The Athena X-IFU Supernova Remnants science case

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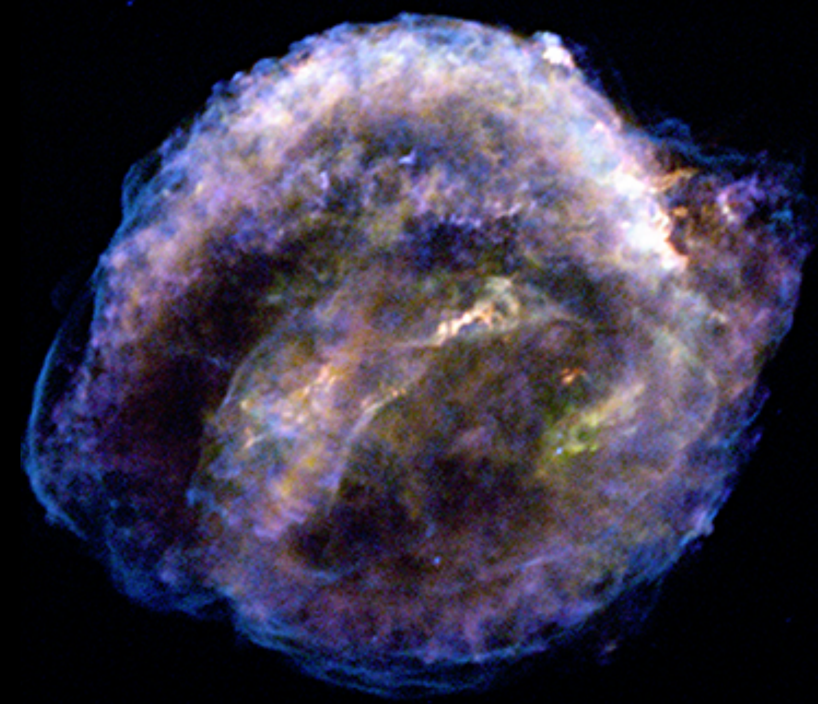
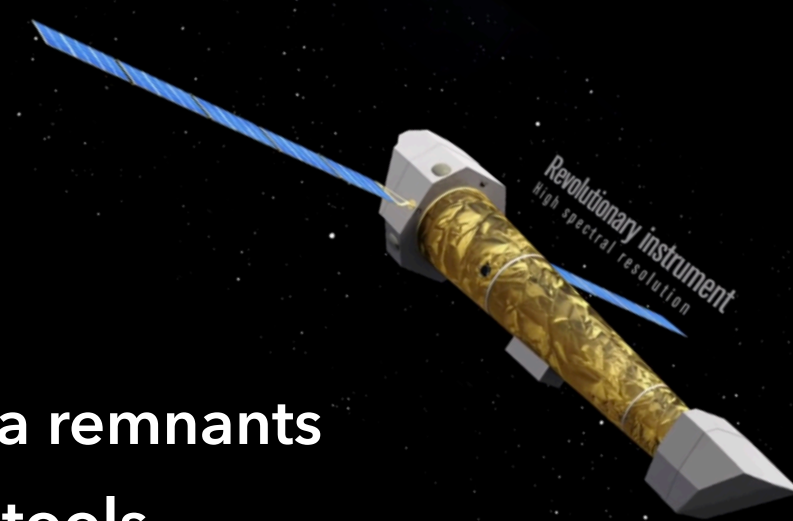
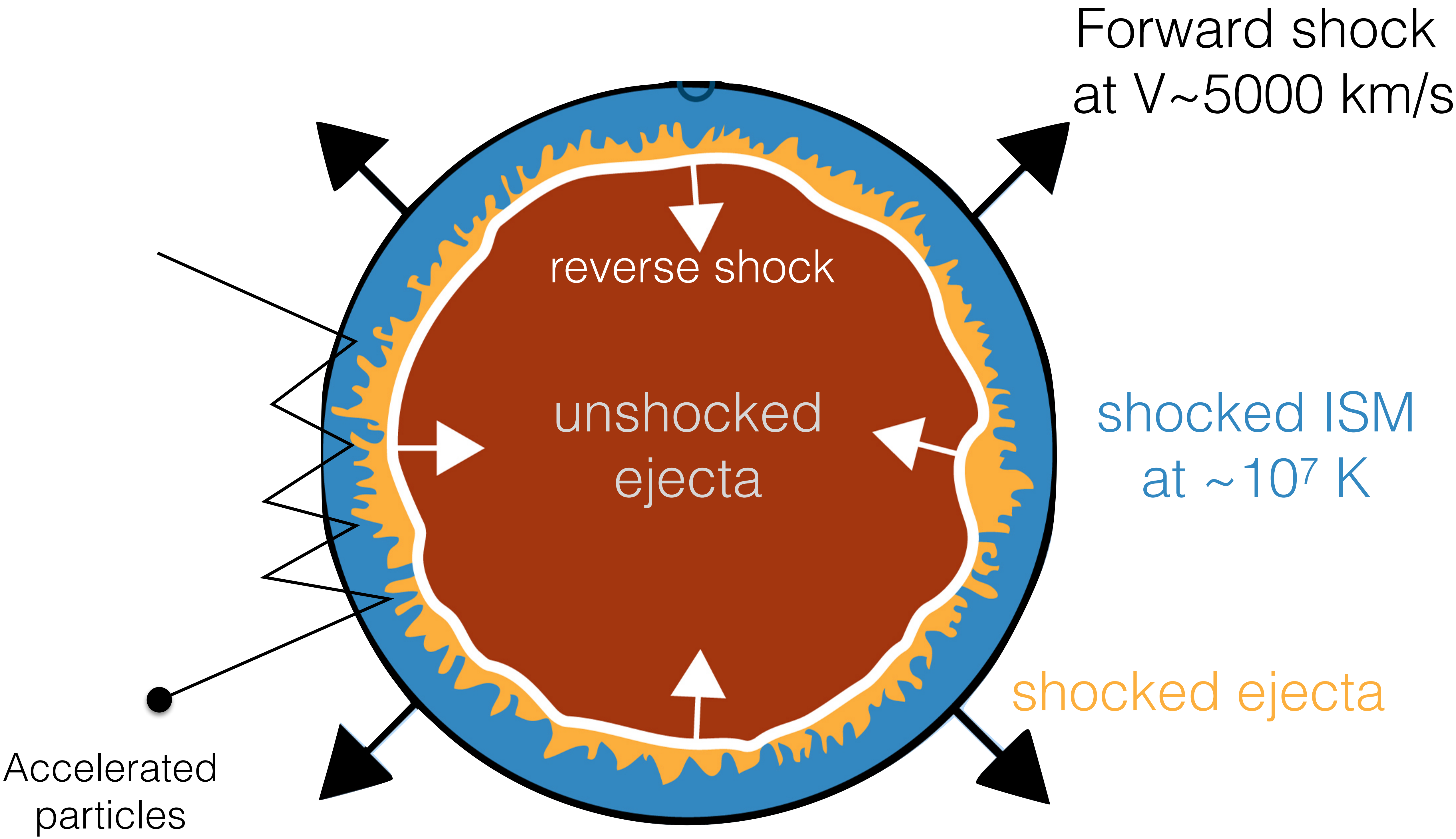




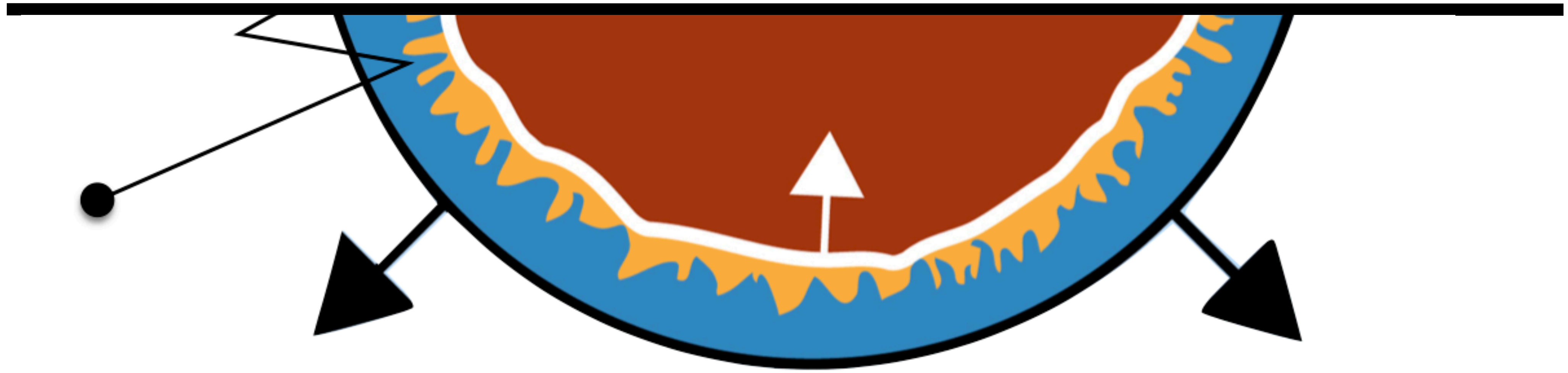
I. Physics of supernova remnants
II. Methods & analysis tools
III. Challenges for the French community

Supernova Remnant: what do we see ?



(c) A. Bordenave

What do we learn ?



Accelerated particles

- Acceleration mechanism
- Composition (e^- and/or p)
- **Acceleration efficiency**
- Maximal energy reached
- Escape (diffusion)

Shocked ISM

- Probe of the ISM:
  - density, metalicity
  - clues for SN progenitor
  - acceleration initial conditions
- **Collisionless shock physics:**
  - **mass & V_{shock} relation**
  - **e^-/p T° equilibration**

Shocked ejecta

- Supernova yield:
  - SN type
  - mass of progenitor
  - **metalicity of progenitor**
- **Morphology and kinematics:**
  - **3D ejecta distribution**
  - **SN explosion mechanism**

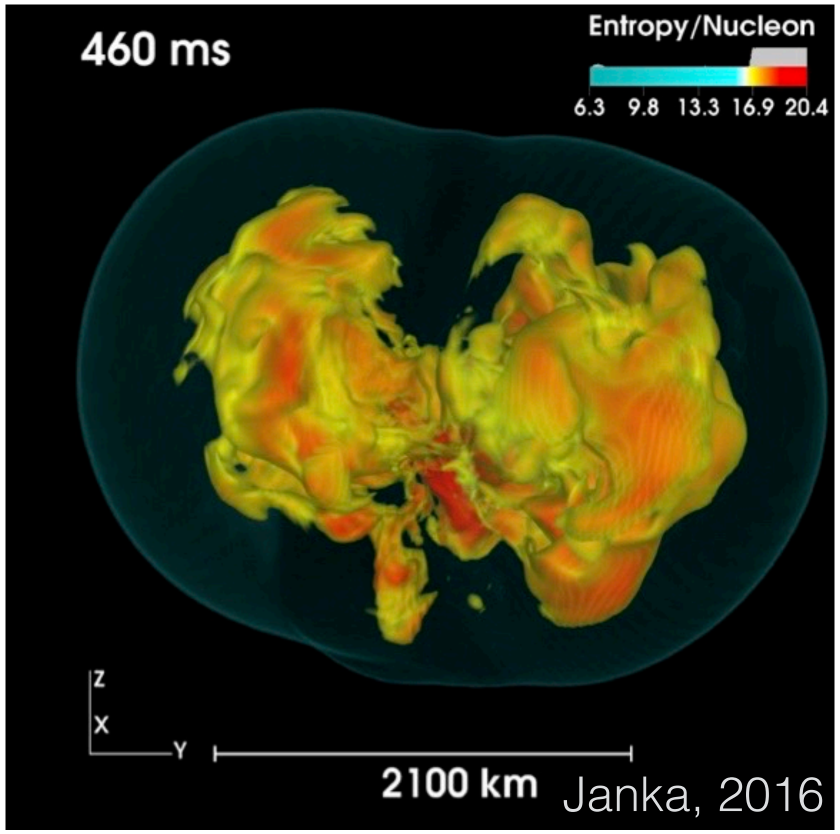
Messengers:

Radio, X, Gamma-rays, ν

Optical, UV, X-rays

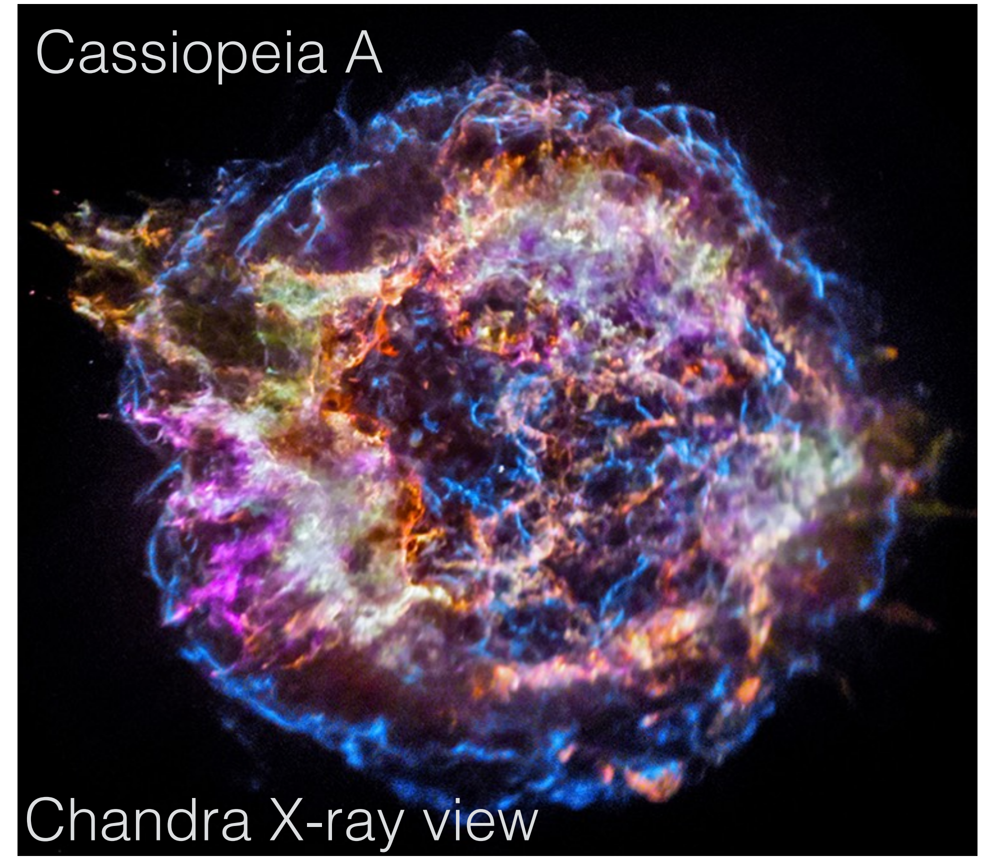
IR, optical, X-rays

Core collapse explosion mechanisms



T=460 ms

?



T=340 ans

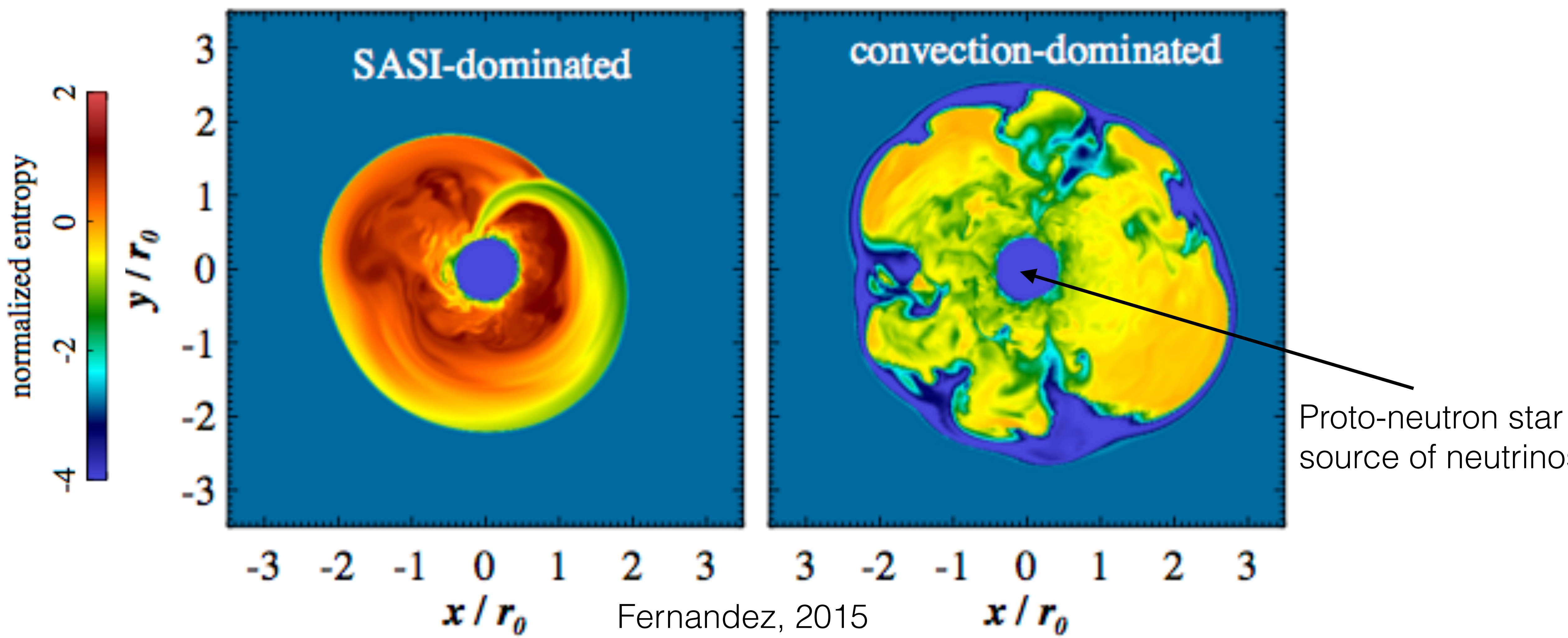
- **What can the remnant tell us about the supernova explosion ?**
- **Explosion mechanisms leave fingerprints in the ejecta**
- **Key observables: 3D distribution, ejecta velocity and abundances ratio**
- **Proper motion (over 10-20 yrs) & radial velocity (Doppler effect)**

How do core collapse SN explode ?

- Shock powered by energy deposition from the 10^{53} ergs in neutrinos
- Role of hydro instabilities in neutrino heating
  - Sloshing motions (SASI). ~large scale
  - Neutrino buoyant convection. ~smaller scale

