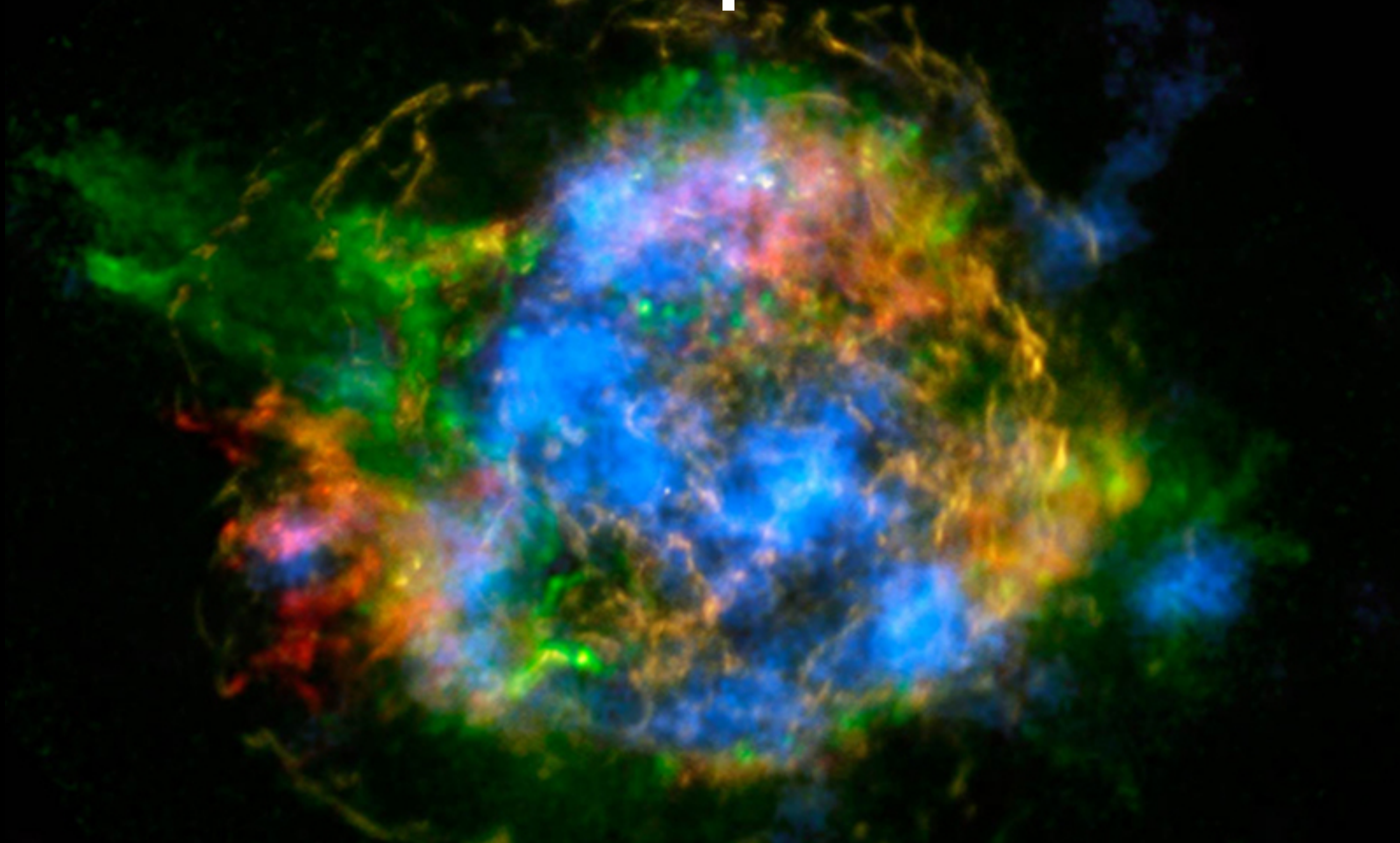
Probing the stellar nucleosynthesis and explosion with X-ray and gamma-ray observations of supernova remnants



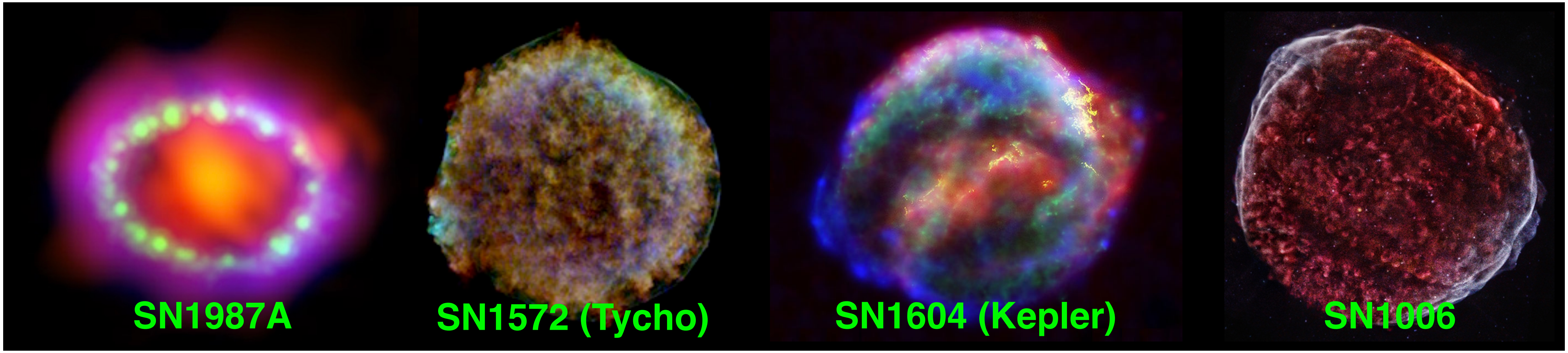
Hiroya Yamaguchi

(ISAS/JAXA, Univ of Tokyo)

Talk plan

- Physics of supernova remnants (SNRs)
    - Why X-ray and gamma-ray observations are crucial
    - What we can learn from SNRs
- Nucleosynthesis and related physics in the **core** of both core-collapse and thermonuclear (Type Ia) supernovae that can be probed by SNR observations

Supernova remnants

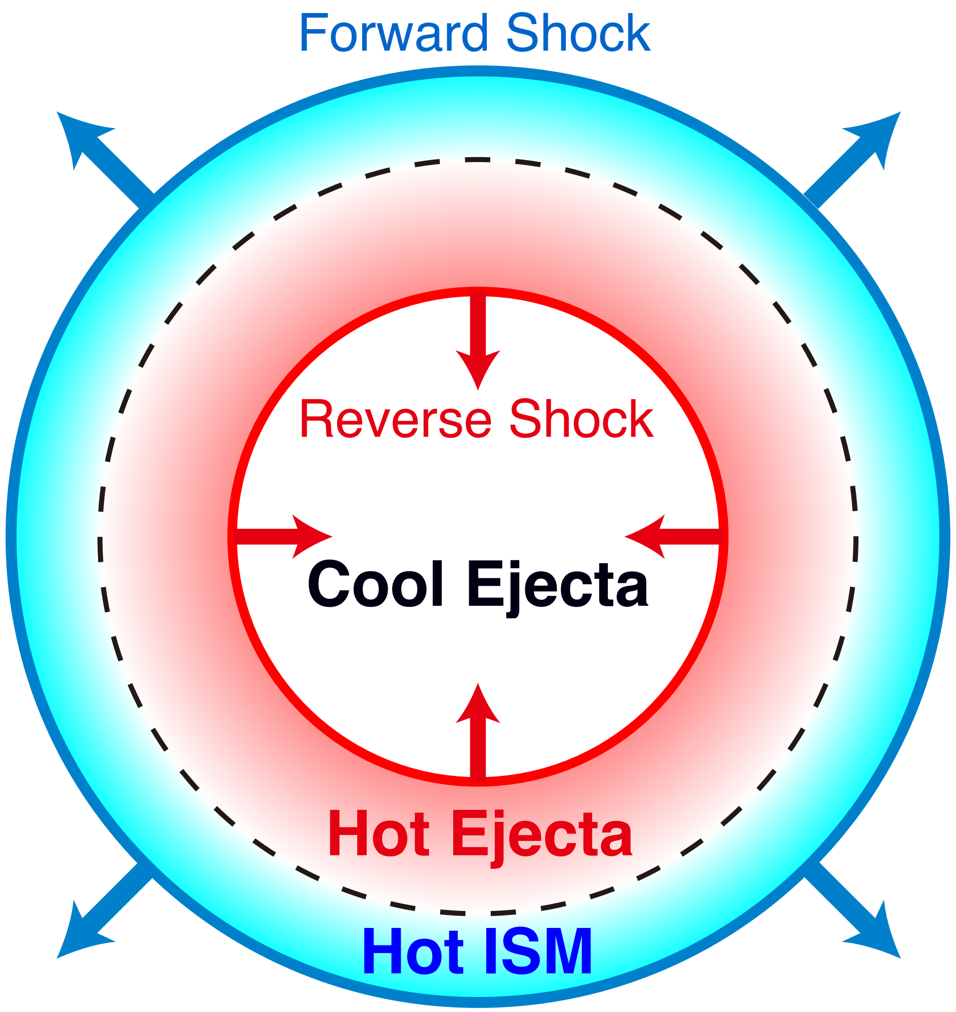


Spatially extended objects that offer up-close view of stellar explosions

cf. SNe are found more frequently (each day)
but far too distant to resolve

Chemical composition and distribution (i.e., origin of matter) can be investigated in detail.

Supernova remnants



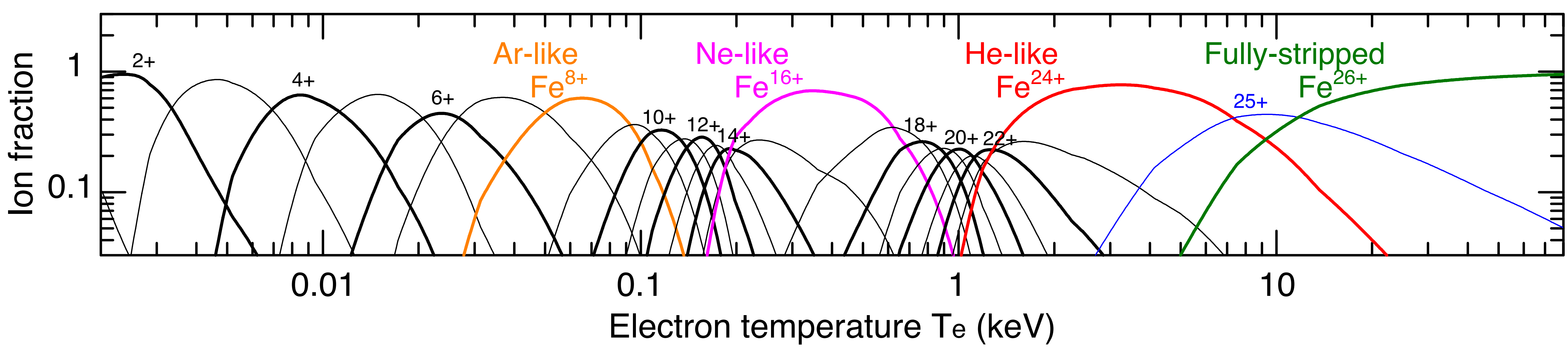
$V_s \approx 3000$ km/s

$k_B T = 3/16 \cdot \mu\, m_p\, V_s$

≈ 10 keV

➔ X-ray emitting

➔ Atoms are highly ionized

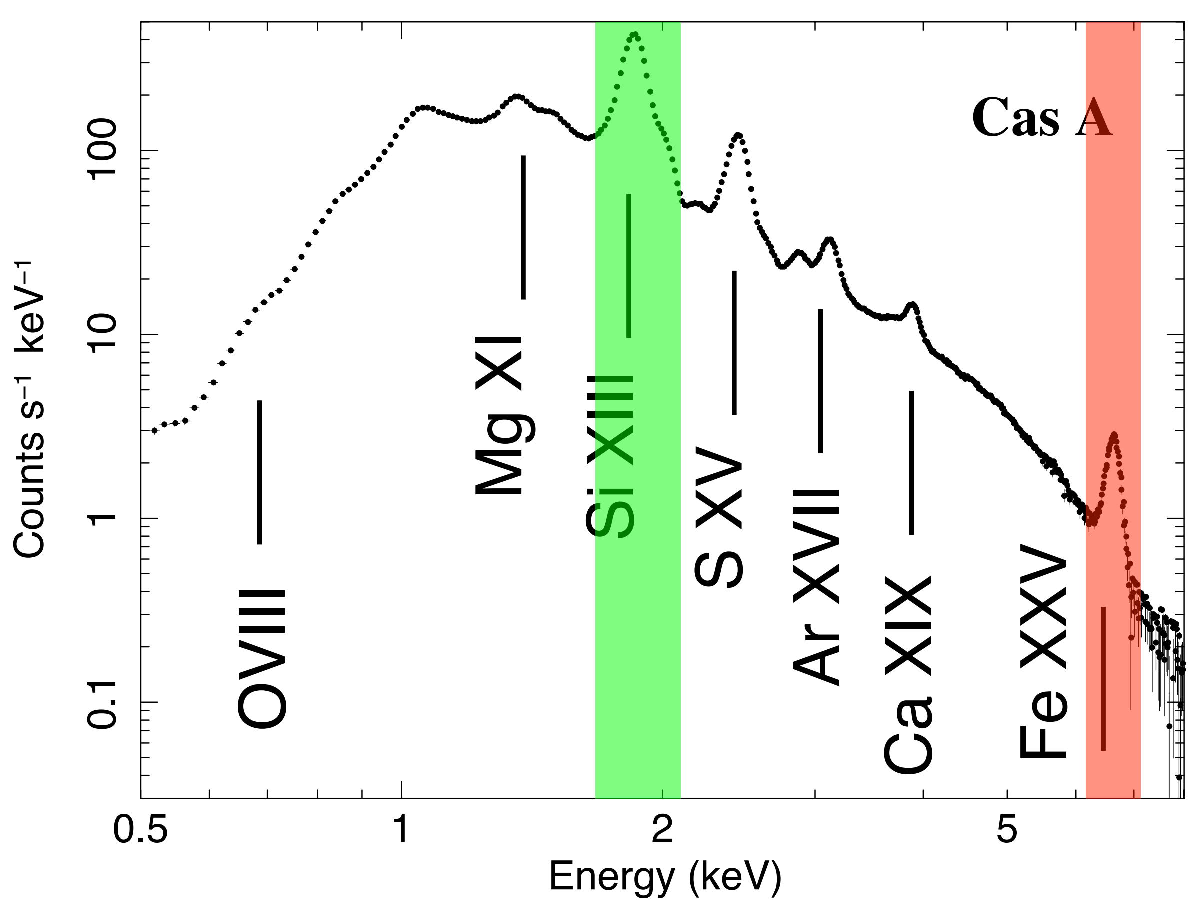


X-ray/γ-ray spectra

Atomic transition

Fe^{24+} + e- → Fe^{24+*} + e-

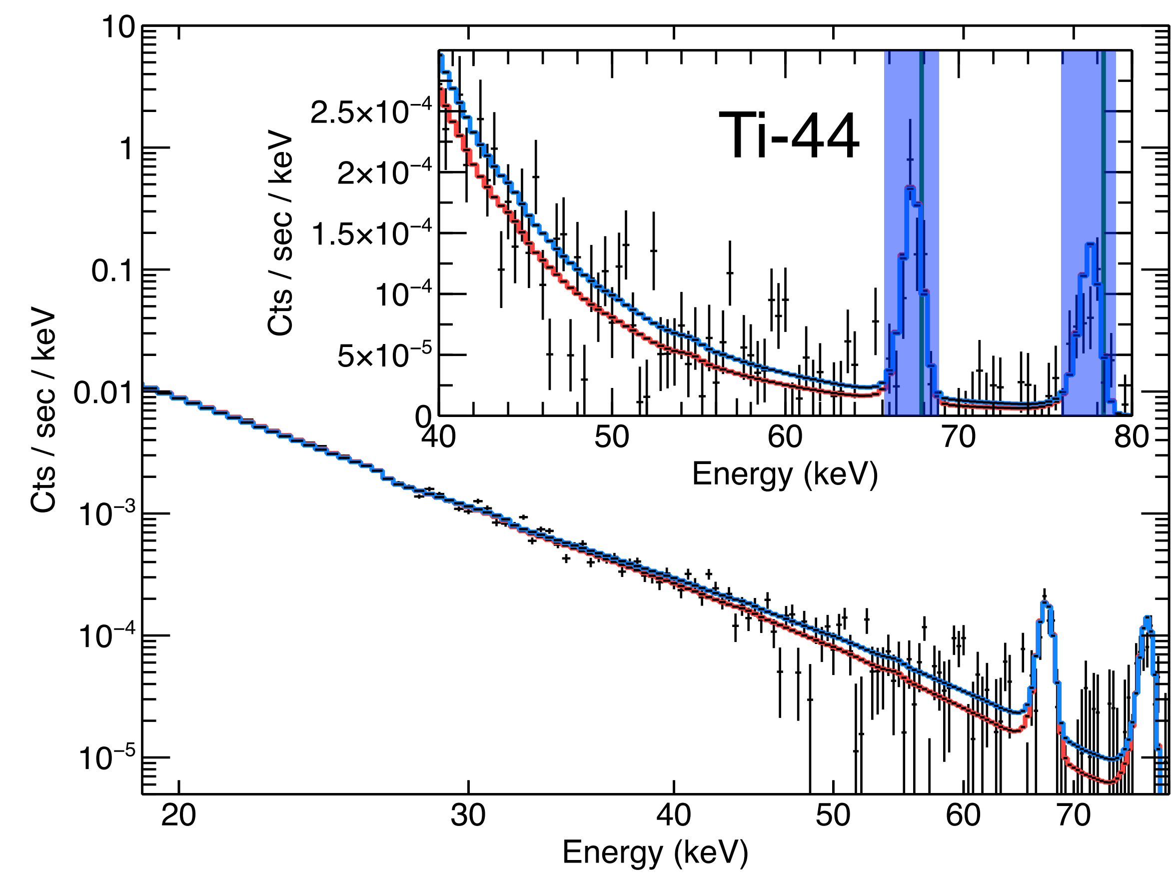
Fe^{24+*} → Fe^{24+} + $h\nu$



Radioactive decay

^{44}Ti → $^{44}Sc^*$ + ν_e

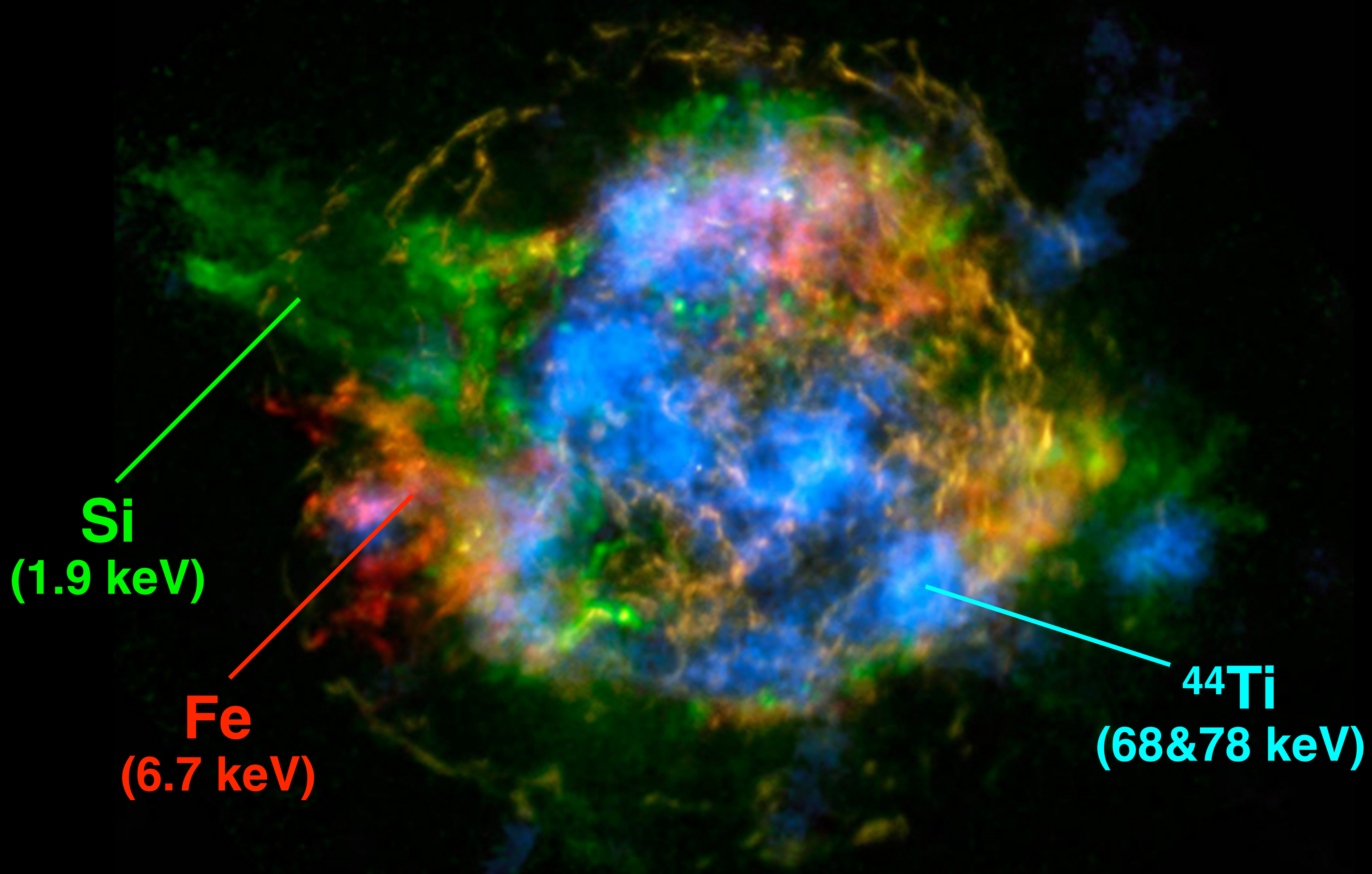
$^{44}Sc^*$ → ^{44}Sc + γ



Bright in X-rays	**Pros**	Real distribution tracable
Shock heating needed	**Cons**	Faint, Age dependent

