Study of Tycho SNR asymmetries with three dimensional velocity vector field

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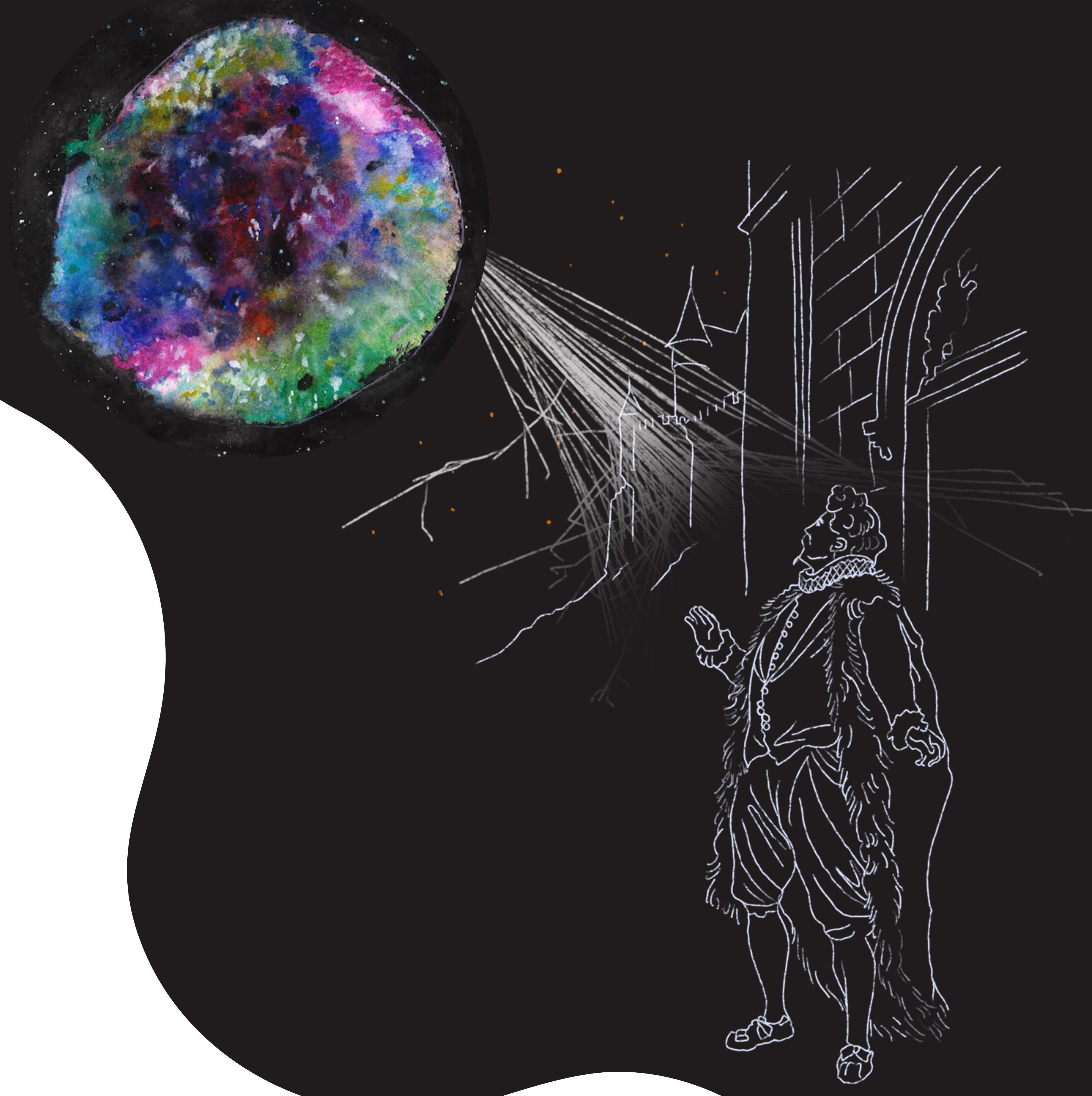
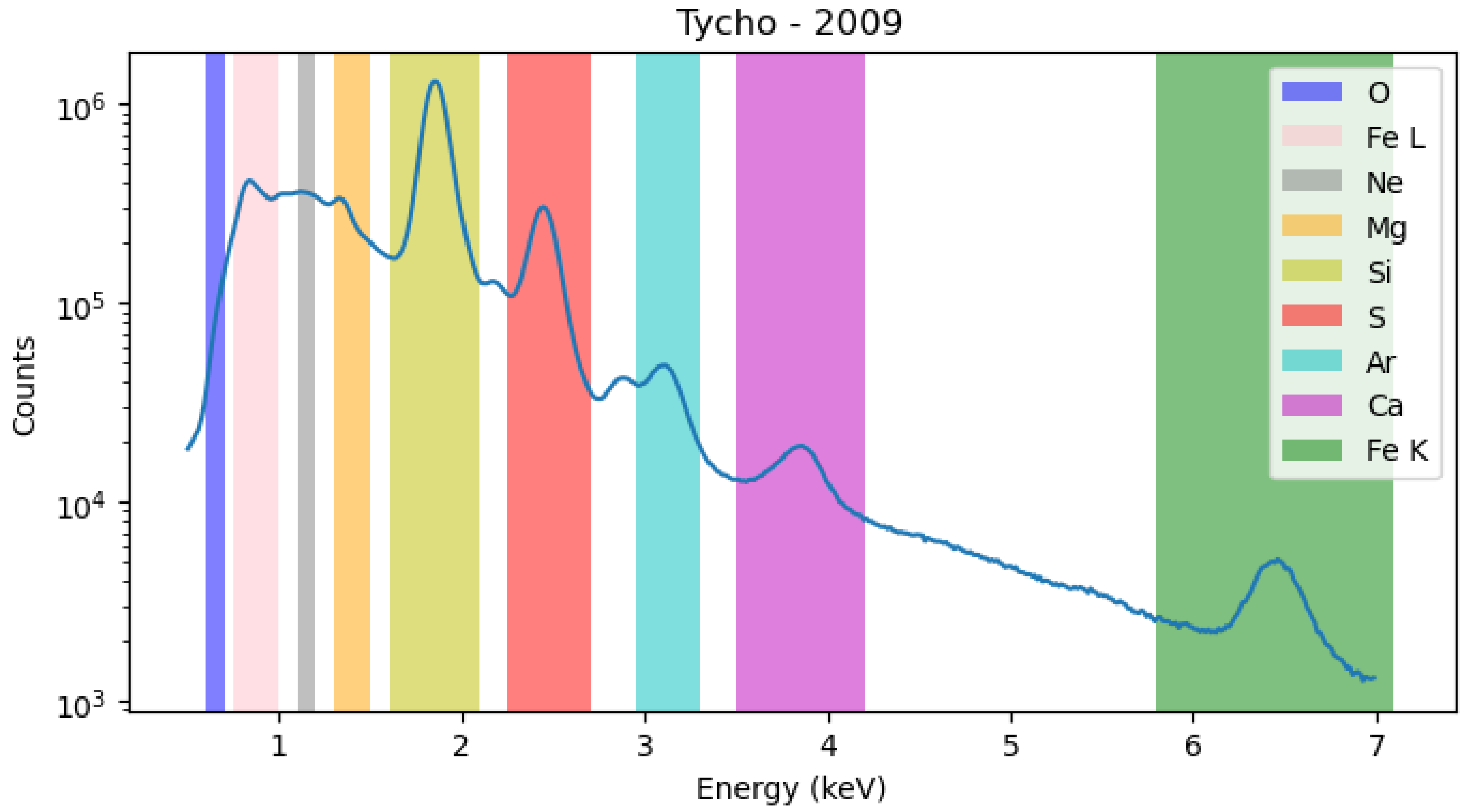
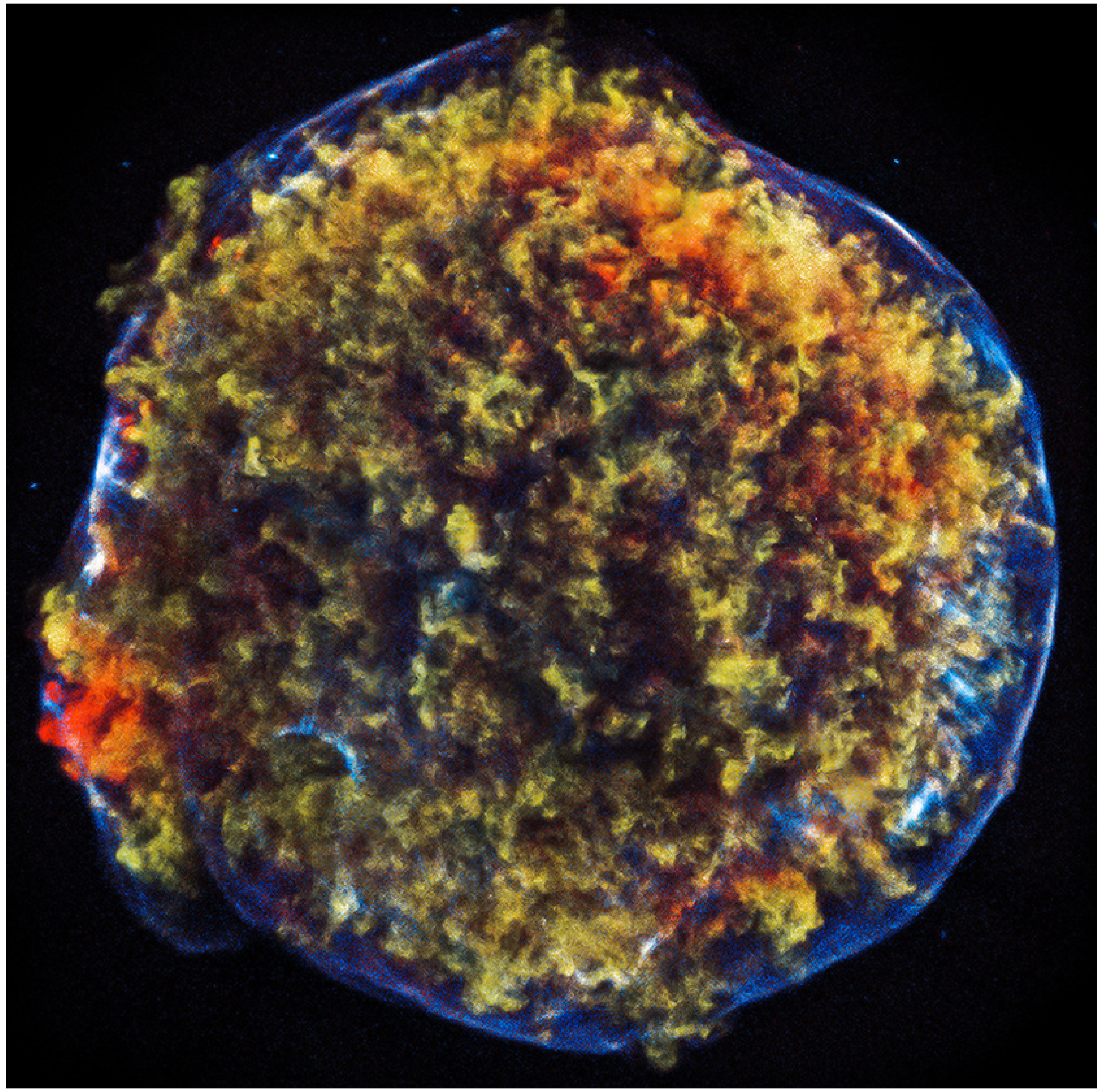


Tycho's SNR

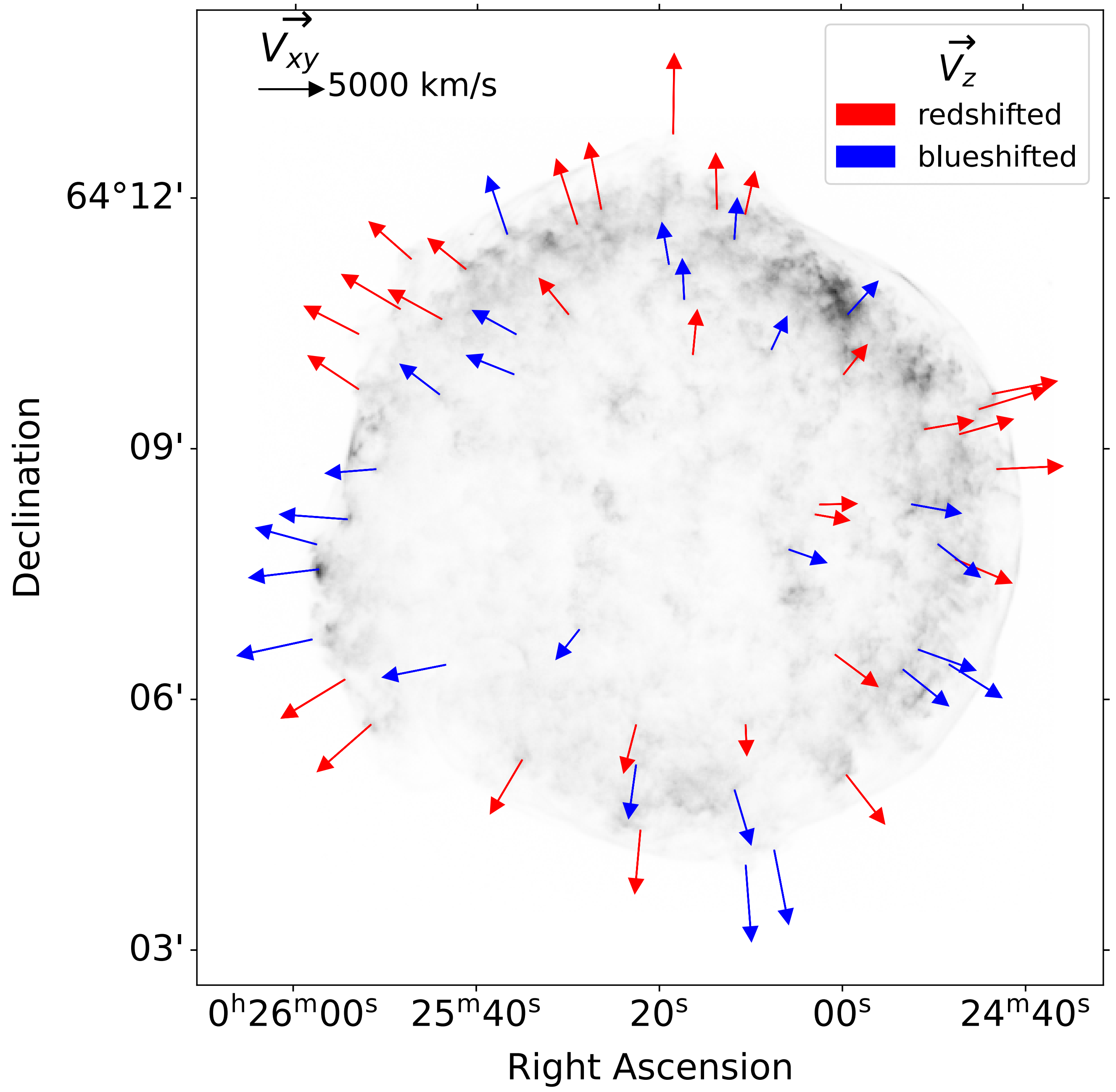
- Explosion in 1572 observed by Tycho Brahe
- Supernova thermonuclear (type Ia)
- Distance : 3.5 kpc
- Size : 12 arcmin
- Observation Chandra space telescope : more than 950 ks (~330 h)





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

Why some new tools about the 3D ejectas dynamics ?



