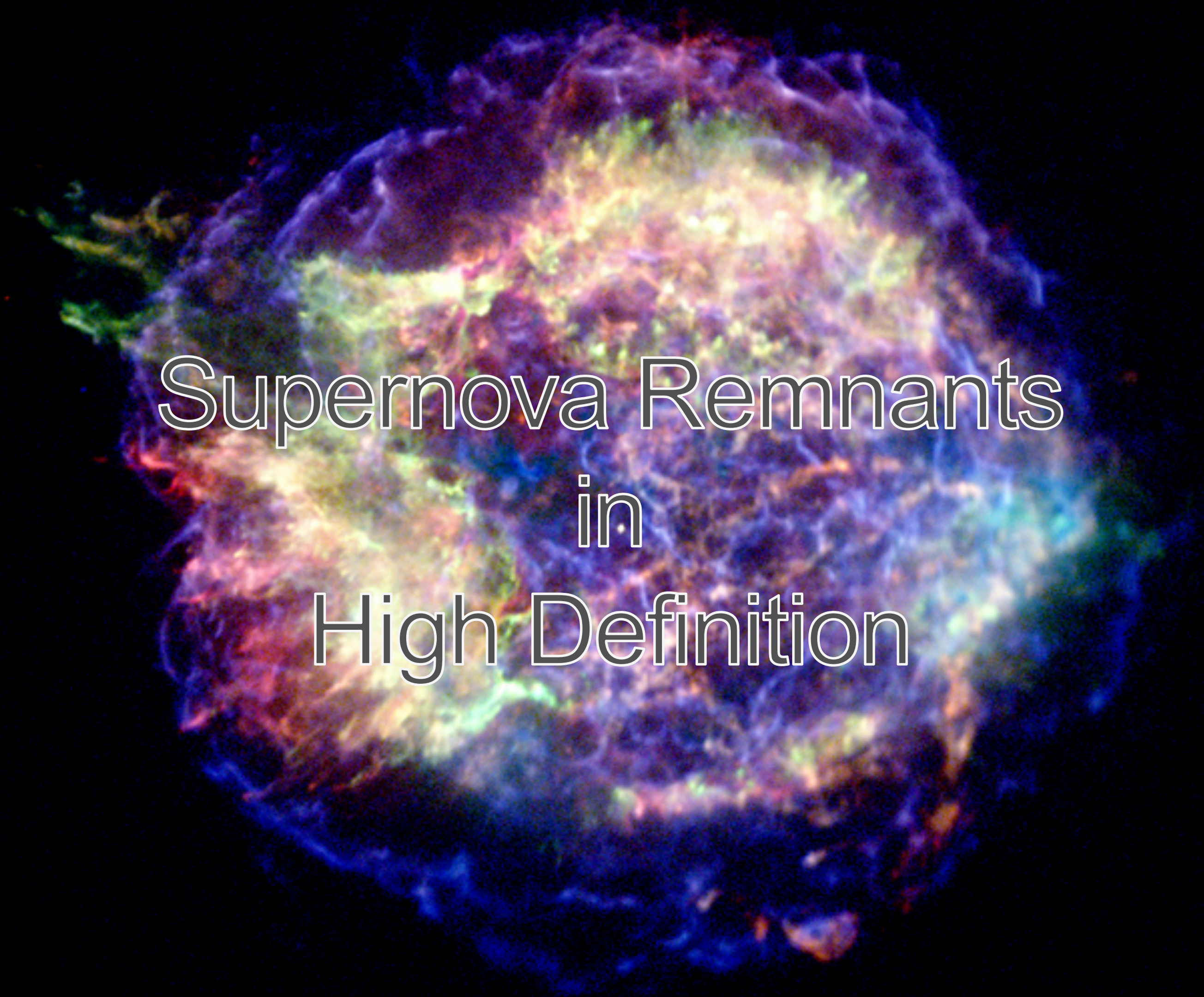
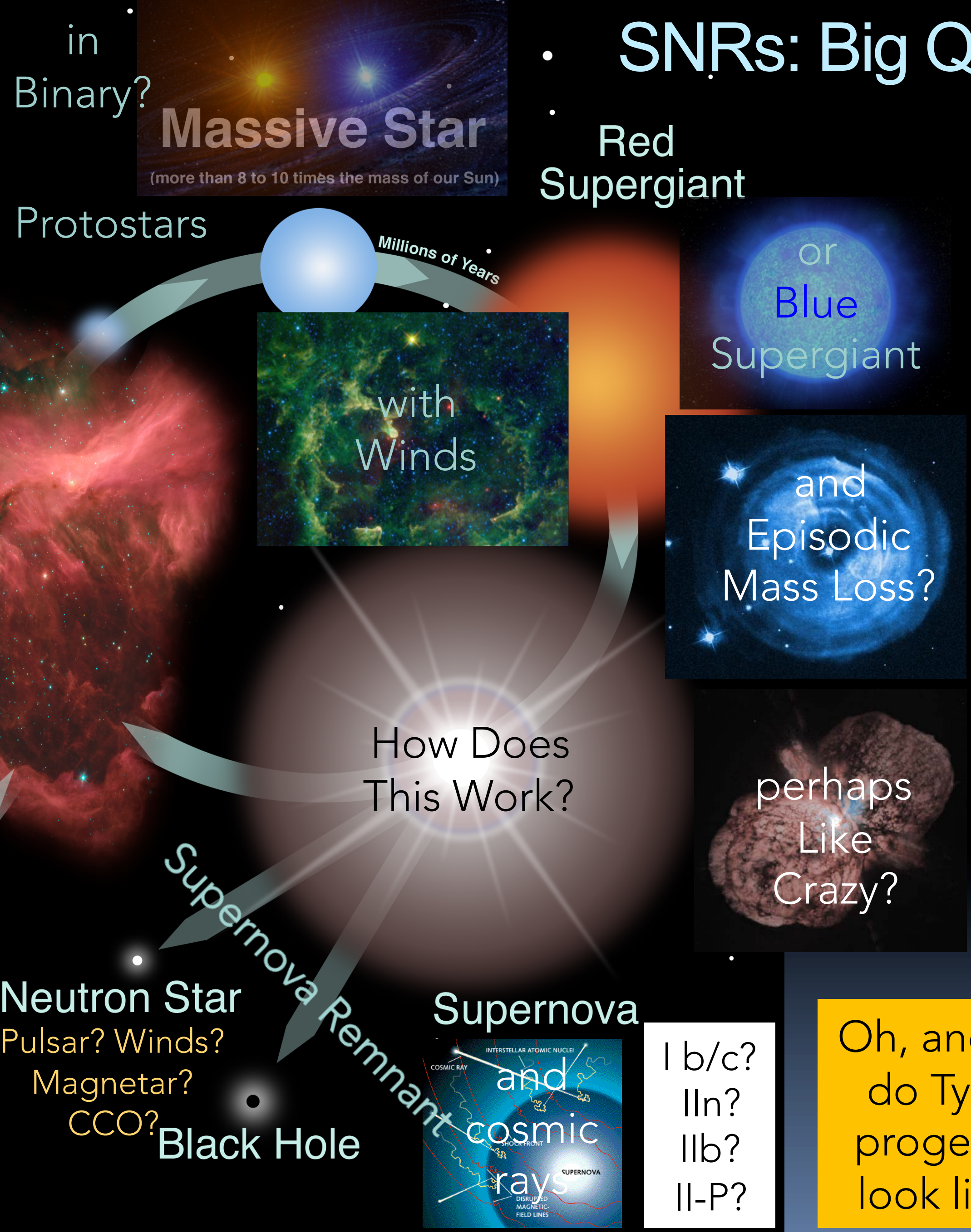
# Supernova Remnants in High Definition



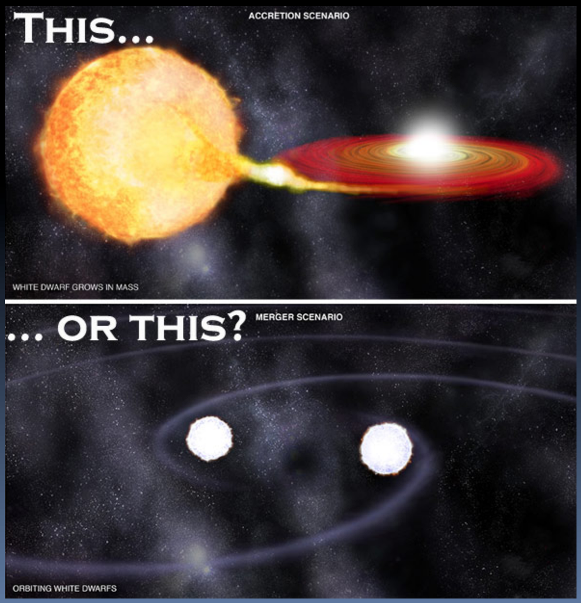
Contributors: Carles Badenes, Chris Freyer, Jack Hughes, Herman Lee, Laura Lopez, Dan Patnaude, Steve Reynolds, Tea Temim, Brian Williams, Annop Wongwathanarat, Hiroya Yamaguchi

