The University of Texas at Arlington

3-D Mapping of X-ray Emitting Ejecta in Kepler's Supernova Remnant

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25 Years of Science with Chandra

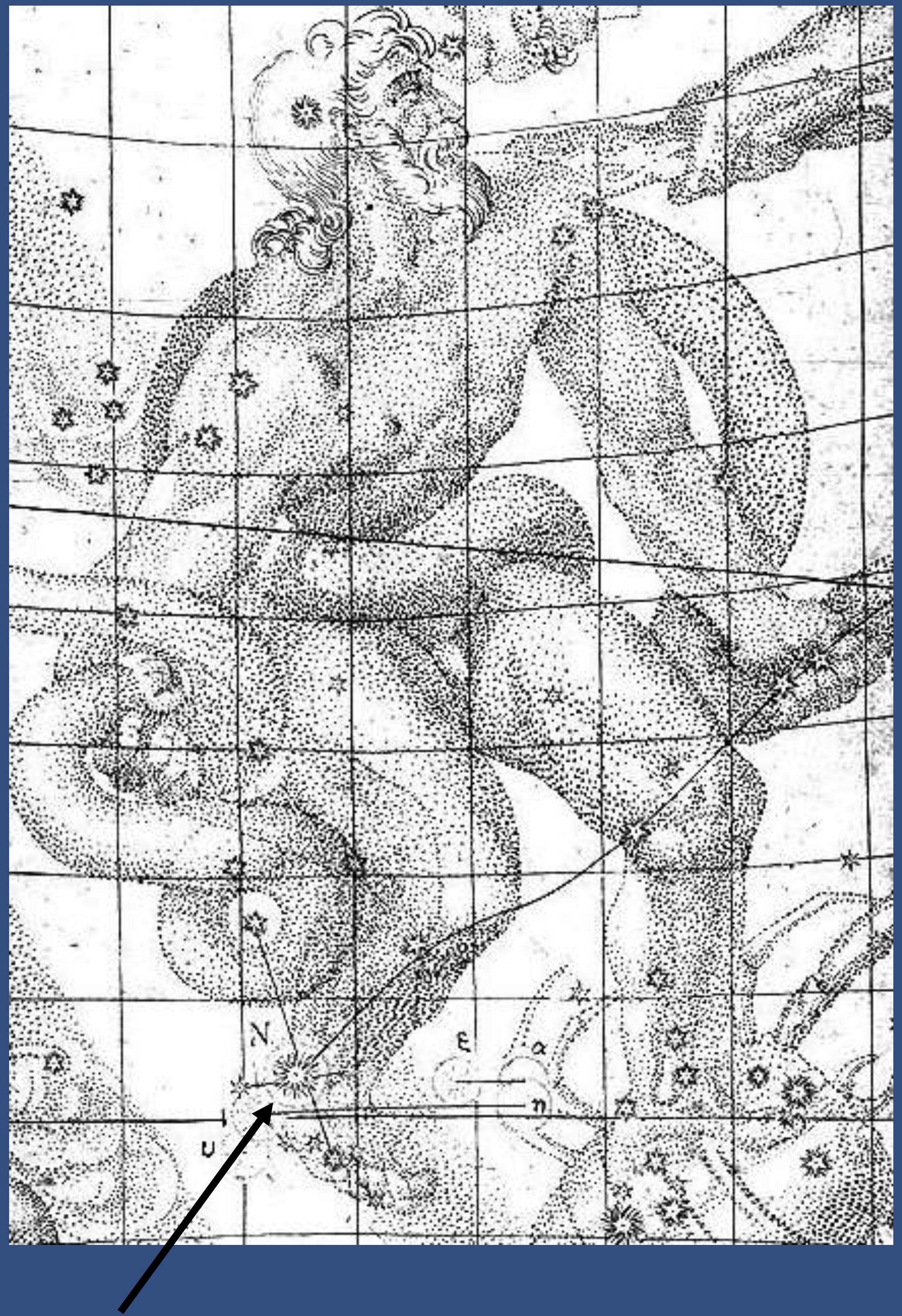
December 04, 2024

Outline

- Kepler's Supernova
- Studying Kepler Using Chandra
- Data Analysis
- Preliminary Results

Kepler’s Supernova - Description

- Supernova occurred in 1604 in the Ophiuchus constellation!
- Last naked eye supernova observed in our Milky way Galaxy!
- Remnant discovered in 1941 by at the Mount Wilson Observatory. (Baade 1943)
- Type Ia supernova (Reynolds et al 2007, Chiotellis et al 2012)



De Stella Nova, 1606, J. Kepler

Kepler’s Supernova - Description

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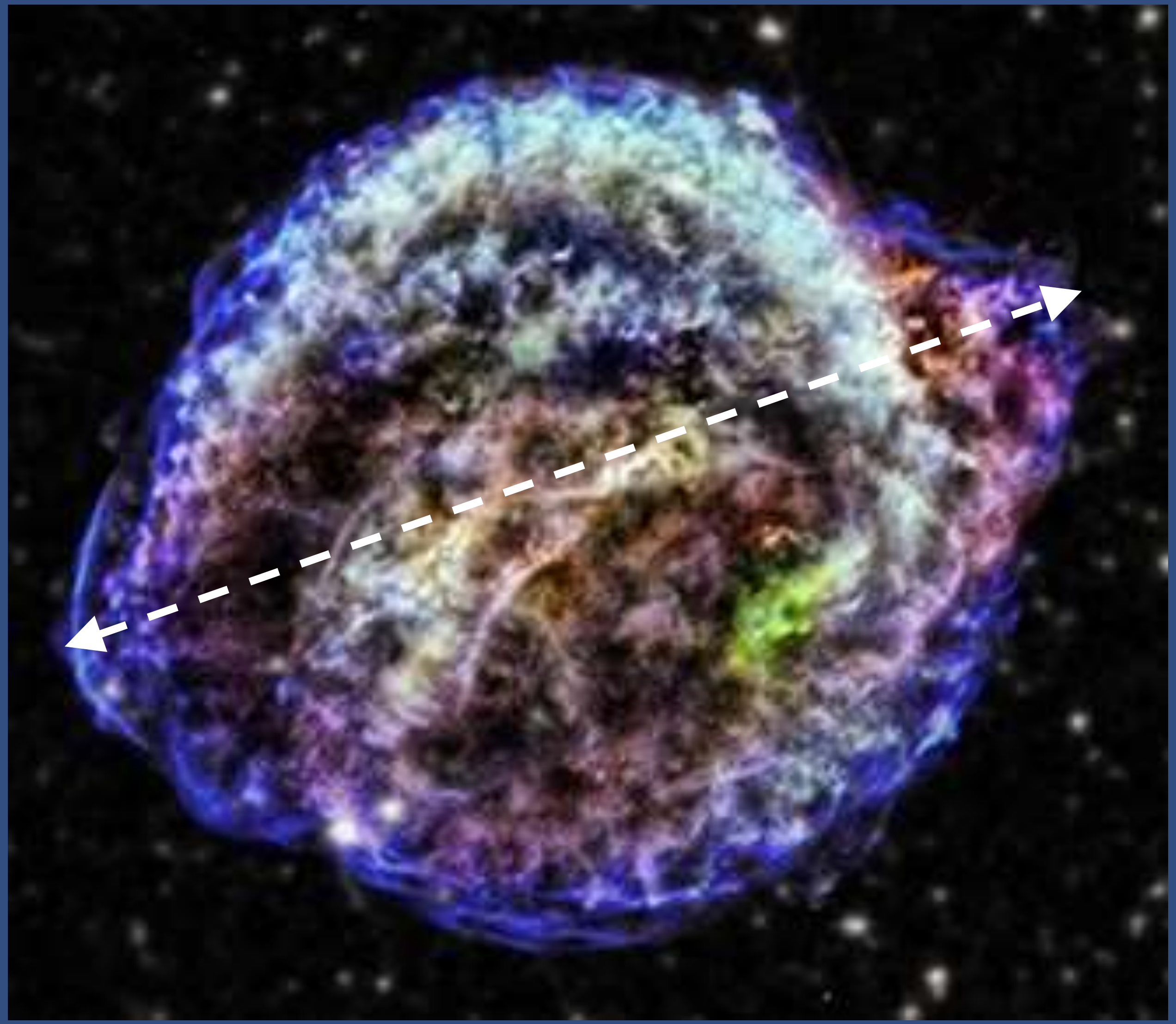
Structure

- Widest diameter measures ~ 4.6 arcmin. (Reynolds et al 2007)
- Spherically asymmetric, two protruding ears (Reynolds et al 2007)
- Progenitor: Super-Solar metallicity star and had an AGB companion (Burkey et al 2012, Chiotellis et al 2012, Park et al. 2013).
- The northern shell shows evidence of a dense CSM (Blair et al. 1991).
- Non-standard Type Ia SNR.



Kepler’s SNR X-ray Image (0.1-10 keV)
NASA/CXC/NCSU/S.Reynolds et al

Distance – 6.0 ± 1.5 kpc (Millard et al 2020)

Why Study Kepler's SNR?

Scientific Motivation:

- SN/SNR is inherently a 3D phenomenon, thus revealing their true 3D structure is critically important for realistic modelling of SN.
- Kepler, a young ejecta-dominant SNR, provides an excellent opportunity to explore the 3D structure of SN ejecta through high-resolution X-ray imaging spectroscopy with deep exposure.

