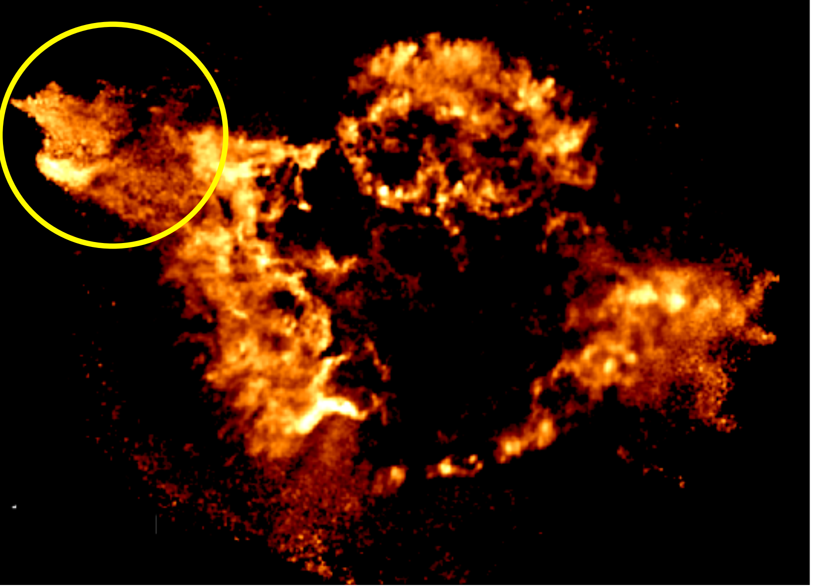

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Discovery of Titanium-K Lines in the Northeastern Jet of Cas A

Takuma Ikeda, Yasunobu Uchiyama (Rikkyo University)

Outline

Introduction

- ^{44}Ti in explosive nucleosynthesis
- Cassiopeia A: Previous results

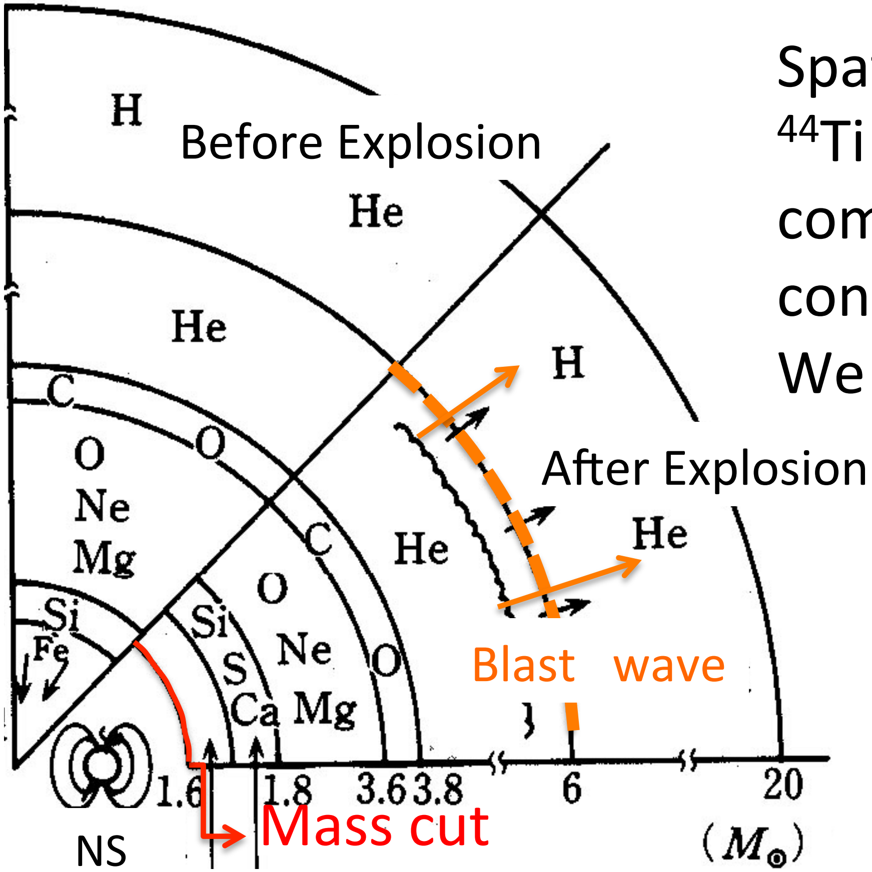
Cas A jet with Chandra

- Spectral and image analysis
- Estimation of Ti mass in jet
- Comparison to nucleosynthesis model

Summary

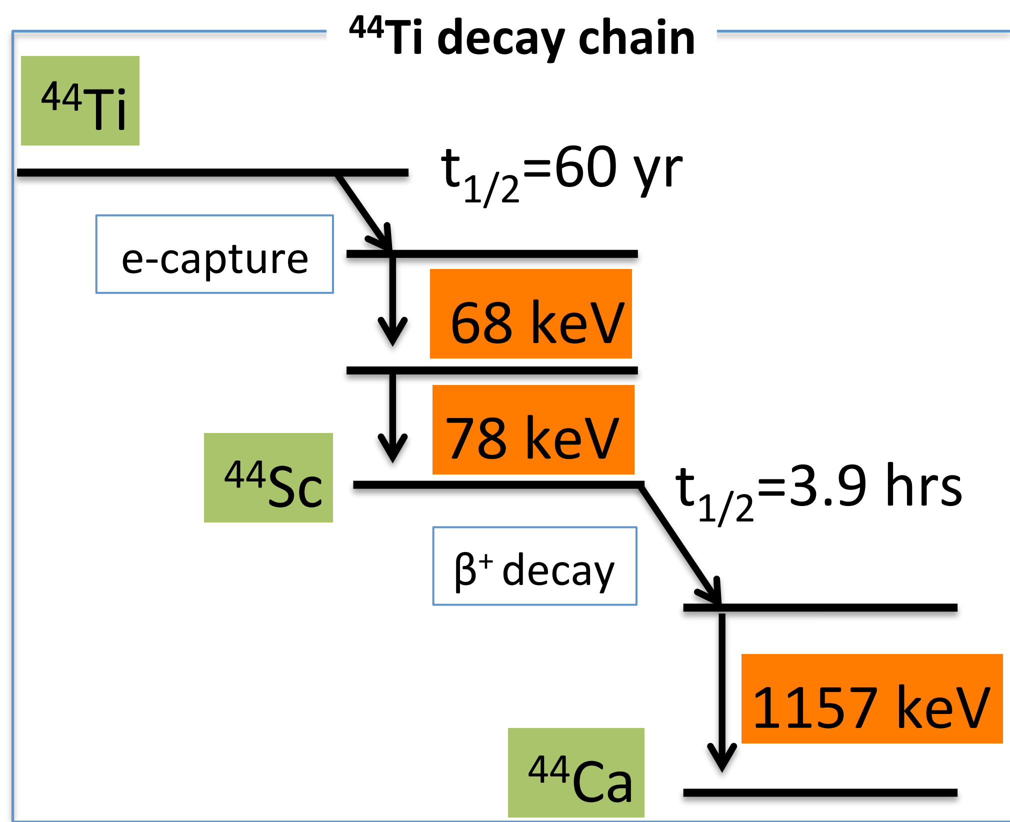
^{44}Ti in Explosive Nucleosynthesis

Spatial distribution and the amount of ^{44}Ti produced at mass cut (between compact object and ejecta) reflect the condition of explosion.
We can learn about explosion mechanism.