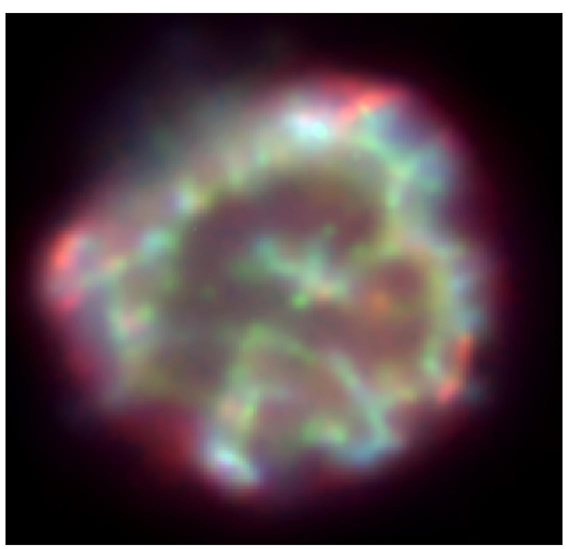
Narrow band image

Chandra and NuSTAR view of Cassiopeia A



SN type discrimination

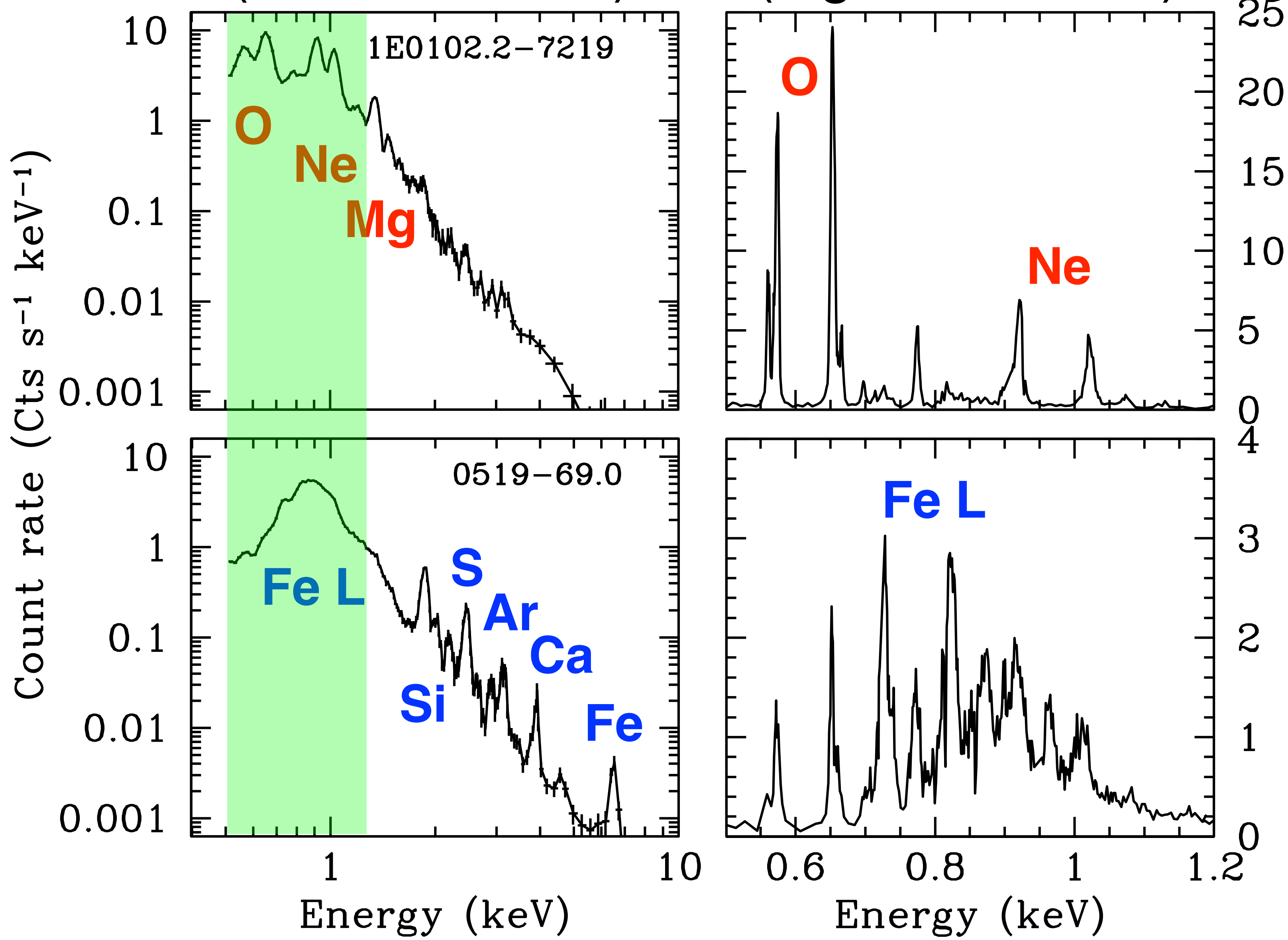
SNR 0102-72.3



SNR 0519-69.0

CCD
(low resolution)

Grating
(high resolution)



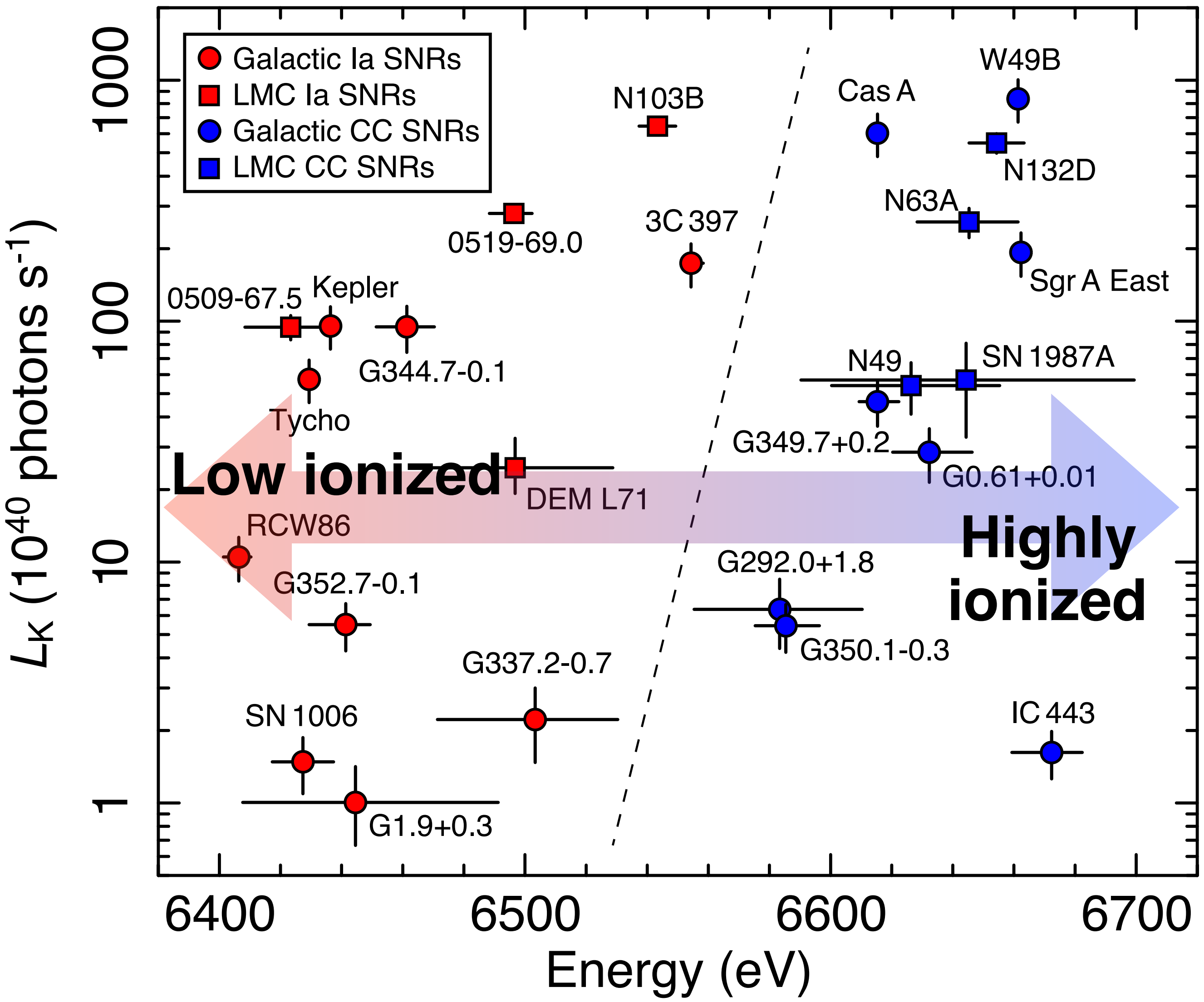
Core-collapse

Type Ia
(thermonuclear)

Vink 2012

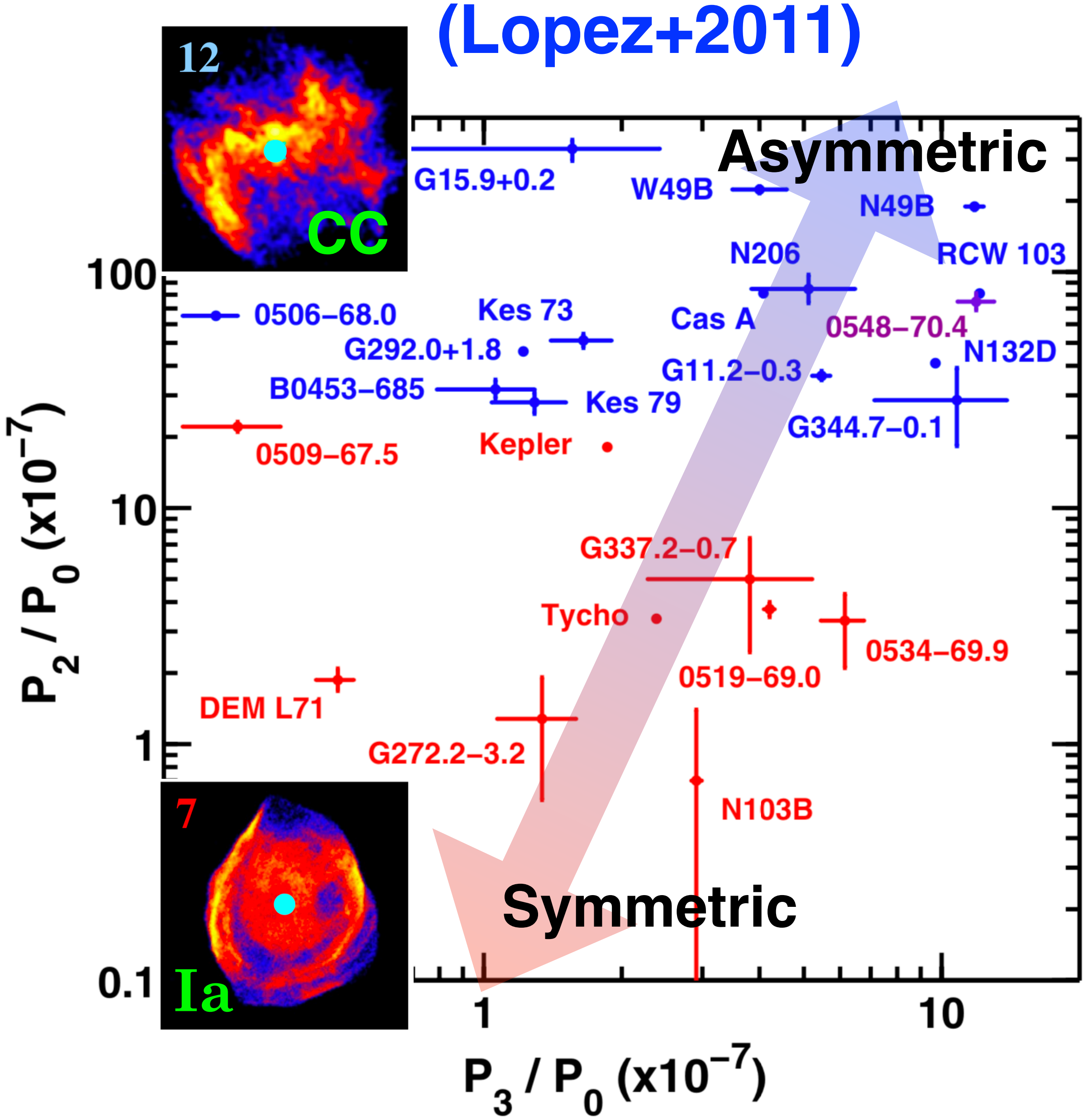
SN type discrimination

Fe ejecta ionization state
(Yamaguchi+2014)



Massive stars explode in denser environment

X-ray Morphology
(Lopez+2011)



Massive stars explode more asymmetrically

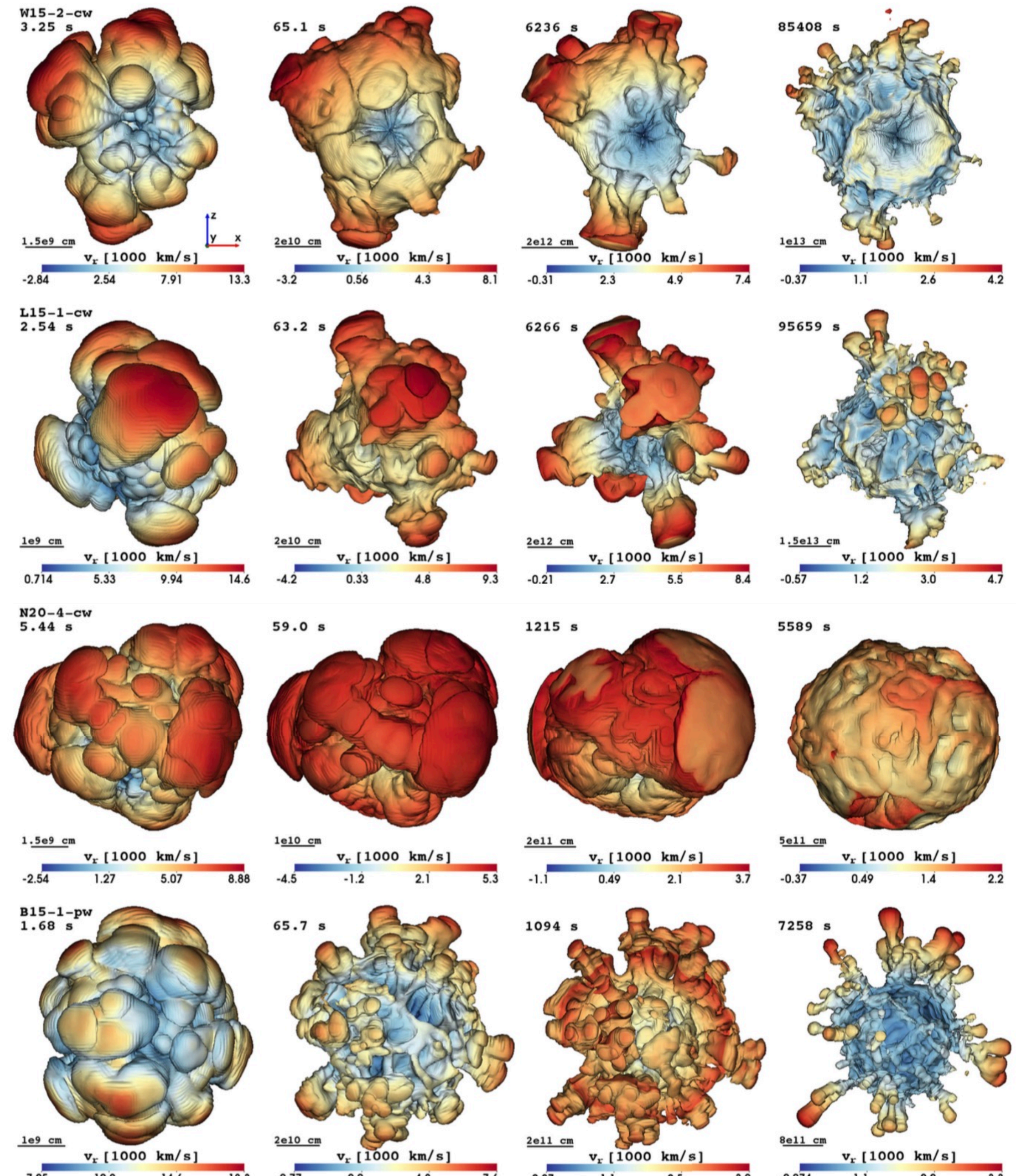
Origin of asymmetric explosion

Simulations of CC SNe suggest distribution of ^{56}Ni depends sensitively on progenitor structure

(Wongwathanarat et al. 2015)

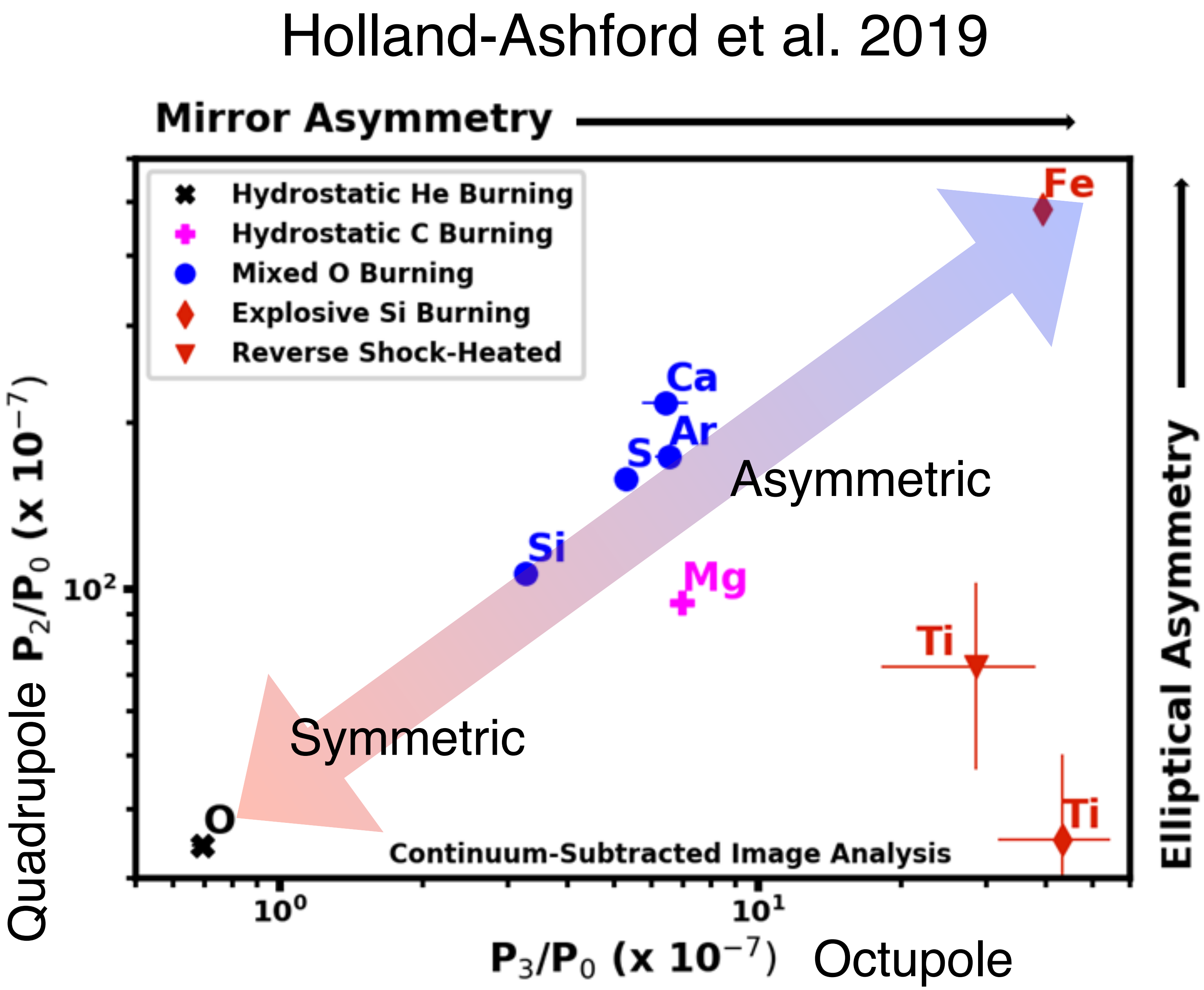
Lighter elements (e.g., O) are less affected by explosion asymmetries

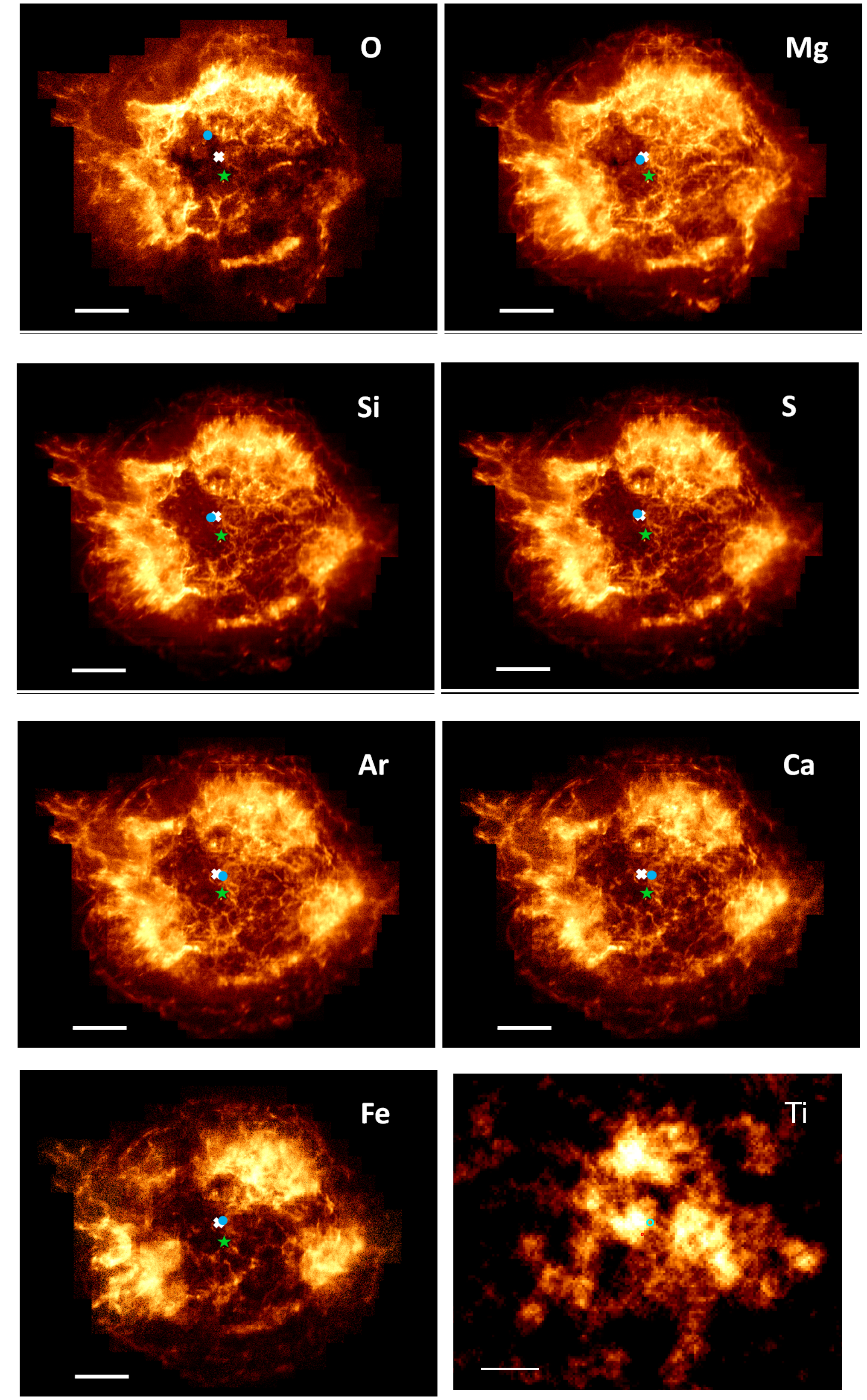
(e.g., Wongwathanarat et al. 2013, Janka et al. 2017)