Objective

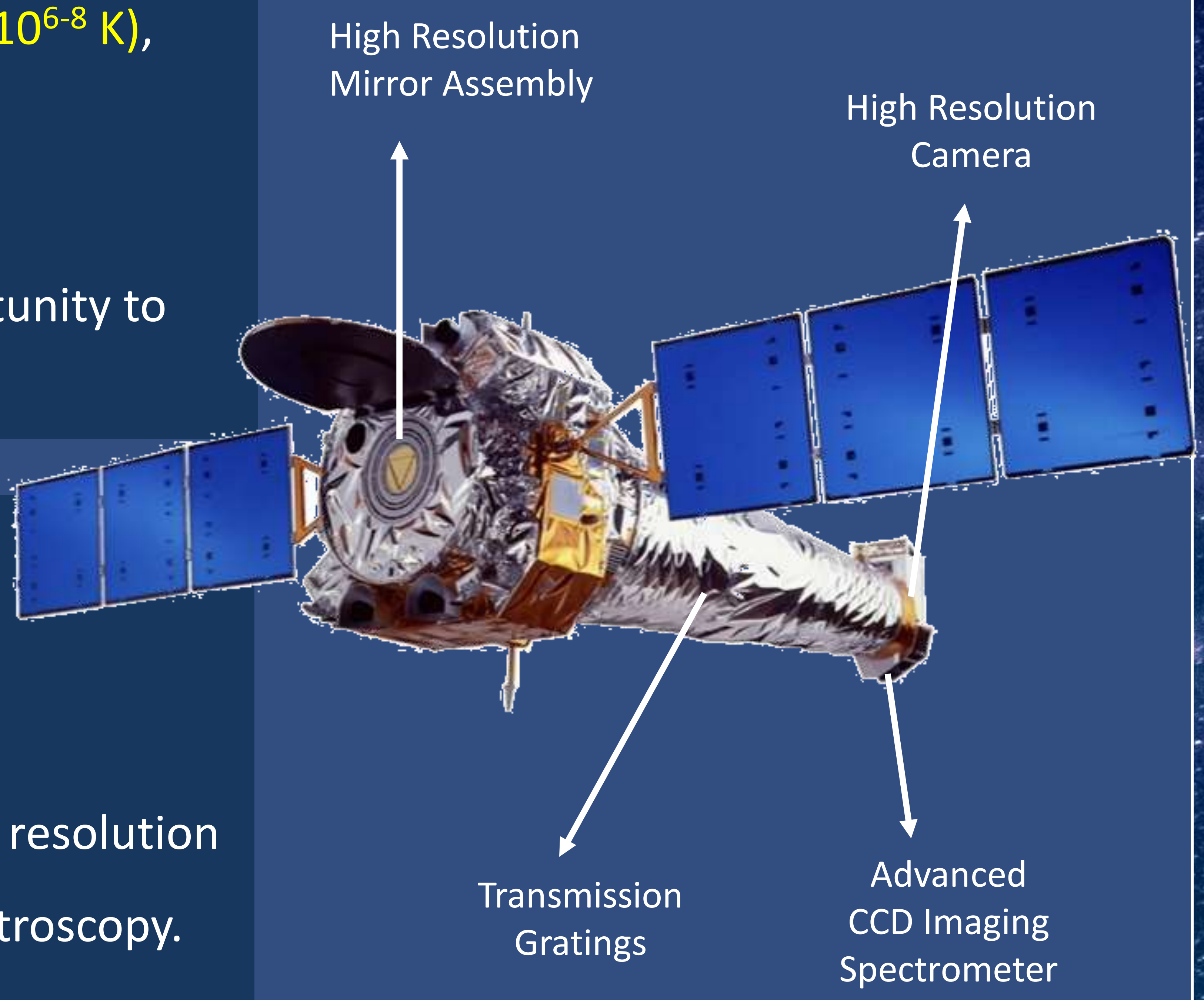
- Construct a 3D map of ejecta velocities.
- Emission distribution offers observational constraints essential for constructing accurate explosion model.

Studying Kepler Using Chandra

- At “young ages” ($\lesssim 10^4$ yr after explosion), SNRs are hot gas ($T \sim 10^{6\text{-}8}$ K), which efficiently radiates in X-rays.
- X-ray observations are effective to study them.
- High resolution X-ray imaging spectroscopy is an excellent opportunity to study SNRs.

Chandra X – ray Observatory

- High resolution of < 0.5”
- Energy range from ≤ 0.1 to 10 keV
- Advanced CCD Imaging Spectrometer (ACIS) can get high spatial resolution images while HETG/LETG can get high resolution dispersed spectroscopy.



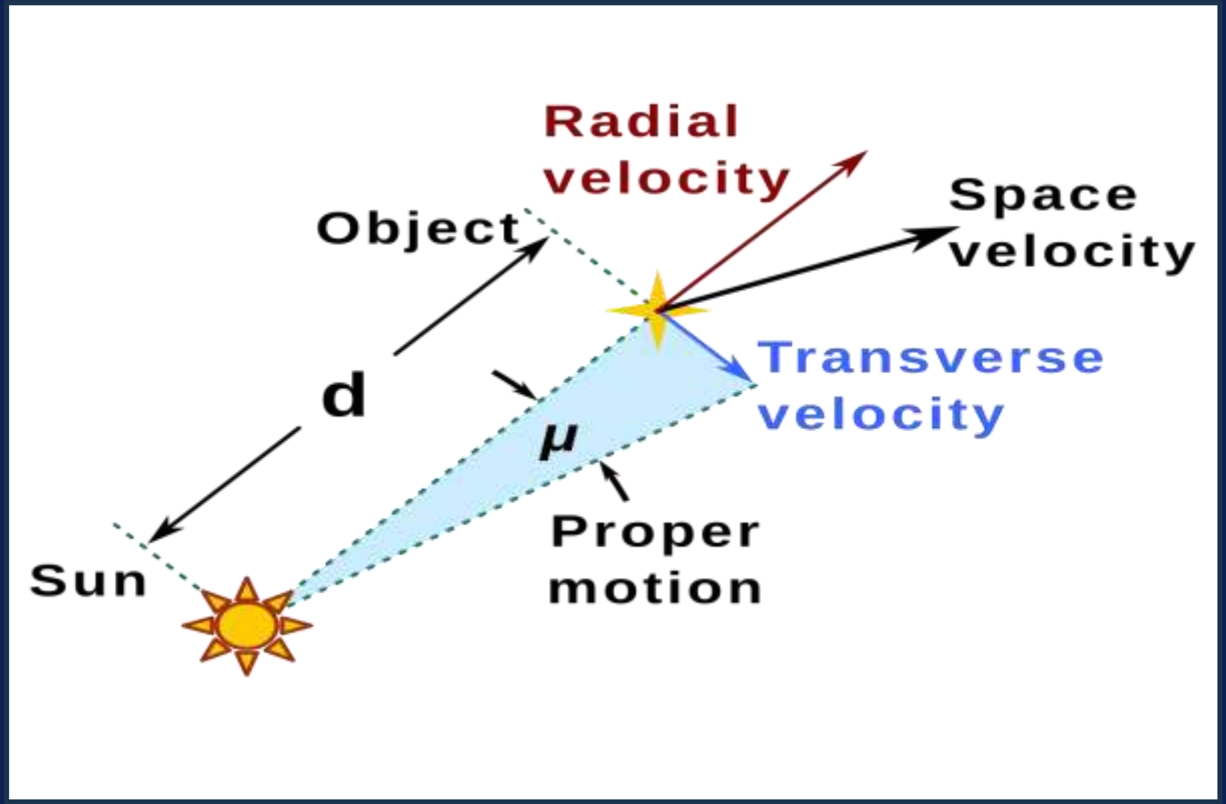
NASA’s *Chandra X-ray Observatory*
1999 – present

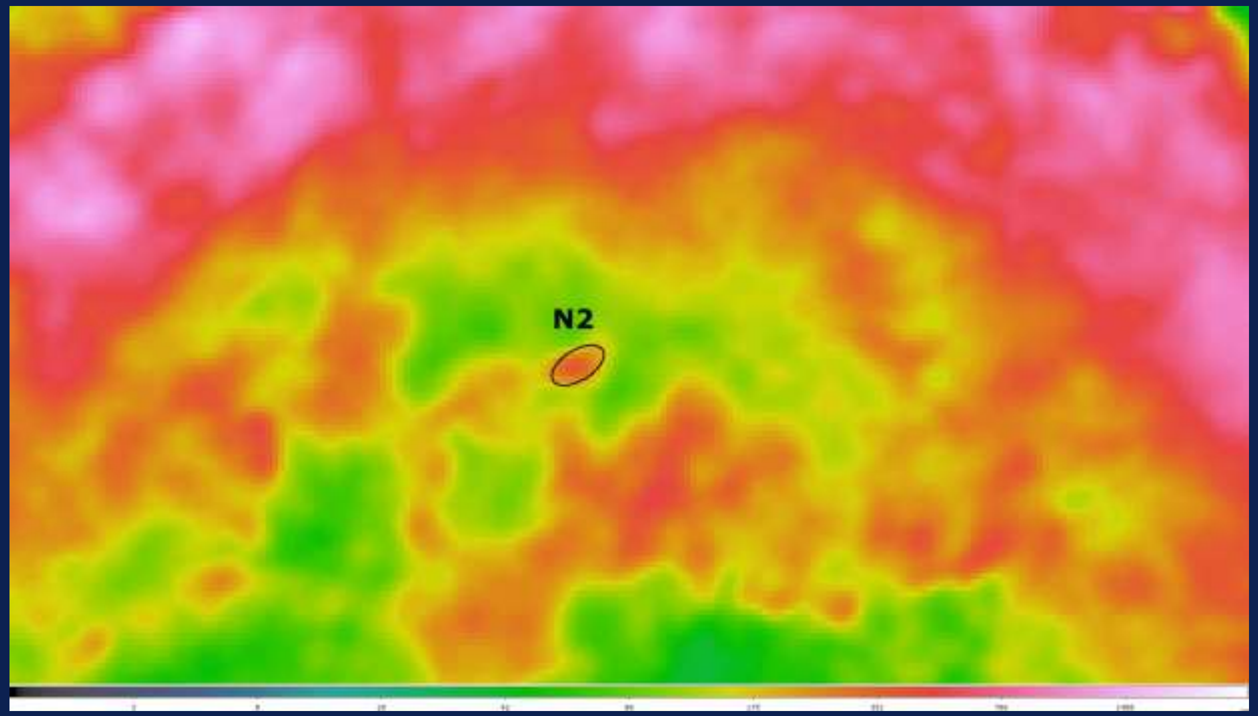
Creating 3D Map for Kepler

- To create 3D map of SNR, we measure space velocities of ejecta knots which has two components:
  1. Radial Velocity
  2. Transverse Velocity

Step 1: Spectral Analysis

- Select regions based on isolation and sufficient photon counts using archival ACIS exposure (~1 Ms) images.
- Classify regions as ejecta or circumstellar medium (CSM) by fitting elemental abundances using a plane-parallel shock model.





