High-entropy ejecta plumes in Cassiopeia A from neutrino-driven explosion

Sato et al. (2021a), Nature; Sato et al. (2021b), to be submitted

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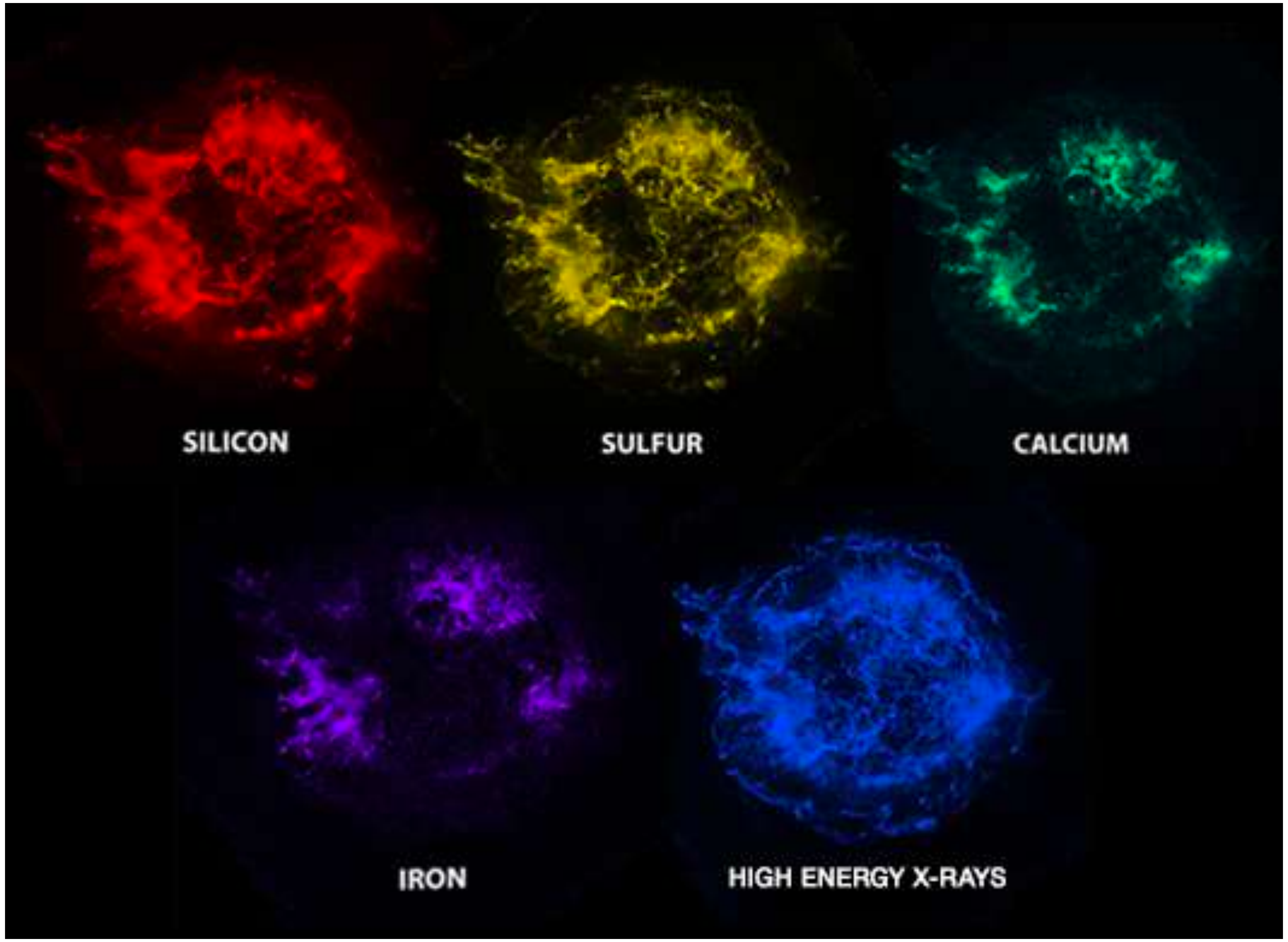
X-ray observations of supernova remnants

X-ray observations allow us to investigate the distribution and composition of elements at the same time.

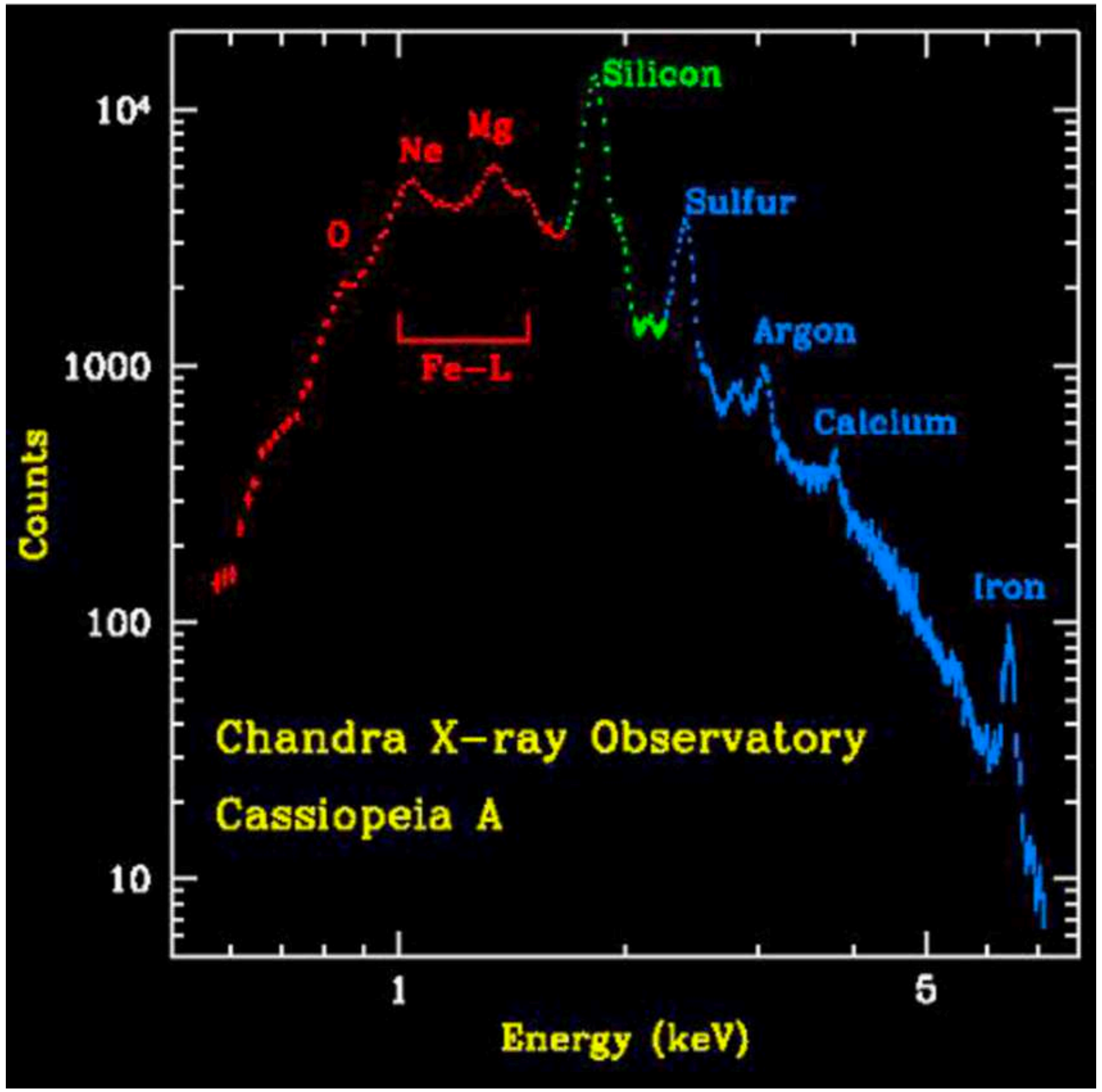
X-ray imaging

(Distribution of each element)