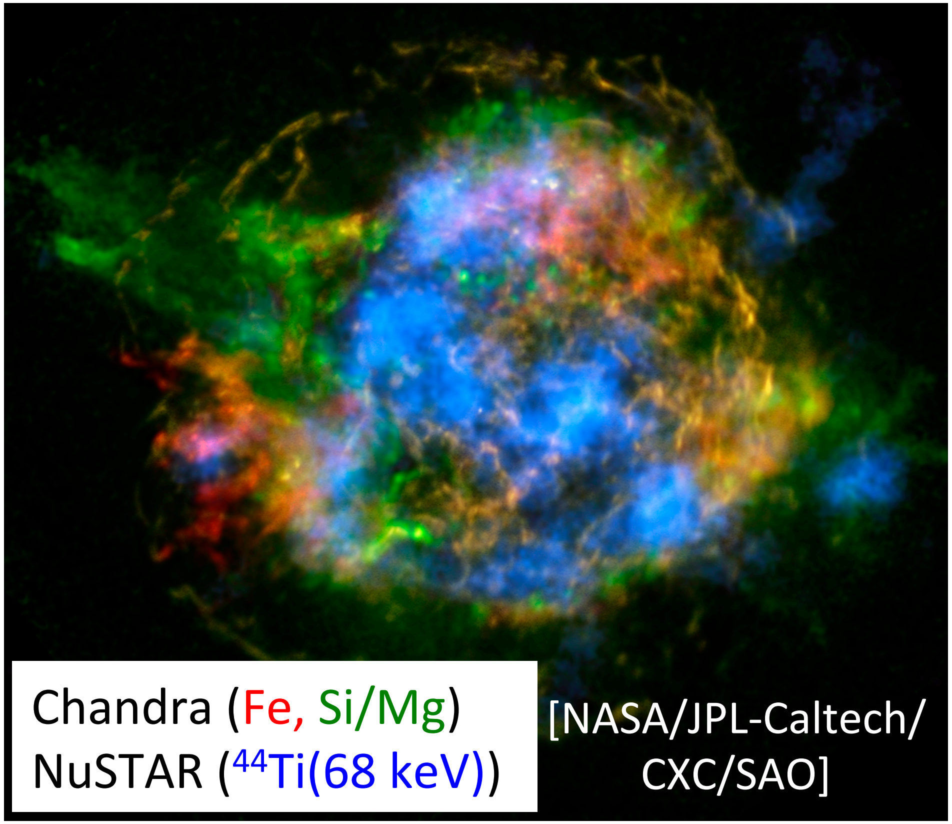


Inner composition at before and after SNe
[Kumagai,Nomoto,1991]

^{44}Ti decays into ^{44}Sc by e-capture (half-life 60yr) and
^{44}Sc decays into ^{44}Ca by beta decay (half-life 3.9hrs)



X-ray Observation of Cassiopeia A



- Age: ~330 yr [Fesen 2006]
- Distance: 3.4 kpc [Reed+ 1995]
- Progenitor mass: ~16 $M_\odot$ [Lee+ 2014]
- Initially synthesized ^{44}Ti mass: $1.37 \pm 0.19 \times 10^{-4}$ $M_\odot$ [Siegert+ 2015]

Cassiopeia A (Cas A)

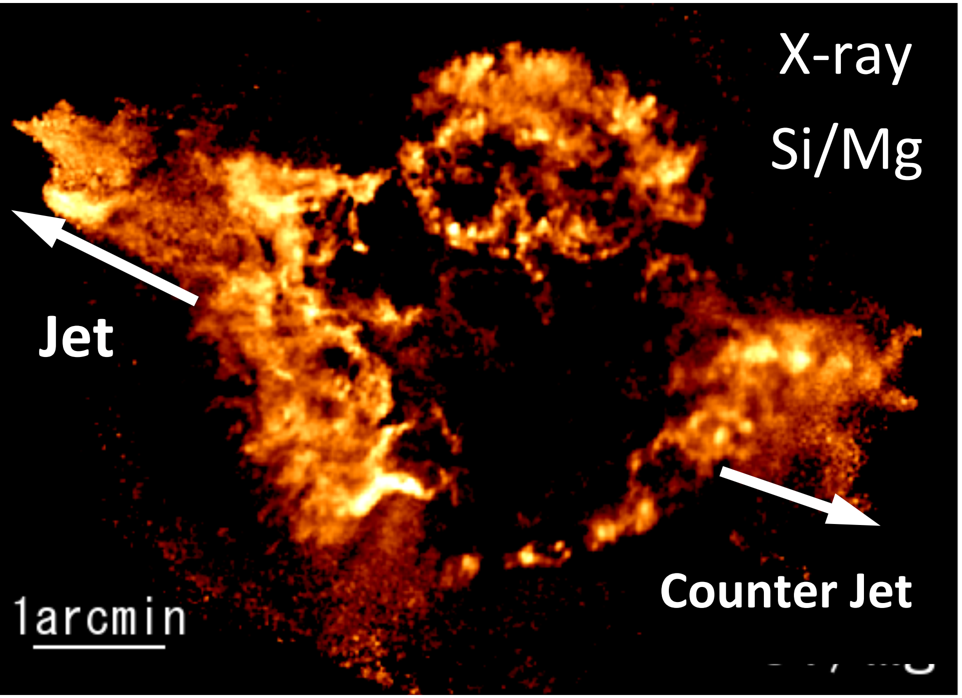
Detections of 1157 keV,68 keV, 78 keV lines (^{44}Ti decay).

^{44}Ti's spatial distribution differs from that of Fe K lines measured with the Chandra X-ray Observatory.

No any Ti-K line detections so far. Stable ^{48}Ti is mainly produced decay from ^{48}Cr. ^{48}Cr mass can be enhanced by "alpha-rich freeze out", which produces ^{44}Ti.

Modest amount of ^{44}Ti and Fe in northeastern jet.

