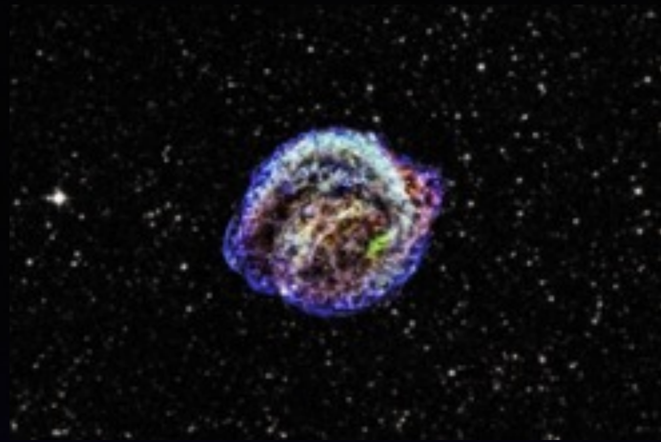
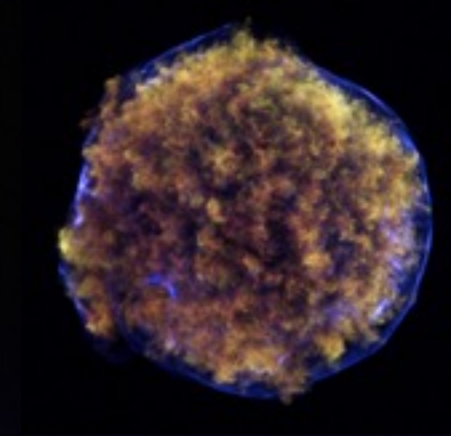
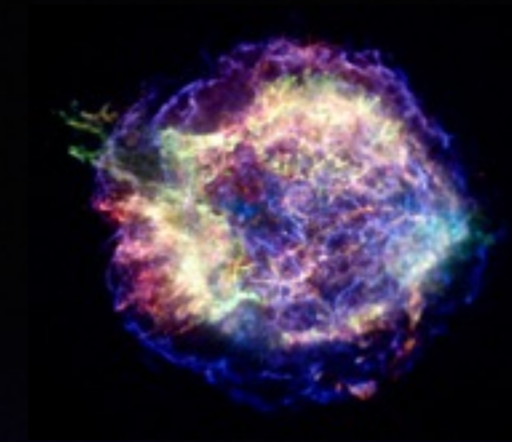


Observing Supernova Remnants with Lynx

Laura A. Lopez
Ohio State University

August 9, 2017

Conclusions

Chandra has revolutionized our view of supernova remnants: their explosive origins, shock heating, dynamical evolution, particle acceleration properties, and associated neutron stars.

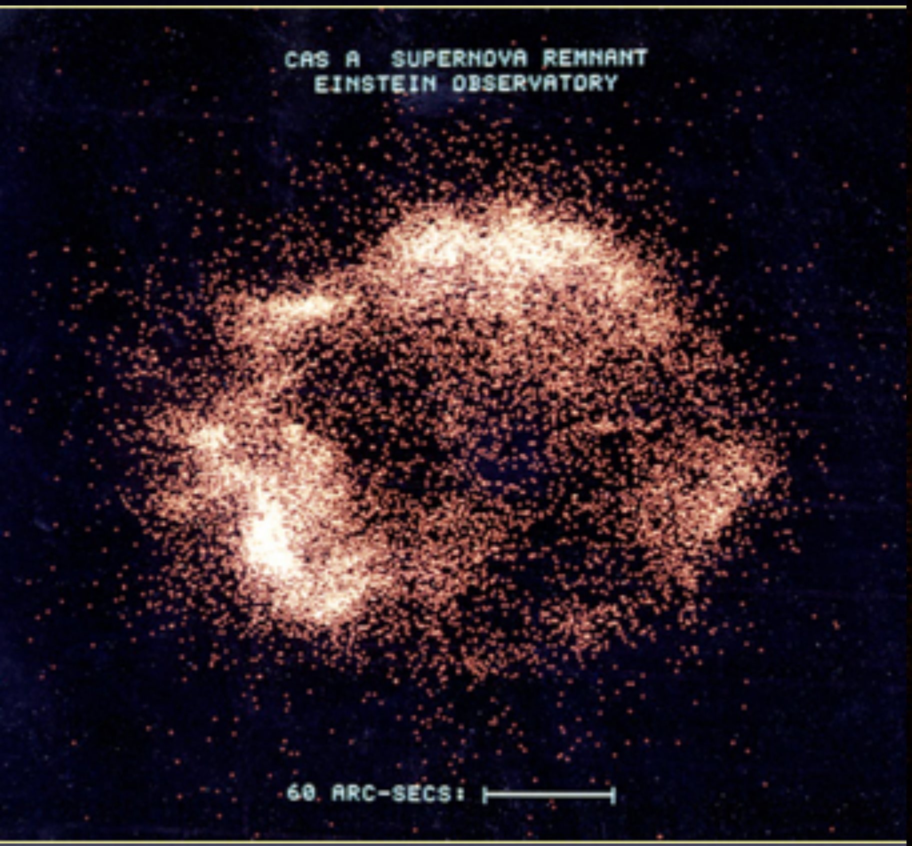
Limitations of current facilities: challenges associated with gratings spectra of extended objects, sensitivity (and spatial resolution) to probe extragalactic populations

SN simulations are finally making predictions for chemical yields, spatial distribution and kinematics of metals, formation and kicks of neutron stars. X-ray data gives ability to test models in ways that cannot be done at any other wavelengths.

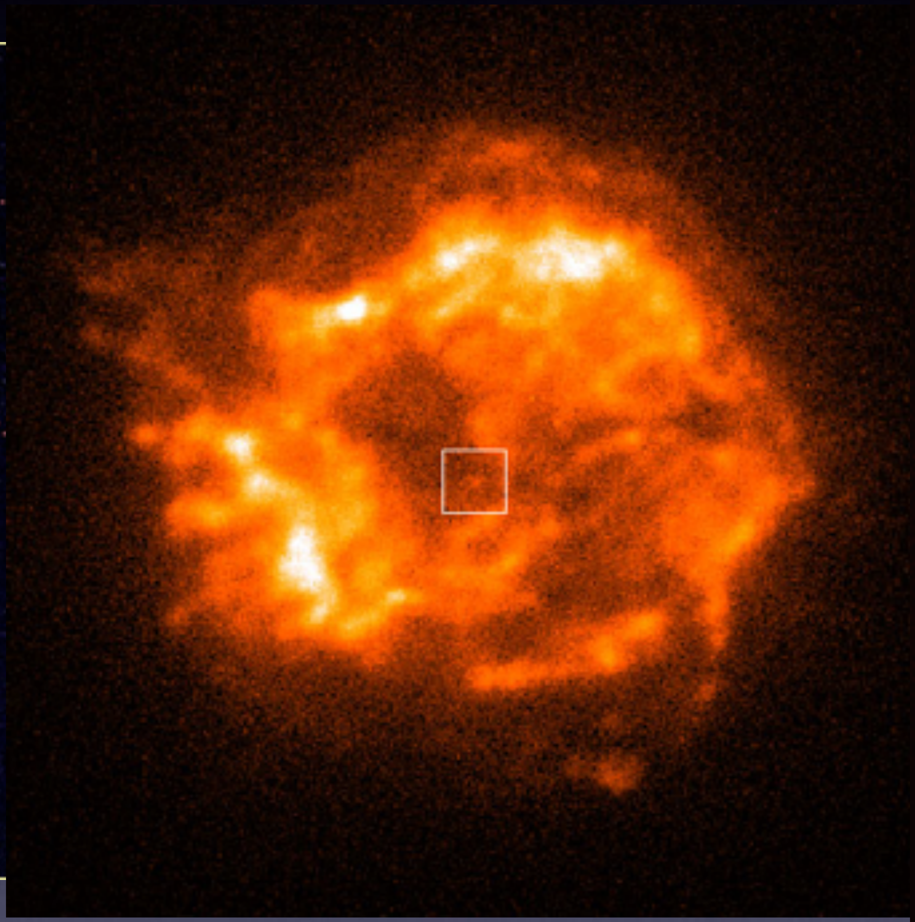
Lynx will give 3D structure of tens of SNRs and enable characterization of hundreds of SNRs in the Local Group - key to understanding explosion mechanisms and SN feedback

Chandra's Legacy

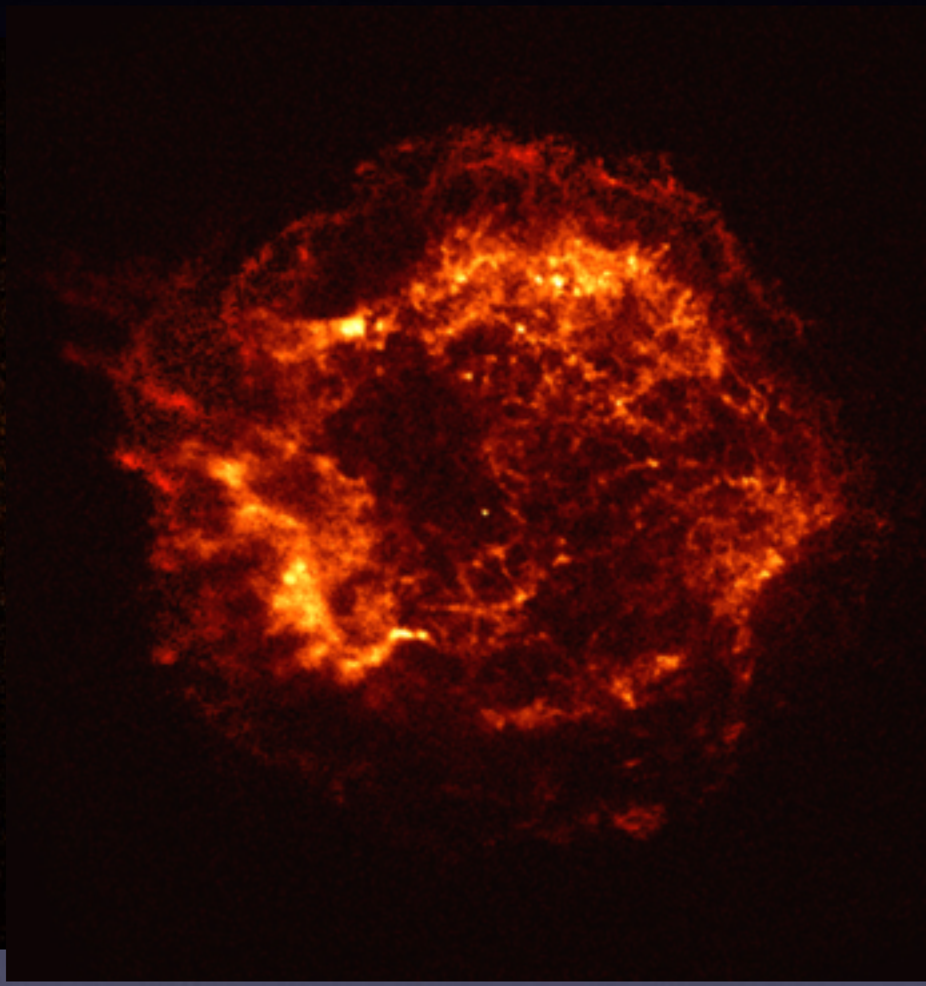
The X-ray View of Cassiopeia A



Einstein Observatory

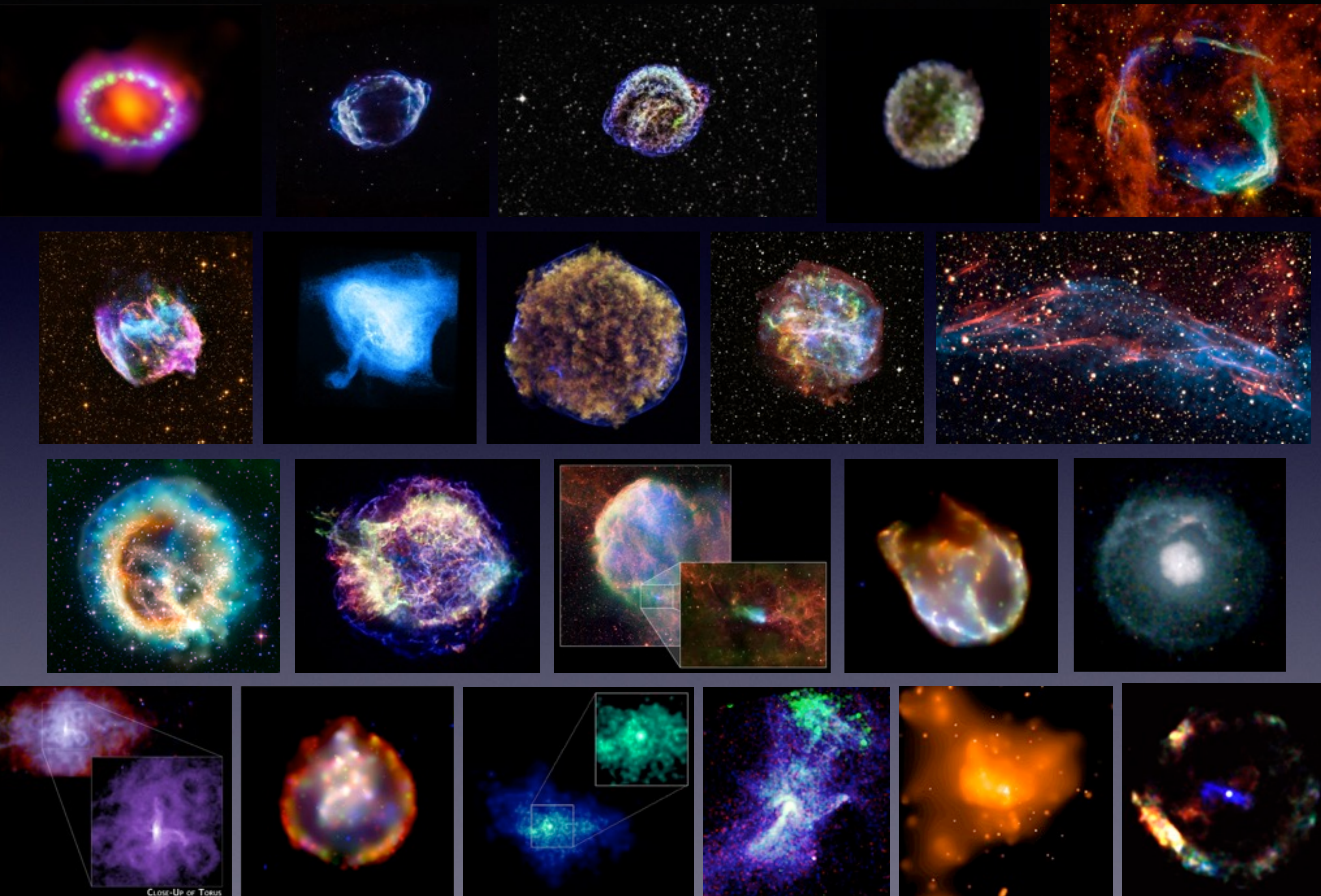


ROSAT



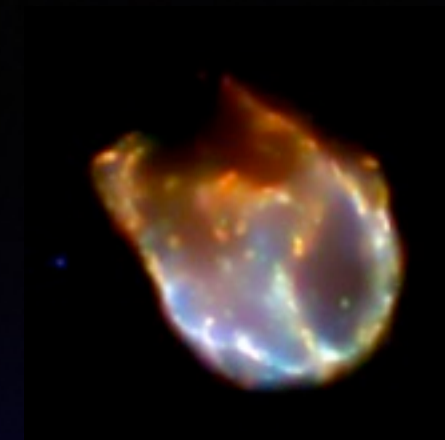
Chandra

56 Chandra press releases on supernova remnants



Why Remnants, and why X-rays?



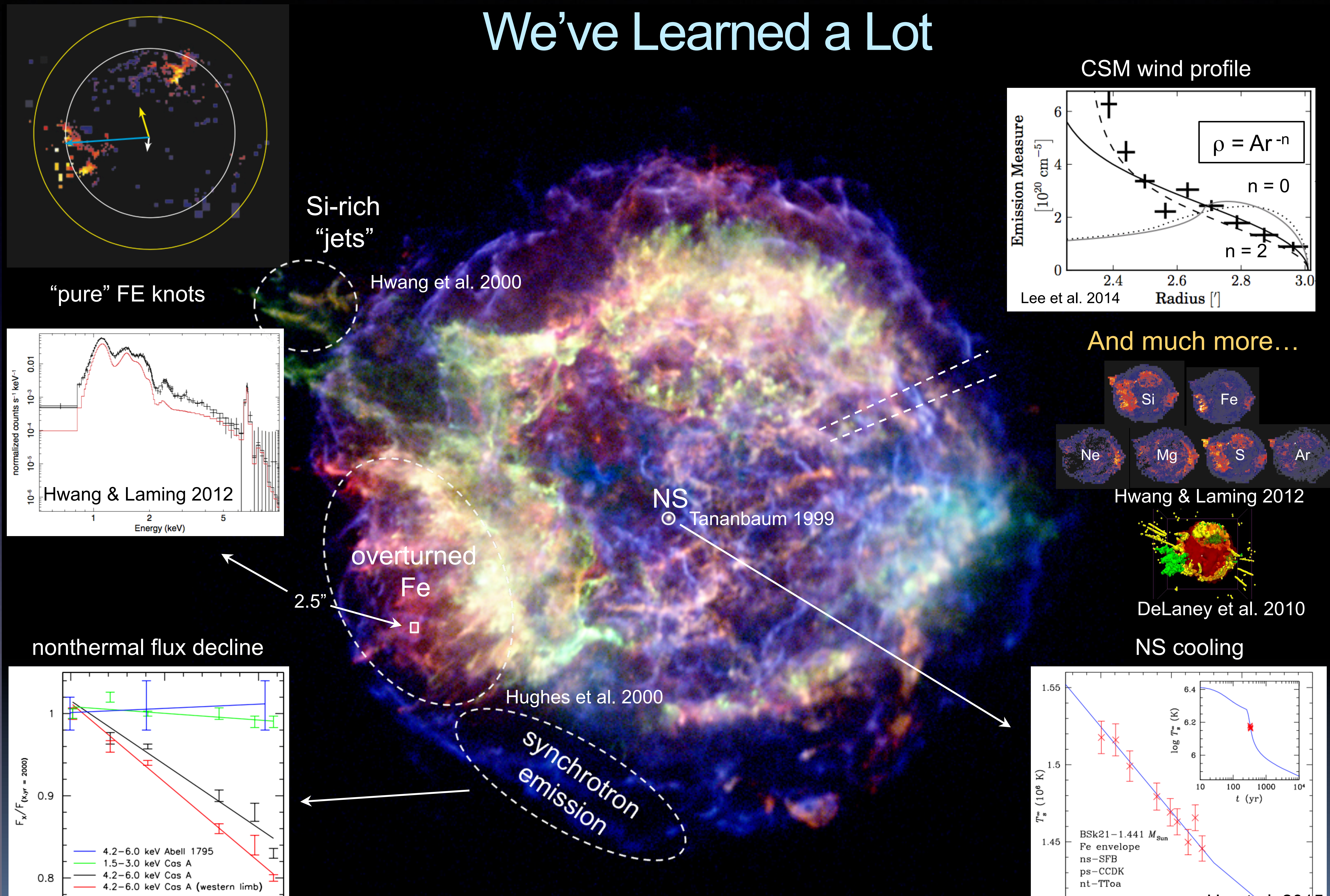

Although dedicated surveys find extragalactic supernovae each day, these objects are far too distant to resolve.

