Chemical Enrichment in Supernova Remnants with IXO

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Supernova explosion mechanisms are not fully understood

Core Collapse in $M>8M_{sun}$
(Type II, Ib, Ic)

Neutrino convection ?
Jets ?

What is the mass cut for the neutron star/black hole ?

Thermonuclear in WD binary
(Type Ia)

Single degenerate ?
Or double ?

How does burning ignite and proceed?

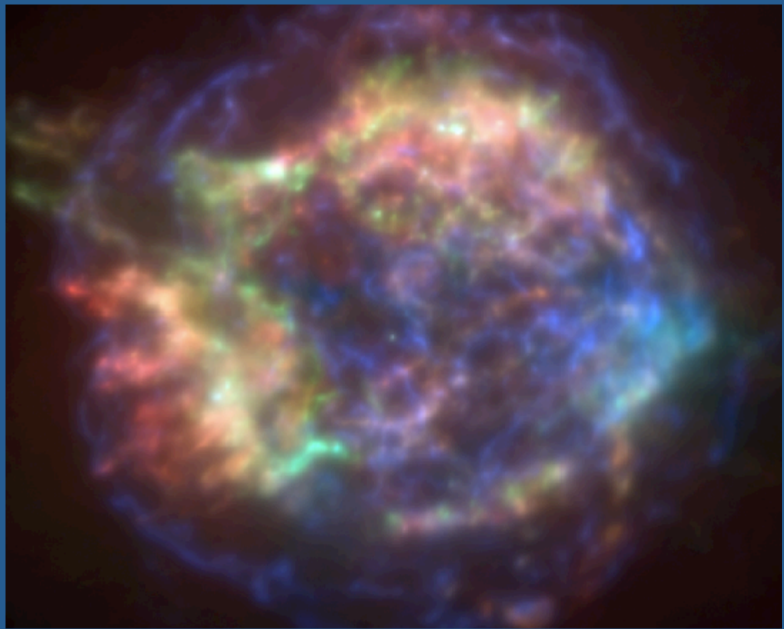
The KEY is Fe

For either type of supernova, Fe production is closely dependent on the details of the explosion mechanism

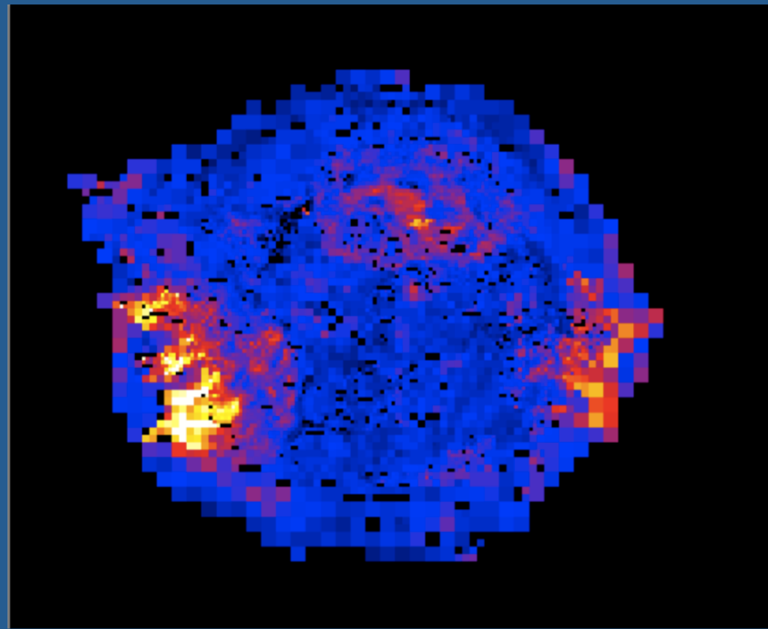
Supernova remnants offer a detailed look at specific explosion outcomes and environments

Cassiopeia A

core-collapse SNR with the most prominent Fe emission



Cas A Chandra image at IXO resolution
Red: Fe, Green: Si
Image Credit: Hughes et al. Astro2010S, 136



Chandra Fe abundance map
(Hwang & Laming, 2010 TBS)

Heavy mass loss prior to explosion (Young et al. 2006)
Advanced evolutionary state: reverse shock has heated a substantial portion of Fe ejecta in 330 yr (Laming & Hwang 2003)
Si and Fe distributions are distinct (Hughes et al. 2000, Hwang et al. 2000, Willingale et al. 2002, DeLaney et al. 2010)

Fe Production by α-rich freeze-out

α-rich freezeout is complete Si burning that takes place at higher temperature/lower density compared to incomplete Si burning