Jet in Cassiopeia A



The speed of Jet: [Fesen+ 2006]

10000~14000 km/s

Non-Jet ejecta speed: [Rutherford+ 2013]

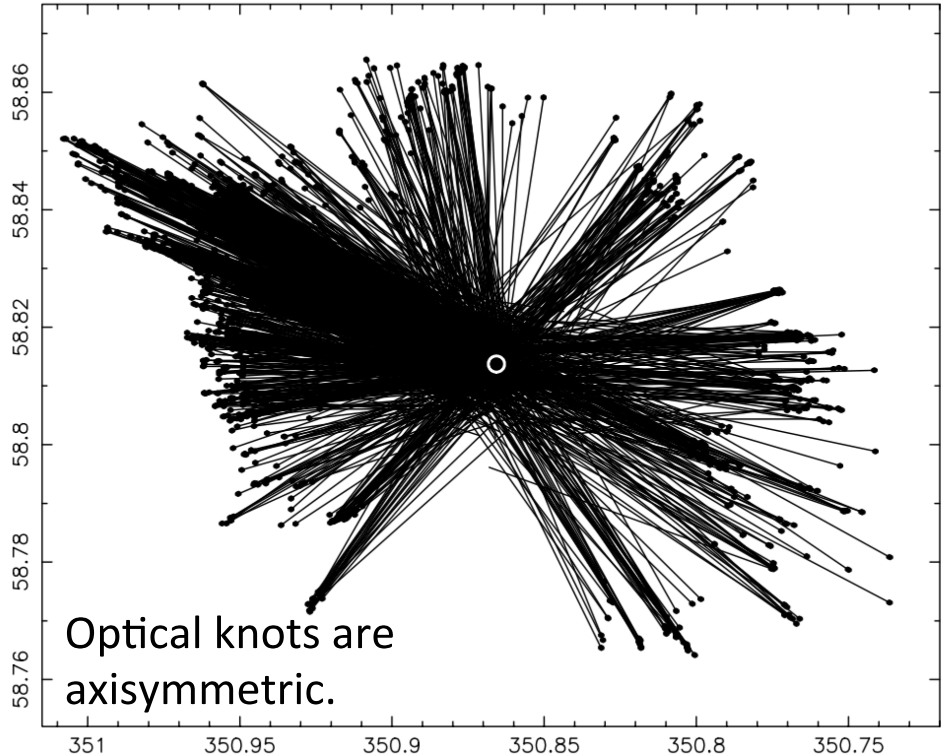
1000~3000 km/s

Jet's kinetic energy: [Fesen+ 2015]

$\sim 1 \times 10^{50}$ erg

Jet area has ~10% flux compared with other ejecta area.

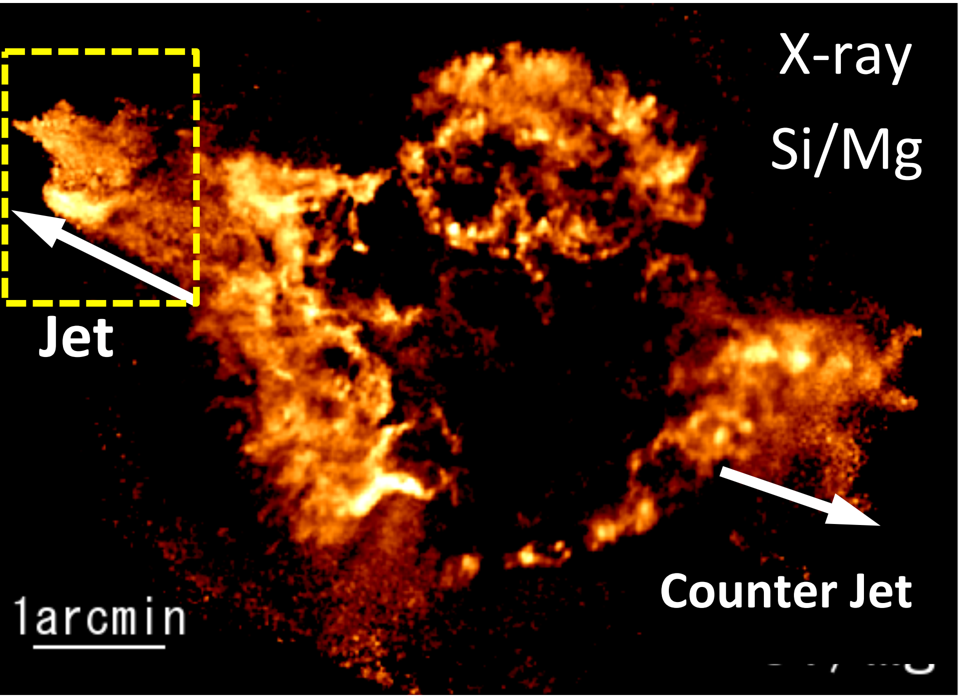
Cas A has a Si-rich jet extending northeastward and counter jet extending southwestward



Optical knots' proper motion [Fesen+ 2006]

"Jet" origin remain unsettled whether axisymmetric circumstellar interaction [Blondin, 1996] or bipolar explosion?

Jet in Cassiopeia A



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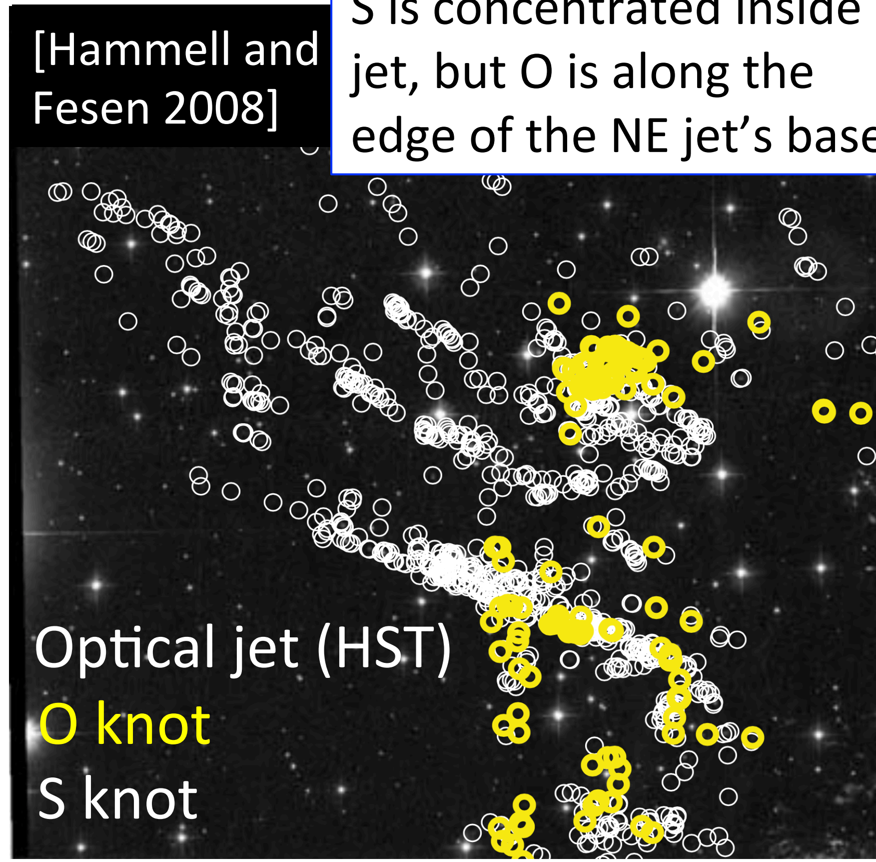

S is concentrated inside jet, but O is along the edge of the NE jet's base.

S jet penetrated surrounding O–layer?

Synchrotron component is overlaid in counter jet direction. Focus only NE jet for analysis.