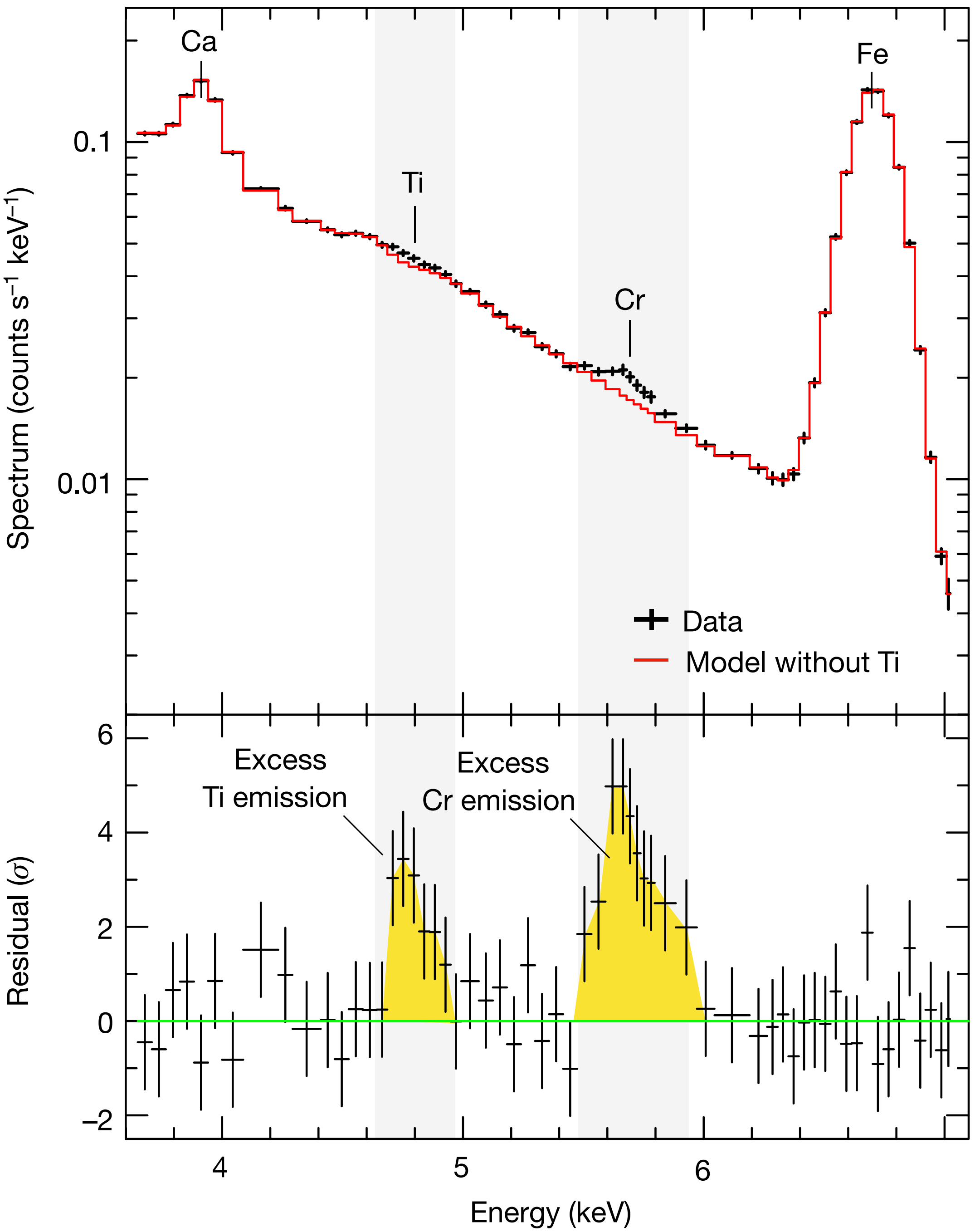
see J. Guilet's talk

Neutrinos produce low density, high temperature regions

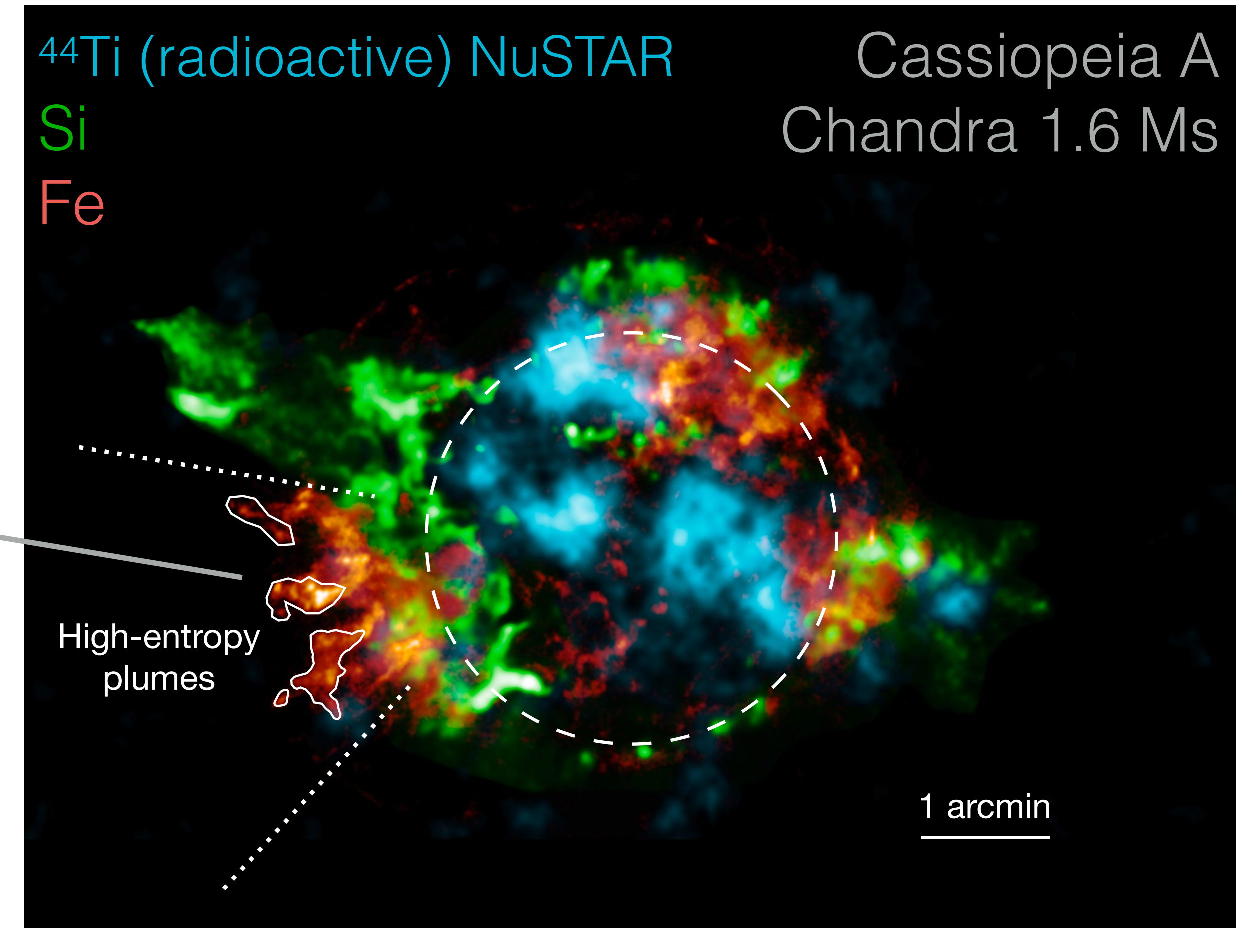


Fernandez, 2015

High entropy neutrino driven convection explosion

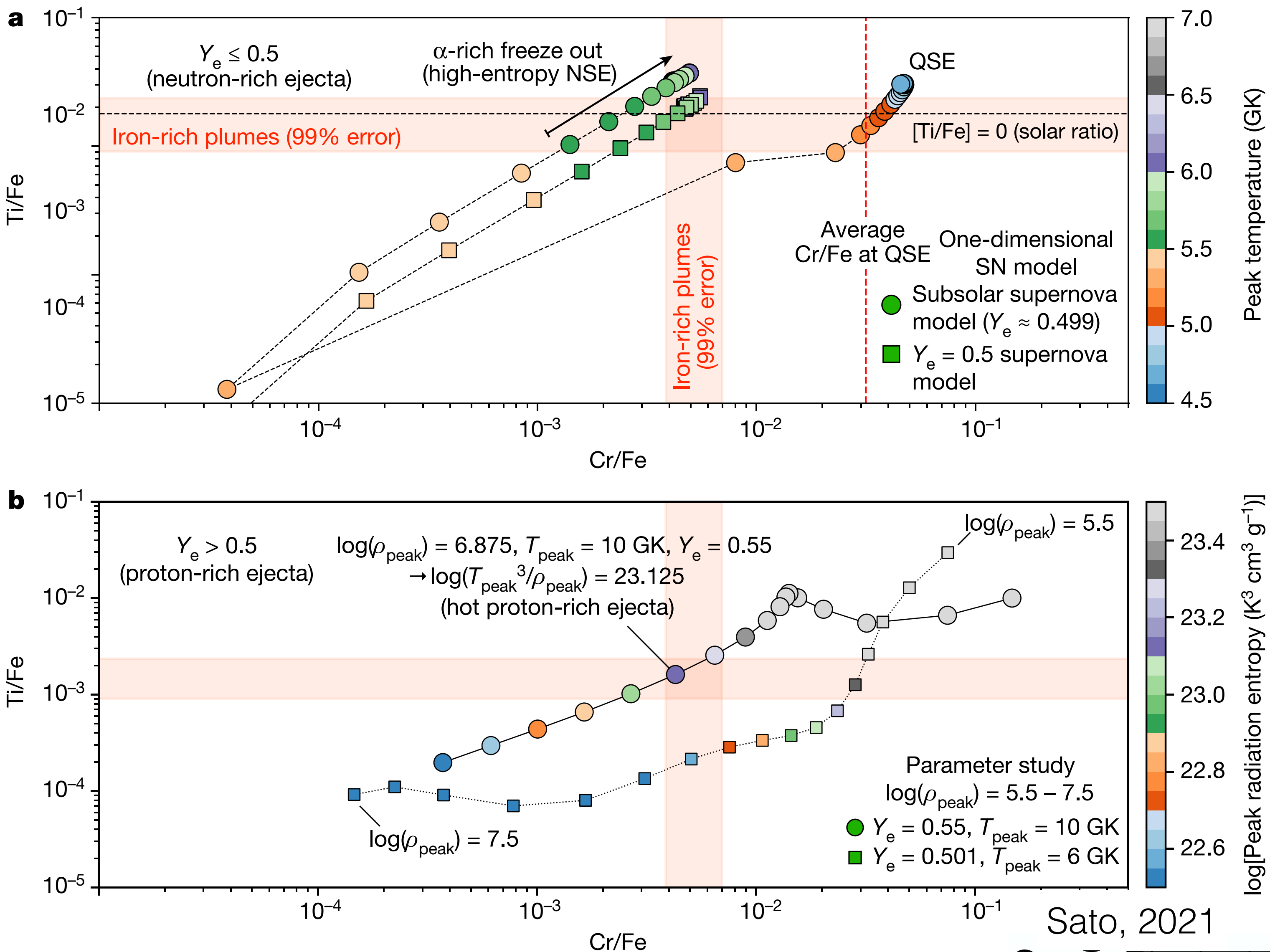


Sato, 2021



- **Detection of stable ^{48}Ti coincident with Fe, Cr**
- **High yield of proton-rich ejecta evidence of strong neutrino convective heating**
- **Outward Ti, Cr, Fe plumes due to buoyant high entropy (low density, high temperature) bubbles pushing ejecta outwards**

High entropy neutrino driven convection explosion



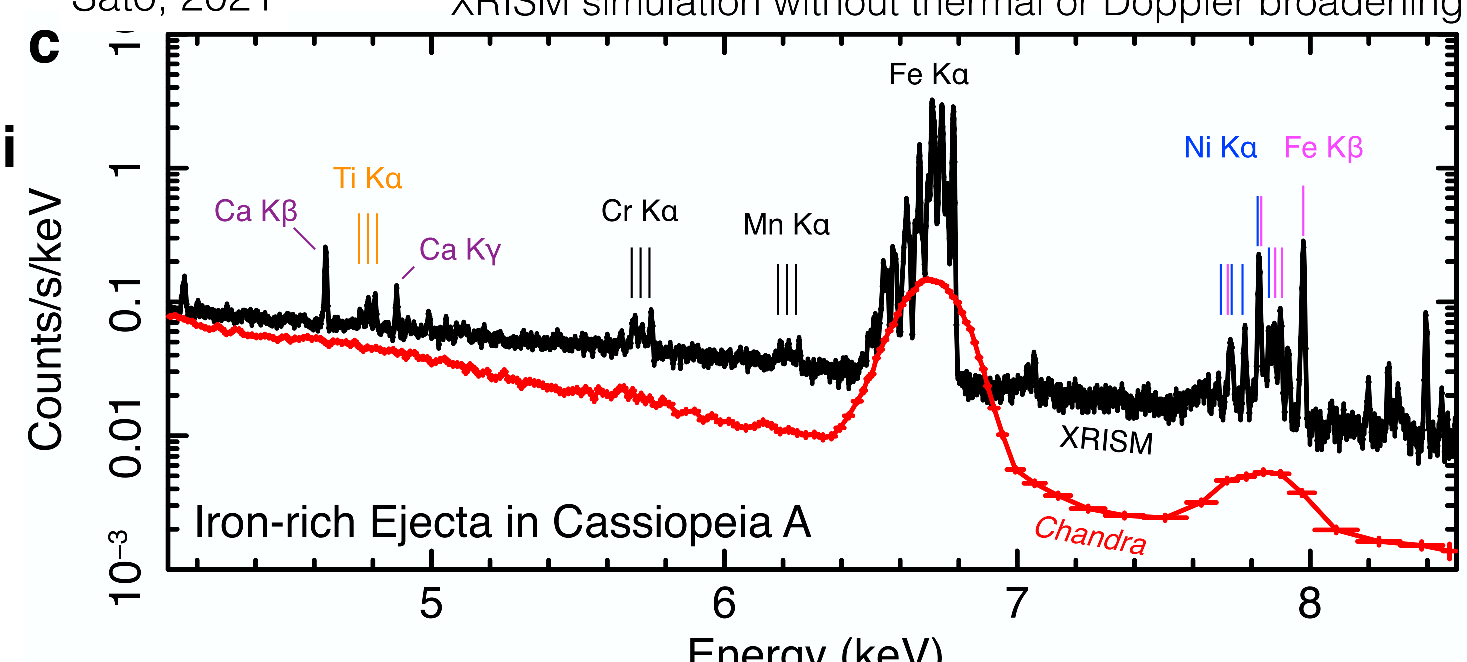
- **Ratio of Cr, Ti, Fe can constrain:**
  - **core temperature at explosion**
  - **exposure to neutrino heating**