The ashes have a distinctive composition:
mostly ^{56}Ni and a small amount of radioactive ^{44}Ti and other (stable) isotopes, mostly in Fe group

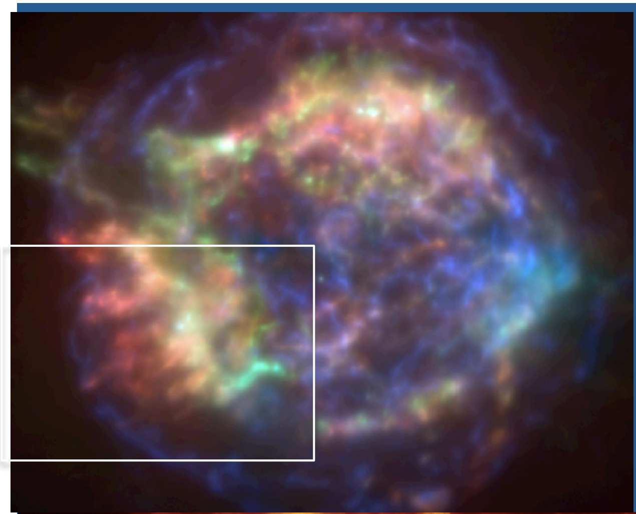
Nothing else….

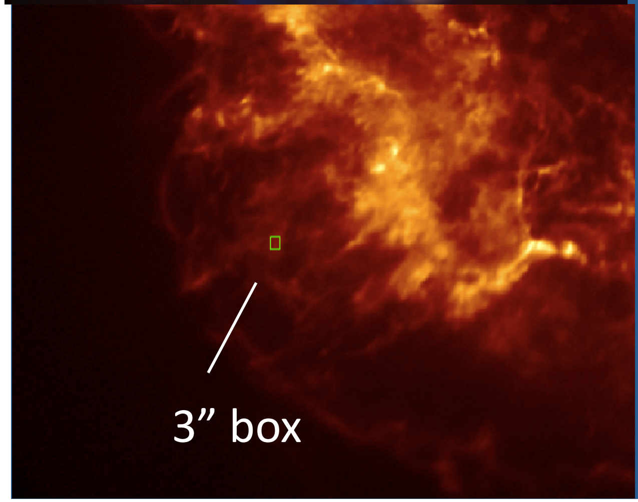
^{44}Ti -> ^{44}Sc -> ^{44}Ca has been detected for Cas A through the nuclear de-excitation lines:

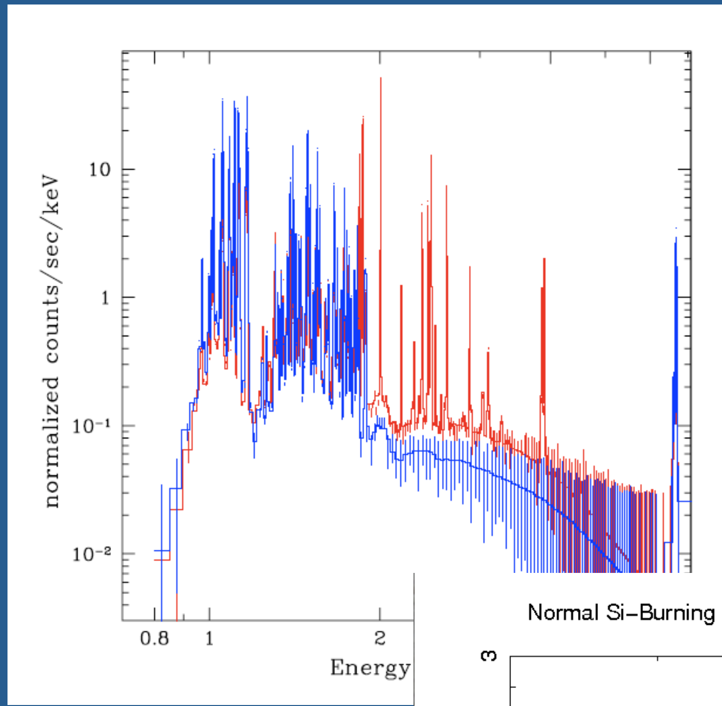
^{44}Sc at 67.9, 78.4 keV (Vink et al. 2001)
^{44}Ca at 1157 keV (Iyudin et al. 1994)
INTEGRAL (Renaud et al. 2006, Martin et al. 2009)

No strong velocity constraints yet (future hard X-ray missions)
γ-ray detectors cannot localize the emission