Plot with data from Williams et al, 2017

Origin of asymmetries ?

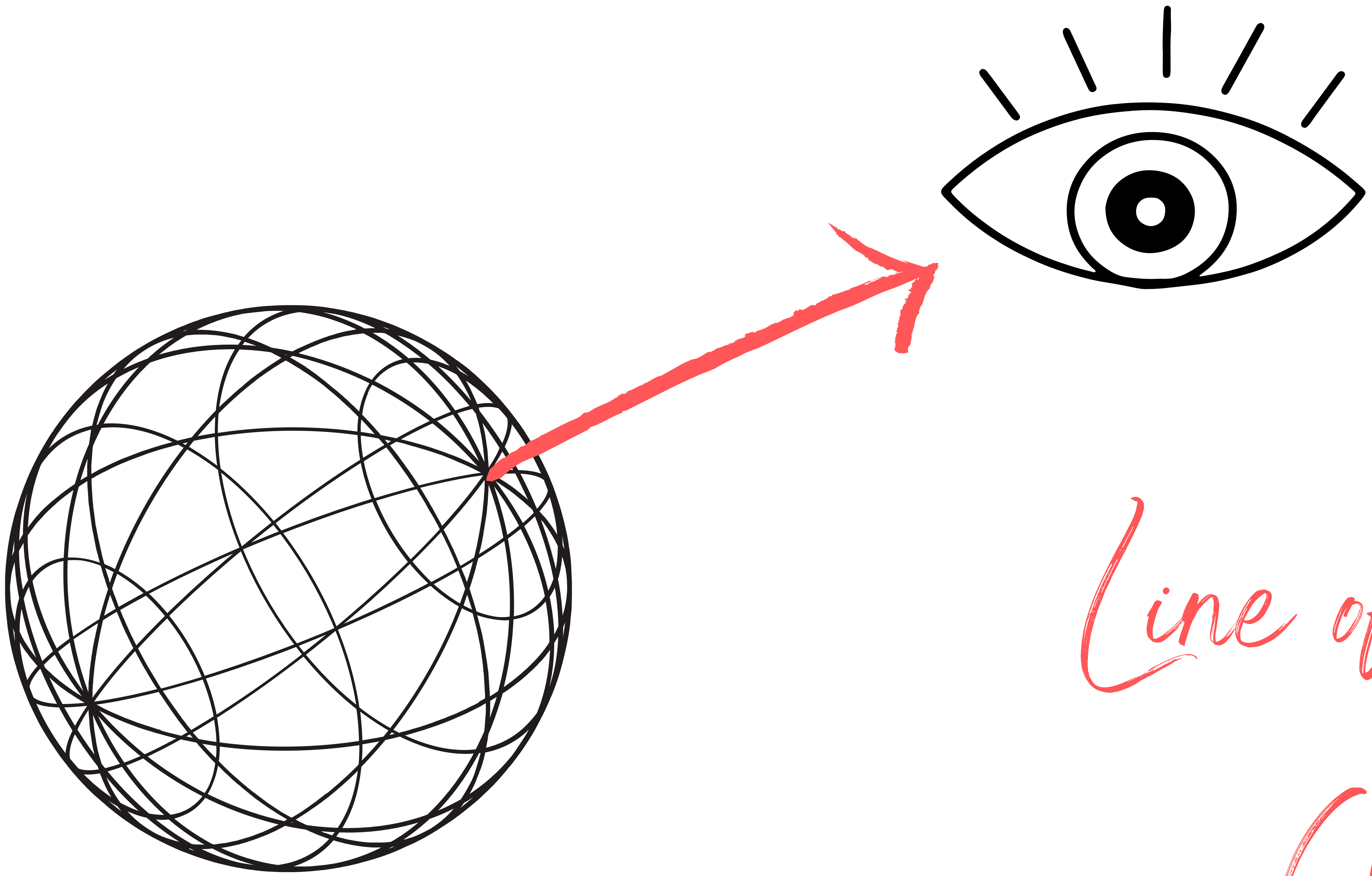
- Innate : anisotropy during the explosion
- Acquired : inhomogeneties in the CSM

Current methodology

- *Plane of sky* : two 1D profiles 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
- Not enough velocity vectors to do statistics



Line of Sight

(V_2)

The GMCA tool

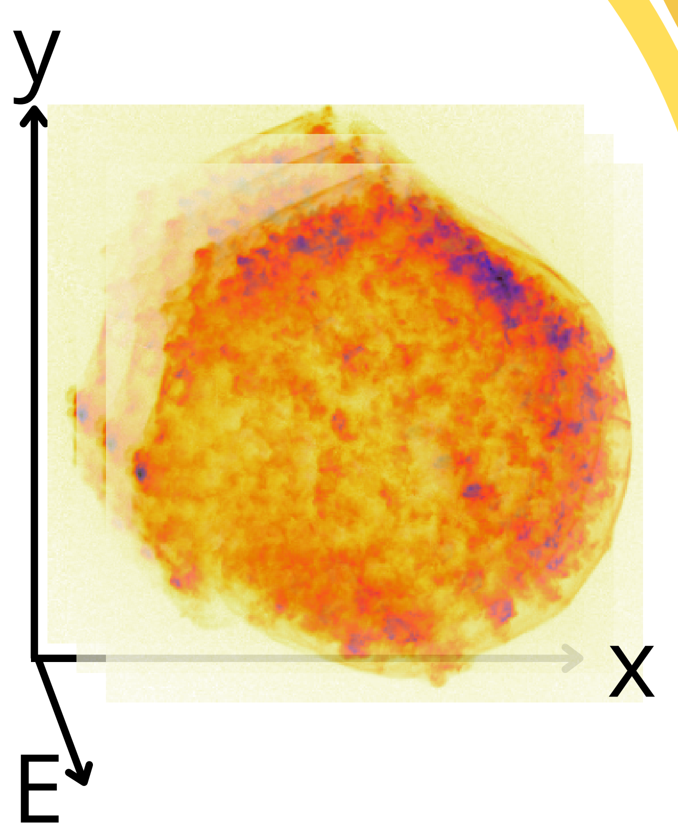
$$Cube = \sum_i Spectrum_i \; Image_i$$

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

Bobin et al, 2015

Picquenot et al, 2021

Inputs



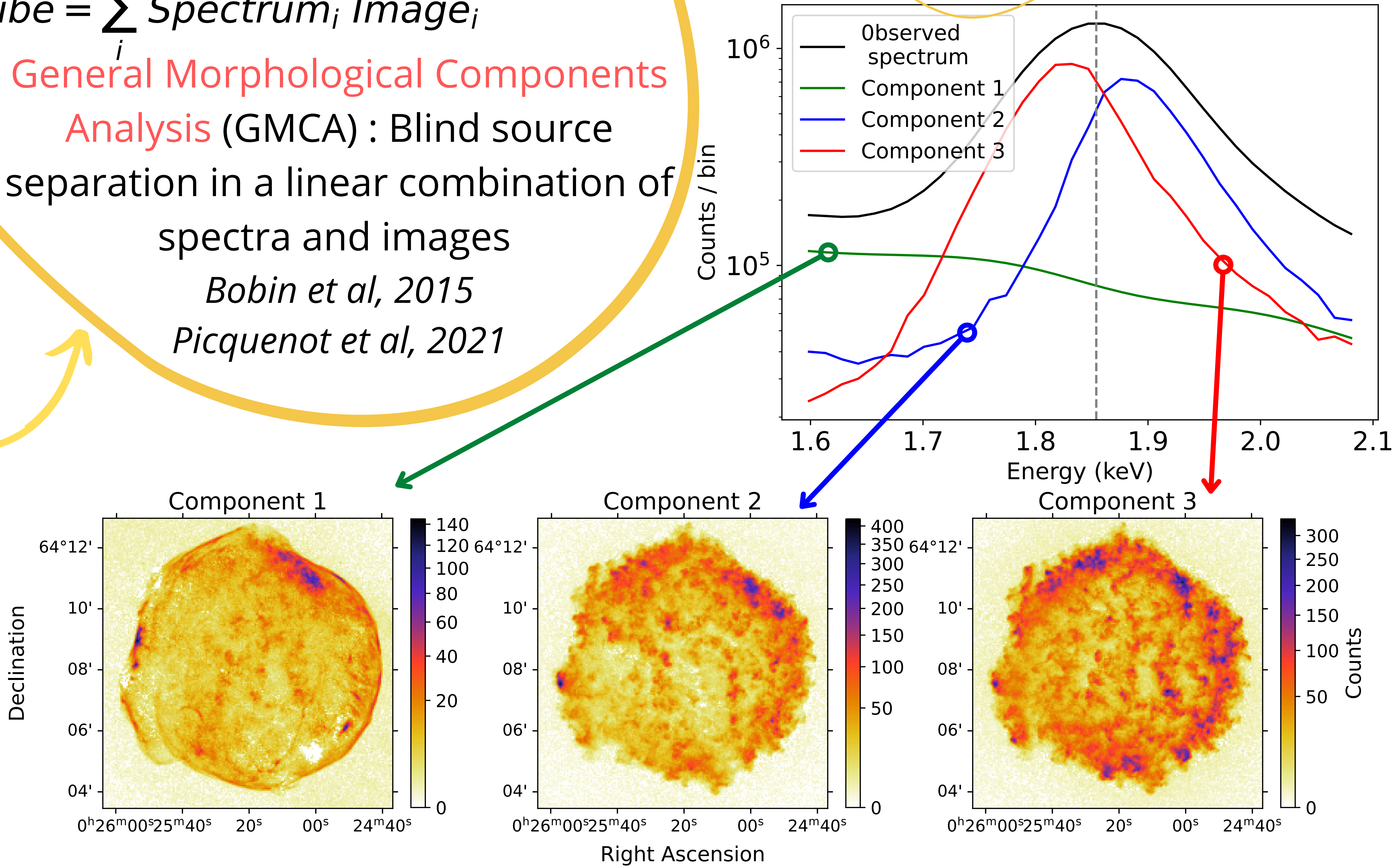
Cube of Tycho's SNR, 2009

Si line

(1.6 - 2.1 keV)

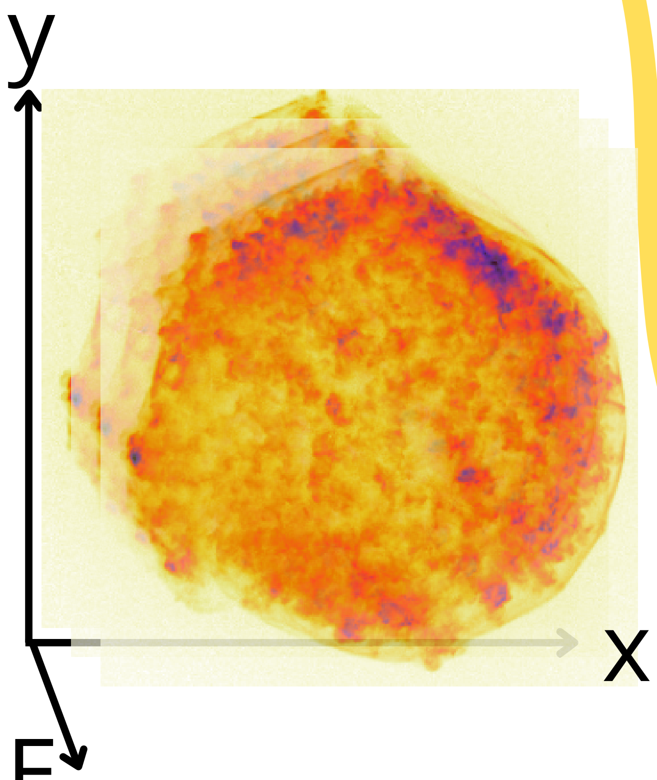
Chandra telescope

Results



The GMCA tool

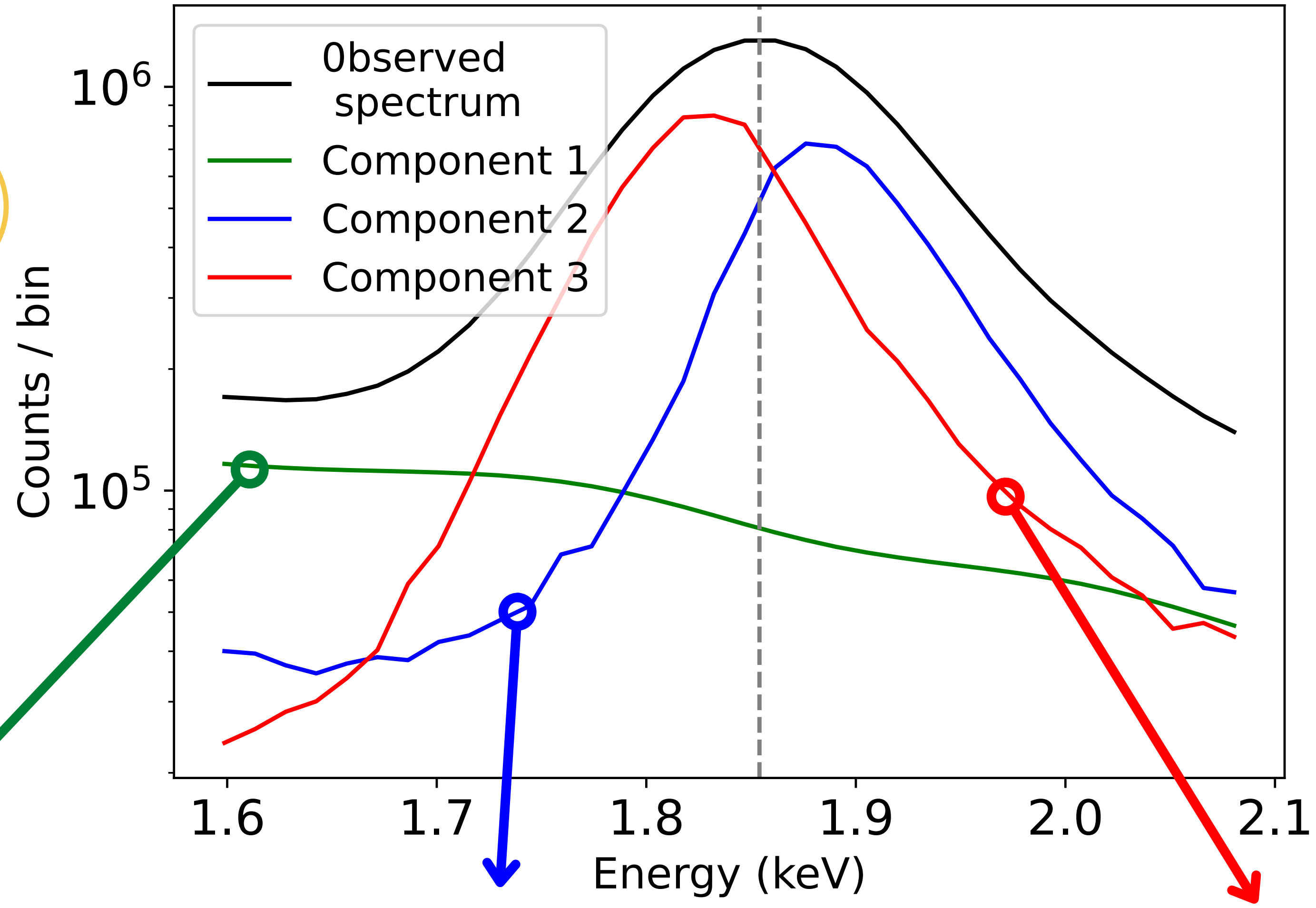
Inputs

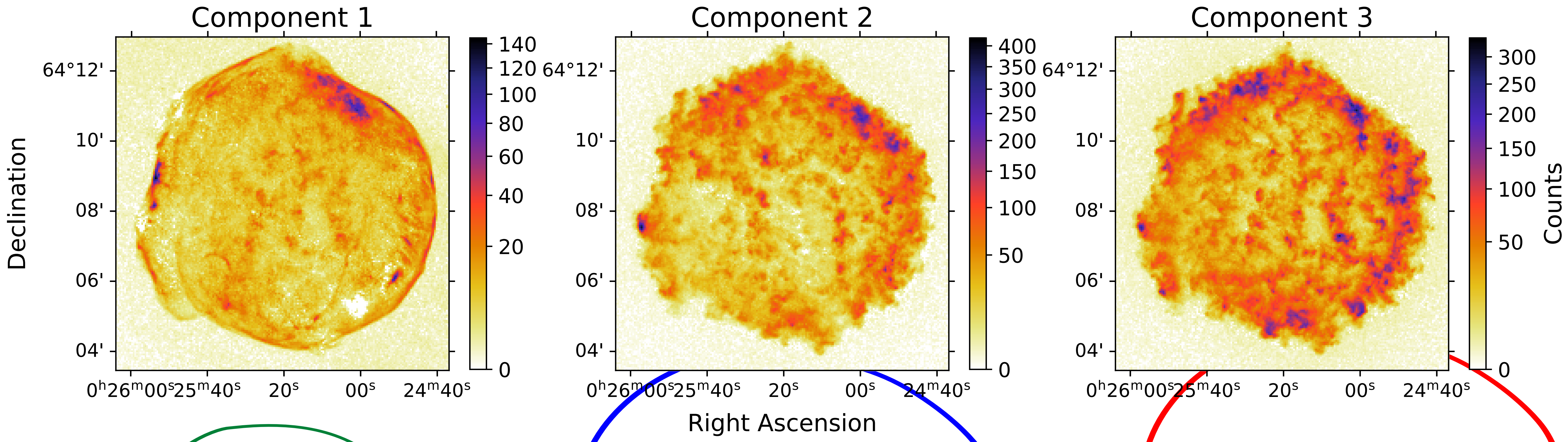


Cube of Tycho
2009
Si line

GMCA

Results





Interpreted as ...

