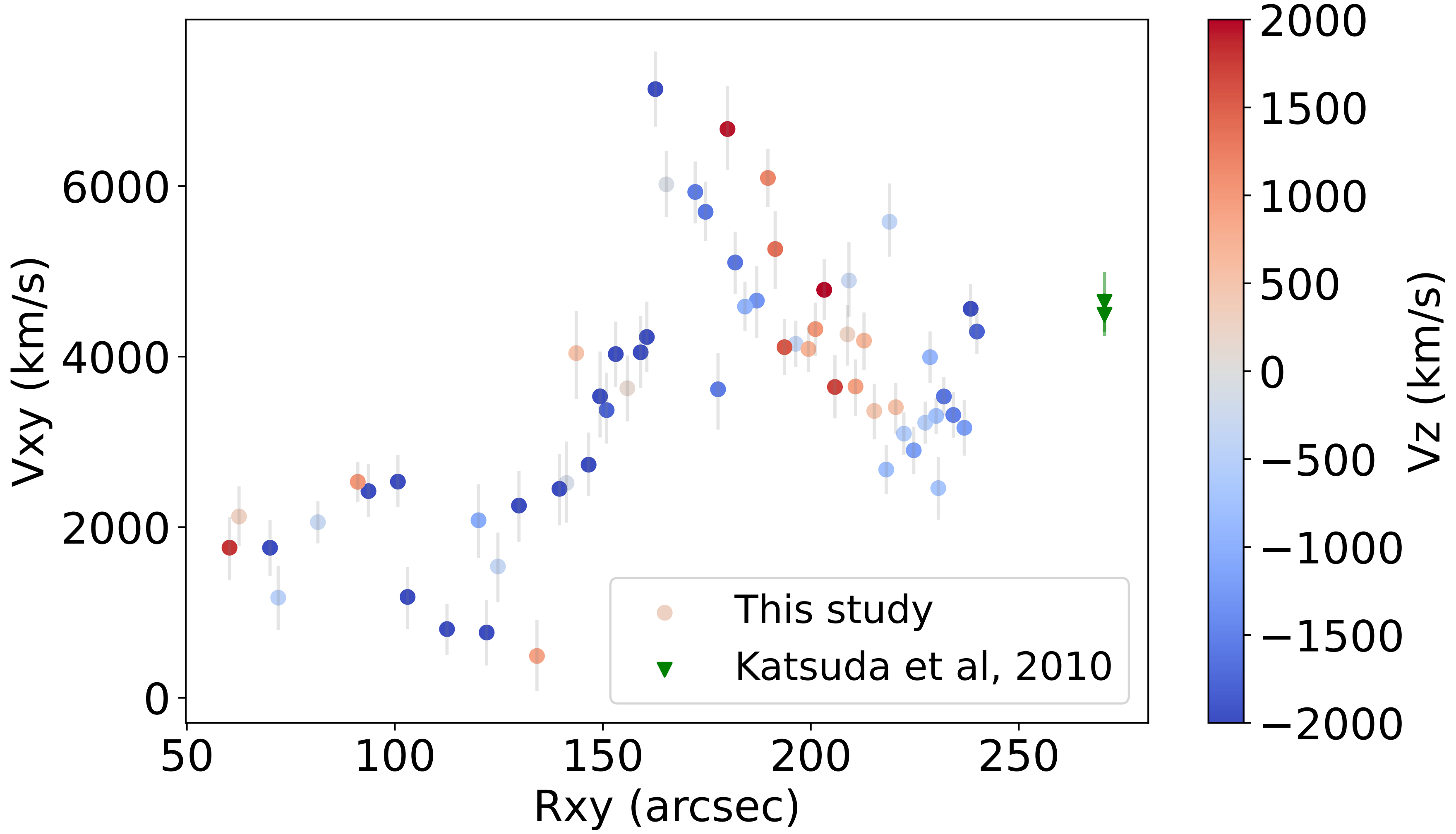


Some anomalies in the velocity vector field

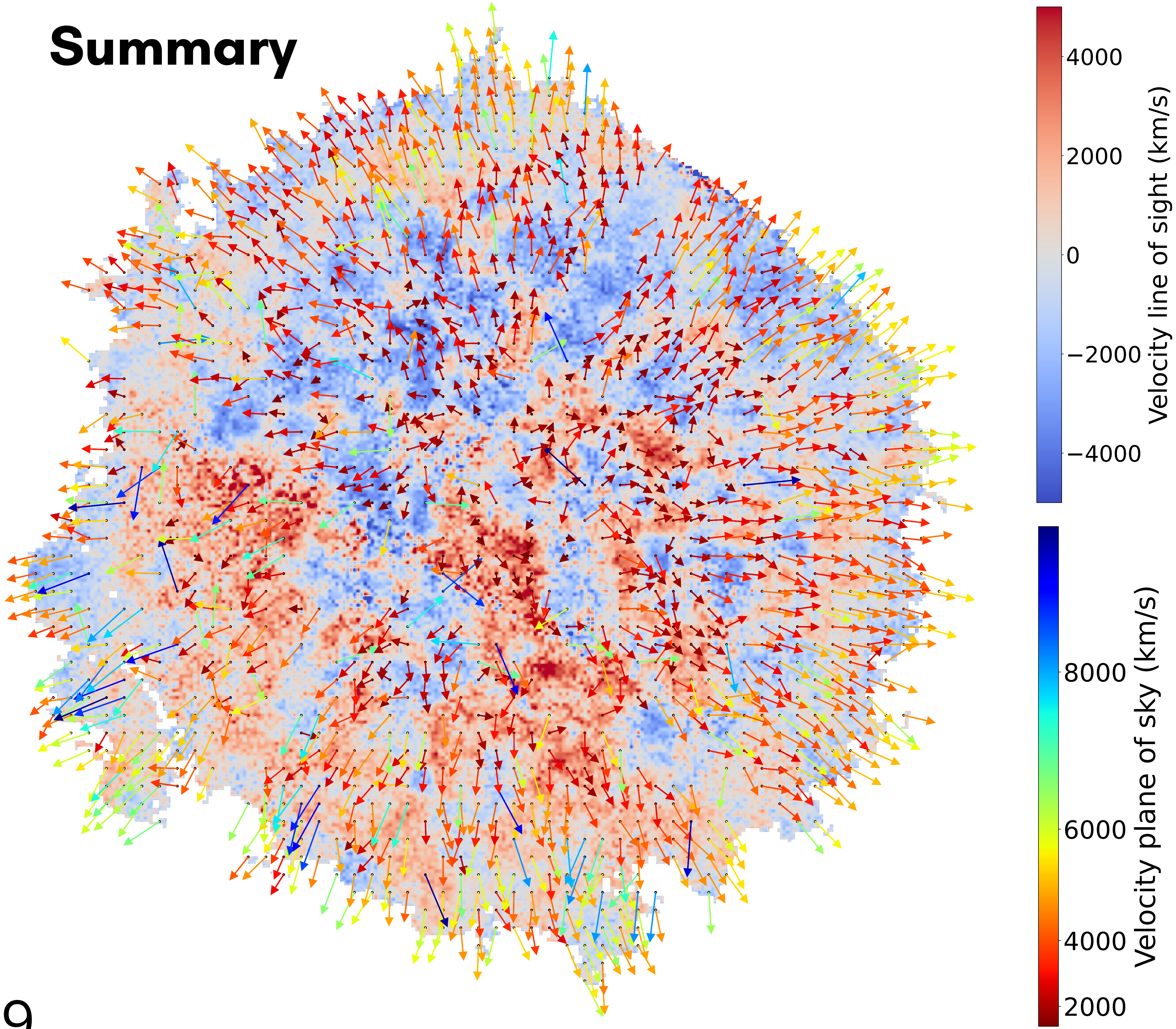
An example in a North East

- Strange acceleration in the plane of sky near the edge of the SNR
- Correlation with the velocity in the line of sight
- Proof of an latest interaction with a cloud ?