Wongwathanarat et al. 2015

Observational test using X-rays





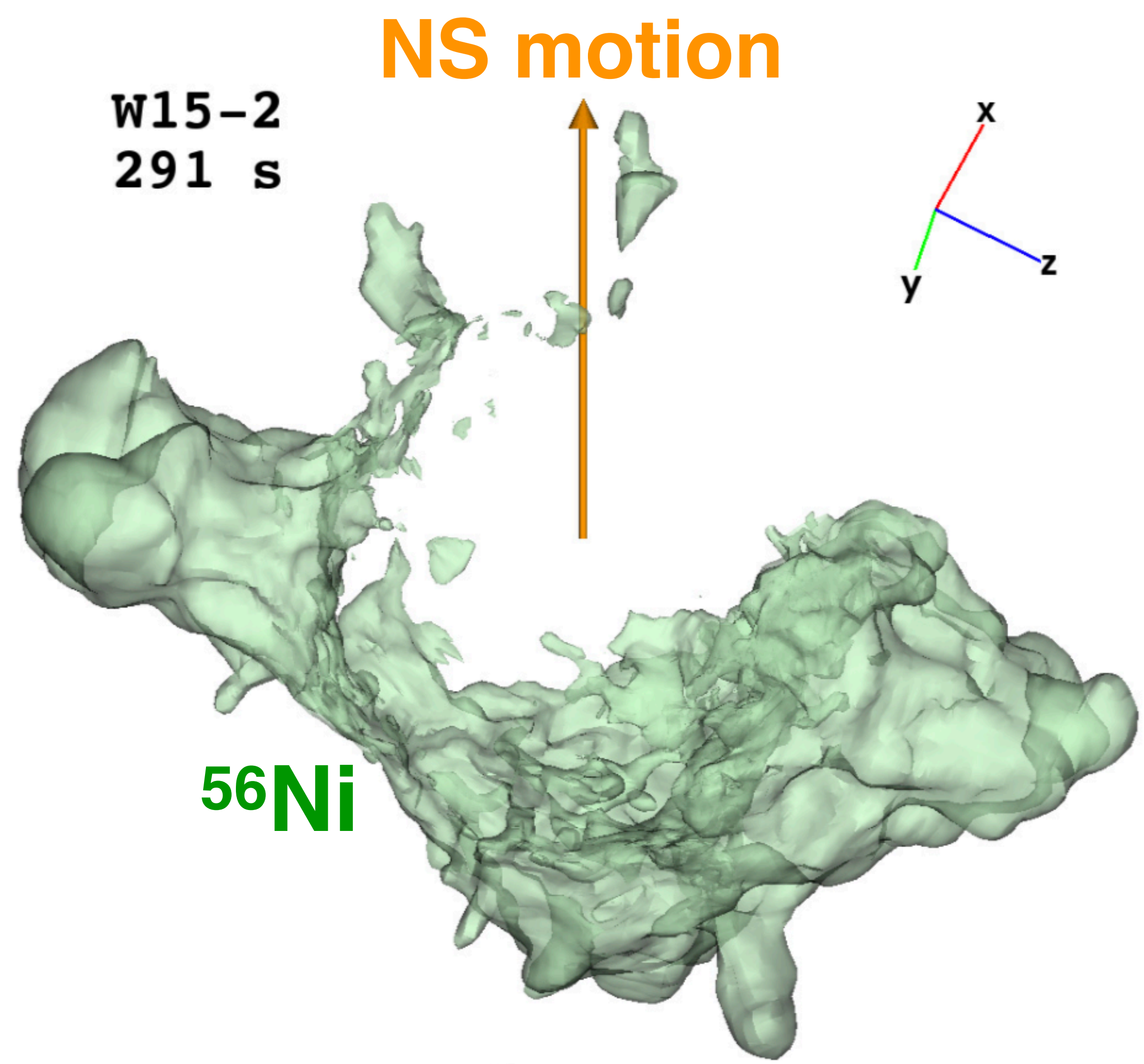
Heavier elements distributed more asymmetrically than lighter elements

Neutron star kick: theory

Neutron stars commonly have v ≳ 100 km/s

If a neutron star is recoiled by asymmetric mass ejection, NS goes opposite to heavy ejecta
(e.g., Wongwathanarat et al. 2013, Janka 2017)

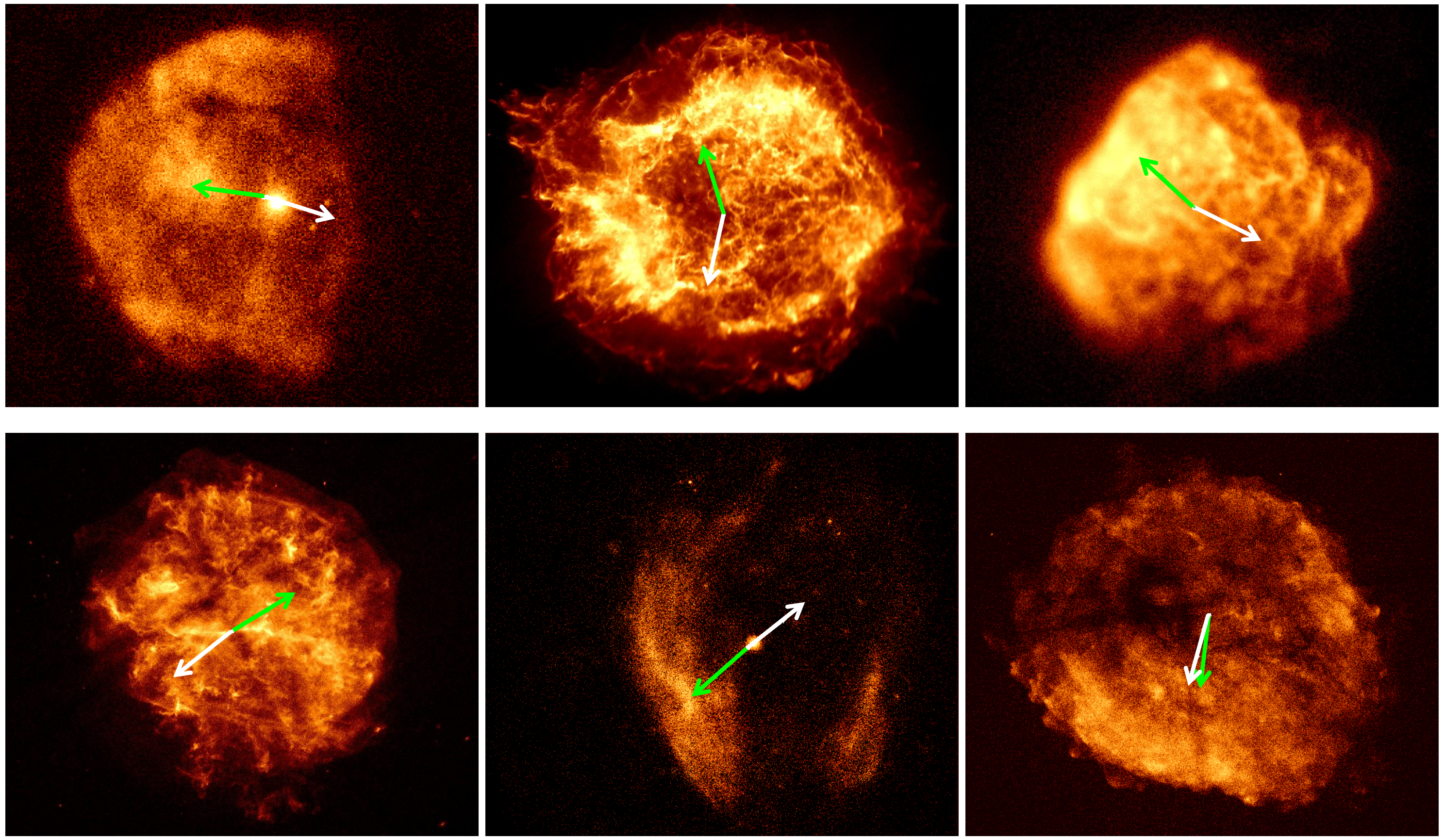
If the NS kick arises from anisotropic neutrino emission, NS goes in the same direction as heavy ejecta
(e.g., Fryer & Kusenko 2006)



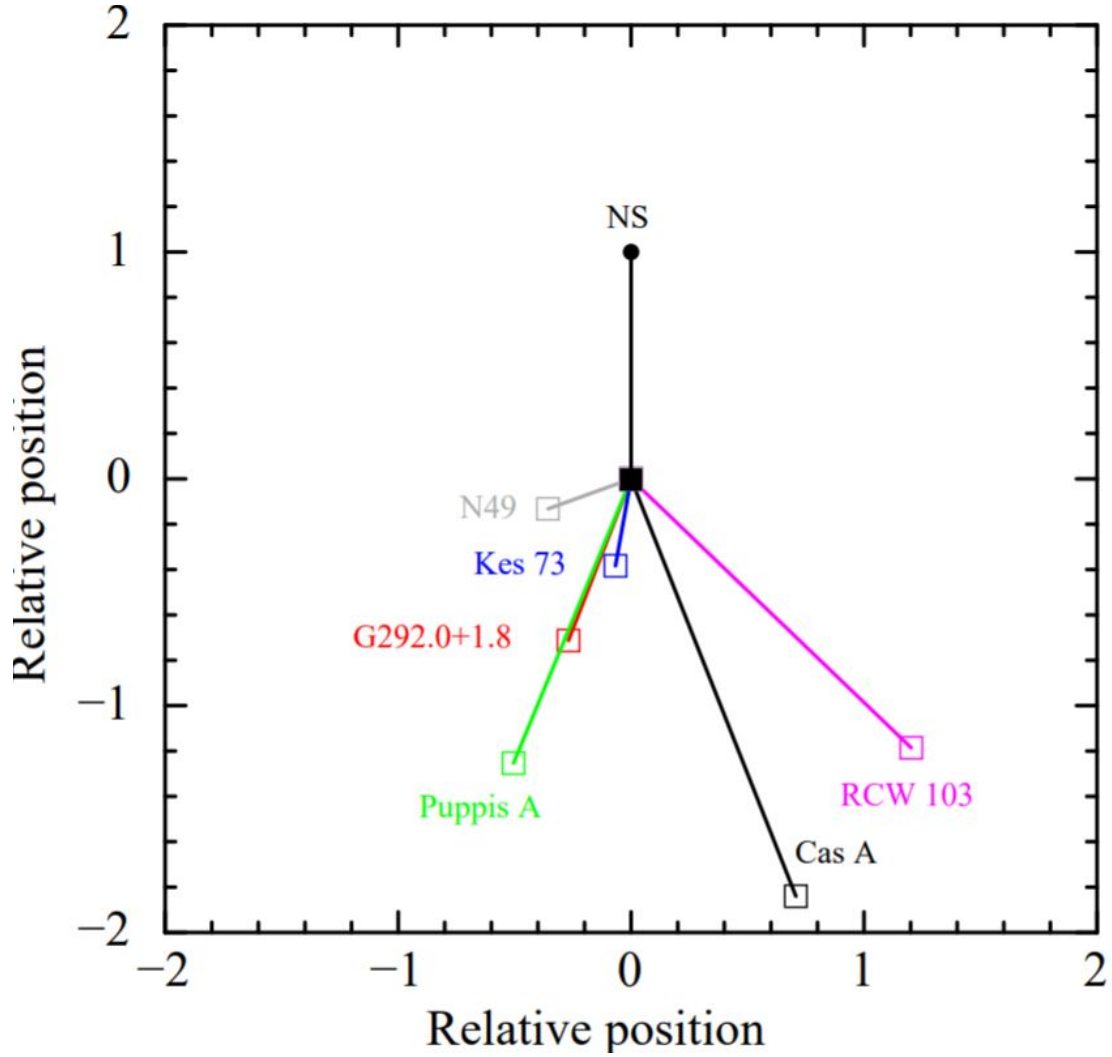
Wongwathanarat et al. 2013

Neutron star kick: observations

White: NS direction
Green: Ejecta direction



Holland-Ashford et al. 2017



Katsuda et al. 2018

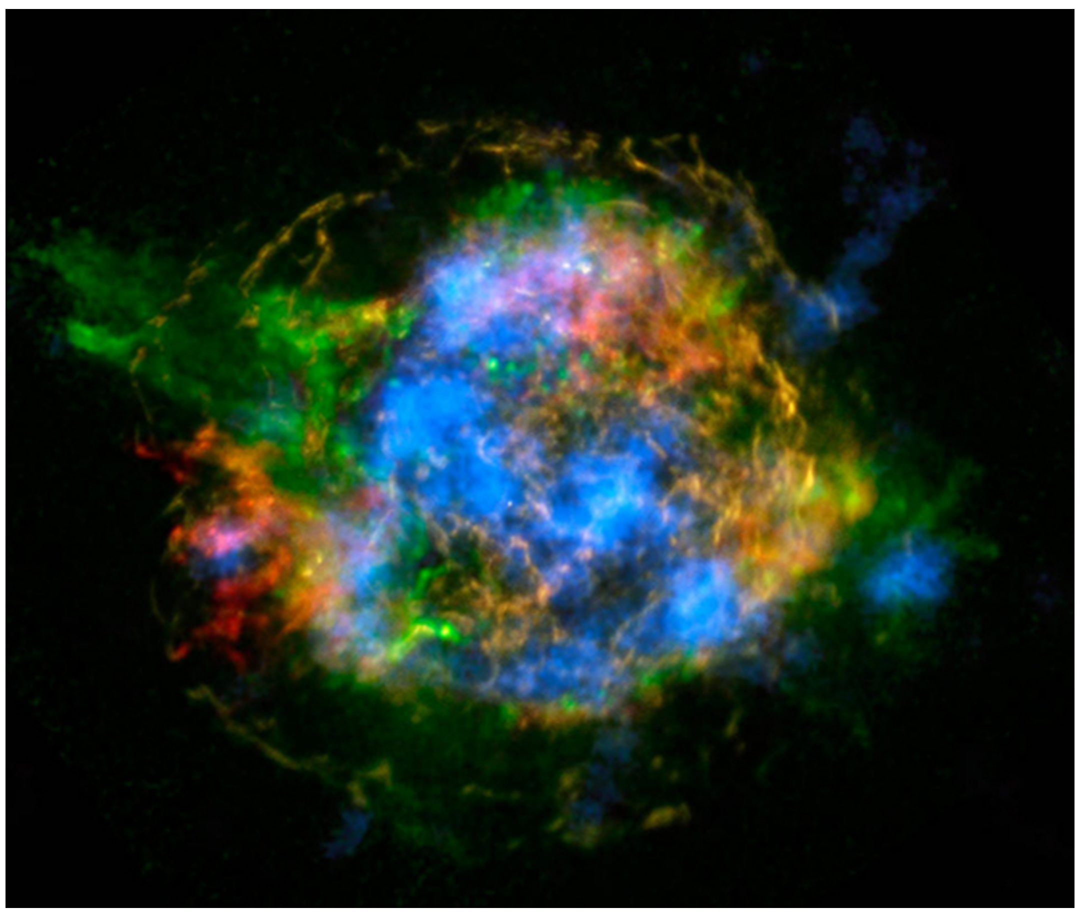
Asymmetric mass ejection scenario supported

^{44}Ti in Cassiopeia A

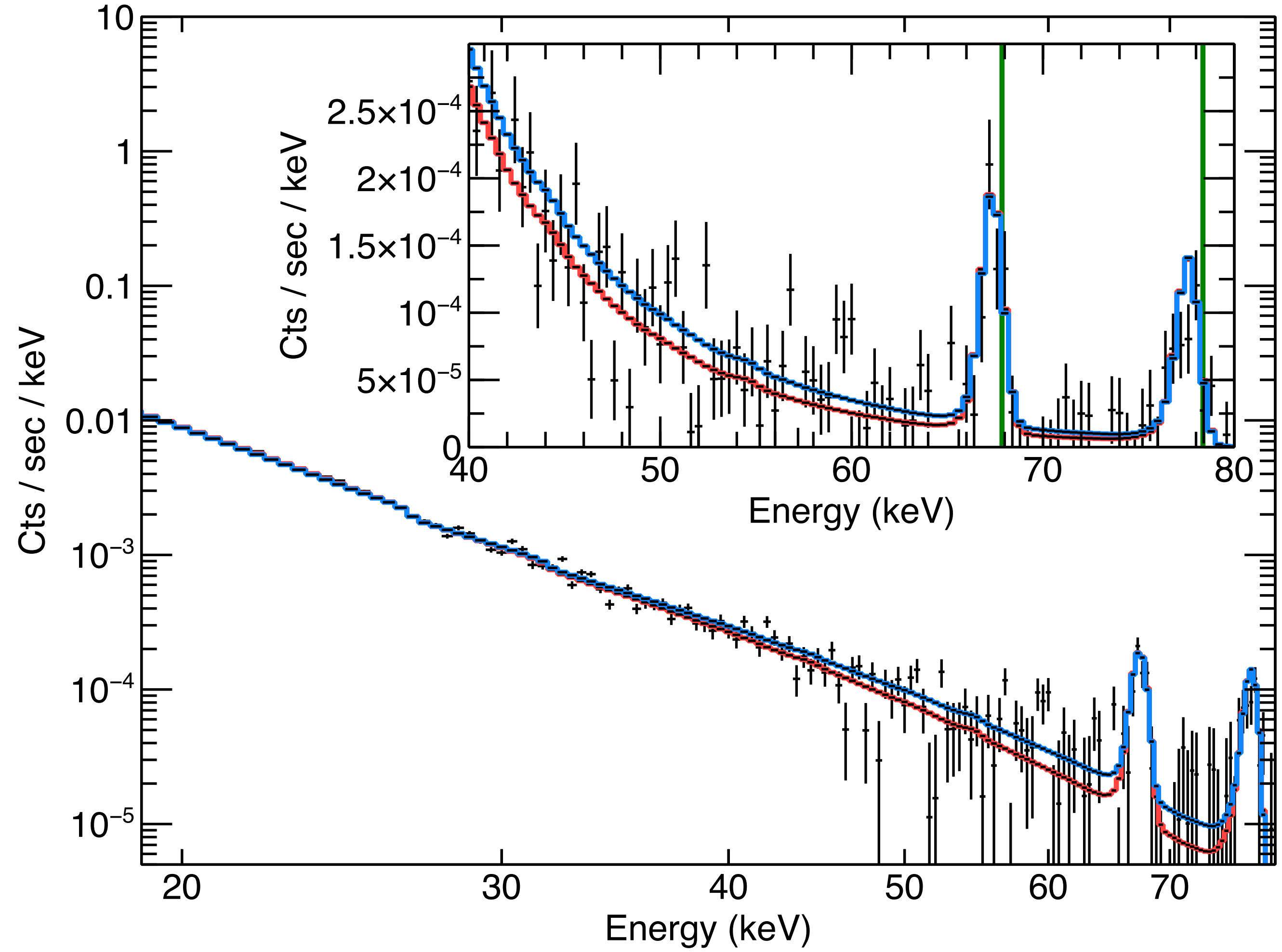
^{44}Ti is generated in the innermost, high-entropy region, so the best species to trace the physics of core-collapse SNe

^{44}Ti initial mass $\approx 2 \times 10^{-4}\ M_\odot$

^{44}Ti emission highly redshifted



Grefenstette et al. 2014; 2017



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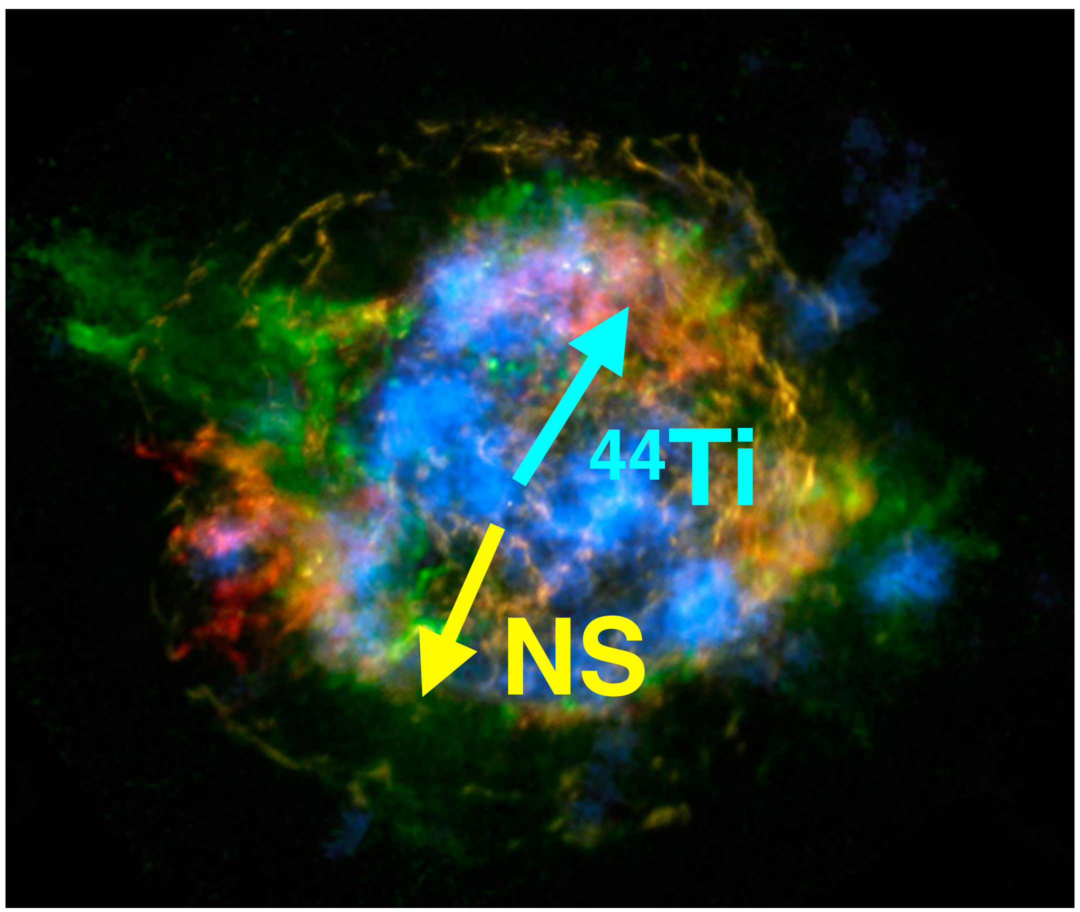
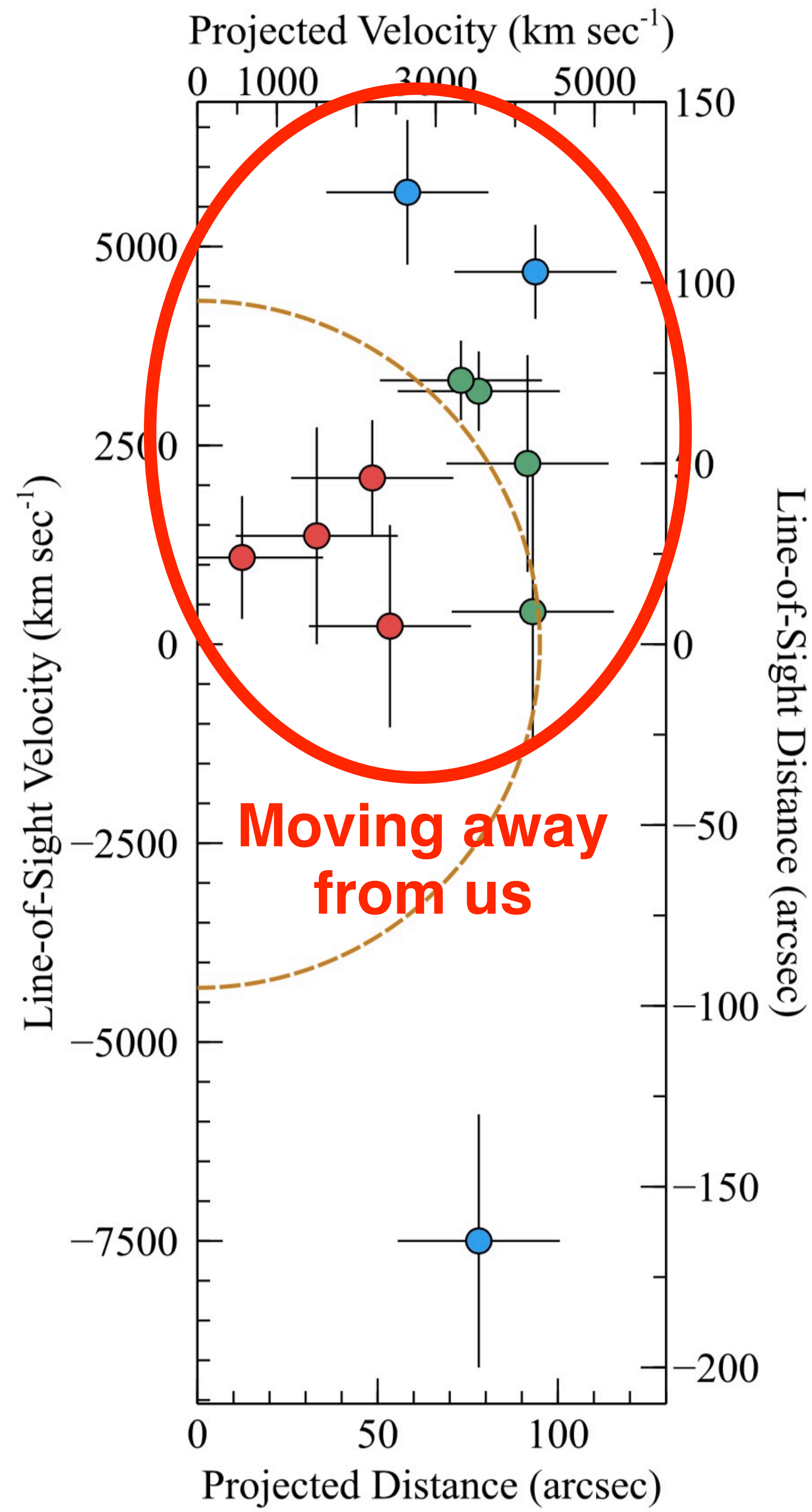
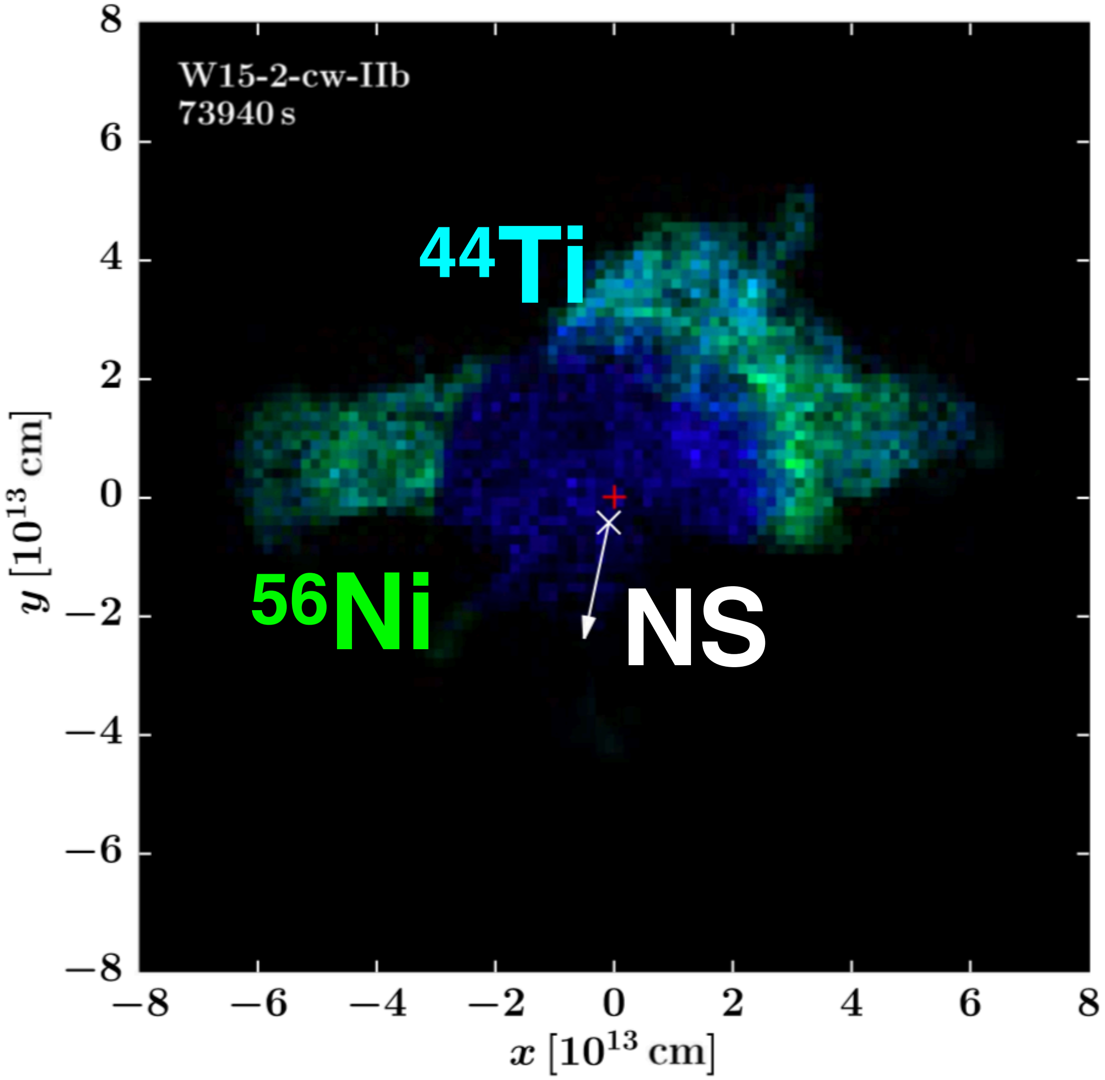