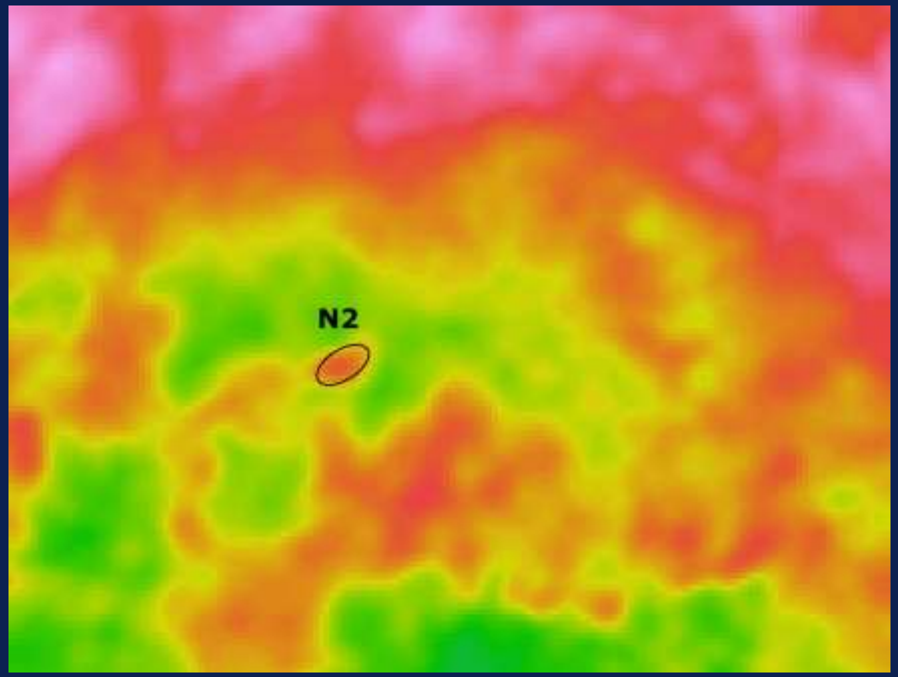
Creating 3D Map for Kepler

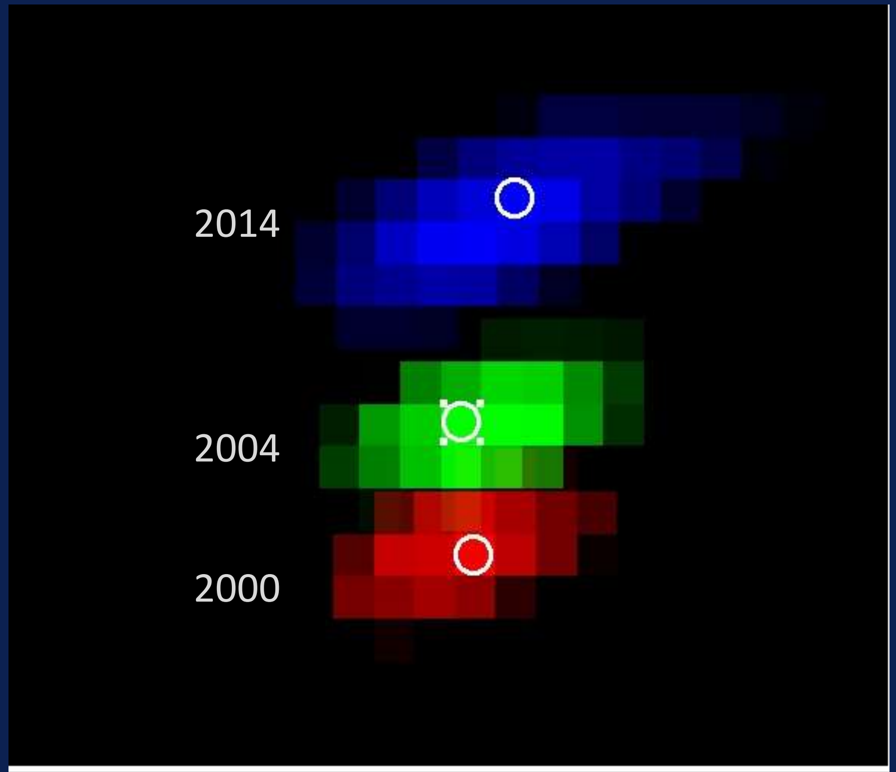
Step 2: Radial Velocity measurement

- Since Kepler's SNR is abundant in Si (Cassam-Chenaı et al. 2004), Si XIII He-α (1.86 keV) line center energy is measured for each region based on its temperature and ionization timescale.
- Using this ratio, radial velocity is calculated by measuring the doppler shift in the Si line by fitting gaussian curve onto the HETG data.

Step 3: Transverse Velocity

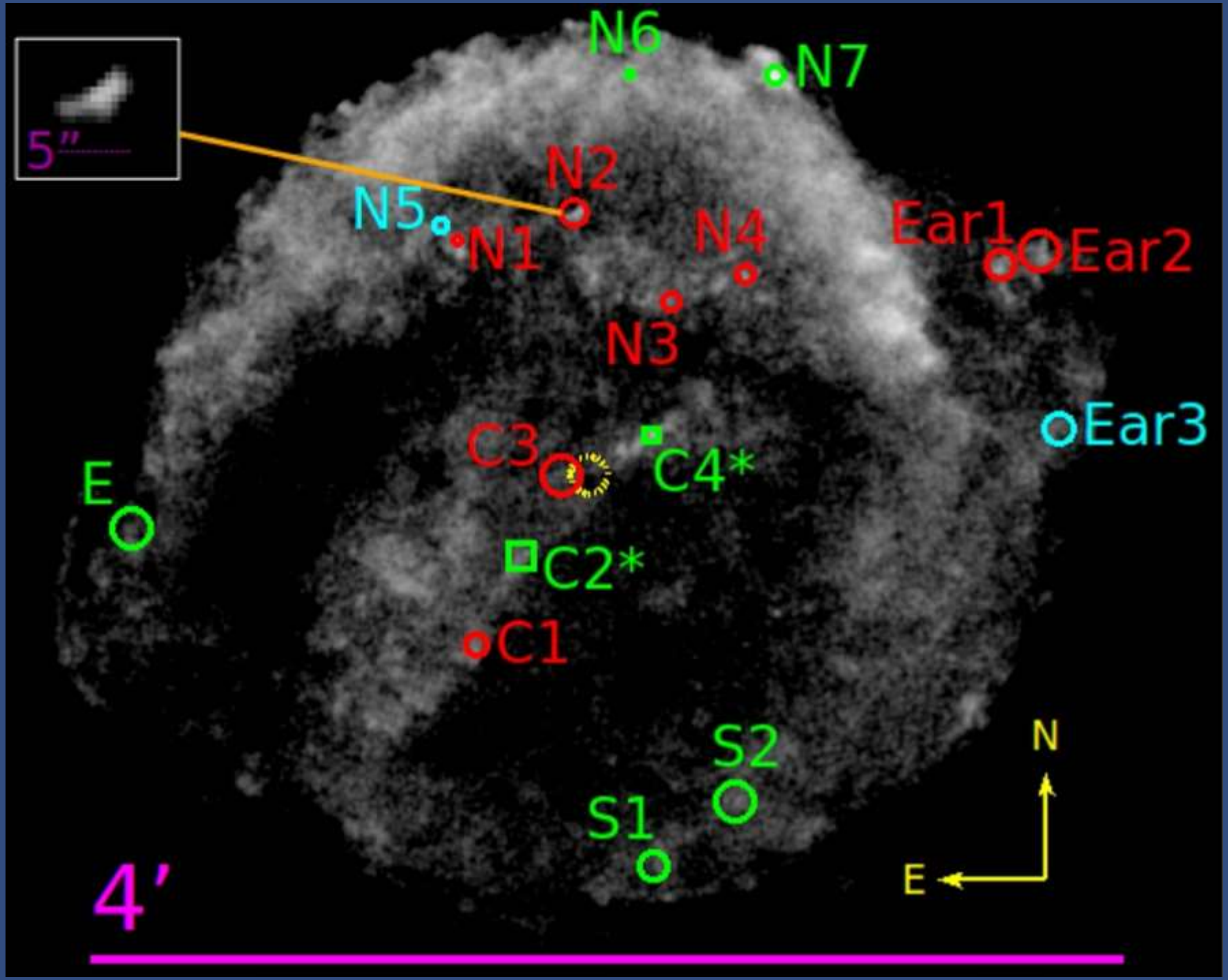
- Track the motion of each region using ACIS images from 2000 to 2022 and calculate proper motion using Cash statistics.
- Calculate transverse velocity from proper motion and distance.