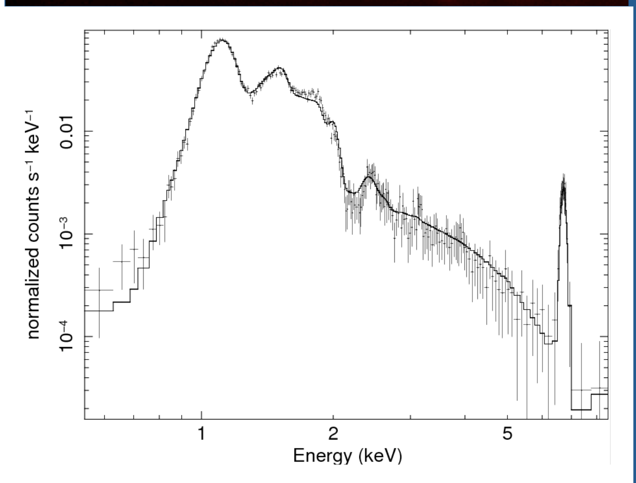
Pure Fe from α-rich freeze-out



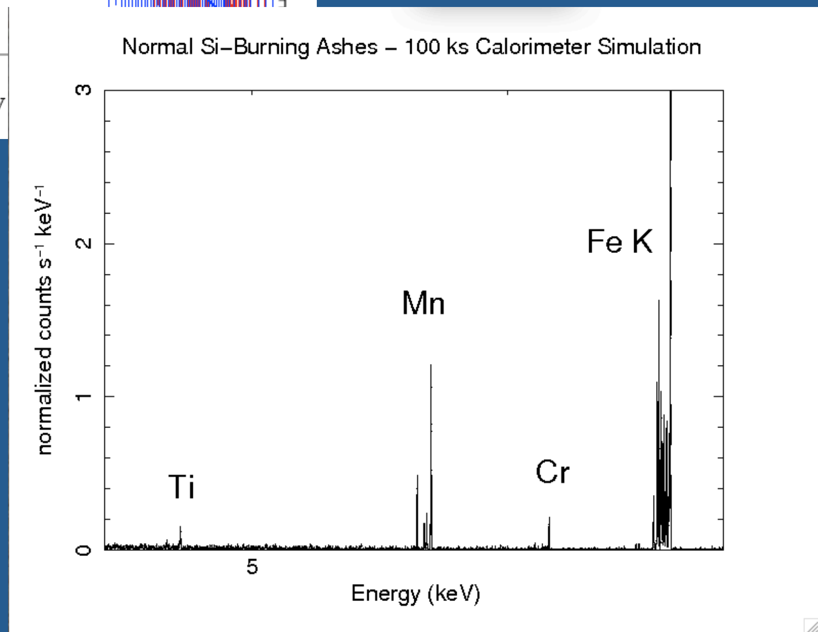




Broadband: (blue) pure Fe
(red) mixed with intermediate mass elements
(Hughes et al. Astro2010S, 136)



Hwang & Laming 2003
Chandra ACIS
Fe/Si > 8 solar



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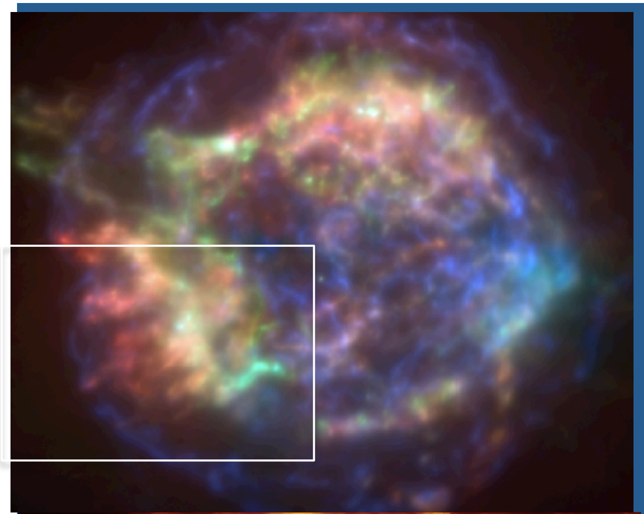