Synchrotron emission

Blueshifted ejecta emission

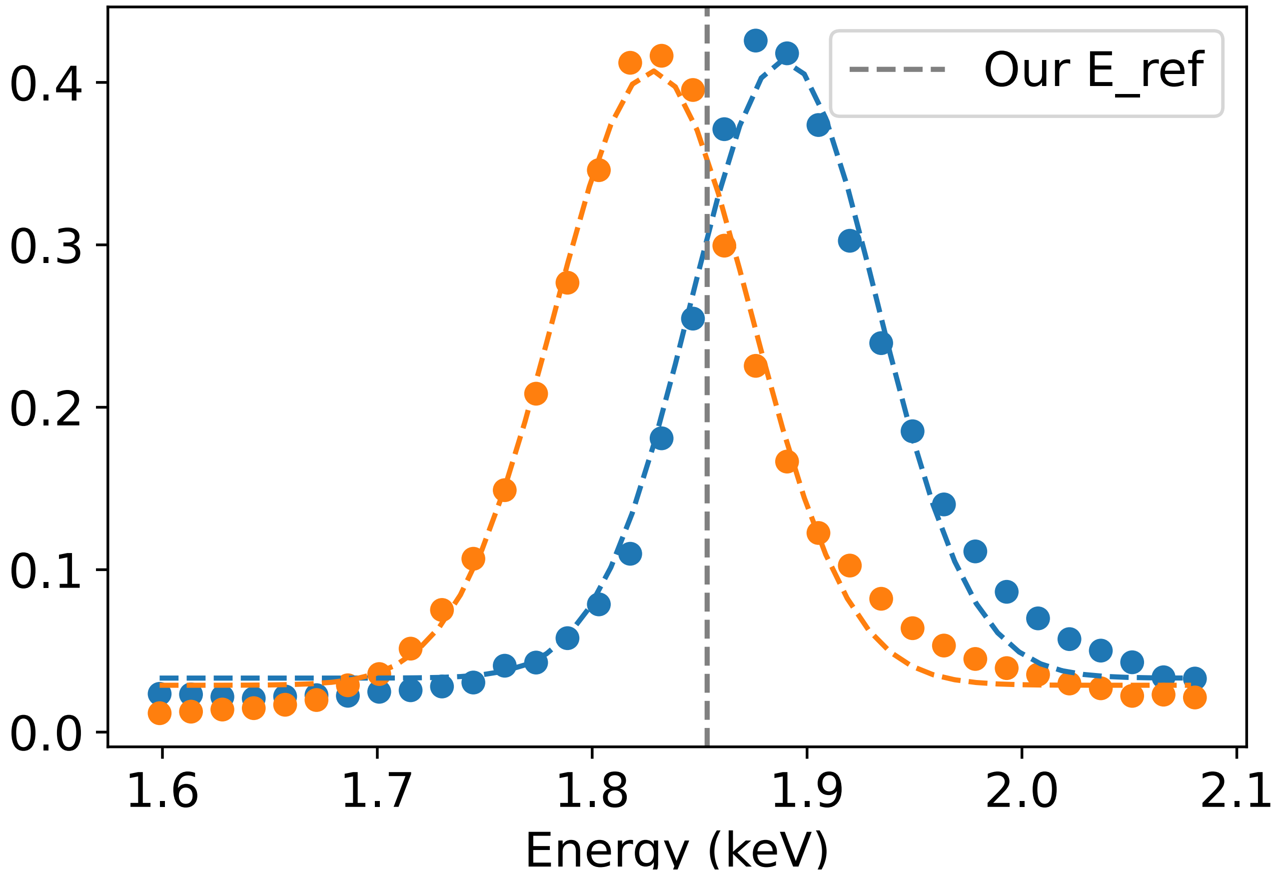
Redshifted ejecta emission

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



3) Silicon line peak is spectrum derivative in each pixel

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

Line of sight velocity from the energy centroid

Methodology

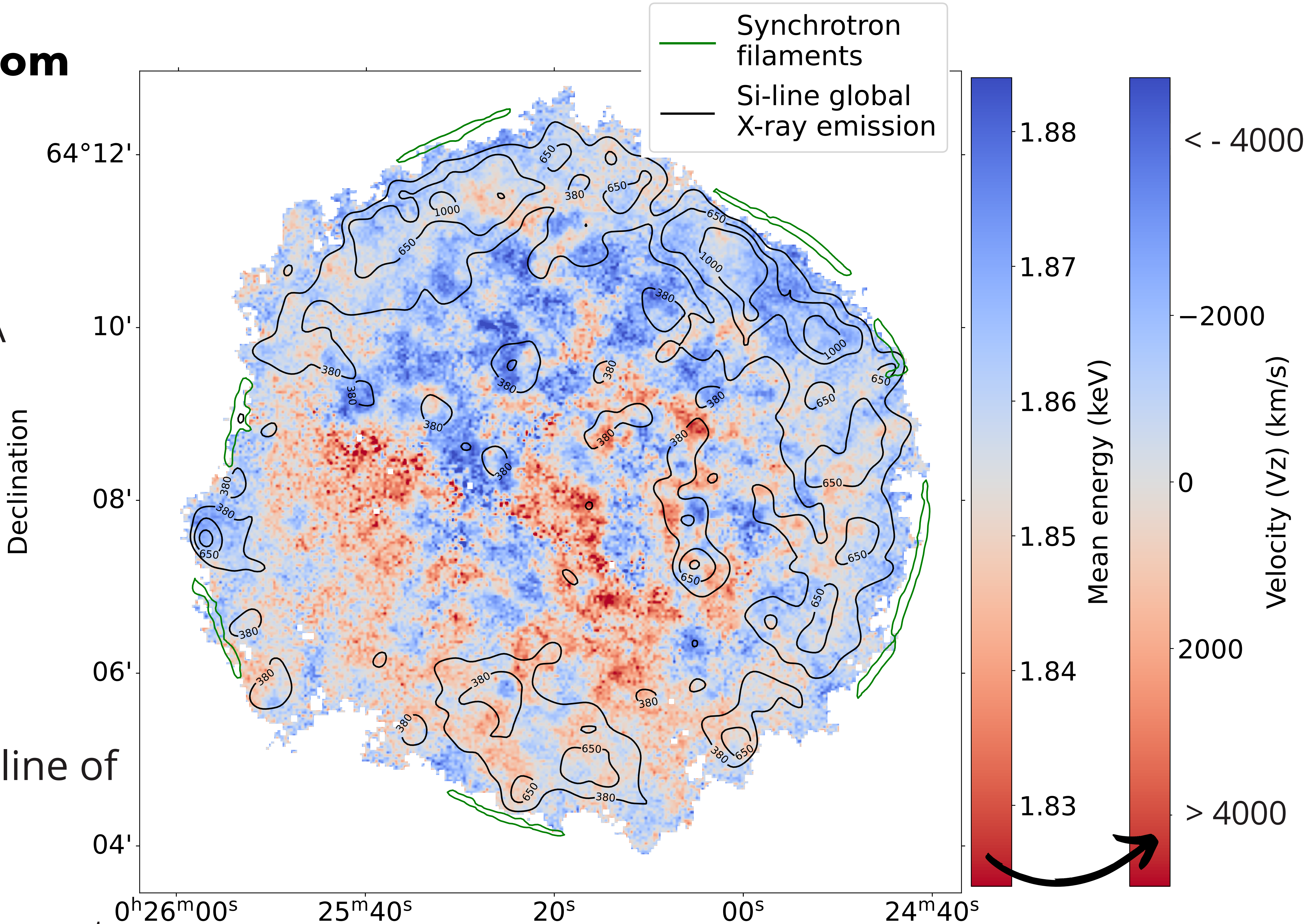
Combine red/blue GMCA images weighted by GMCA spectral parameters