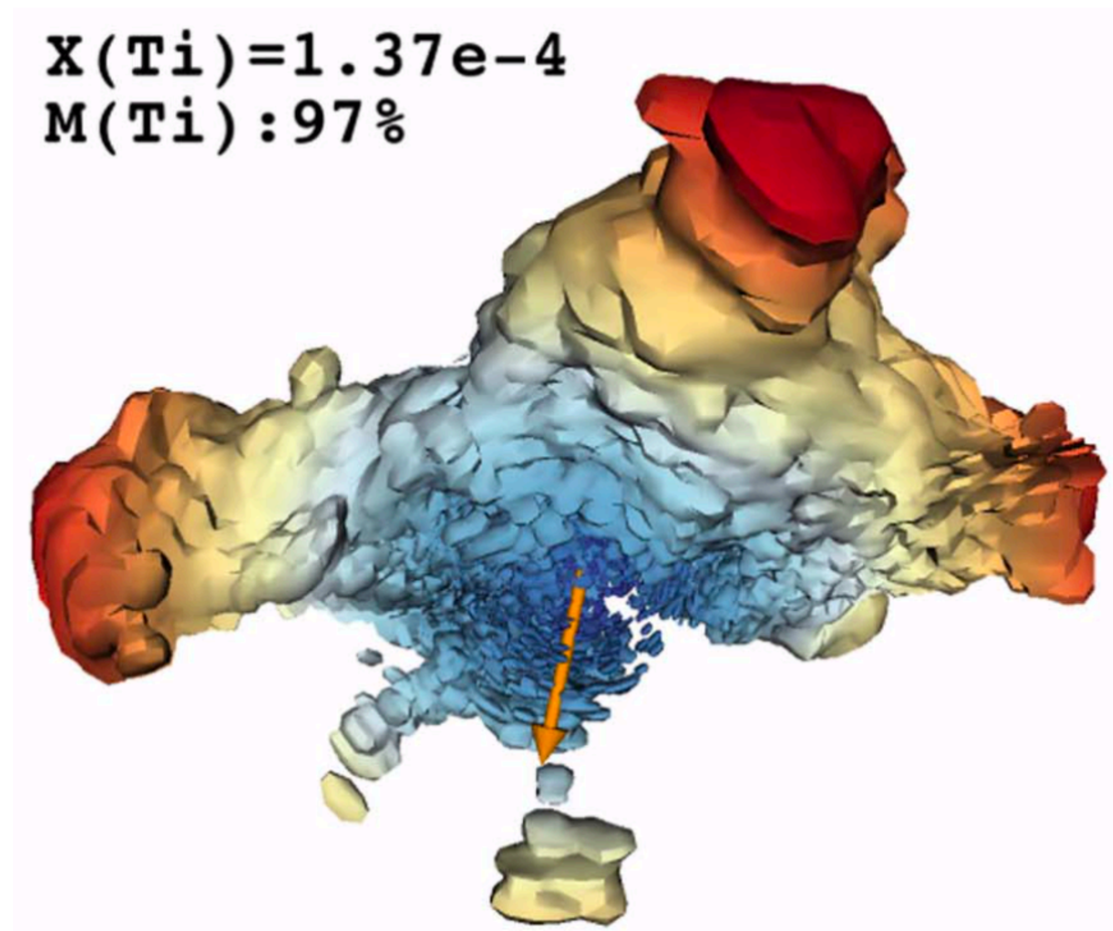
Grefenstette et al. 2014; 2017



^{44}Ti in Cassiopeia A

Wongwathanarat et al. 2017

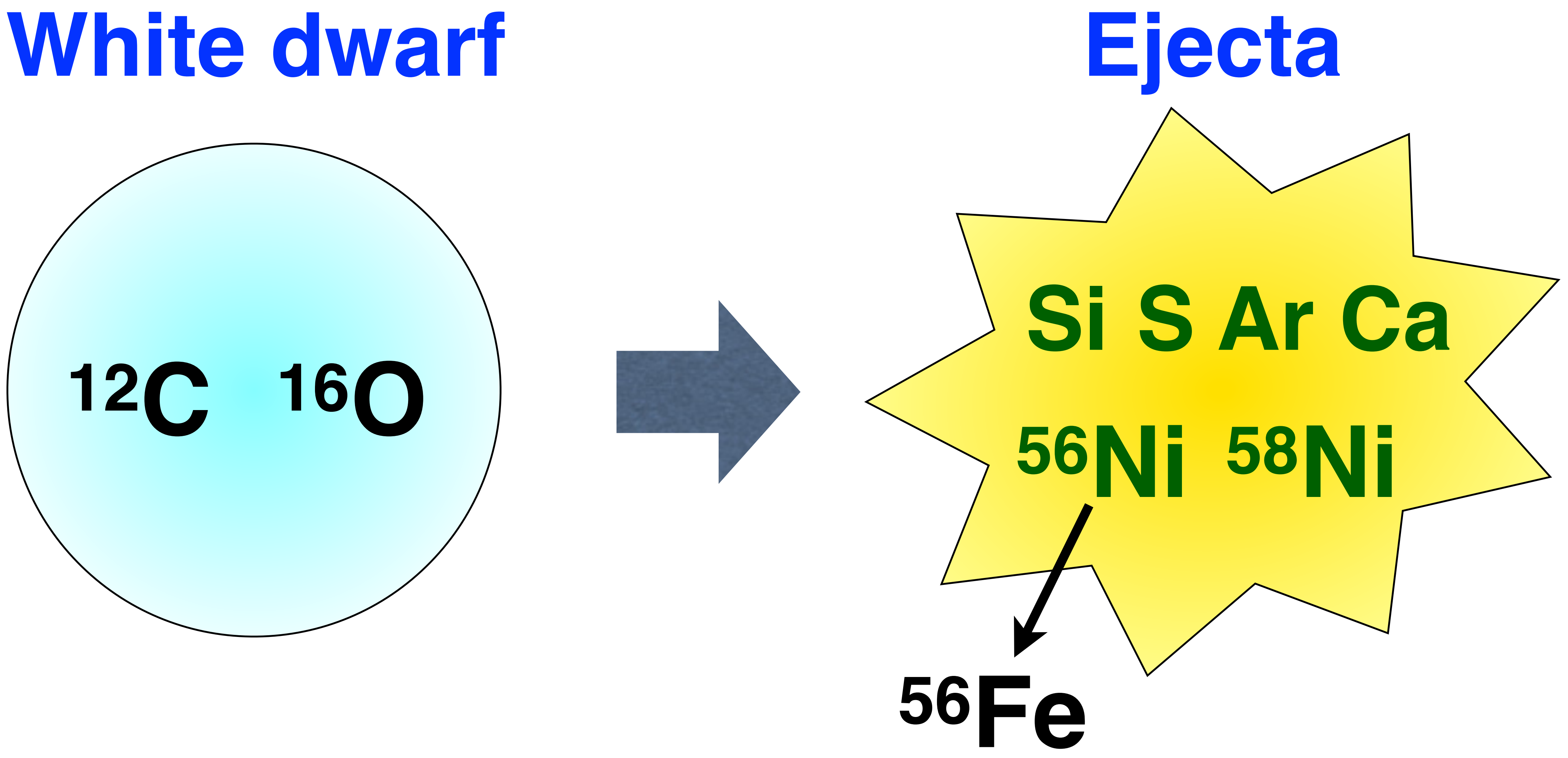




^{44}Ti (and ^{56}Ni) are expelled in the hemisphere opposite to the NS kick direction

Asymmetric core-collapse explosion is the key for both NS kick and efficient production of ^{44}Ti

Thermonuclear (Type Ia) SNe

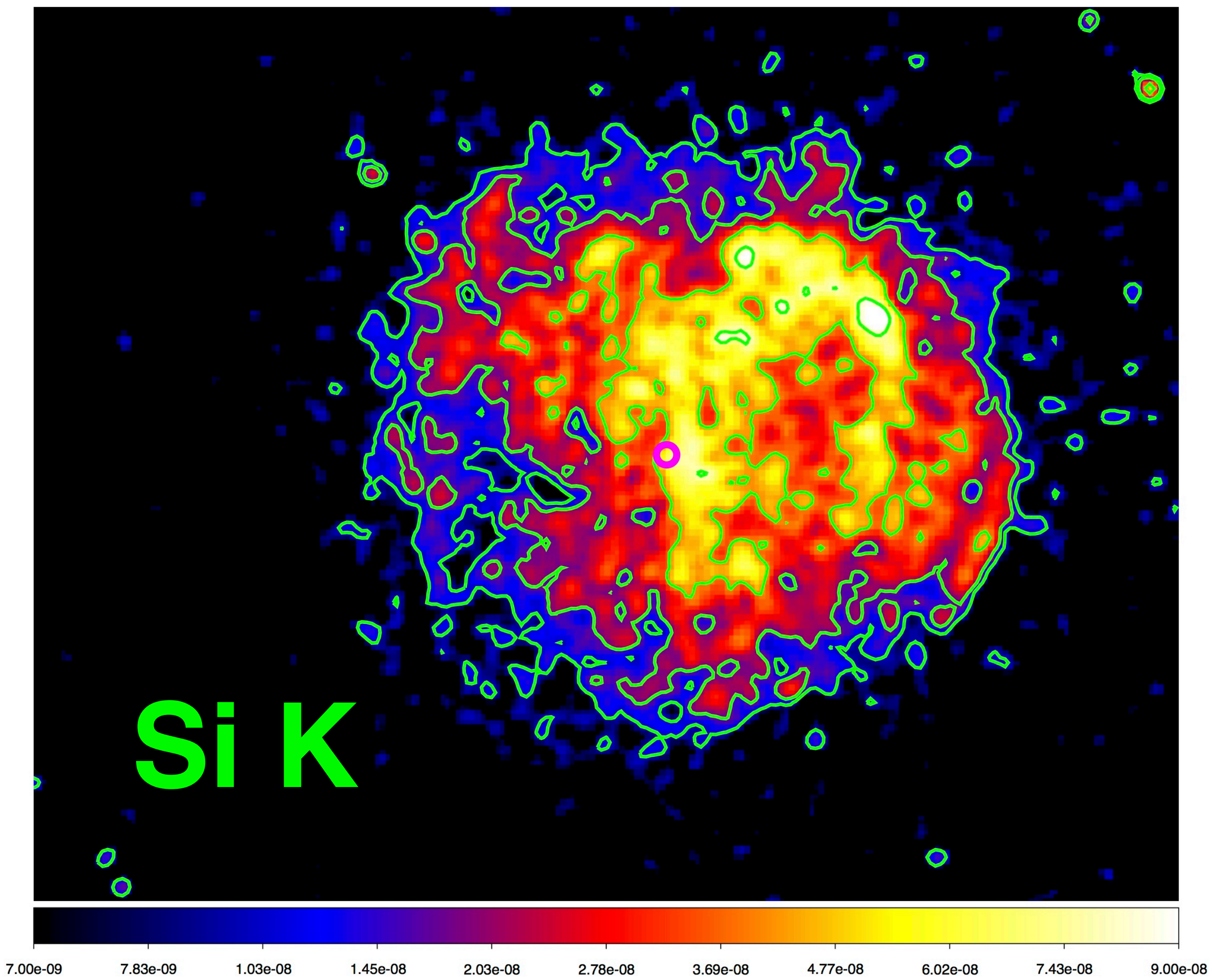


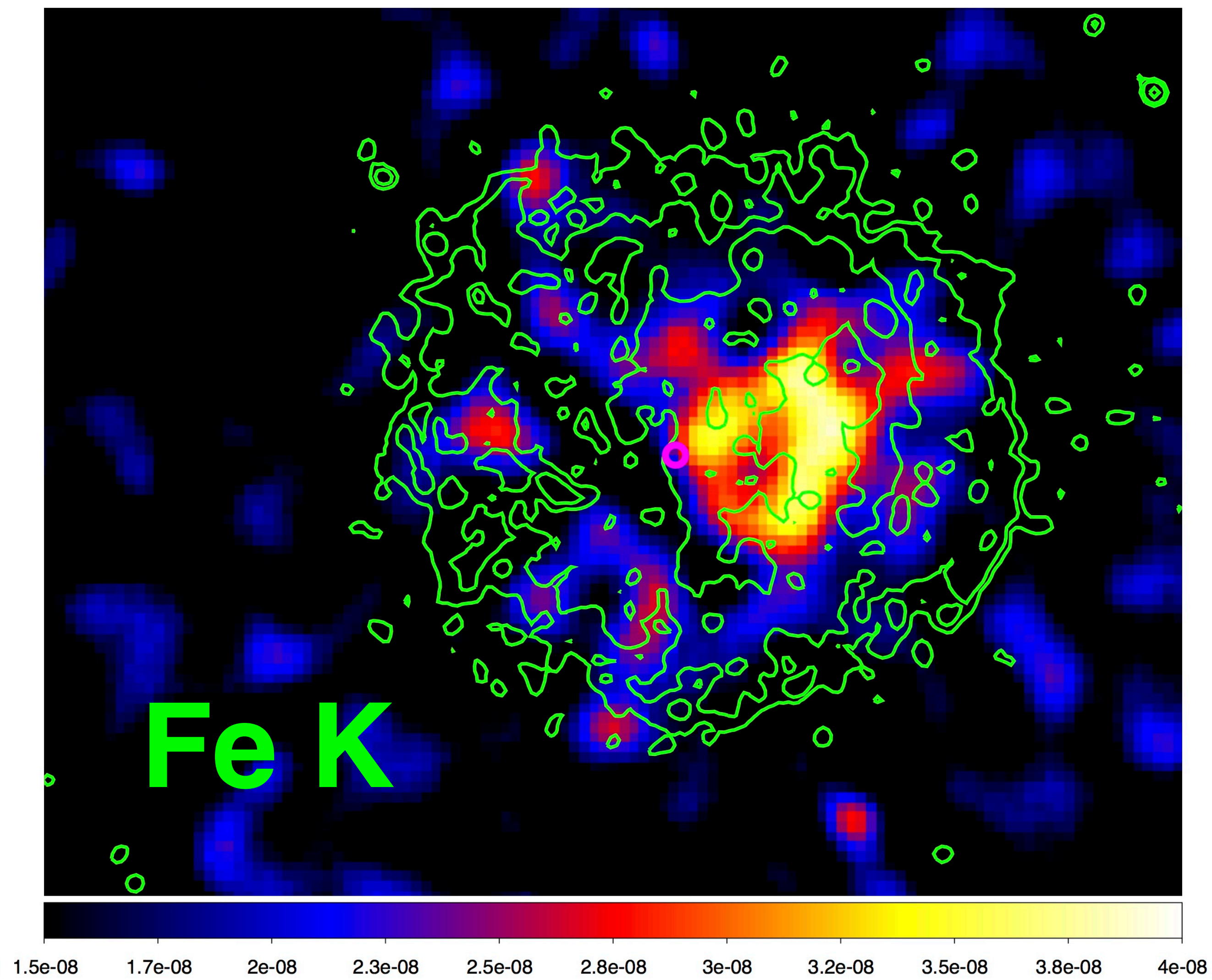
How does the nuclear burning proceed?

What is the mass of the progenitor WD?

Ejecta distribution in SNR Ia

Chandra deep observation G344.7-0.1 (PI: HY)

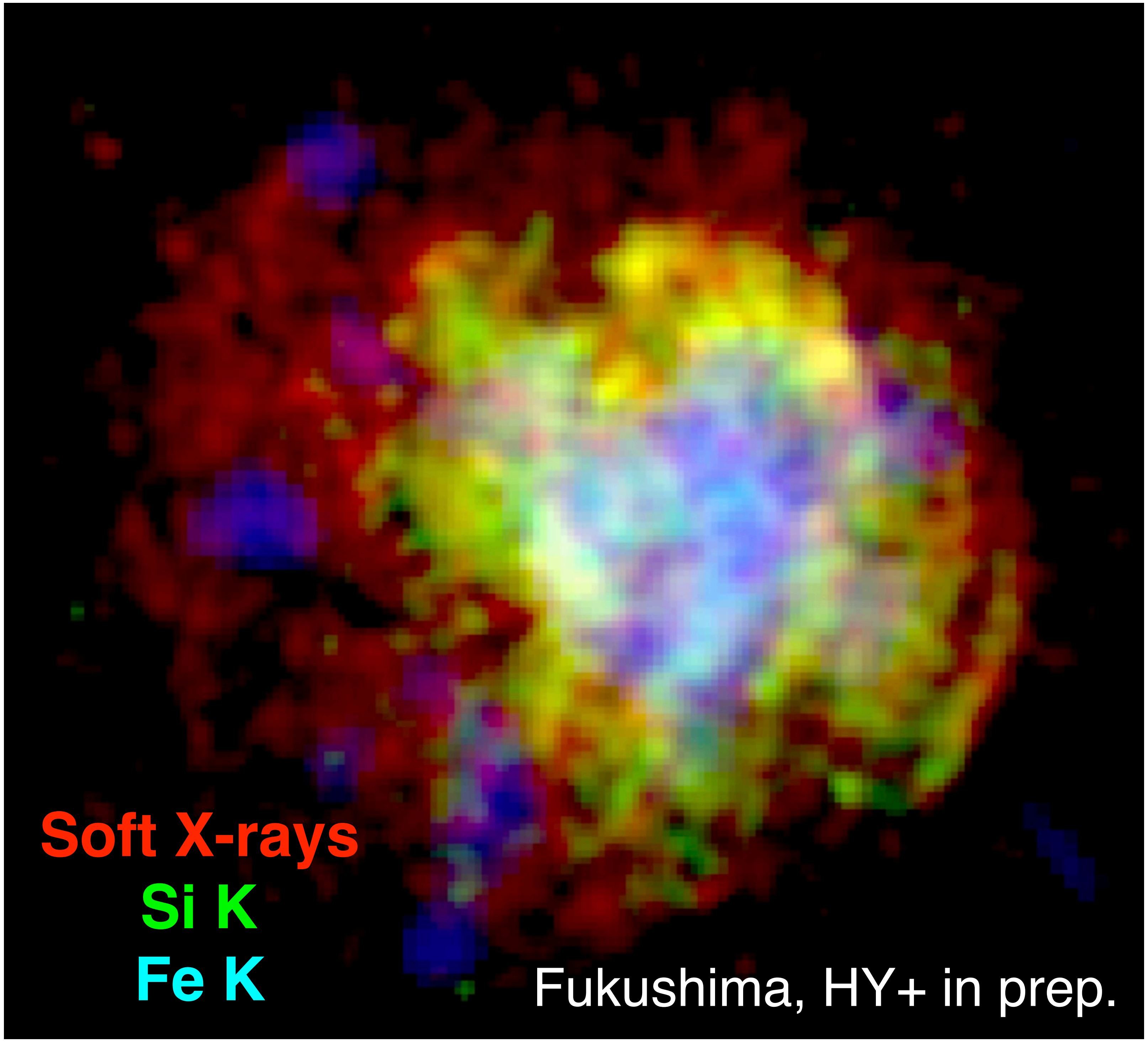




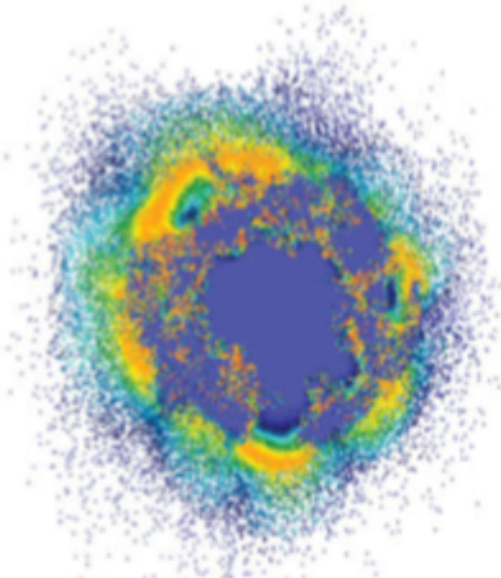
Fe ejecta surrounded by Si ejecta shell

(Fukushima, HY+ in prep.)