# SNRs: Big Questions

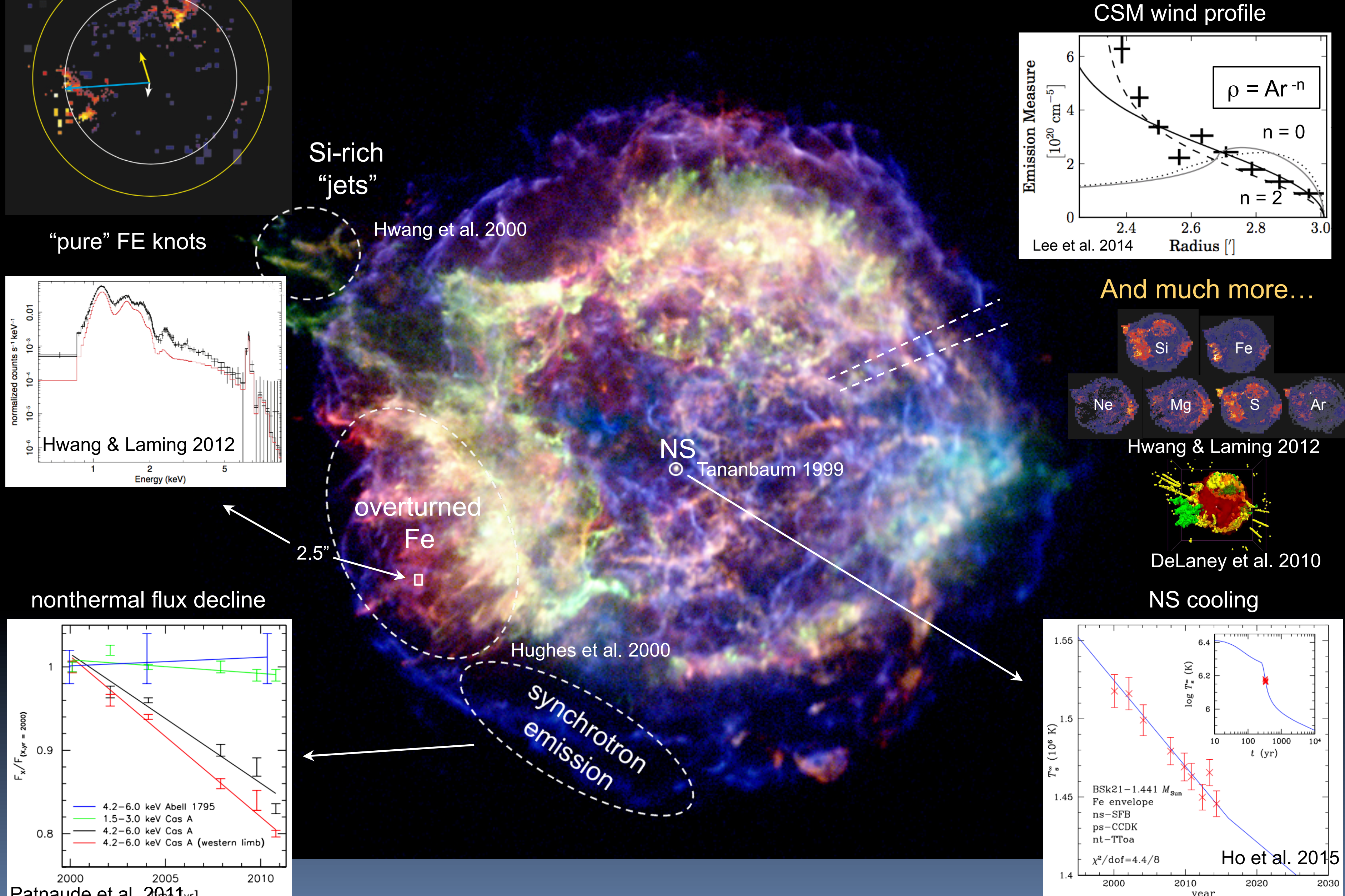



- How do supernovae explode?
- What are the progenitors?
- How are cosmic rays accelerated?
- How does shock heating work?

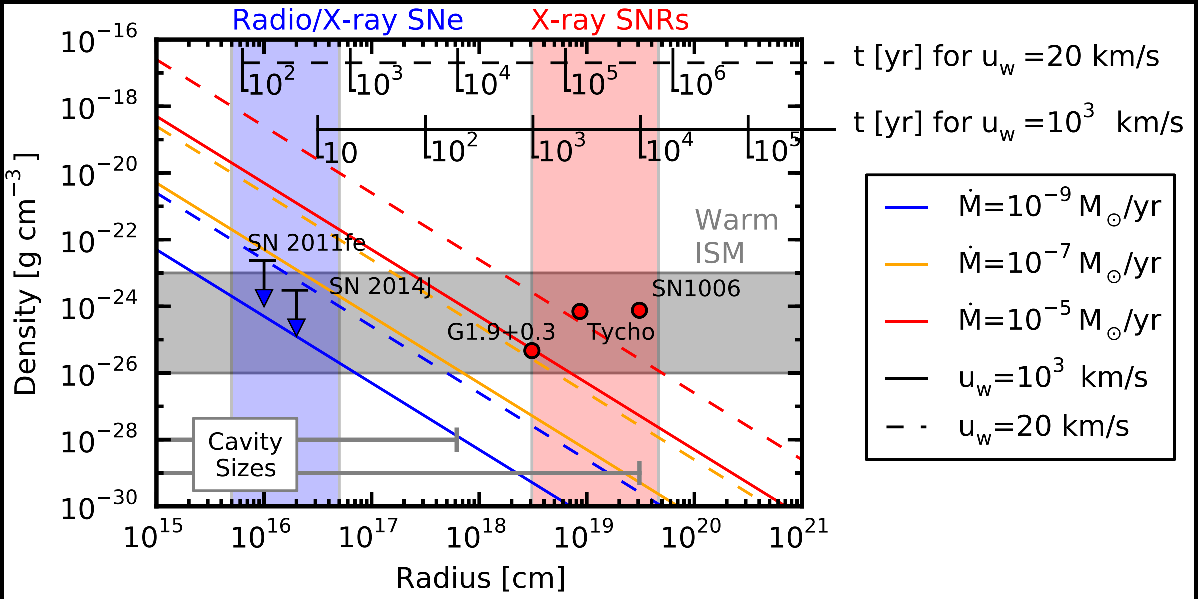
Oh, and what do Type Ia progenitors look like???