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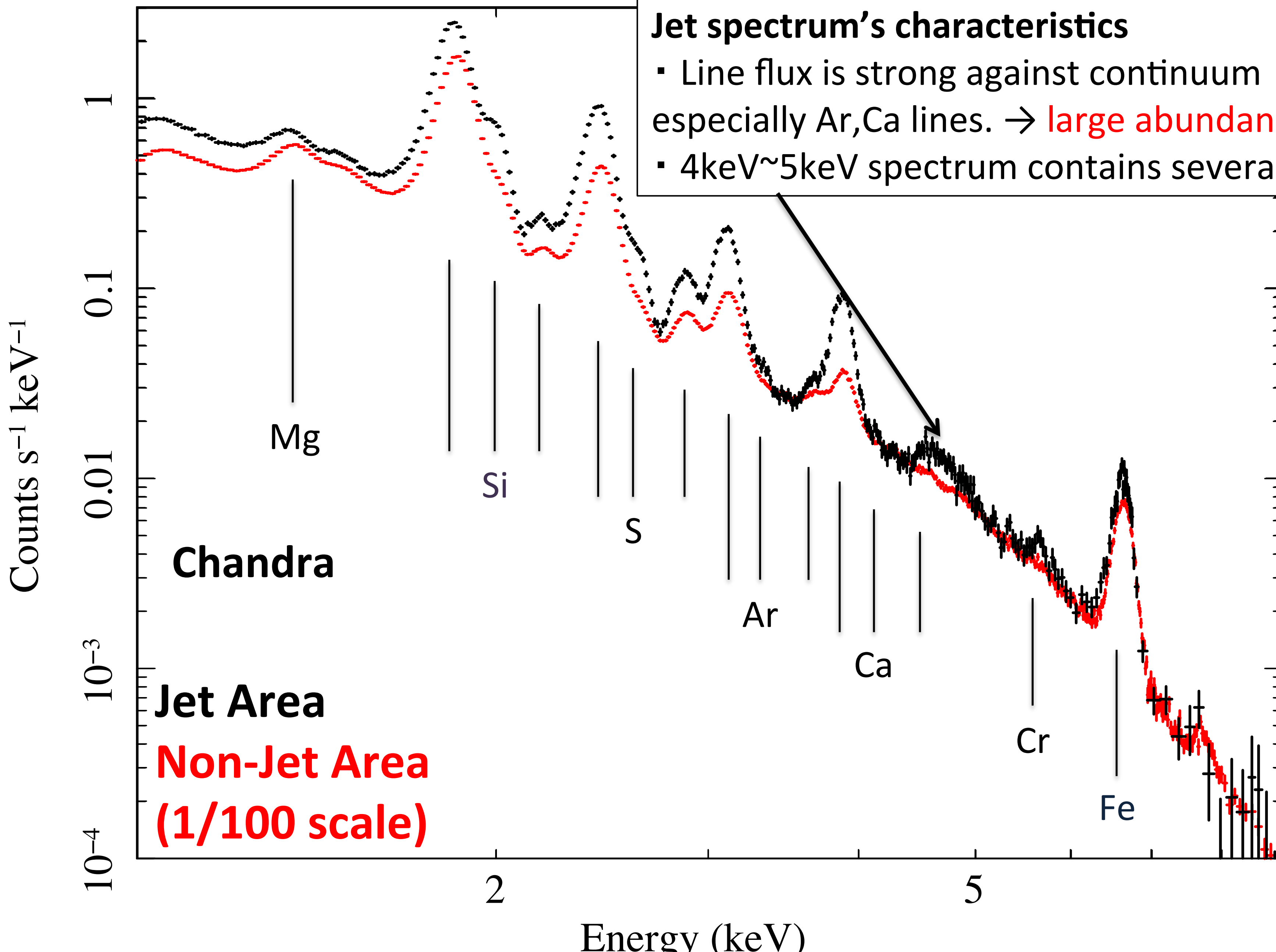
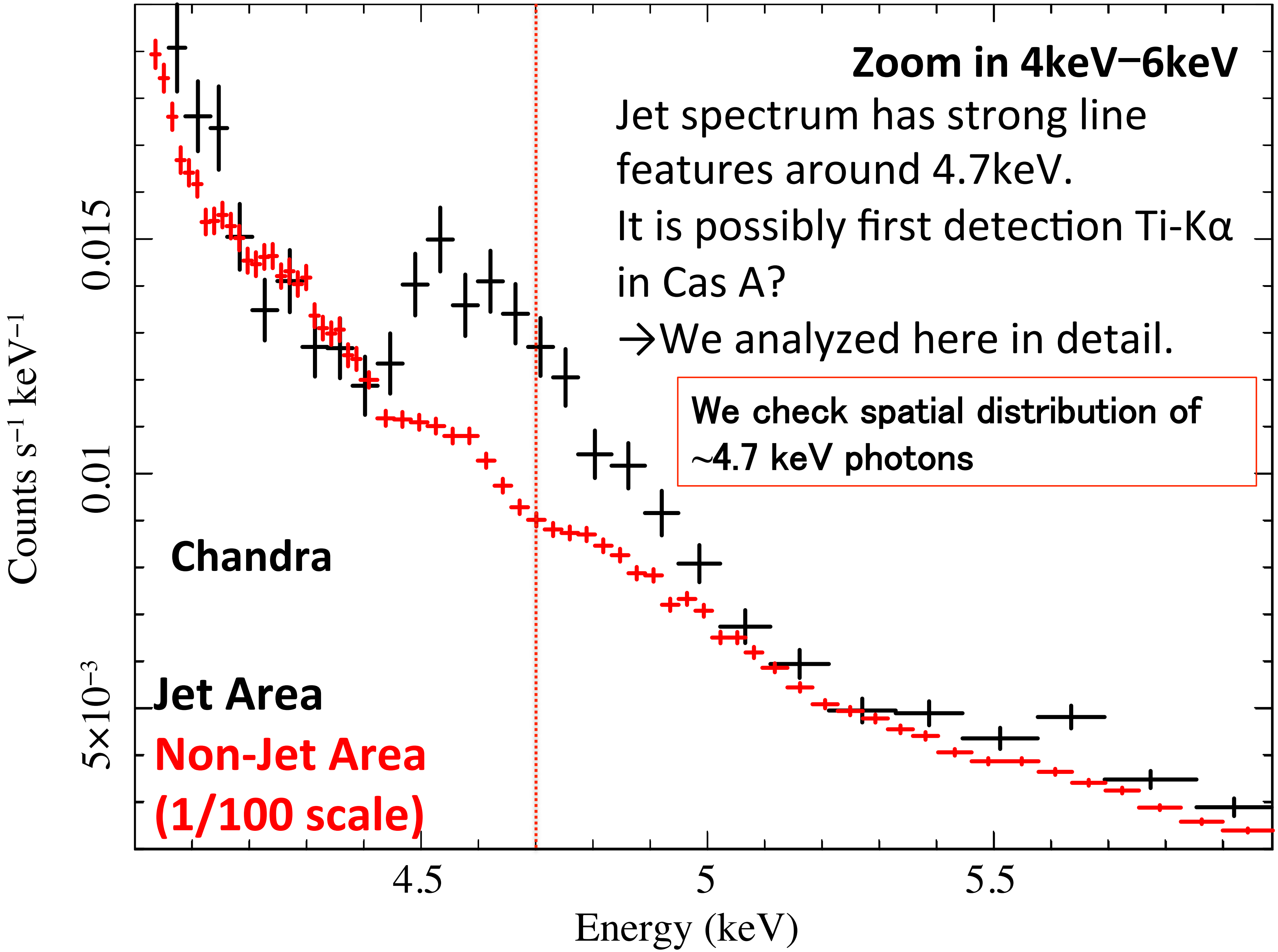
Comparison jet to non-jet area spectrum



Jet spectrum's characteristics

- Line flux is strong against continuum especially Ar,Ca lines. → large abundance
- 4keV~5keV spectrum contains several lines.