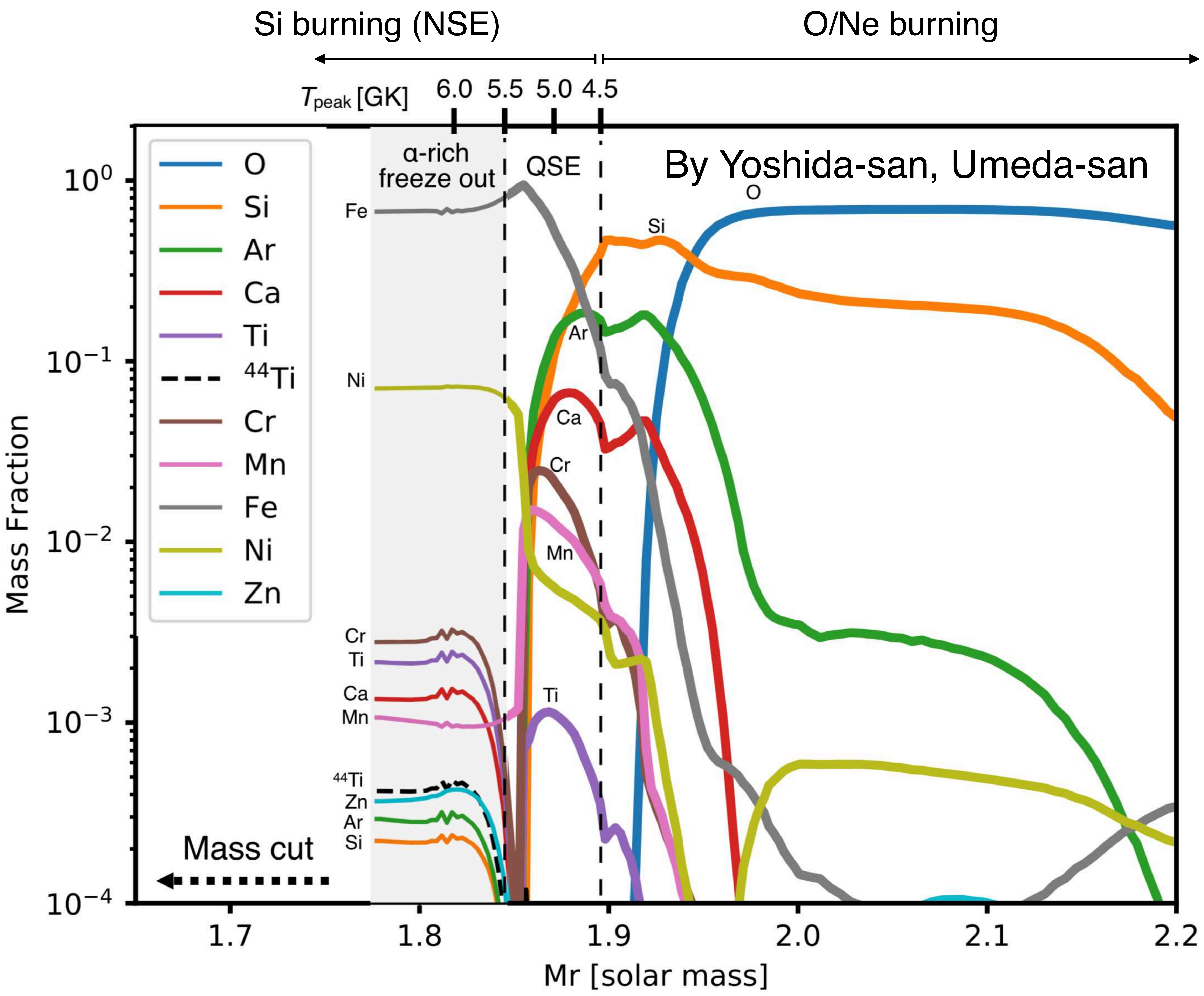


X-ray spectroscopy

(Abundance, kT, ionization state…)



Nucleosynthesis of core-collapse supernovae



In the Si burning layer (innermost region),

only a few physical parameters determine the elemental composition (alpha-rich freezeout)

$$T_{\mathrm{peak}},\ \rho_{\mathrm{peak}},\ Y_e$$

+ thermal evolution

If we could measure the abundance in that layer, we could estimate the physical parameters around the central region of exploding stars

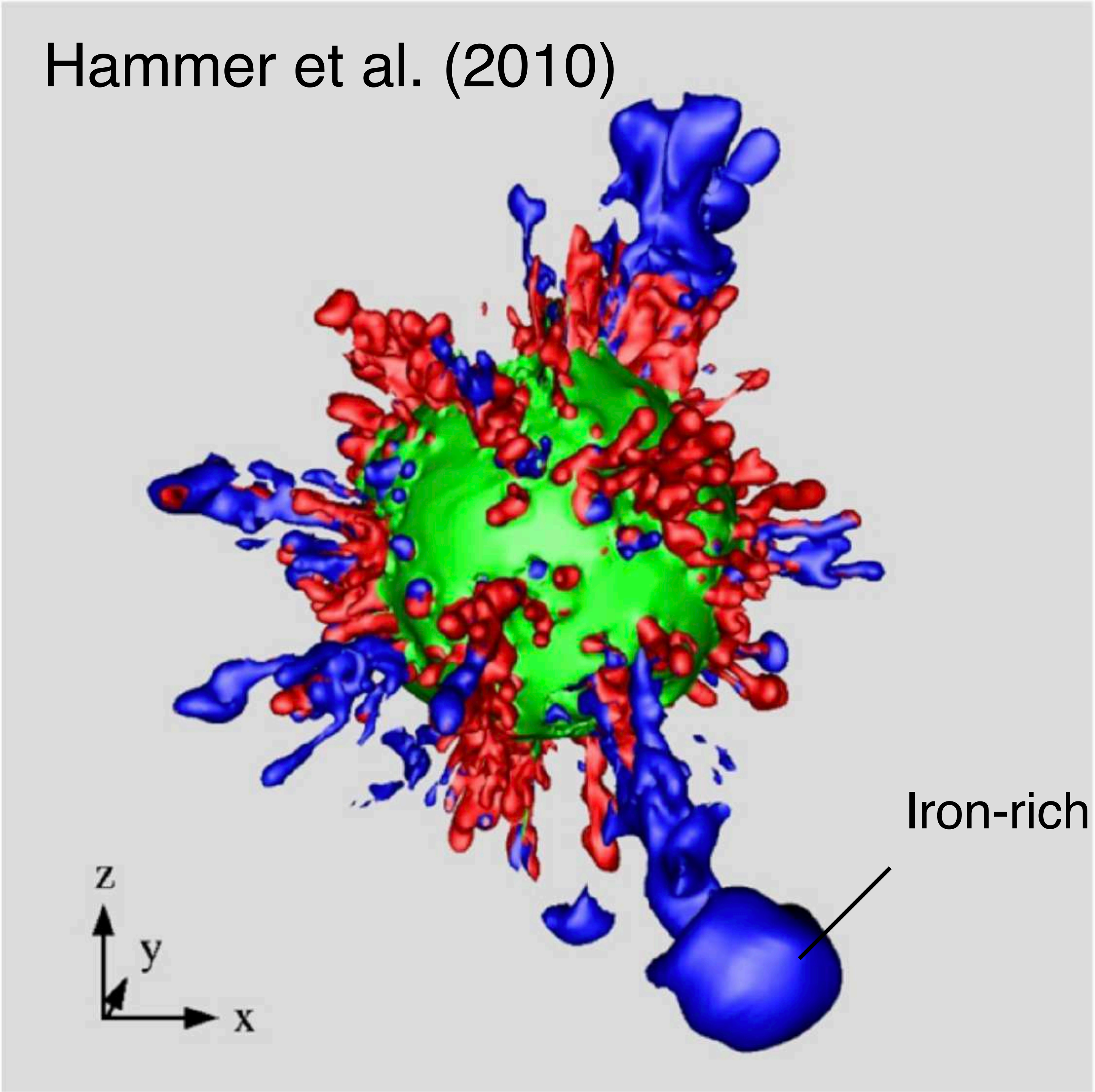
(Until now, ^{44}Ti was only one tool)