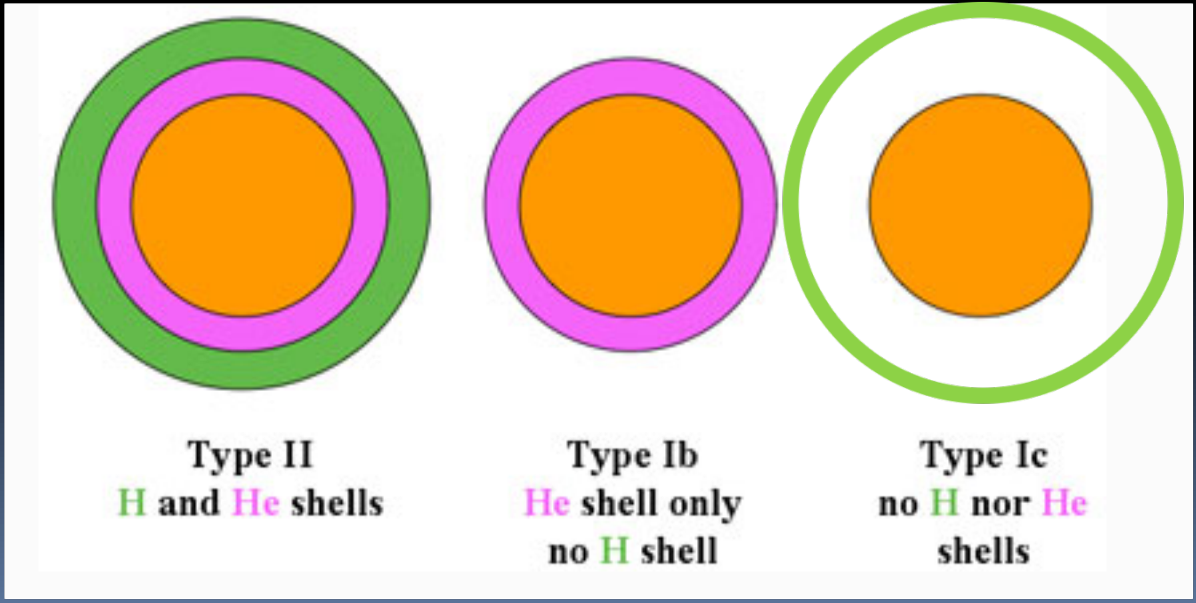


# We've Learned a Lot



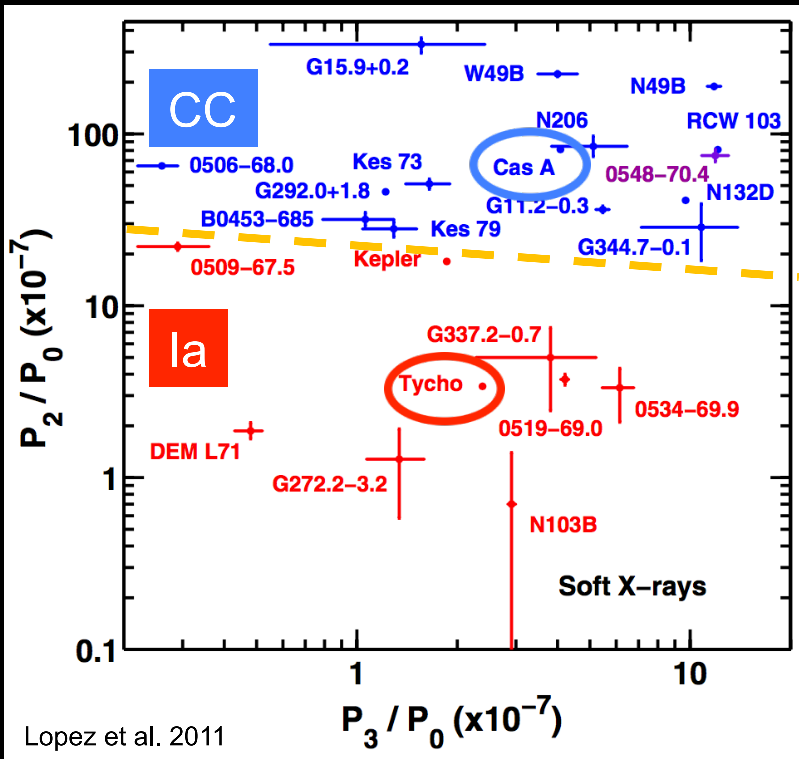
# Probing Mass Loss

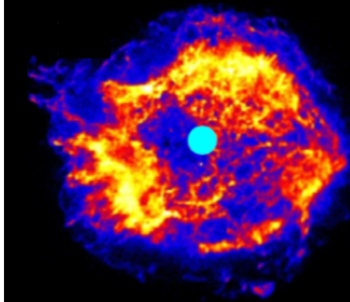


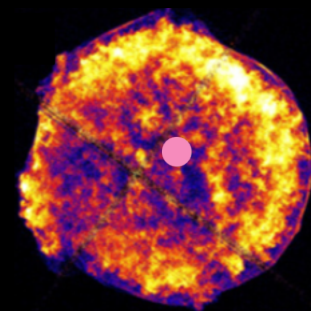




- Progenitor mass loss determines many characteristics of both SNe and their SNRs
  - e.g., SN 2001em is a Type Ib/c that is now showing much brighter X-rays than makes sense for that picture
    - ▹ significant episode of late-phase mass loss?
  - SN 2010mc showed huge mass-loss event 40 days prior to explosion
    - ▹ wind-driven pulsations?
- SNe probe very recent mass loss; SNRs probe mass loss over Kelvin-Helmholtz timescale for post-MS evolution.
  - High sensitivity & spec. resol. needed for SN evolution study
  - High sensitivity & spectral resolution needed for SNRs

# Supernova Types



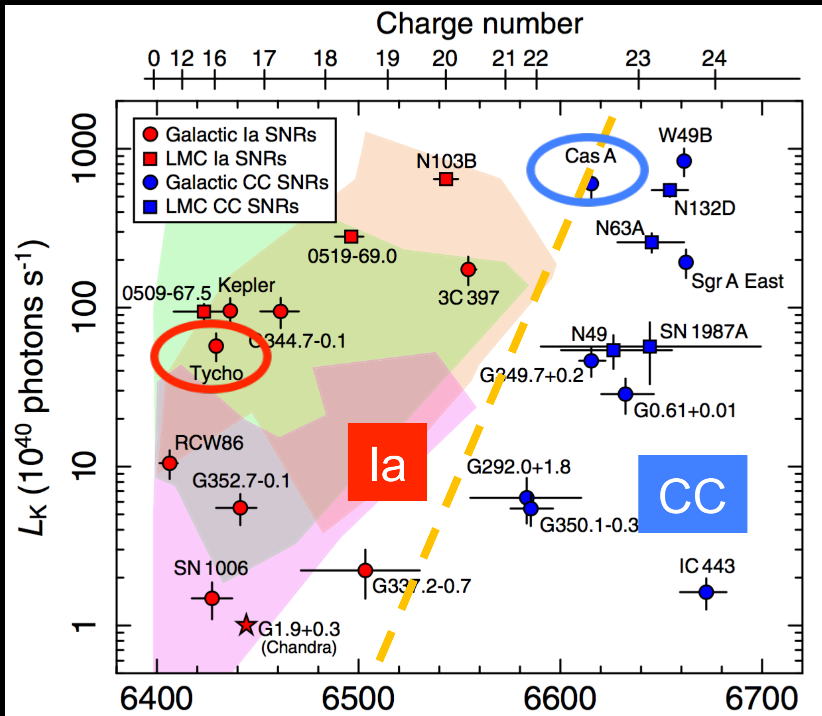





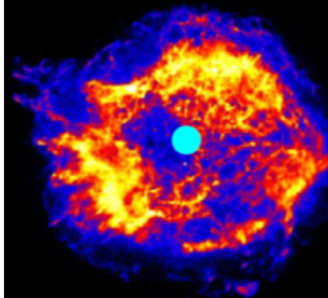
- Understanding the demographics of SNRs allows us to understand the progenitors, how they evolved, and how they exploded.
  - Step 1: Core-collapse or Type Ia?
  - This can be determined with good spectra, or by identifying accompanying NS/PWN
  - Are there other ways (e.g., for fainter SNRs?)

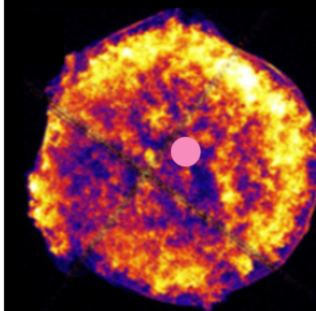
- Moments of brightness distribution relative to emission centroid are different for core-collapse and Type Ia remnants
  - High resolution/area for distant SNRs

# Supernova Types



Yamaguchi et al. 2014

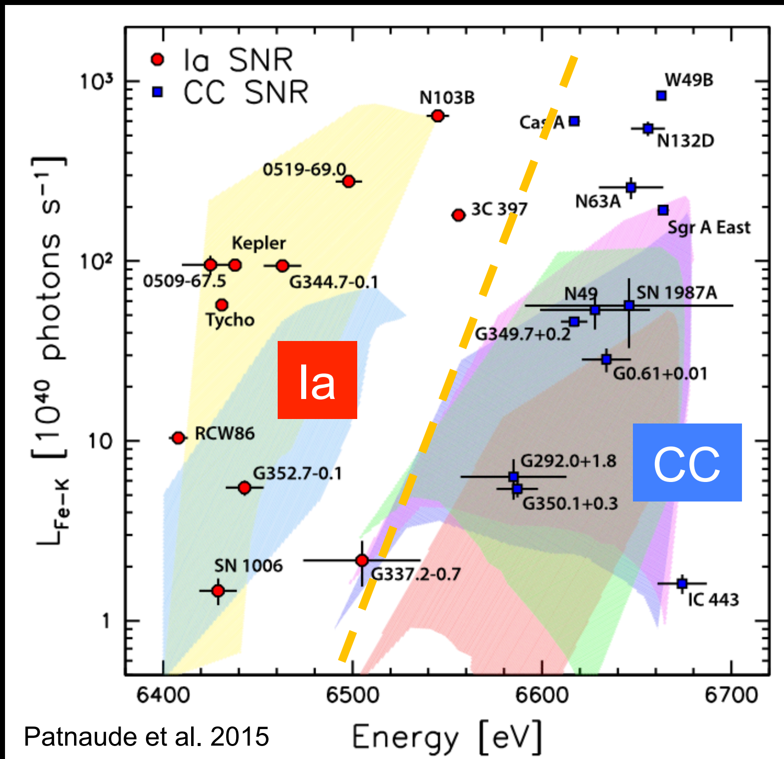


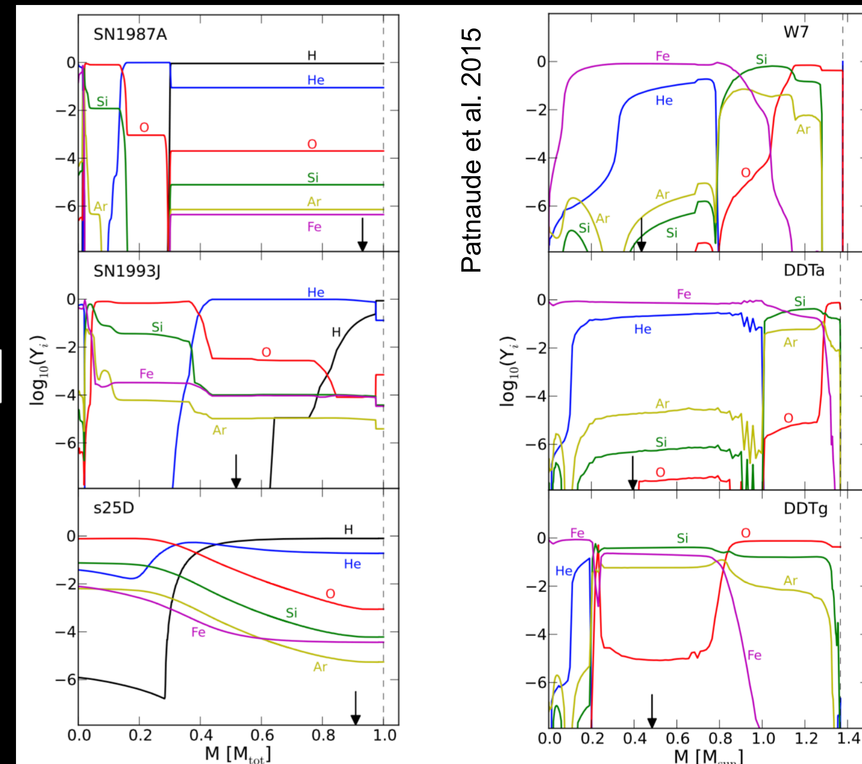


- Understanding the demographics of SNRs allows us to understand the progenitors, how they evolved, and how they exploded.
  - Step 1: Core-collapse or Type Ia?
  - This can be determined with good spectra, or by identifying accompanying NS/PWN
  - Are there other ways (e.g., for fainter SNRs?)