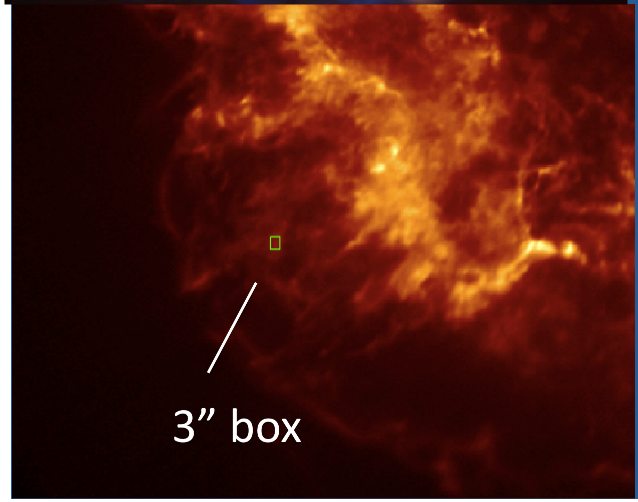

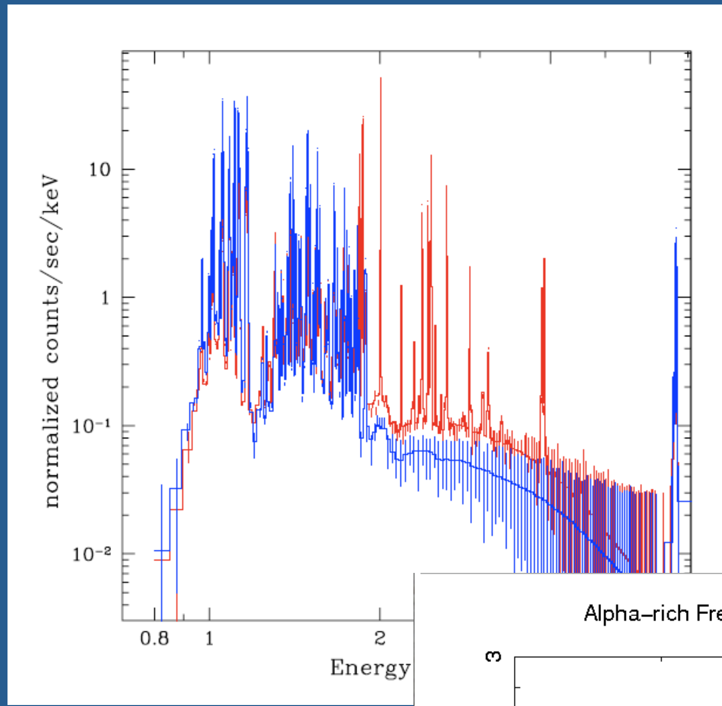

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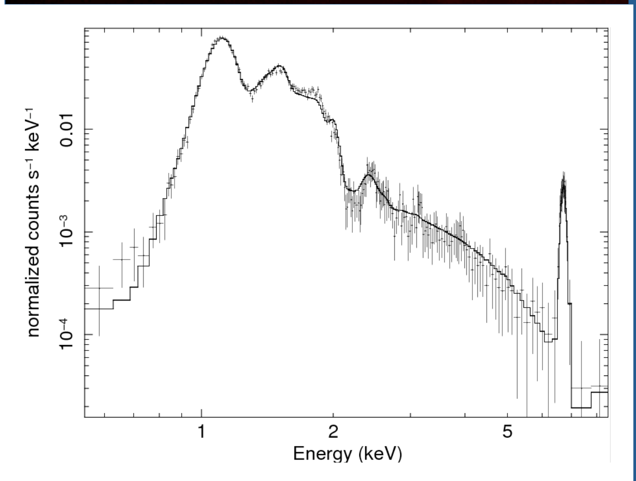
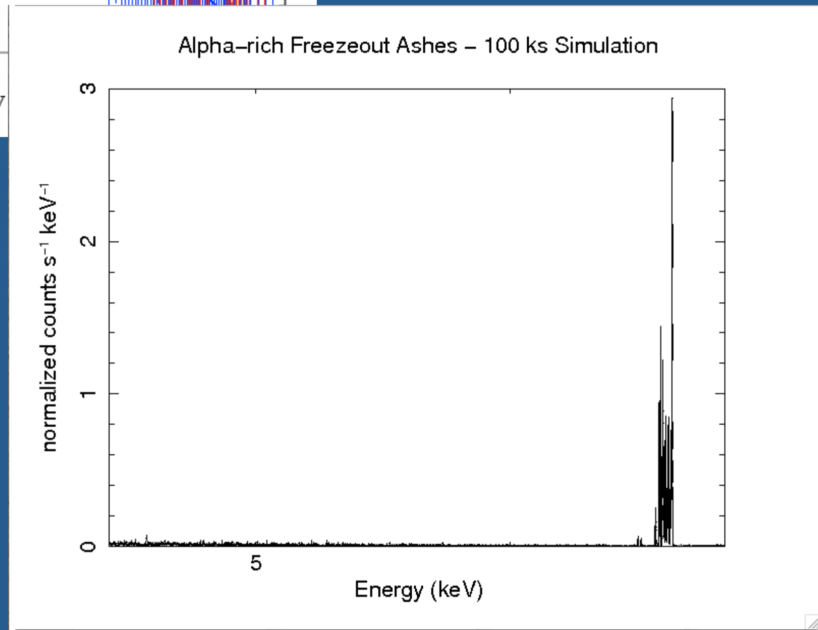