Supernova remnants (SNRs) offer an up-close view (at sub-pc scales) of the explosions and their surroundings.

The metals synthesized in supernovae are heated to X-ray emitting temperatures ($>10^7$ K) by the reverse shock, and they stay X-ray bright for many thousands of years after the explosion. Thus, X-rays are key to studying the nucleosynthetic products of explosions and their dispersal into the ISM.

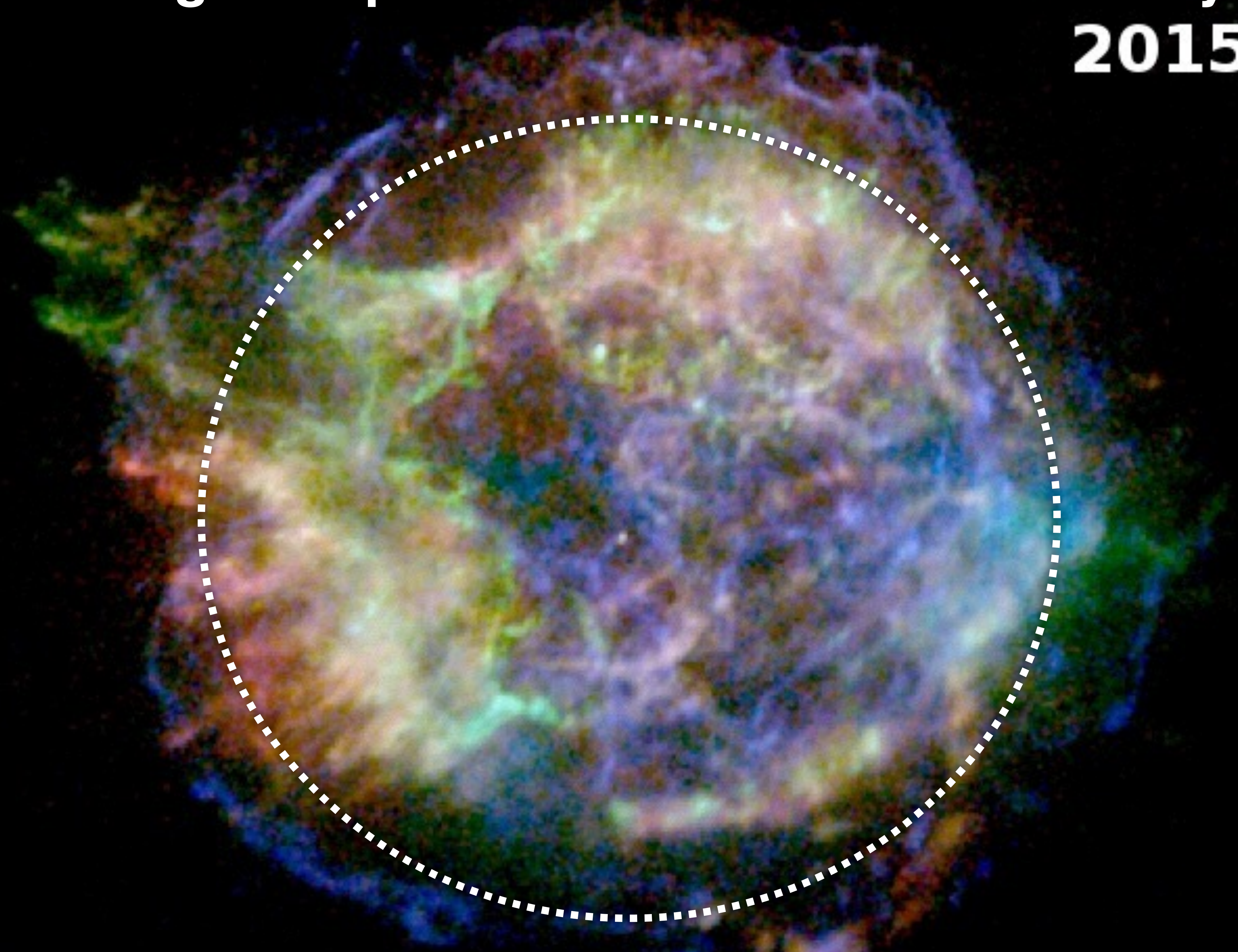
What have we learned?

We've Learned a Lot



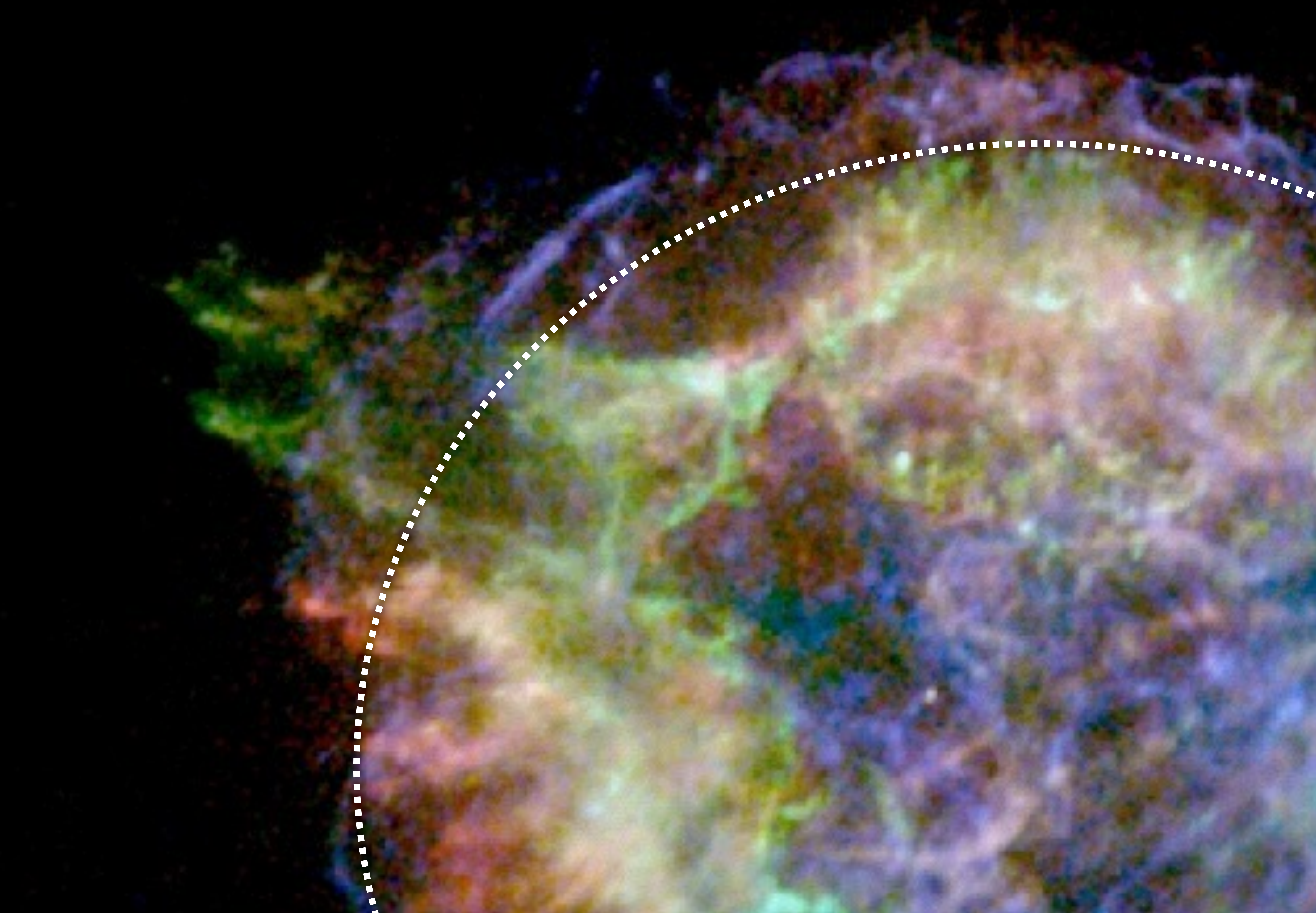
Slide Credit: Pat Slane

Strengths: Spatial Resolution and Sensitivity



Advances: Detect expansion and get explosion site; identify neutron stars

Strengths: Spatial Resolution and Sensitivity



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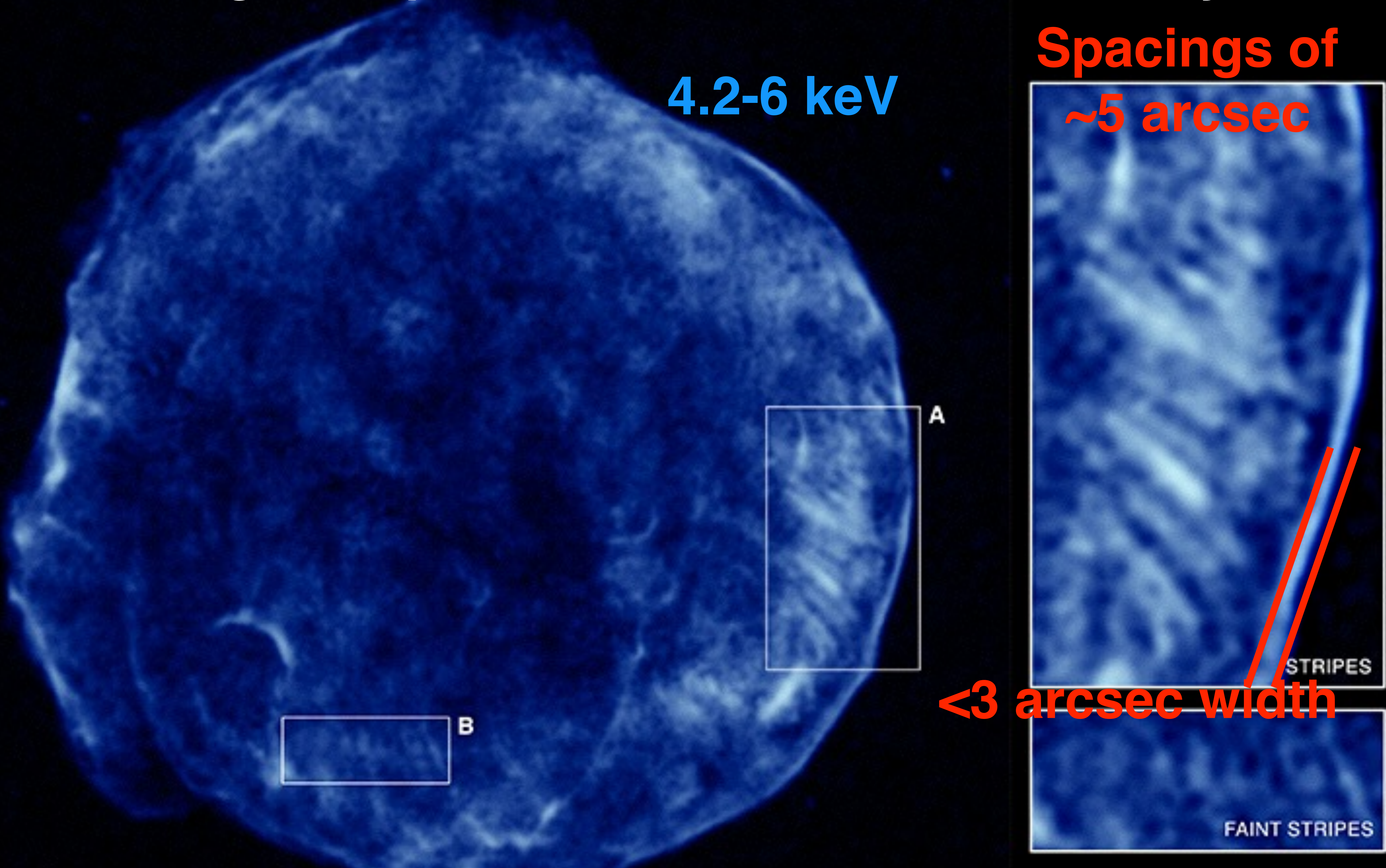
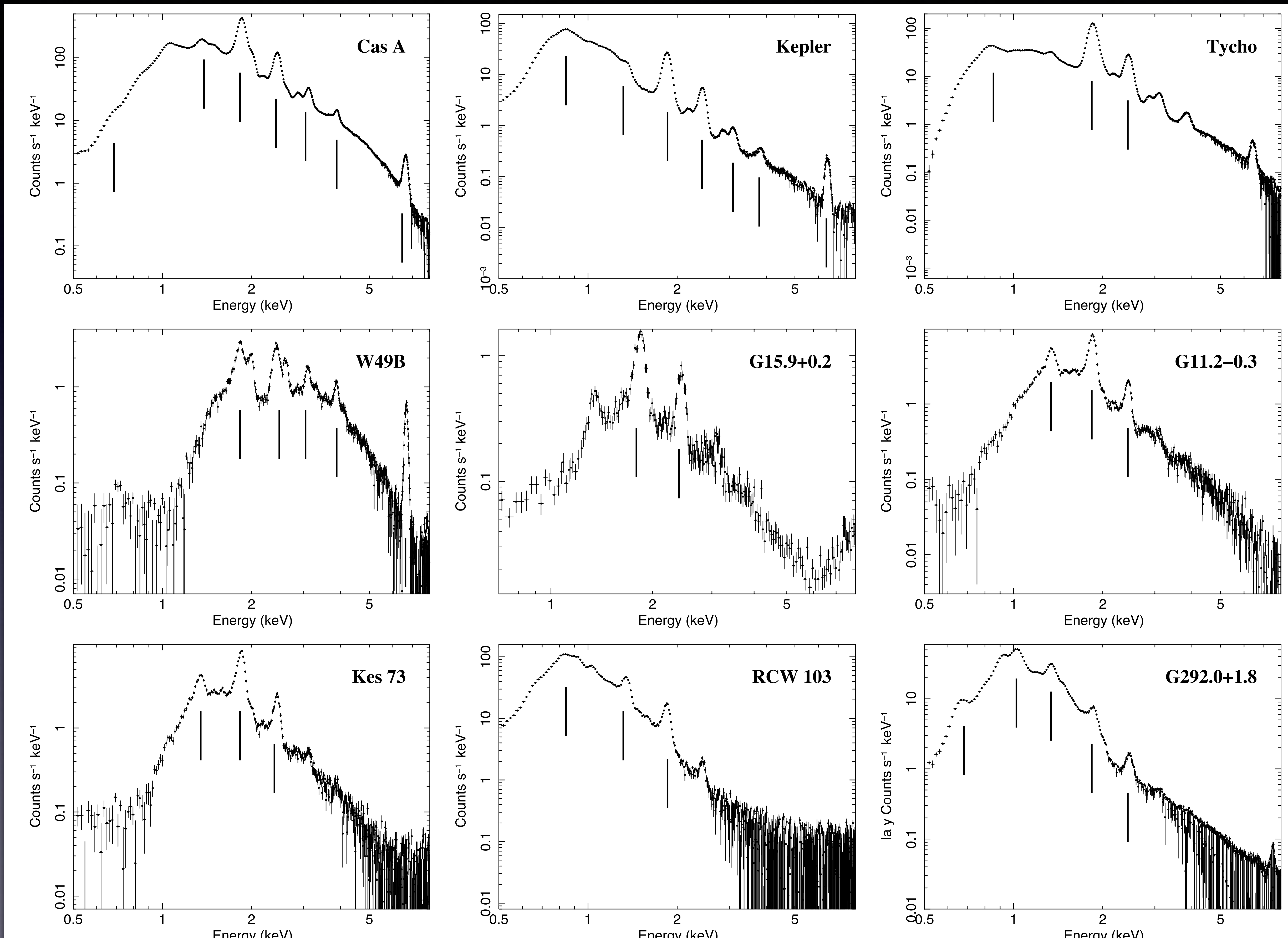


Advances: Resolve non-thermal filaments
Constrain particle acceleration properties