Summary



Methodology line of sight (Vz)

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

-> Large scale velocity assymetry

Methodology plane of sky (Vxy)

- New method to mesure proper motion with 2D profils
- Obtention of hundreds vector

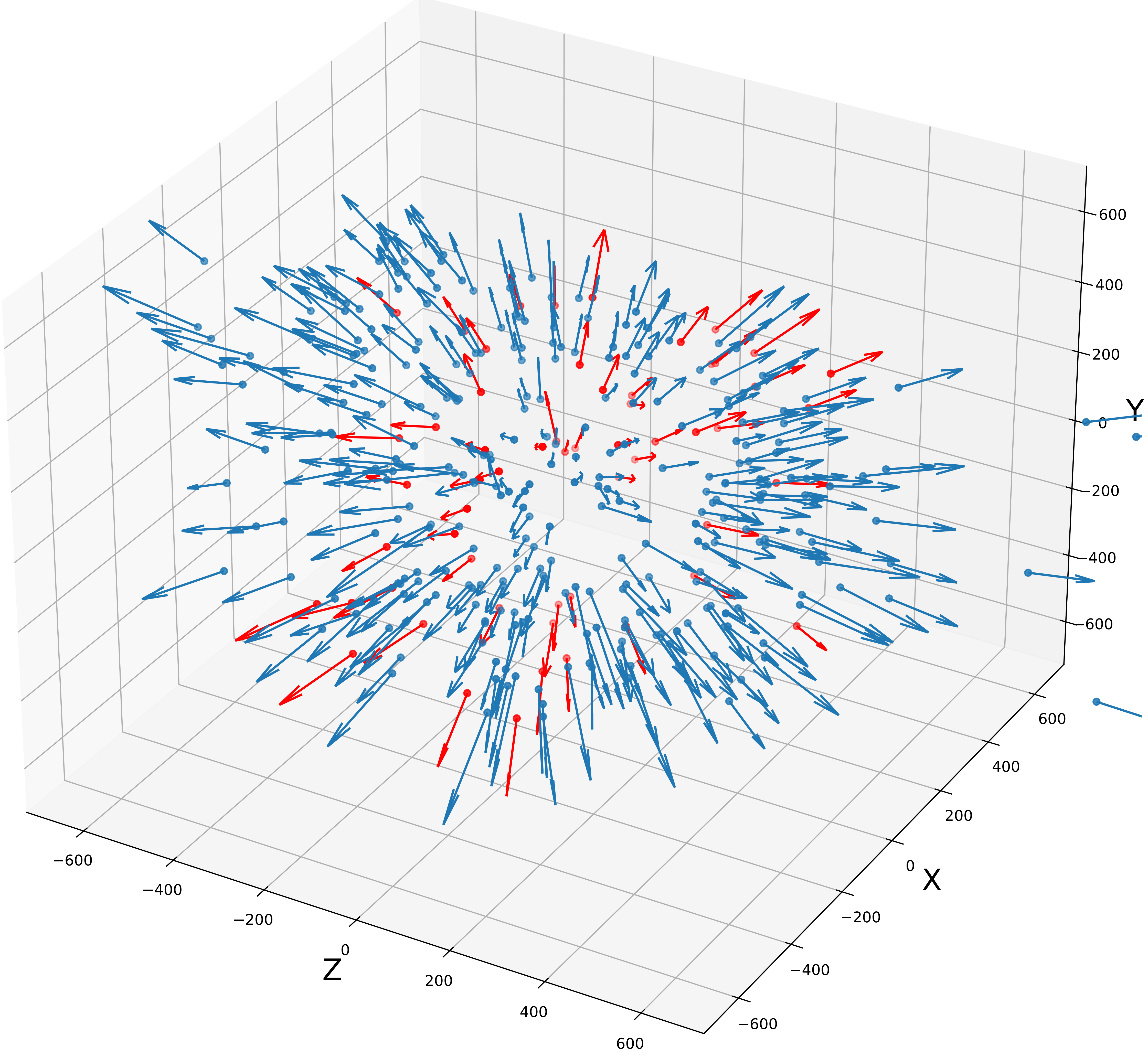
-> Velocity anomalies and jets

Toward a 3D visualisation

- Combine our velocities in the plane of sky and line of sight

- Necessary to understand the assymetries : is it some jets from explosion or due to interaction with the surrounding medium ?