- Moments of brightness distribution relative to emission centroid are different for core-collapse and Type Ia remnants
  - High resolution/area for distant SNRs
- Fe-K flux/centroid is a diagnostic as well

# Supernova Types



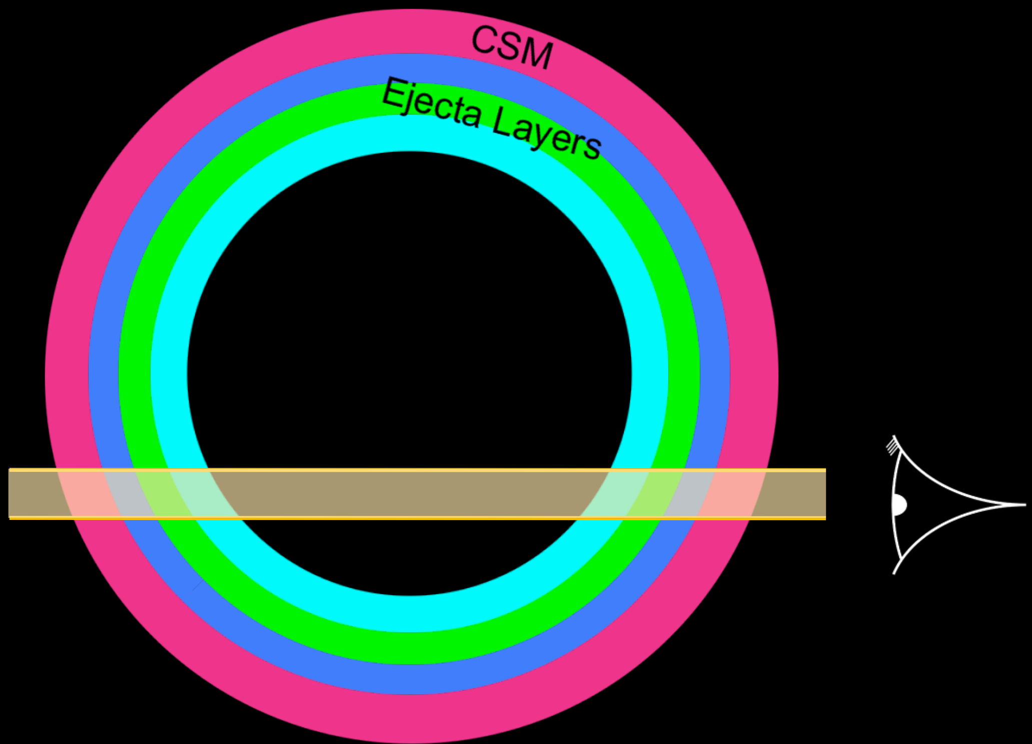



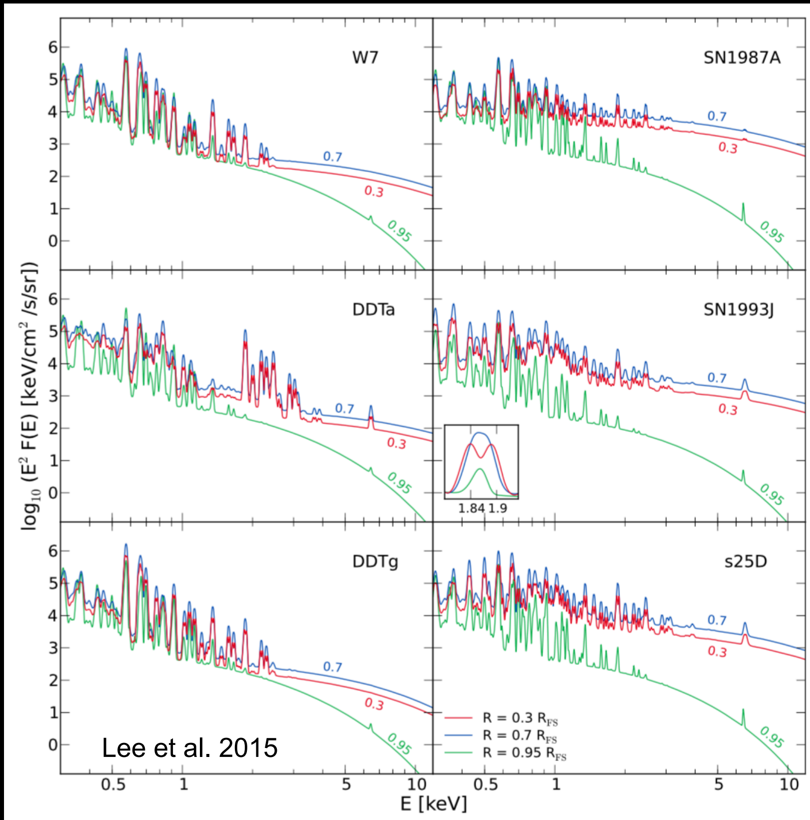

- Understanding the demographics of SNRs allows us to understand the progenitors, how they evolved, and how they exploded.
  - Step 1: Core-collapse or Type Ia?
  - This can be determined with good spectra, or by identifying accompanying NS/PWN
  - Are there other ways (e.g., for fainter SNRs?)

- Moments of brightness distribution relative to emission centroid are different for core-collapse and Type Ia remnants
  - High resolution/area for distant SNRs

- Fe-K flux/centroid is a diagnostic as well
  - Density structure of ejecta yields higher Fe-K ionization states in CC remnants