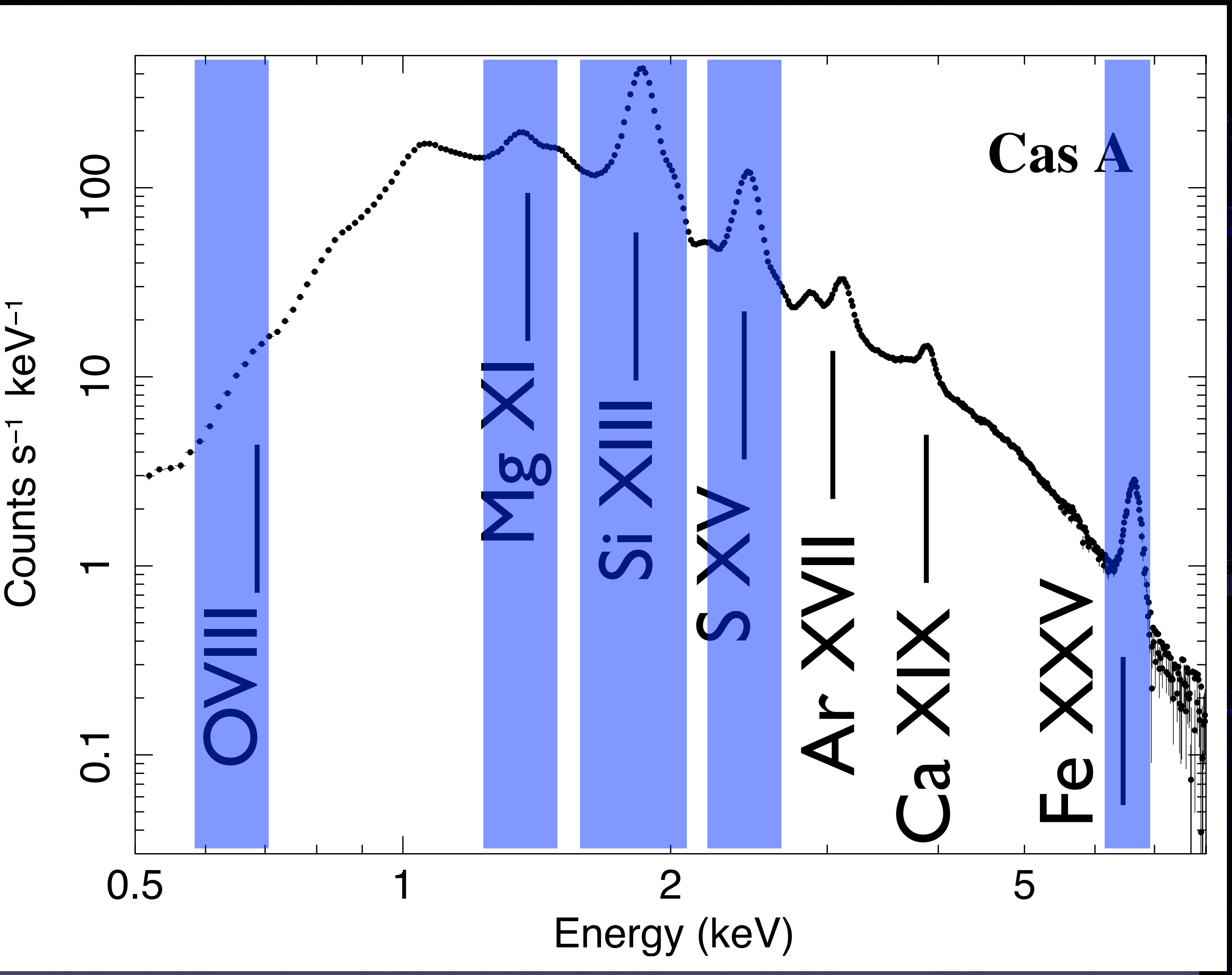
Eriksen et al. 2011

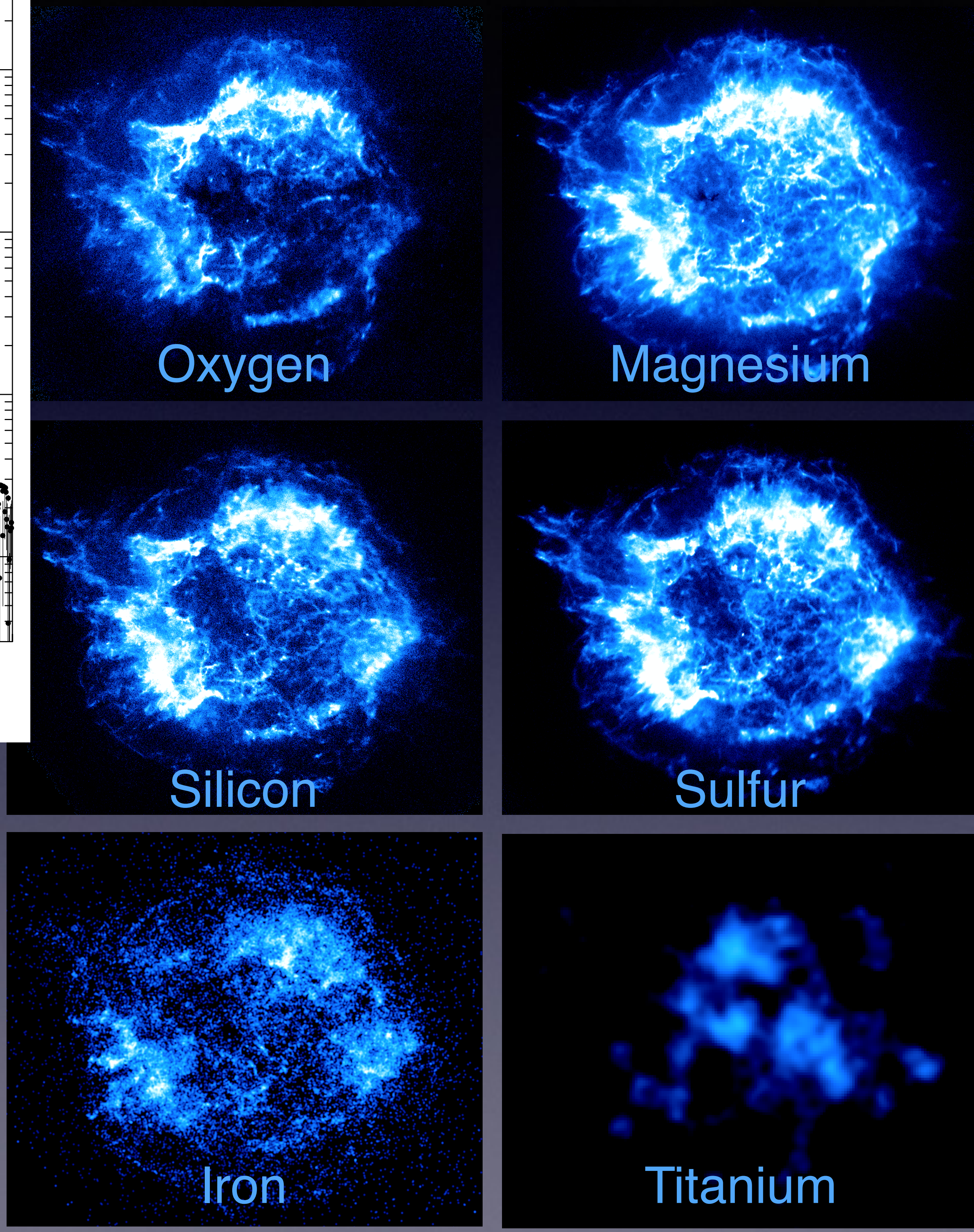
Strengths: Moderate Energy Resolution of CCDs



Lopez et al. 2011

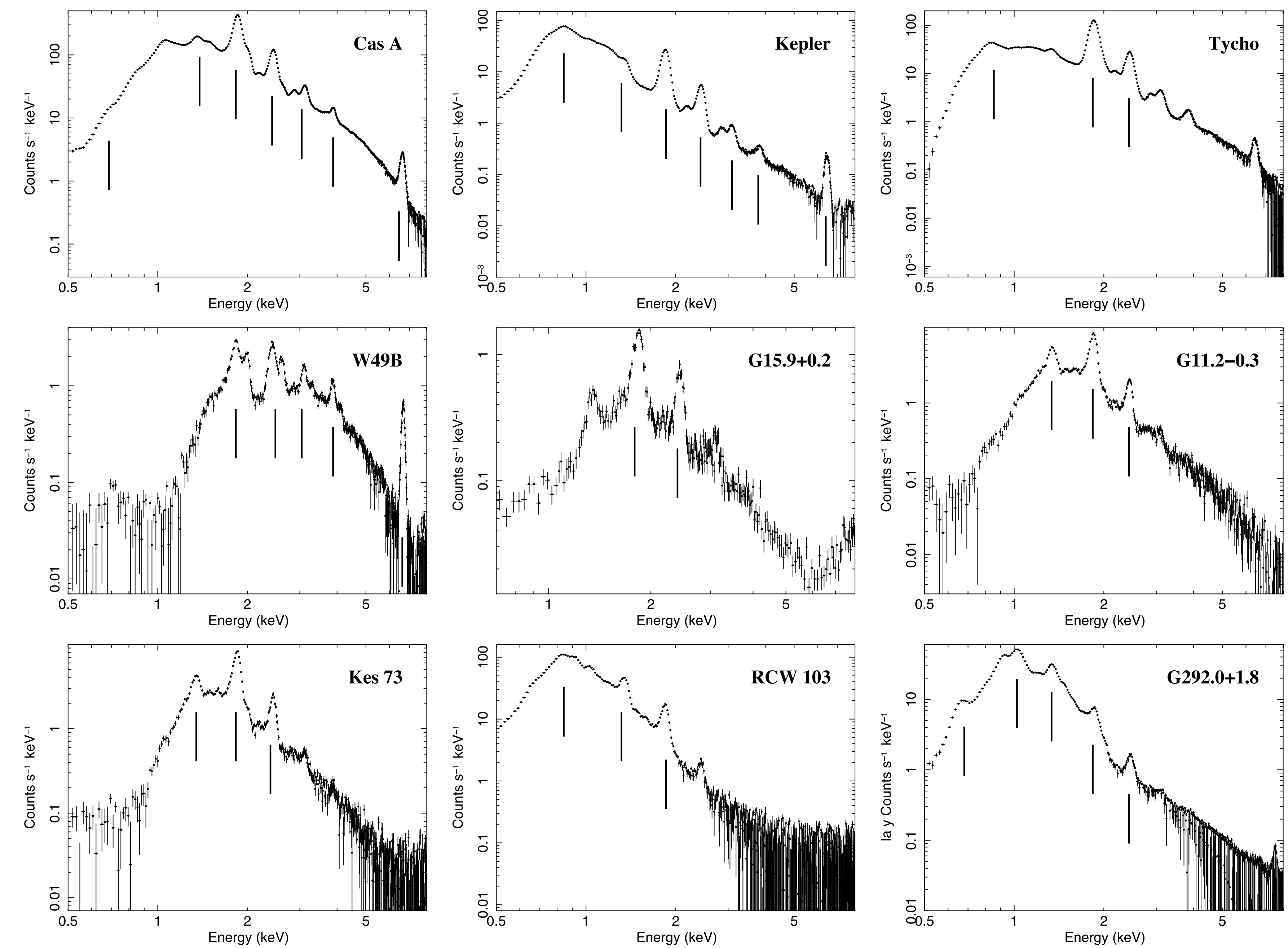
Strengths: Narrow-band Images of Metals





Advances: Metals can have vastly different morphologies

Strengths: Moderate Energy Resolution of CCDs



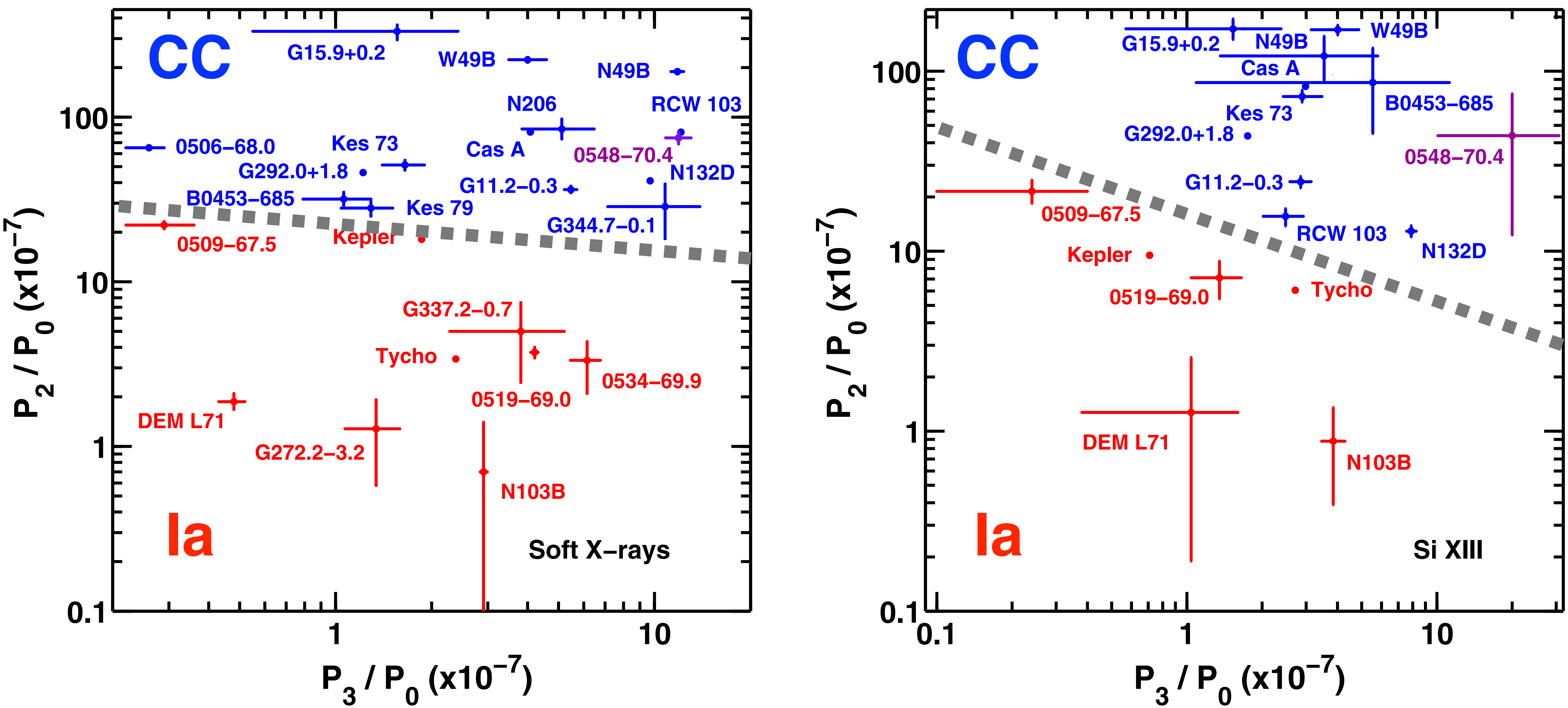
We get:
- -column density
- -temperature
- -ionization state
- -relative metal abundances
- -emission measure

Lopez et al. 2011

Advances: Spectra enable typing of SNRs (Type Ia or core-collapse) using abundance ratios (e.g., O/Fe) or via identification of central NSs or pulsar wind nebulae

Advances: Other Ways of Typing SNRs

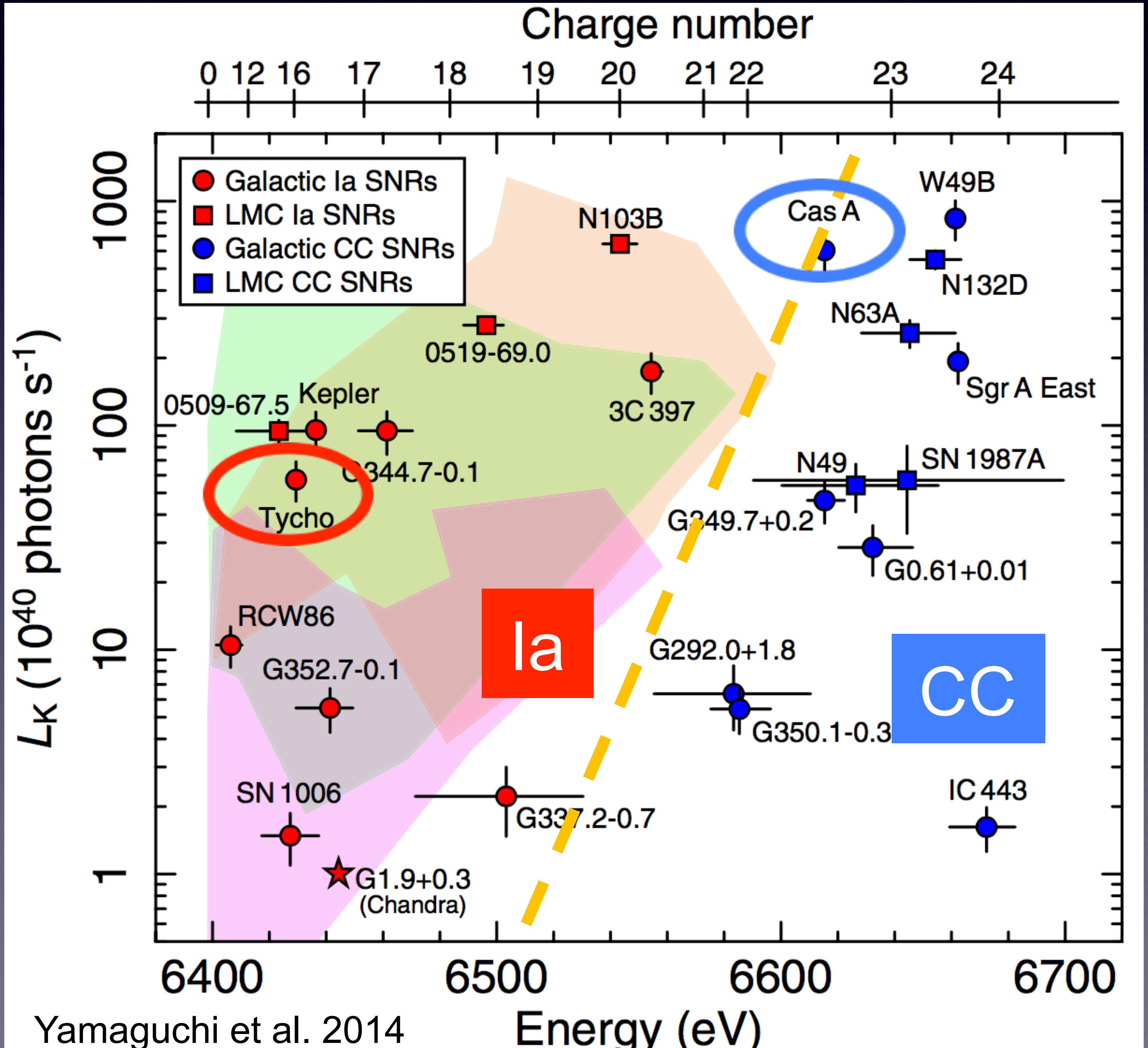
Typing SNRs through spectra enabled us to explore other ways to probe explosive origin - Type Ia SNRs have more circular and mirror symmetric X-ray emission than CC SNRs



Lopez et al. 2011

Advances: Other Ways of Typing SNRs

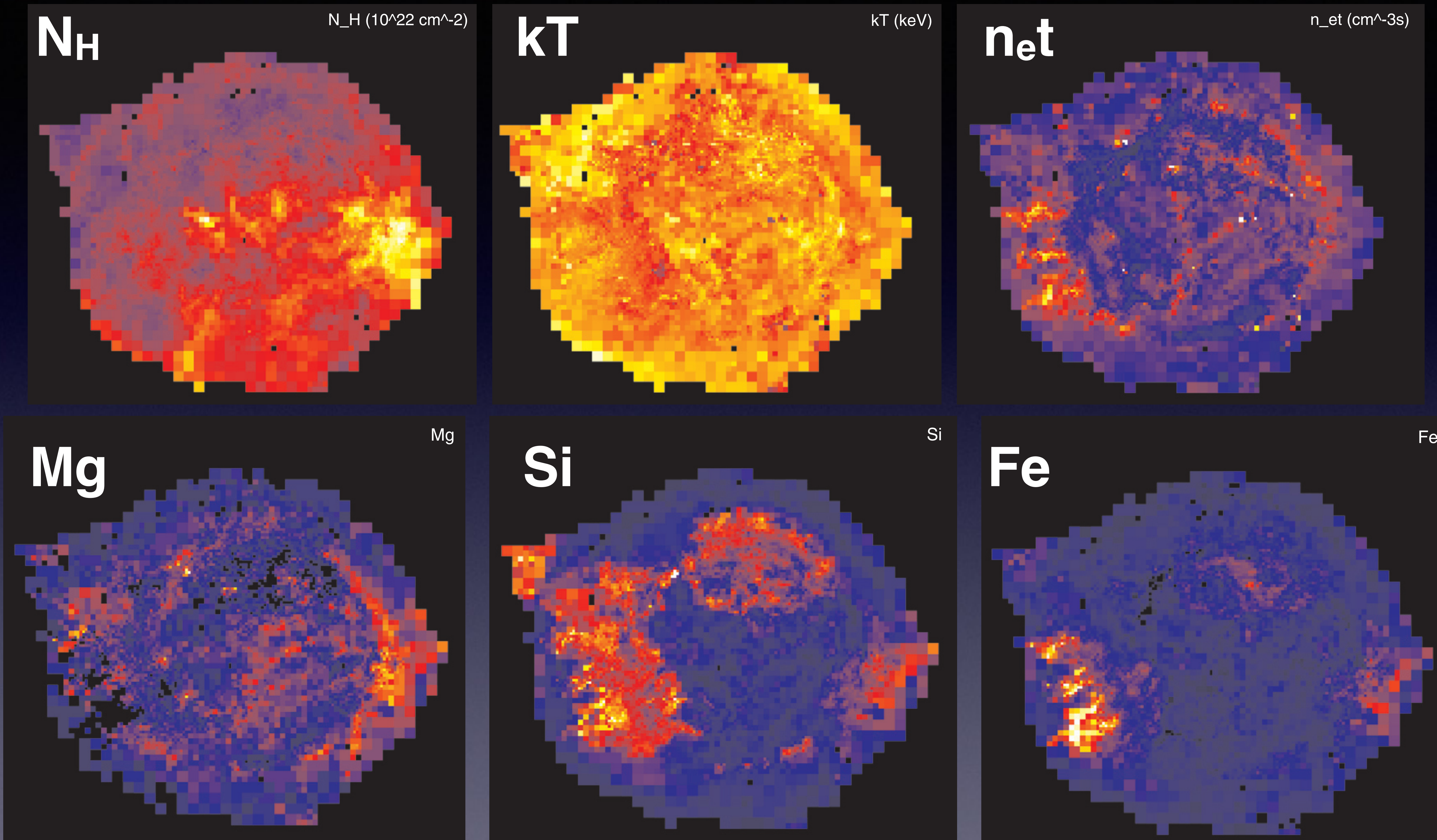
Fe K centroid gives types (Type Ia SNRs have lower Fe K centroid energy than CC SNRs), likely because of different ejecta density structures