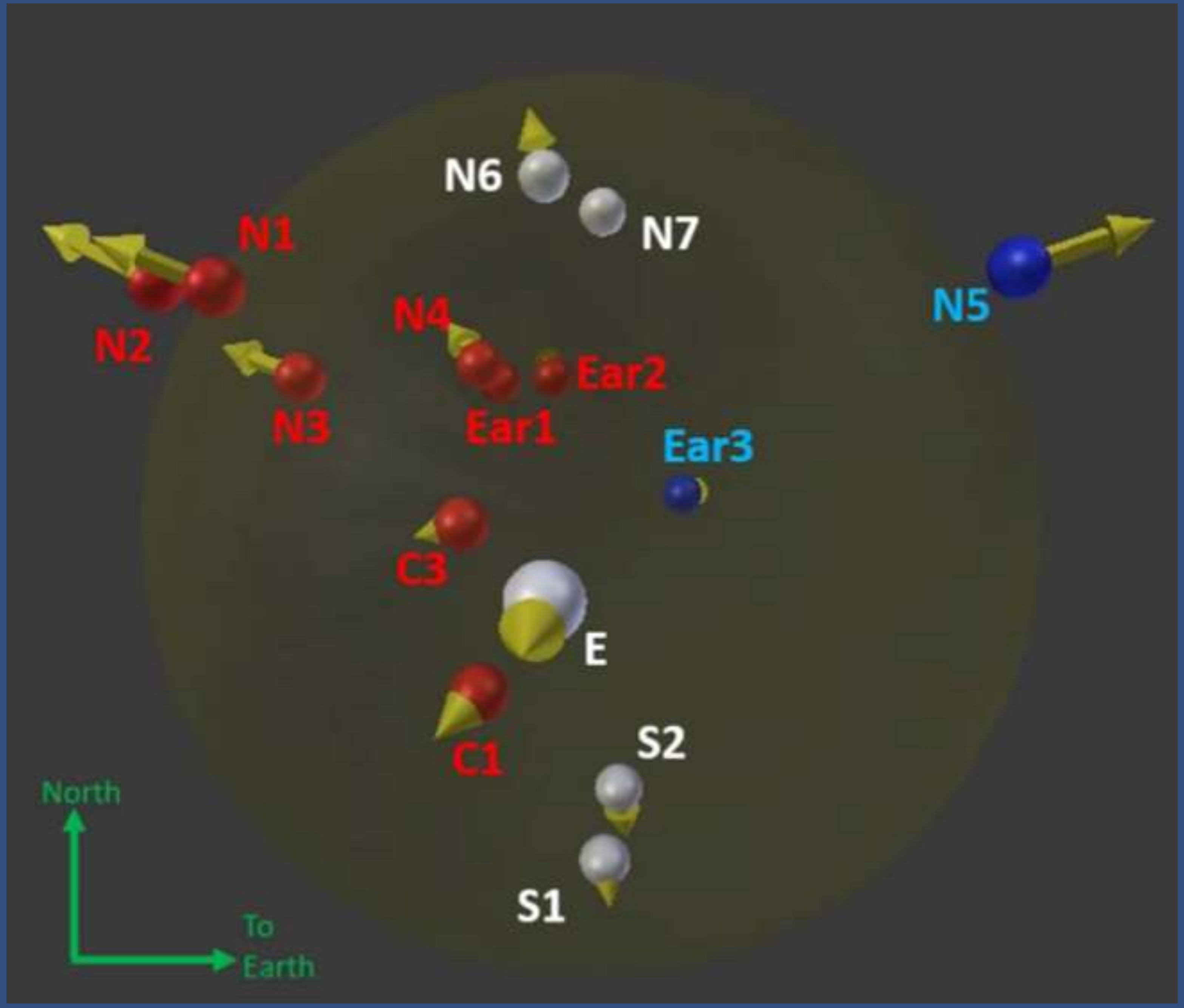




Tracking Proper Motion of a region

Creating 3D map for Kepler – Previous Work



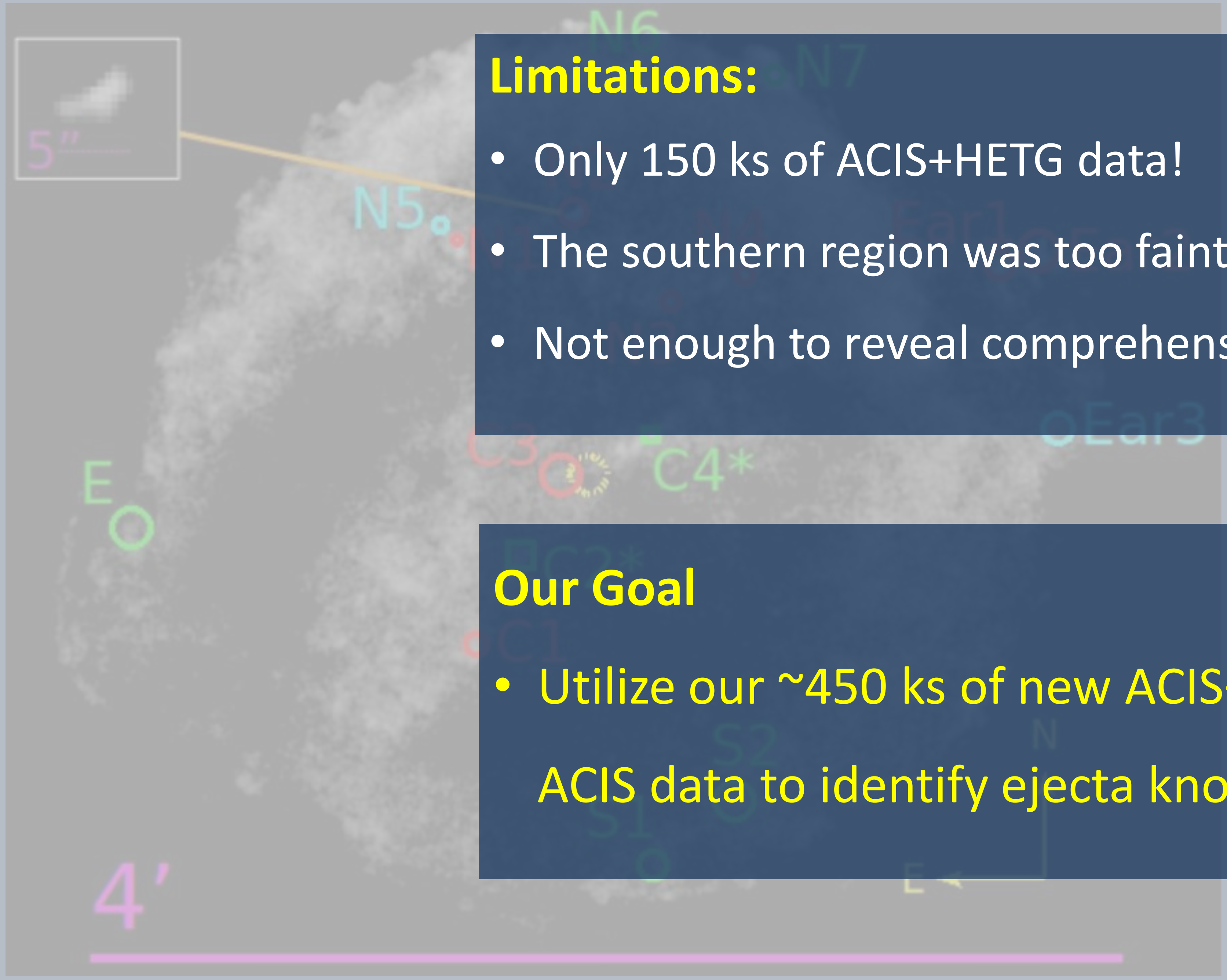


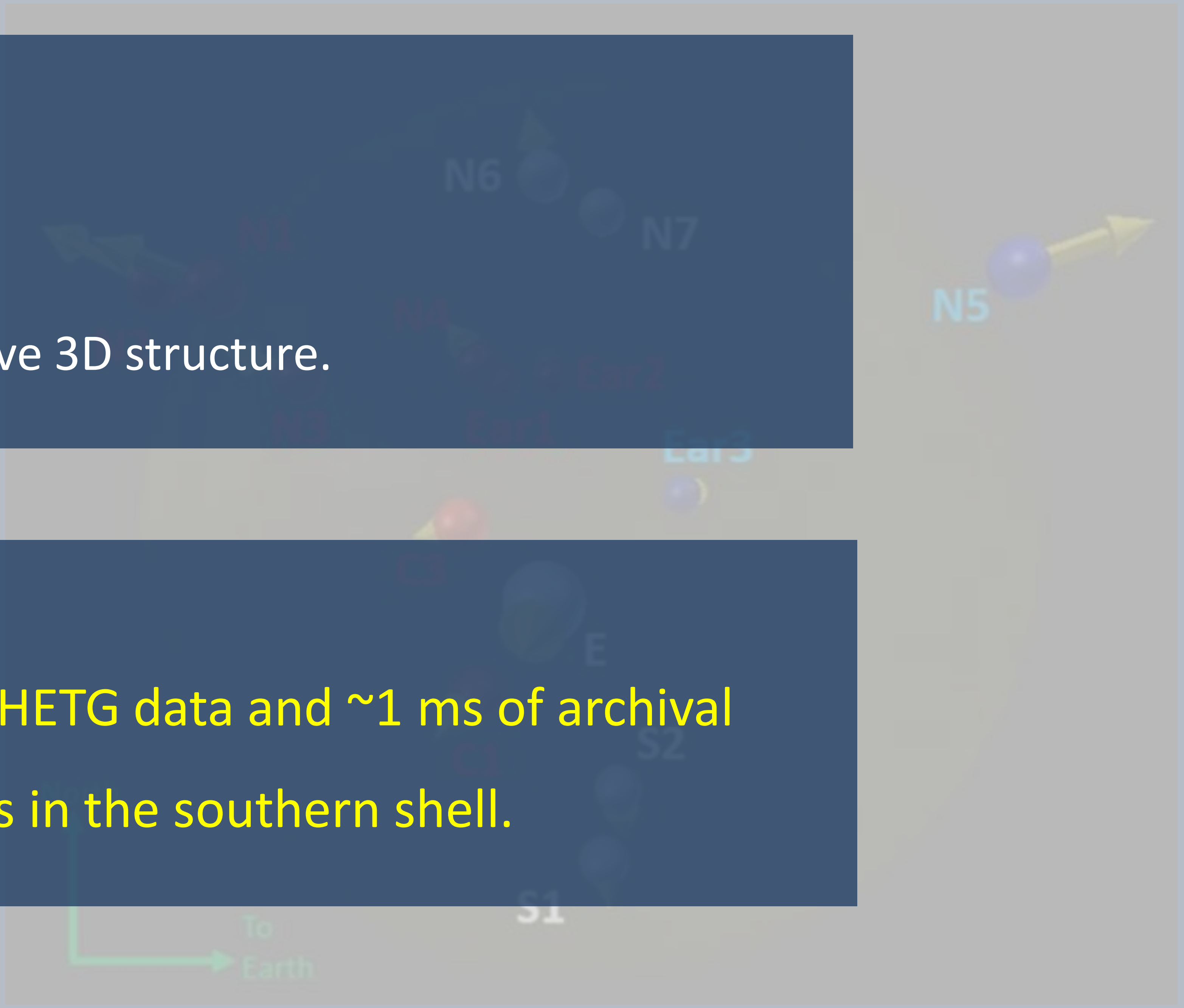
From Millard et al 2020. A) Identified 15 ejecta knots and 2 CSM knots with upto 8000 km/s radial velocities.

B) 3D map of the knots with red balls showing redshifted regions, blue as blue shifted and white as negligible doppler shift.

Arrows represents space velocities as high as ~ 10,000 km/s.

Creating 3D map for Kepler – Previous Work





Limitations:

- Only 150 ks of ACIS+HETG data!
- The southern region was too faint.
- Not enough to reveal comprehensive 3D structure.