Can we observe other elements and obtain more detail information of the innermost region?

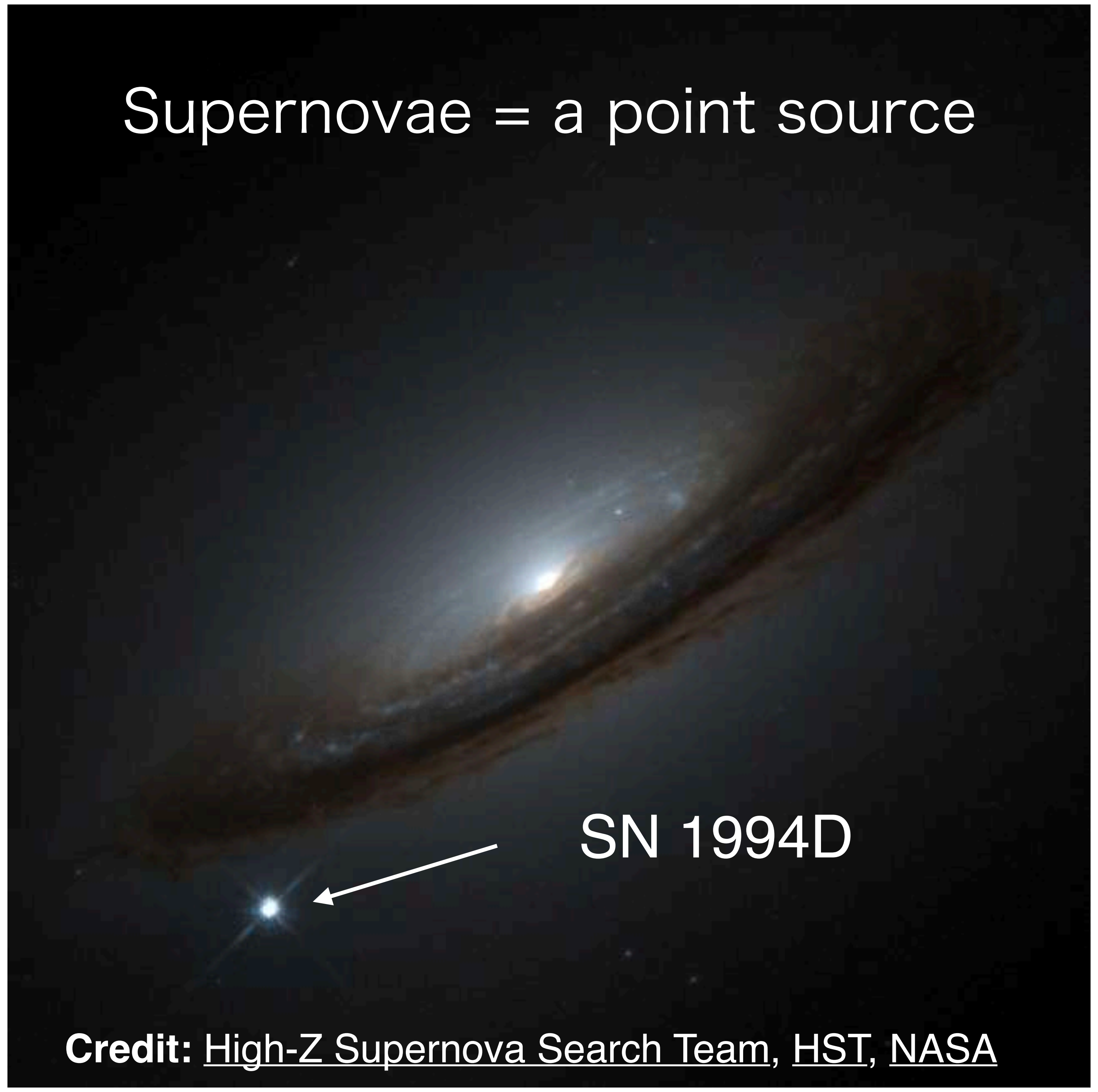
Asymmetric structures and elements produced by neutrino heating

Neutrino heating makes convective bubbles, and then we could expect

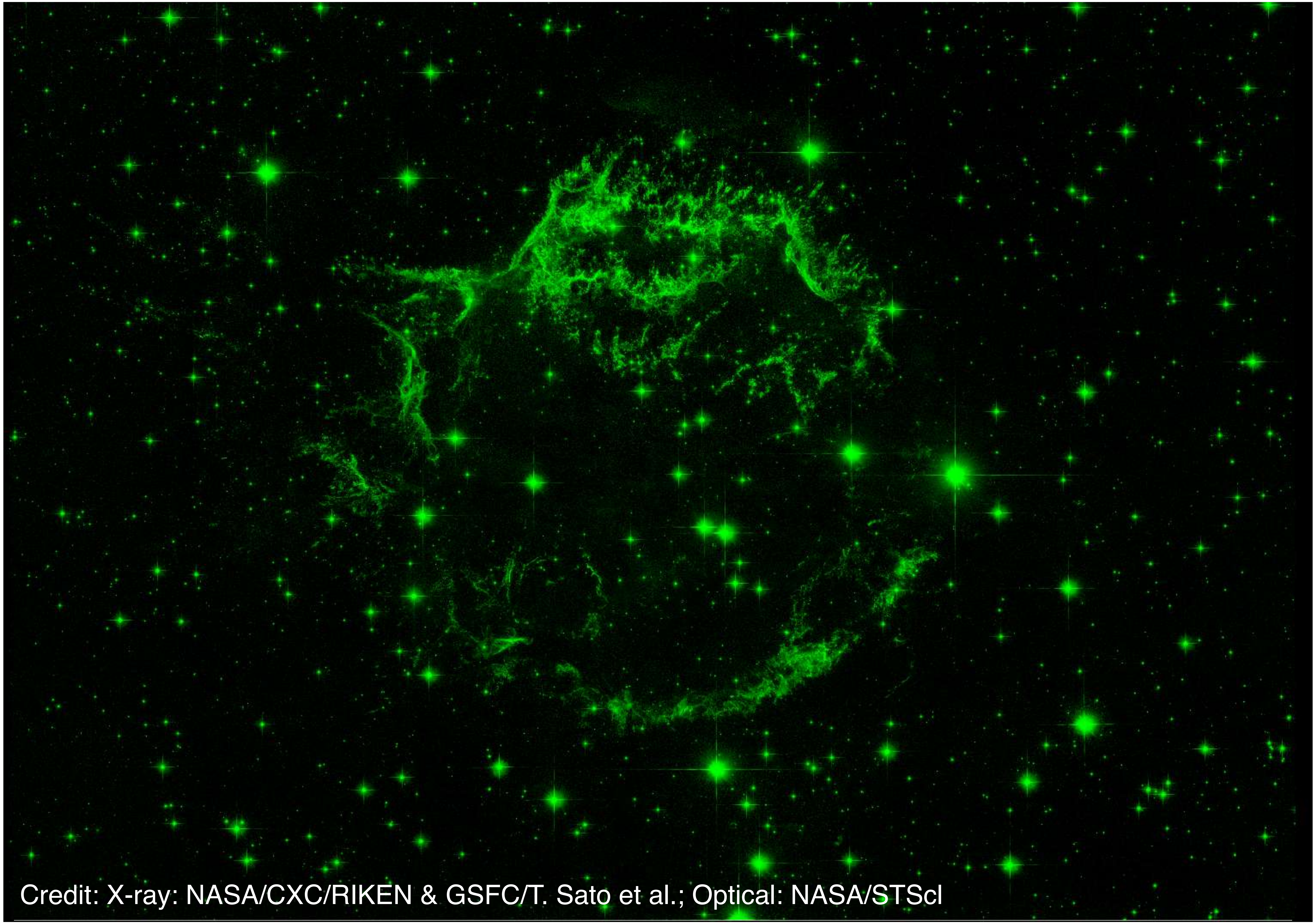
High-entropy (high temperature+low density) + **Fe-rich** plumes