Yamaguchi et al. 2014

Yamaguchi et al. 2014

Strengths: Spatially-Resolved Spectroscopy



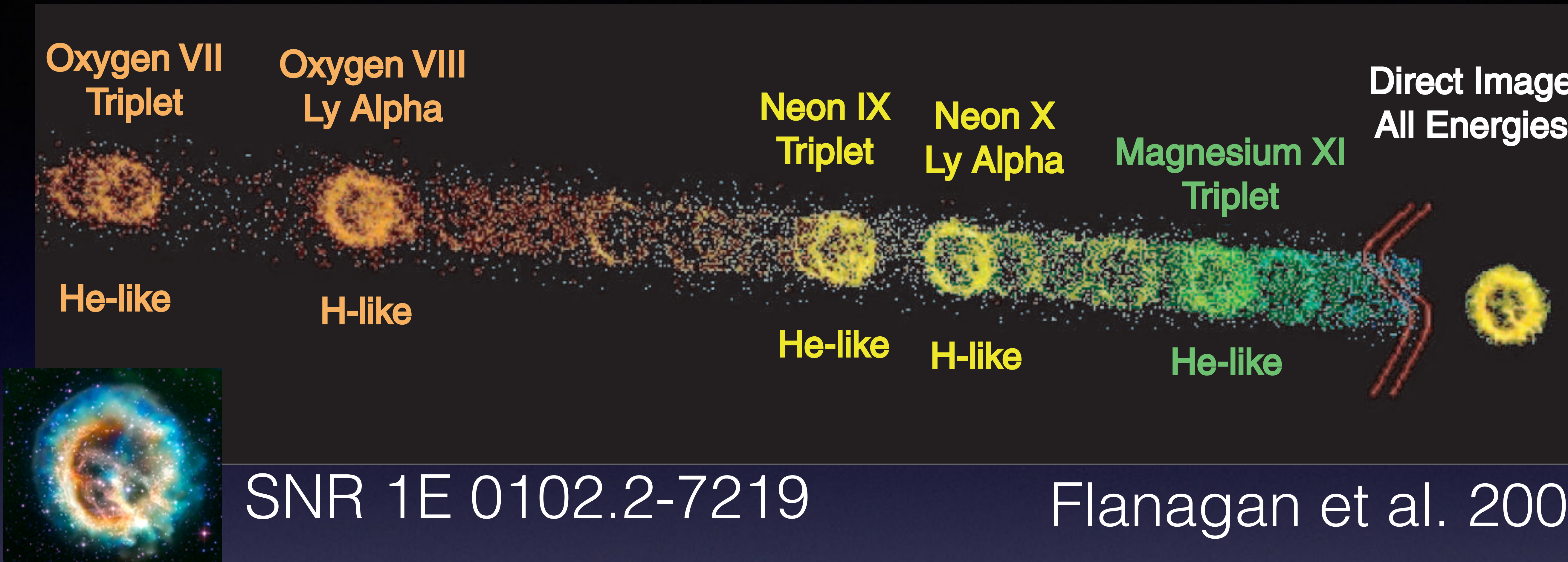
Hwang & Laming 2012

Advances: 2D knowledge of thermal plasma properties

Supernova Remnants - Available Samples

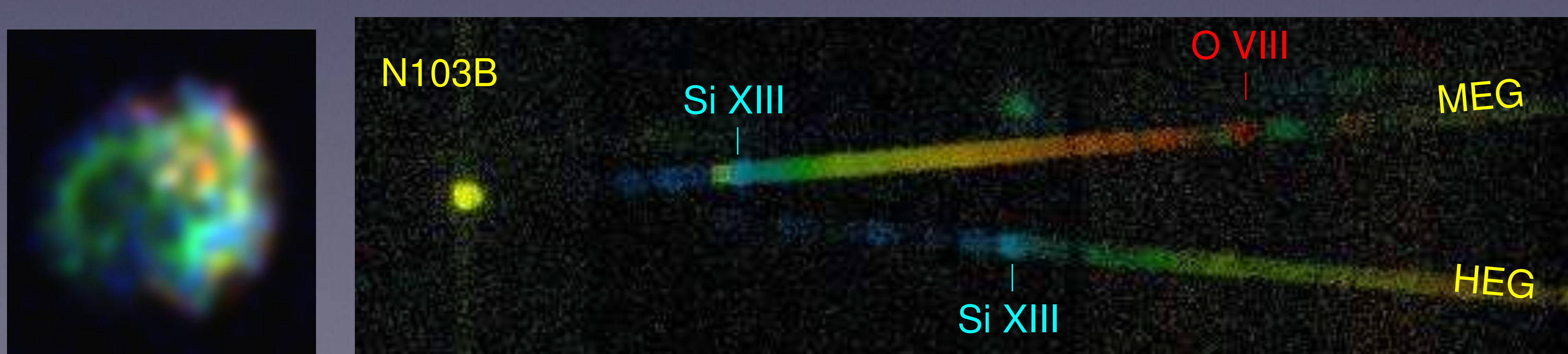
- 375 SNRs in Milky Way, LMC, and SMC (Badenes et al. 2010, Green 2014). ~46 in M31, >100 in M33 (Long et al. 2010, Sasaki et al. 2012)
- ~45 SNRs within 5 kpc (Kaplan et al. 2004)
- ~170 MW SNRs have been detected with X-ray telescopes
- ~110 are <20’ in diameter
- ~20 are classified as Type Ia SNRs based on abundances
- ~70 have detected neutron stars
- >40 have pulsar wind nebulae

Room for Improvement: Using Gratings on SNRs



SNR 1E 0102.2-7219

Flanagan et al. 2004



Dewey 2002

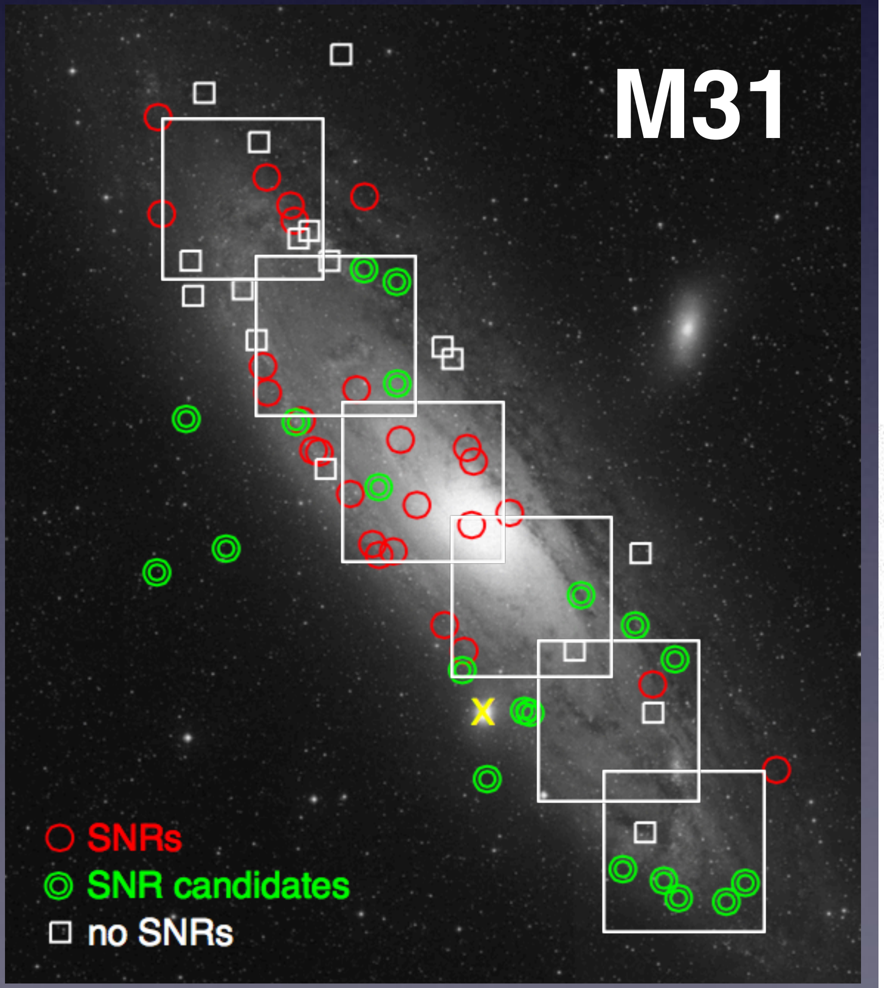
Room for Improvement: Sensitivity to Study Extragalactic Samples of SNRs

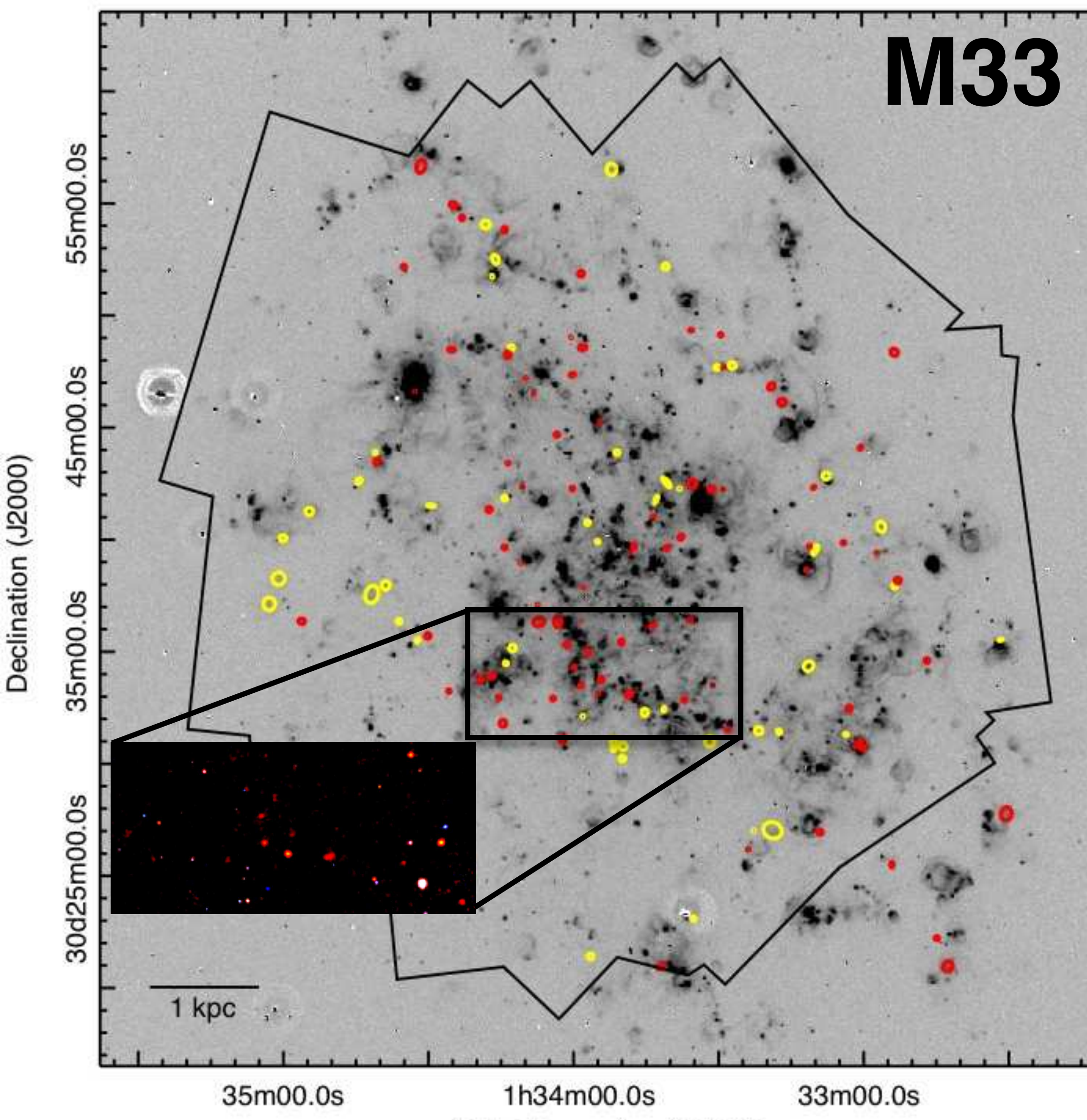
Hundreds of SNRs in Local Group galaxies.

In ~200 ks exposures of M33 with *Chandra*, ~half of SNRs were detected and only ~10% had sufficient counts to do spectral analysis. Most SNRs have not been “typed”.

Left: 46 SNRs
+ candidates
(Sasaki et al. 2012)

Right: 137 SNRs
+ candidates
(Long et al. 2010)

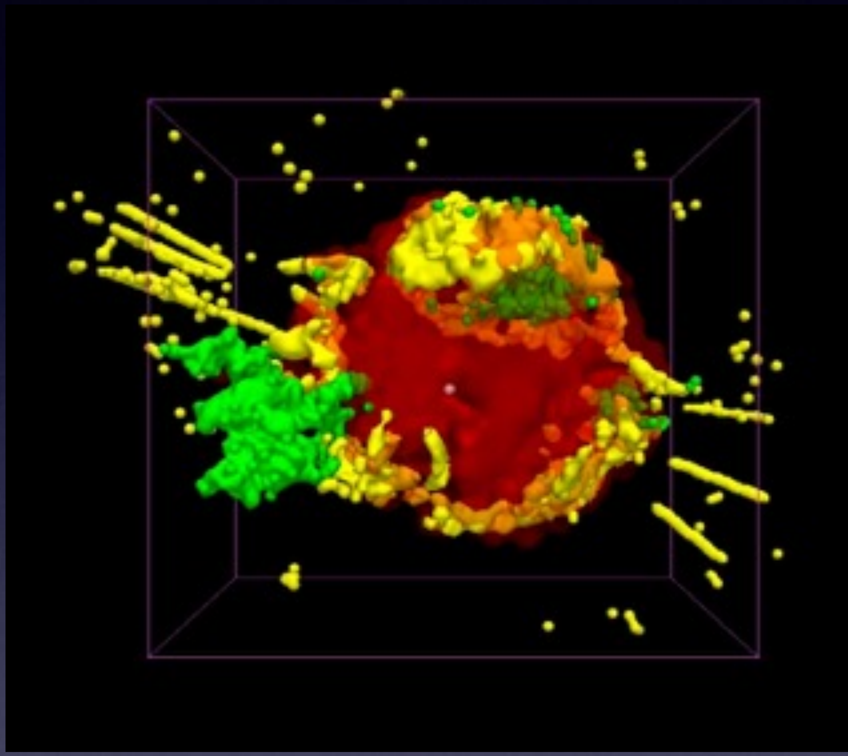




Supernova Remnants in 3D with Lynx

Observe young (ejecta-dominated) SNRs with micro-cal to determine mass, composition, motion of ejecta knots and shock physics (heating and equilibration timescale)

- Cas A, G292.0+1.8, G11.2-0.3, G15.9+0.2, RCW 103, Kes 79, W49B, Kes 73, RCW 86, Tycho, Kepler, SN 1006, 3C 397, G344.7-0.1, G272.2-3.2



DeLaney et al. 2010

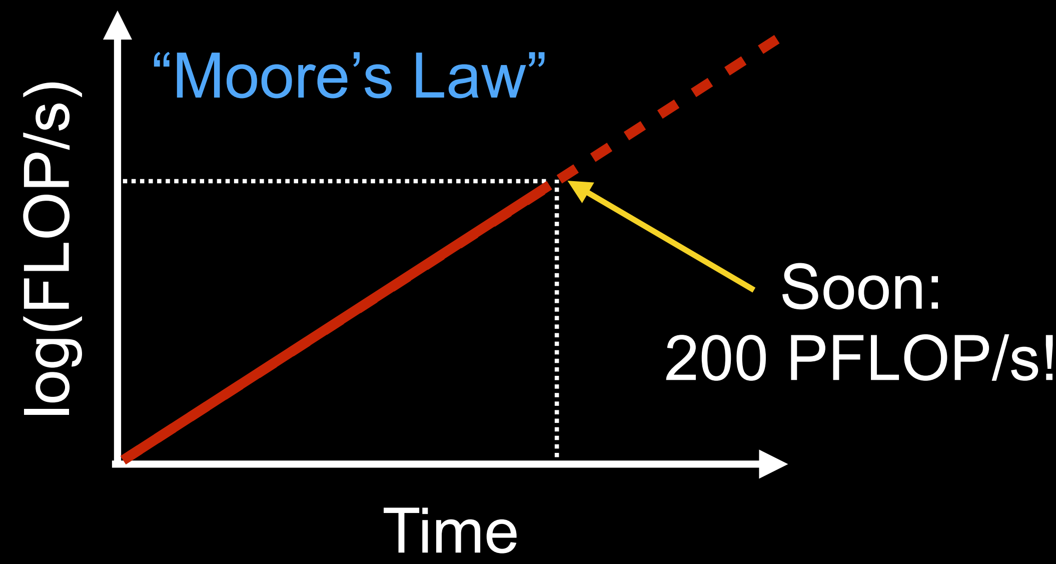
Measure SNR expansions (via proper motions) and neutron star velocities using Chandra+Lynx

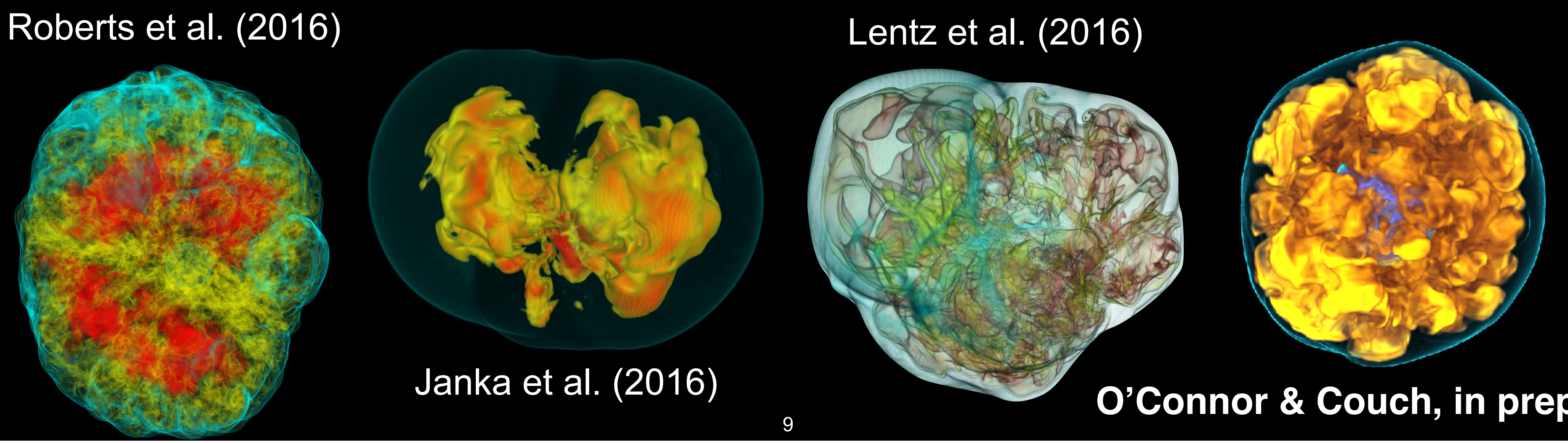
v =1000 km/s is 0.4” in 10 years for D = 5 kpc

Spectra+proper motions give 3D structure of ejecta, key to probing explosion asymmetries and density distributions of ejecta and CSM.