Results

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

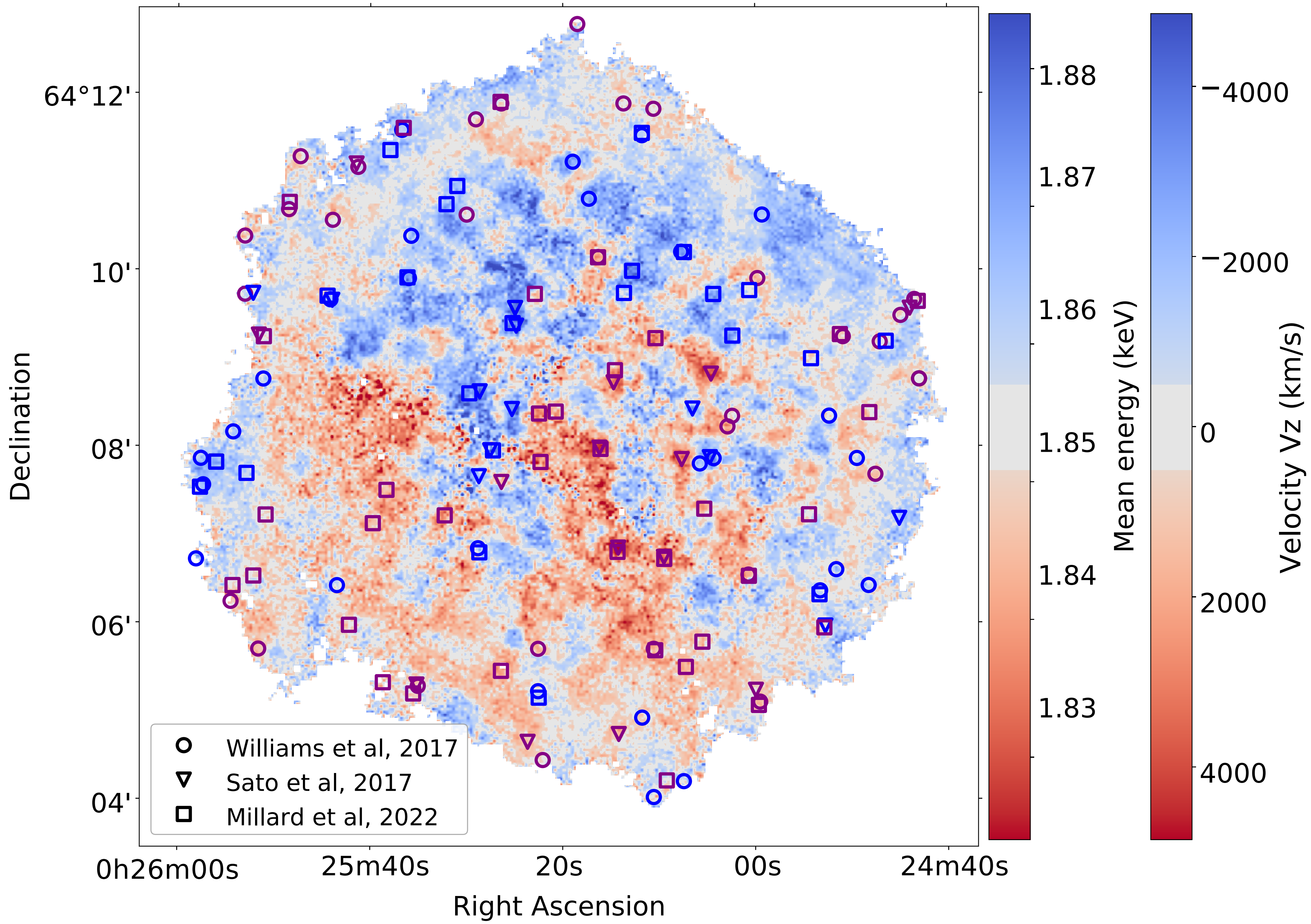
Limits

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

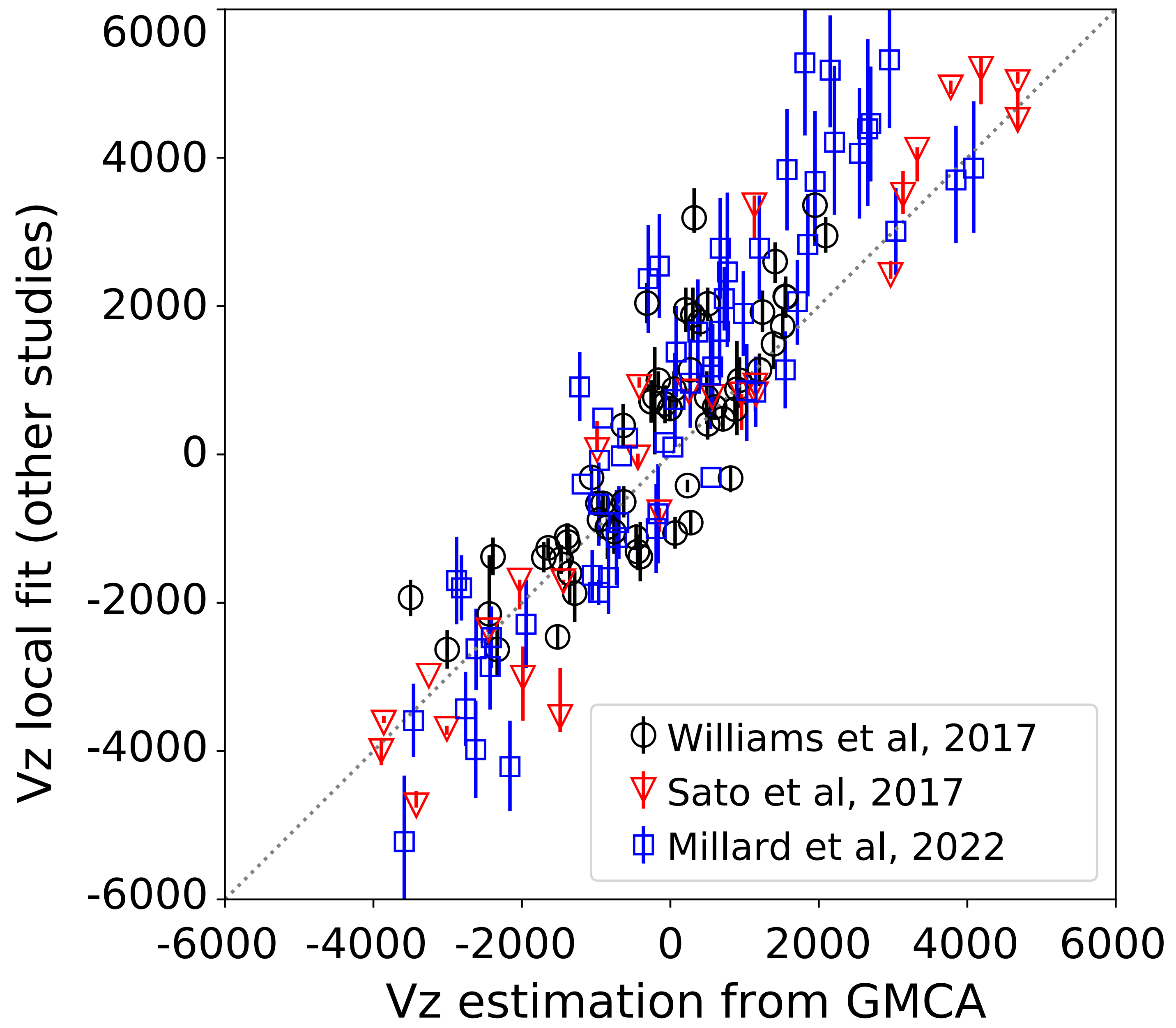


$$v_z = \frac{E_c - E_{ref}}{E_{ref}} c$$

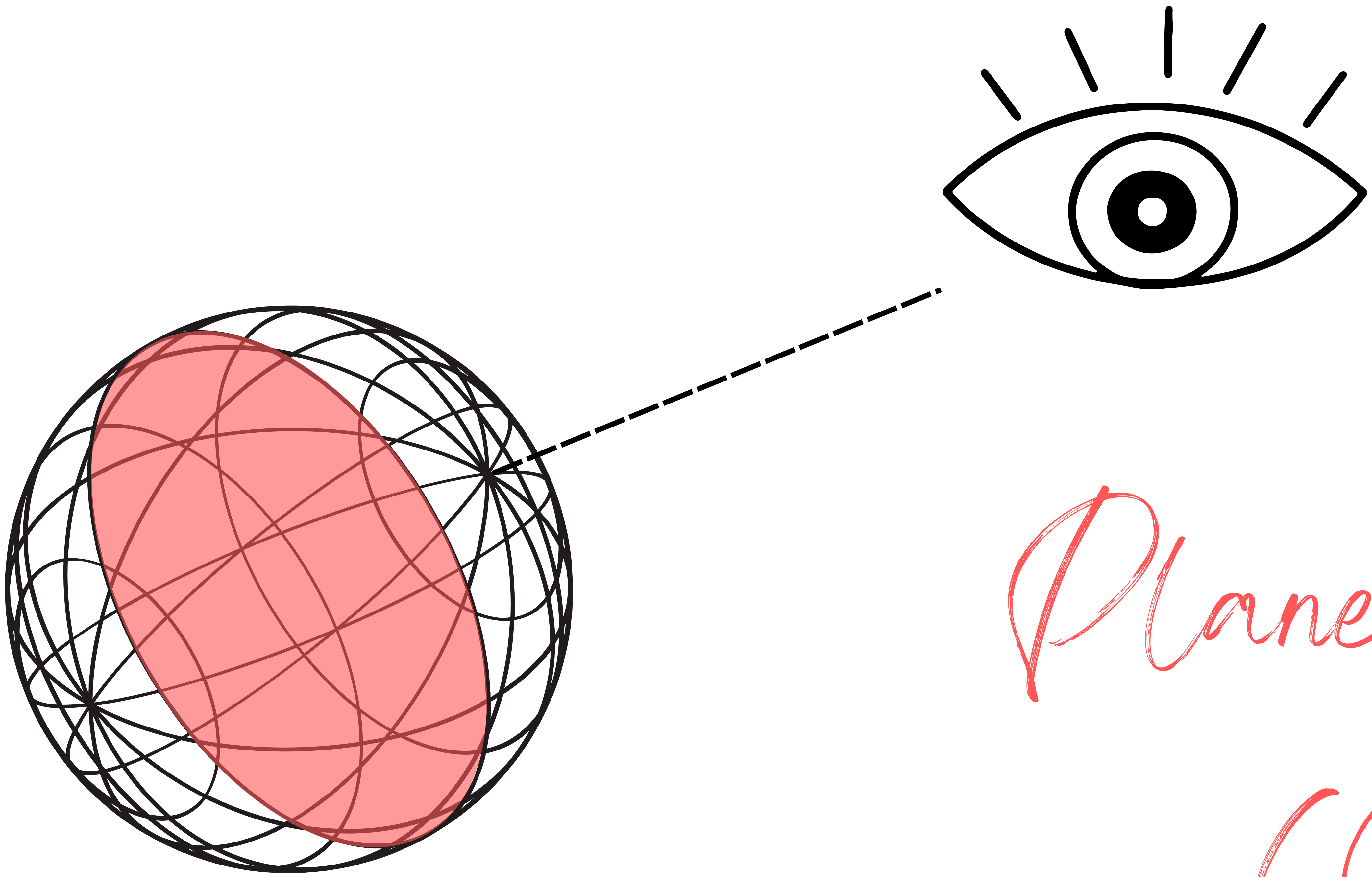
Cross checking our method



Comparing the velocity from previous studies with our values at same position.



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



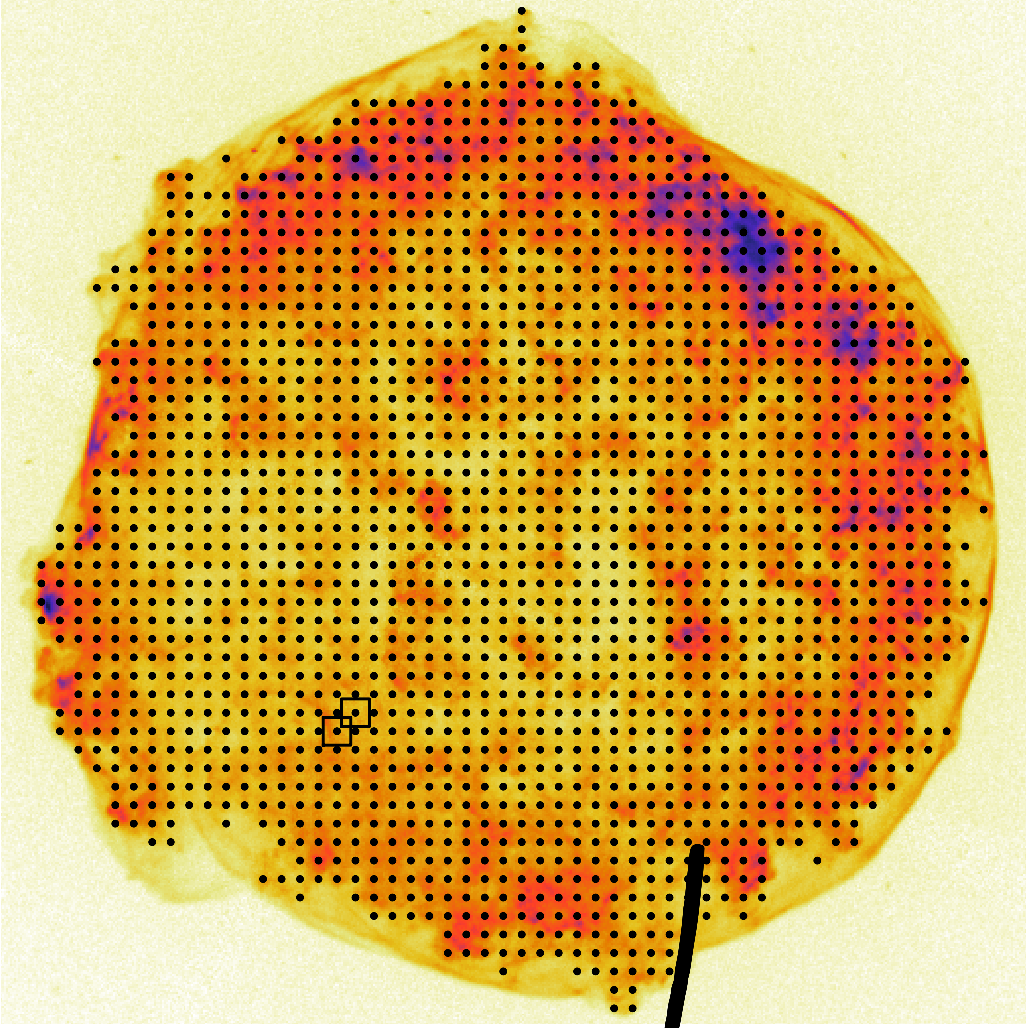
Plane of the sky

(Vxy)

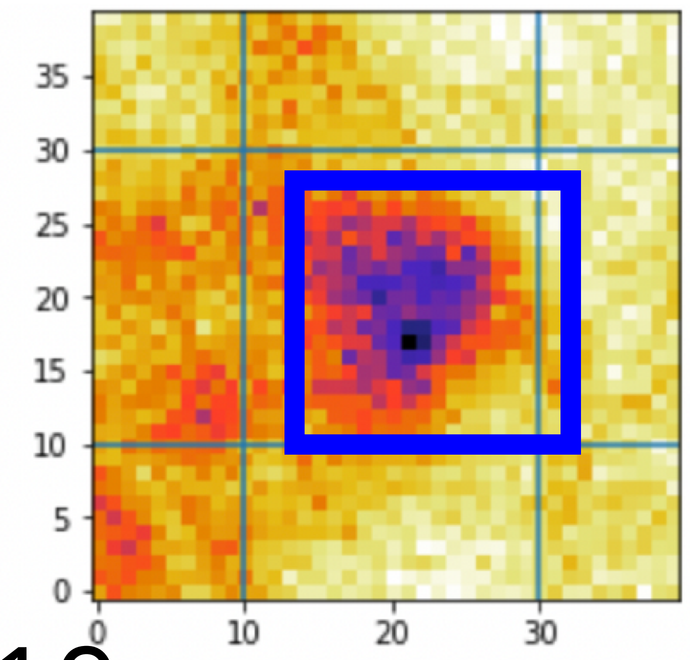
Velocity in the plane of sky : a new method

Tracking 2D features between epochs

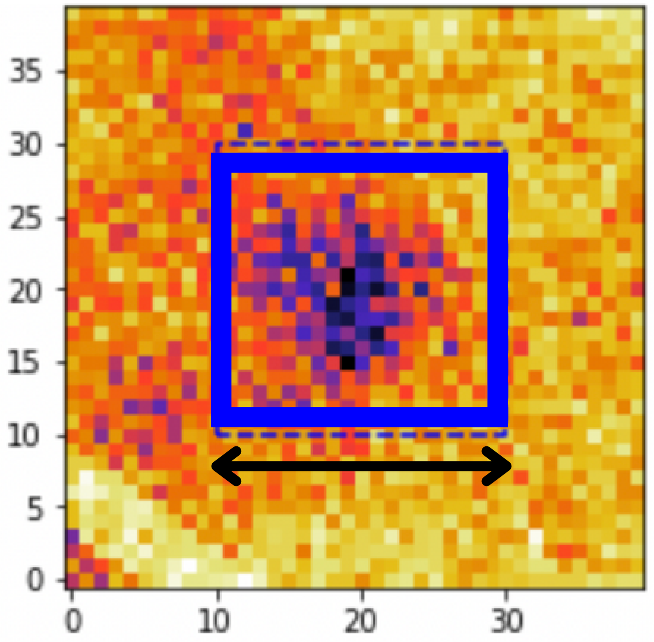
- Inspired from optical flow
- Adapted to the Poisson statistic
- 3D interpolation for sub-pixel precision
- Complete uncertainties ellipse
- Algorithm transparency