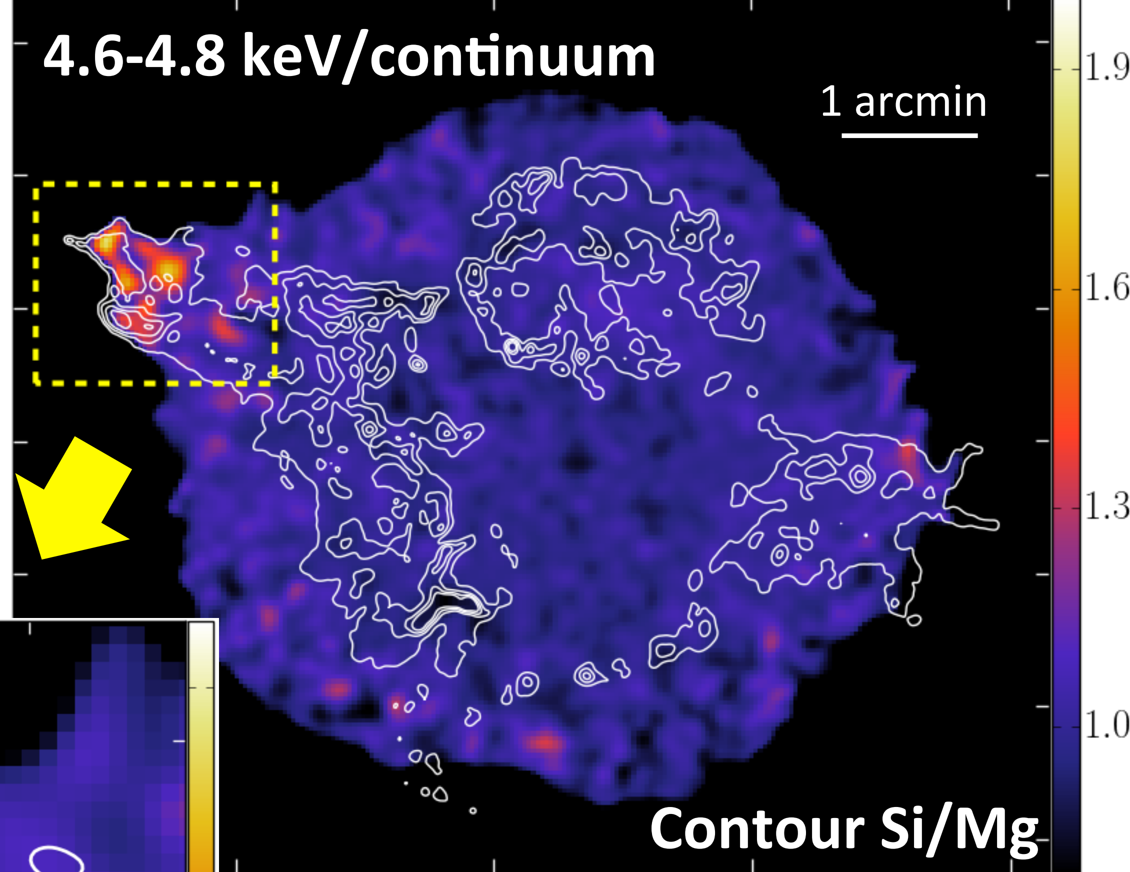
Comparison jet to non-jet area spectrum

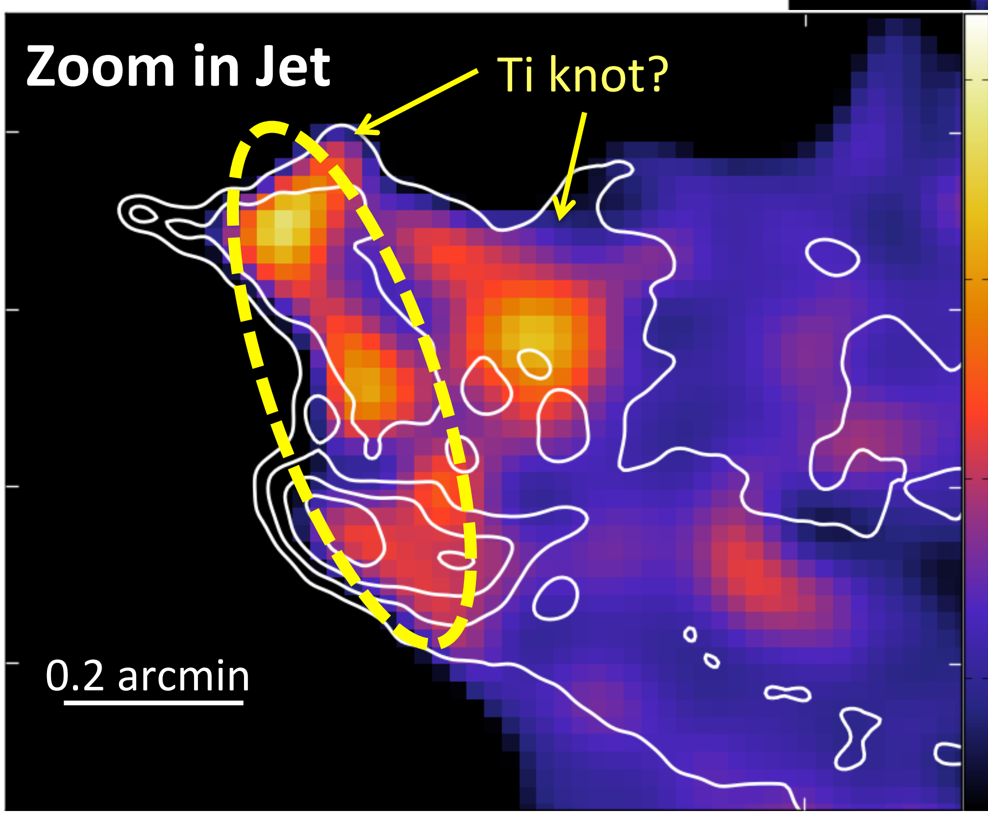


Spatial distribution: ~4.7 keV line

~4.7 keV line map shows

- Detected only tip of Jet
- different distribution from Si, Fe
- Knot-like distribution





- "knots" are seen in jet

→Spectral analysis for sub-regions.

- Ti−Kα is blended with Ca line

→We chose the elliptical region (yellow) where Ca line is weak and Ti line is strong.