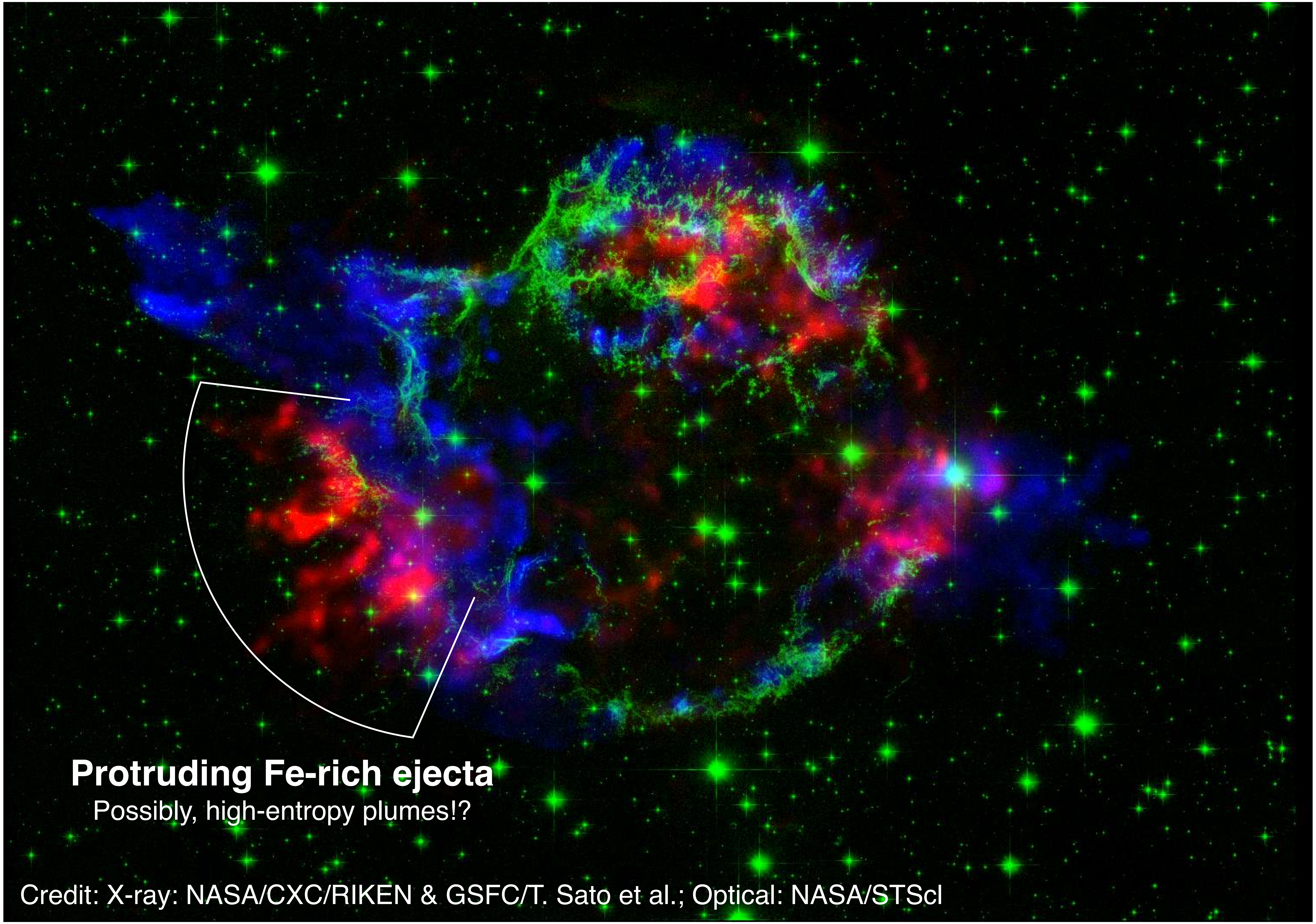


However…



We found such Fe-rich ejecta and investigated its elemental composition


Credit: X-ray: NASA/CXC/RIKEN & GSFC/T. Sato et al.; Optical: NASA/STScI

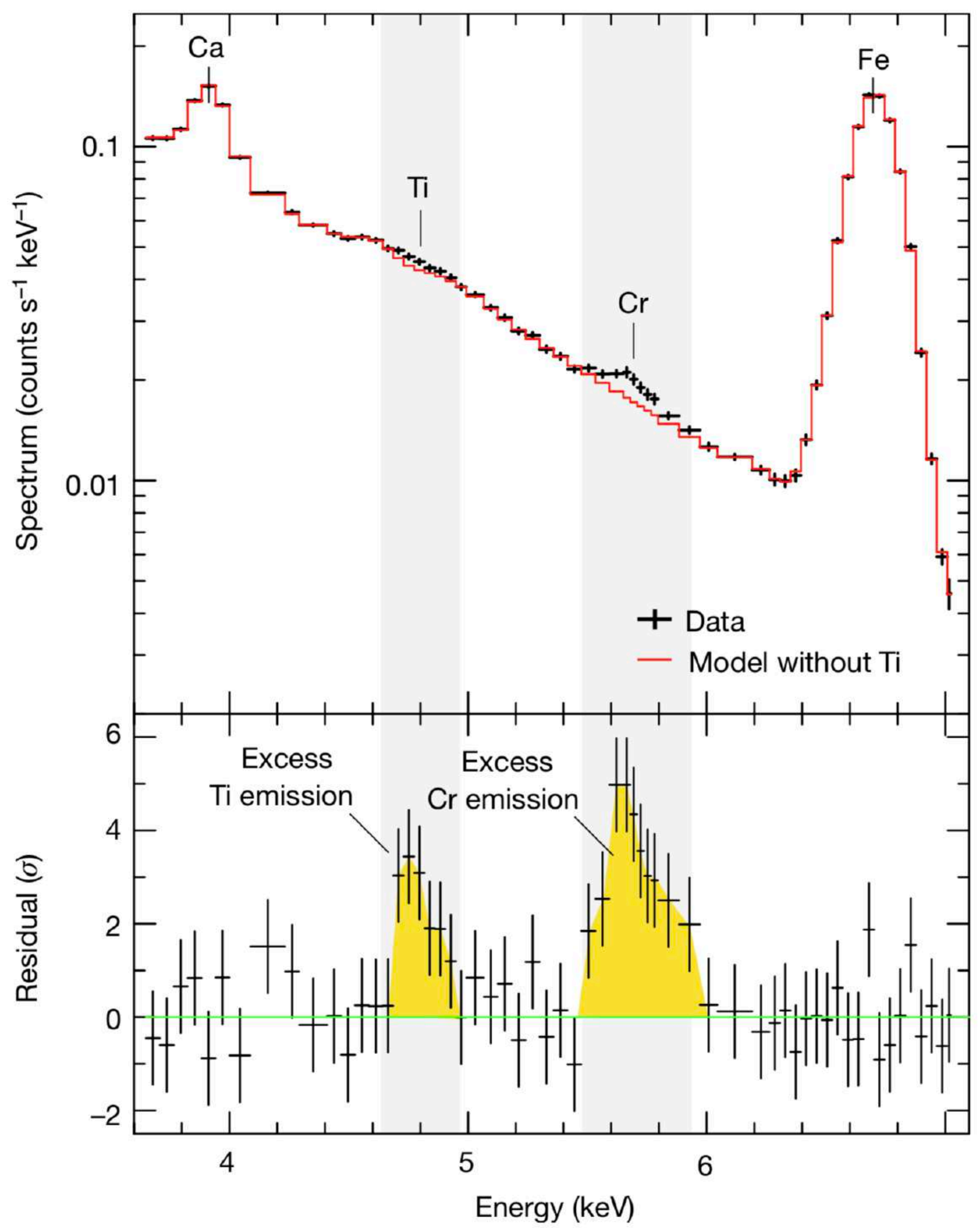


Protruding Fe-rich ejecta
Possibly, high-entropy plumes!?
Credit: X-ray: NASA/CXC/RIKEN & GSFC/T. Sato et al.; Optical: NASA/STScI

Observation and Comparison with Theory

Ti and Cr produced in high-entropy region have been found for the first time!

Discovery of Ti, Cr in X-ray spectrum