Ultimate aim: test SN models

Era of 3D CCSN Simulation

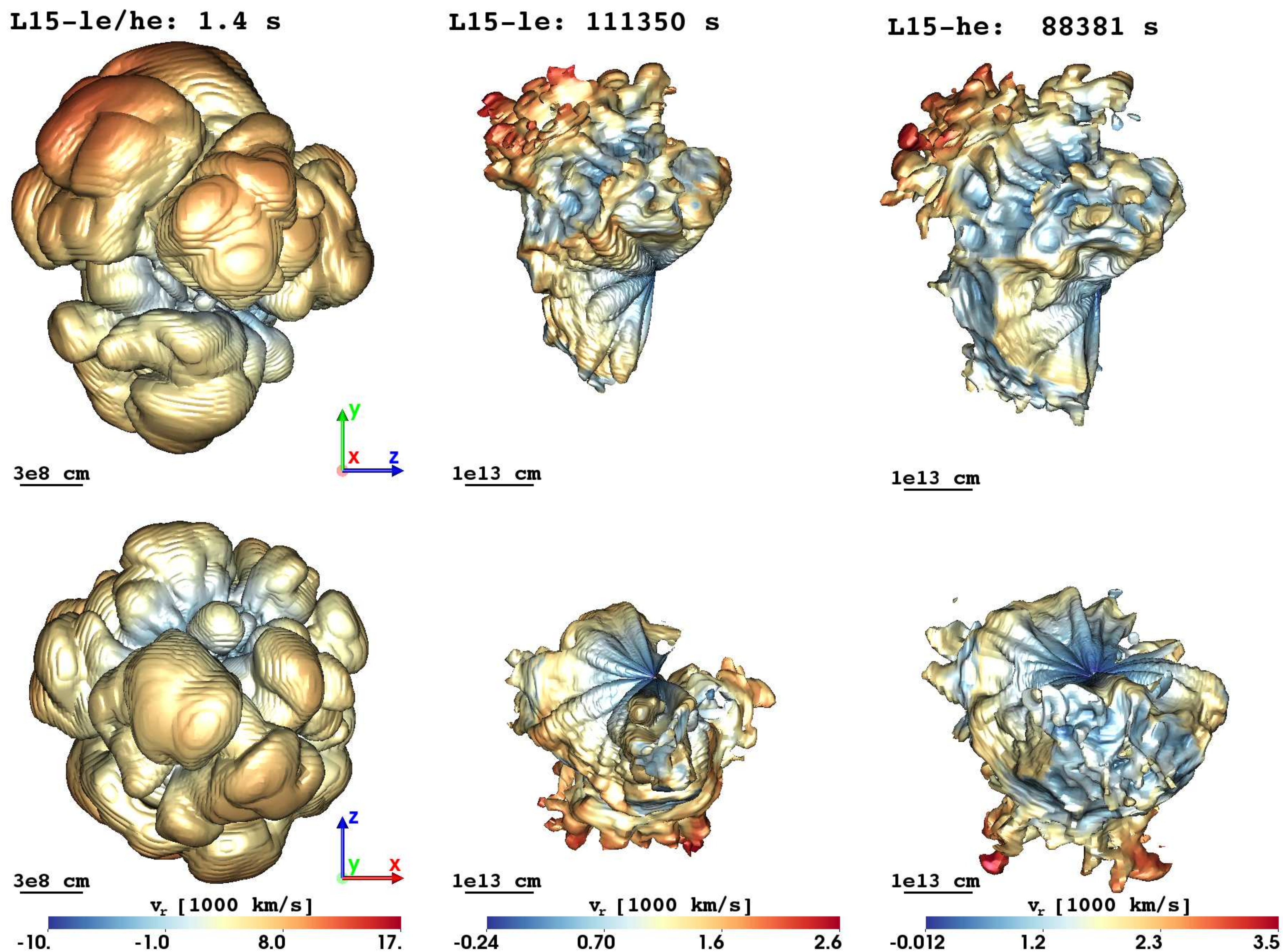




From: Sean Couch

Using 3D explosions, simulators find:
Large-scale compositional asymmetries
Neutron stars kicks up to 1,000 km/s
Light curves match observations

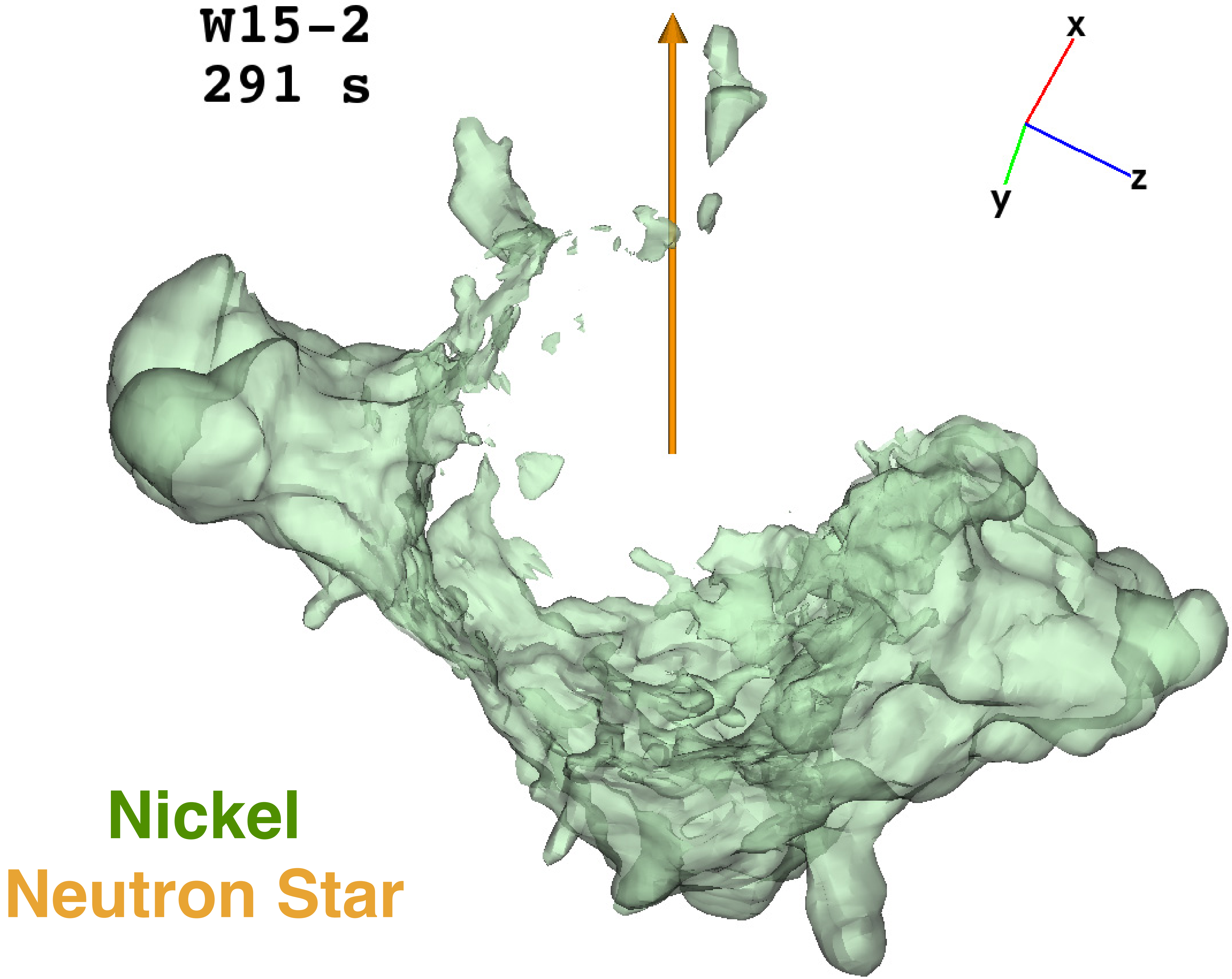
Morphology of radioactive ^{56}Ni in two 3D CC SN models



Colors represent velocities

Utrobin et al. 2017
arXiv: 1704.03800

3D Supernova Visualization



Wongwathanarat et al. 2013

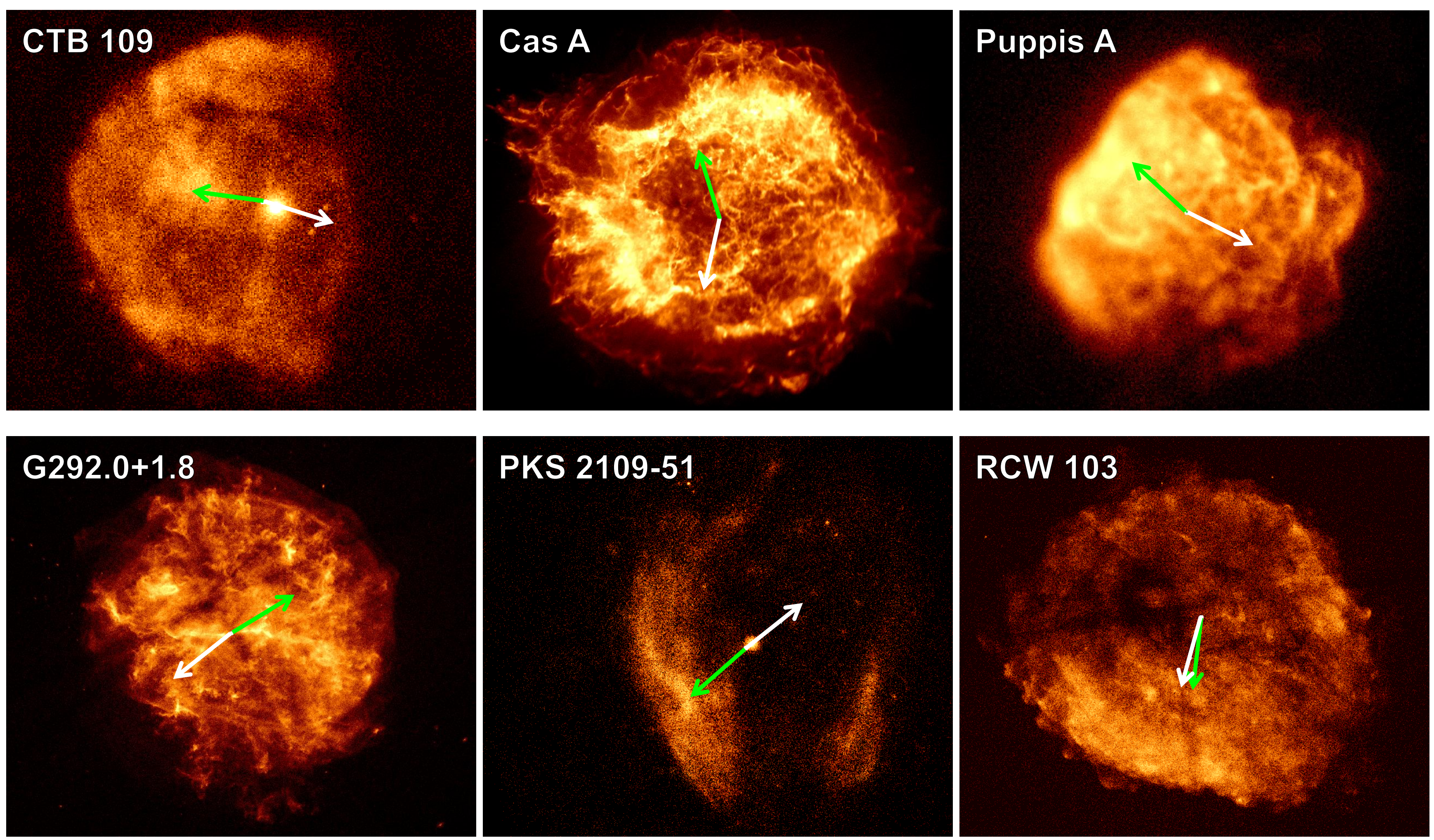
Predict heavy metals (Fe, Ti) trace explosion asymmetries

Measure Neutron Star Motion Relative to Ejecta

Measure NS proper motions and compare to narrow-band images of metals and 3D structure of ejecta

Analysis of Chandra data for small sample shows ejecta opposite to NS direction

Dipole Direction (bulk of ejecta);
Neutron Star Direction

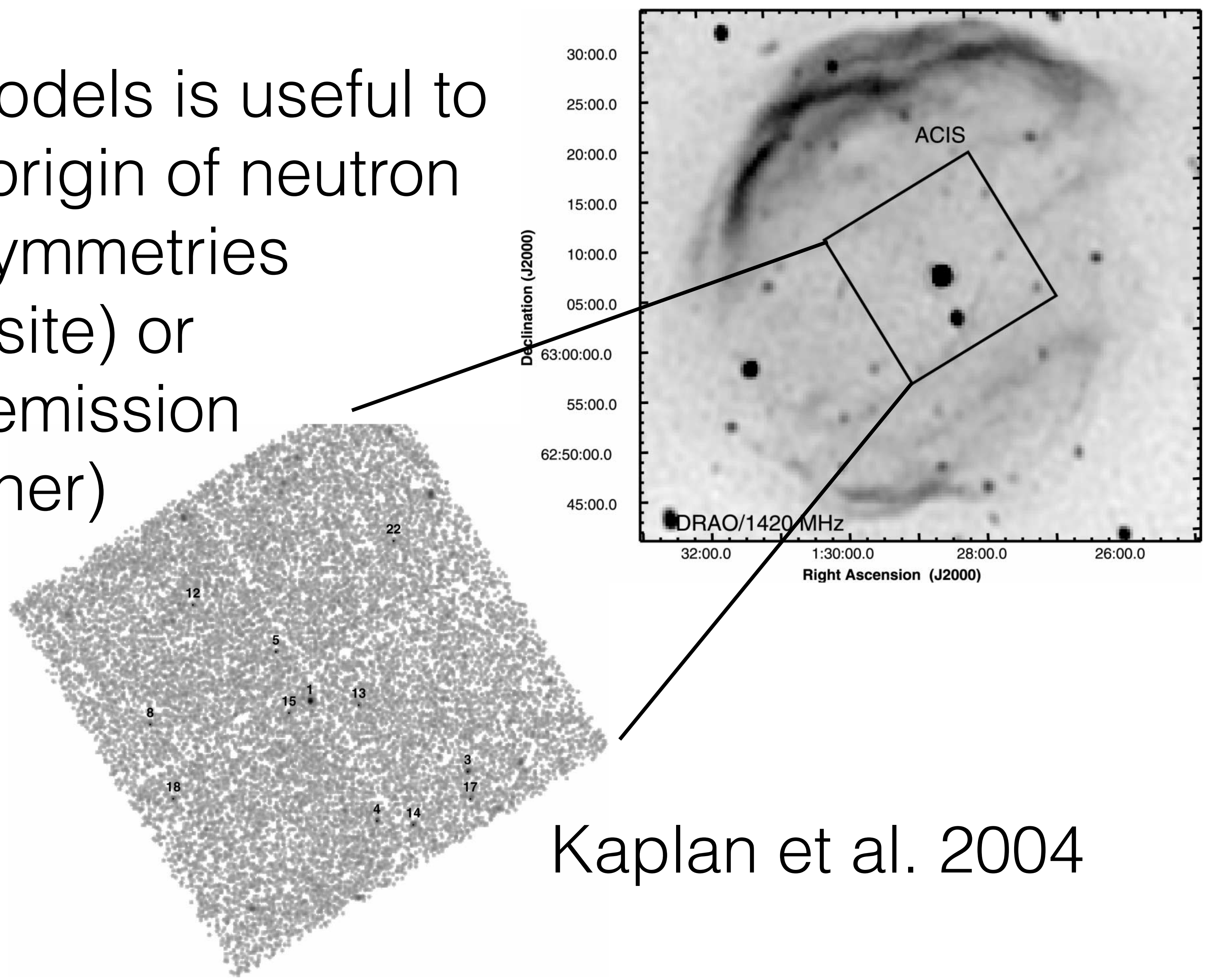


Holland-Ashford, Lopez et al. 2017

Measure Neutron Star Motion Relative to Ejecta

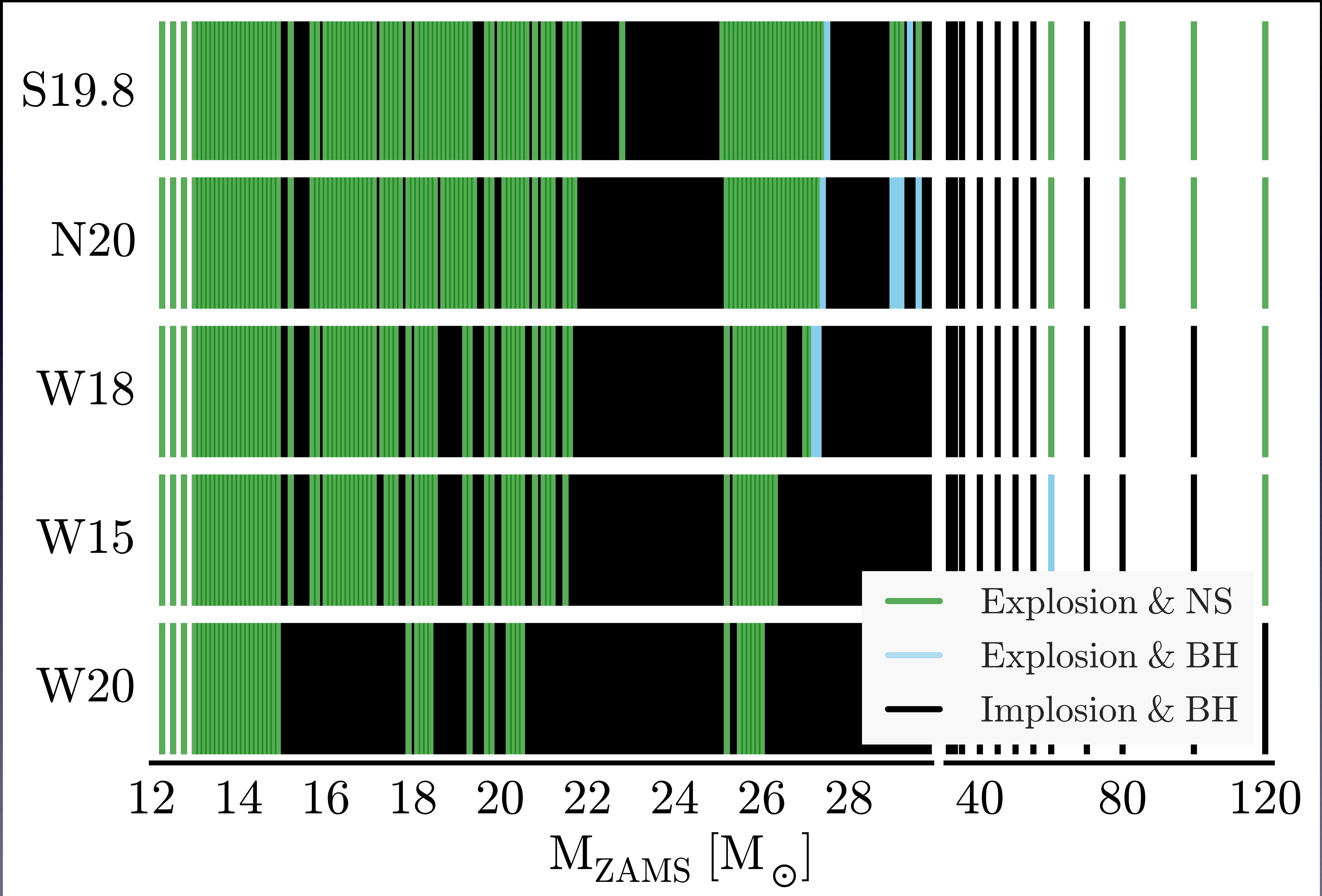
Micro-cal makes identification of NSs easy by detecting lines from chromospheres. Spatial resolution is crucial to localize NSs and measure proper motions.