Spectral Analysis 1: Ti line

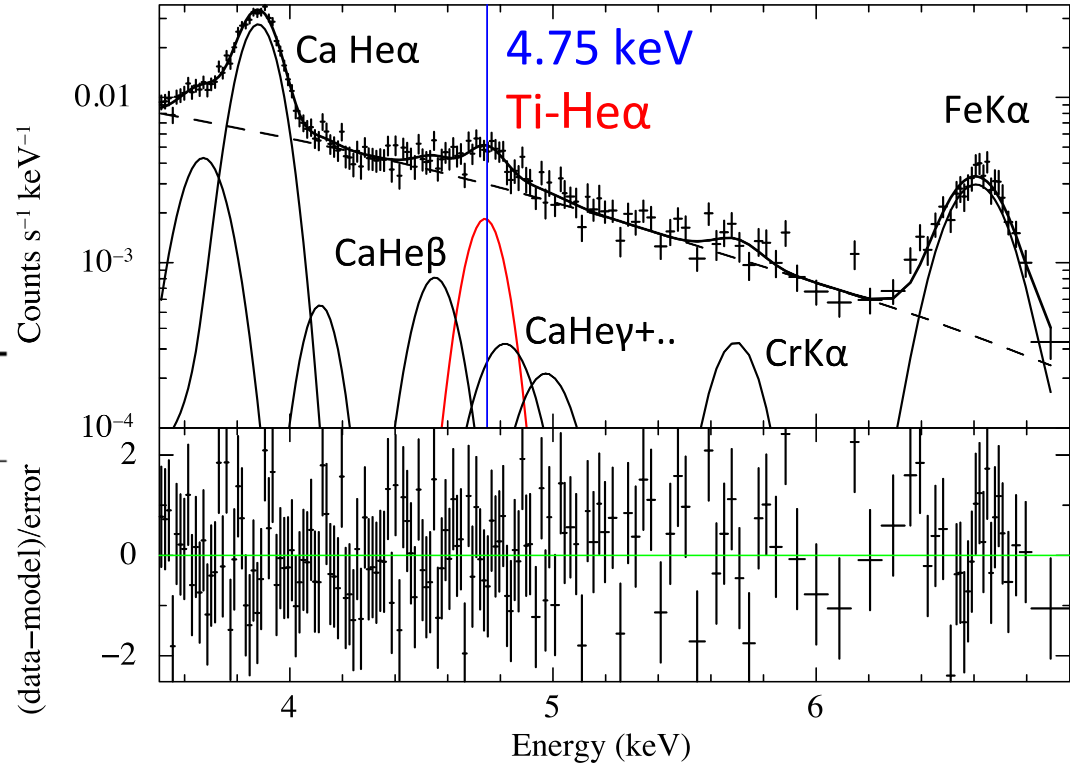
The feature in 4.4-5.0 keV:
a peak at 4.75 keV
→ This cannot be explained by broadening of Ca lines

Ion	E_{line} (keV)	transition	Emissivity (ph cm^3 s^{-1})
Ca XIX	4.584	n:3→1 l:1→0	5.874e-19
Ti XXI	4.708	n:2→1 s:1→0	4.280e-20
Ti XXI	4.756	n:2→1 l:1→0	1.184e-19
Ca XIX	4.822	n:4→1 l:1→0	1.875e-19
Ca XX	4.862	n:3→1 l:1→0	8.401e-20
Ca XX	4.864	n:3→1 l:1→0	1.670e-19

The range of 4.5-4.8 keV line list (kT_e=3 keV) [ATOMDB]

Plasma with electron temperature of 3 keV without Ti lines cannot explain this component.

Detected Ti–K line is statistically significant.



Jet spectrum model: BREMSS + gauss

Add a gaussian model as Ti K-line

χ^2/d.o.f=273.6/228 → 233.9/226

$\Delta\chi^2$~40 → 5.6 σ

Line energy $4.75_{-0.04}^{+0.02}$ keV

→ Ti Heα: 4.71-4.76 keV is consistent.

Discussion 1: Ti's isotope

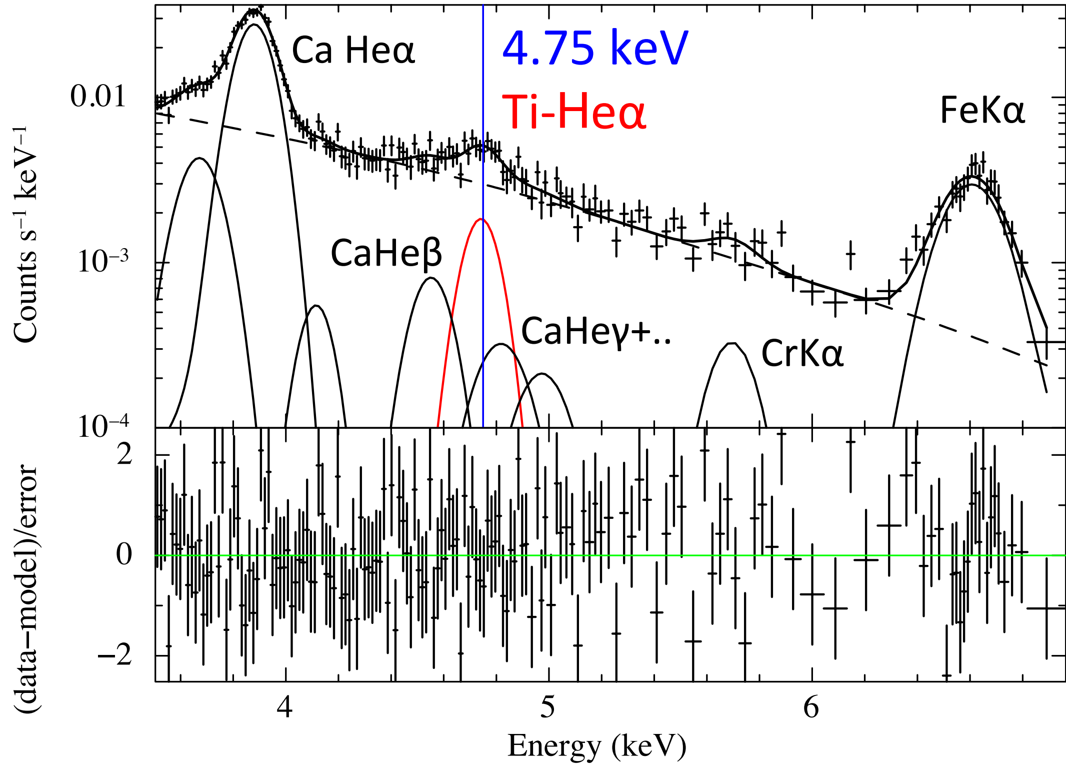
The analysis by using Non-equilibrium ionization model
(vvpshock model in XSPEC)

The amount of Ti in jet:
0.6-3×10^{-5} $M_\odot$

If this Ti is ^{44}Ti,
68/78 keV line flux from jet is
>4×10^{-5} photons/s/cm^2
at present.

→larger than observed with NuSTAR.
(**1.5 +/-0.3 ×10^{-5} ph/cm^2/s** for Cas A total)[Grefenstette+, 2014]

Ti in jet traced by Ti–K is not ^{44}Ti.