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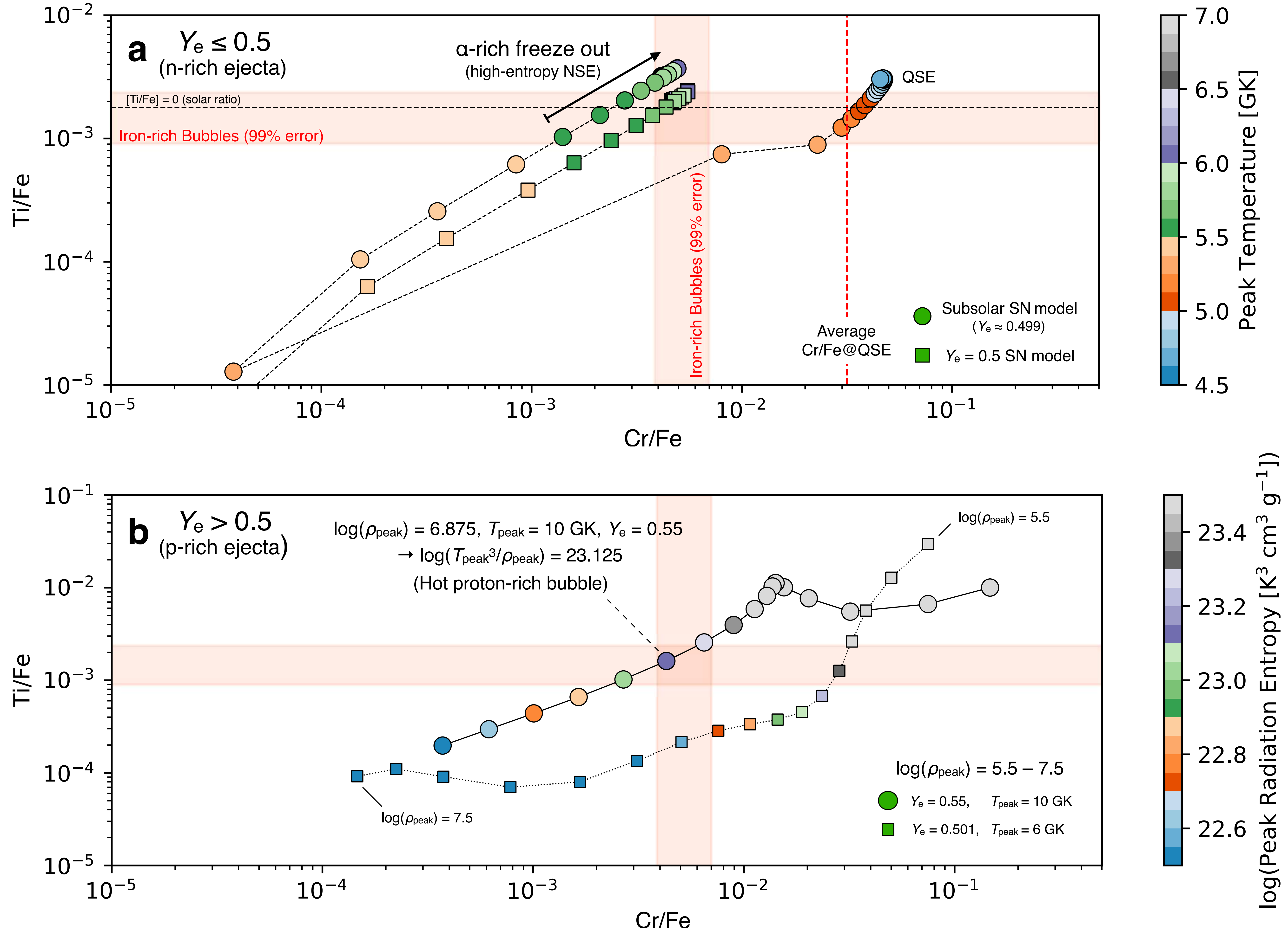


The observation indicates that the Fe-rich ejecta could be the high-entropy ejecta plumes from the neutrino convection

(Note: we cannot completely dismissed the production at the neutron-rich region)

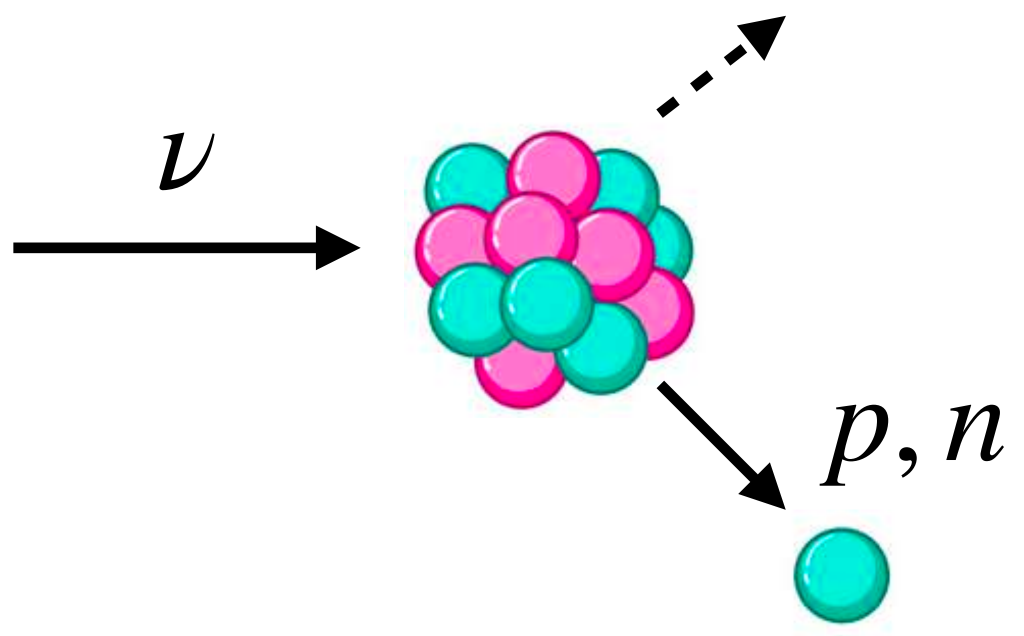
On-going project: Observational verification of neutrino process

Neutrino effects in SNe are unclear, both observationally and theoretically

Can we discuss the effects using X-ray observations?