Comparison to SN models is useful to test models and the origin of neutron star kicks - ejecta asymmetries (ejecta and NS opposite) or anisotropic neutrino emission (ejecta and NS together)



Kaplan et al. 2004

Fates of Explosions

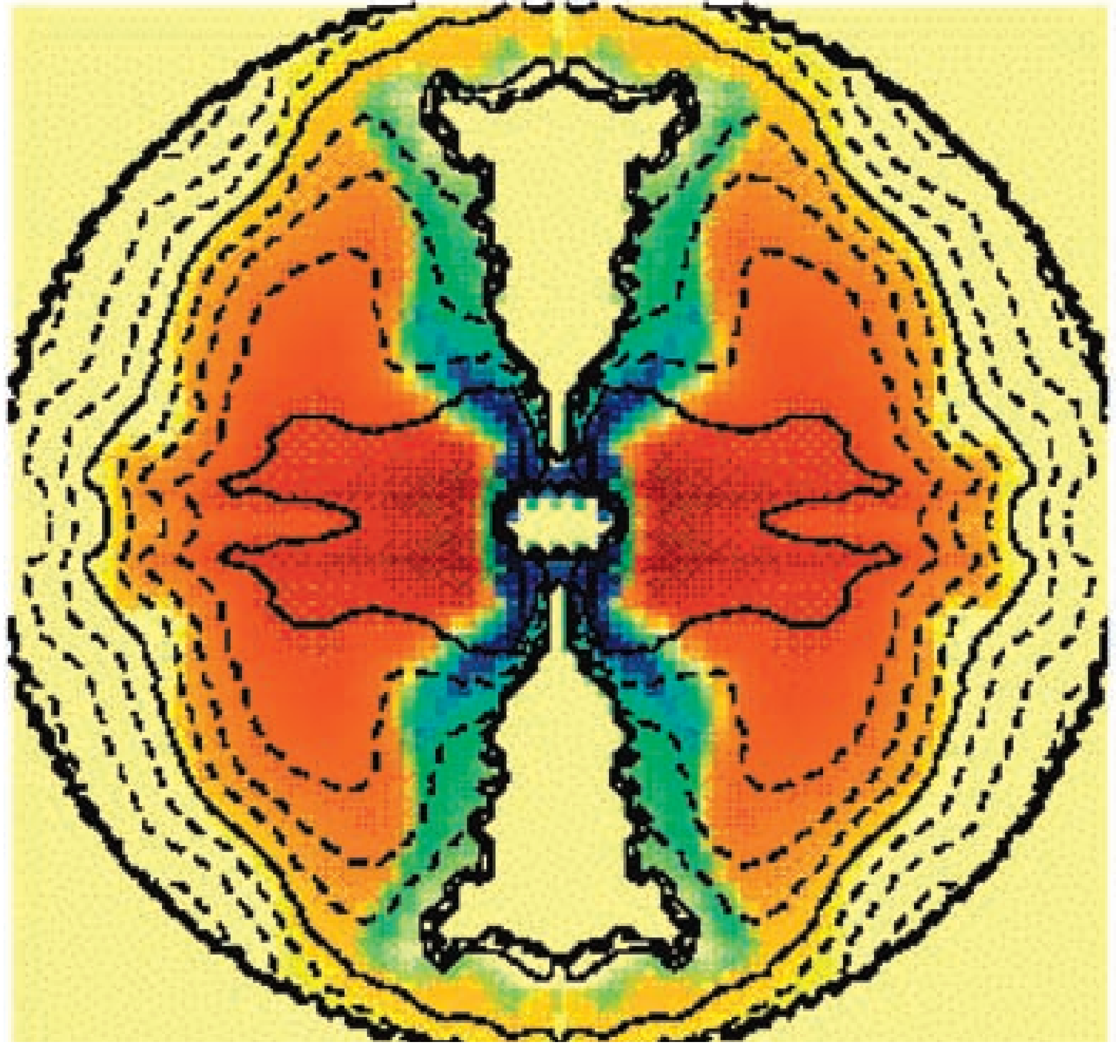


Sukhbold et al. 2016

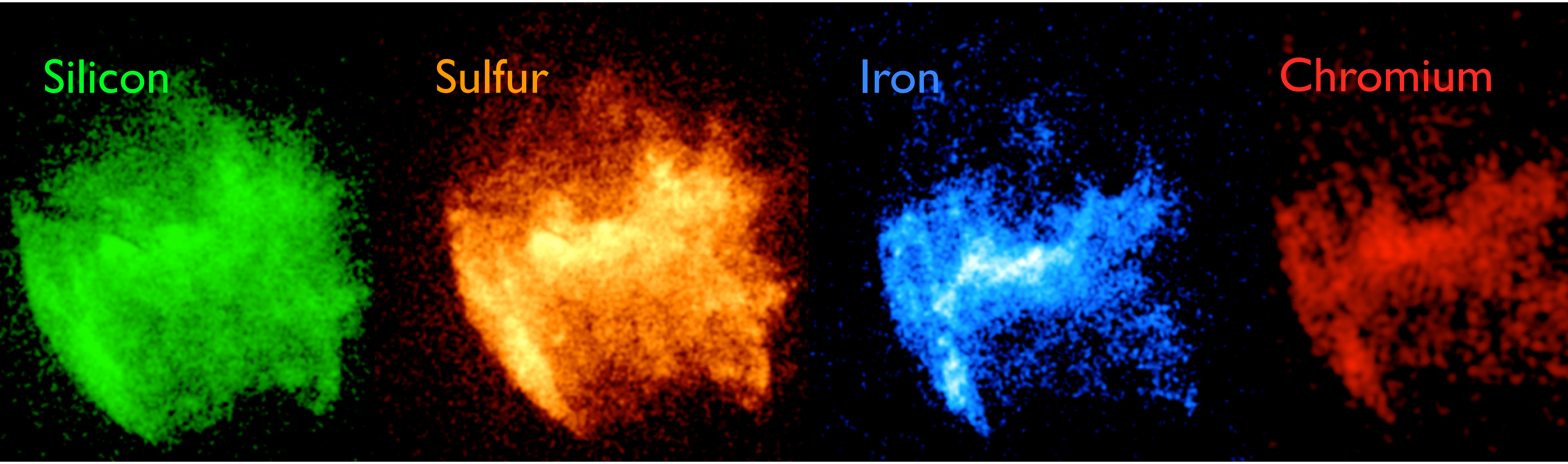
Jet-Driven Explosions

Theorists predict that a rapidly-rotating progenitor can have jet-driven explosions.

Lynx imaging and micro-cal can look for segregation of iron from lighter elements as well as confirm that heavy elements are ejected at faster velocities.



Nickel; Oxygen Mazzali et al. 2006



Lopez et al. 2013

Supernova Remnants with Lynx

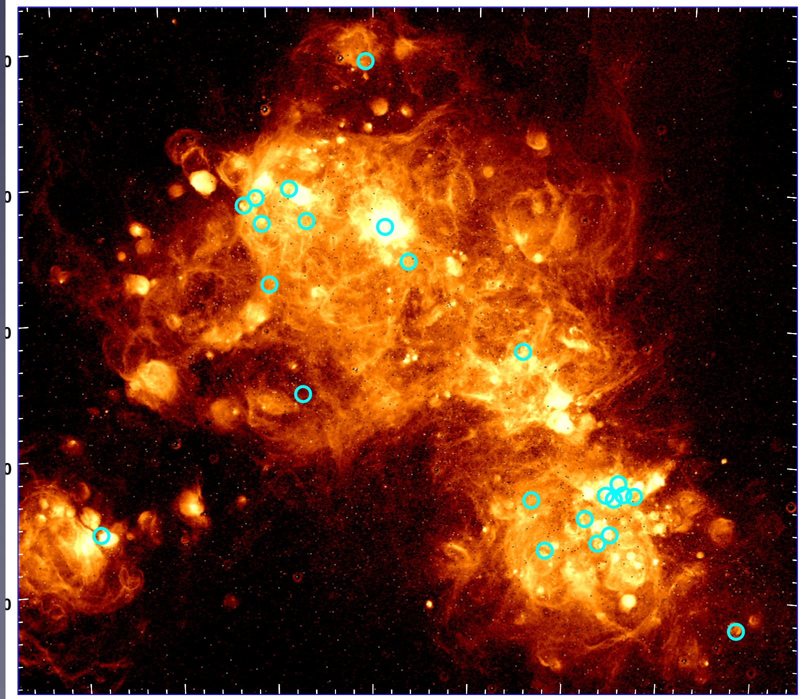
Study populations of SNRs in MW and nearby galaxies (LMC, SMC, M31, M33).

In LMC and SMC especially, can do detailed studies with imaging and micro-cal similar to those of MW studies to get 3D structure, ejecta mass and composition, shock heating properties, particle acceleration properties, and associated neutron stars.

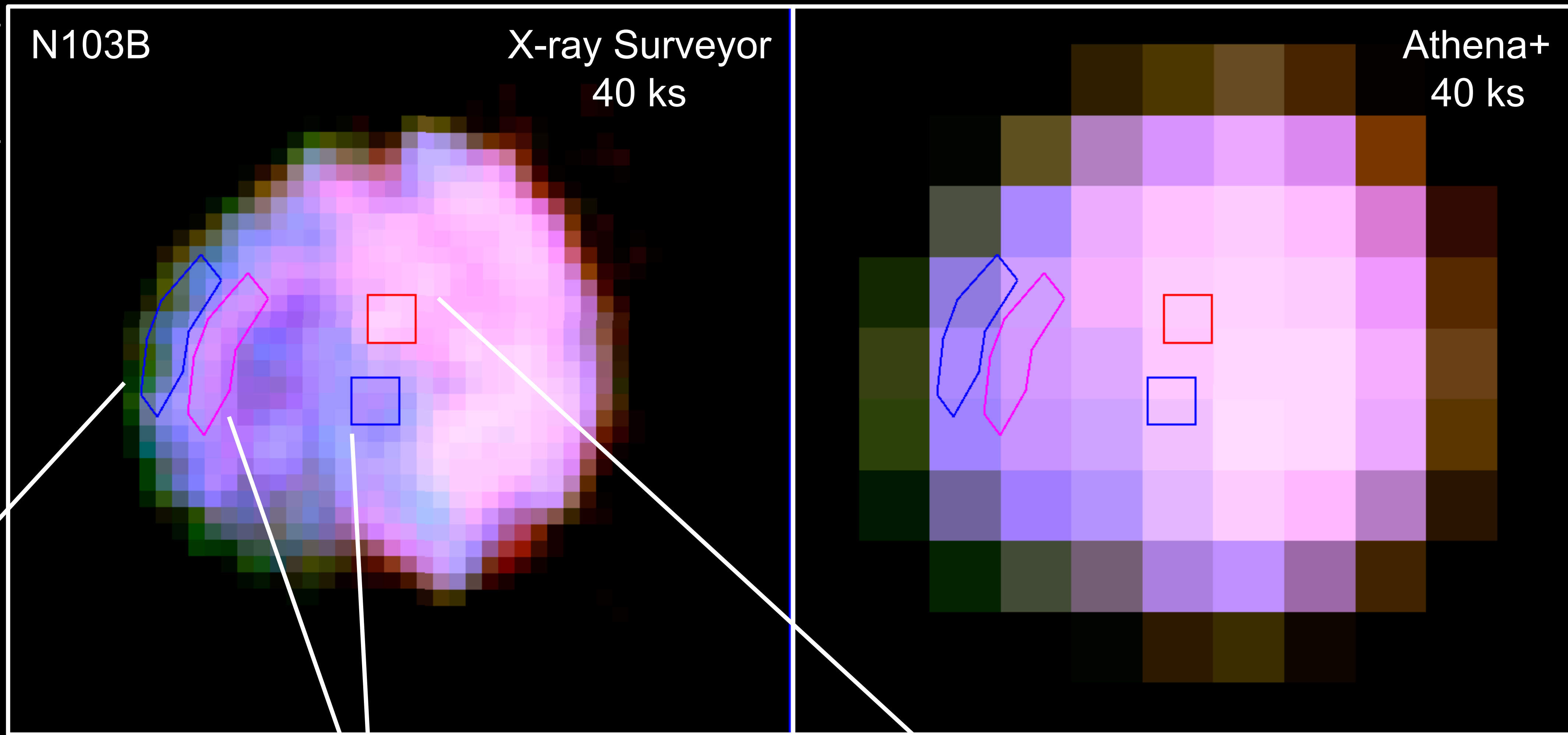
Possibly measure expansion of LMC SNRs using Chandra to Lynx baselines:

v =5000 km/s is 0.5” in 24 years for D = 50 kpc

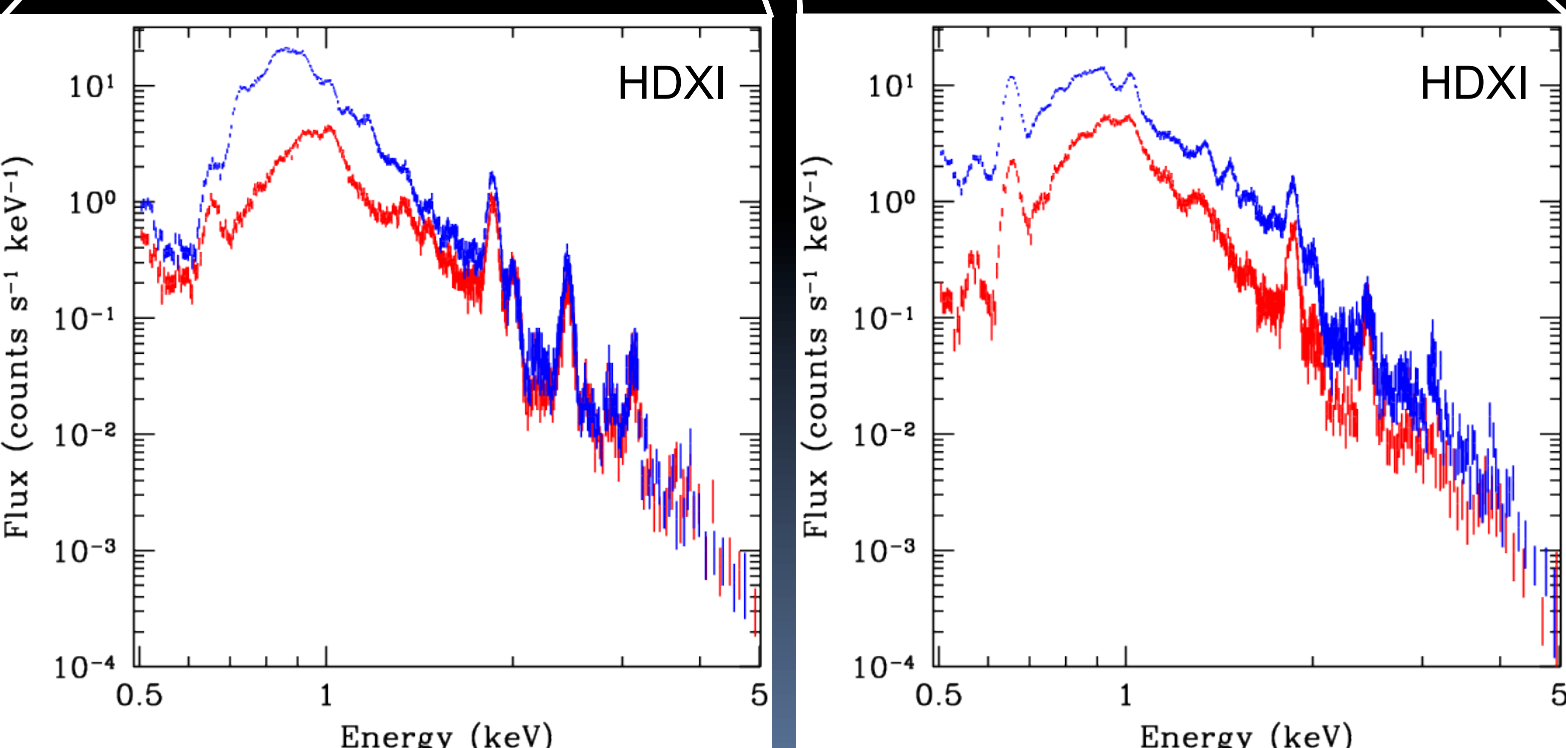
Badenes et al. 2010:
50 SNRs in LMC;
23 in SMC