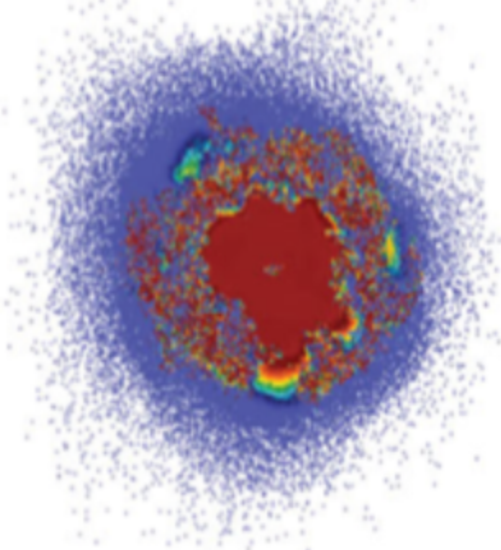
Ejecta distribution in SNR Ia



Si



Seitenzahl et al. 2013



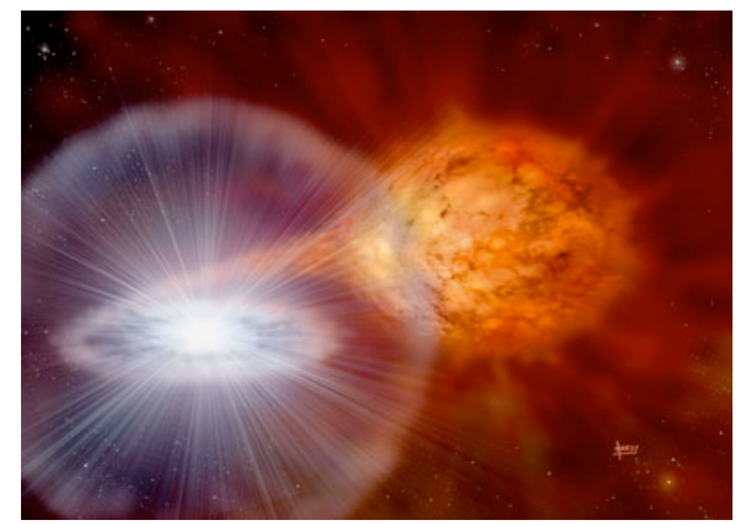
Fe

Pre-explosion WD mass

SNe Ia show almost uniform brightness
(used as cosmological standard candles)

Pre-explosion WD mass somehow regulated?

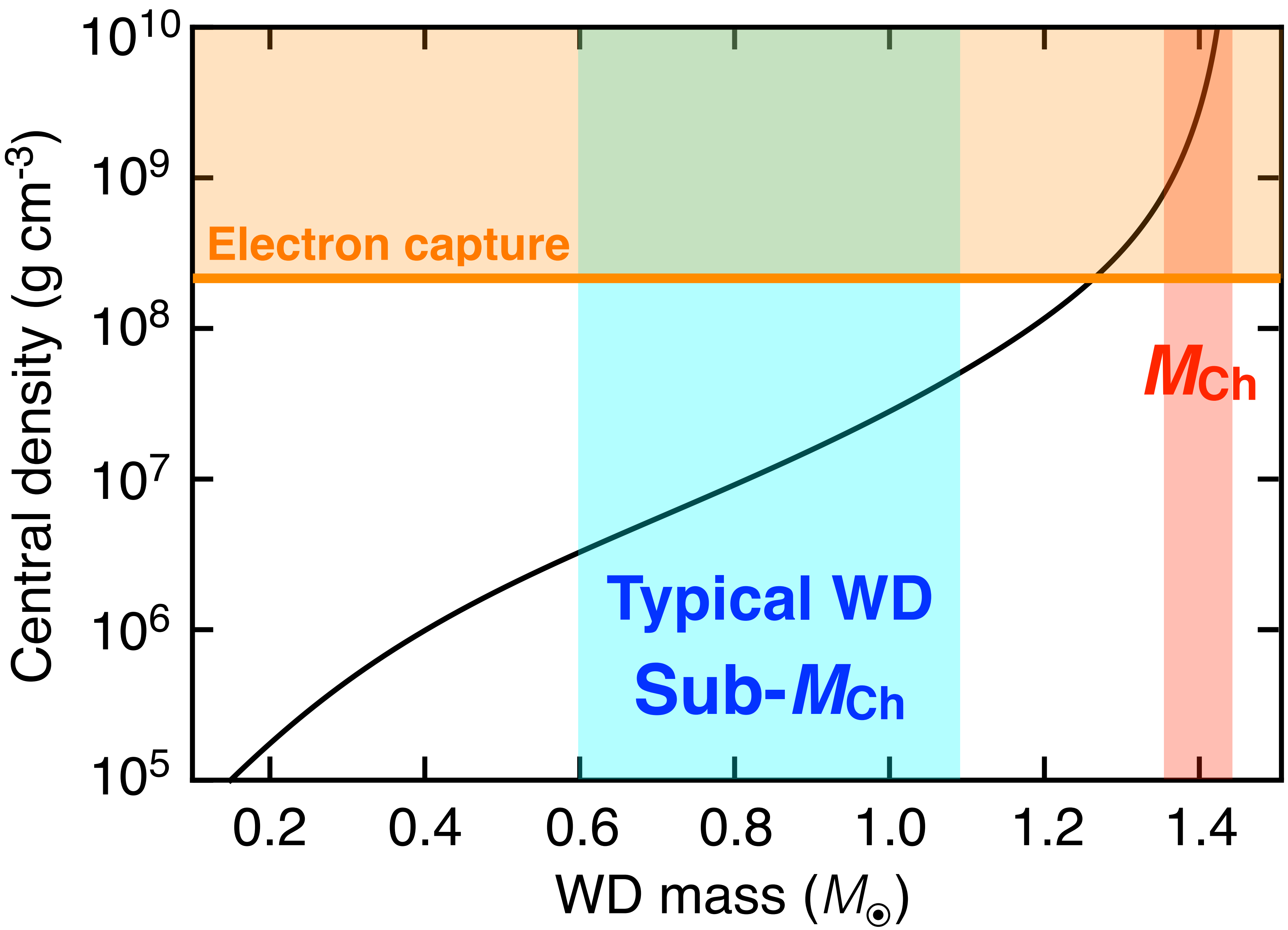
Explodes with the mass near the Chandrasekhar limit (M_{Ch}) after mass accretion from companion?



This scenario recently doubted

Sub-M_{Ch} scenario supported more often

Difference in nucleosynthesis

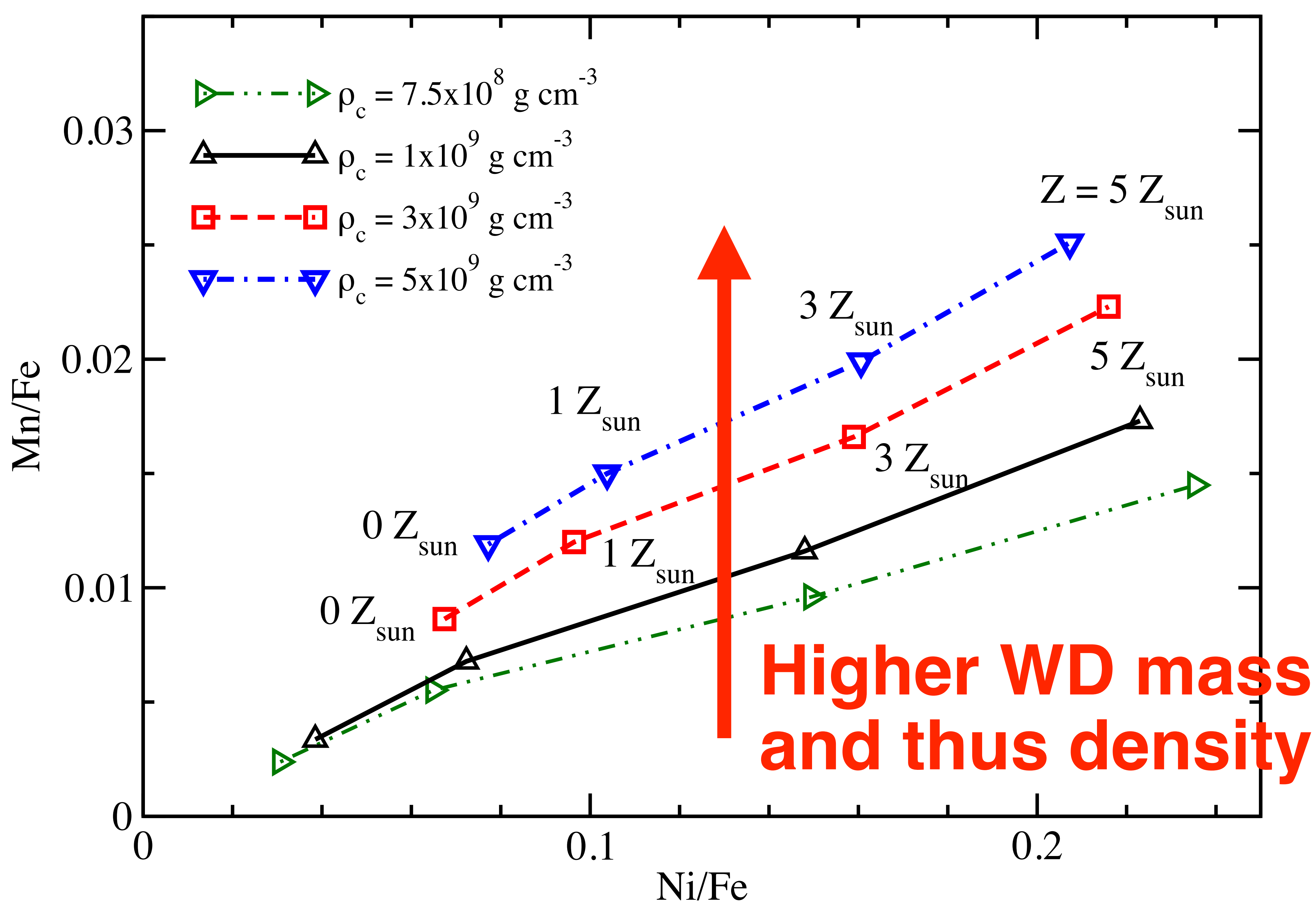


Electron capture: $\boldsymbol{p} + \mathbf{e}^- \rightarrow \boldsymbol{n} + \boldsymbol{\nu}_\mathbf{e}$ (only in ~M_{Ch} WD)

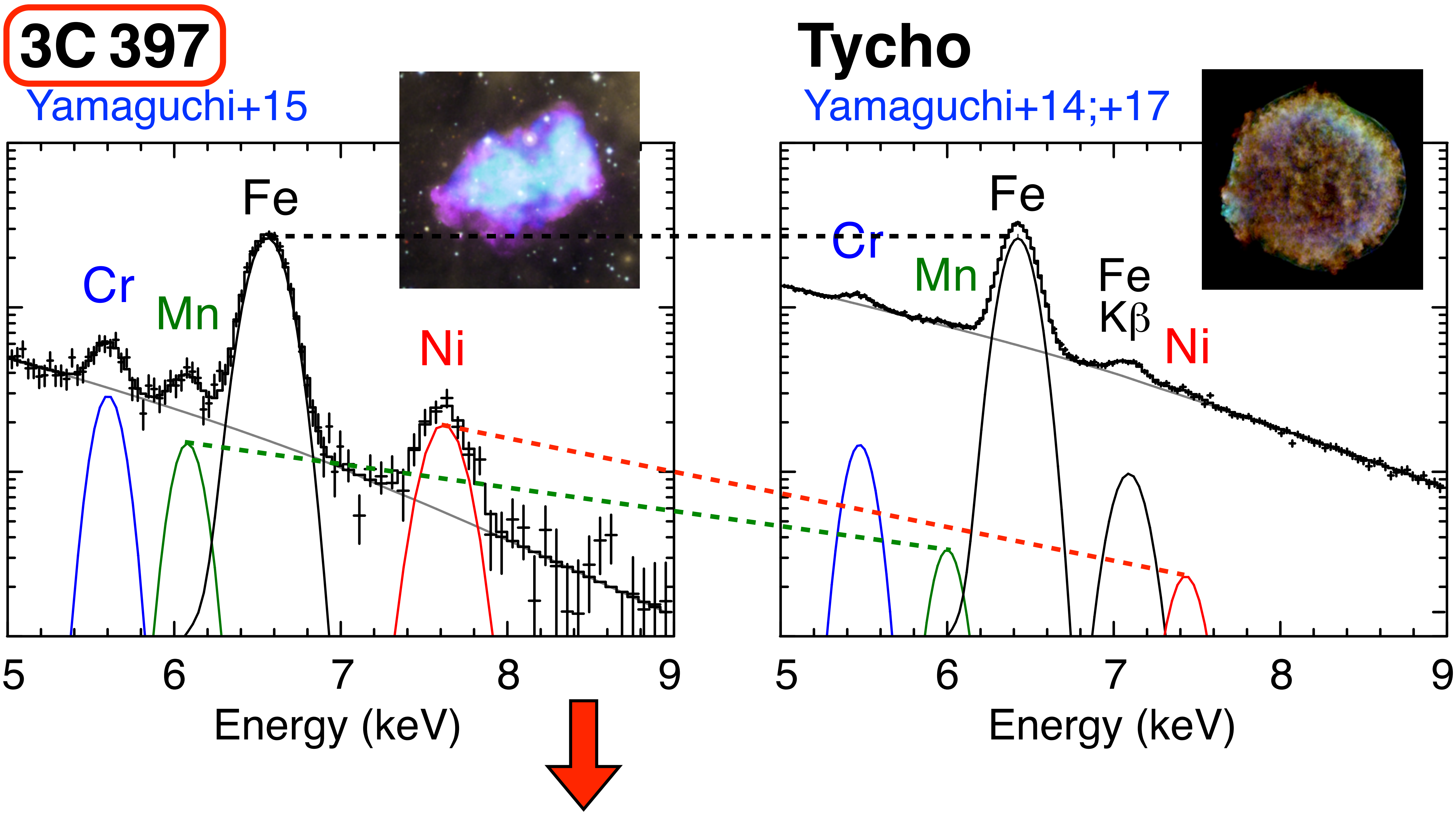
High abundance of n-rich species (^{55}Mn, ^{58}Ni) expected

Density-dependent nucleosynthesis

Leung & Nomoto (2018)



Discovery of Mn- & Ni-rich SNR Ia

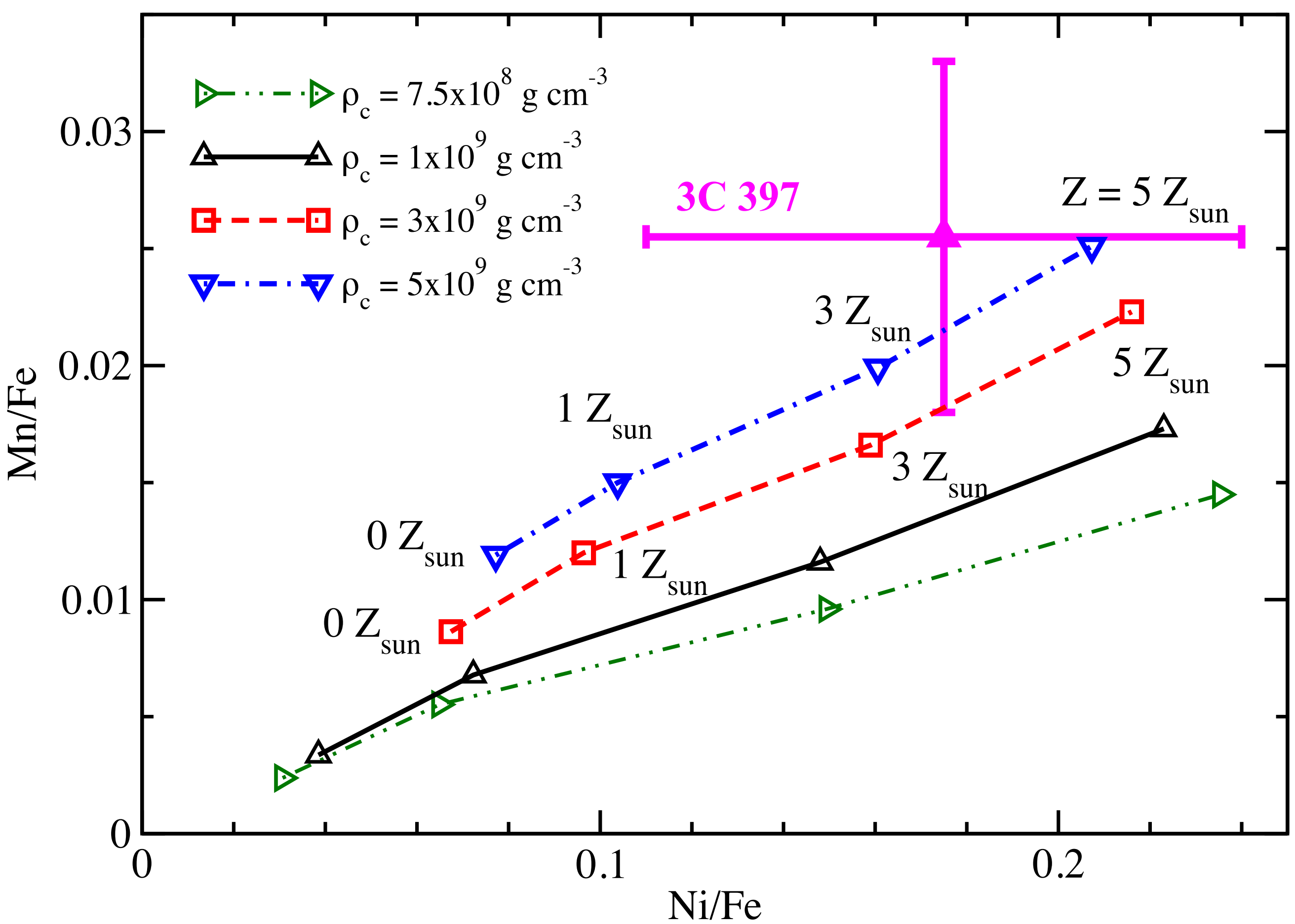


Ni/Fe ≈ 0.17 Mn/Fe ≈ 0.025

Comparison with models

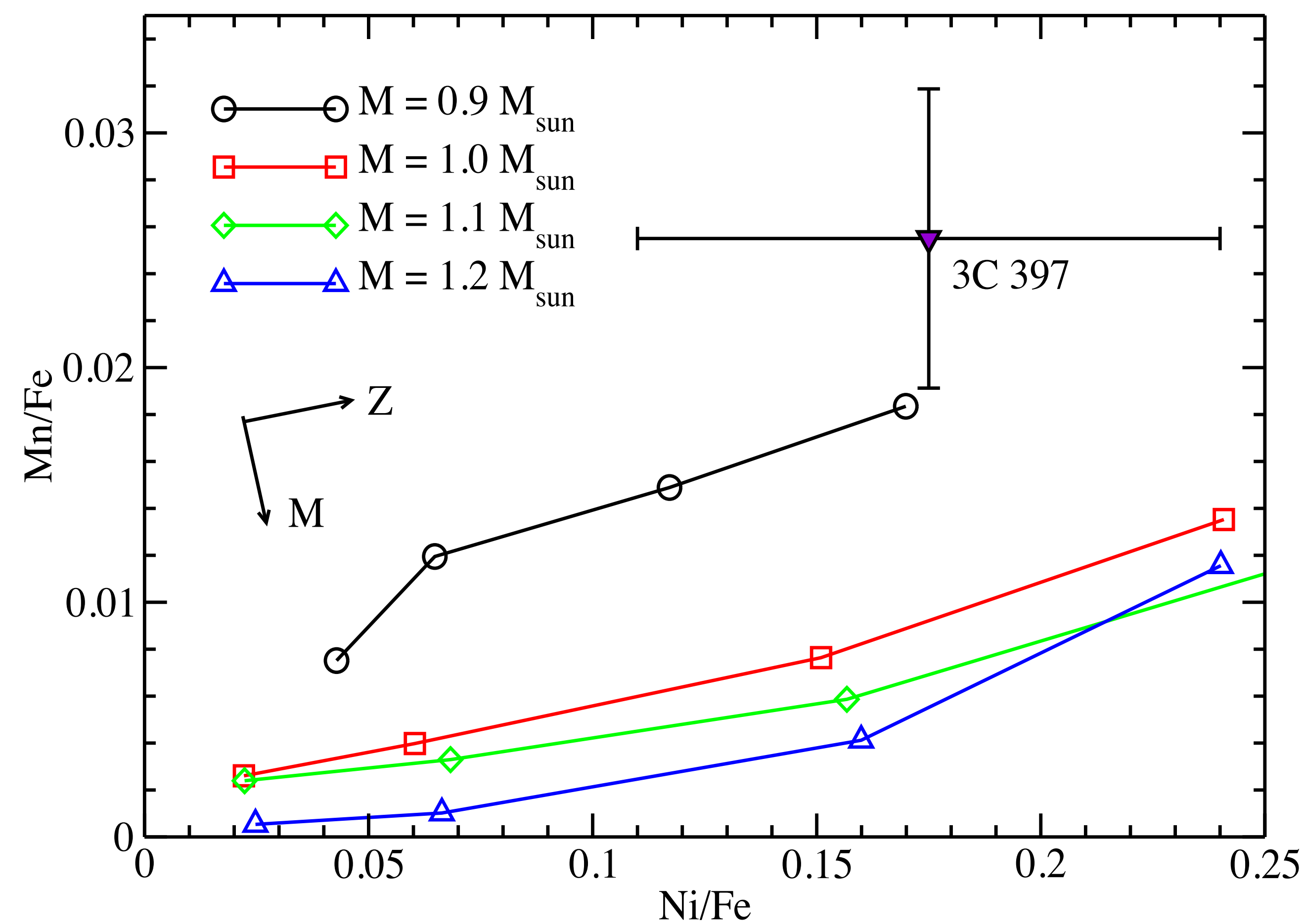
near-M_{Ch} SNe Ia

Leung & Nomoto (2018)



sub-M_{Ch} SNe Ia

Leung & Nomoto (2019)



3C 397 originate from near-M_{Ch} with a VERY high central density and relatively high metallicity

Implication for galactic chemical evolution

Cr, Mn, Ni/Fe ratios are too high compared to the solar values

Other Type Ia SNRs always show sub-solar ratios

Mass ratio

	3C 397	Solar
Cr/Fe	2.1-3.4%	1.3%
Mn/Fe	1.8-3.3%	0.8%
Ni/Fe	12-24%	5.4%

If 3C 397 is a typical near-M_{Ch} SNR Ia, or if high ρ_c (~ 5 x 10^9 g cm^{-3}) is typical for near-M_{Ch} progenitors, near-M_{Ch} WDs must not be the majority.