Neutrino-matter interactions
→ *ν*-process (neutrino nucleosynthesis)

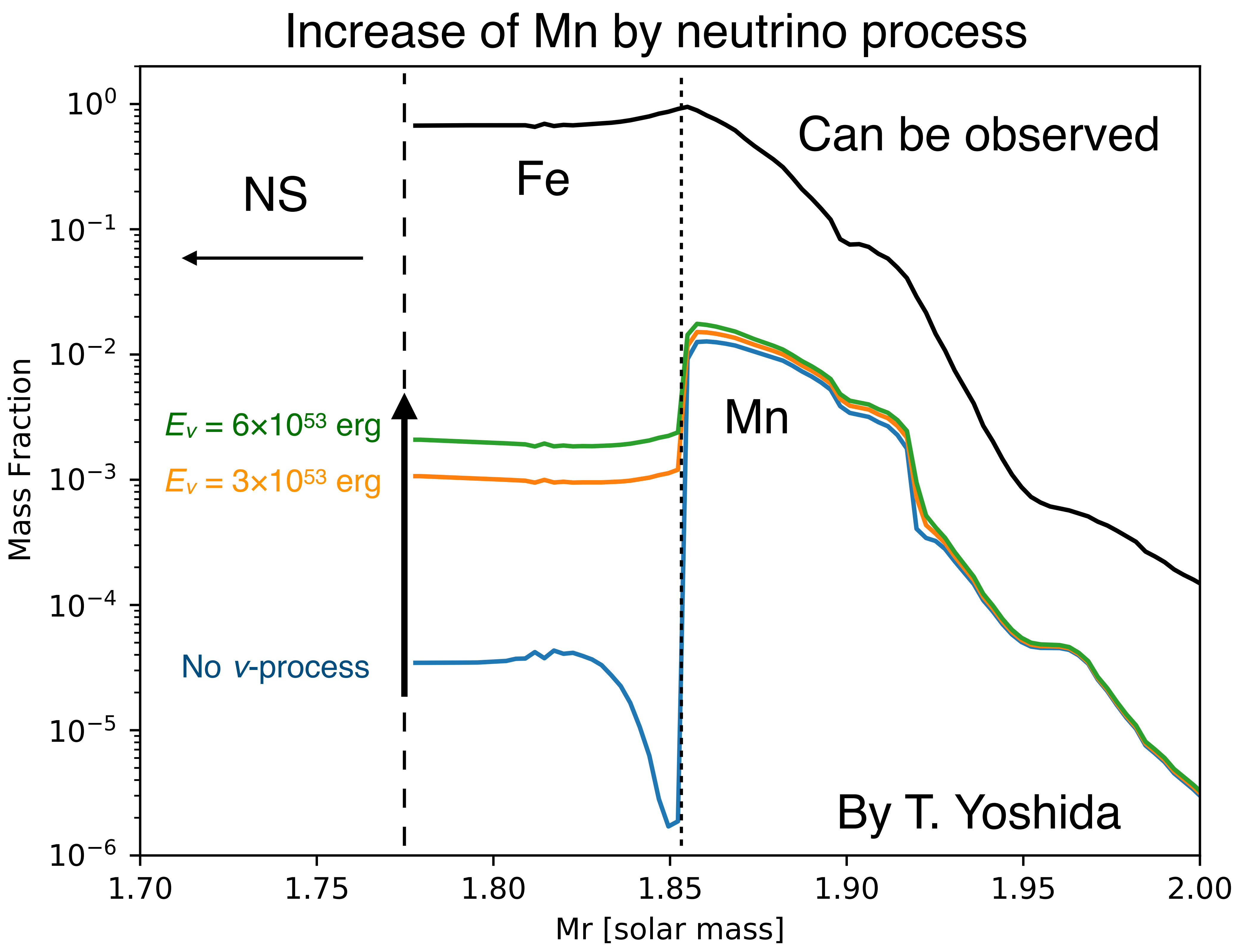
ν-process : spallation by neutrinos



Significant reaction

$$^{56}\mathrm{Ni}(\nu, \nu' p)^{55}\mathrm{Co}$$

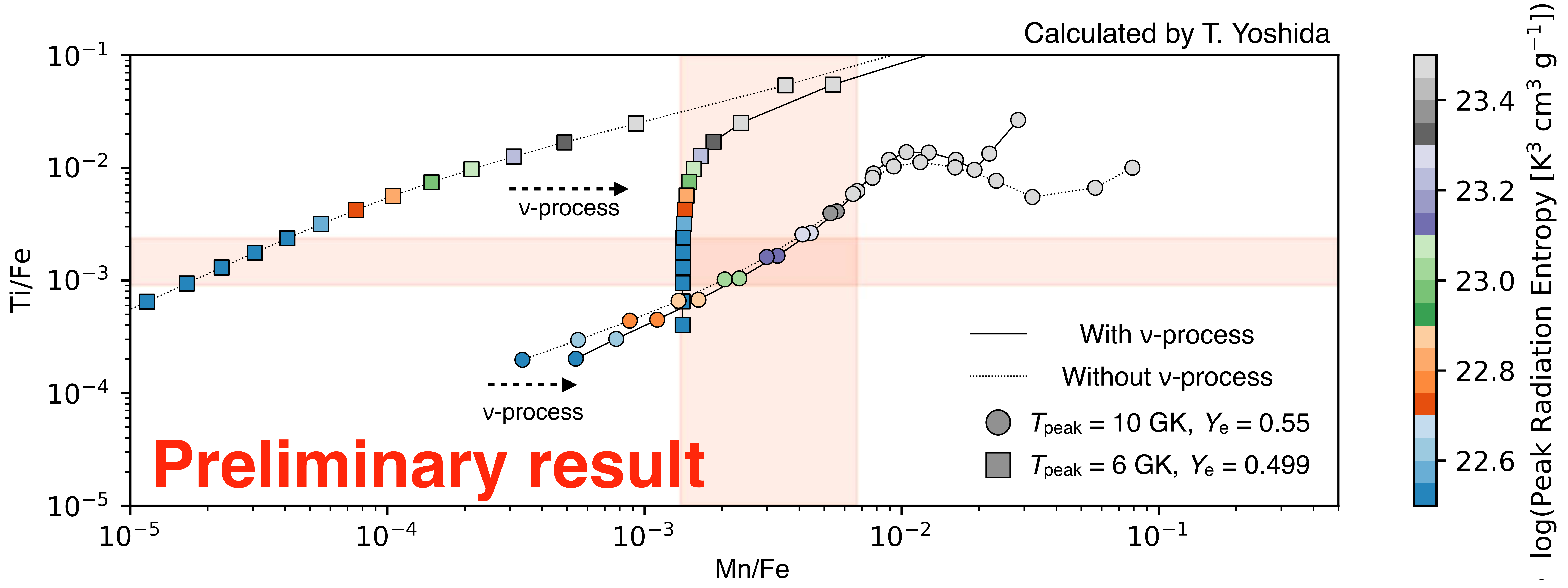
$$^{55}\mathrm{Co} \rightarrow {}^{55}\mathrm{Fe} \rightarrow {}^{55}\mathrm{Mn}$$