-But how to represent it in 3D ?



1. 3D Printing

- Very convenient for simulation visualization

- We must create the file for the printer. And we do not find 3D printers in the street !

-How to represent the velocity vector field ?

https://chandra.harvard.edu/deadstar/tycho.html

2. Pâte à modeler

- Very convenient as a support of discussion

-Not very serious and scientific during conferences

-Not transparent (the X-ray data are optically thin)

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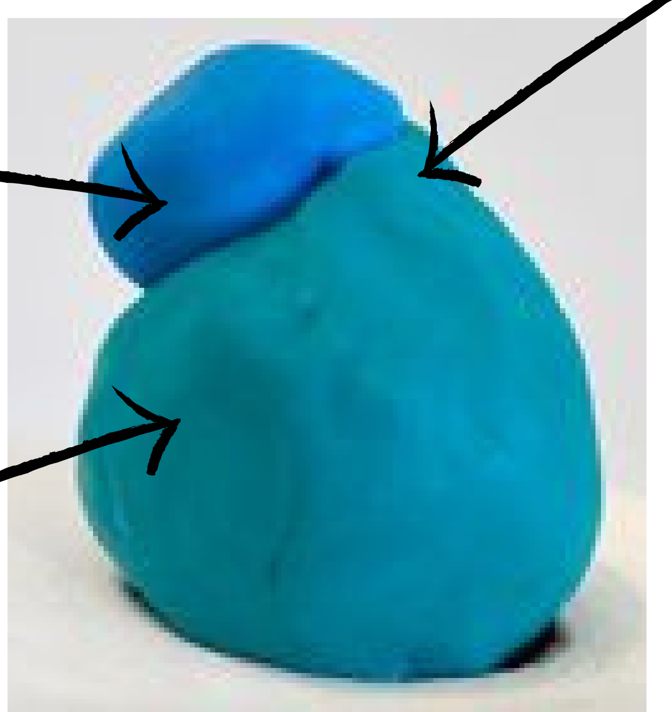

Fig 1 : The SNR and a cloud

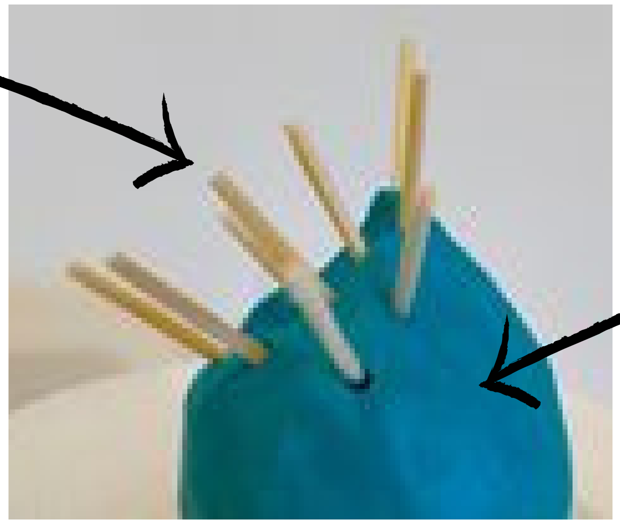

Fig 2 : The impact on the velocity vector field

3. Virtual Reality

- Very useful to see from another angle the data, to manipulate it in 3D

- Difficult to use it as a scientific result, it will remain a help to visualisation and vulgarisation

[MAYBE ONE DAY BEFORE THE END OF MY THESIS ...]

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 archive
- Williams et al, 2017
- Sato et al, 2017

Phew it's over ...