Magellanic Cloud SNRs



B. Williams (GSFC)

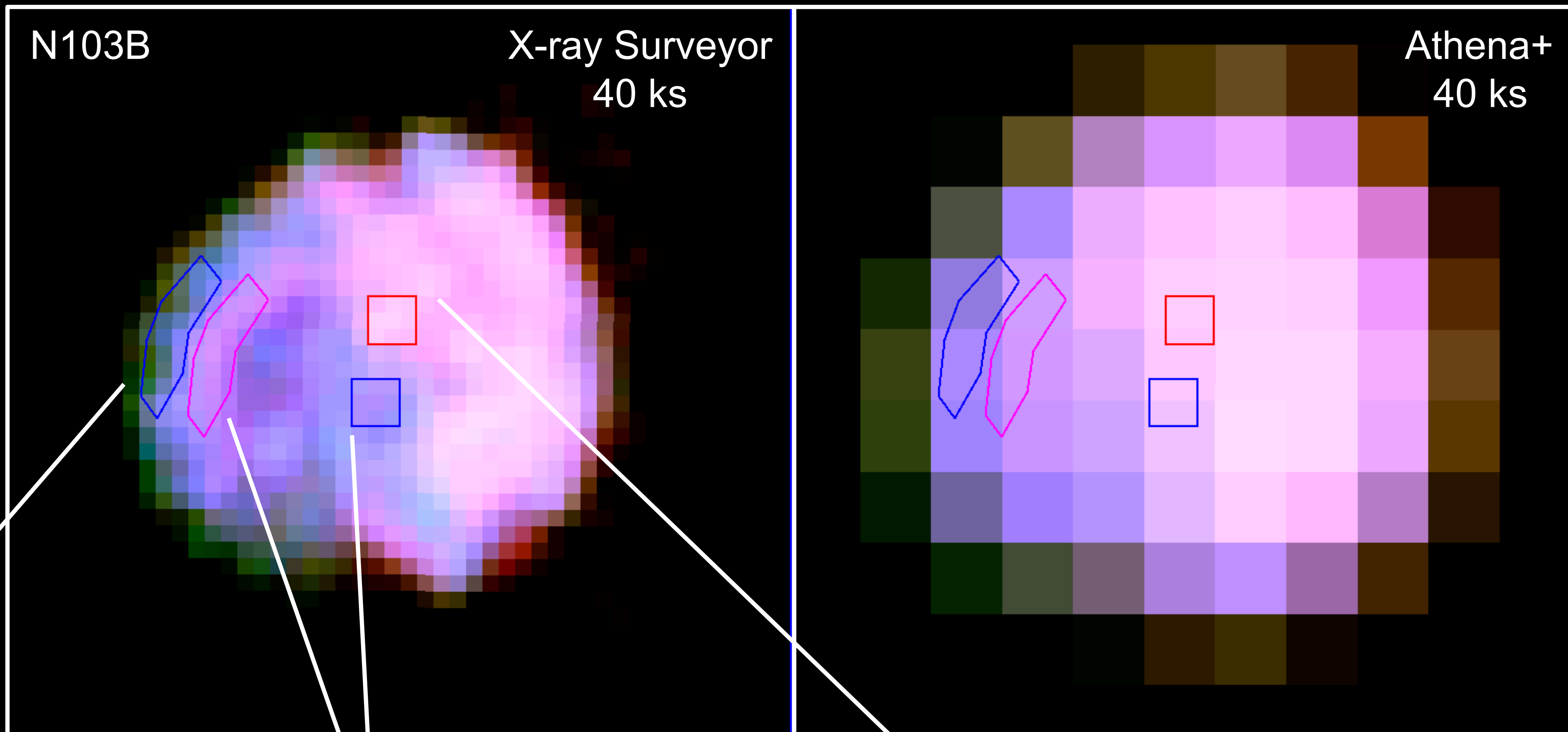


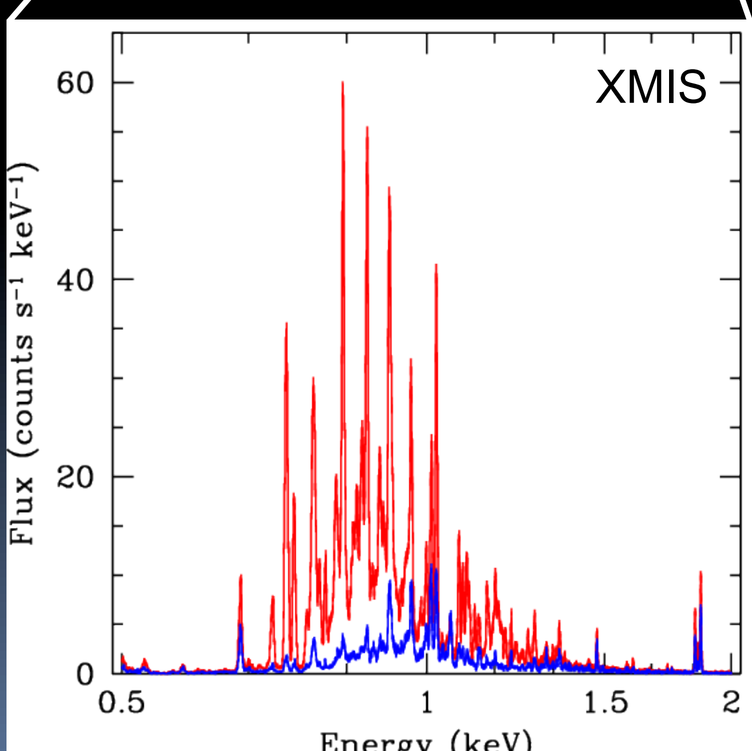
Example: N103B in LMC

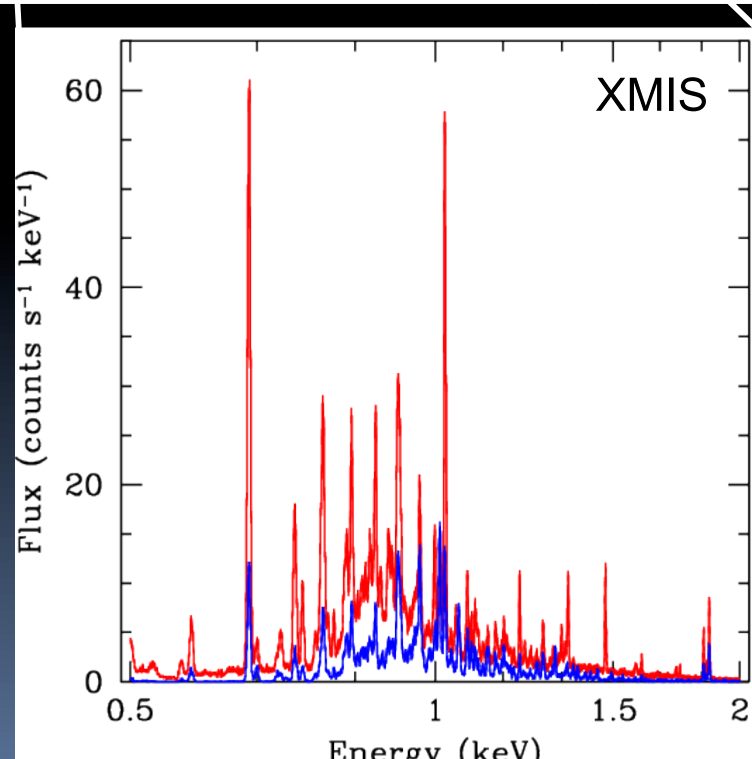
- Type Ia SNR similar to Kepler
  - strong evidence for CSM interaction
- Chandra studies show evidence for spectral variations on multiple scales
- Arcsecond resolution required to probe spectrum on physically important scales.

Magellanic Cloud SNRs

B. Williams (GSFC)







Example: N103B in LMC

- Type Ia SNR similar to Kepler
  - strong evidence for CSM interaction
- Chandra studies show evidence for spectral variations on multiple scales
- Arcsecond resolution required to probe spectrum on physically important scales.

Magellanic Cloud SNRs

Evolution of SN 1987A, including the possible detection of a central neutron star - need sub-arcsecond resolution.

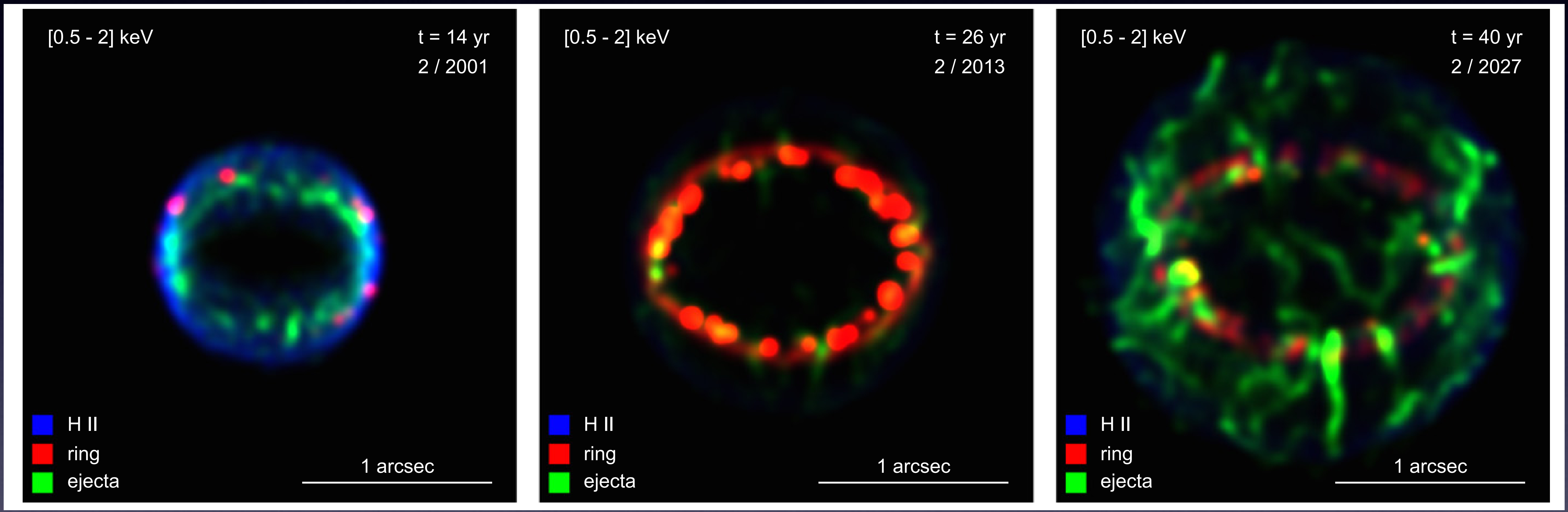


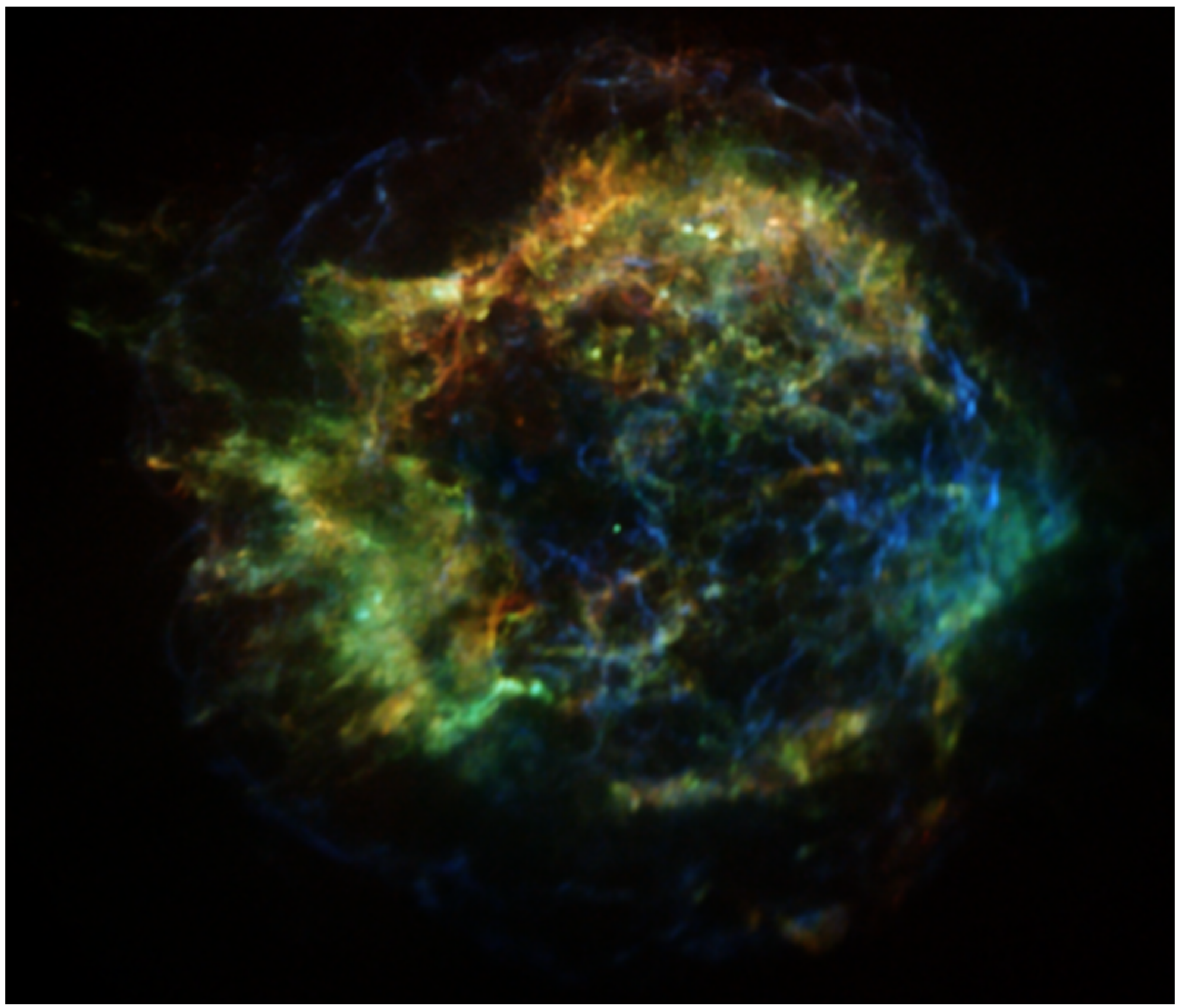
Figure 8. Three-color composite images of the X-ray emission in the [0.5, 2] keV band integrated along the line of sight at the labeled times. Each image has been normalized to its maximum for visibility and smoothed with a Gaussian of size 0.025 arcsec. The colors in the composite show the contribution to emission from the different shocked plasma components, namely the ejecta (green), the ring (red), and the H II region (blue).

Orlando et al. 2015

Neutron Stars in the Magellanic Clouds

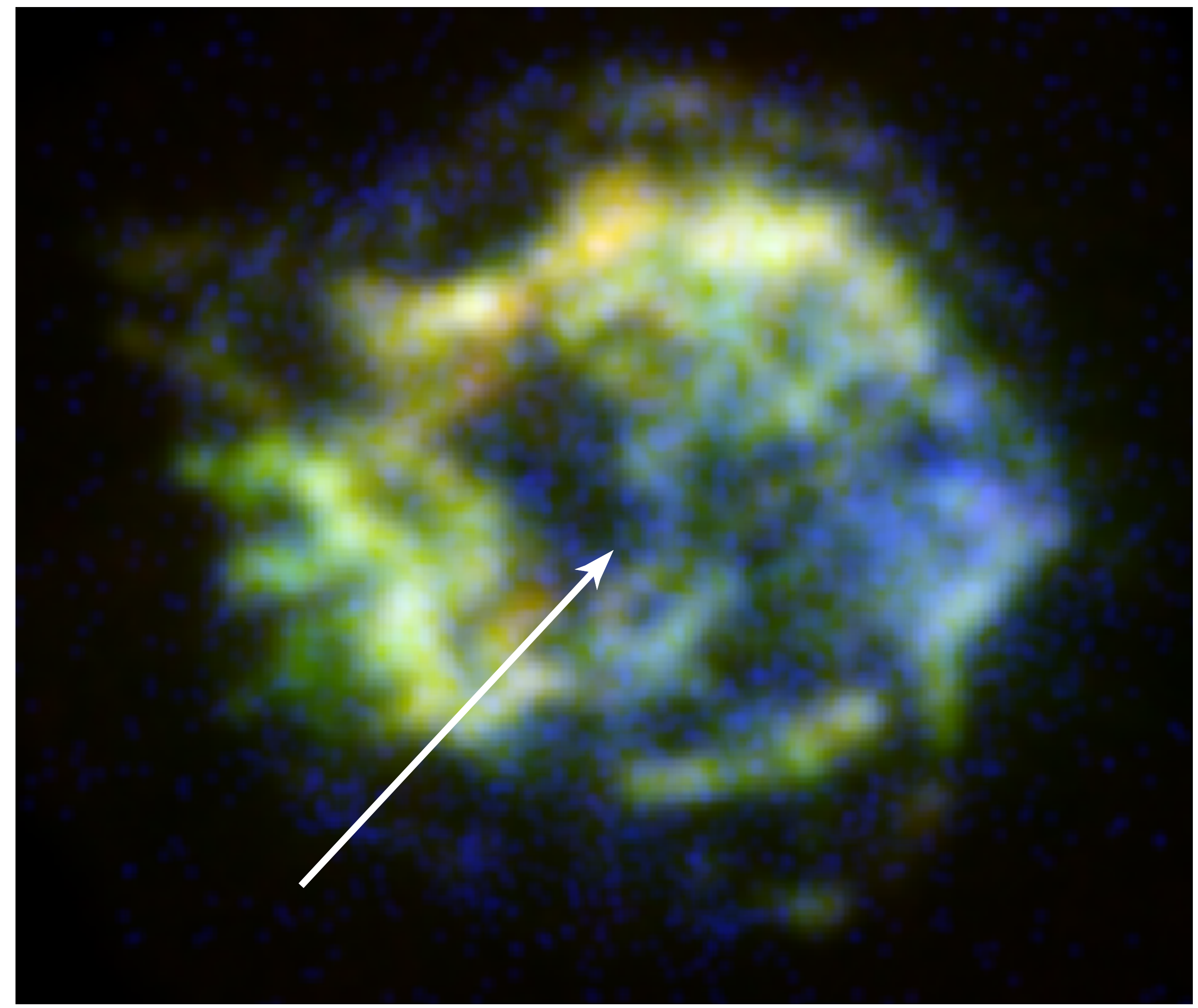
Find or set limits on neutron stars in the LMC/SMC SNRs
Using modest (50 ks) observation, should see Cas A NS in LMC. Possible targets are oxygen-rich N132D and E0102.