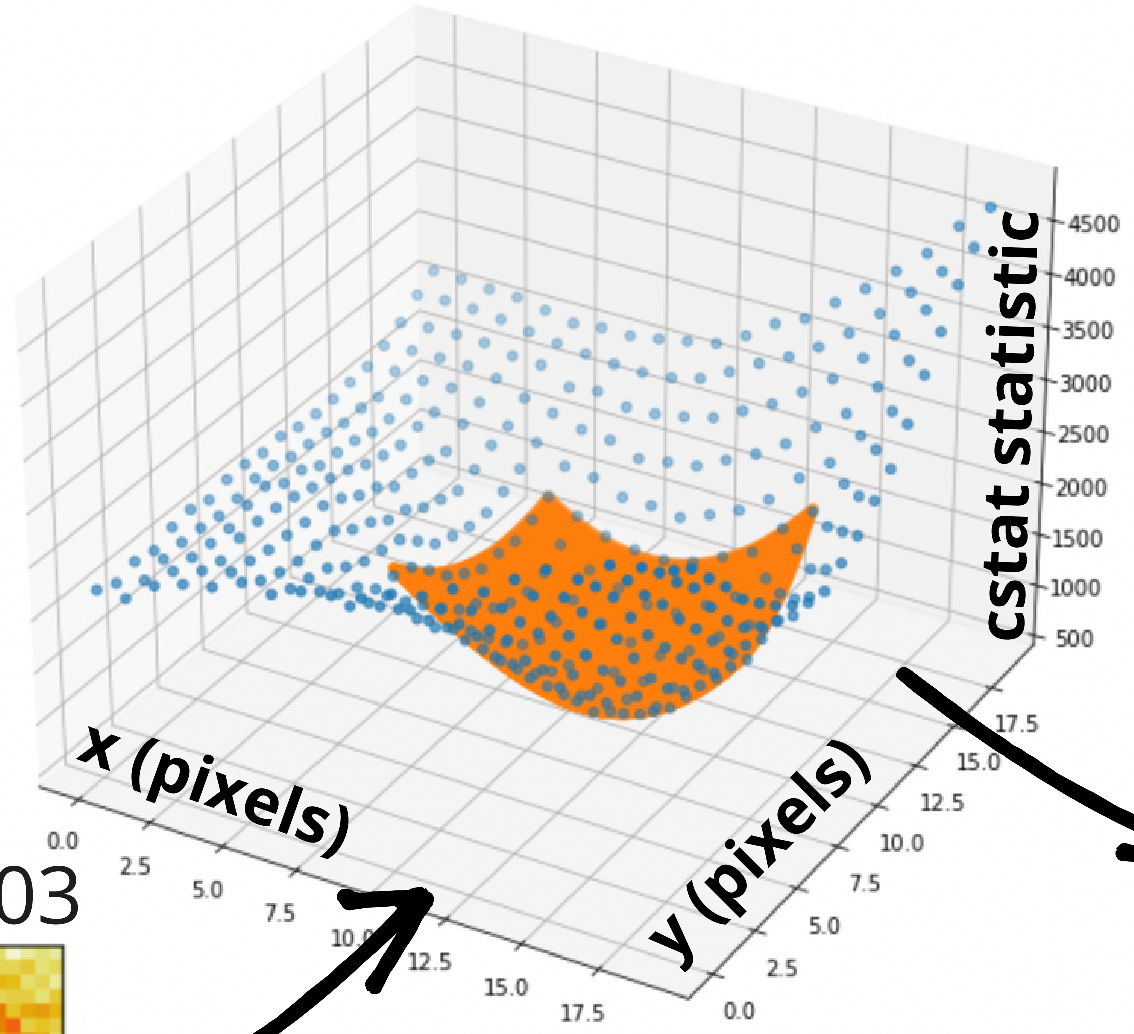
Model 2009



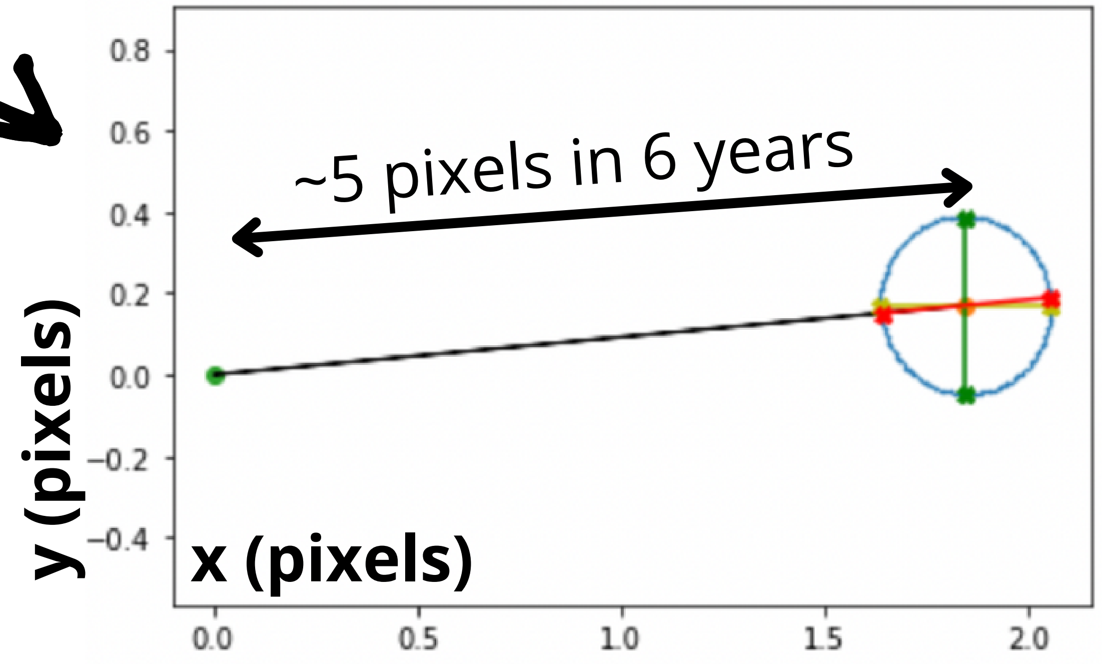
Observation 2003



20 pixels ~10 arcsec



Statistical landscape (cstat function)



Shift vector and uncertainties

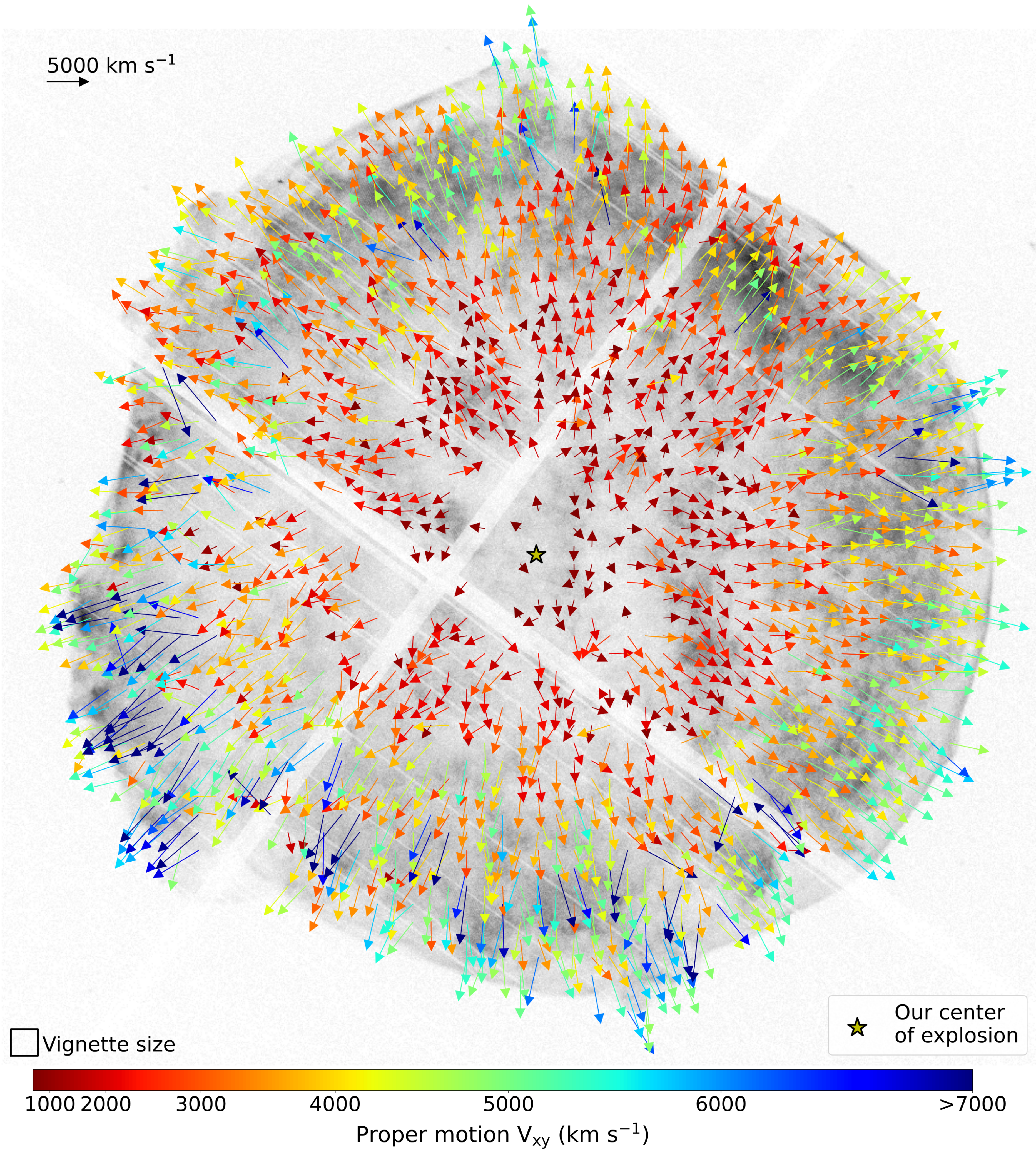
Vector field Vxy in plane of sky

Results

- **Thousands of vector** (1722), allowing a statistical study

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

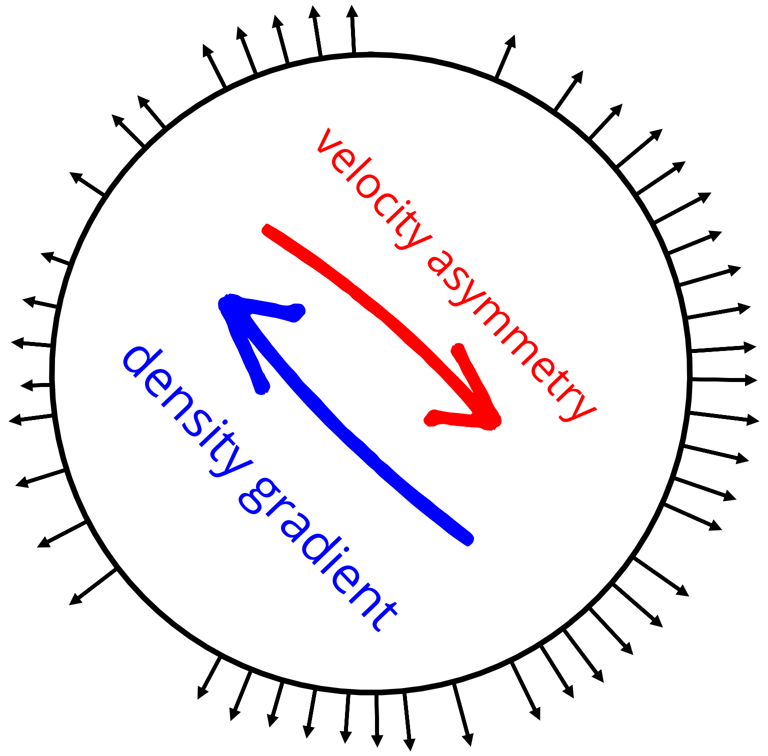
- local behaviour, no large scale regularisation



Large scale asymmetry

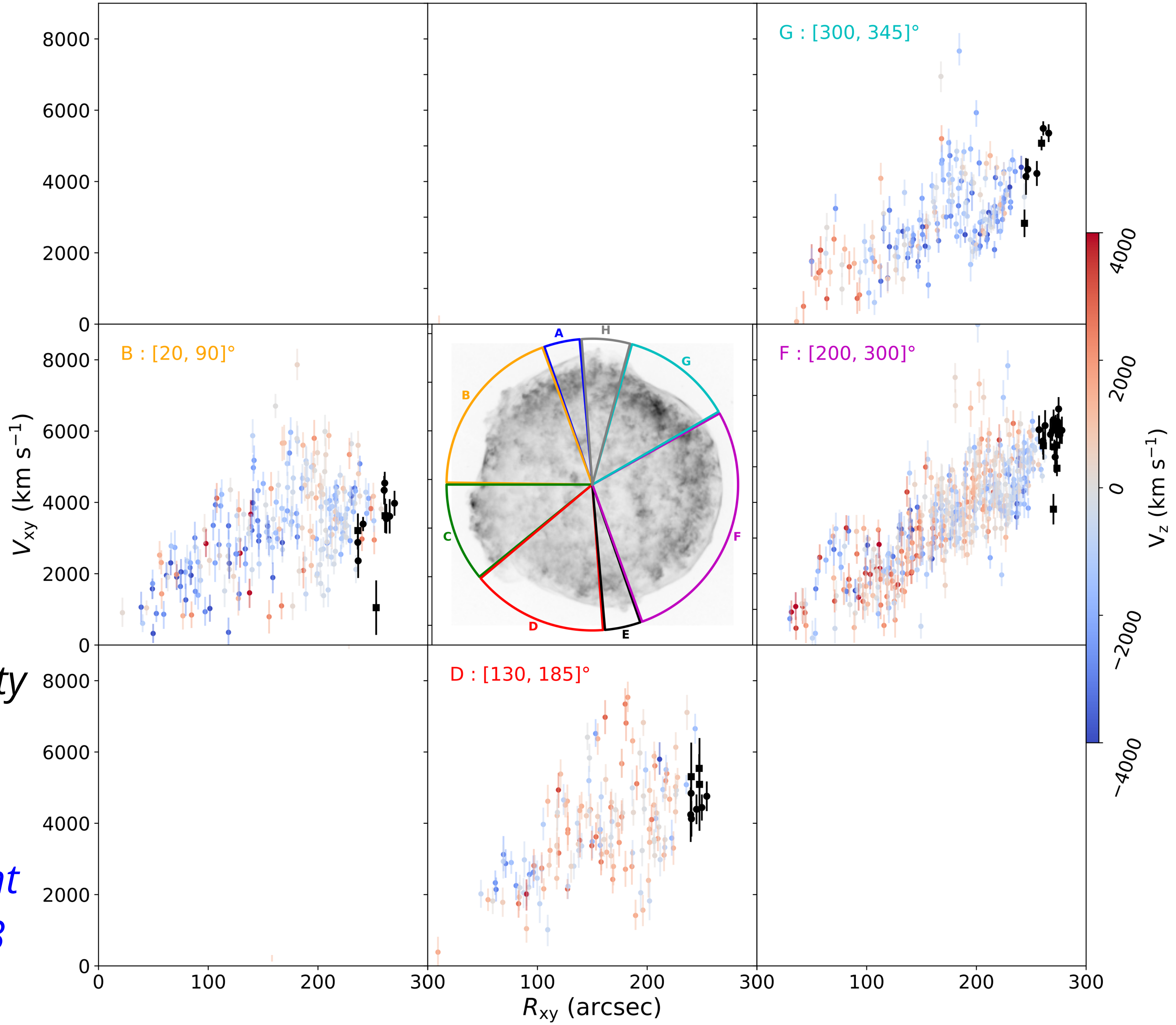
- Known velocity asymmetry of the forward shock explained by a density gradient

- For the ejecta : change of behaviour East/West, with the expected linear profile for the low-density side



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

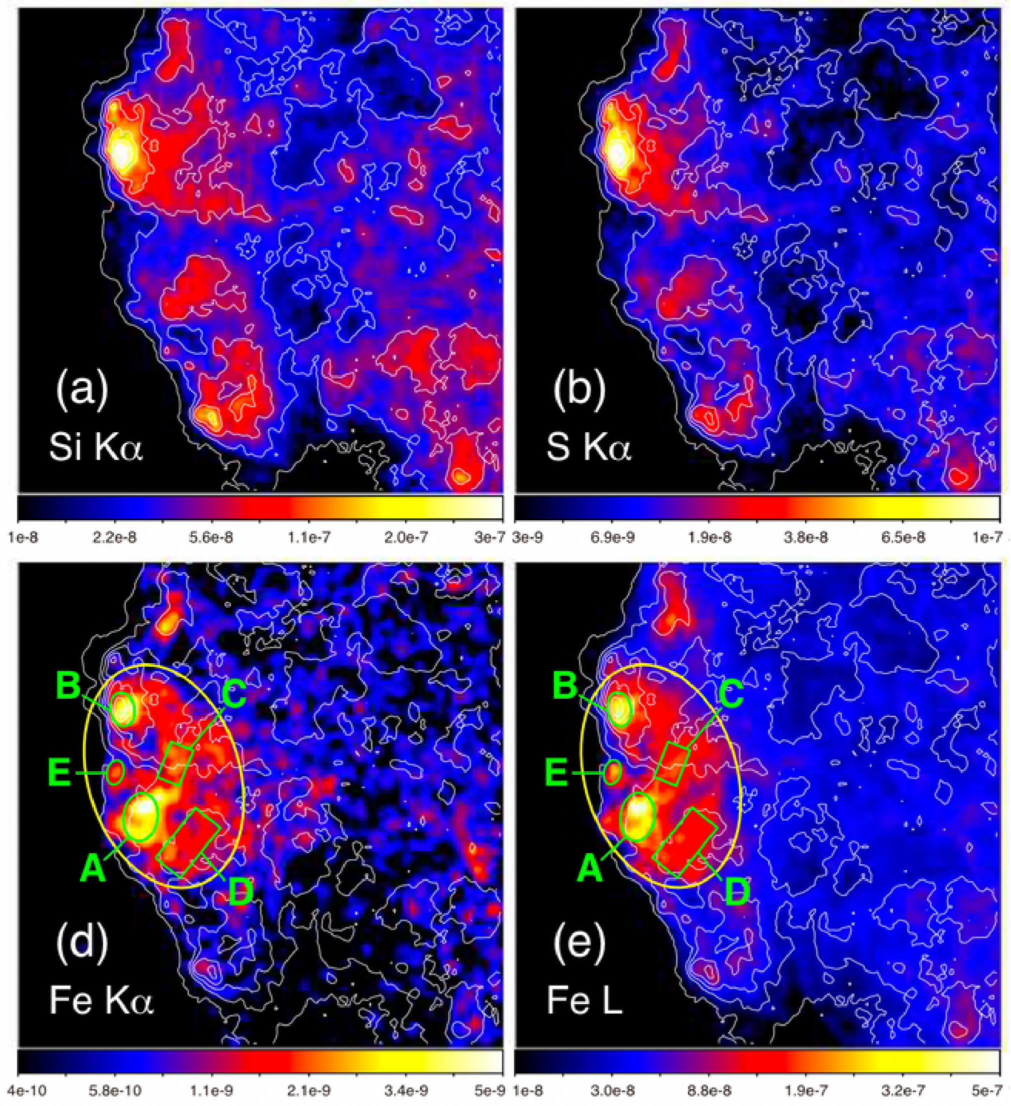
CSM density gradient
Williams et al, 2013
(Infrared)