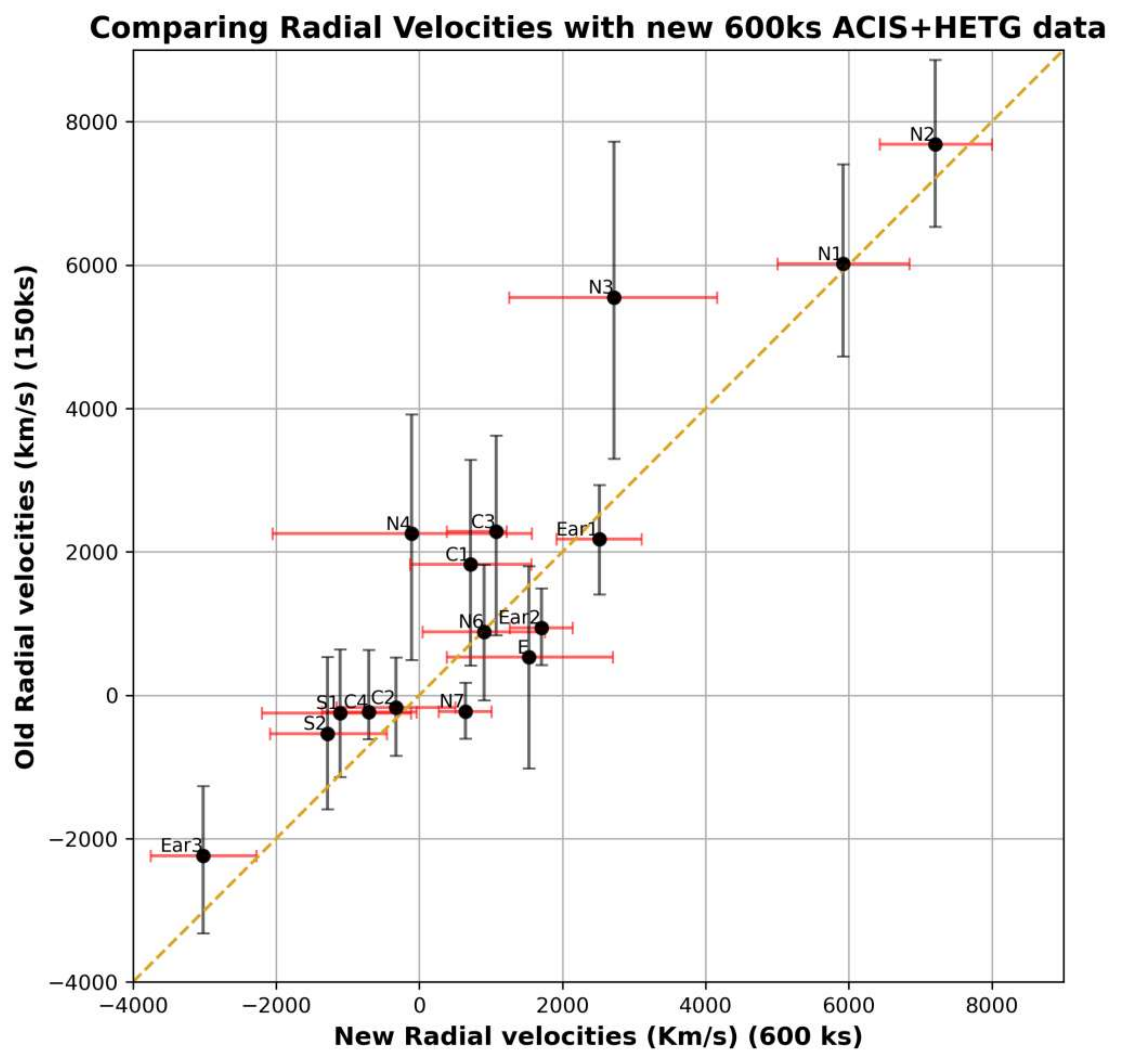
Our Goal

- Utilize our ~450 ks of new ACIS+HETG data and ~1 ms of archival ACIS data to identify ejecta knots in the southern shell.

From Millard et al 2020. A) Identified 15 ejecta knots and 2 CSM knots with upto 8000 km/s radial velocities.

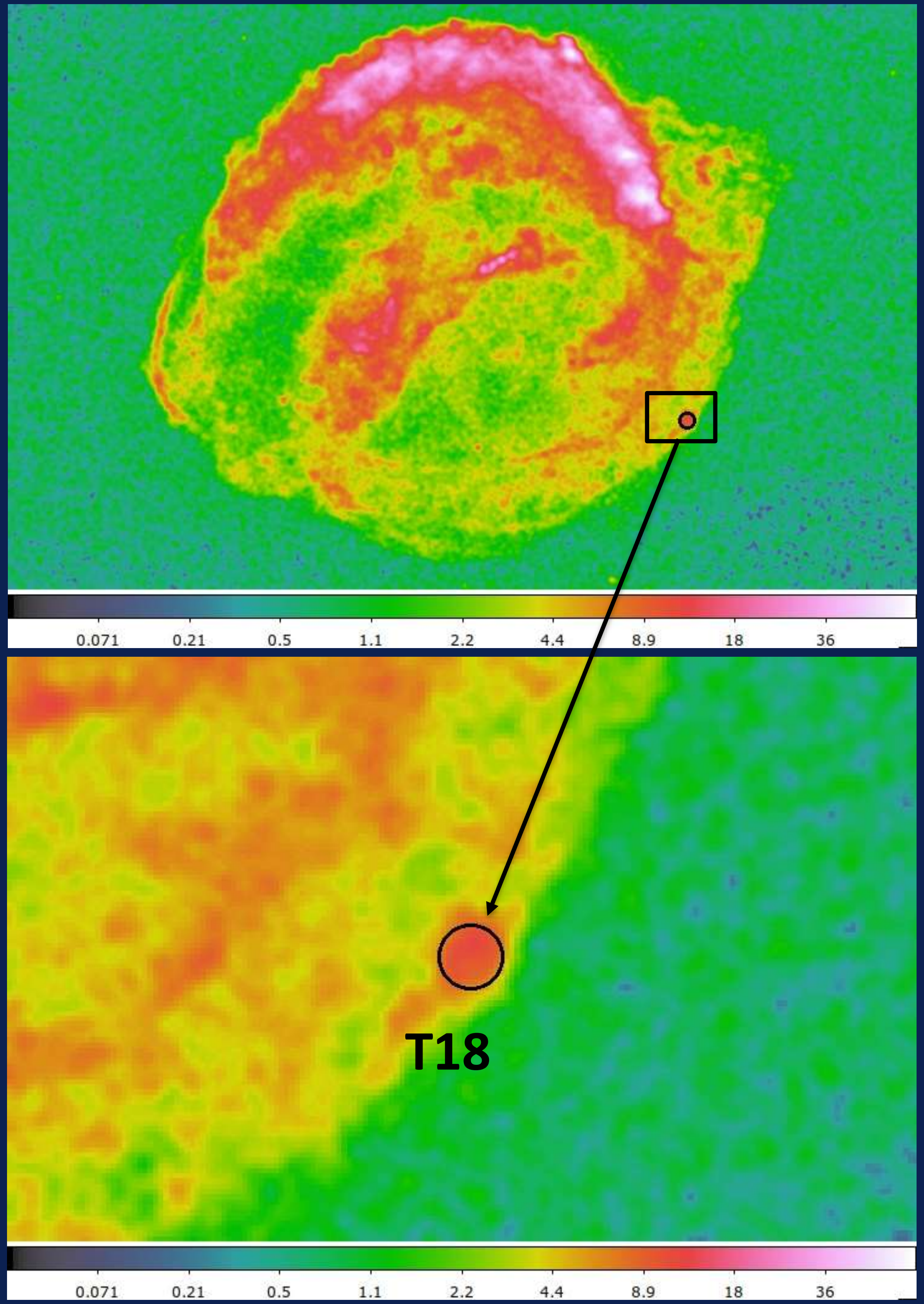
B) 3D map of the knots with red balls showing redshifted regions, blue as blue shifted and white as negligible doppler shift.

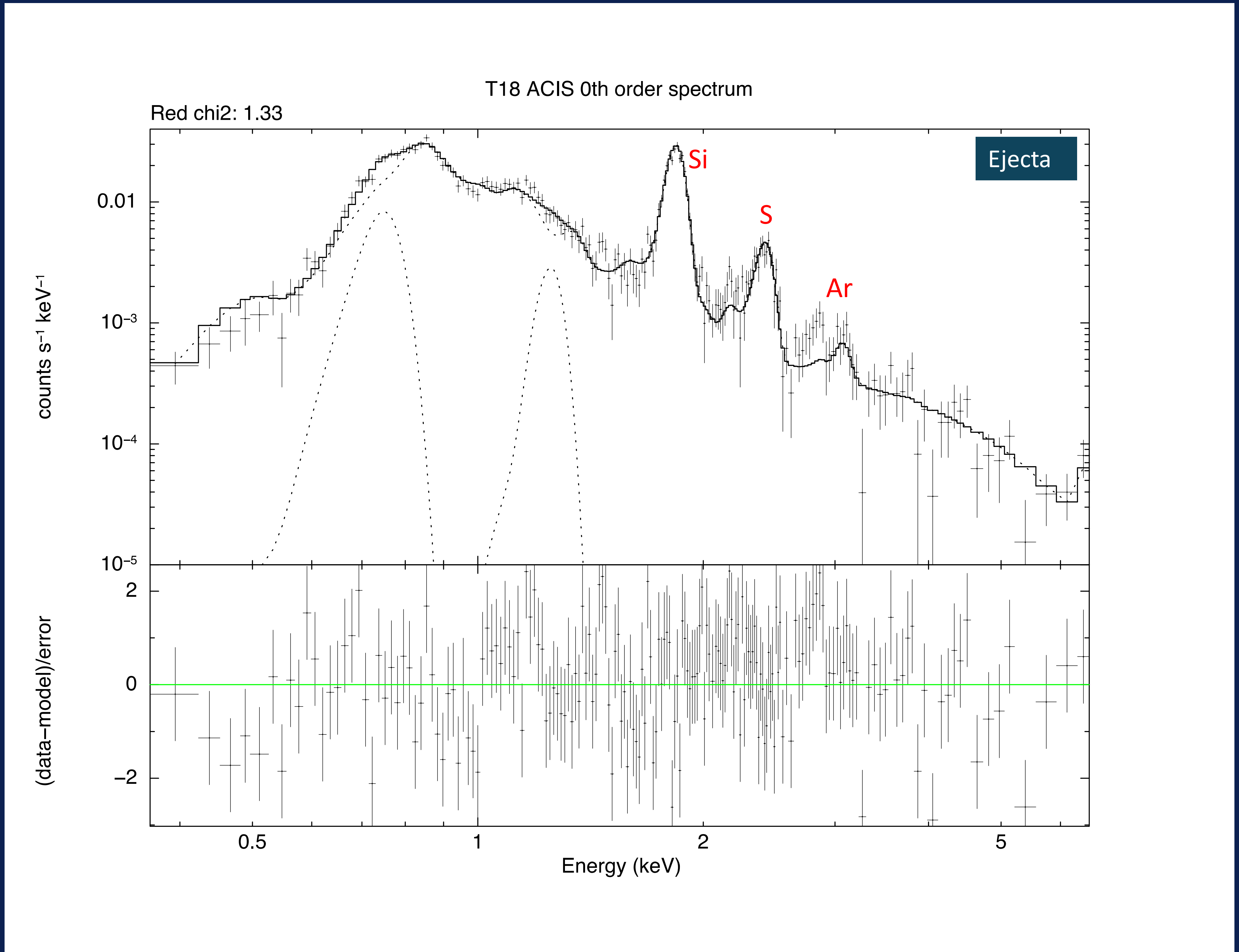
Arrows represents space velocities as high as ~ 4600 km/s.