- **=> Evidence for a neutrino-driven convective supernova engine**

Fe, Ti, Cr from alpha-rich freeze outLighter element (Si,S) from QSE

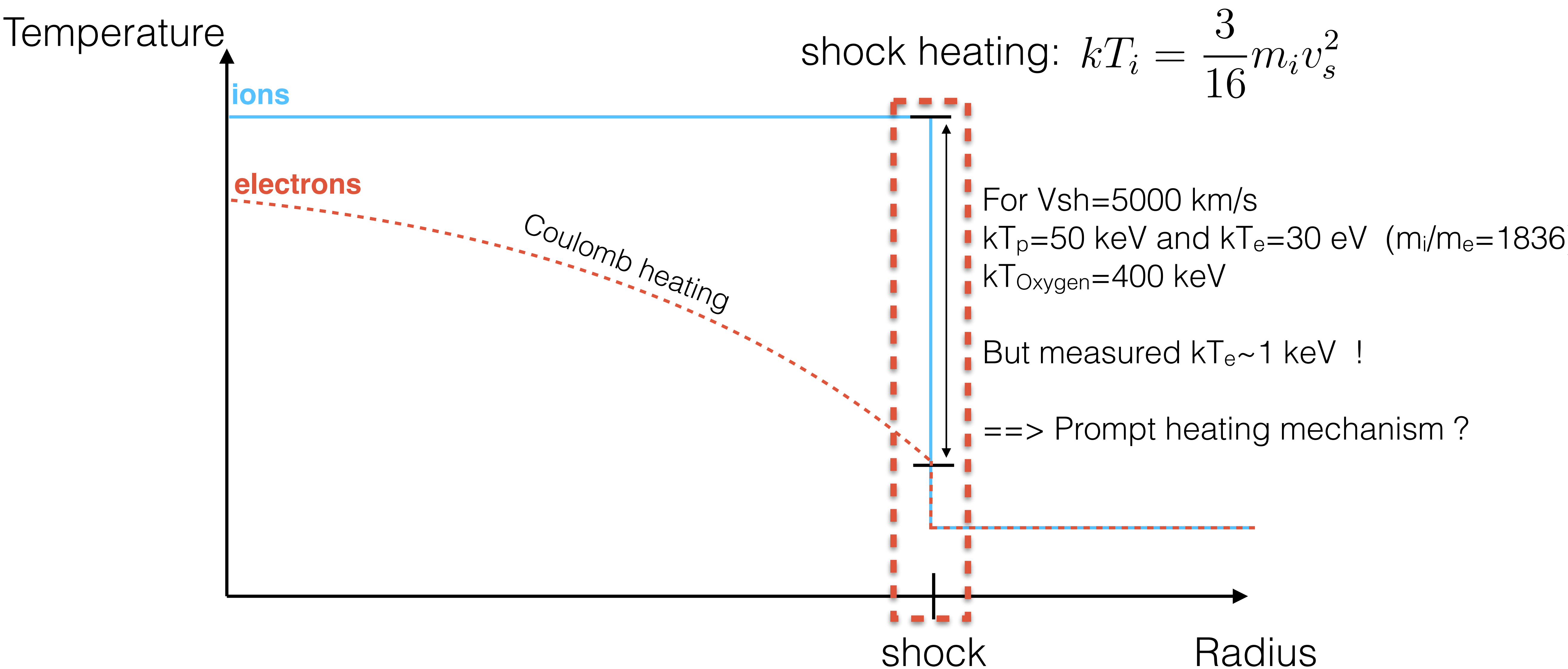
Sato, 2021

XRISM simulation without thermal or Doppler broadening



- **XRISM simulations to isolate Ti, Cr, Mn, Ni**
- **Due to average XRISM PSF, many line of sight will be mixed and faint lines diluted**
- **=> Need for a better PSF and FoV (X-IFU)**

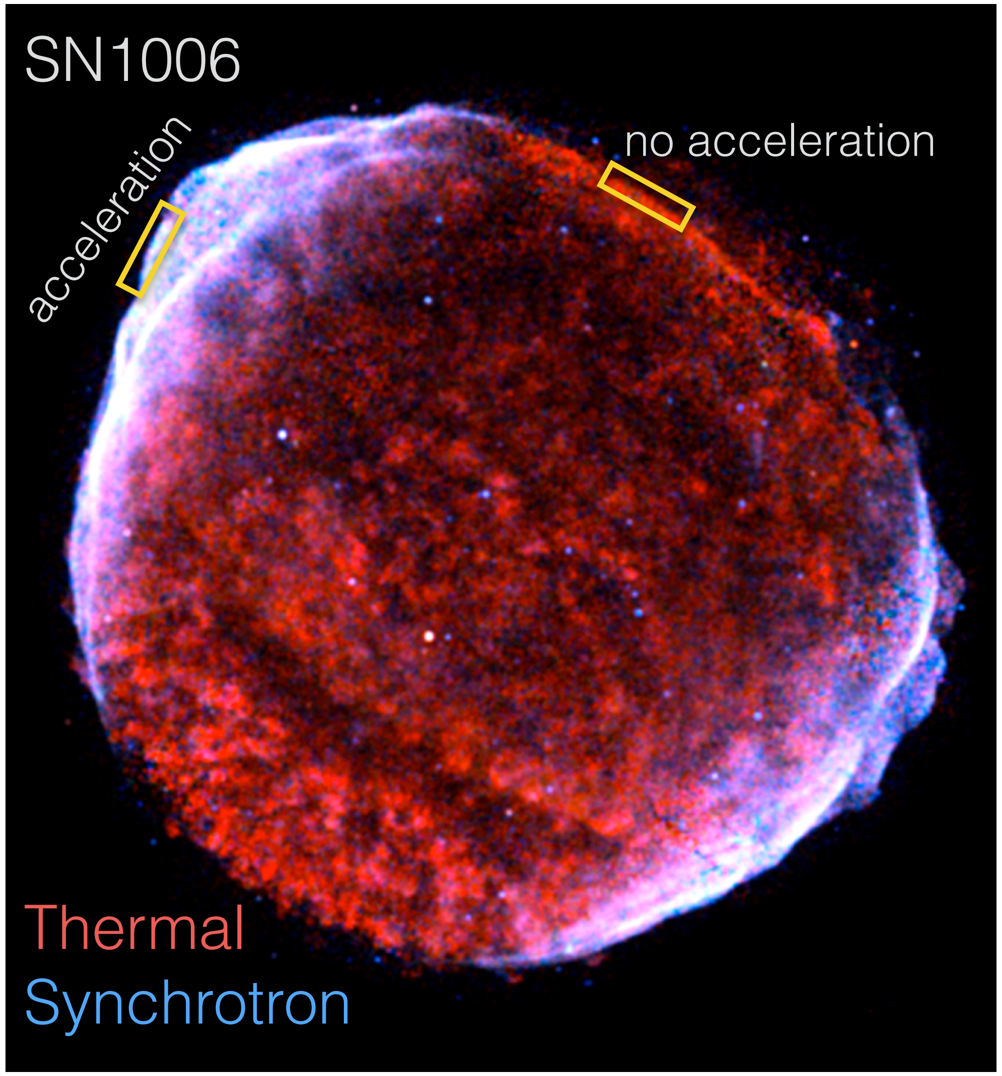
Collisionless shock heating



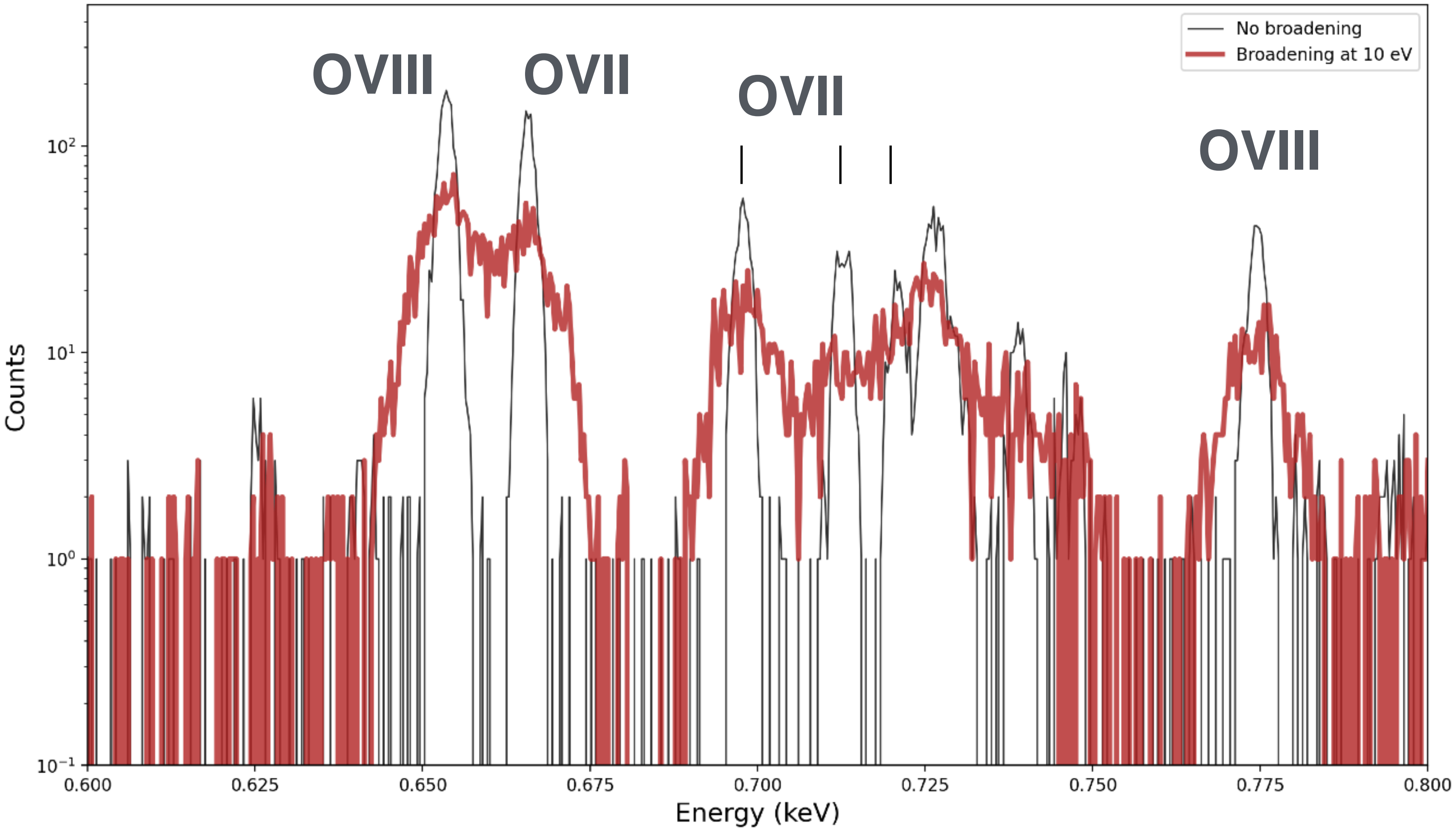
- **X-ray CCD cameras can only measure kT_e via Bremsstrahlung**
- **High resolution spectro can measure kT_p via ion line broadening**
  - **Study of shock in SNRs can probe kT_p for different ions & velocity**
  - **Understand prompt heating mechanism**
  - **A high spatial resolution is needed to isolate heating at the shock & reduce ejecta contamination**