X-ray observations of supernova remnants allow us to discuss neutrino-matter interactions for the first time（Sato et al., to be submitted）

On-going project: Observational verification of neutrino process

We can not explain the observation without the neutrino-matter interactions



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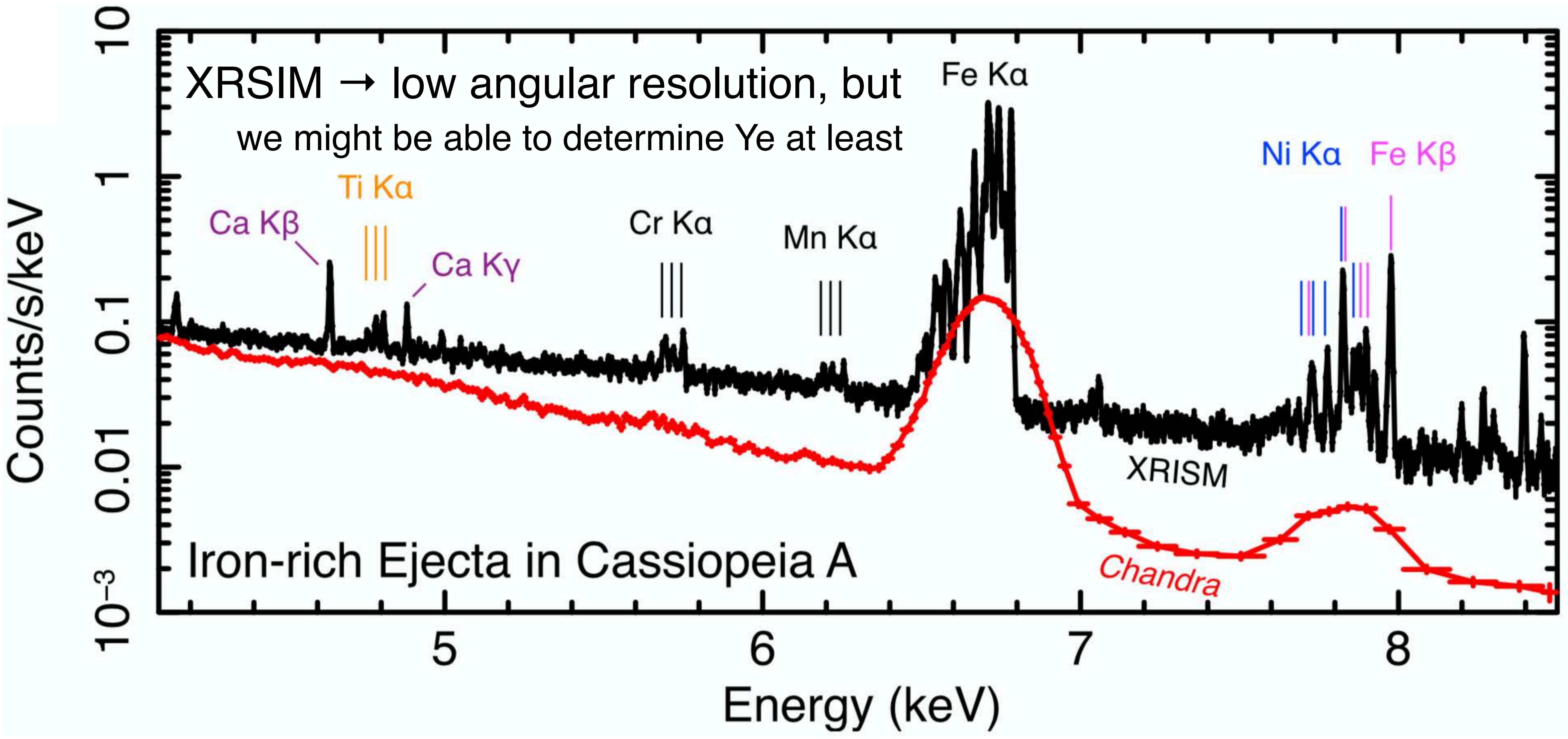
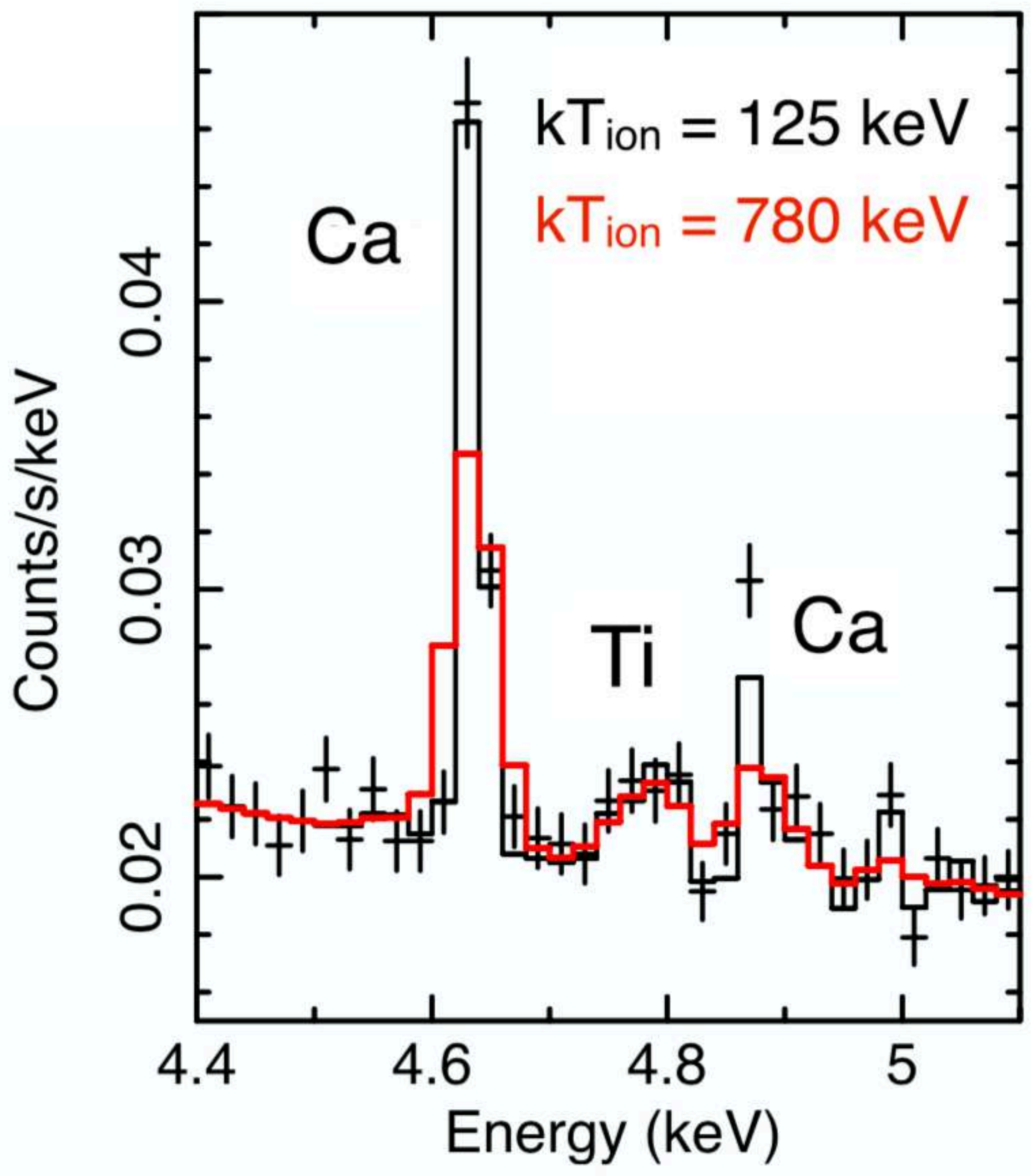
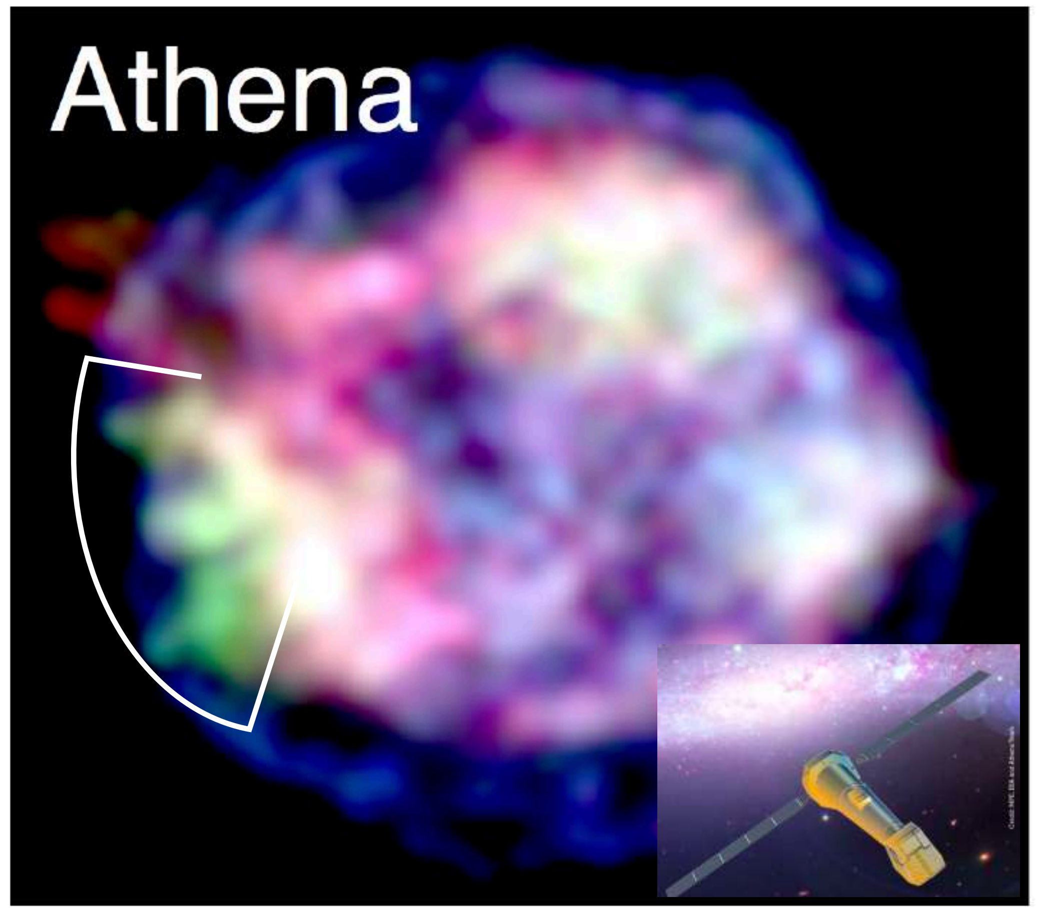
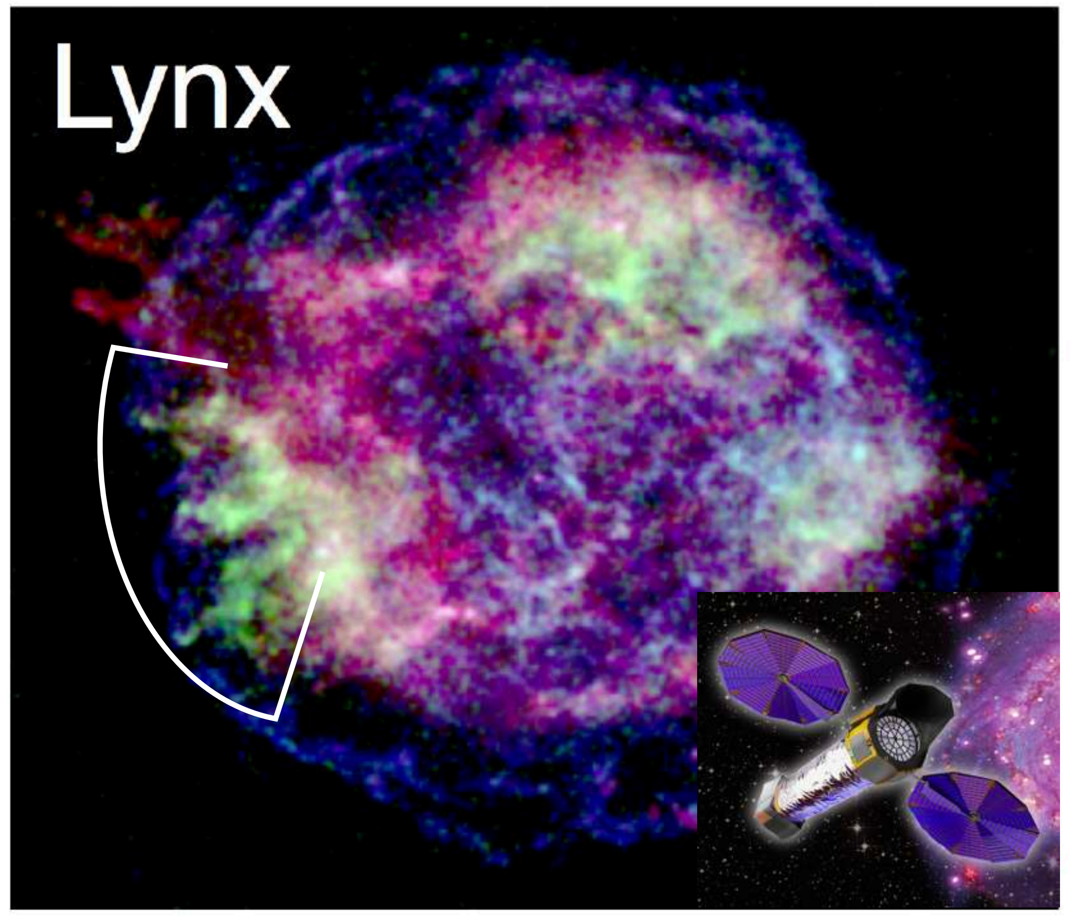
Future works: X-ray calorimeter missions from 2020's to 2030's









L. Lopez et al. (Astro2020 Science White Paper)

Perspectives for 2030's

1. Entropy/Ye distributions
2. odd-Z elements (ν-process, proton-rich ejecta?)
3. More detailed neutrino physics?

Summary

A X-ray observations of supernova remnants allow us to measure the distribution and composition of elements at the same time.
This is a useful method to probe the explosion mechanisms of SNe.

The discovery of the structure from the deepest part of the supernova explosion allows us to discuss in detail the activity of the explosion center, including the influence of neutrinos.

In the future, the combination of observational research using future X-ray missions and theoretical research using supercomputers will bring us much closer to understanding the mechanism of supernova explosions.