Region	Old Vr (km/s) (Millard, M et al. 2020)	New Vr (Km/s)
N2	7684^{+1155}_{-1177}	7207^{+772}_{-794}
N1	6019^{+1294}_{-1385}	5921^{+713}_{-929}
N3	5550^{+2253}_{-2172}	2719^{+1464}_{-1442}
C3	2281^{+1449}_{-1337}	1071^{+1684}_{-1543}
N4	2252^{+1761}_{-1664}	-108^{+1768}_{-1449}
Ear1	2180^{+778}_{-752}	2513^{+590}_{-593}
C1	1823^{+1408}_{-1458}	714^{+842}_{-855}
Ear2	942^{+525}_{-546}	1706^{+442}_{-440}
N6	883^{+954}_{-933}	996^{+857}_{-848}
E	531^{+1551}_{-1269}	1534^{+1149}_{-1173}
C2	-175^{+672}_{-700}	-327^{+822}_{-828}
N7	-225^{+382}_{-398}	642^{+373}_{-369}
C4	-233^{+382}_{-862}	-705^{+653}_{-668}
S1	-246^{+897}_{-882}	-1109^{+1009}_{-996}
S2	-536^{+1060}_{-1067}	-1285^{+800}_{-834}
Ear3	-2239^{+1087}_{-973}	-3018^{+734}_{-744}

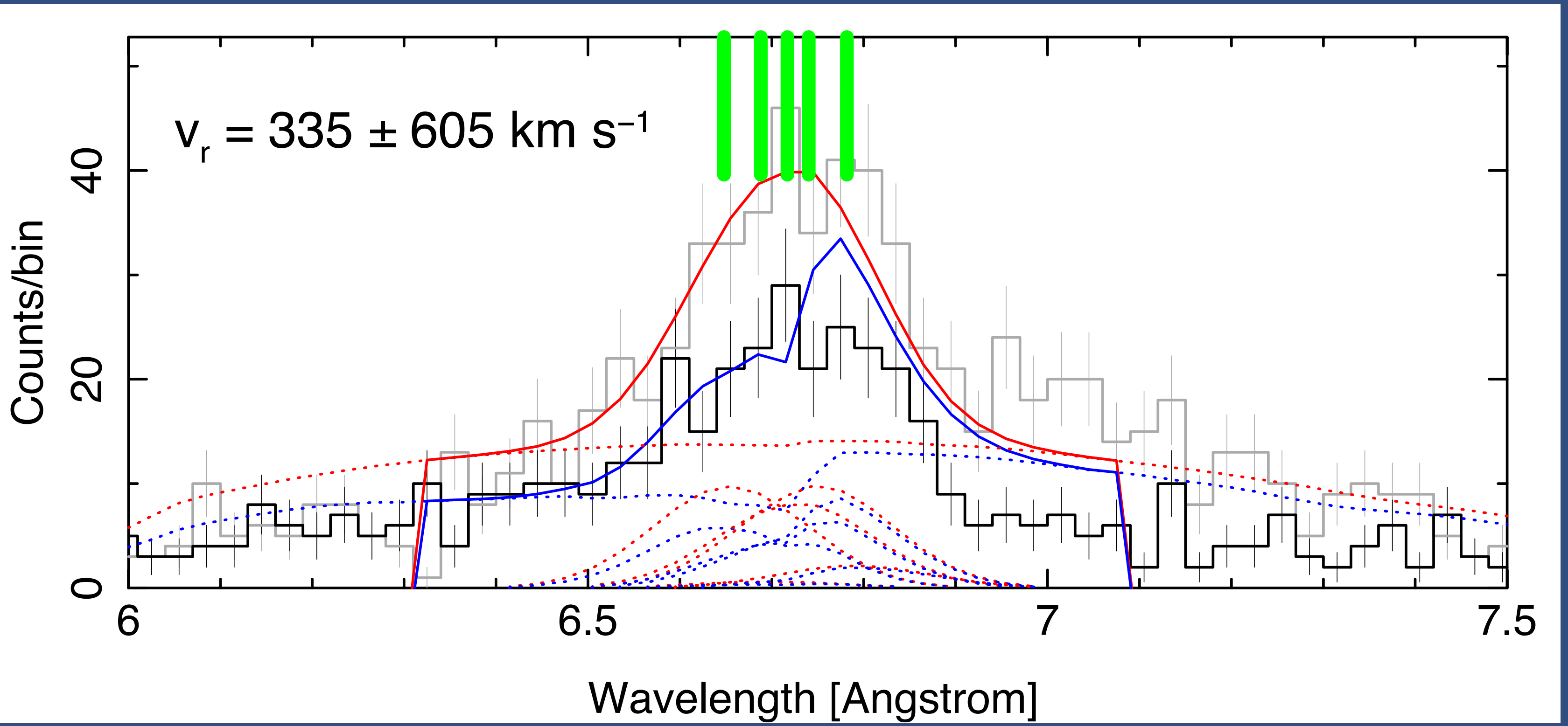
Creating 3D Map for Kepler – New Regions