Probing acceleration efficiency via line broadening

- **Efficient particle acceleration pumps energy out of the shock**
  - **Less energy is available for shock heating**
    - **Measuring kT_p (line broadening) in regions with/without particle acceleration could probe the fraction of shock energy transfered to Cosmic-Rays**

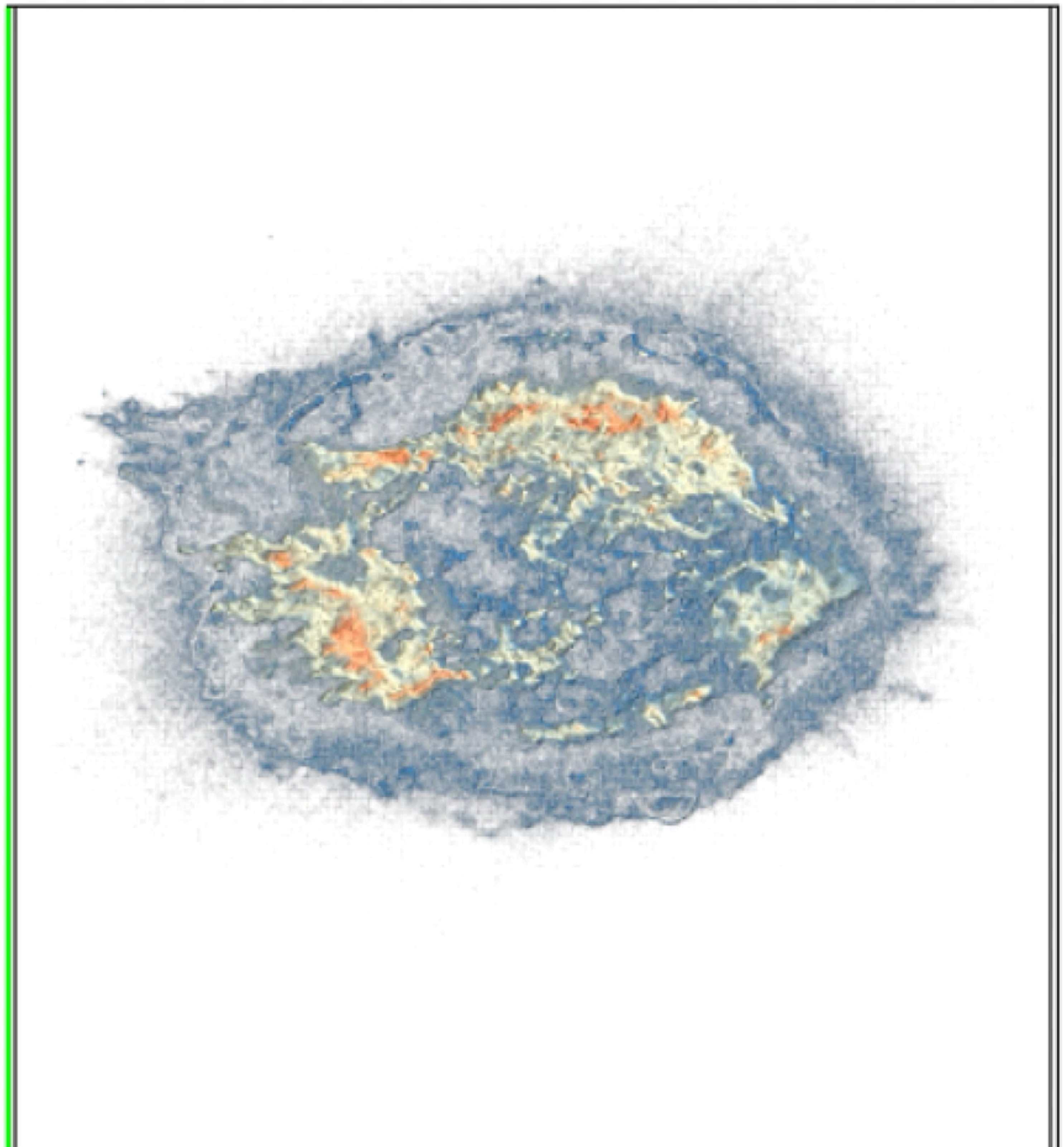


XIFU SN1006 T=50 ks kT=1.5 keV tau=5e9 5''x60'' box



Data analysis - A 3D approach

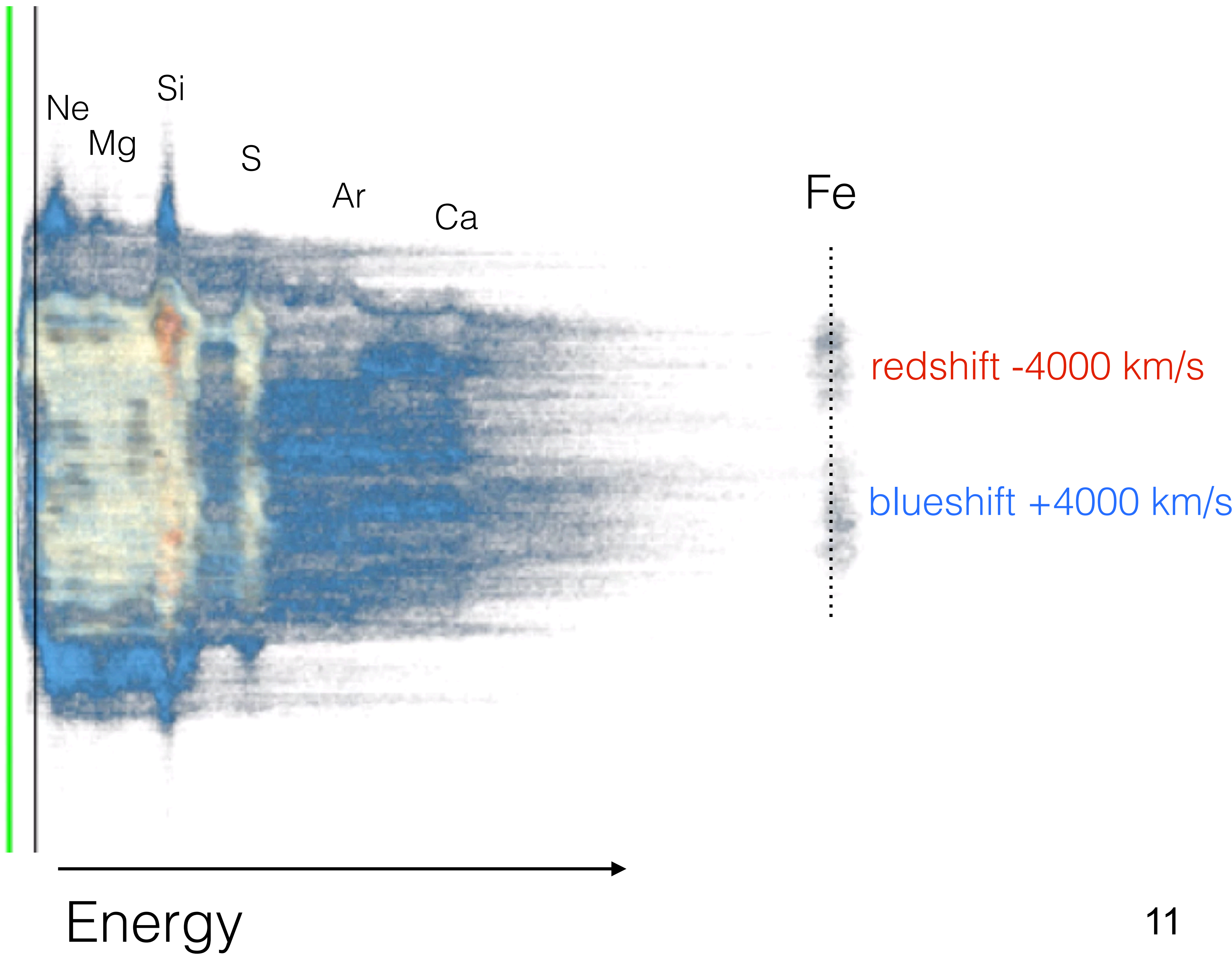
CasA Chandra X,Y,E cube



Data visualization of CassiopeiaA seen with Chandra

Data analysis - A 3D approach

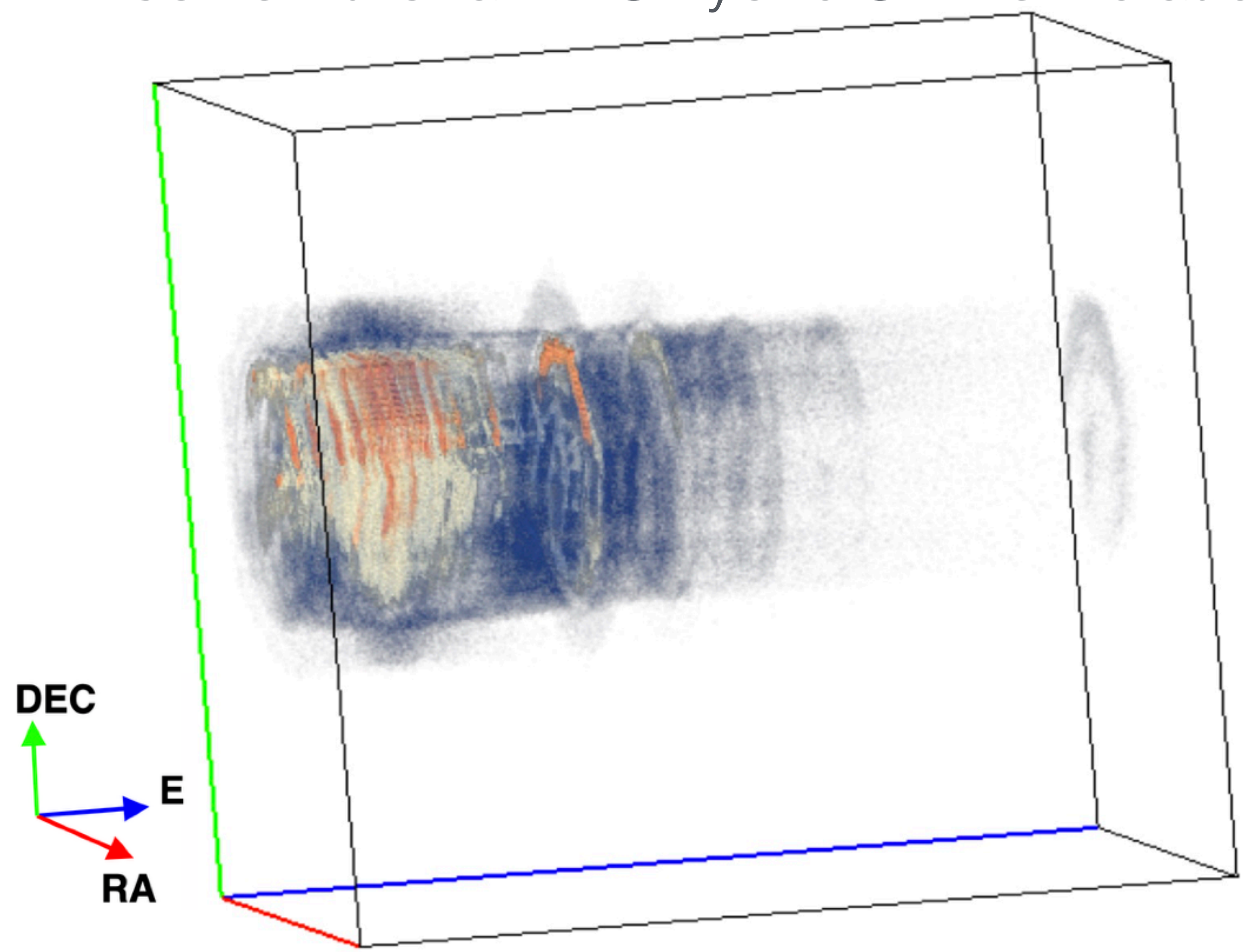
CasA Chandra X,Y,E cube



Data visualization of CassiopeiaA seen with Chandra

Athena X-IFU:
a transformational view of the X-ray Universe

50 ks Athena XIFU Tycho SNR simulation



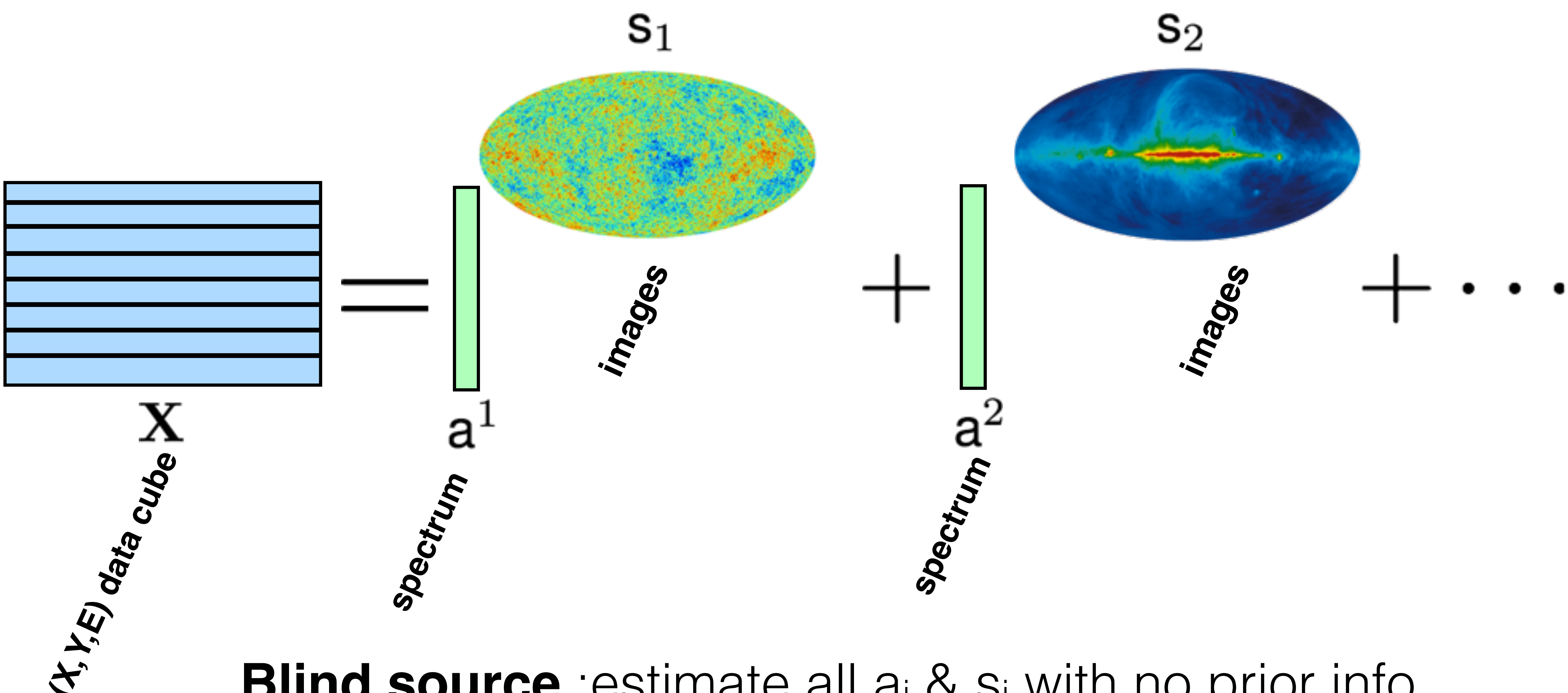
Compared to XRISM X-IFU will be a game changer for extended sources (pixels, FoV, PSF)