Sub-M_{Ch} SNe Ia are required to achieve the solar abundance of the Fe-peak elements.

Summary

- X-ray and gamma-ray observations of SNRs are crucial to understand the origin of matter and chemical evolution of galaxies
- Focused on ‘innermost’ nucleosynthesis in both core-collapse and thermonuclear SNe
  - High-entropy products (e.g., ^{44}Ti) are efficiently synthesized in highly-asymmetric CC SNe
  - Neutron-rich species (e.g., ^{55}Mn, ^{58}Ni) are efficiently synthesized in high-density SNe Ia

Back-up slides

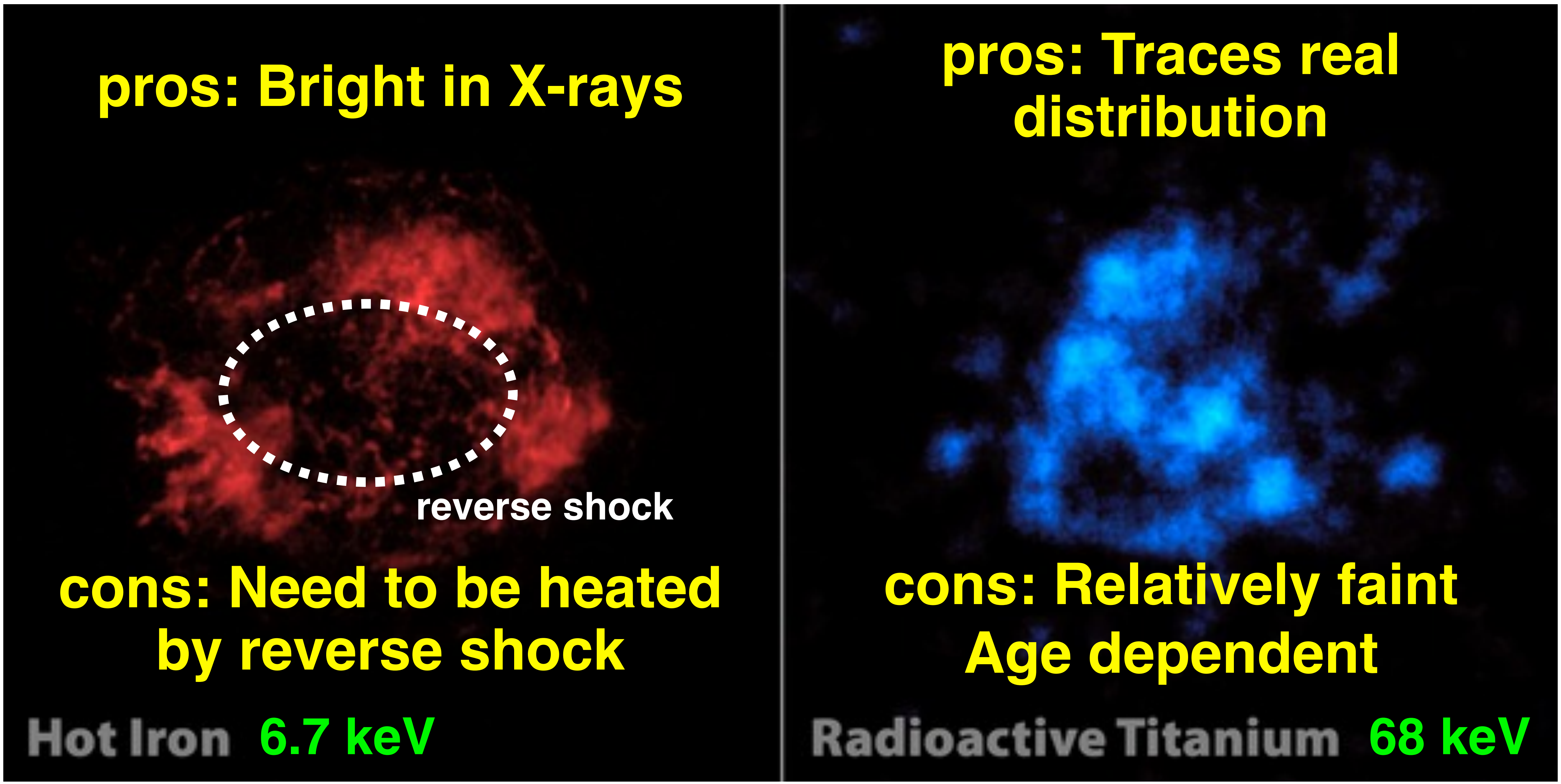
X-ray image

Atomic transition

$Fe^{24+*} \rightarrow Fe^{24+} + h\nu$

Radioactive decay

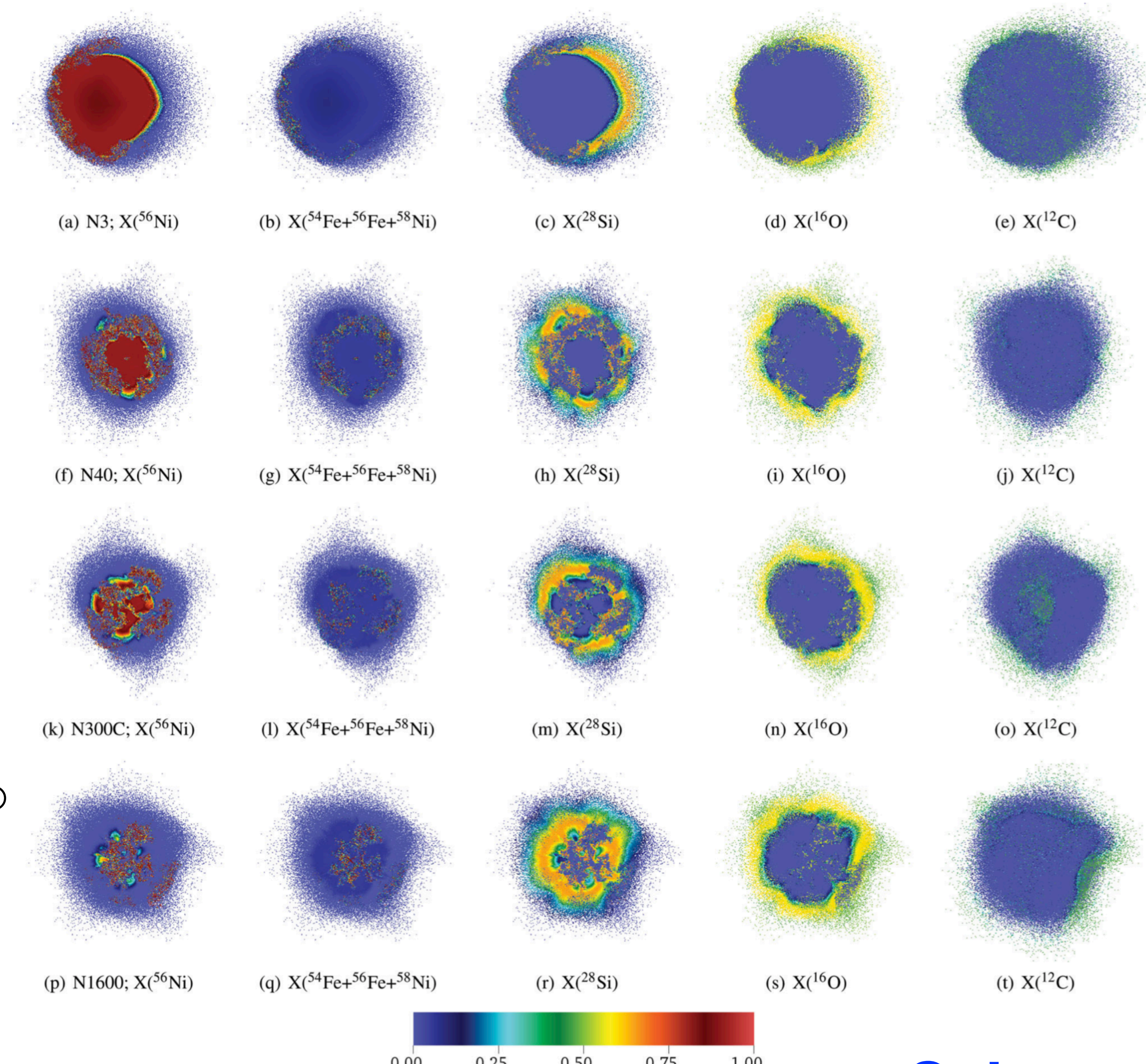
$^{44}Ti \rightarrow {}^{44}Sc^{*} + \gamma \rightarrow {}^{44}Sc + \gamma$



Ejecta distribution as a probe for explosion mechanisms

Bright
^{56}Ni ~ 1M$_\odot$

Faint
^{56}Ni ~ 0.4M$_\odot$

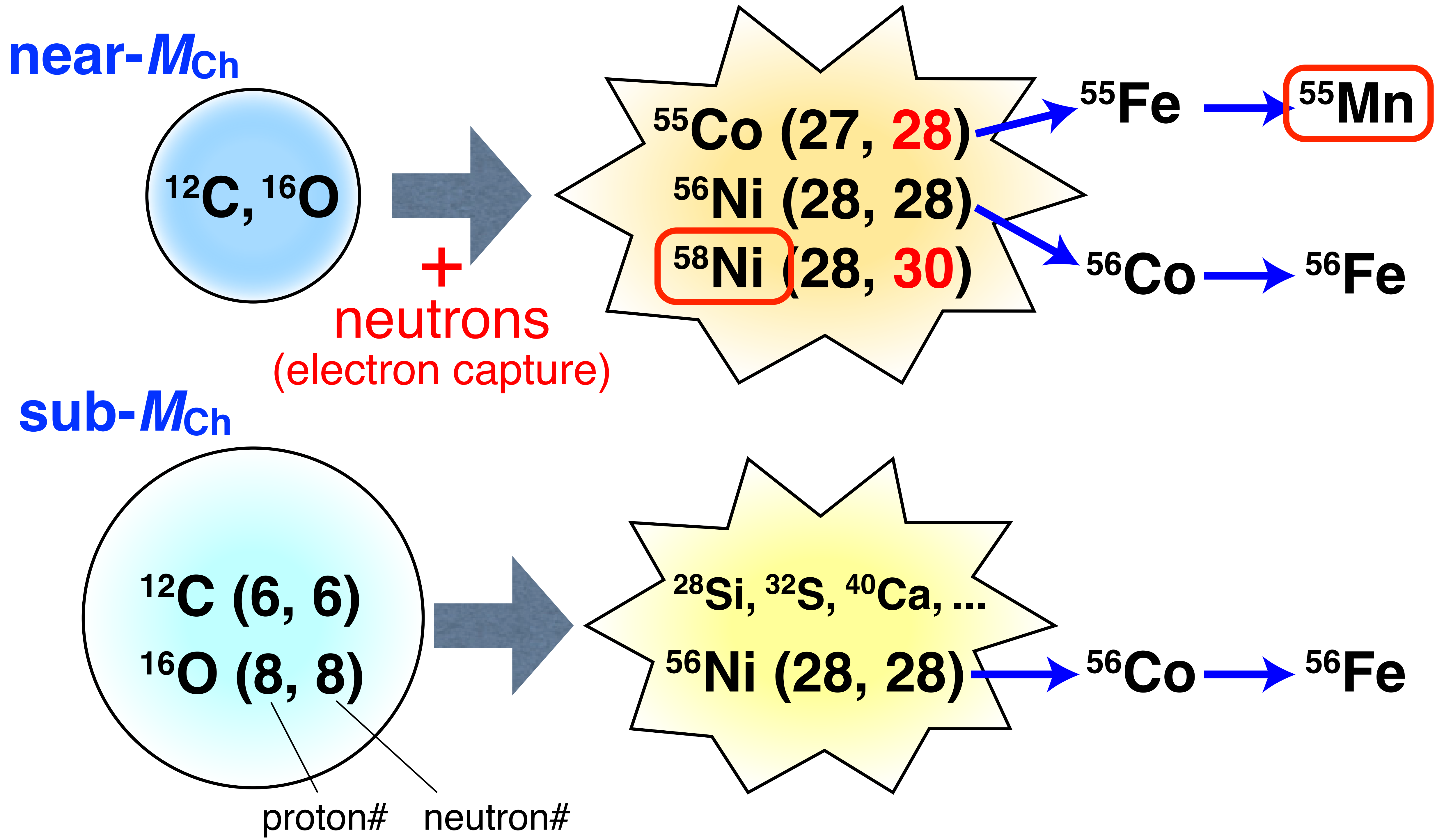


Asymmetric

Symmetric Clumpy

Seitenzahl+2013

Density-dependent nucleosynthesis



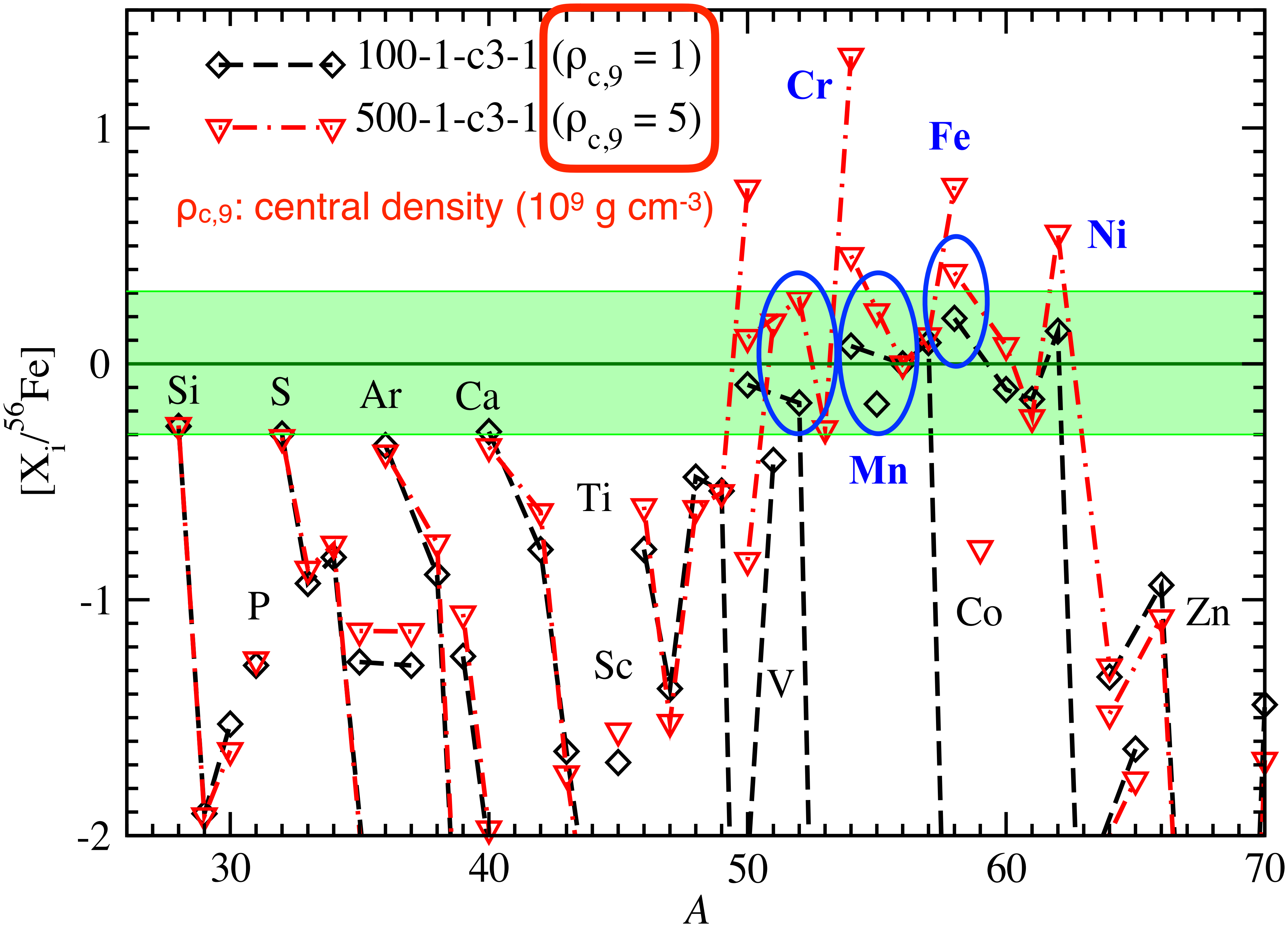
More Ni and Mn produced in ~M_{Ch} SN Ia

Suggested association

	SD	DD
Primary/ejecta mass	M_{Ch}	sub-M_{Ch}
Electron capture	Yes	No
Secondary	MS or RG	WD
CSM	Yes	No

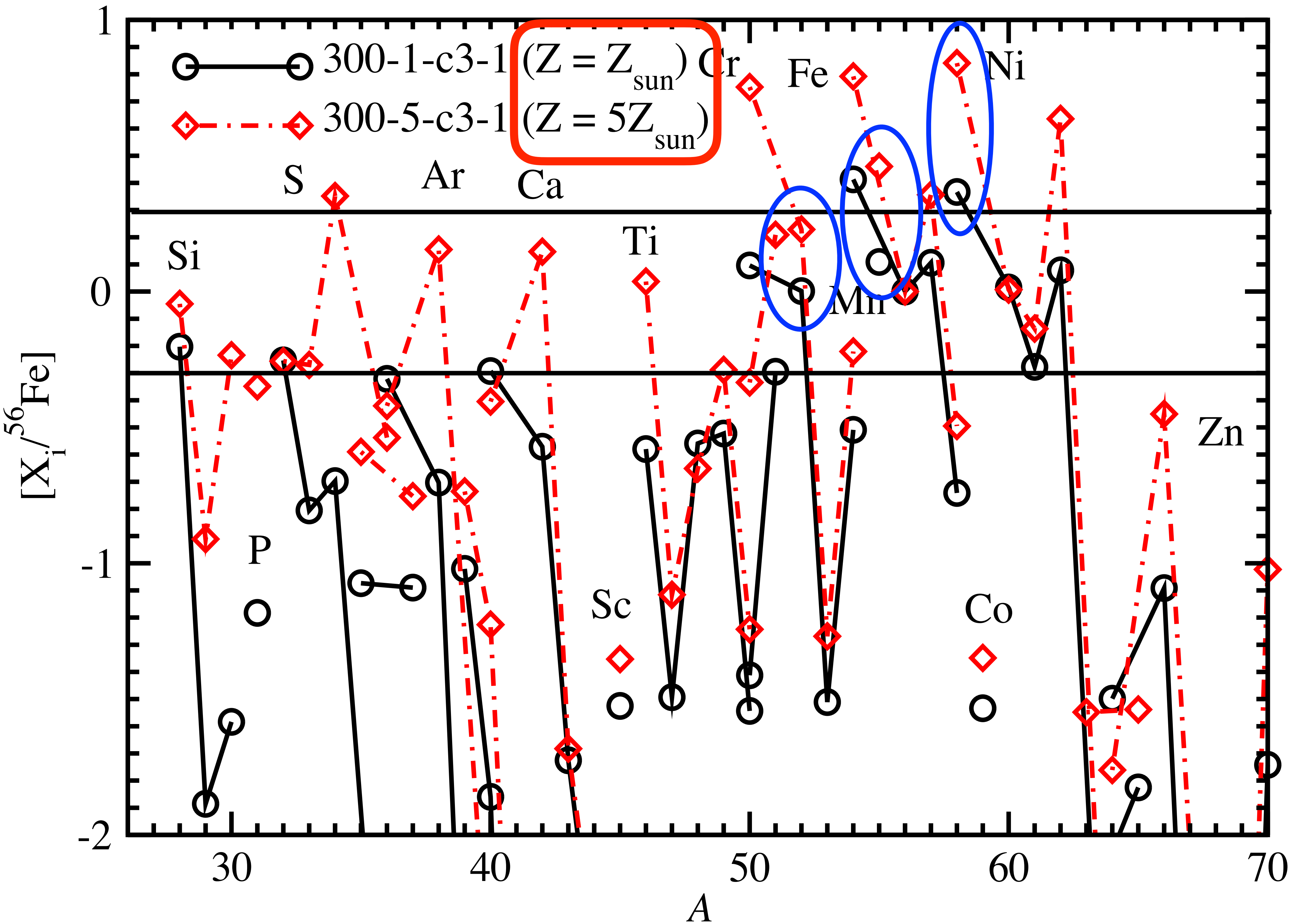
Central density effect

Leung & Nomoto 2017



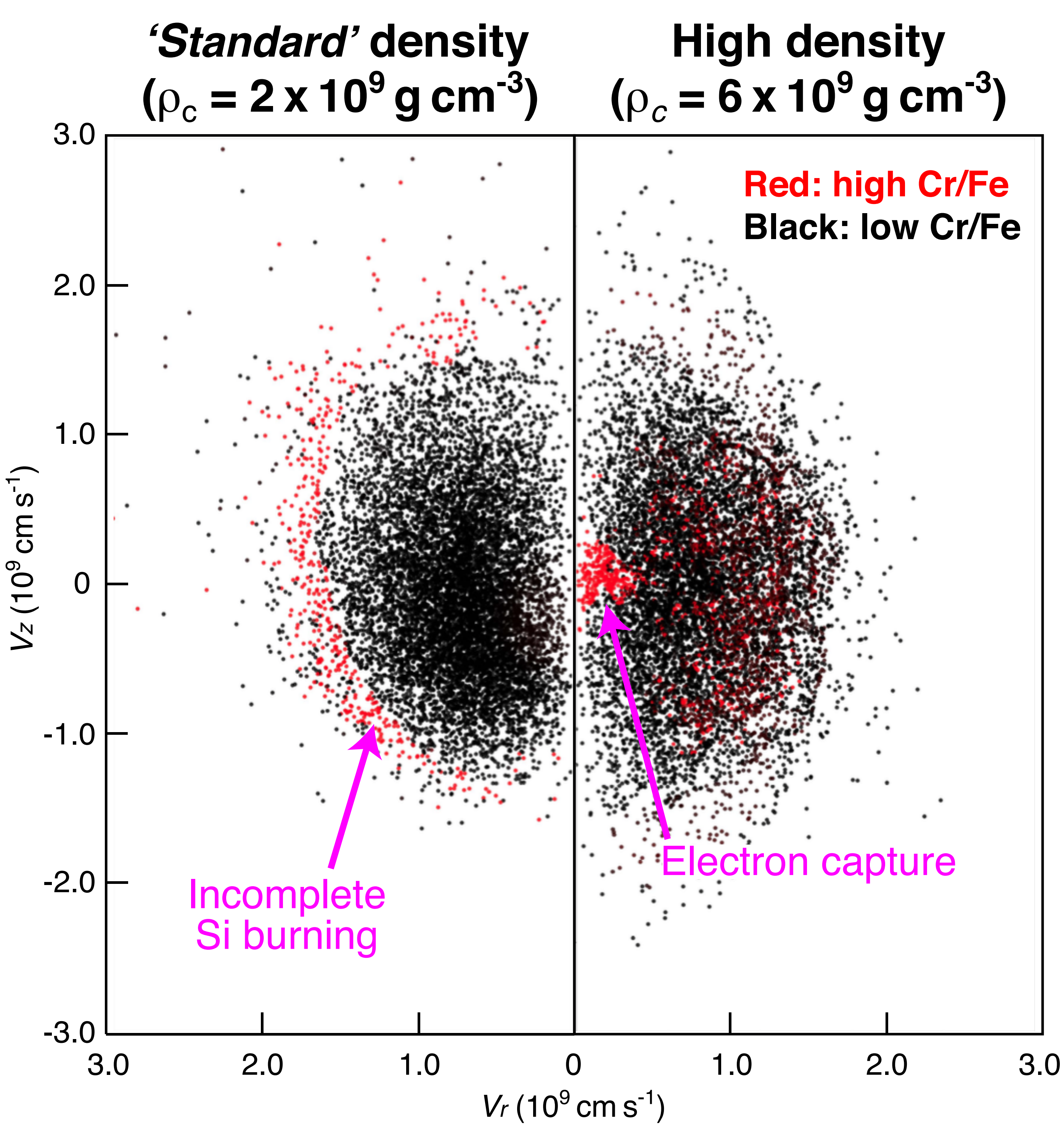
Metallicity effect

Leung & Nomoto 2017



To disentangle the degeneracy…

Cr’s (and Mn’s) origin/distribution are the key



High metallicity case:

Cr, Mn (Ar, Ca)

➔ Si burning

Ni ➔ *n*-rich NSE

High density case:

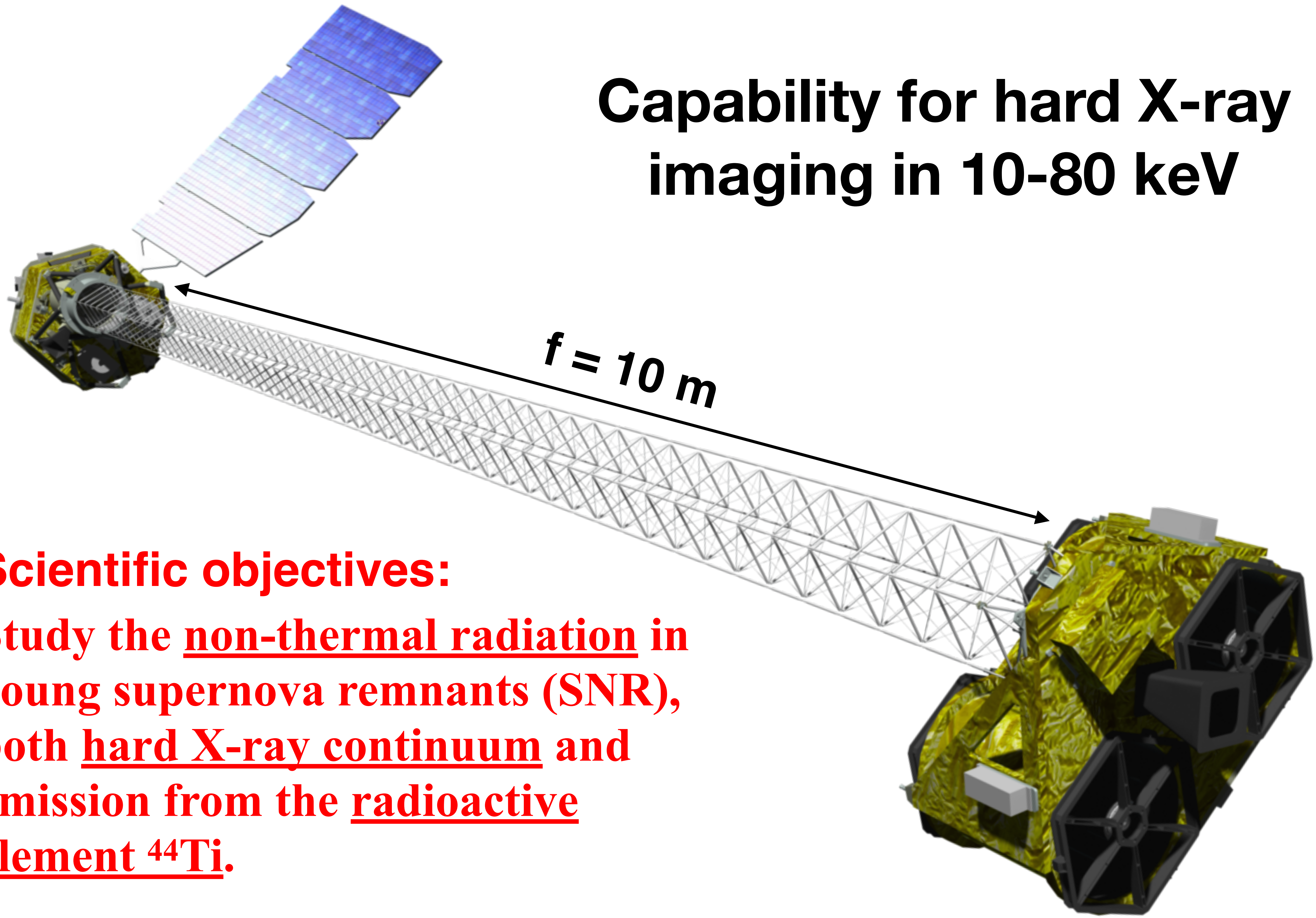
Cr, Mn, Ni

➔ *n*-rich NSE

(3 elements coincident)

NuSTAR!?

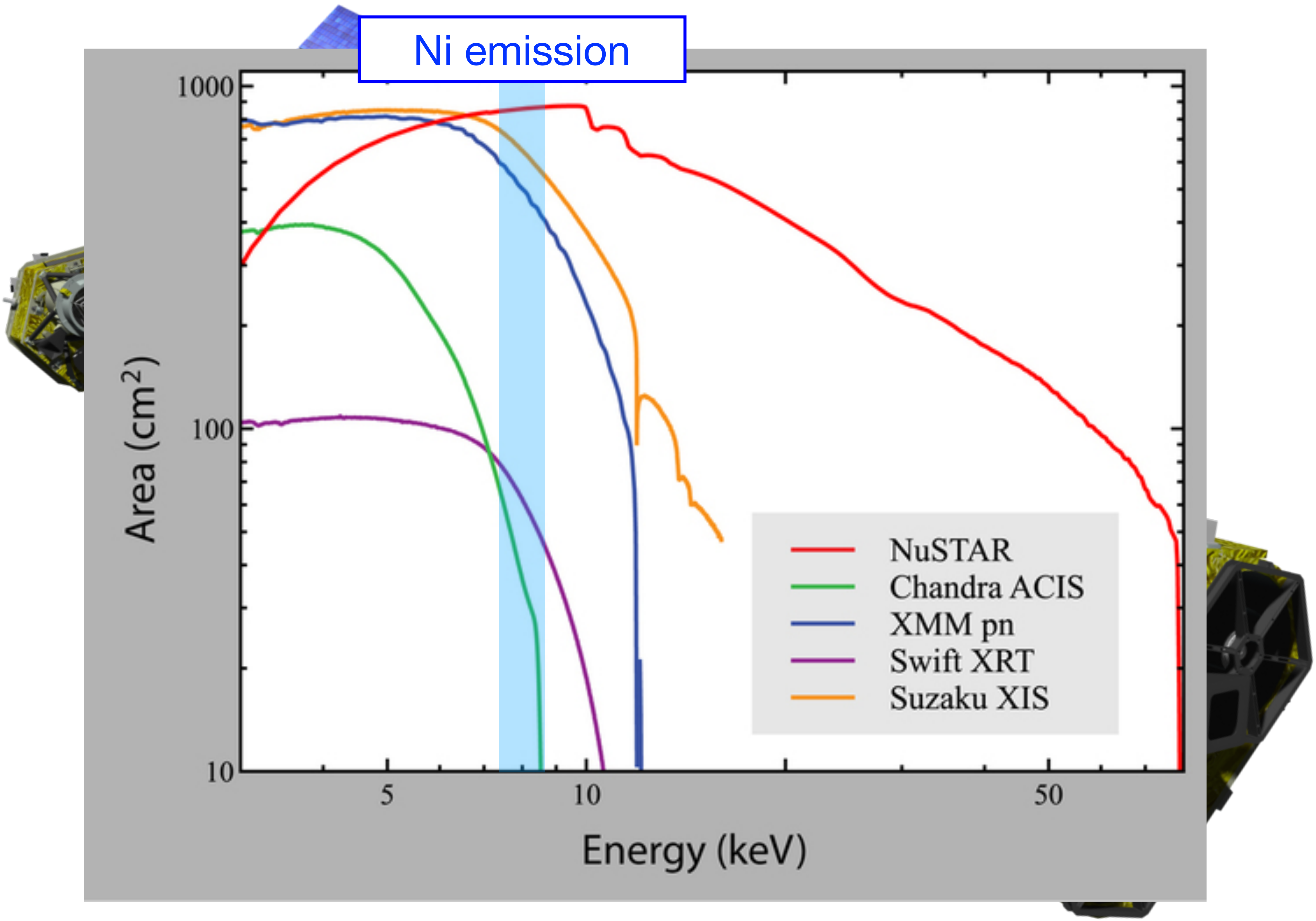
Capability for hard X-ray imaging in 10-80 keV



Scientific objectives:

Study the <u>non-thermal radiation</u> in young supernova remnants (SNR), both <u>hard X-ray continuum</u> and emission from the <u>radioactive element ^{44}Ti</u>.

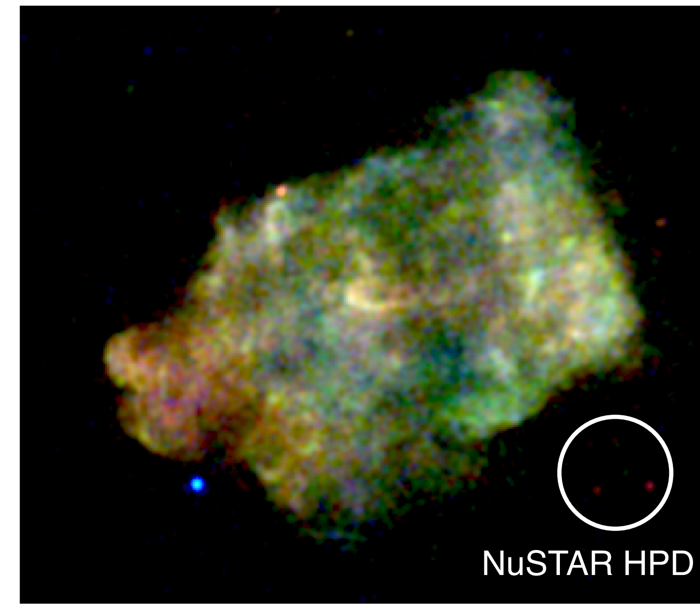
NuSTAR!?

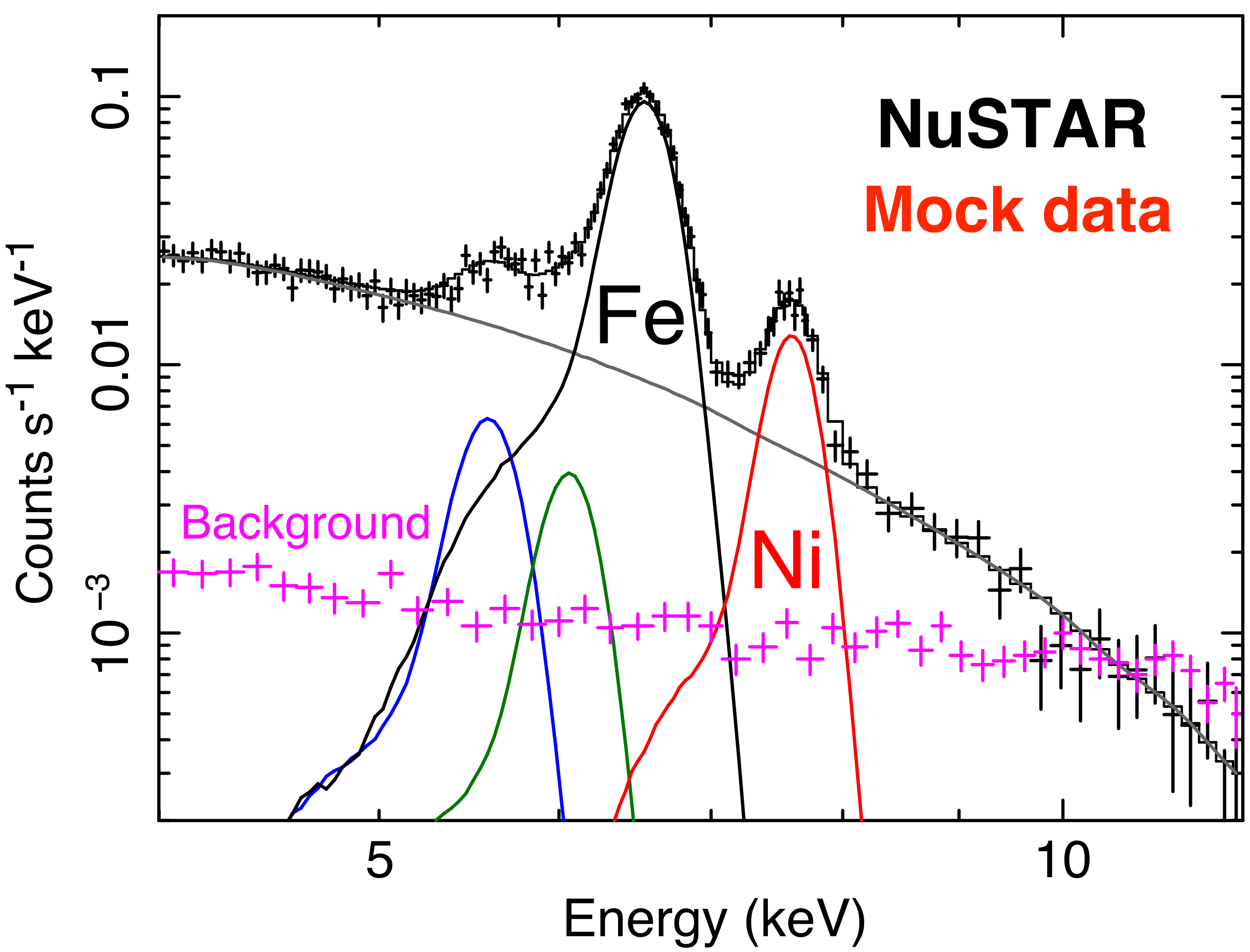

Ni emission
1000
100
10
5
10
50
Area (cm²)
Energy (keV)
NuSTAR
Chandra ACIS
XMM pn
Swift XRT
Suzaku XIS

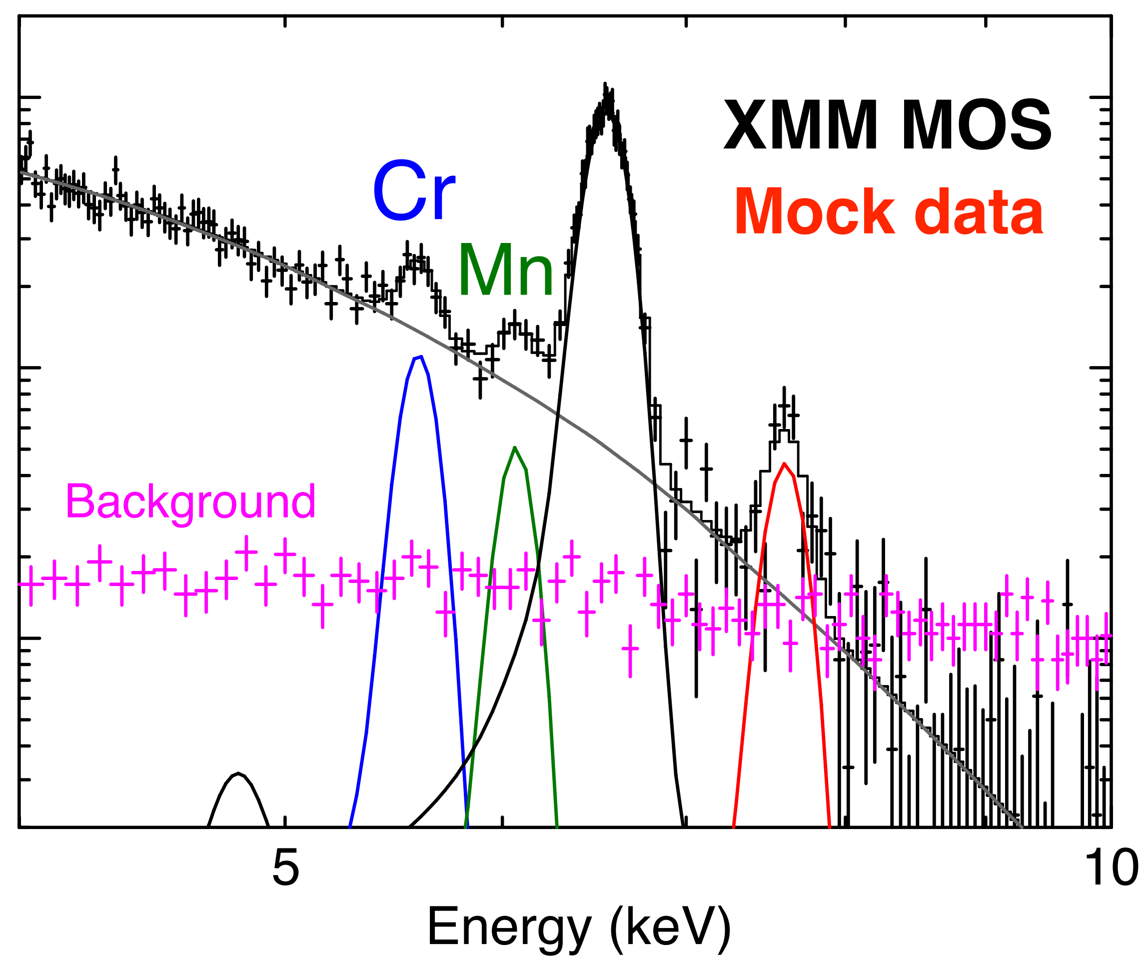
Objective of 3C 397 observations

Comparison of morphologies of Ni (NuSTAR) and Cr (XMM)

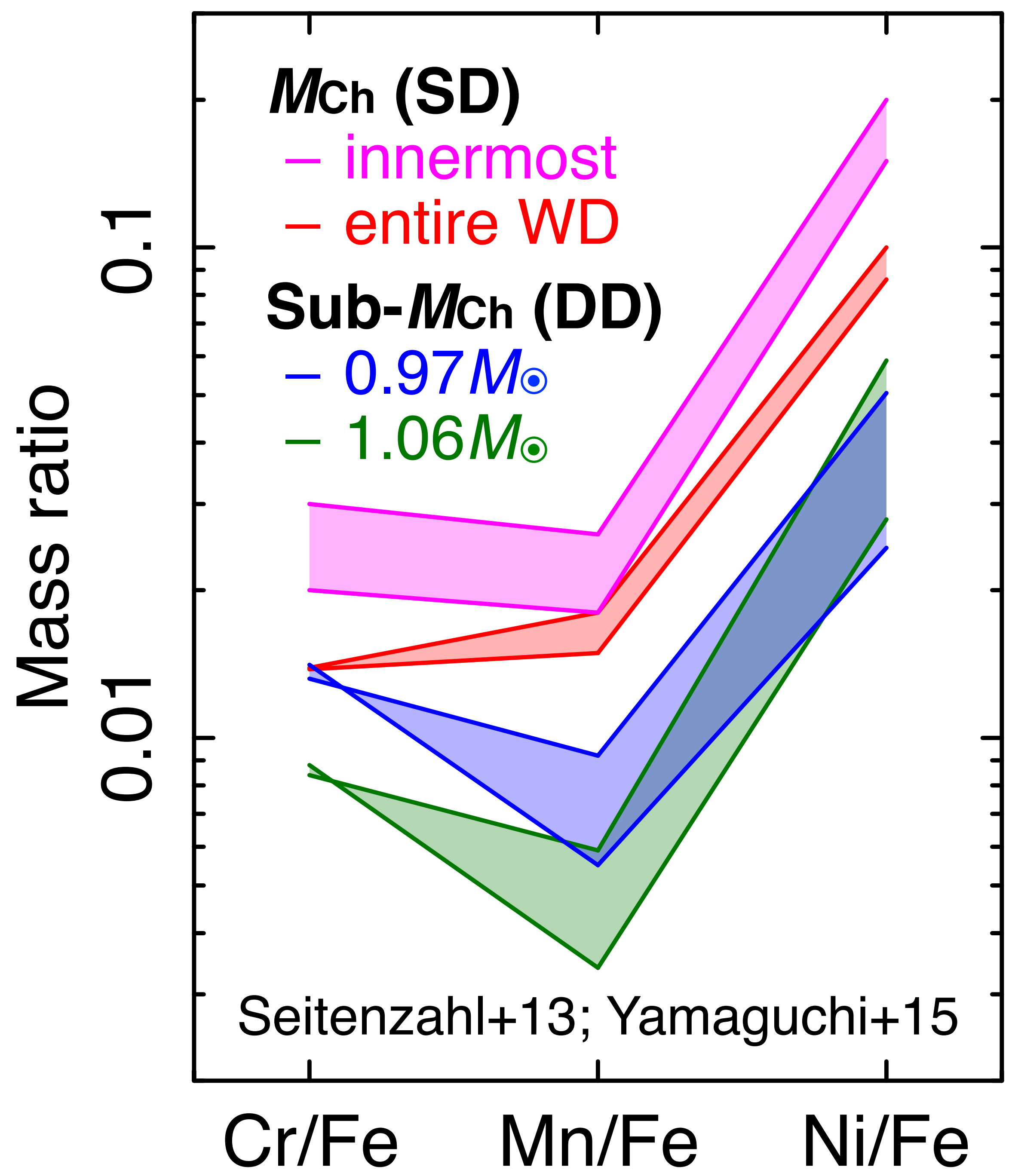
If identical, high density progenitor is very likely