NO Mn, Cr, or appreciable ^{48}Ti for α-rich freezeout

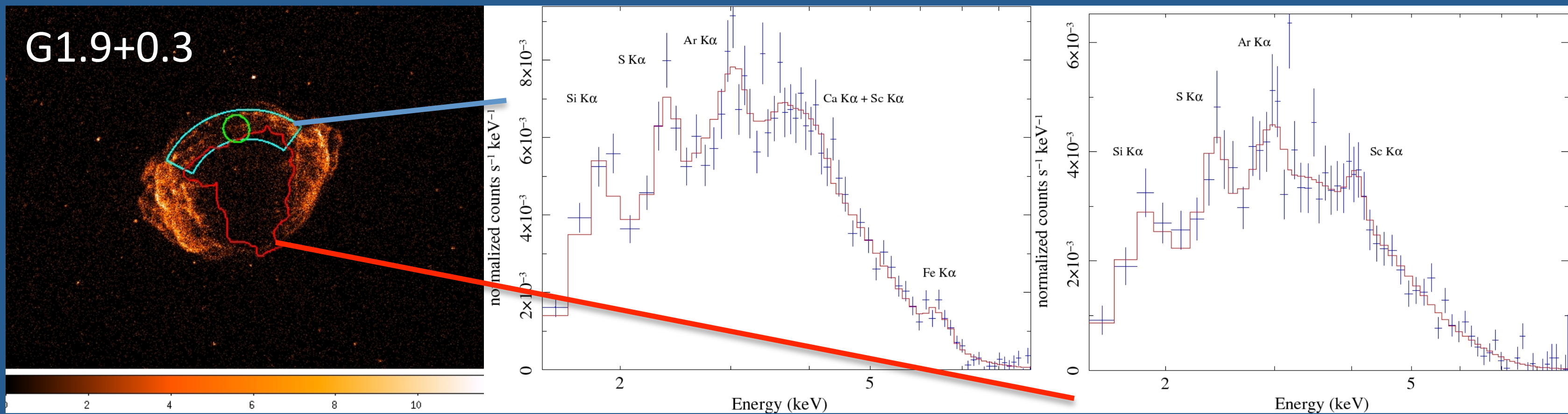
Hwang & Laming 2003
Chandra ACIS
Fe/Si > 8 solar



Innershell lines of ^{44}Sc will locate α-rich freezeout sites

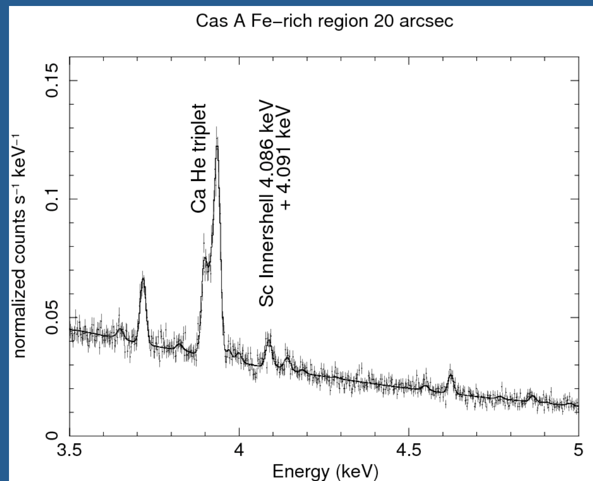
$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$

Innershell lines of ^{44}Sc are at 4.086 and 4.091 keV, near the He-like blend of Ca
So far, no success in Cas A with CCDs (Theiling & Leising 2006)
Only detection is in the youngest (~100 yr old) Galactic SNR G1.9+0.3 with Chandra (Borkowski et al. 2010 TBS)



IXO will not only resolve, but in some cases also map these lines, showing directly the sites of α-rich freezeout

Right: 100 ks IXO calorimeter simulation for 20” square Fe-rich region in Cas A
Other likely sources include SN1987A



IXO may also measure and map other X-ray lines associated with radioactive decays

^{59}Ni -> ^{59}Co (half-life 75 yr) produced in innermost ejecta by α-rich freezeout and normal Si burning
Lines at 6.915 and 6.930 keV with fluxes of a few 10^{-6} $cm^{-2}s^{-1}$ predicted (entire SNR) for Tycho's SNR and SN 1006 (Leising 2001)
Lower fluxes for core-collapse events