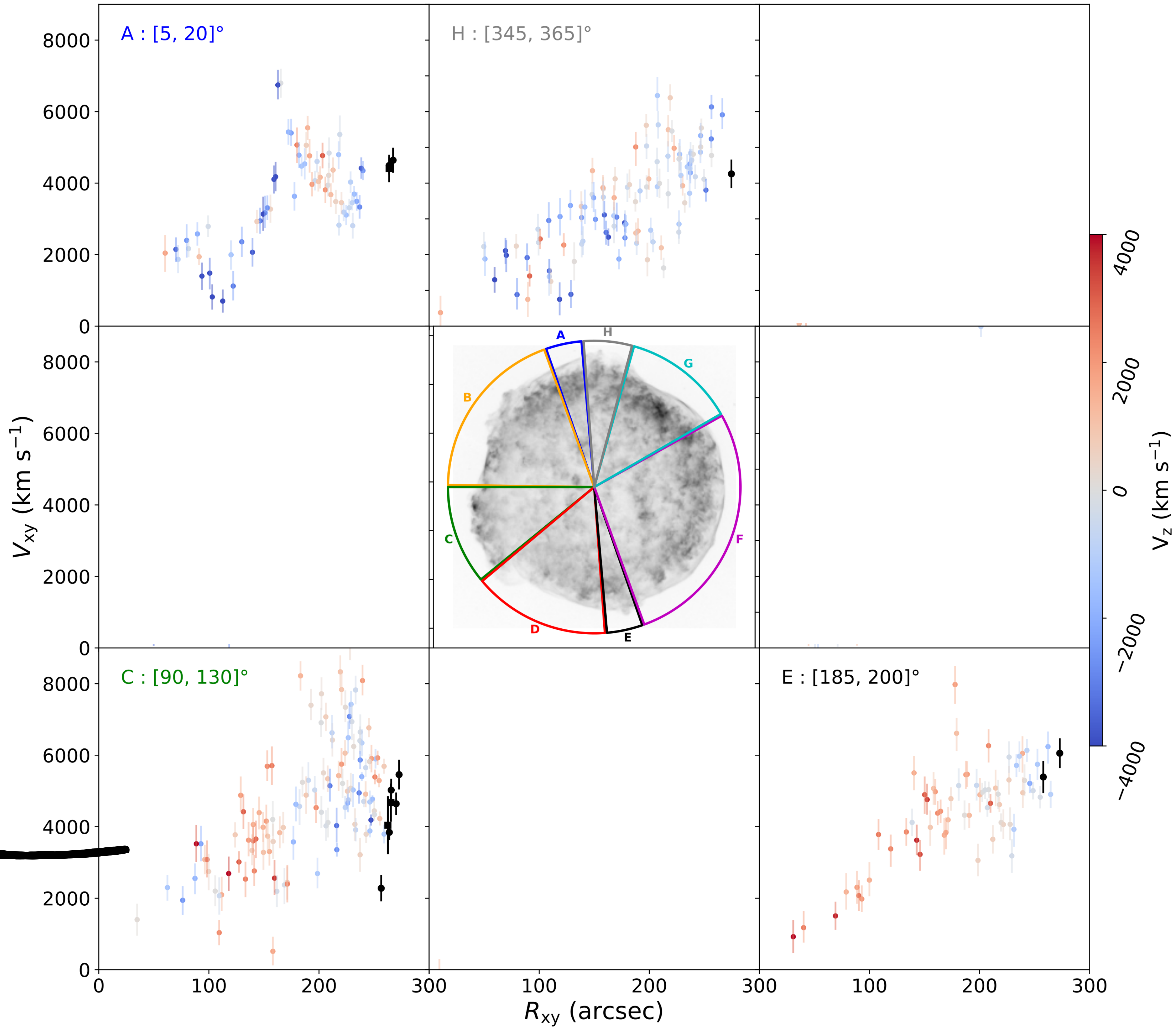
Fast iron and silicon knots

- Small scale deviations from the expected linear profile

- Fast dense "bullets" of iron and silicon produced during the explosion



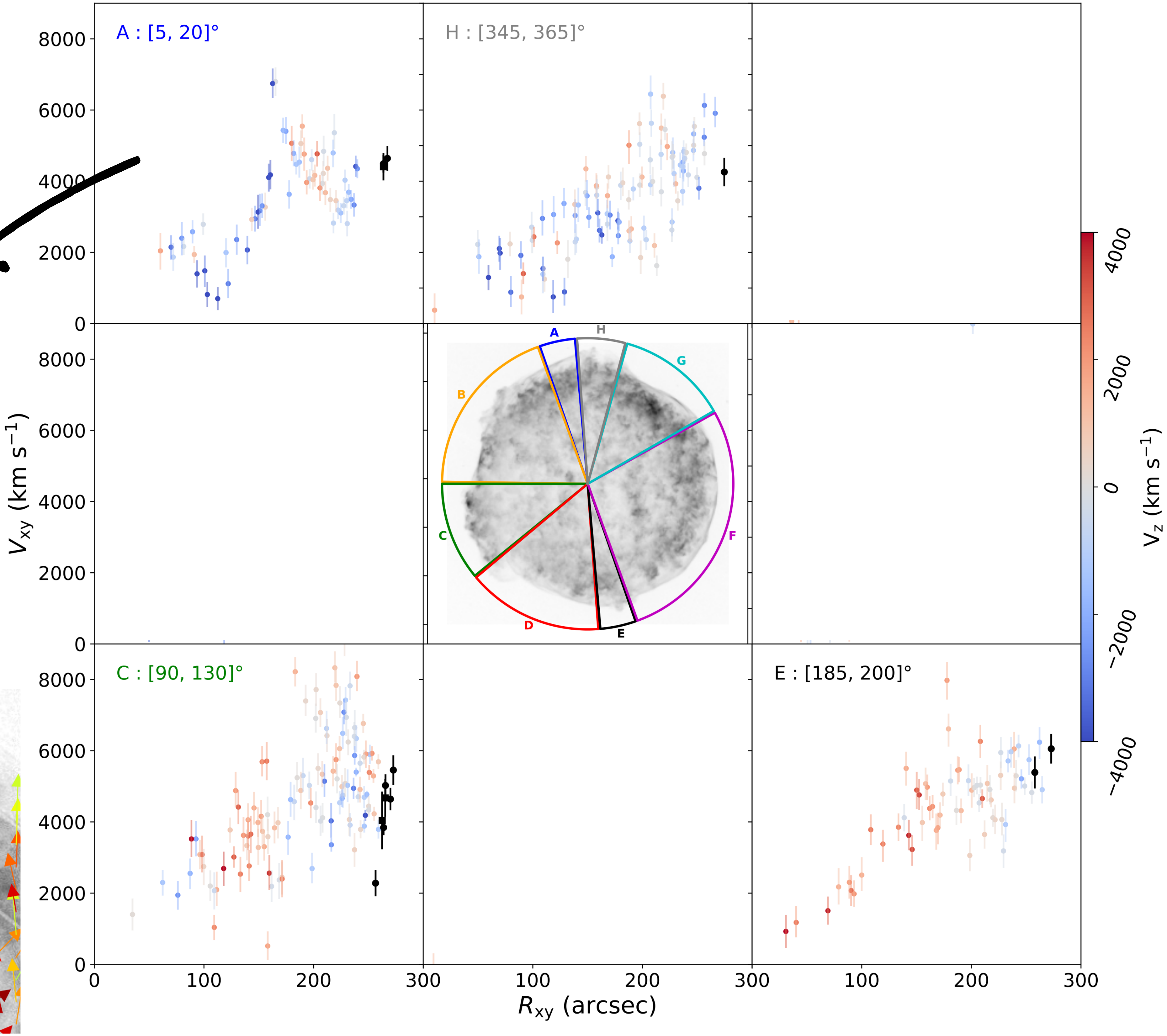
Yamaguchi et al, 2018



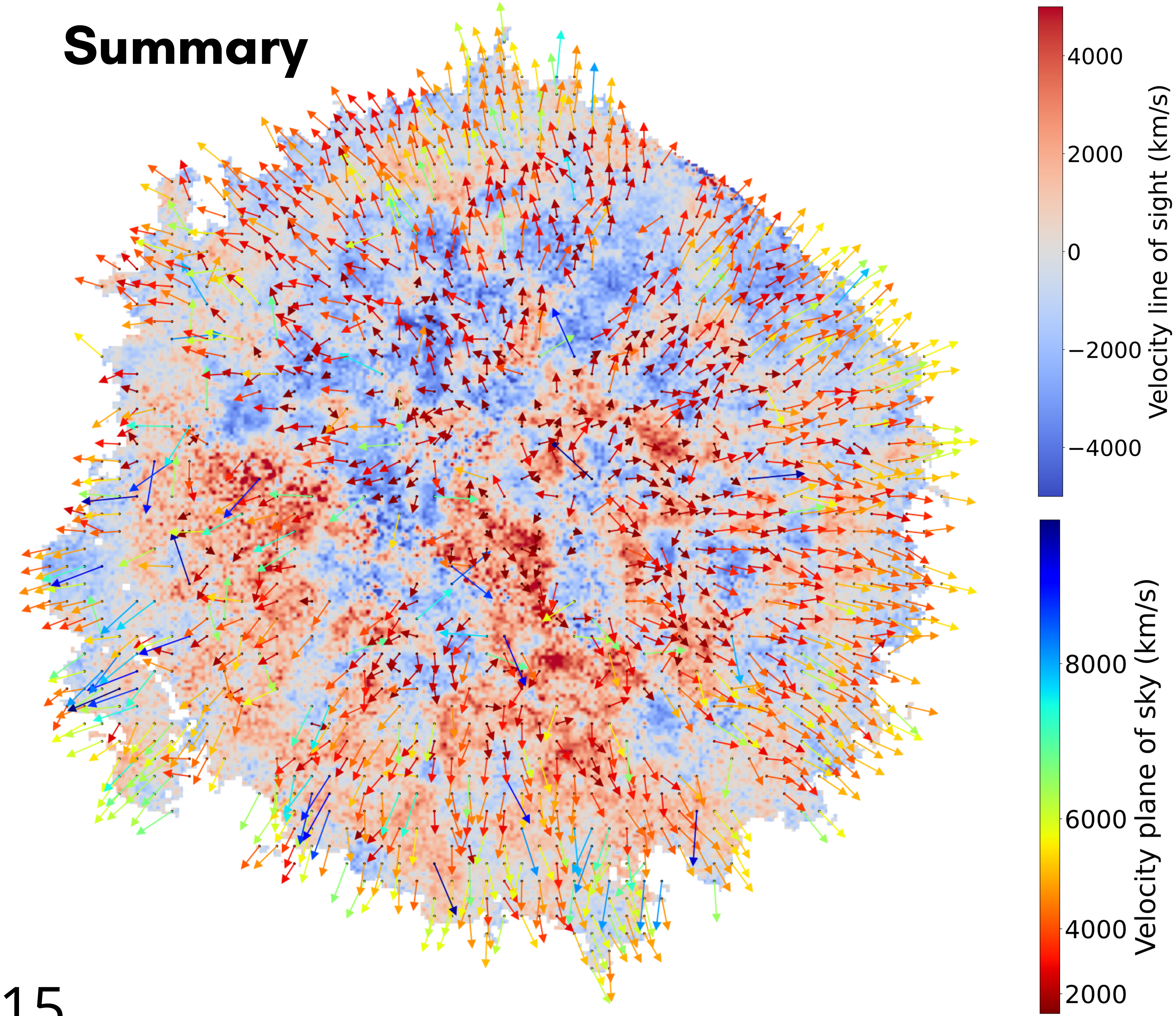
Probe the interactions with the environment

- Slow down of the ejecta near the edge of the SNR
- Known overdensity in radio (Zhou et al, 2016) in this zone

A proof of an 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

North/South velocity asymmetry

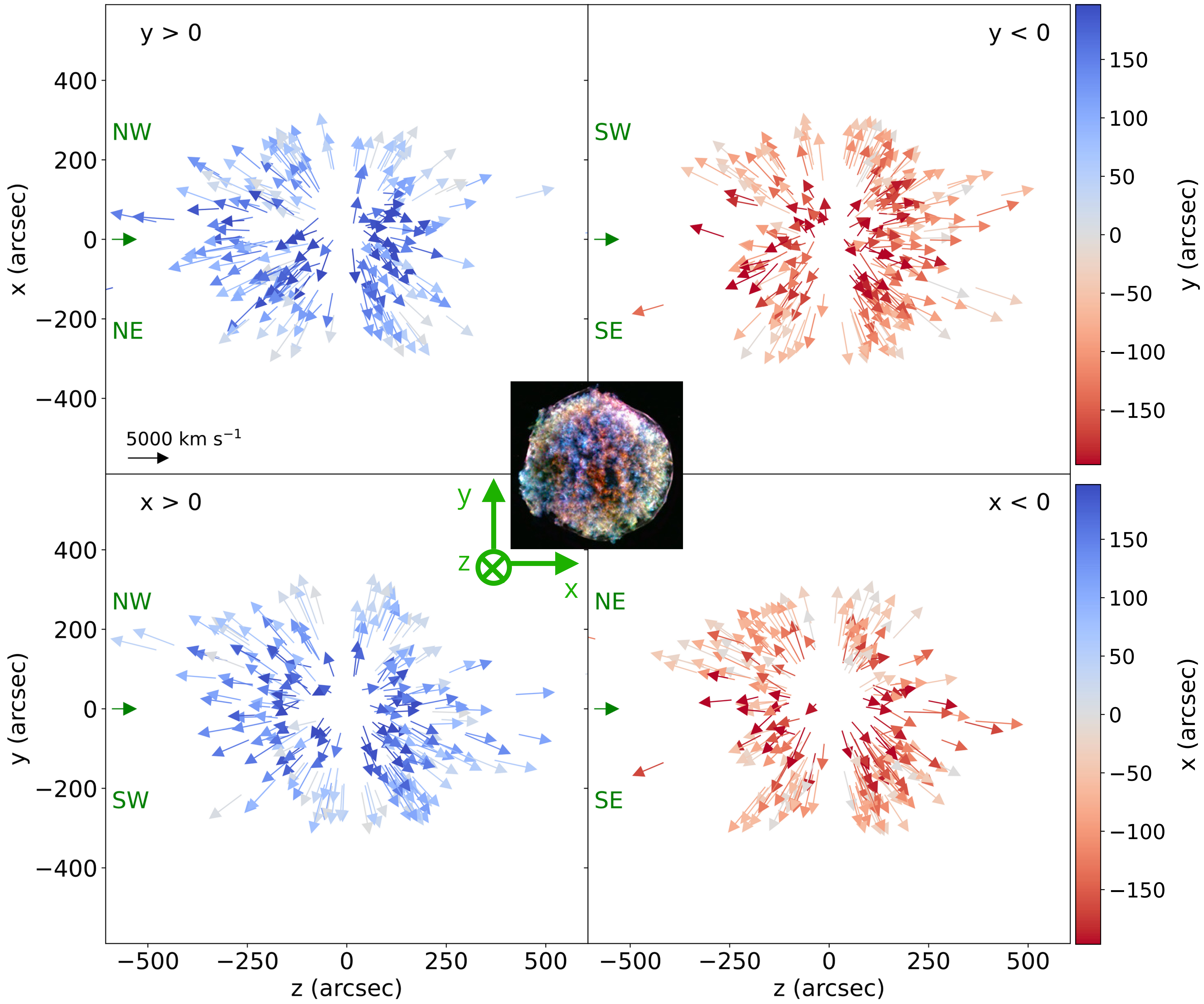
Methodology plane of sky (Vxy)