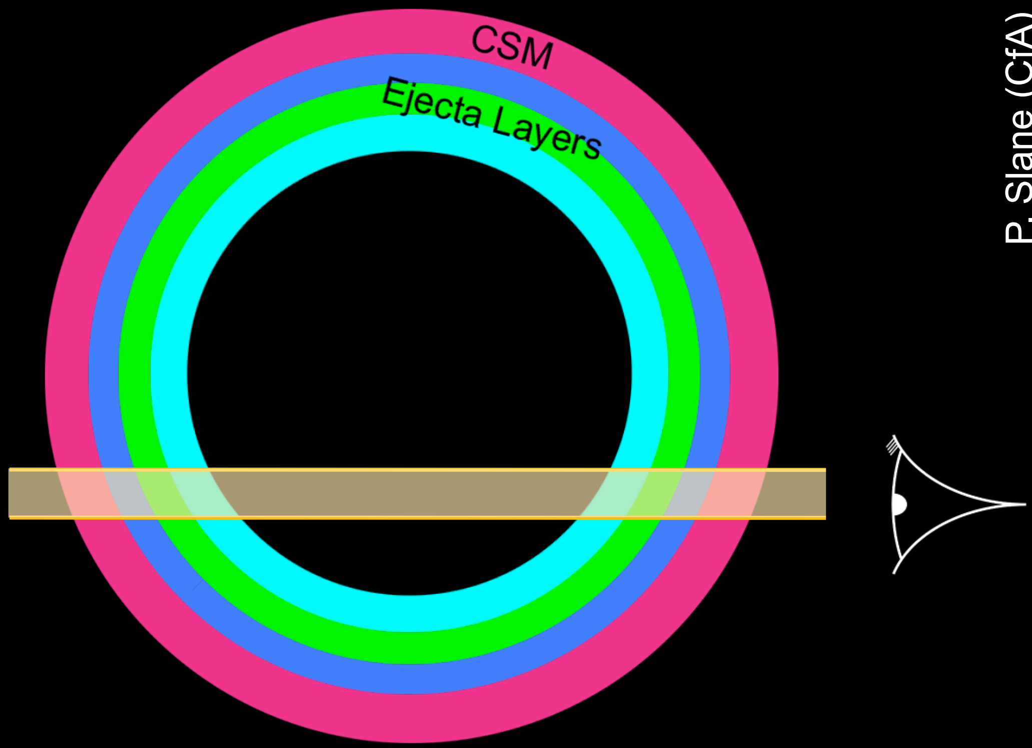
# SNR Dynamics and Shock Physics



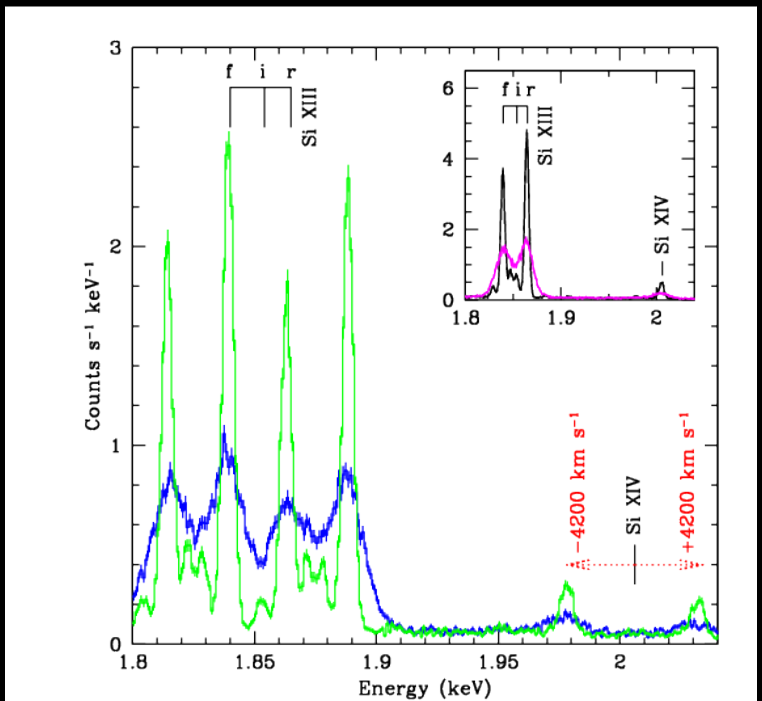




- Hydrodynamical simulations using realistic ejecta composition and density profiles for core-collapse and Type Ia models
  - Follow heating and ionization; couple to emission code to produce spatially-resolved spectral predictions
  - Include effects of cosmic-ray acceleration

# SNR Dynamics and Shock Physics




P. Slane (CfA)




SN 1993j ejecta, Age = 500 yr; R = 0.3 $R_{SNR}$

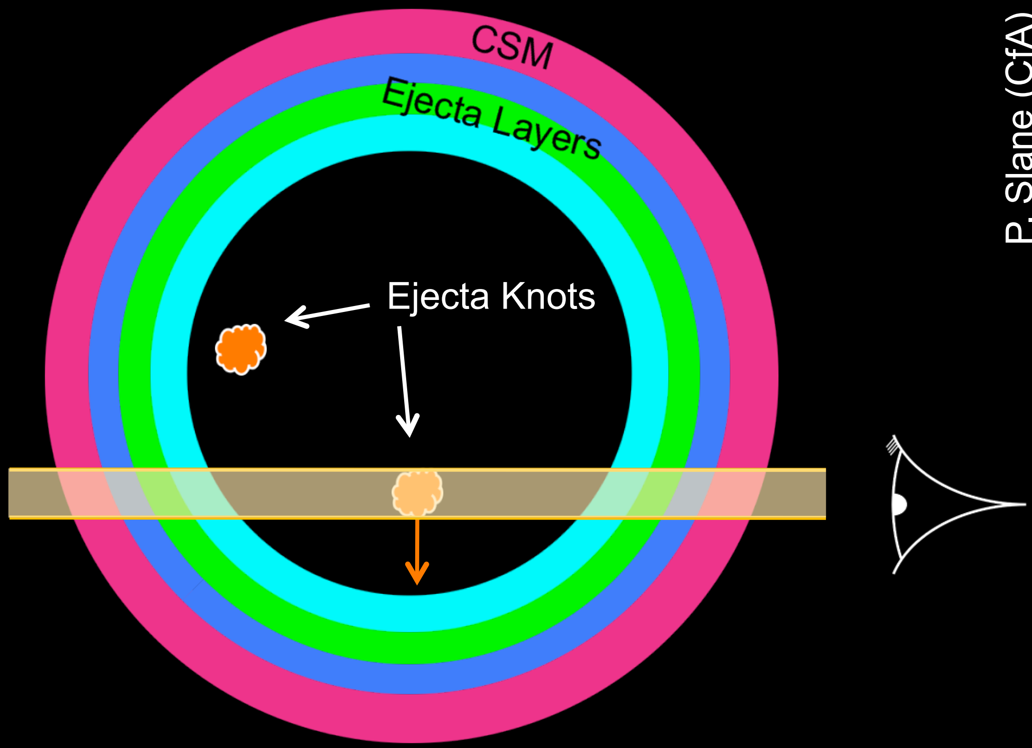
- High resolution spectra are required to determine velocities through Doppler motions
  - Crucial for establishing 3D structure of SNRs
  - Constrain explosion asymmetries
- Determine mass/composition/motion of ejecta knots

- Line broadening constrains heating in shock/postshock region, and turbulence

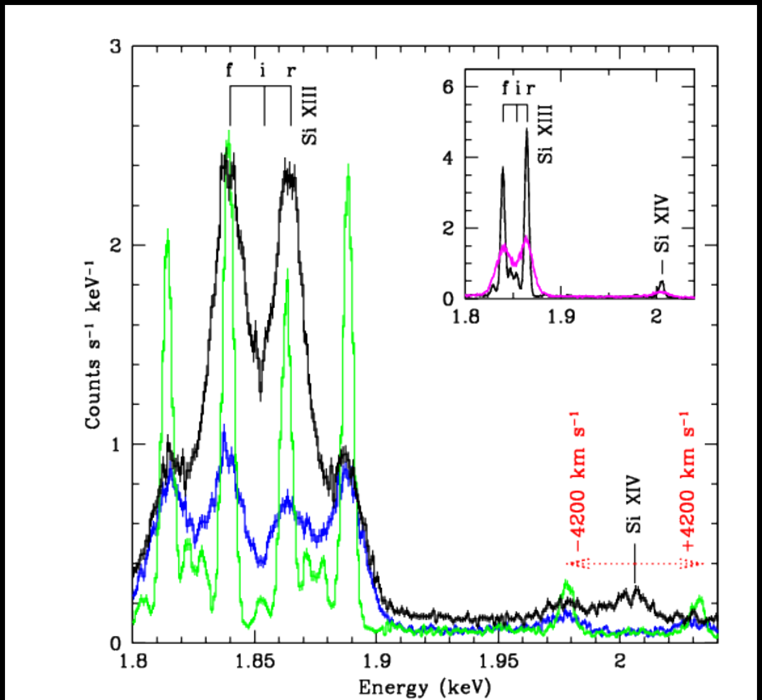
$$\Delta E = \frac{E_0}{c}\left[\frac{2kT}{m} + v_{turb}^2\right]^{1/2}$$

- Thermal broadening depends on ion mass
  - Heating/equilibration timescale?
  - Separate from turbulent component (crucial for explosion physics)

# SNR Dynamics and Shock Physics




P. Slane (CfA)




SN 1993j ejecta, Age = 500 yr; R = 0.3 $R_{SNR}$

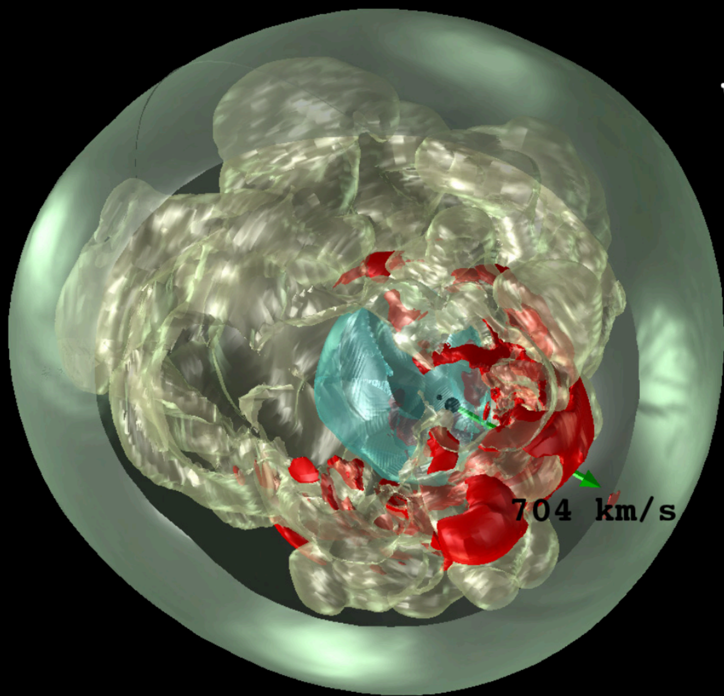
- High resolution spectra are required to determine velocities through Doppler motions
  - Crucial for establishing 3D structure of SNRs
  - Constrain explosion asymmetries
- Determine mass/composition/motion of ejecta knots

- Line broadening constrains heating in shock/postshock region, and turbulence

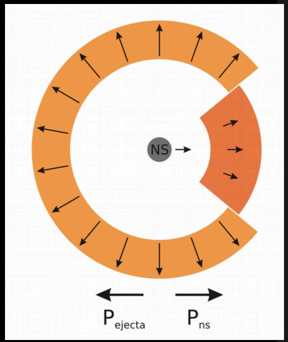
$$\Delta E = \frac{E_0}{c}\left[\frac{2kT}{m} + v_{\rm turb}^2\right]^{1/2}$$