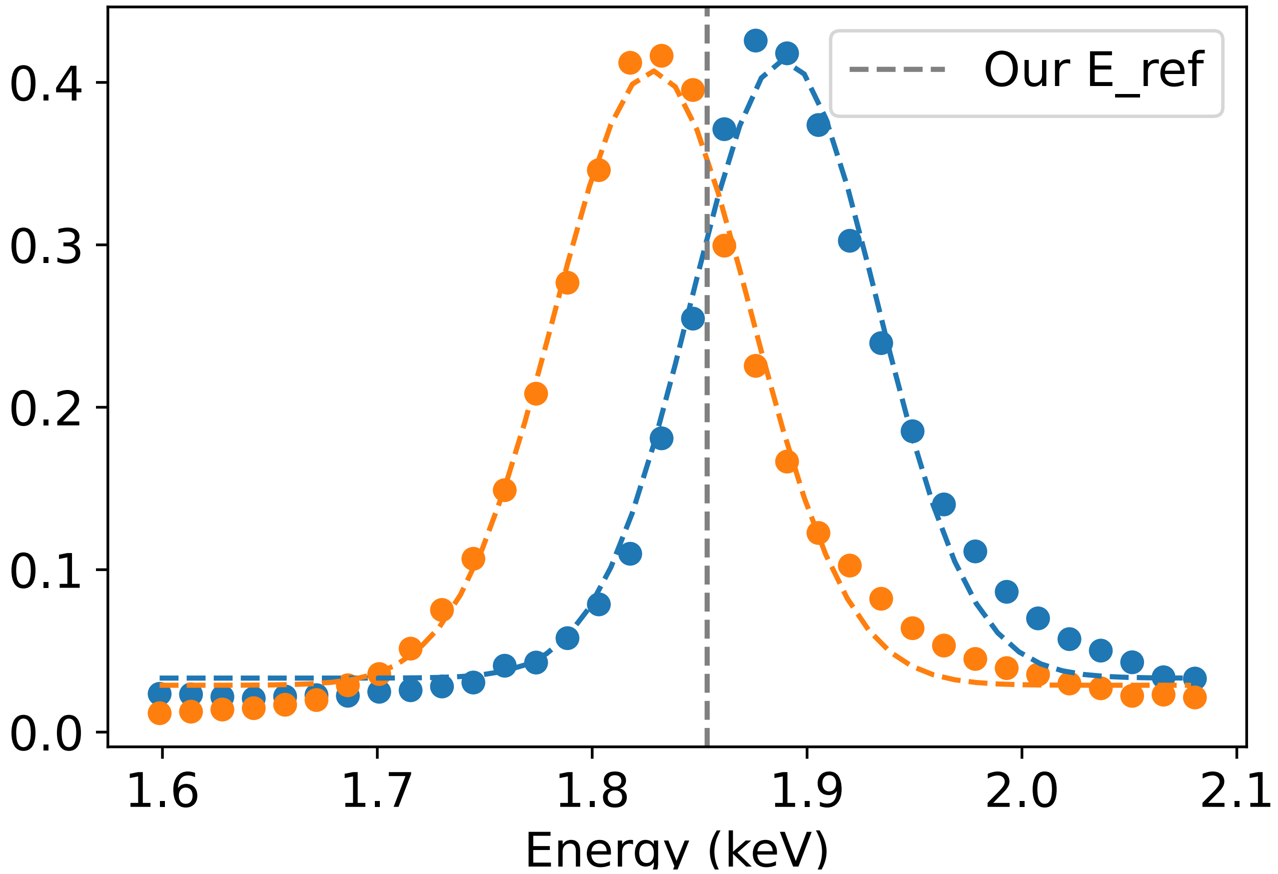
But there are some backups !