- **Athena : high effective area, ~eV spectral resolution**
- **How to analyze such datasets ?**
  - **Cubes of $N_x, N_y, N_E \sim 3\times10^3 \times 3\times10^4$ => 100 millions voxels**
- **Need to consider the cube as a whole not only 2D then 1D**
  - **Disentangling components using spectro-morphological diversity**

Blind source separation example:
Generalized Morphological Component Analysis (Bobin 2015)

Main idea: different physical components (e.g. CMB vs synchrotron) have different morphological & spectral signatures in the data cube

Assumption: Linear combination : data = Σ $spec_i$*$image_i$

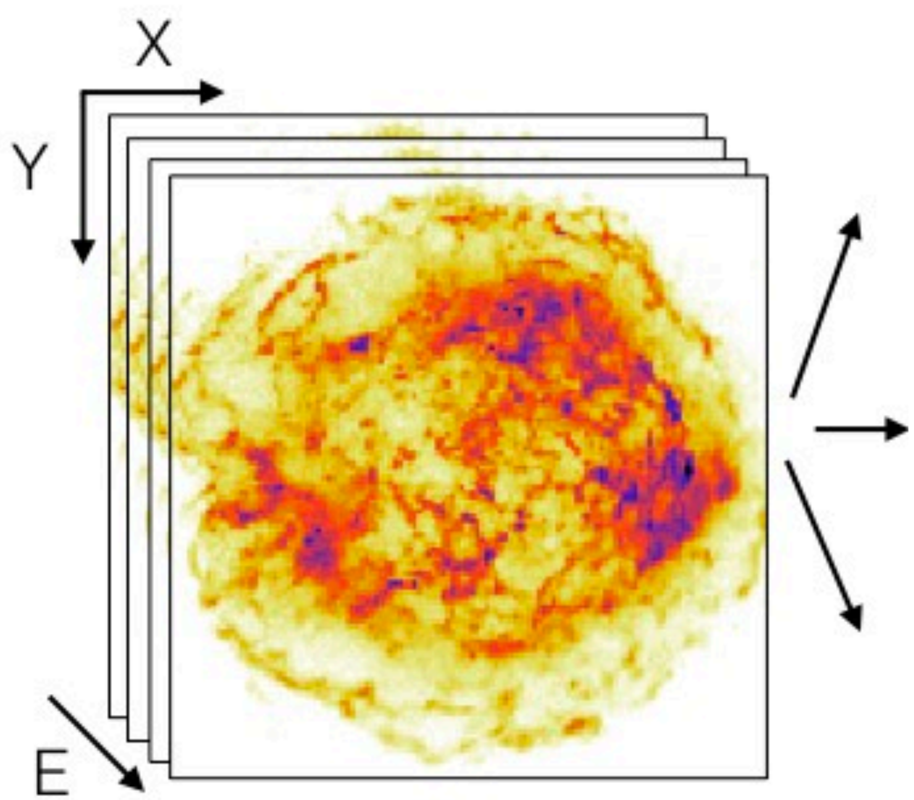


Blind source :estimate all a_i & s_i with no prior info
Number of components fixed by the user

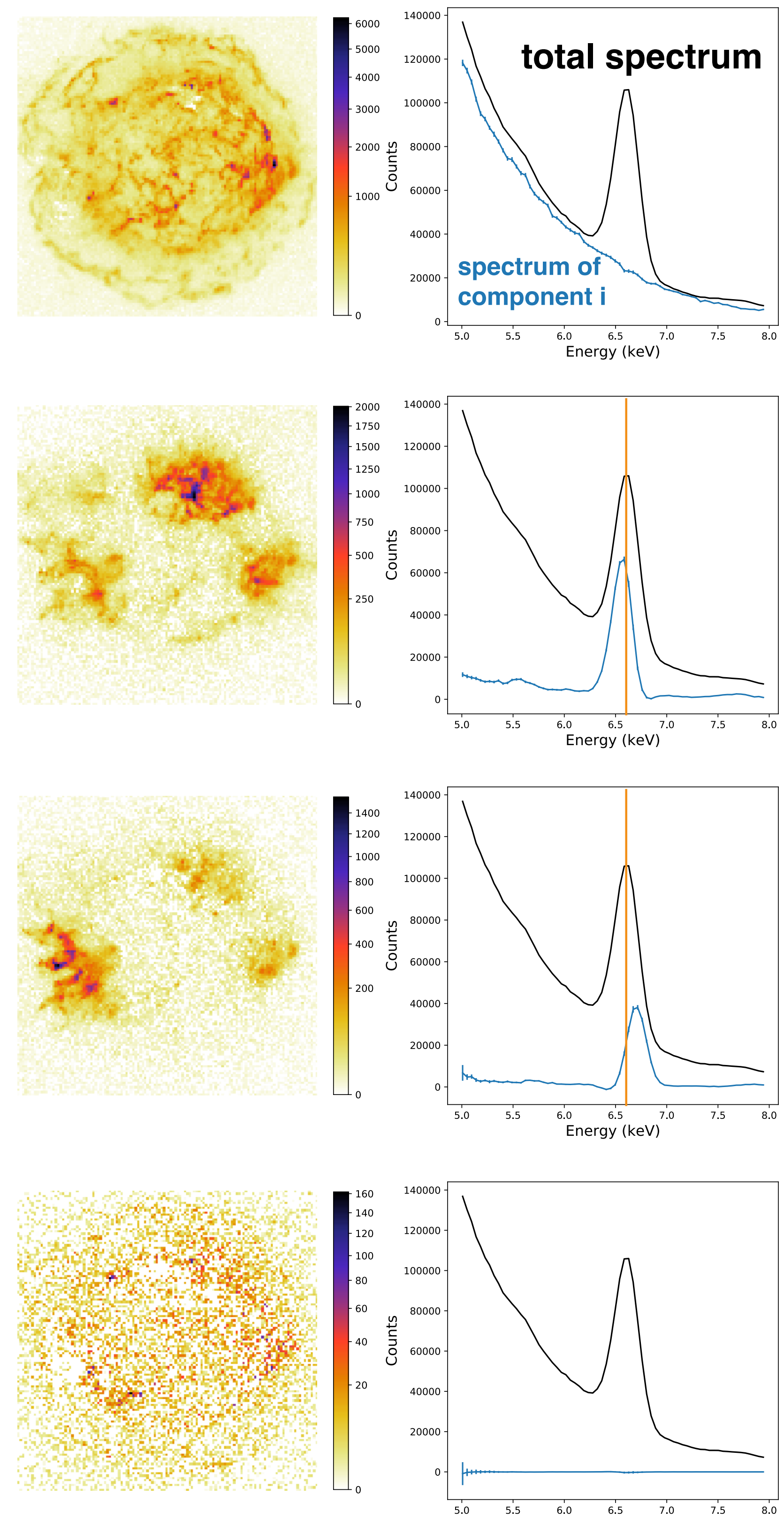
Application to CasA Chandra dataset

Methodology, Toy models & application examples from Picquenot, Acero, et al., 2019

Cassiopeia A Chandra dataset is a photon gold mine
(~200 millions photons !)