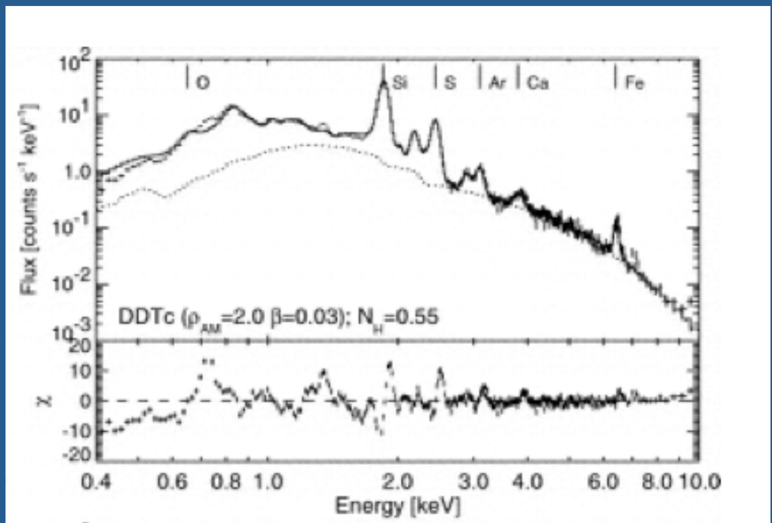
^{55}Fe -> ^{55}Mn (half-life 2.7 yr) mostly in incomplete Si burning
Lines at 5.888 and 5.899 keV
SN 1987A may be a possible target

These X-ray lines from radioactive decays directly trace Fe production and allow a detailed look at the nucleosynthesis and dynamics of the inner ejecta

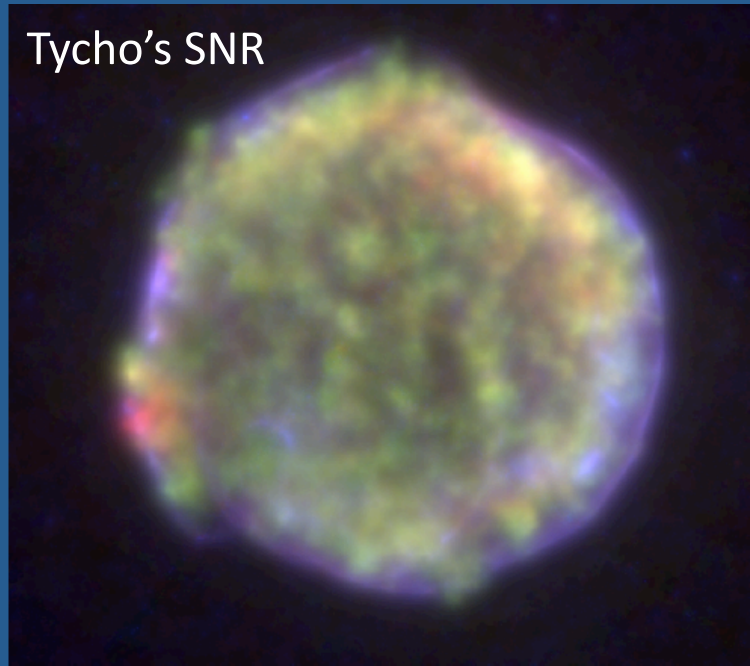
Type Ia Supernovae

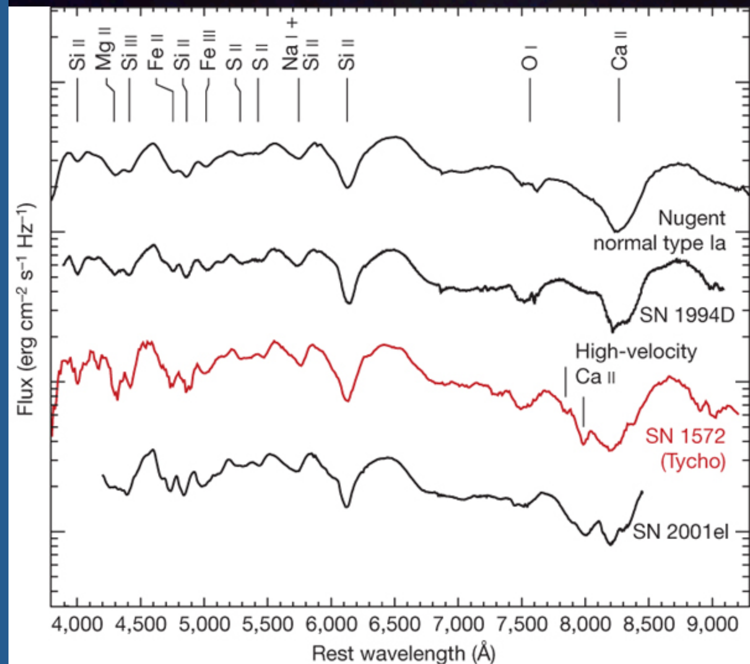
Use for cosmology calibrates intrinsic supernova brightness to light curve shape
Light curves are powered by radioactive decays, primarily ^{56}Ni
Mass of Fe depends on explosion details