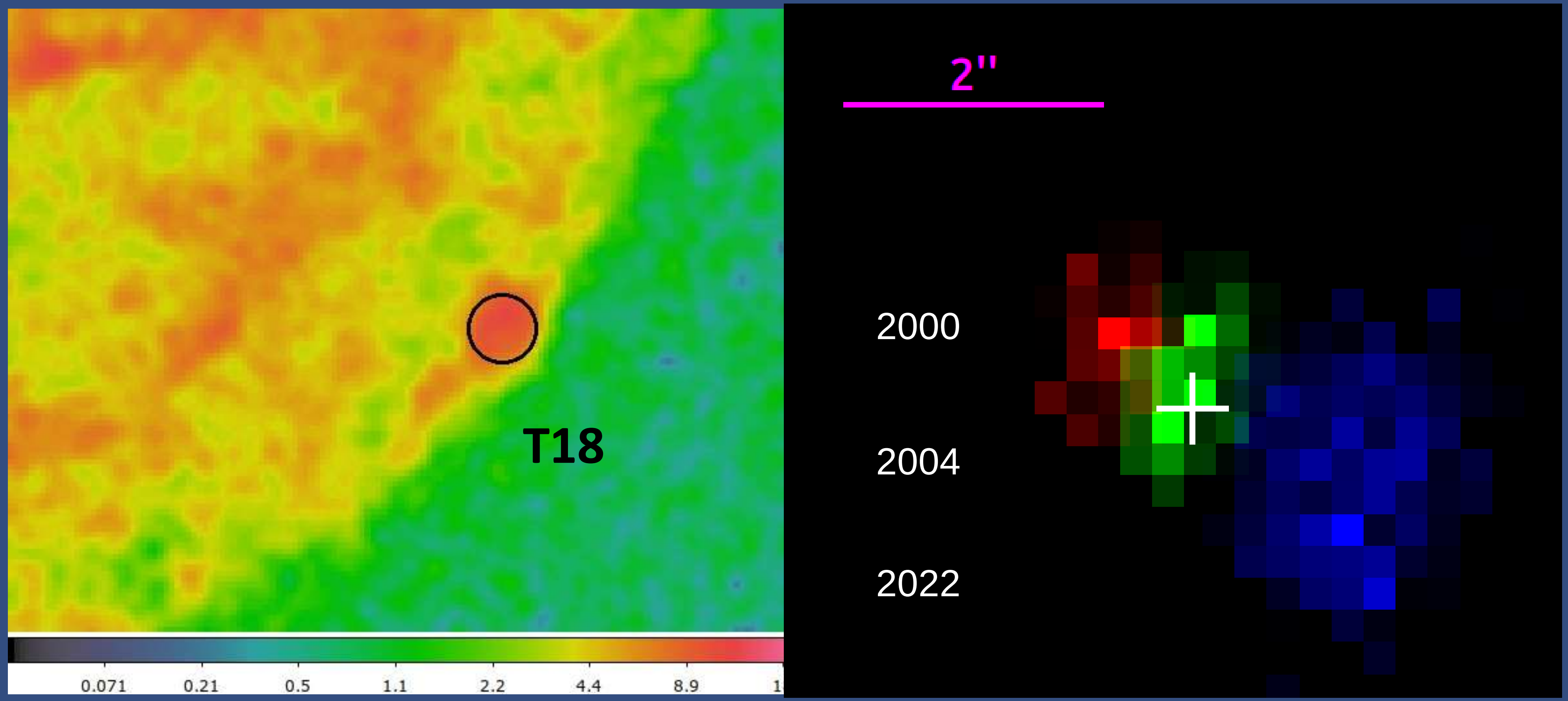




Abundances
Si - 5.35
Fe - 1.95

Creating 3D Map for Kepler – New Regions

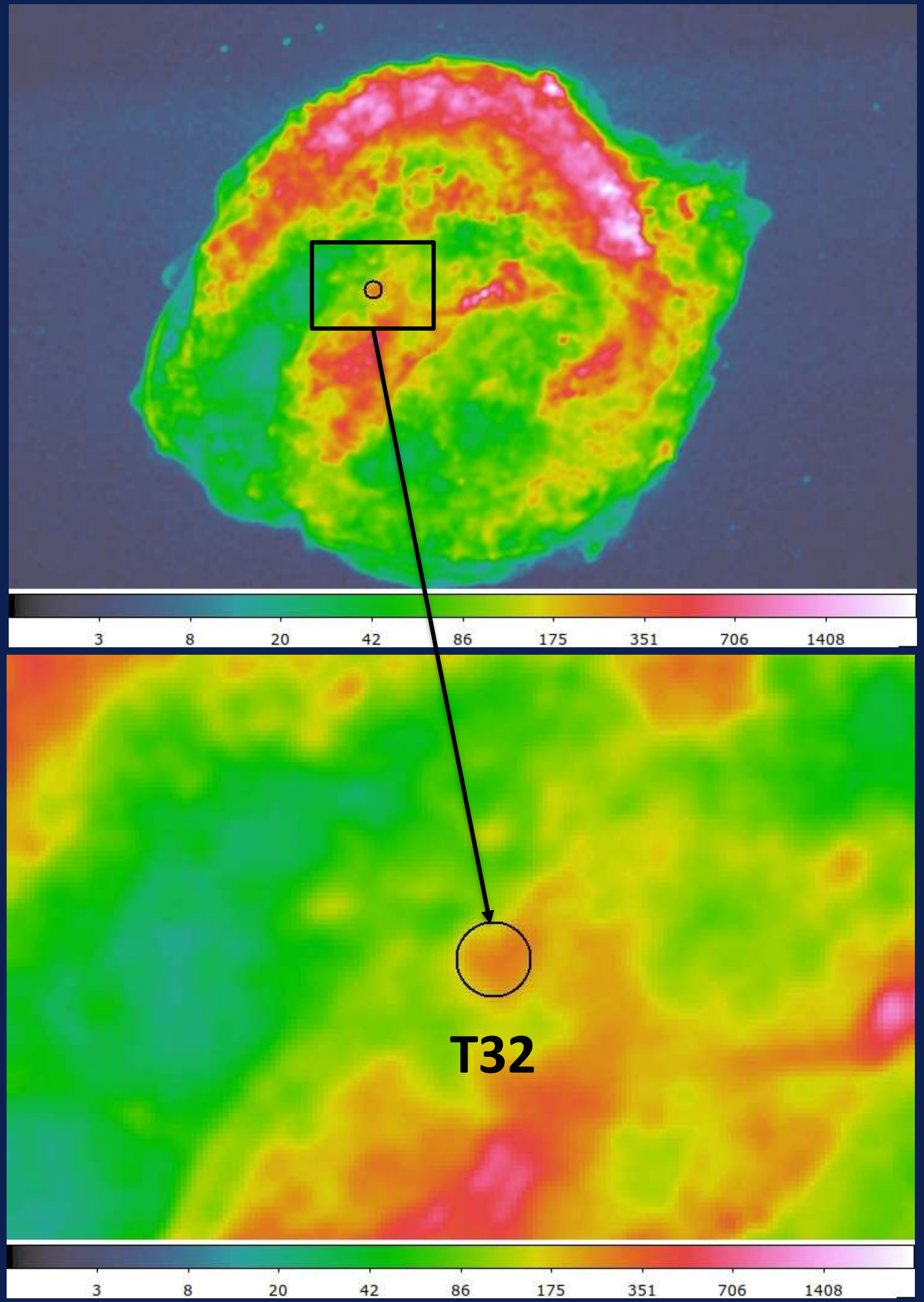


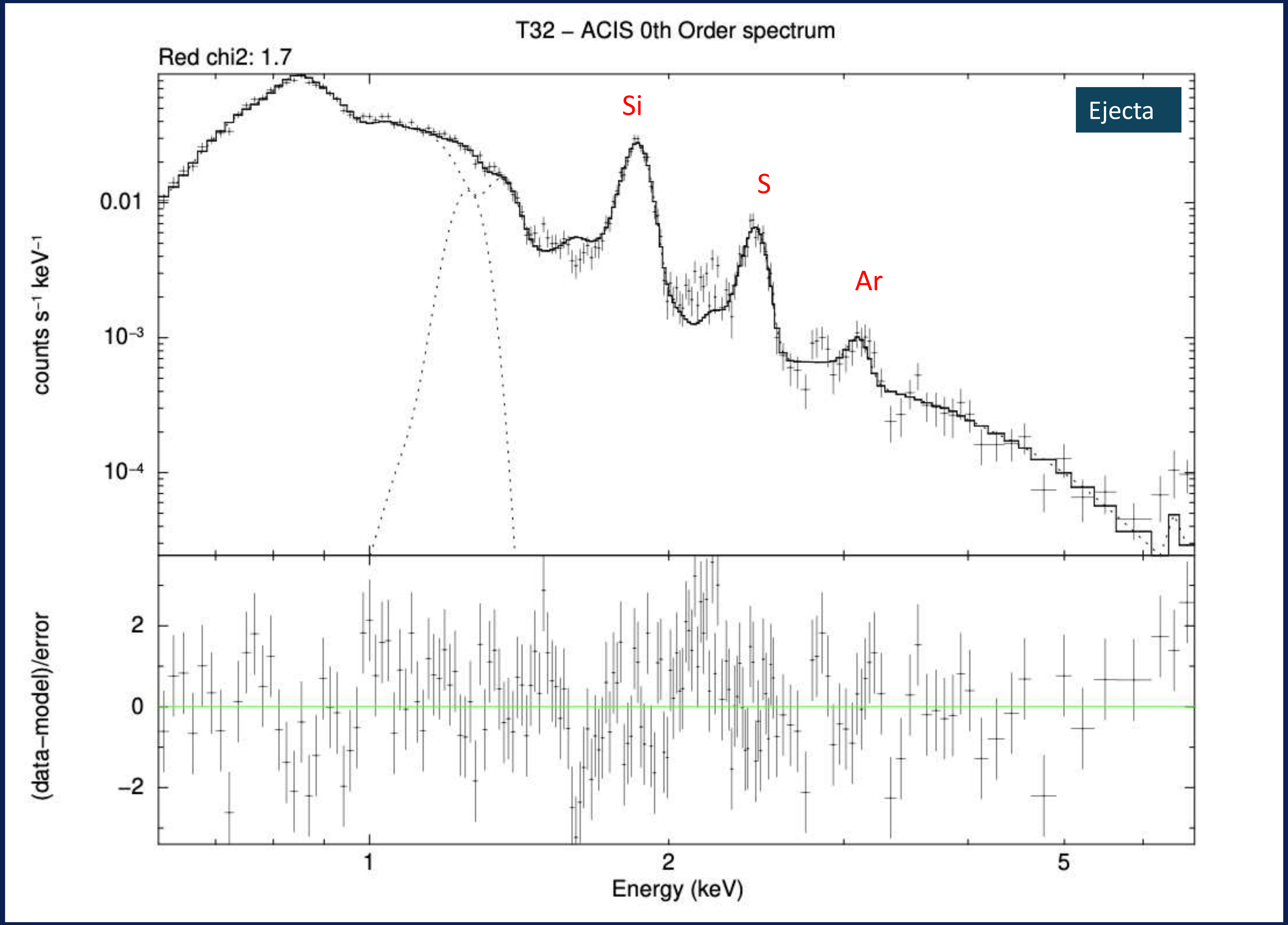


Region – T18	Radial Vr km/s (600ks)
Radial Velocity	335^{+605}_{-605}
Red chi2	1.64
Si band Counts	906
Radius	3.0"

Region – T18	Proper Motion (arcsec/yr)
RA	0.0783
DEC	-0.0668
Total PM	0.0989
Transverse Velocity	2814^{+1584}_{-1584} km/s
Space Velocity	2834^{+1572}_{-1572} km/s

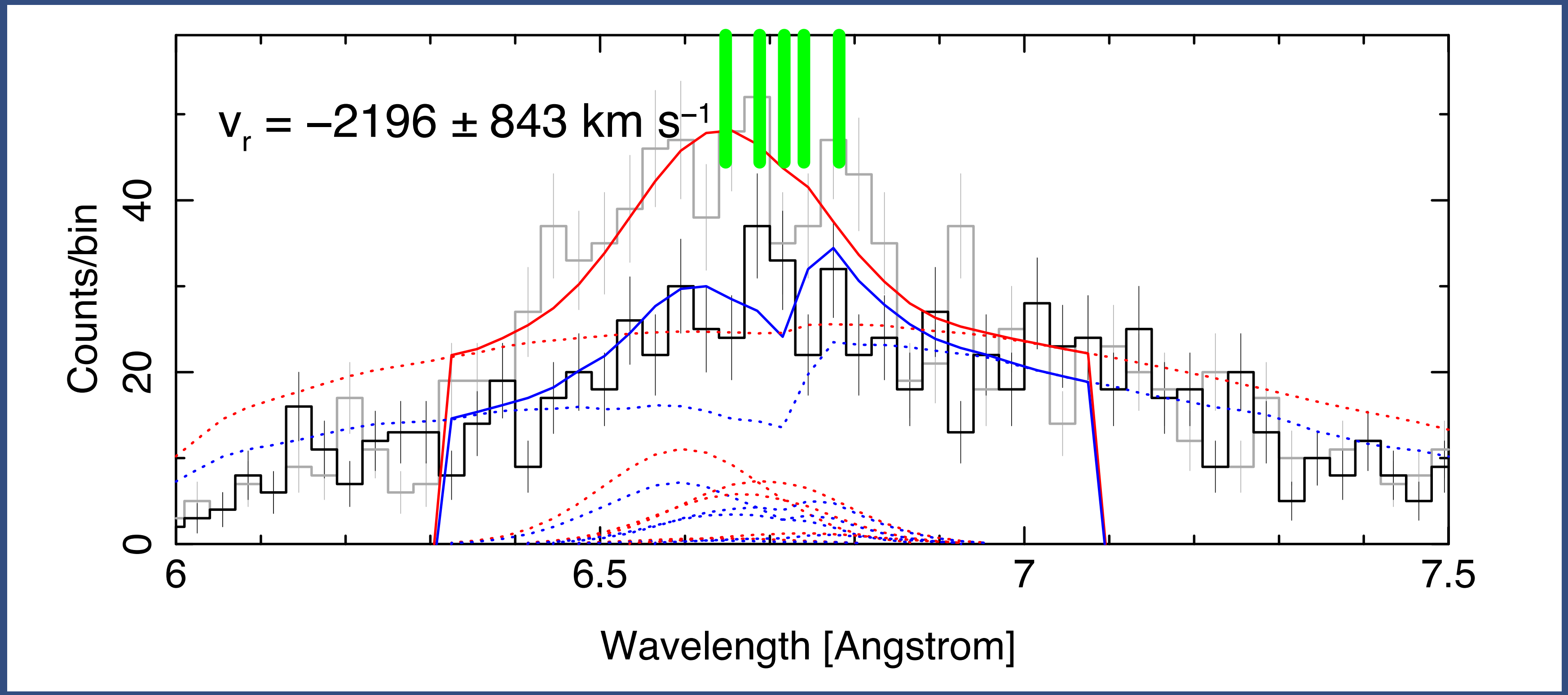
Creating 3D Map for Kepler – New Regions