- New method to measure proper motion with 2D profiles
- Resulting of thousands of vectors

Deviations to the expected spherical expansion

Toward a 3D reconstruction

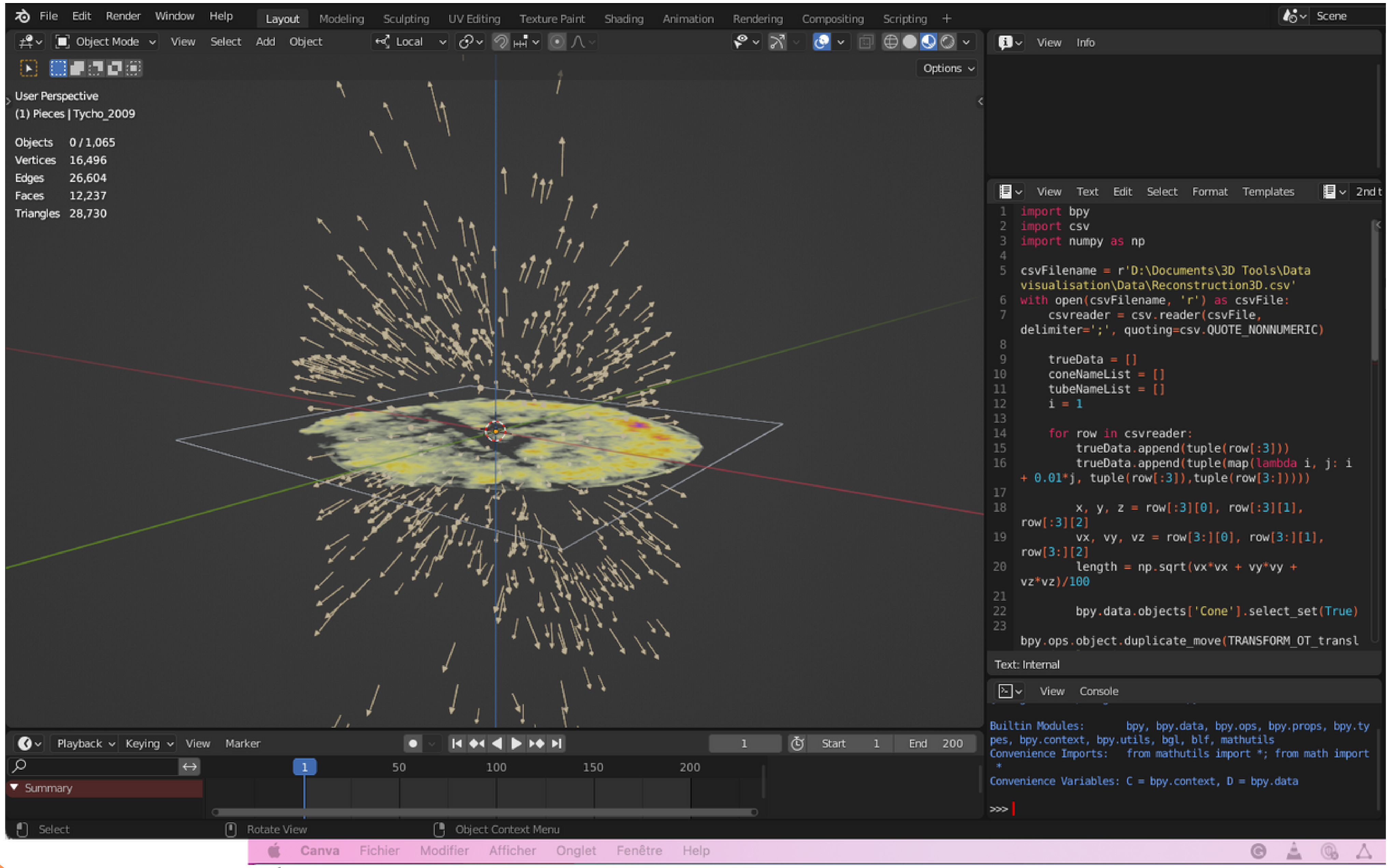
- Localize the vector in the line of sight
- For now more hypothesis are needed



3D representations

3D print of simulations

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



Perhaps one day a 3D file of my analysis to see in VR !

Thanks for your attention

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Illustrations

- Gavin Leroy
- Julie Borgese

Data used in this presentation

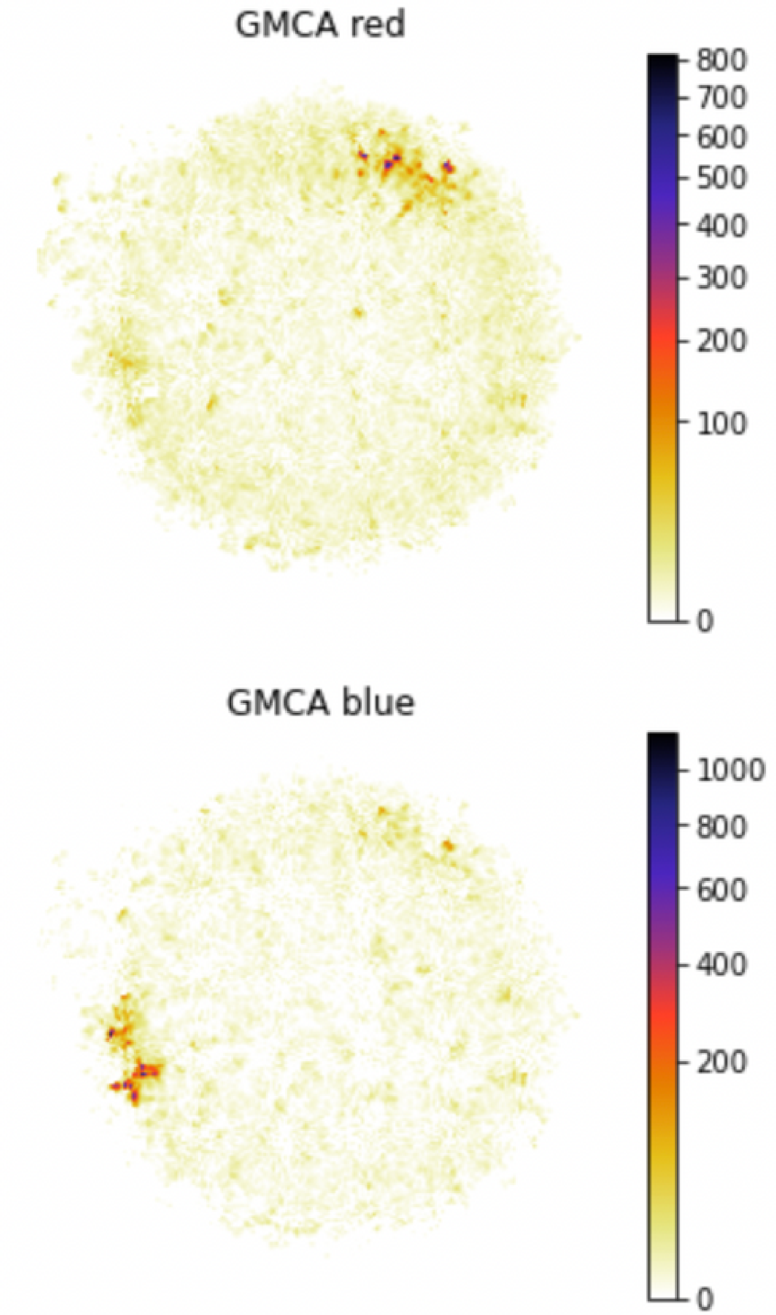
- Chandra telescope archive
- Williams et al, 2017
- Sato et al, 2017
-Yamaguchi et al, 2018

Phew it's over ...

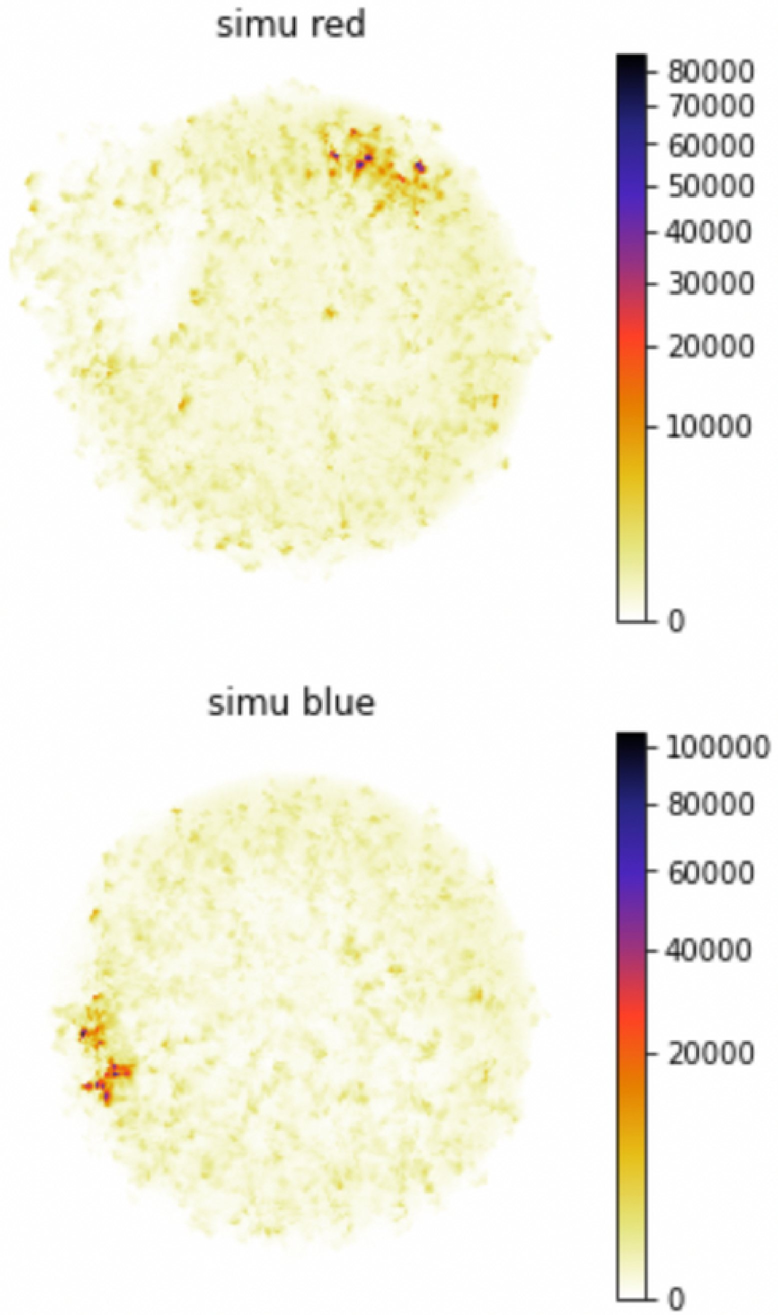
But there are some backups !

GMCA check with simulations

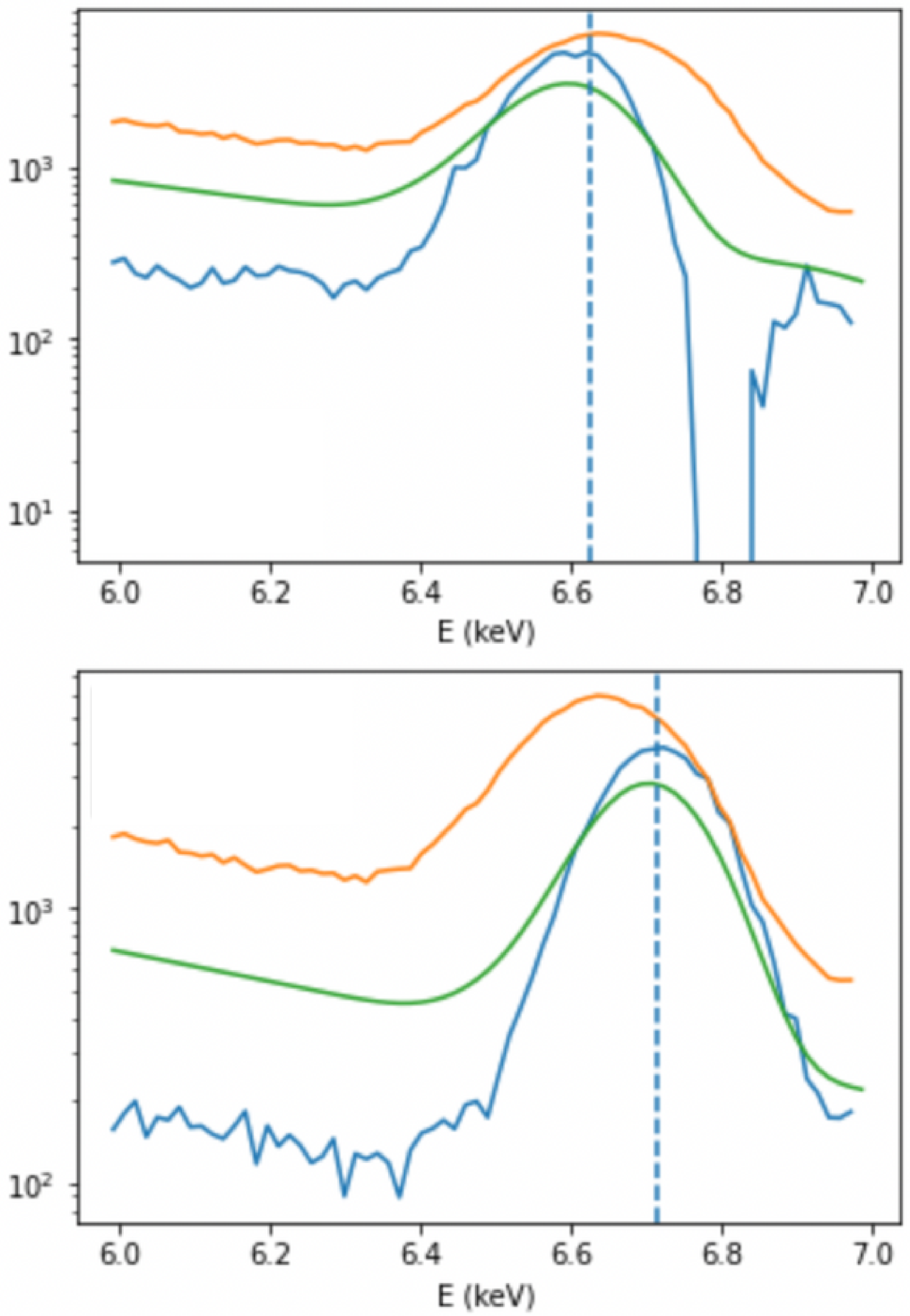
With the data (x,y,z,E) from S. Orlando simulation of CasA, we compare :