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 :

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

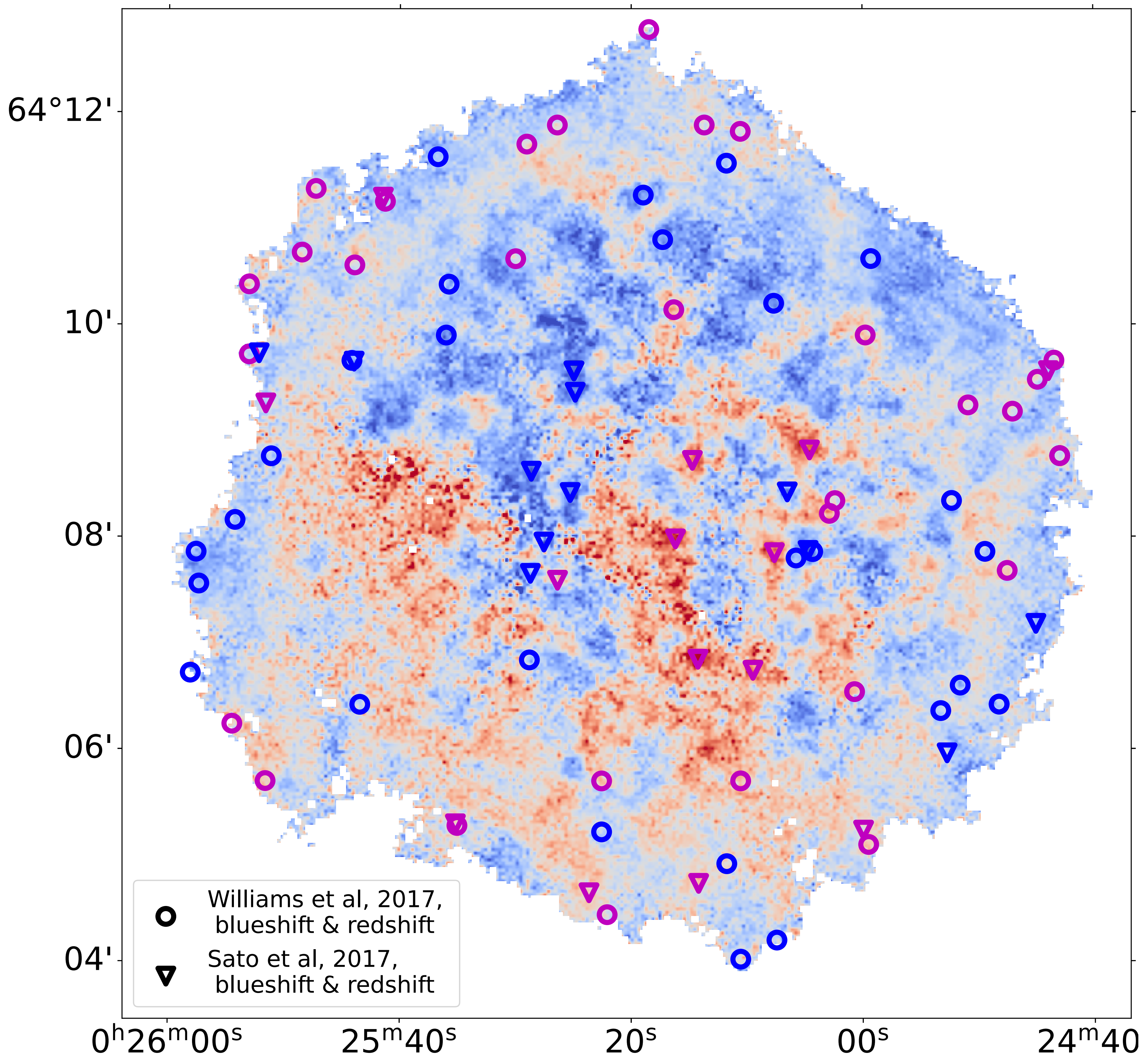
4) And an analytical proxi of the solution is :