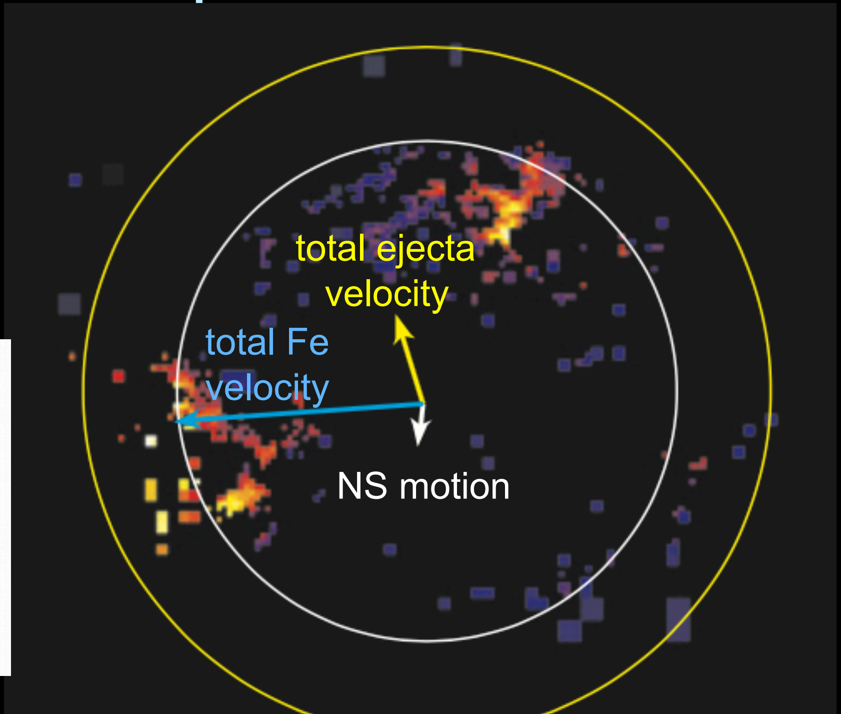
- Thermal broadening depends on ion mass
  - Heating/equilibration timescale?
  - Separate from turbulent component (crucial for explosion physics)

# Asymmetries in SN Explosions




Wongwathanarat et al. 2013



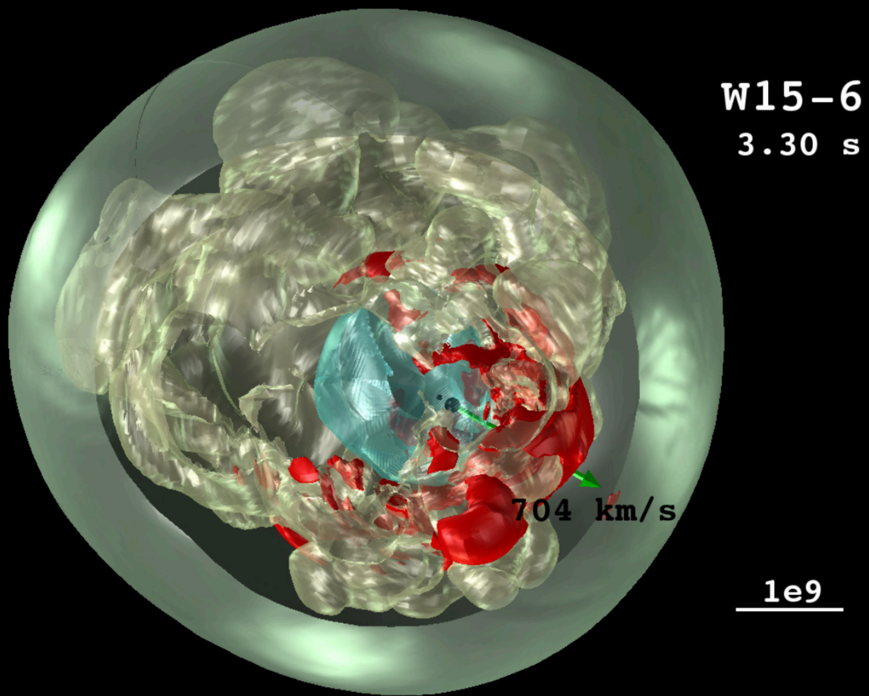




Hwang & Laming 2012

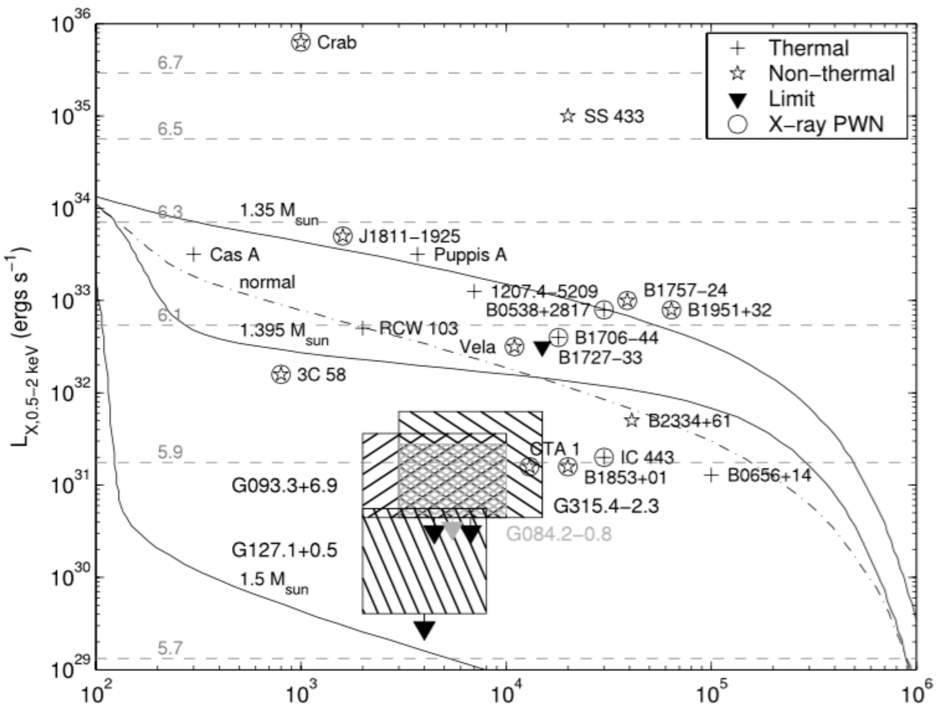
- NS velocities may result from a “tugboat” effect from slower-moving ejecta residing near NS
  - Bulk of the ejecta motion is in opposite direction
  - Prediction is thus that NS proper motion will be anti-aligned with net ejecta momentum
- Cas A ejecta dynamics and apparent NS motion seem to support this based on low-res spectra and gratings spectra of some bright knots

- Deeper searches for NSs within SNRs are needed to investigate connection between proper motions and ejecta asymmetries
  - Requires larger area at soft energies, good angular resolution