5.0-7.5 keV data cube



Synchrotron

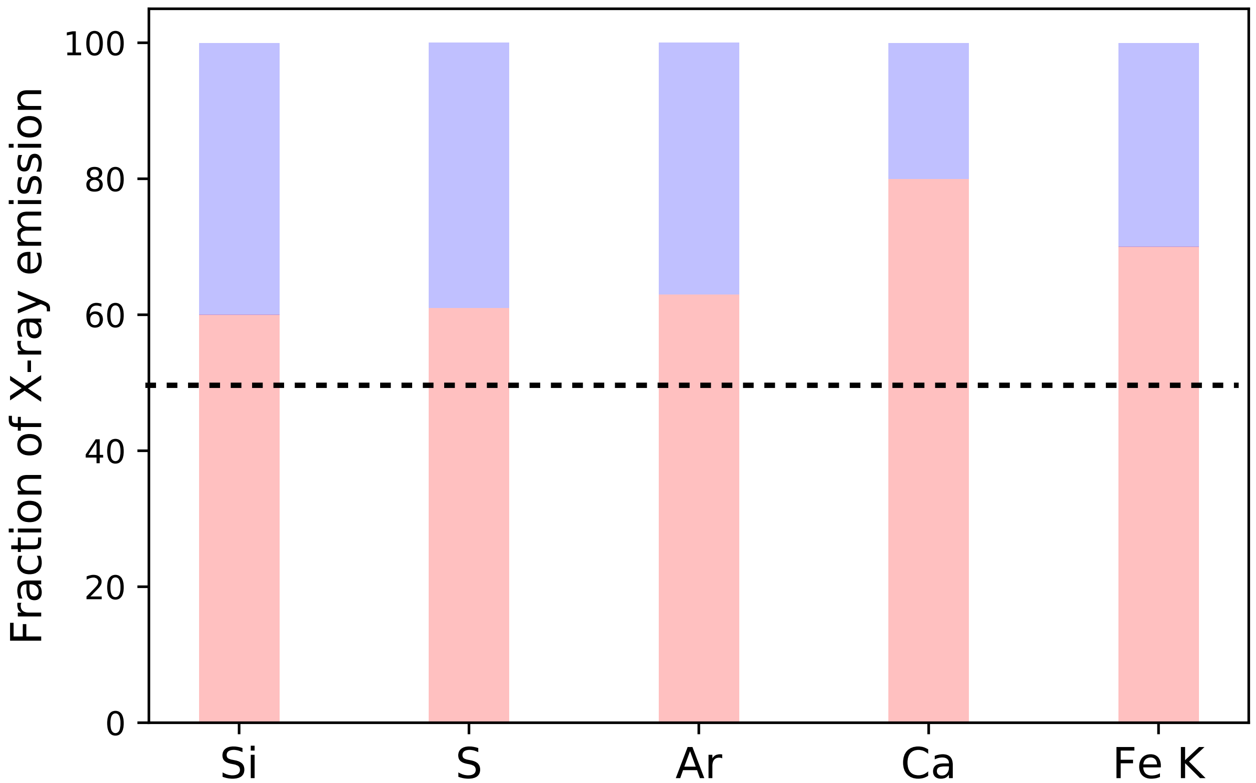
Red-shifted Fe structure

Blue-shifted Fe structure

Noise

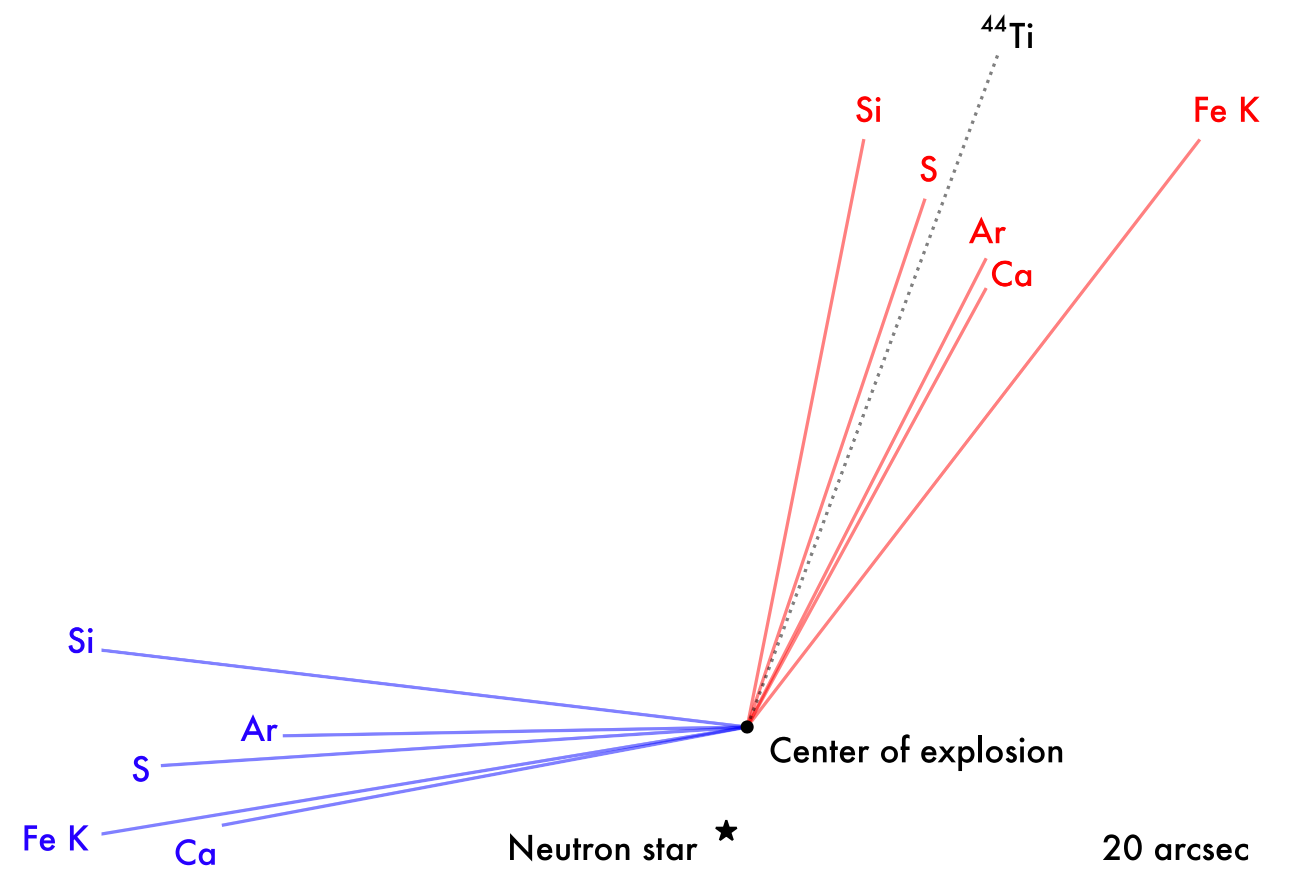
3D assymetries in CasA

Most of the X-ray emission is red-shifted. Similar to ^{44}Ti.



Fraction of the flux in the red/blue shifted component

Most of the material is expelled on the opposite direction of NS.



Picquenot, Acero, et al., 2021

Important role of assymetries in the SN explosion

see J. Guilet's talk

Analysis Challenges

Handling 4D (X,Y,E,T) data

- **X-IFU data are multi-D in nature and we should exploit them more that way data as 3D/4D products (ground segment, pipeline, user analysis, etc)**
- **Need to develop these new product tools & 3D analysis (e.g. deblending)**

Fitting methods

- **Statistical tools (e.g. Bayesian workflows), modern minimizers**
- **Cosmology, surveys, etc have entered the ML & adv. signal processing era. Where is the French X-ray community standing ?**

Astrophysical models & HR spectroscopy

- **Atomic Data base**
- **Multi-D astrophysical models (spatial, spectra, time, polarimetry)**
- **HR spectro: identify expertise in France**
- **Need to put our hands on XRISM data (who has access, proposals ?)**

Training the current+younger generations

==> workshop, Athena summer schools

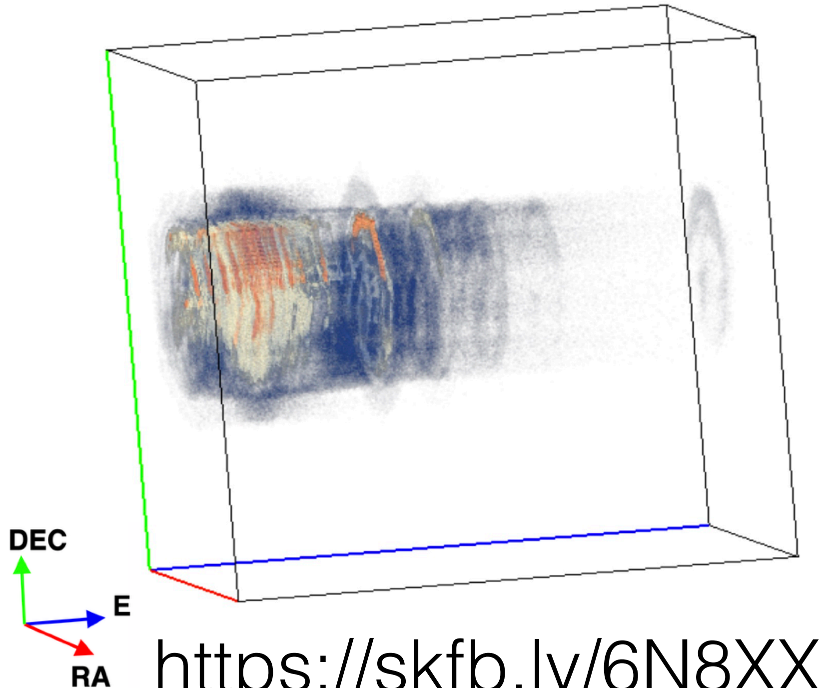
Conclusion

- **Grating spectroscopy and XRISM observations are limited for ext src:**
  - **Imaging + HR spectroscopy with X-IFU is a game changer**

- **SNRs are a laboratory of high-energy astrophysics:**
  - **supernova explosion, collionless shock physics, particle acceleration**