fit parameters from GMCA's spectrum red and blueshifted

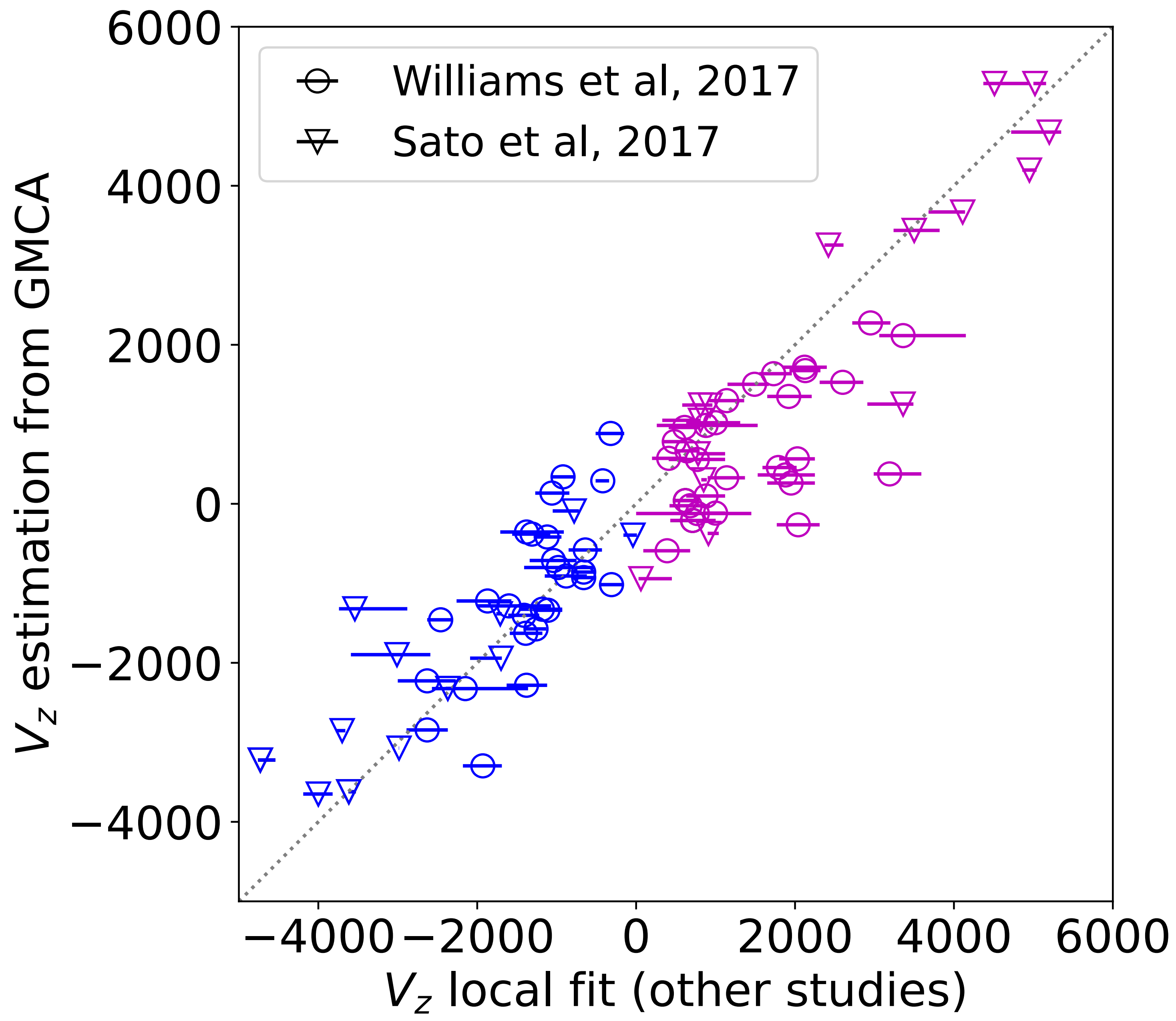
$$E_c = \frac{Image_{ij,r}\frac{\alpha_r}{\sigma_r^2}\ E_{r,mean} + Image_{ij,b}\frac{\alpha_b}{\sigma_b^2}\ E_{b,mean}}{Image_{ij,r}\frac{\alpha_r}{\sigma_r^2} + Image_{ij,b}\frac{\alpha_b}{\sigma_b^2}}$$