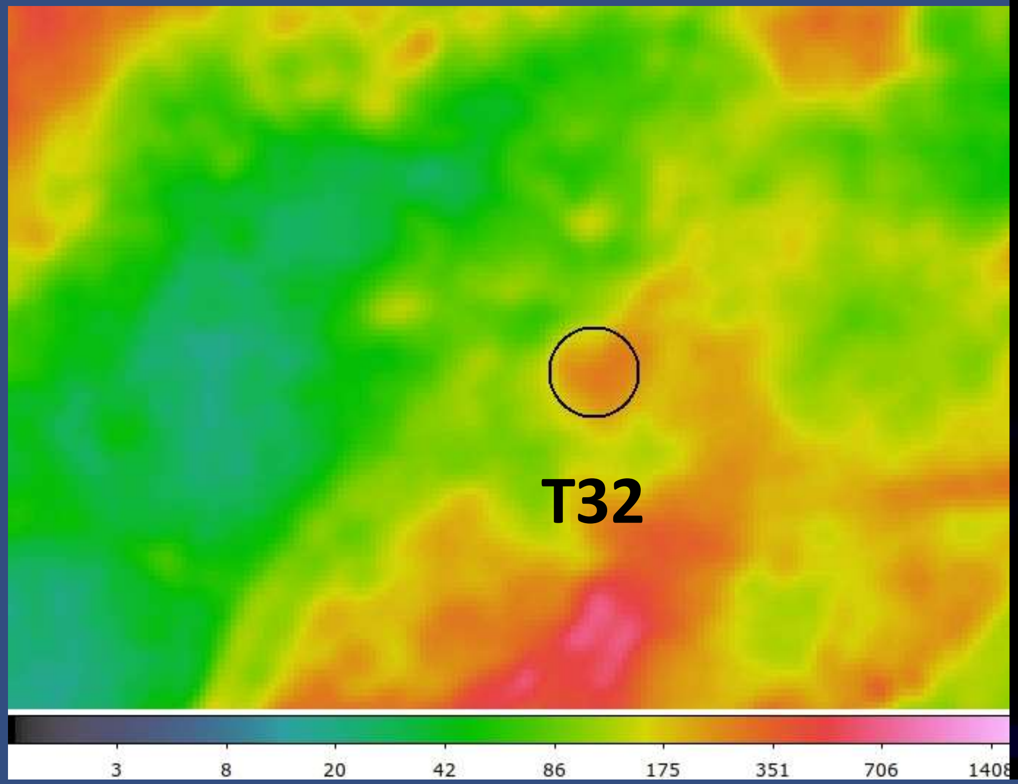


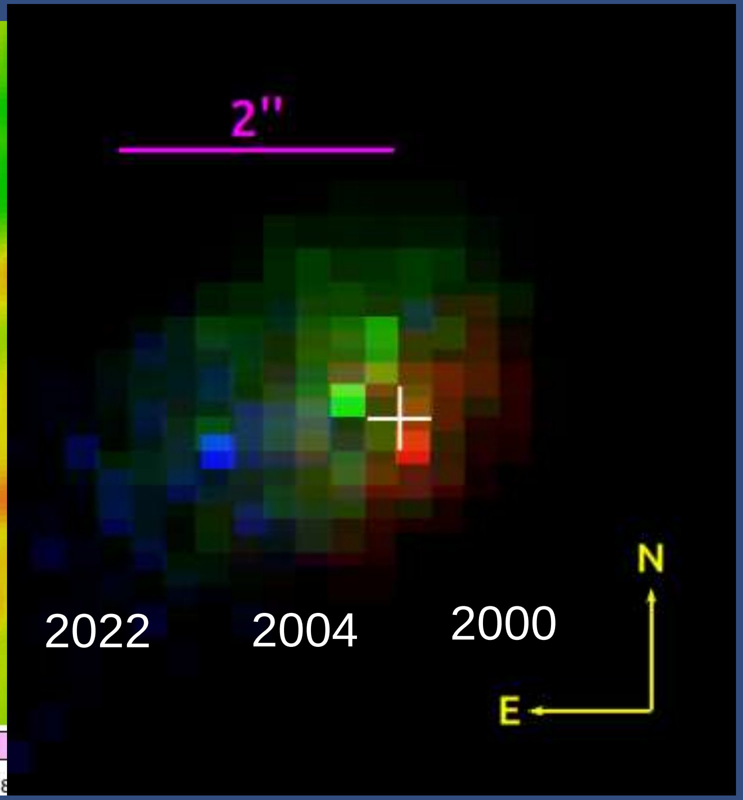
Abundances
Si - 4.12
Fe - 1.82

Creating 3D Map for Kepler – New Regions



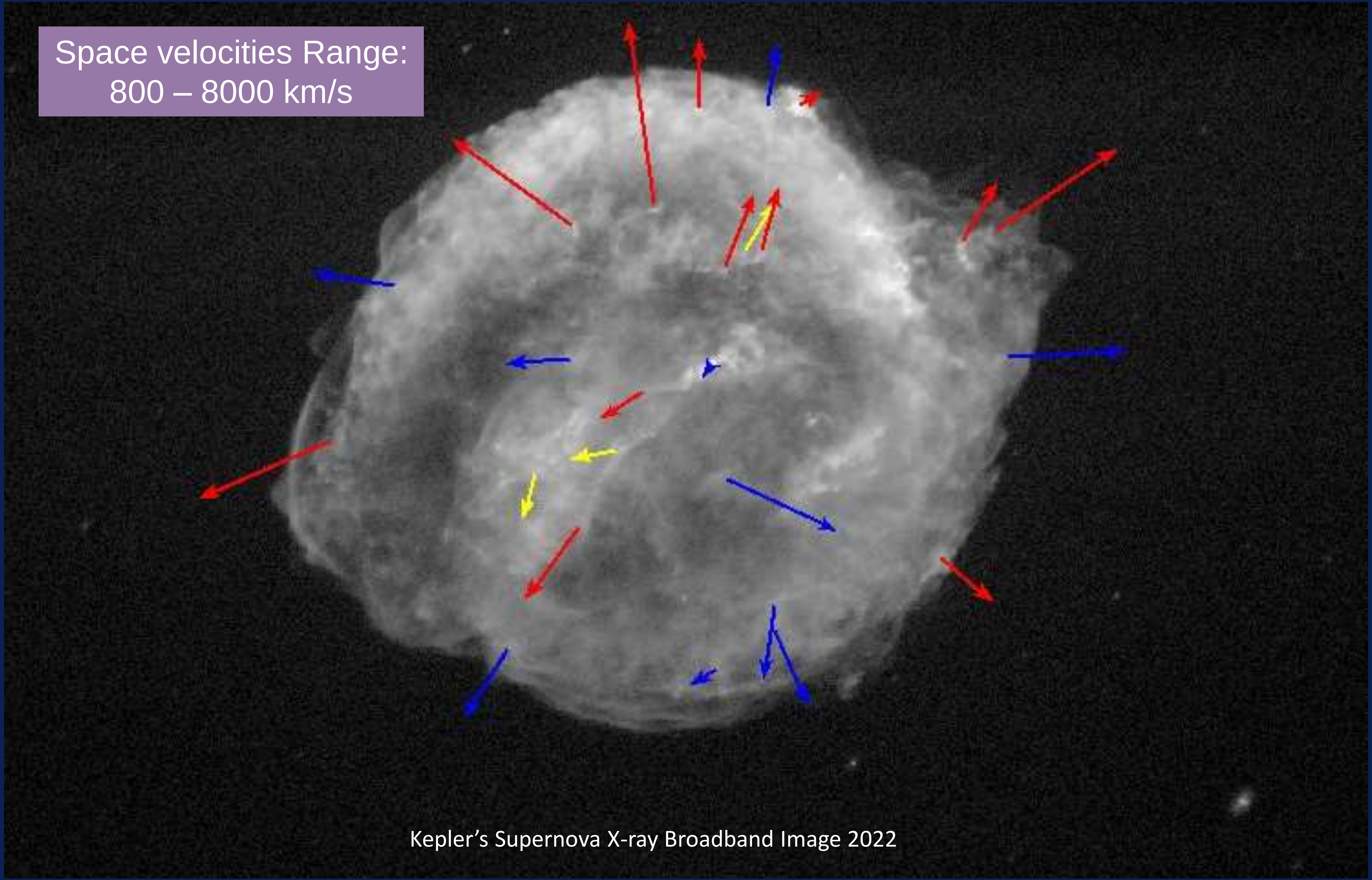
Region – T32	Radial Vr km/s (600ks)
Radial Velocity	-2196^{+840}_{-846}
Red chi2	1.43
Si band Counts	1342
Radius	3.5"





Region – T18	Proper Motion (arcsec/yr)
RA	-0.066
DEC	0.034
Total PM	0.062
Transverse Velocity	1751^{+1615}_{-1615} km/s
Space Velocity	2809^{+1203}_{-1205} km/s

Creating 3D Map for Kepler – Space Velocity Map



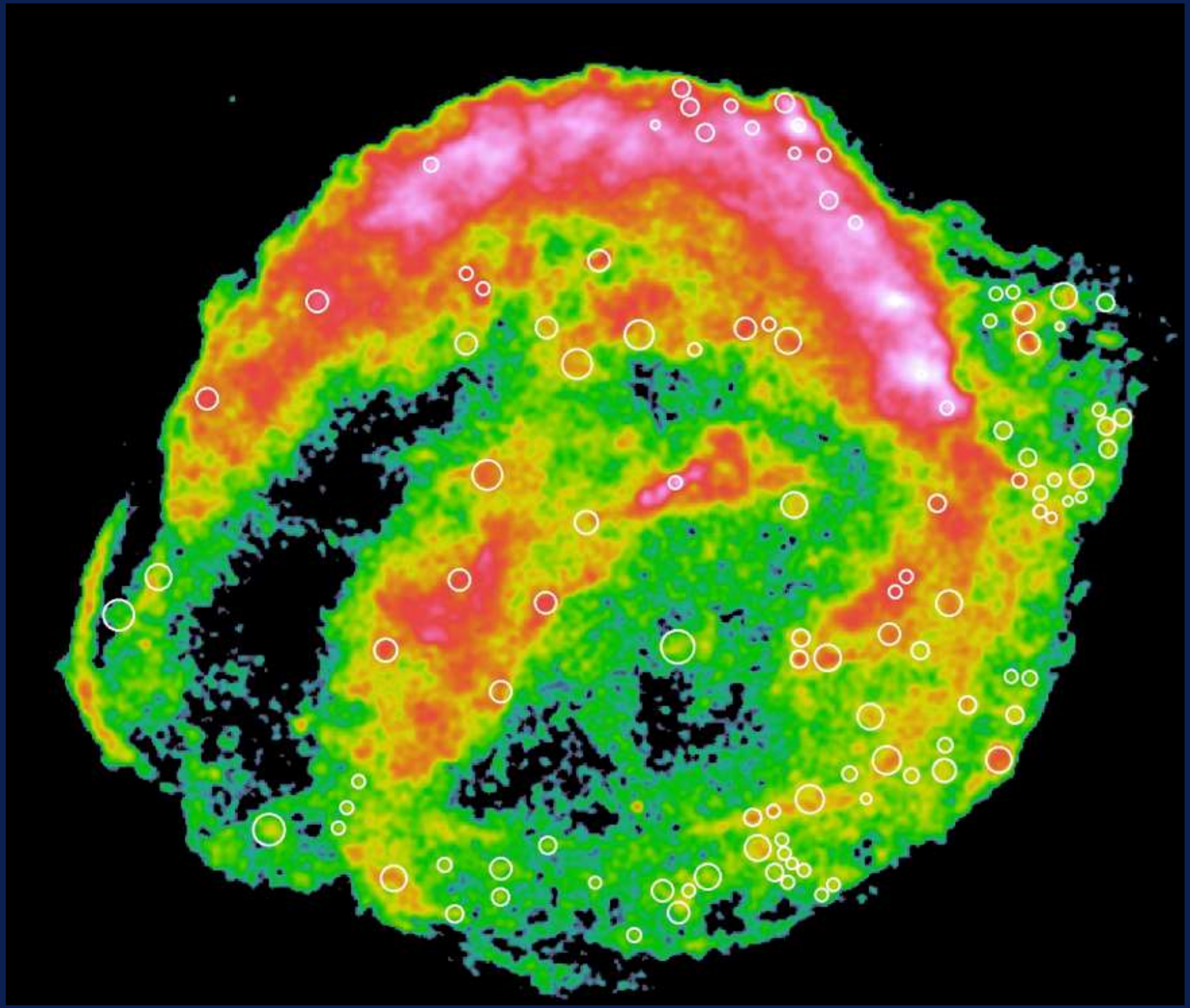
Kepler's Supernova X-ray Broadband Image 2022

Future Work

- Range of Ejecta space velocities: 2000 – 8000 km/s
- Range of CSM space velocities: 800 – 2000 km/s

- Extract spectrum of these potential regions and identify ejecta knots.
- Measure radial velocities and transverse motion of all these regions.

- Find more ejecta regions in the northern shell and central band.
- Create a comprehensive 3D – map using space velocities of all regions.



Thank you!