- **Need to develop specific tools to harness the power of XIFU spectro-imaging capabilities**
  - **deblending of superimposed components**
  - **3D deprojection using Doppler effect**
  - **cube fitting & physical parameter mapping**

Kepler X-IFU simulation

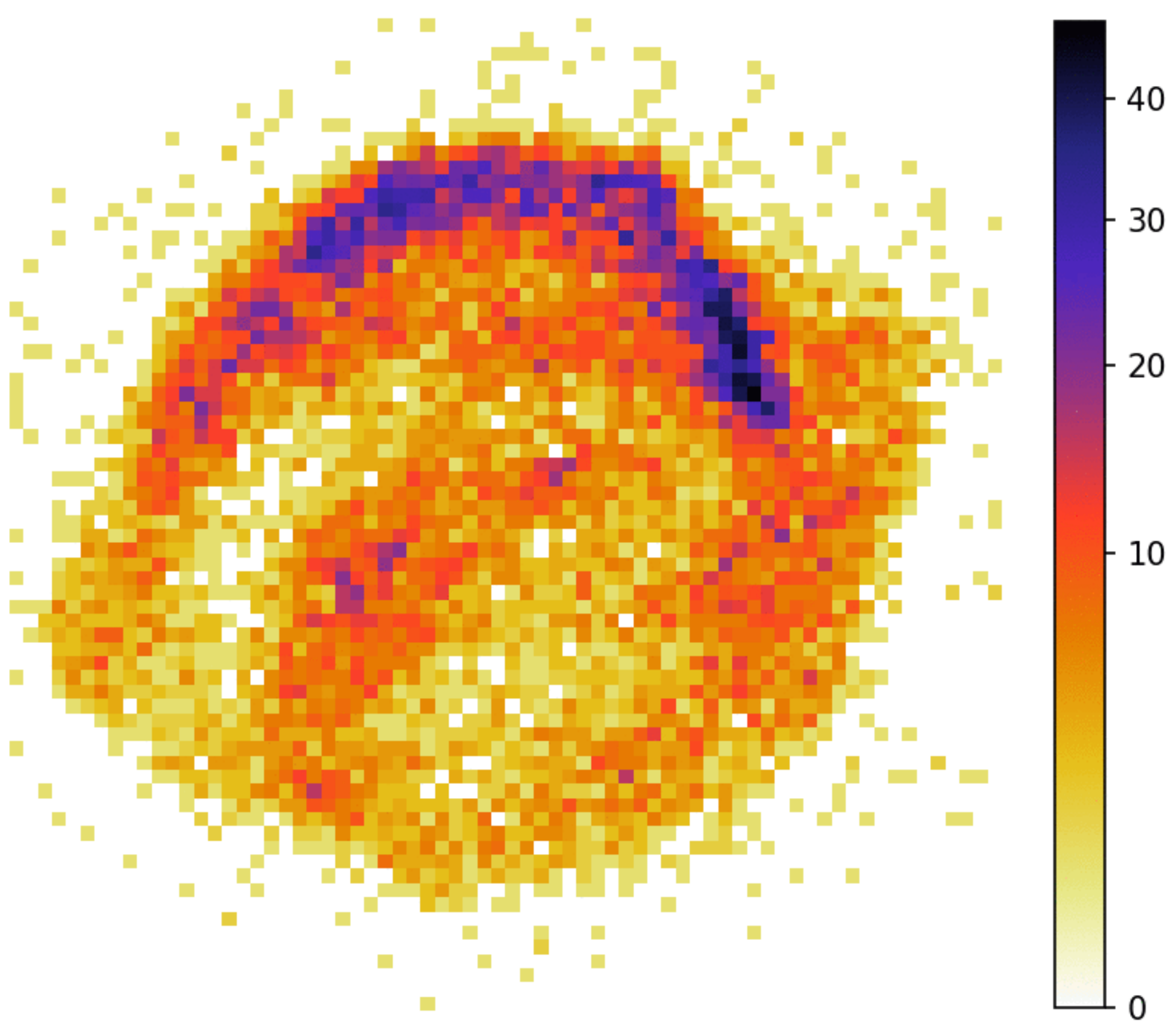


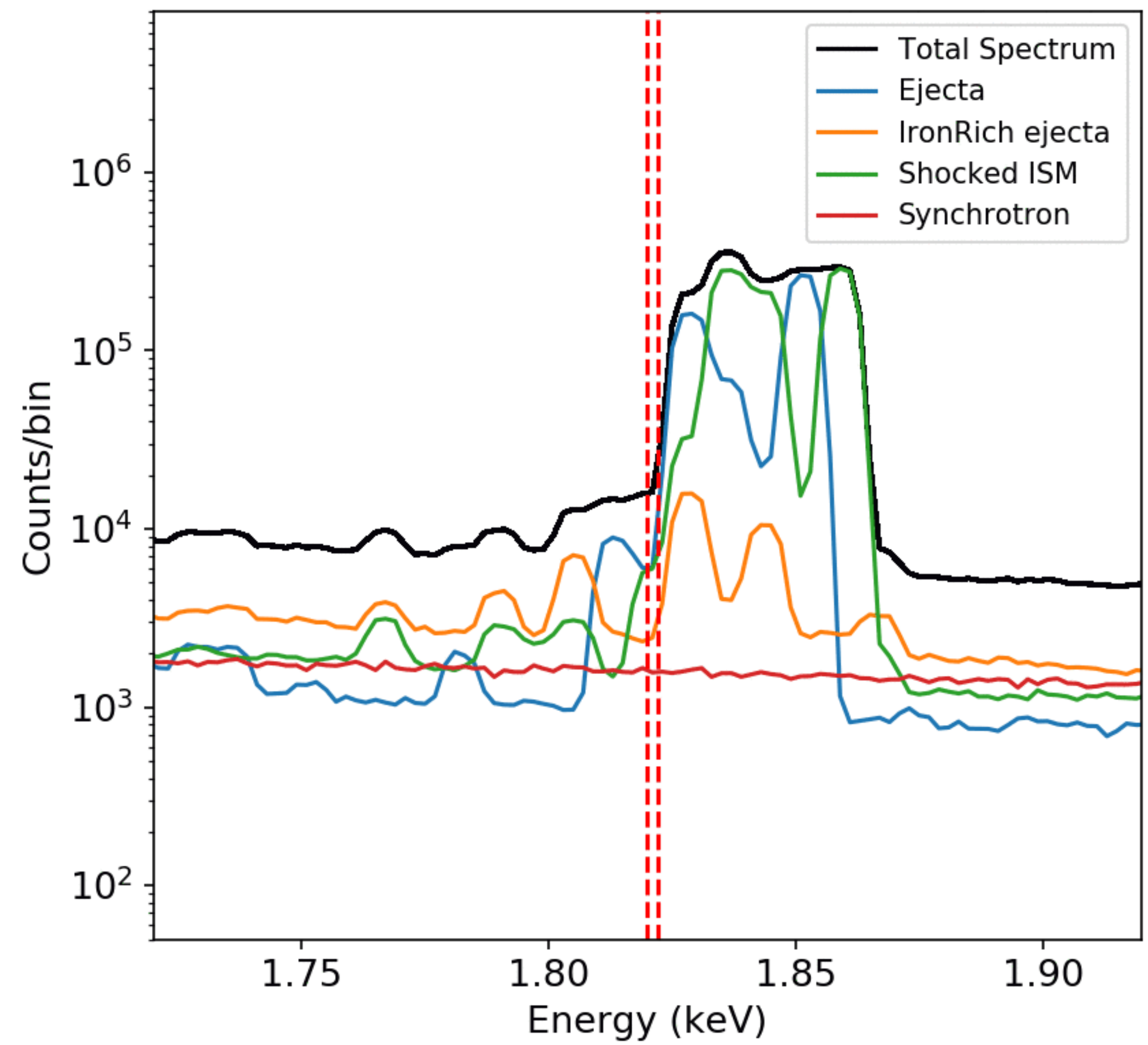
https://skfb.ly/6N8XX

- **Extra-galactic SN & SNRs:**
  - **SN progenitor mass-loss history**
  - **Circumstellar interactions**

Kepler X-IFU simulation around Si XIII line

E= 1.820 - 1.822 keV





Kepler simulation for X-IFU
50 ks

GMCA algorithm (Bobin 2015)

images in wavelet domain data cube spectra images

$$\min_{A,S} \sum_{i=1}^{n} \lambda_i \|S_i\|_p + \|X - AS\|_F^2$$

sparsity constraint term data fidelity term

Estimating both A & S is an ill posed inverse problem.

$\longrightarrow$ Adding a constraint on sparsity of images in the wavelet domain

The algorithm is iterative:

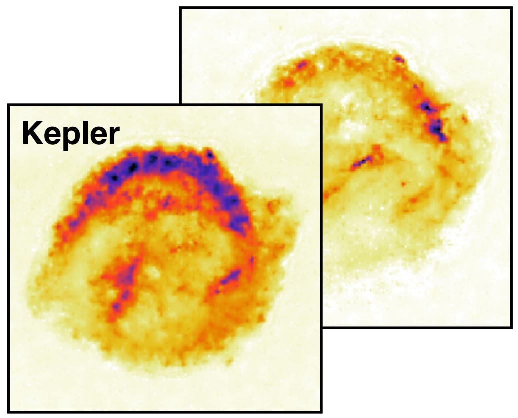
- Step 1: Estimation of S for fixed A, by simultaneously minimizing $\|X - AS\|_F$ and the term enforcing sparsity in the Wavelet domain;
- Step 2: Estimation of A for fixed S by minimizing $\|X - AS\|_F$.

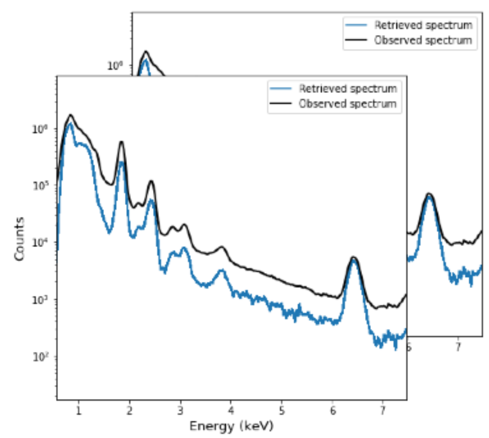
Using GMCA for X-IFU SIXTE simulations

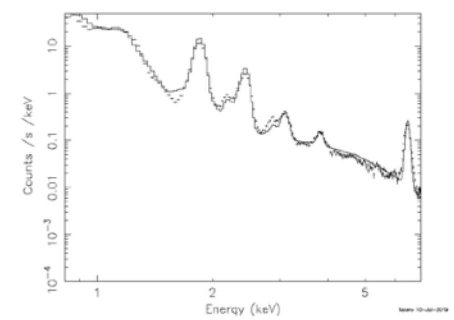
Chandra data cube

Morpho component analysis

N (image, spec)







Xspec

XSPEC model
model TBabs(powerlaw + vnei)
1.50531 0.001 …
2.28824 0.01 …
…

SIMPUT

SIXTE

SIXTE simulation by
Gamil Cassam-Chenaï

Event list

	RA	DEC	E
1	…	…	…
2	…	…	…
3	…	…	…

Data cubes