Jet spectrum model: BREMSS + gauss

Stable Ti mass in nucleosynthesis model
[Thielemann et al. 1995]
^{46}Ti:3×10^{-6} $M_\odot$, ^{47}Ti:5×10^{-6} $M_\odot$
^{48}Ti:1×10^{-4} $M_\odot$, ^{49}Ti:4×10^{-6} $M_\odot$

Detection of ^{48}Ti Kα line

Discussion 2: Comparison to ^{48}Ti mass

Assuming that Ti mass in jet has isotropic distribution in Cas A

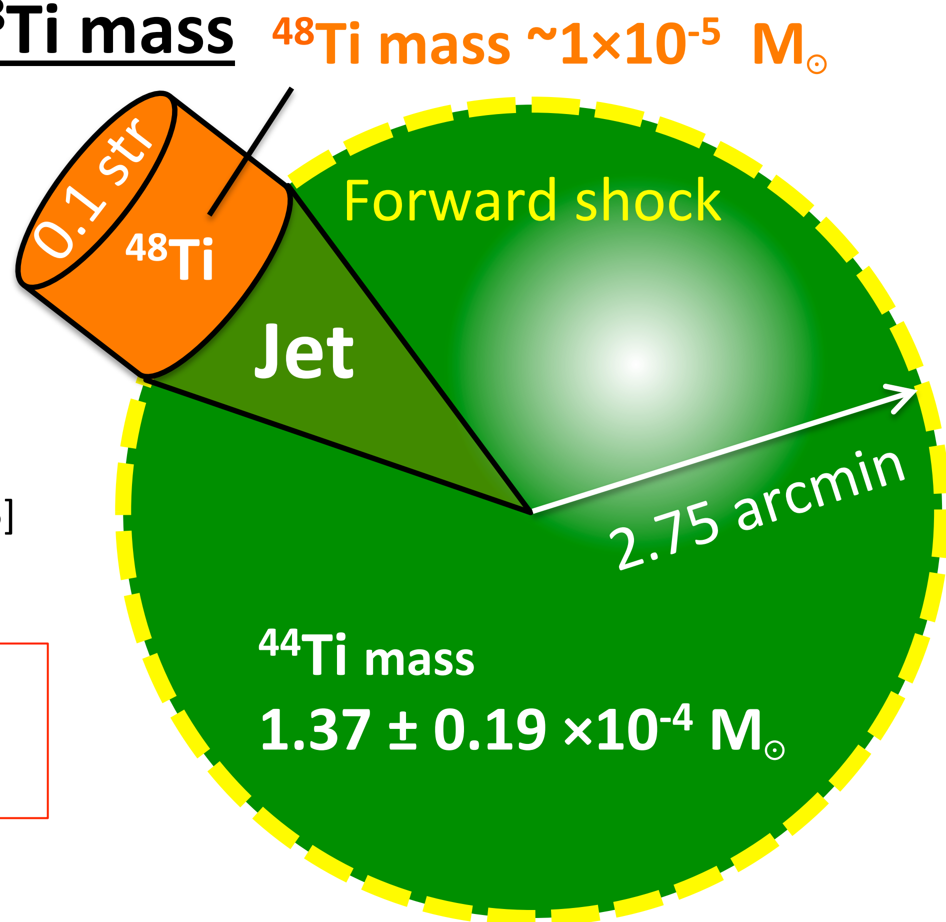
- ^{48}Ti mass in jet: ~1×10^{-5} $M_{\odot}$
- Solid angle Ω of jet: ~0.1 str

→ Total ^{48}Ti mass: ~1×10^{-3} $M_{\odot}$

Nucleosynthesis results [Thielemann+ 1995]

→ Synthesized ^{48}Ti: ~1×10^{-4} $M_{\odot}$

^{48}Ti mass in jet is enhanced in comparison with other regions



Cas A's configuration

Synthesized ^{44}Ti is also larger than spherical model.

Model: 0.2-2×10^{-4} $M_{\odot}$

Observation: 1.37 ± 0.19 ×10^{-4} $M_{\odot}$

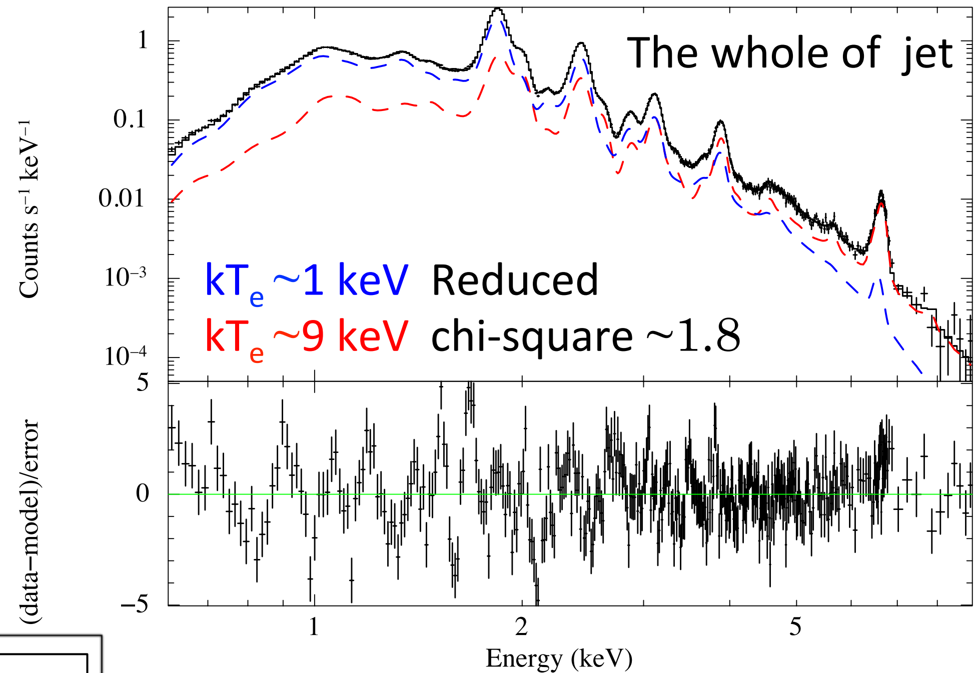
→ The effect of aspherical explosion?

How about abundances of other elements?