SNR X-ray spectra can be used to constrain explosion mechanism (Badenes et al. 2006, 2008)
Delayed detonations favored so far



Tycho's SNR (XMM) with DDT model (Badenes et al. 2006)



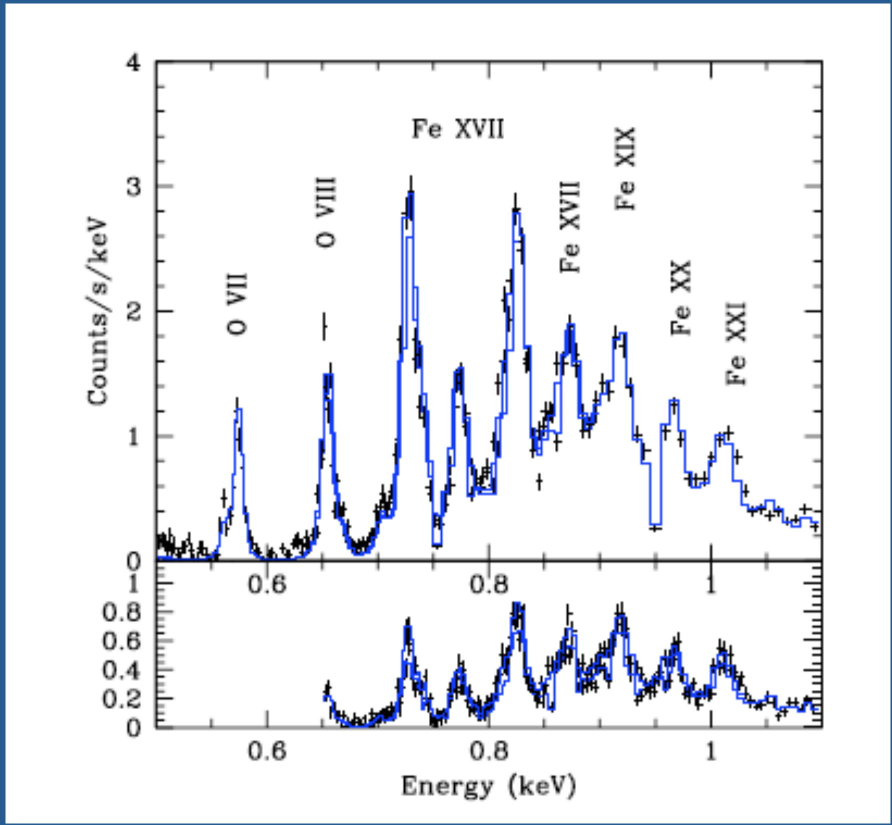


Tycho's SNR echo spectrum matches normal Ia SNe (Krause *et al.* 2008

X-ray analysis (Badenes et al. 2006, 2008; Kosenko et al. 2009, 2010) and light echo spectra concur:

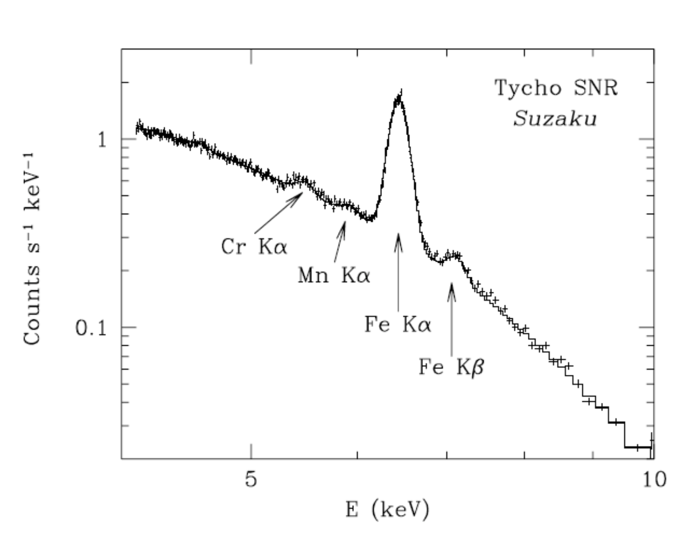
Tycho's SN, 0519-69 had normal Ia energies and Fe masses
0509-675 was more energetic, like SN 1991