Cas A in MW



Chandra 150 ks

Cas A in LMC



Lynx 50 ks

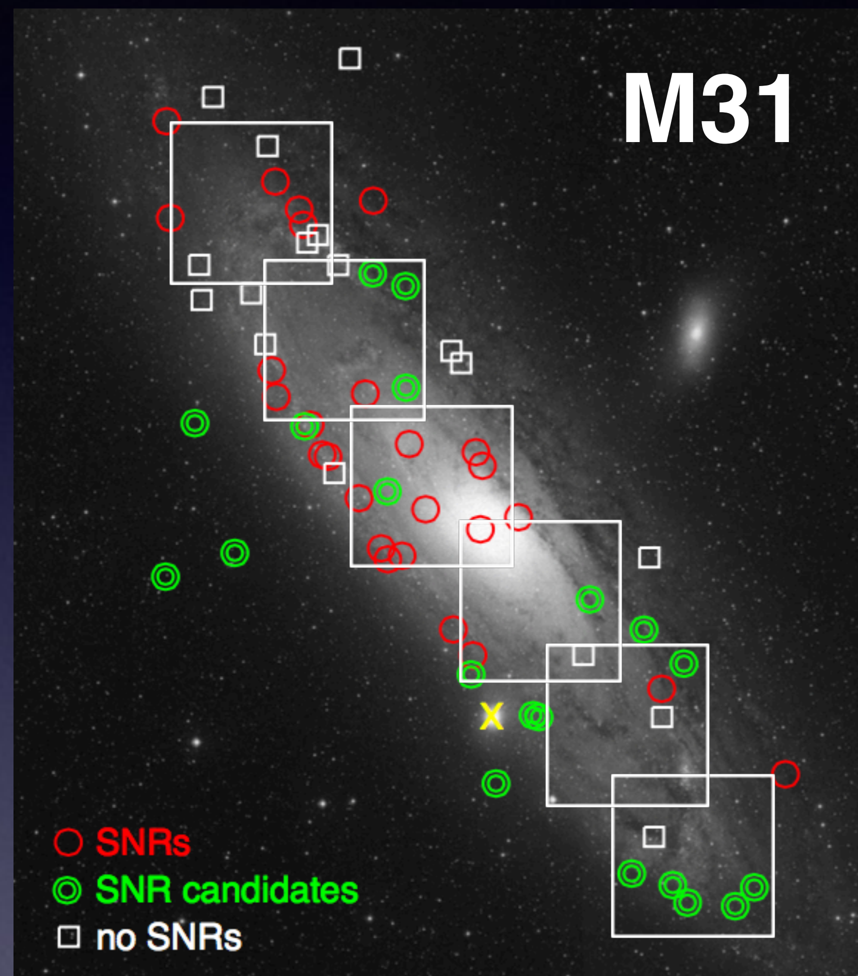
Local Group SNRs

Study populations of SNRs in MW and nearby galaxies

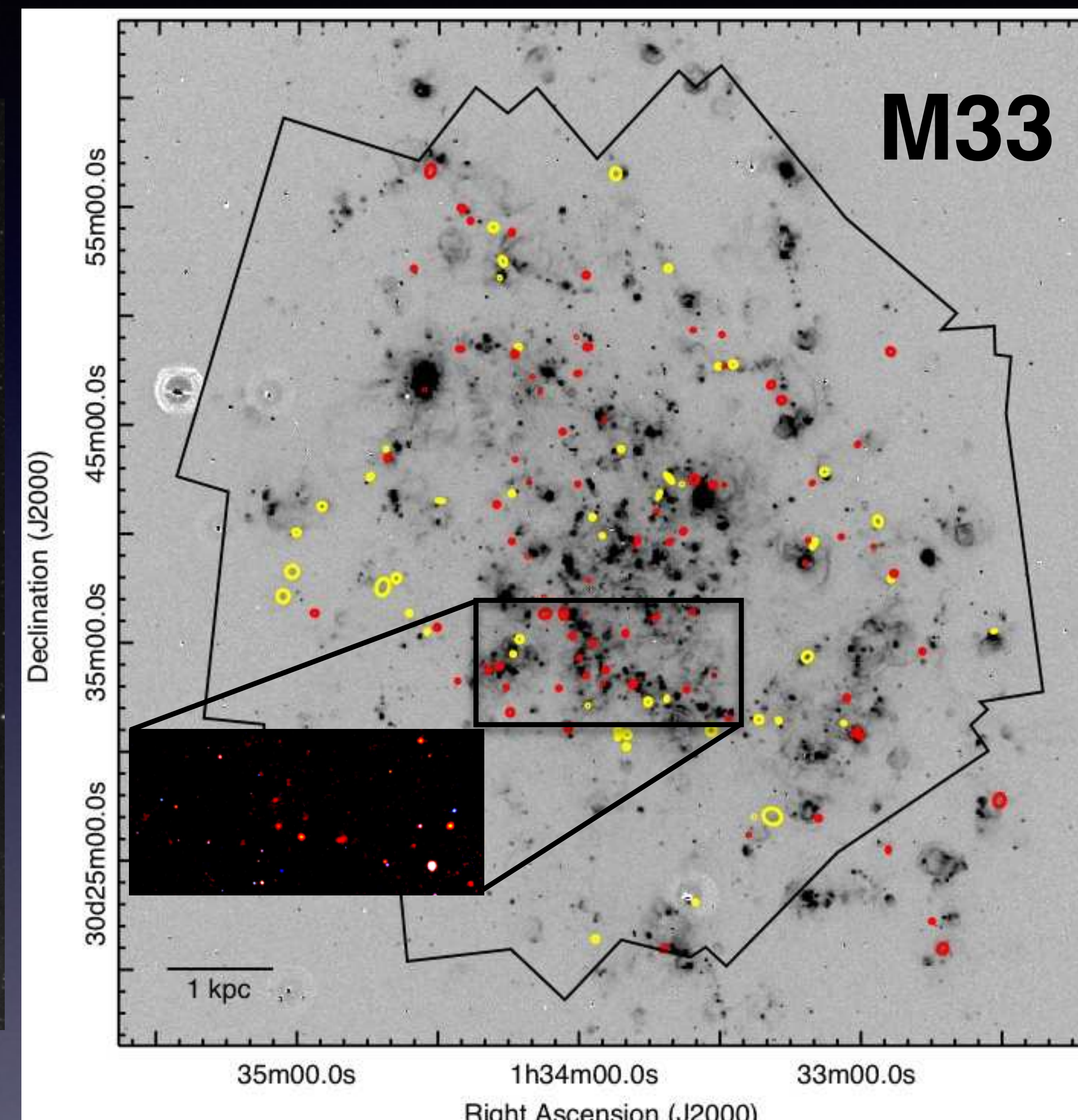
Typical sizes:
~3-30”
(~10-100 pc)

Expect
~10 cts / ks
for 10^{35} erg/s

In M33:
36 SNRs will
have >1000
counts in 100 ks
Lynx exposure



Sasaki et al. 2012:
46 SNRs + candidates

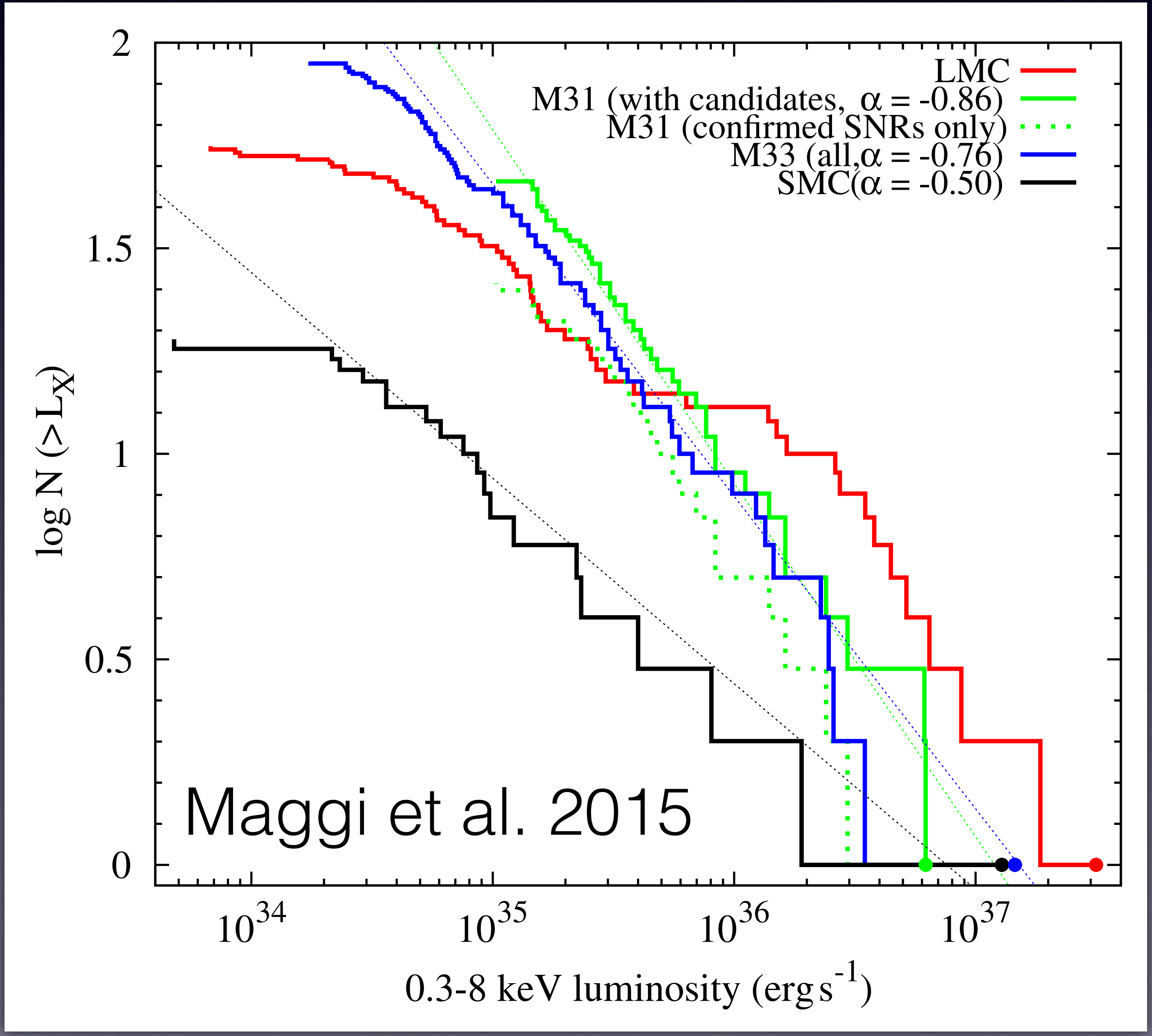


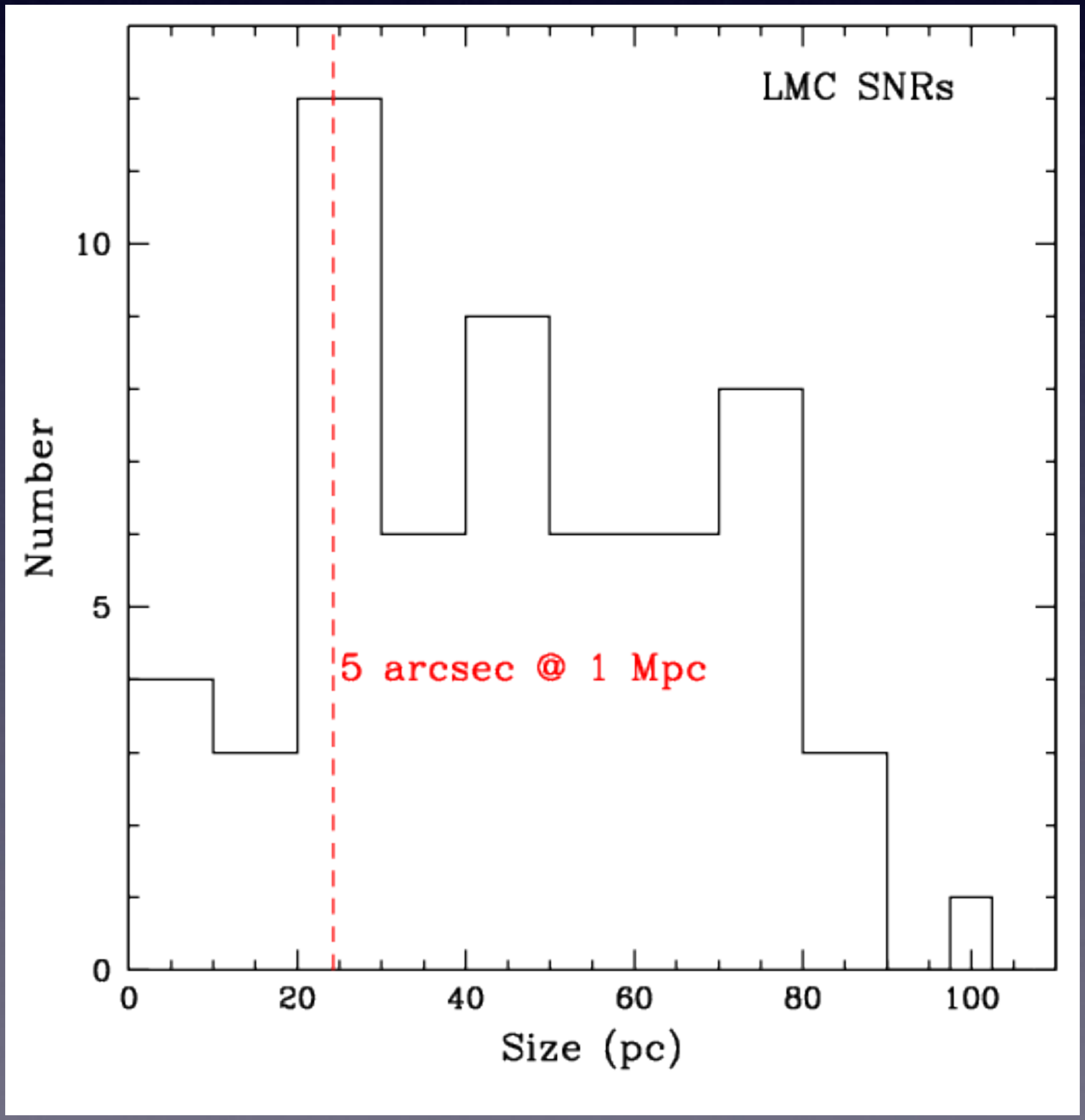
Long et al. 2010:
137 SNRs + candidates

Local Group SNRs

Can spatially resolve most SNRs within 1 Mpc and get spectra from many dozens - identify ejecta, non-thermal, and PWNe.

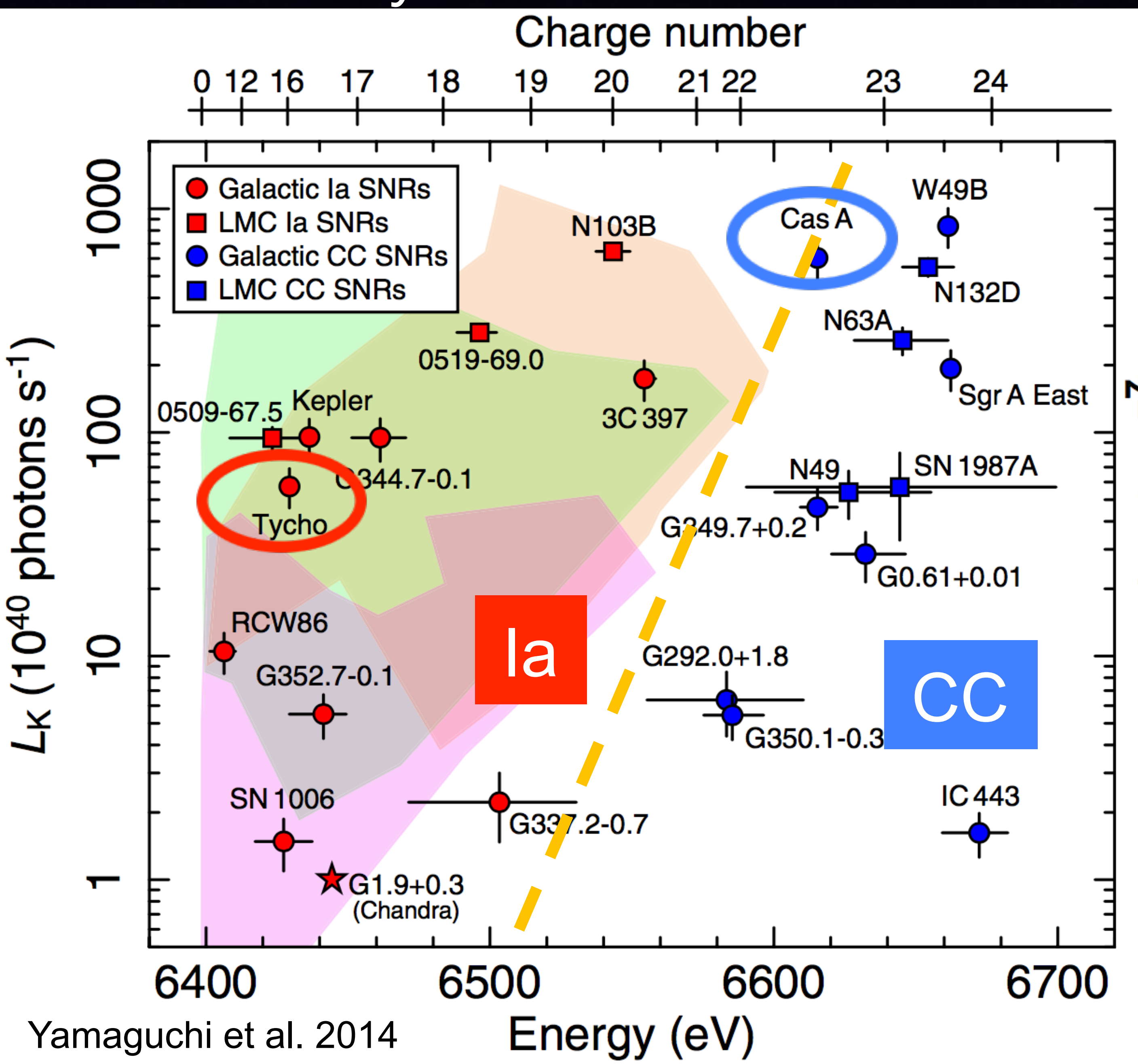
Possible comparison of populations: e.g., compare SNR properties between galaxies, in different galactic environments and metallicities.

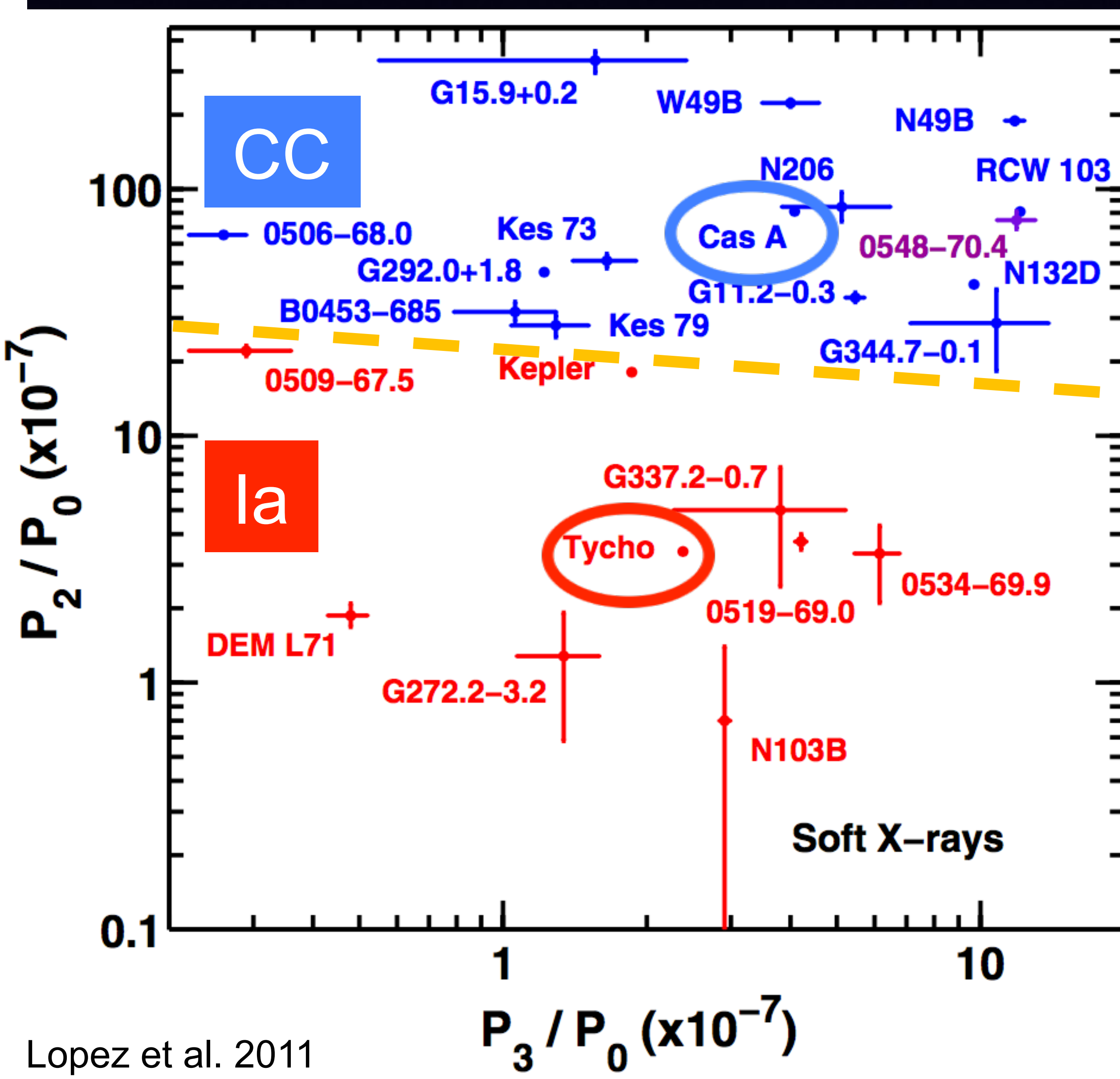




Local Group SNRs

Can type remnants based on the centroid of their Fe-K emission, on their X-ray morphology, and stellar populations in their vicinity.





Typing enables constraints on progenitor scenarios, how/where/when feedback is happening

Conclusions

Chandra has revolutionized our view of supernova remnants: their explosive origins, shock heating, dynamical evolution, particle acceleration properties, and associated neutron stars.

Limitations of current facilities: challenges associated with gratings spectra of extended objects, sensitivity (and spatial resolution) to probe extragalactic populations

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Lynx will give 3D structure of tens of SNRs and enable characterization of hundreds of SNRs in the Local Group - key to understanding explosion mechanisms and SN feedback