# Asymmetries in SN Explosions



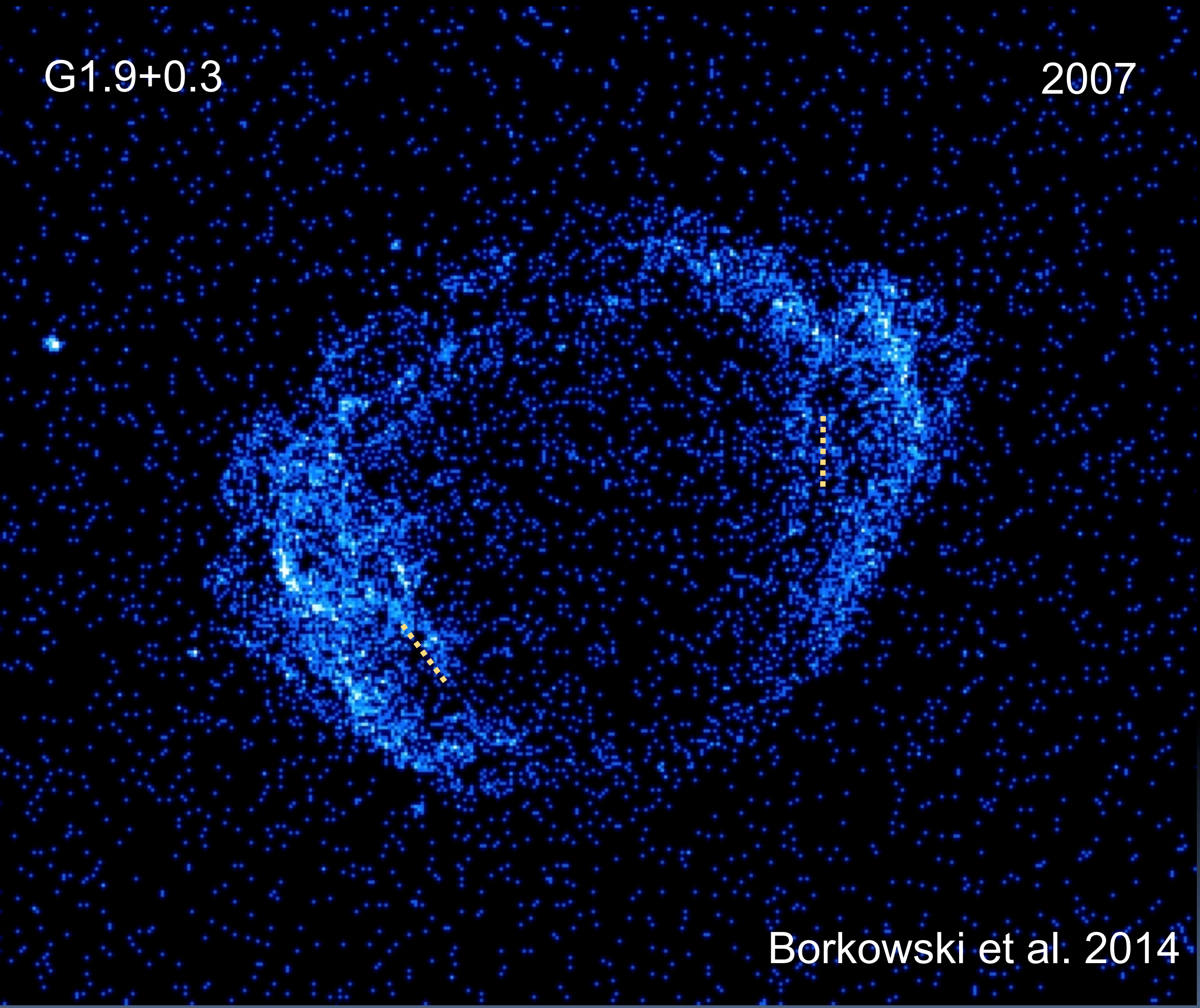

Wongwathanarat et al. 2013




Kaplan et al. 2004

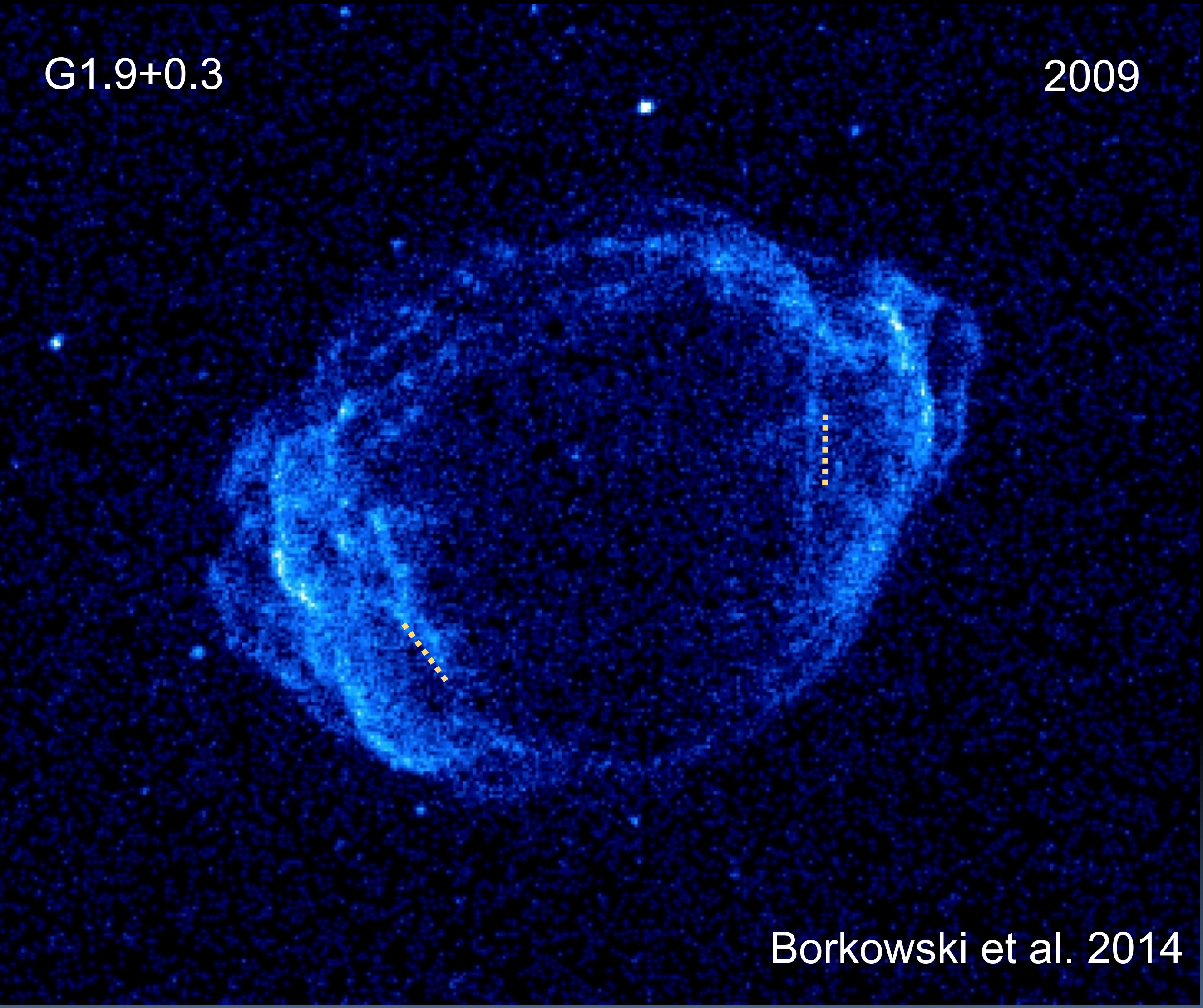
- NS velocities may result from a "tugboat" effect from slower-moving ejecta residing near NS
  - Bulk of the ejecta motion is in opposite direction
  - Prediction is thus that NS proper motion will be anti-aligned with net ejecta momentum
- Cas A ejecta dynamics and apparent NS motion seem to support this based on low-res spectra and gratings spectra of some bright knots
- Deeper searches for NSs within SNRs are needed to investigate connection between proper motions and ejecta asymmetries
  - Requires larger area at soft energies, good angular resolution
  - May also constrain NS masses and connect w/ progenitor properties

# Expansion in 3D



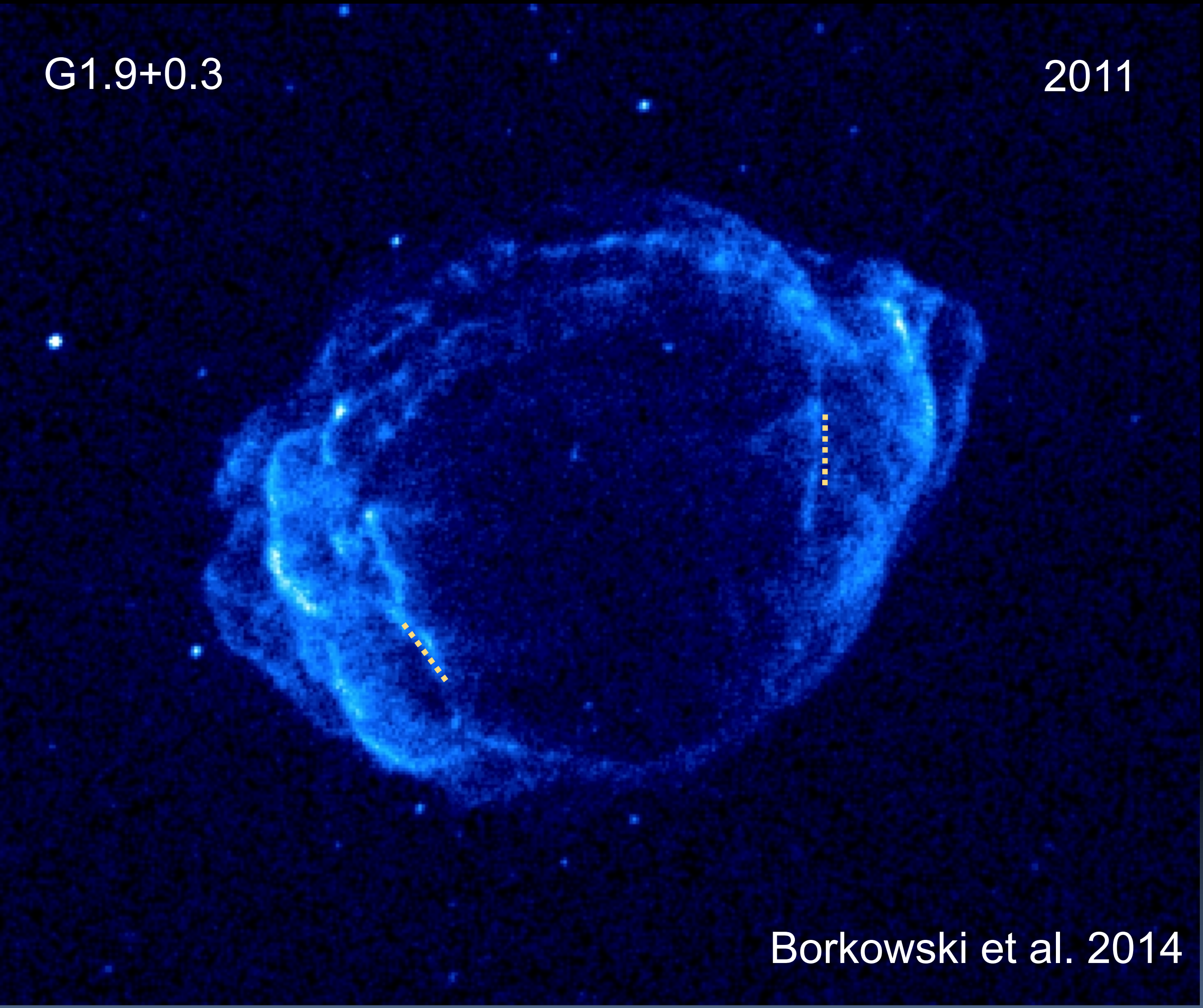

- Coupled with measurements of velocity (through spectra), expansion measurements determine 3D structure of SN ejecta
  - explosion asymmetries; kicks, jet-driven explosions
  - density distributions in CSM and ejecta
- Currently, Cas A expansion measurements are limited by off-axis PSF degradation
  - XRS will provide high resolution across entire remnant
- Expansion measurements for RX J1713 are limited by both off-axis PSF and statistics
  - large area & high resolution will provide dynamics for all young Galactic SNRs