GMCA's image red and blueshifted

Cross checking our method

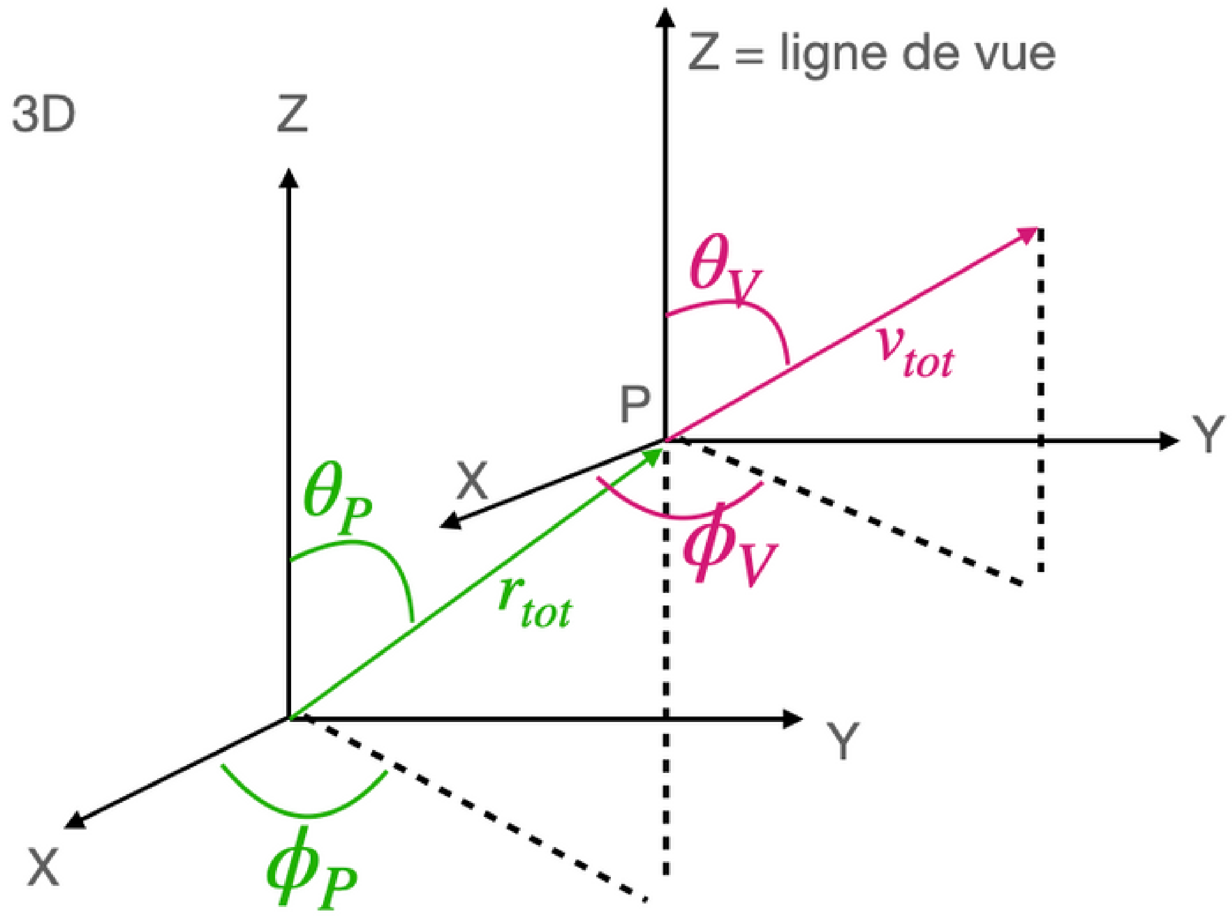


Comparing the velocity from Sato and Williams with our values at same position.



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

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 :

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