Not a clear association with star formation history and explosion energy for the two LMC SNRs (Badenes et al. 2009, Kosenko et al. 2010)

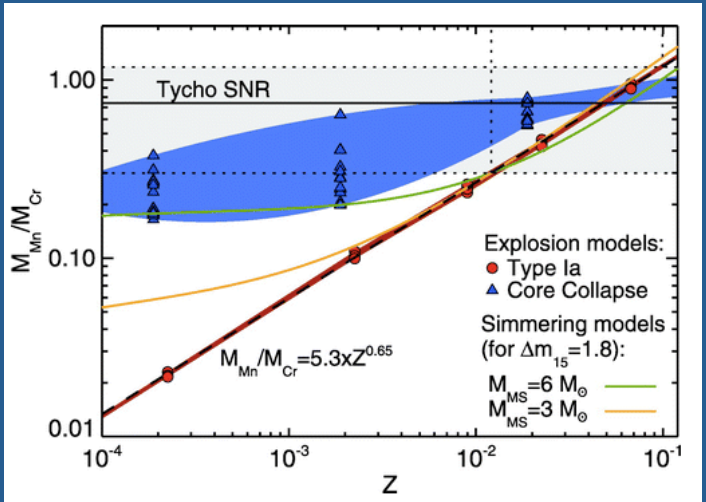


RGS spectra of 0519-69 (Kosenko et al. 2010)
Layered Ia ejecta model required to match line emission
Layered ejecta in Ia SNRs: Tycho, DEM L71A, 0519-69, DEM L238, L249

Clues to Ia Progenitor Properties



Tamagawa et al. 2008



Badenes et al. 2008

Low abundance elements in the Fe group have been detected in SNRs

For Type Ia nucleosynthesis, Mn/Cr mass ratio is sensitive to the initial metallicity of the progenitor (Badenes et al. 2008) *Solar metallicity* for Tycho's SNR and W49B (Badenes et al. 2008 using Tamagawa et al. 2008, Hwang et al. 2000); *significantly enhanced metallicity* for Kepler's SNR (Park et al. 2010)

Cr has been measured in Cas A (Yang et al. 2008, Maeda et al. 2009)

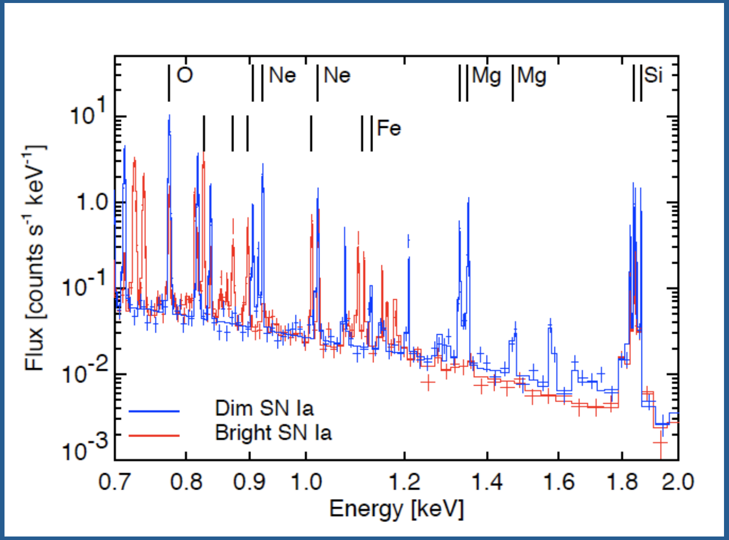
IXO will measure these fluxes easily and should also provide velocities

We need atomic physics calculations to compute emissivities for these elements

Studies of Extragalactic SNRs with IXO

LMC/SMC SNRs can be studied in nearly the same detail as Galactic SNRs

For other Local Group galaxies (M33, M31), IXO will provide the opportunity identify Ia SNRs (bright vs dim) in the context of the local stellar populations



100 ks simulations of 400 yr old SNRs at the distance of M33 show that bright (1 M_{sun} Ni) and dim (0.3 M_{sun} Ni) are easy to distinguish
(Hughes et al. Astro2010S, 136)

Summary

Test nucleosynthesis predictions for a sizable sample of SNRs of all types including less abundant species that are produced with Fe

Obtain detailed measurements of element abundances and ejecta velocities

Infer masses, spatial distribution, and velocities of radioactive species associated with Si-burning near the core of the SN

-> Reconstruct the explosion process, constrain progenitor metallicities (Cr/Mn ratio)

Identify and classify SNe in Local Group within their local stellar context

Spectroscopy of extragalactic SNRs beyond the Local Group