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)

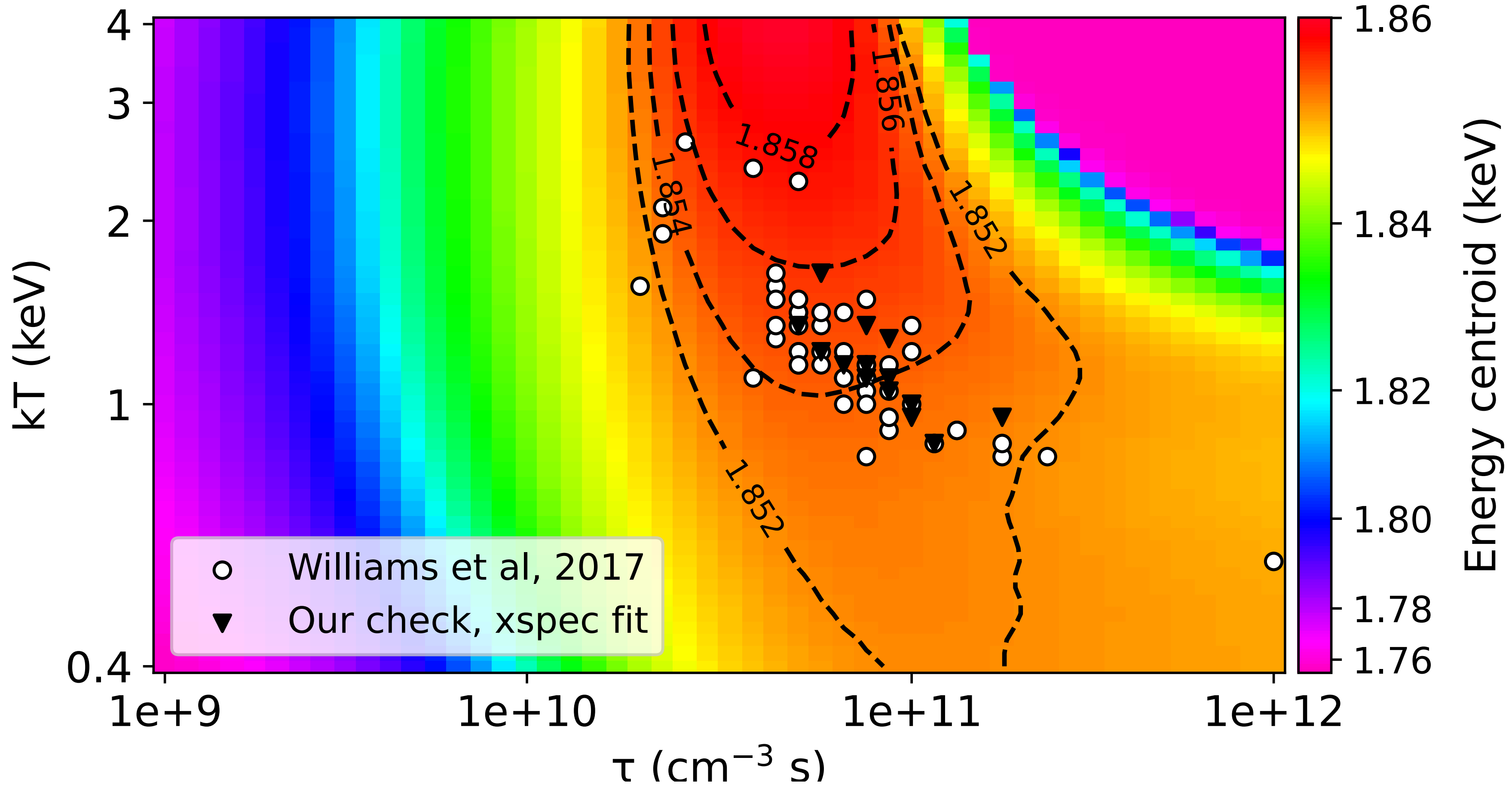


- Total spectrum
- GMCA ouput
- spectrum from half shell

How we choose the energy of reference for the Si line?

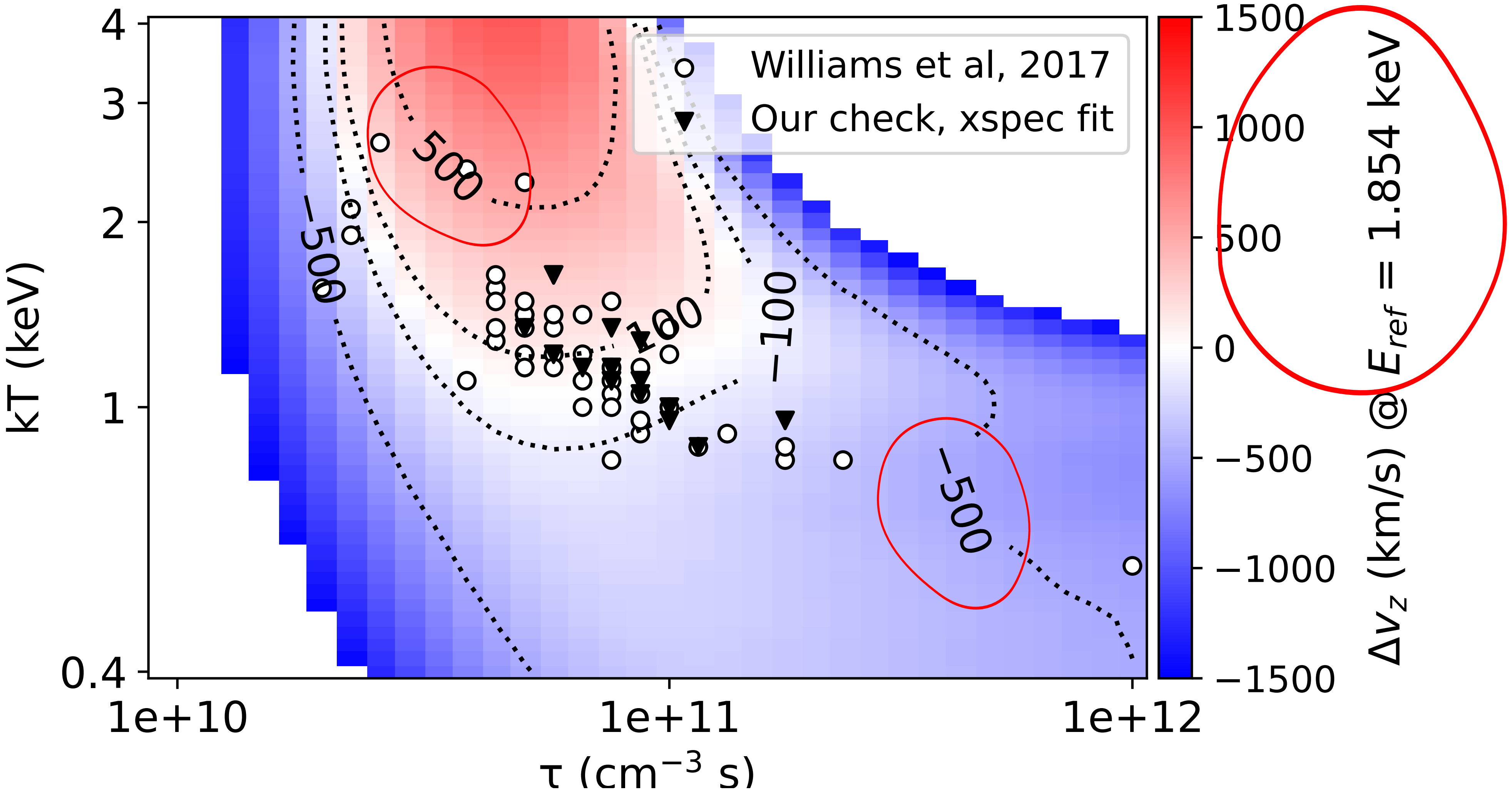
- *Background map* : the theoritical energy centroid of the Si line at rest according kT and tau

- On this map, we put (kT, tau) measures from *spectral local extraction and fitting*

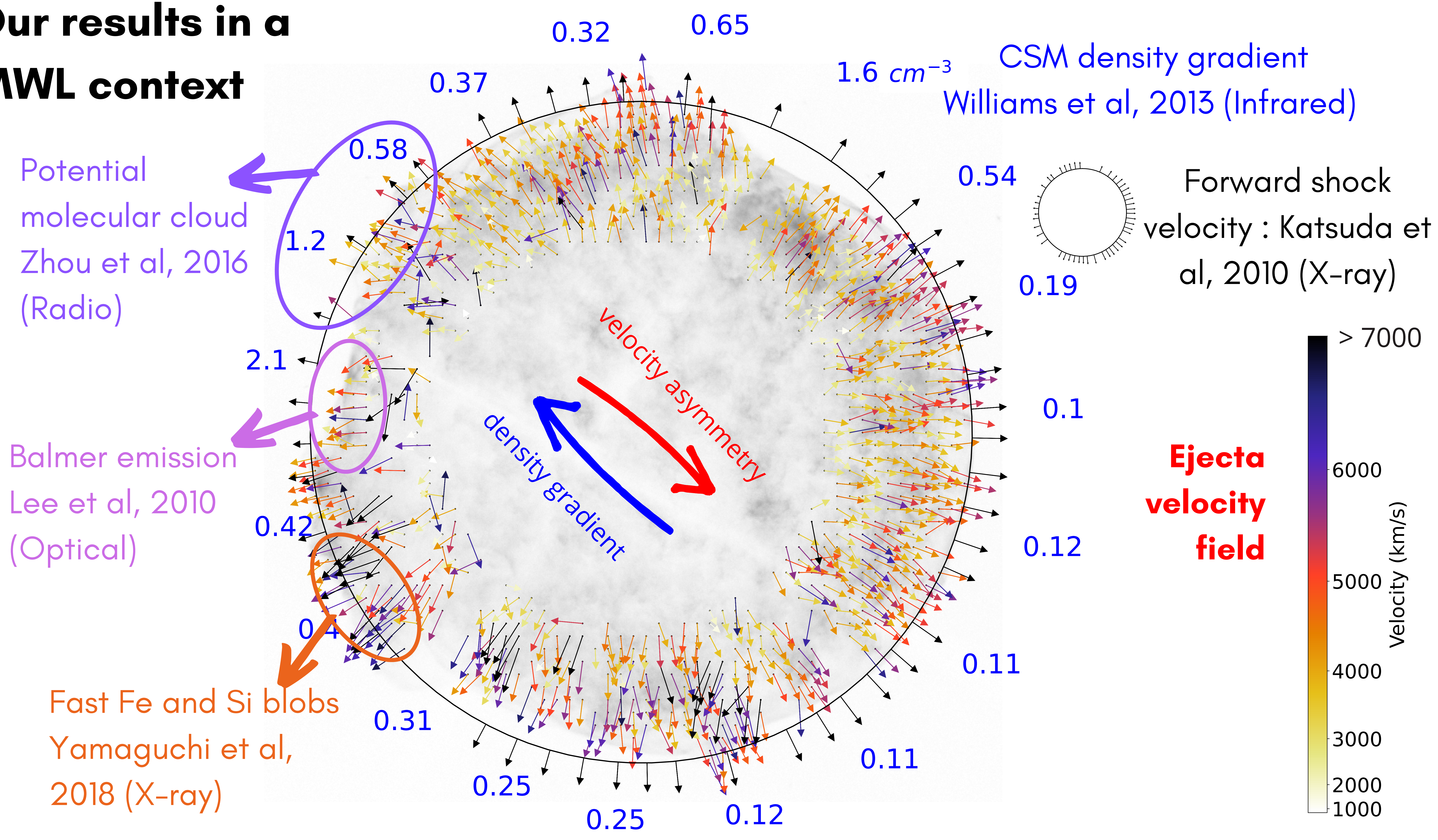


- We take the **mean corresponding energy at rest** as our reference :
Eref = 1.854 keV.

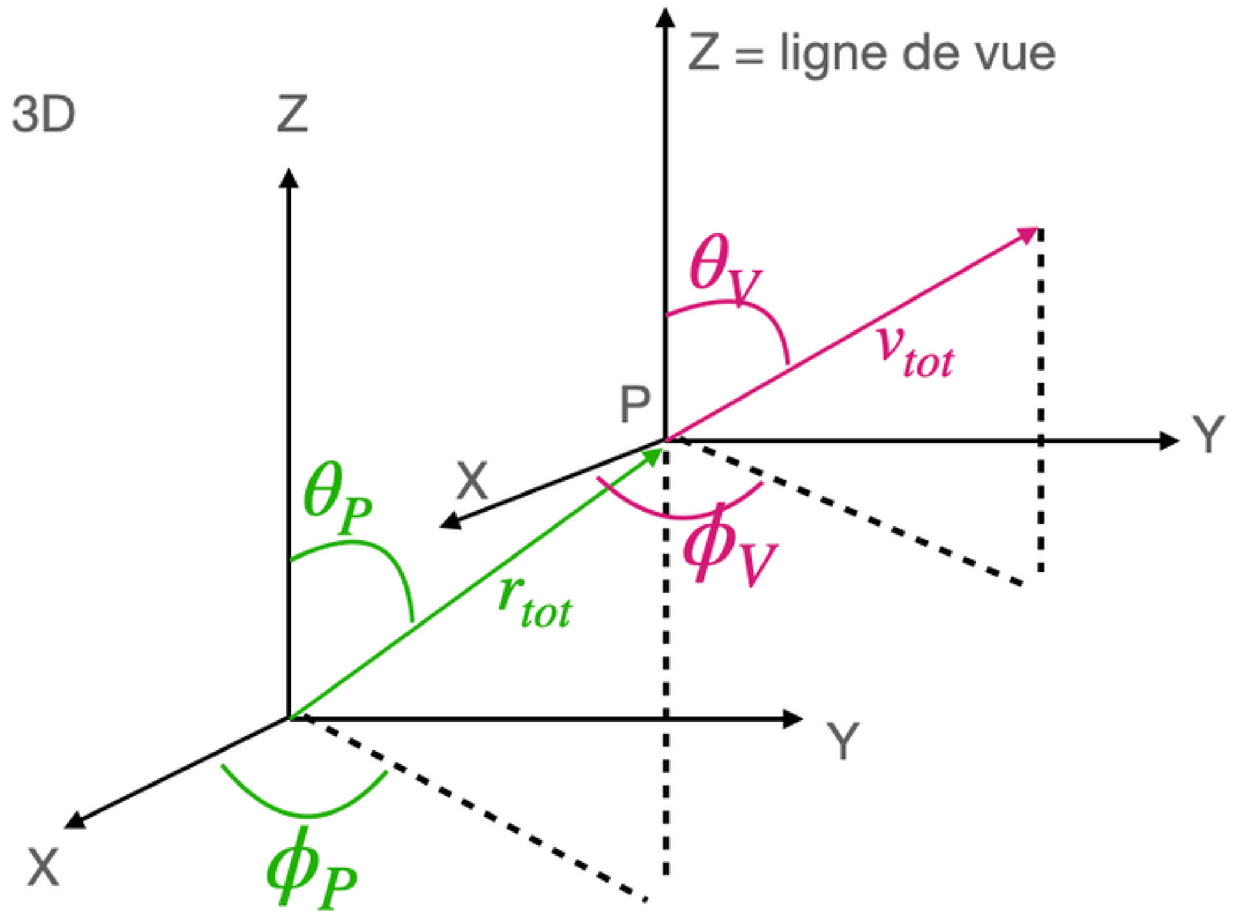
- **Small impact from variation of energy of reference** around our value on the velocities



Our results in a MWL context



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 :

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