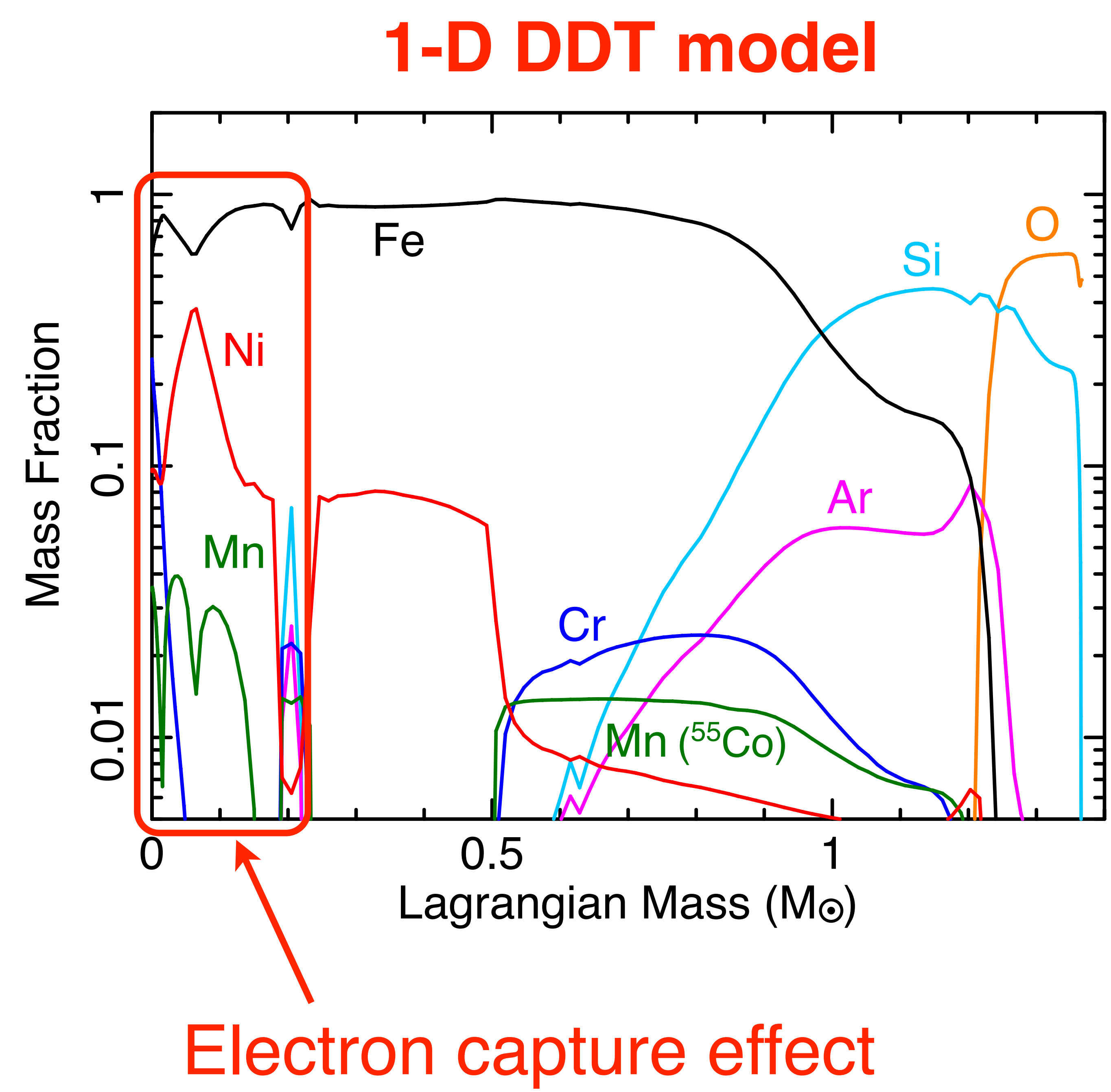






Theoretical predictions

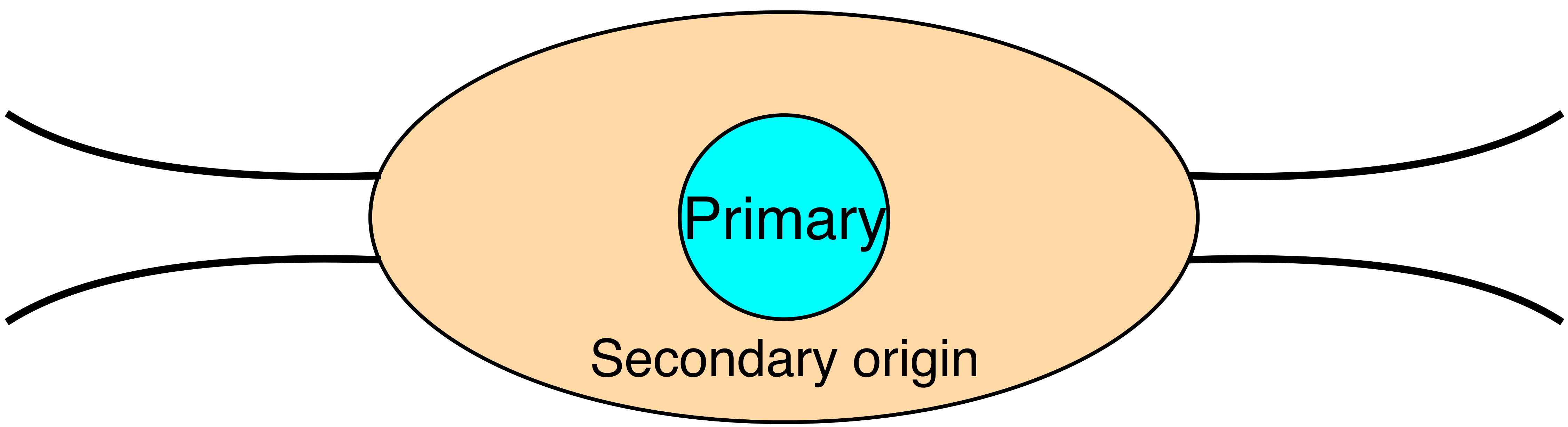




Let's find SNe Ia with high Ni/Fe and Mn/Fe ratios

Classical DD model (80s~90s)

The secondary WD accretes onto the primary so the total mass exceeds M_{Ch} (Webbink 1984)

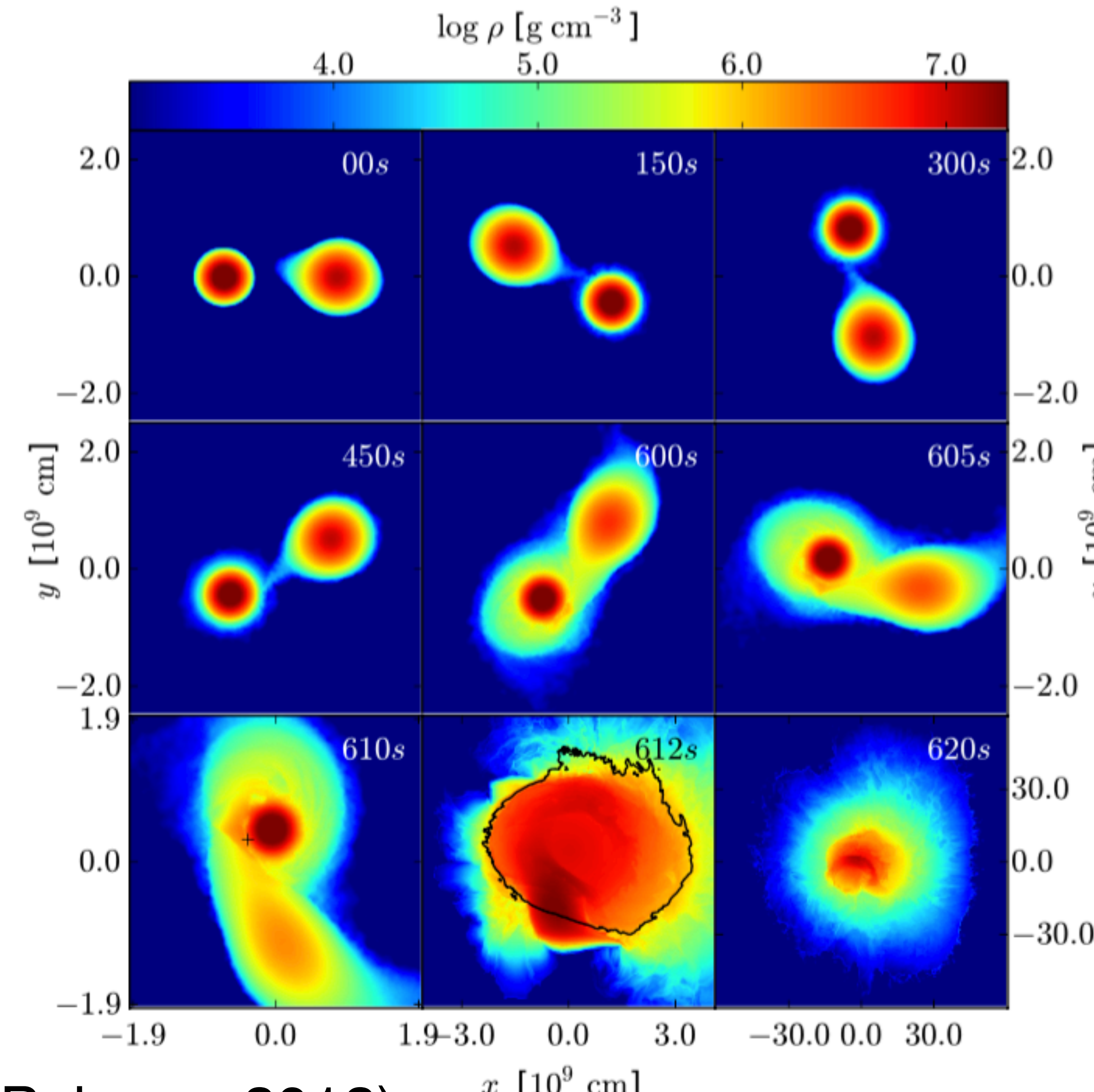


Explosion unsuccessful

Collapse into NS via O-Ne-Mg WD (Saio+1985)

Updated DD model

Violent merger (e.g., Pakmor+2010, 2012)



(Pakmor+2012)

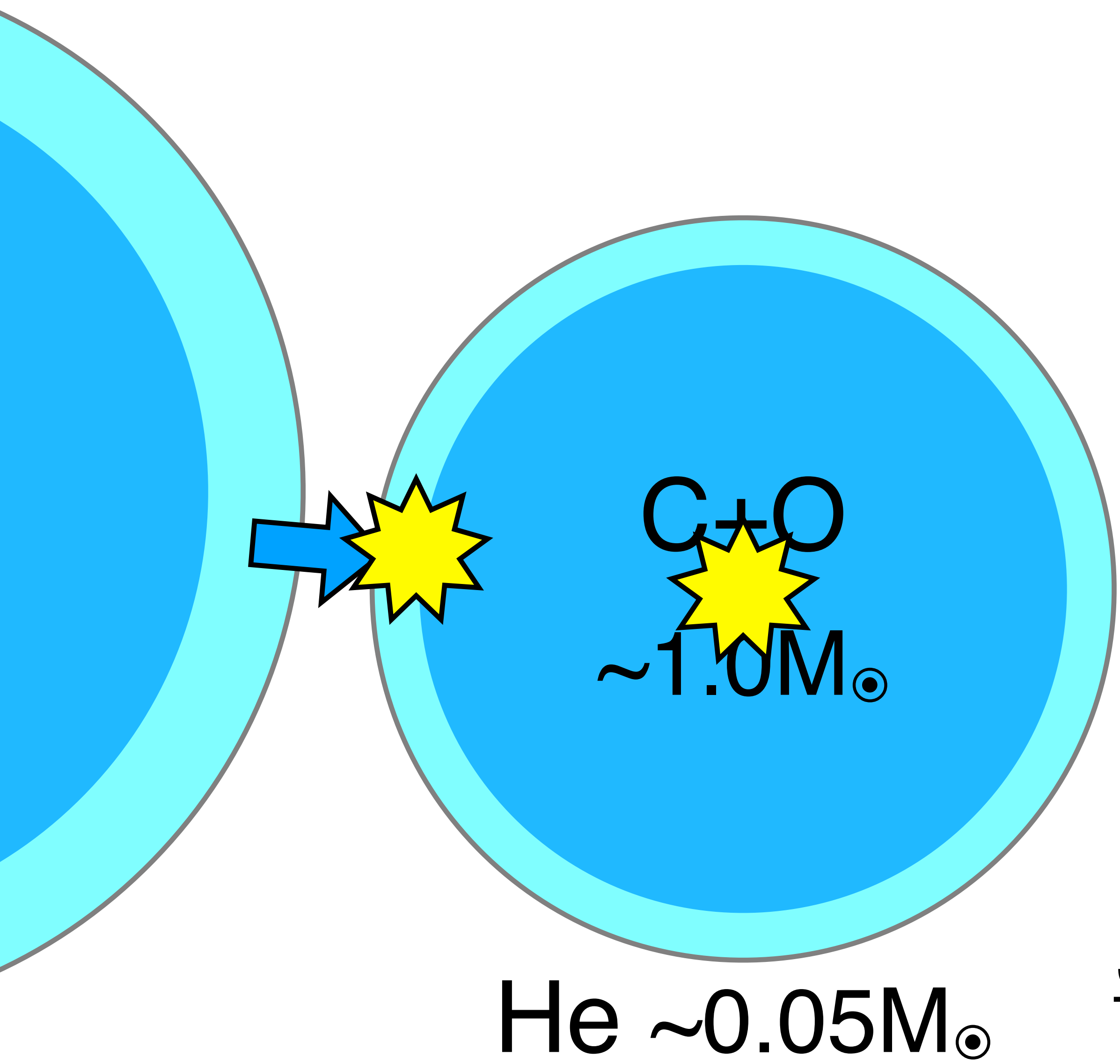
Explodes within ~ 100 s

M_1 ~1.1M$_\odot$, M_2 ~0.9M$_\odot$ required for typical SN Ia

Hard to explain observed SN rate.

Latest DD model

Dynamically-driven double degenerate double detonation (D^6: e.g., Shen+2018)



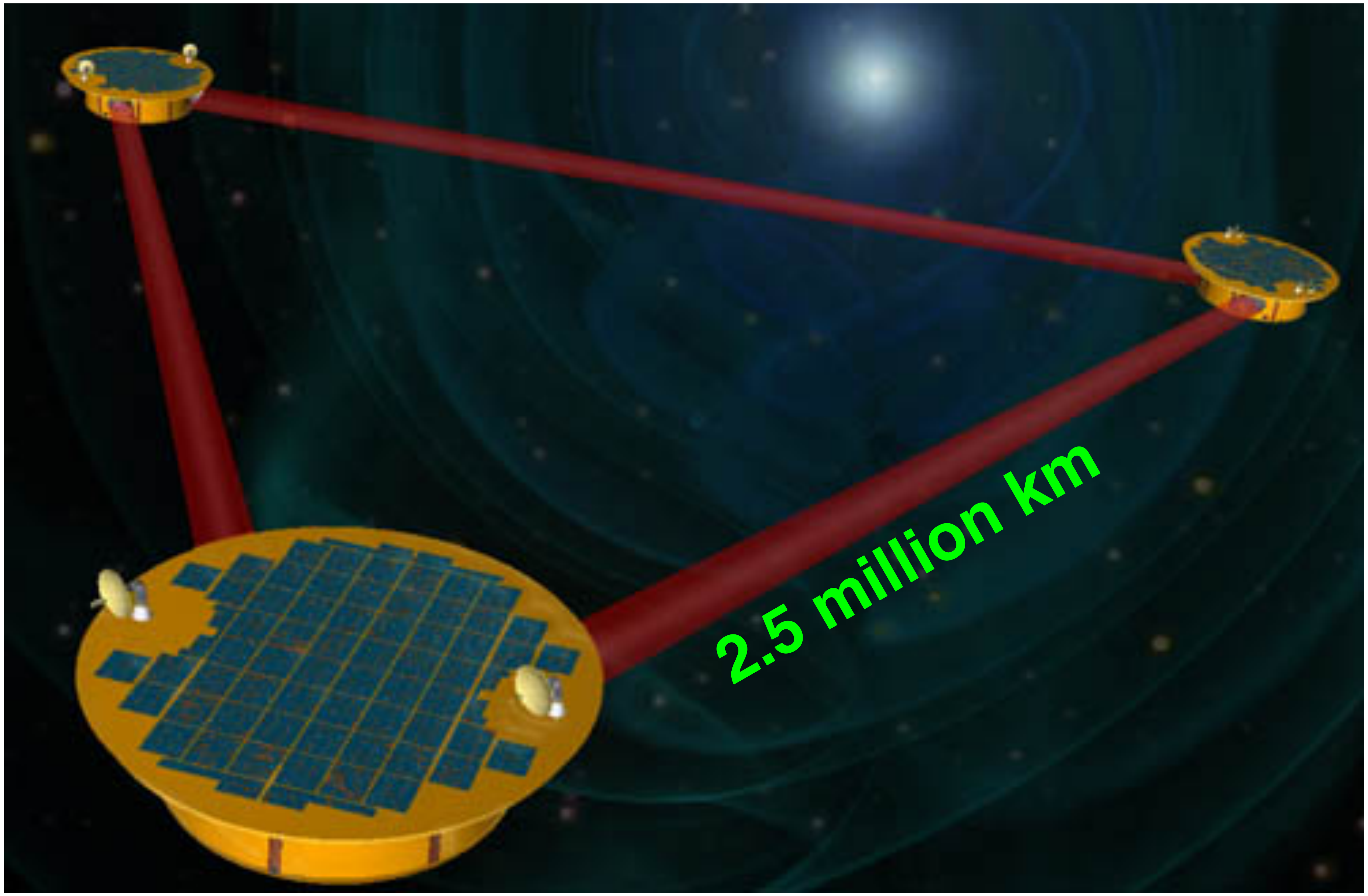
Accretion of tidally stripped materials from secondary ignites He detonation on primary surface

➔ Triggers C detonation

Secondary WD remains intact

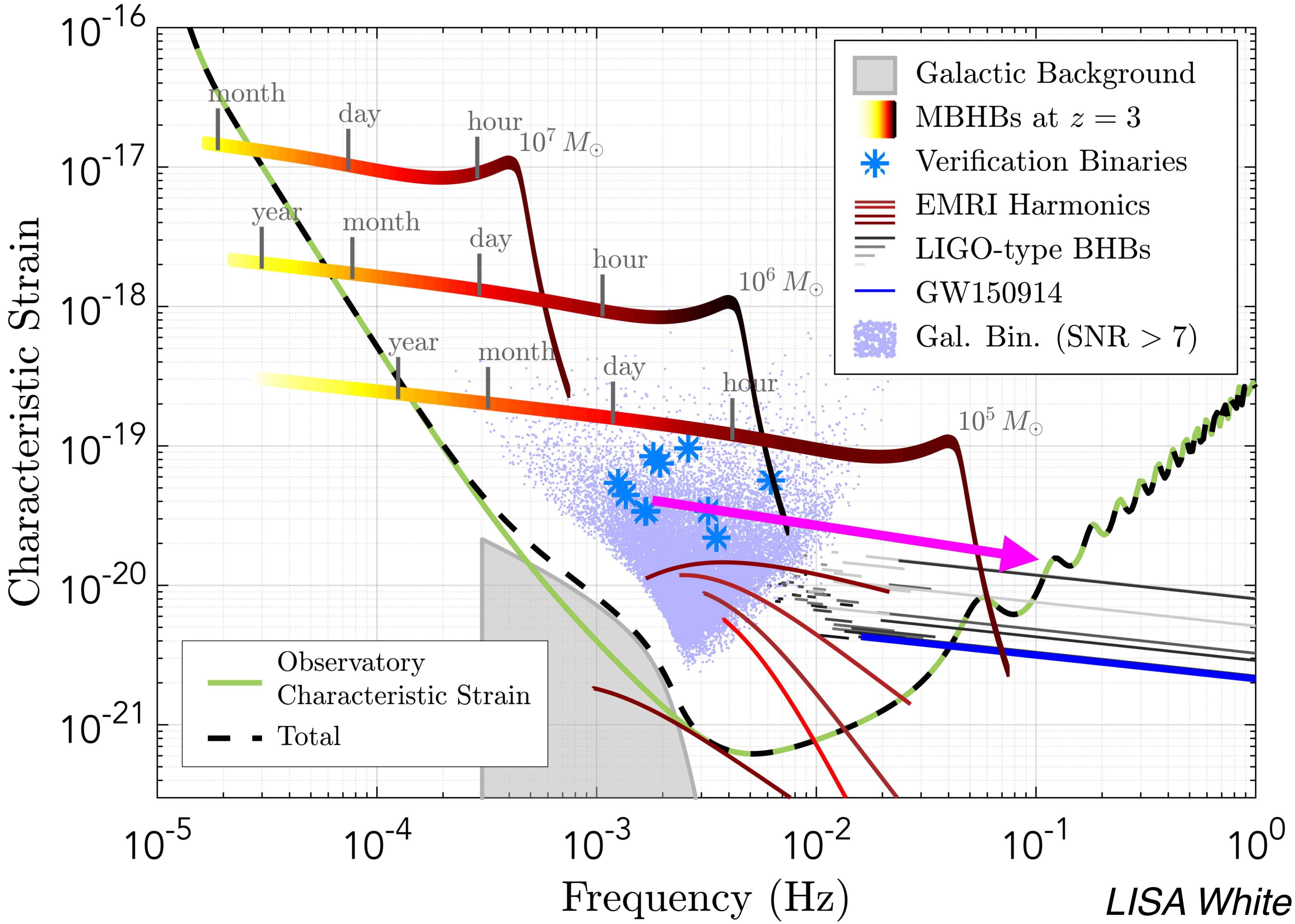
➔ sub-M_{Ch} ejecta + high-v WD

Laser Interferometer Space Antenna (LISA)



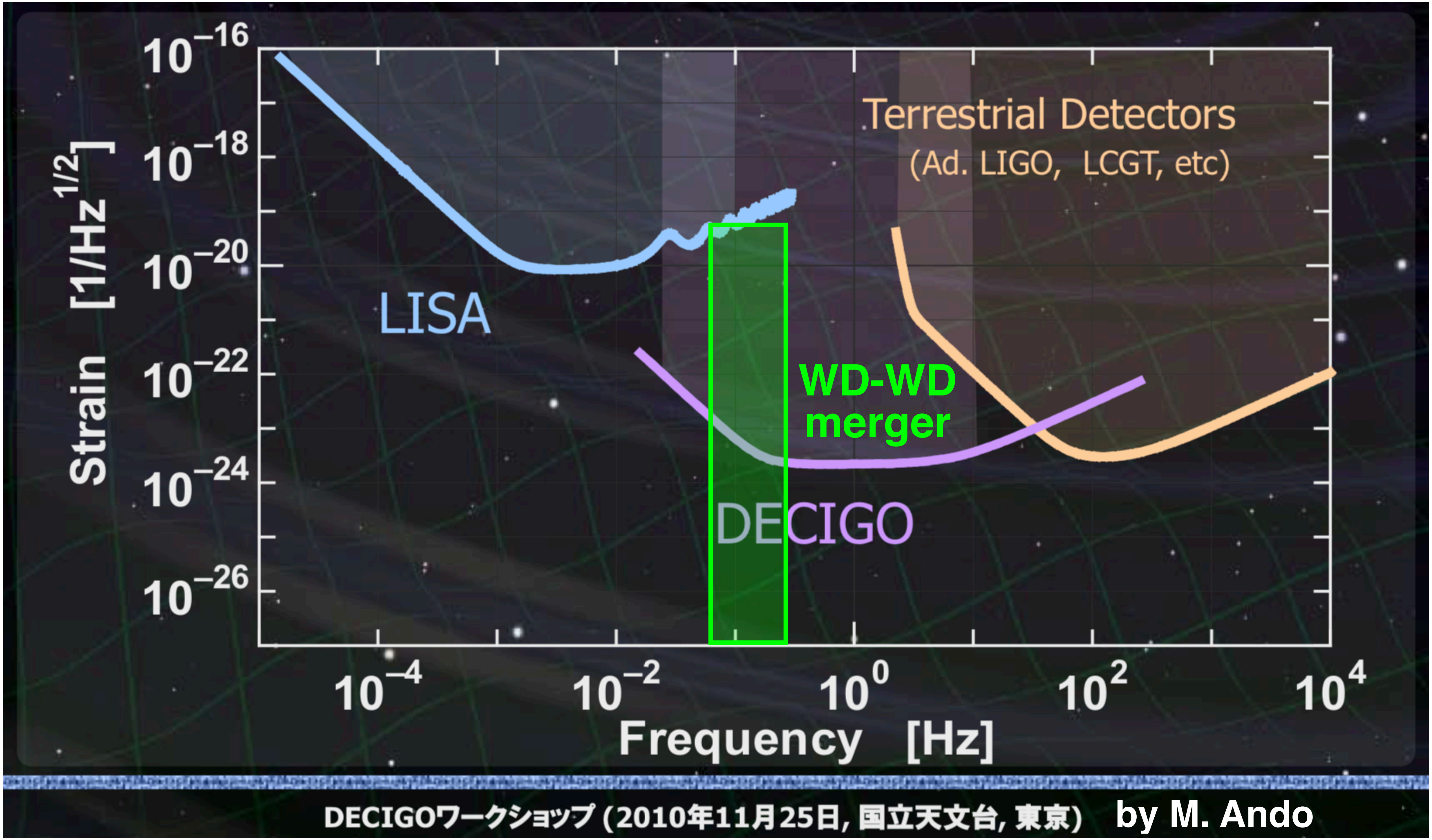
ESA's mission to be launched in ~2034

Laser Interferometer Space Antenna (LISA)



LISA White Paper

DECIGO



Can directly detect WD-WD mergers!