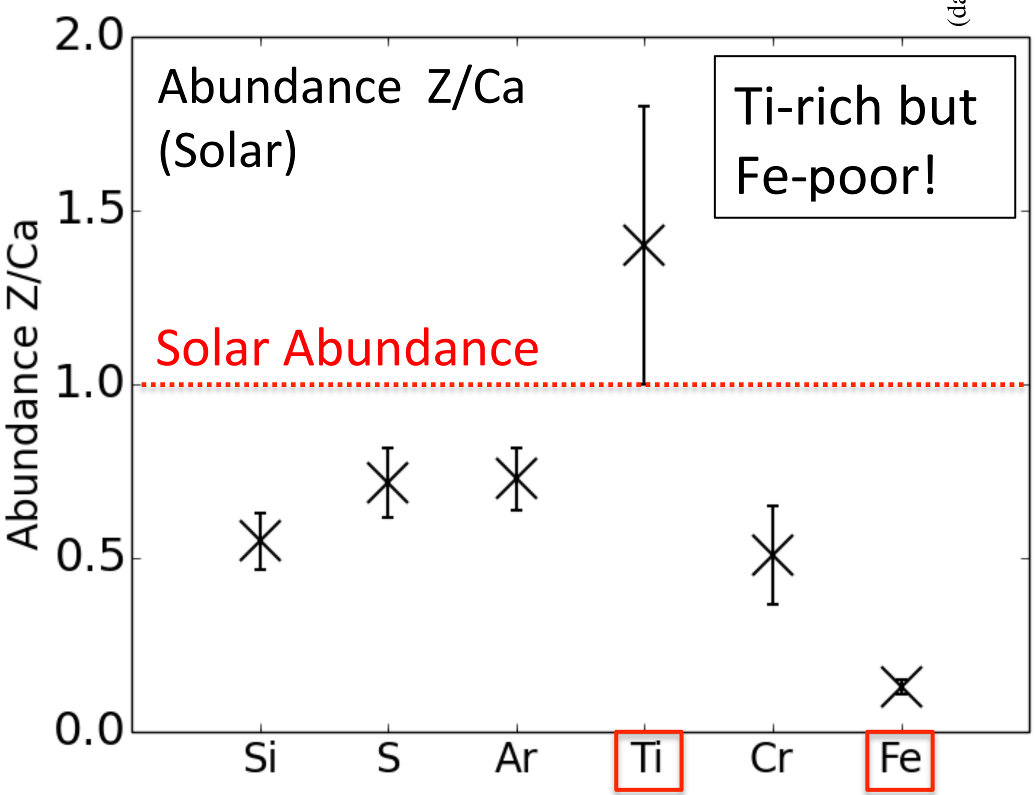
Spectral Analysis 2: Jet Abundance

Using two component Non-equilibrium ionization model, and estimate abundance pattern in jet.

Plot the elements abundance to Ca.
(the unit is solar abundance.)



Jet Spectrum with result of fitting by using NEI model (example)



Jet composed of incomplete Si–burning "ash"?

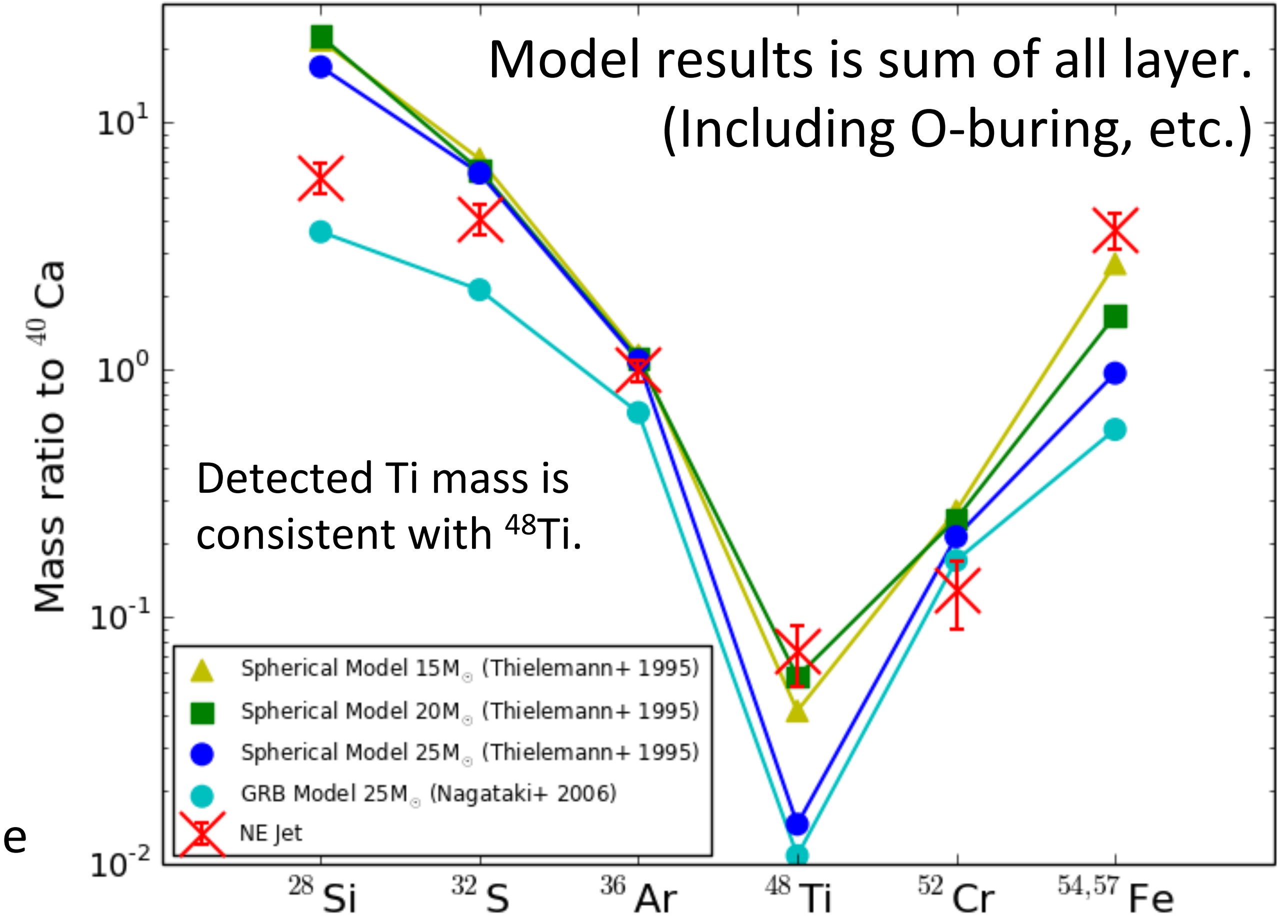
Incomplete Si-burning
(5×10^9 K > T > 4×10^9 K)
→Rich intermediate mass element. (Ar, Ca, Ti...)

Discussion 3: Jet Abundance

We chose isotope which is mainly synthesized by incomplete Si-burning for comparison:
^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{48}Ti, ^{52}Cr, ^{54}Fe, ^{57}Fe
(including daughter nuclei)

We used 3 spherical nucleosynthesis model whose difference is projenitor mass and GRB model.

Calculate mass ratio to ^{40}Ca.



Comparison between observation and model.

Jet abundance is consistent with incomplete Si-burning elements (spherical model is used for now).

SUMMARY

- We have discovered Ti-Kα feature at 4.7 keV in the NE jet of Cassiopeia A.
- Estimated Ti mass is $0.6 \sim 3 \times 10^{-5} M_\odot$ in Cas A jet.
- If this titanium is ^{44}Ti, it is inconsistent with 68 keV observation. We conclude that Ti-Ka is mainly produced by stable Ti.
- Ti in jet traced by Ti–K is ^{48}Ti from the viewpoint of nucleosynthesis.
- The analysis by using Non-equilibrium ionization model lead jet abundance, and it suggests jet is composed of incomplete Si-burning elements.