# Expansion in 3D



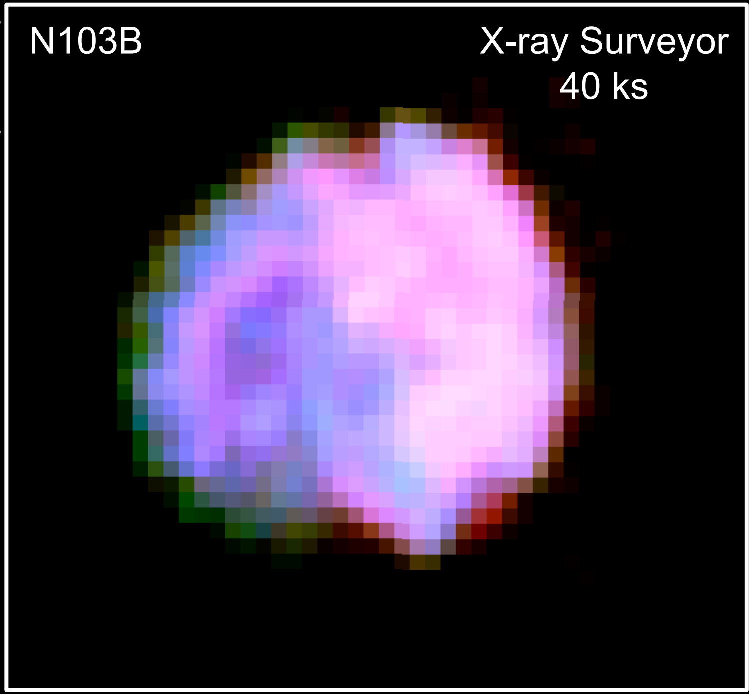

- Coupled with measurements of velocity (through spectra), expansion measurements determine 3D structure of SN ejecta
  - explosion asymmetries; kicks, jet-driven explosions
  - density distributions in CSM and ejecta
- Currently, Cas A expansion measurements are limited by off-axis PSF degradation
  - XRS will provide high resolution across entire remnant
- Expansion measurements for RX J1713 are limited by both off-axis PSF and statistics
  - large area & high resolution will provide dynamics for all young Galactic SNRs

# Expansion in 3D




- Coupled with measurements of velocity (through spectra), expansion measurements determine 3D structure of SN ejecta
  - explosion asymmetries; kicks, jet-driven explosions
  - density distributions in CSM and ejecta
- Currently, Cas A expansion measurements are limited by off-axis PSF degradation
  - XRS will provide high resolution across entire remnant
- Expansion measurements for RX J1713 are limited by both off-axis PSF and statistics
  - large area & high resolution will provide dynamics for all young Galactic SNRs

# Magellanic Cloud SNRs



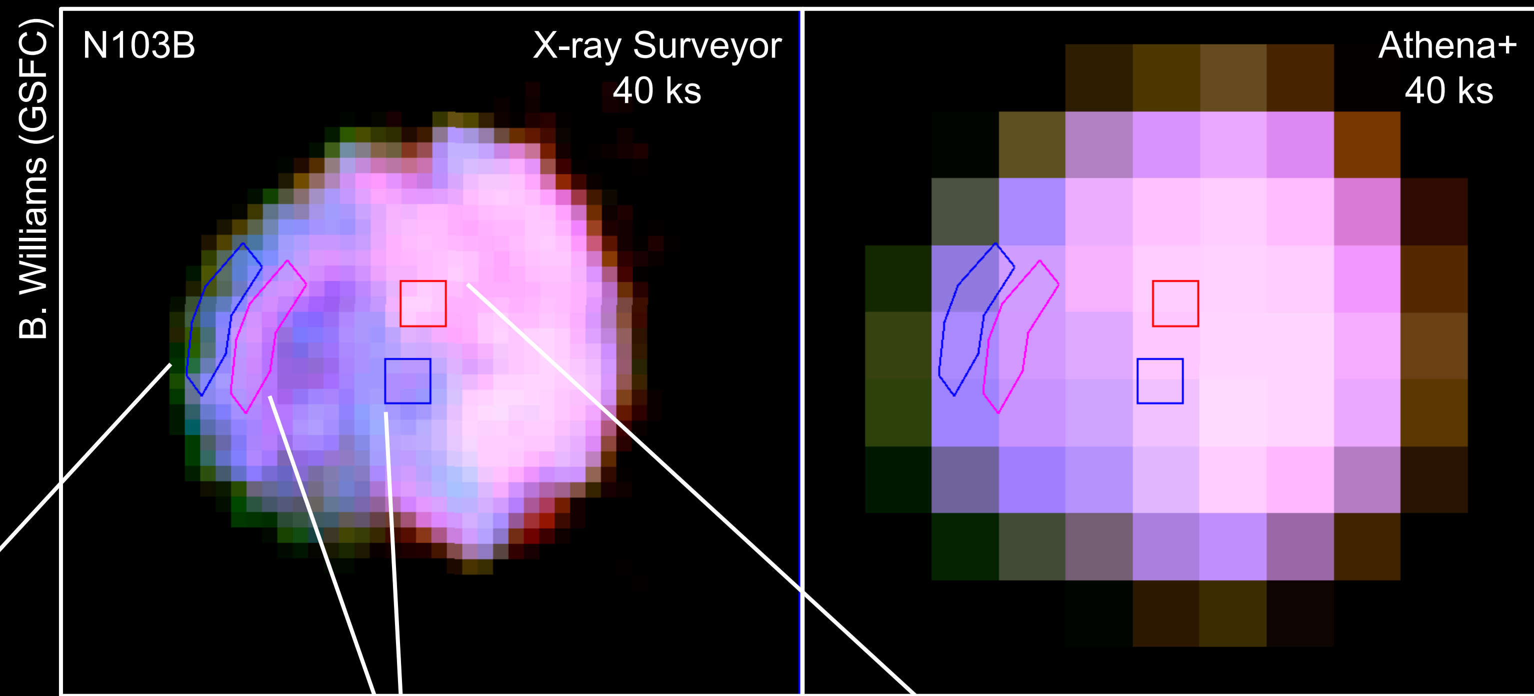

B. Williams (GSFC)

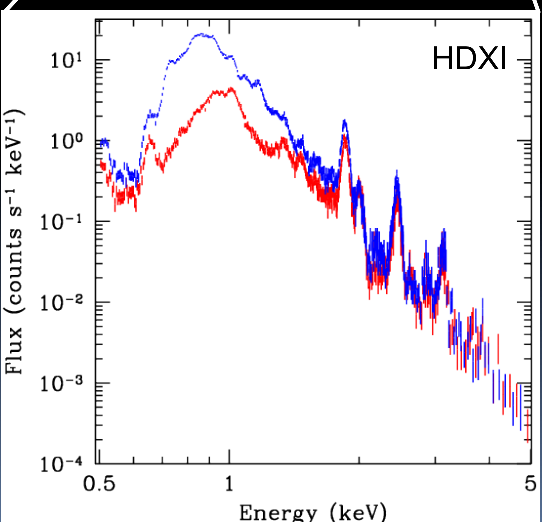
Example: N103B in LMC

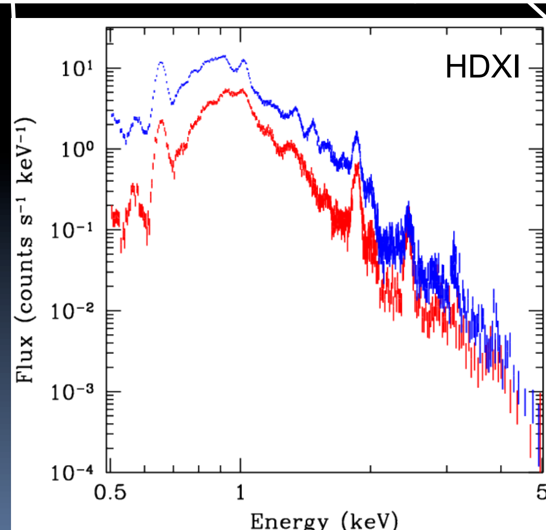
- Type Ia SNR similar to Kepler
  - strong evidence for CSM interaction

- Chandra studies show evidence for spectral variations on multiple scales.

# Magellanic Cloud SNRs



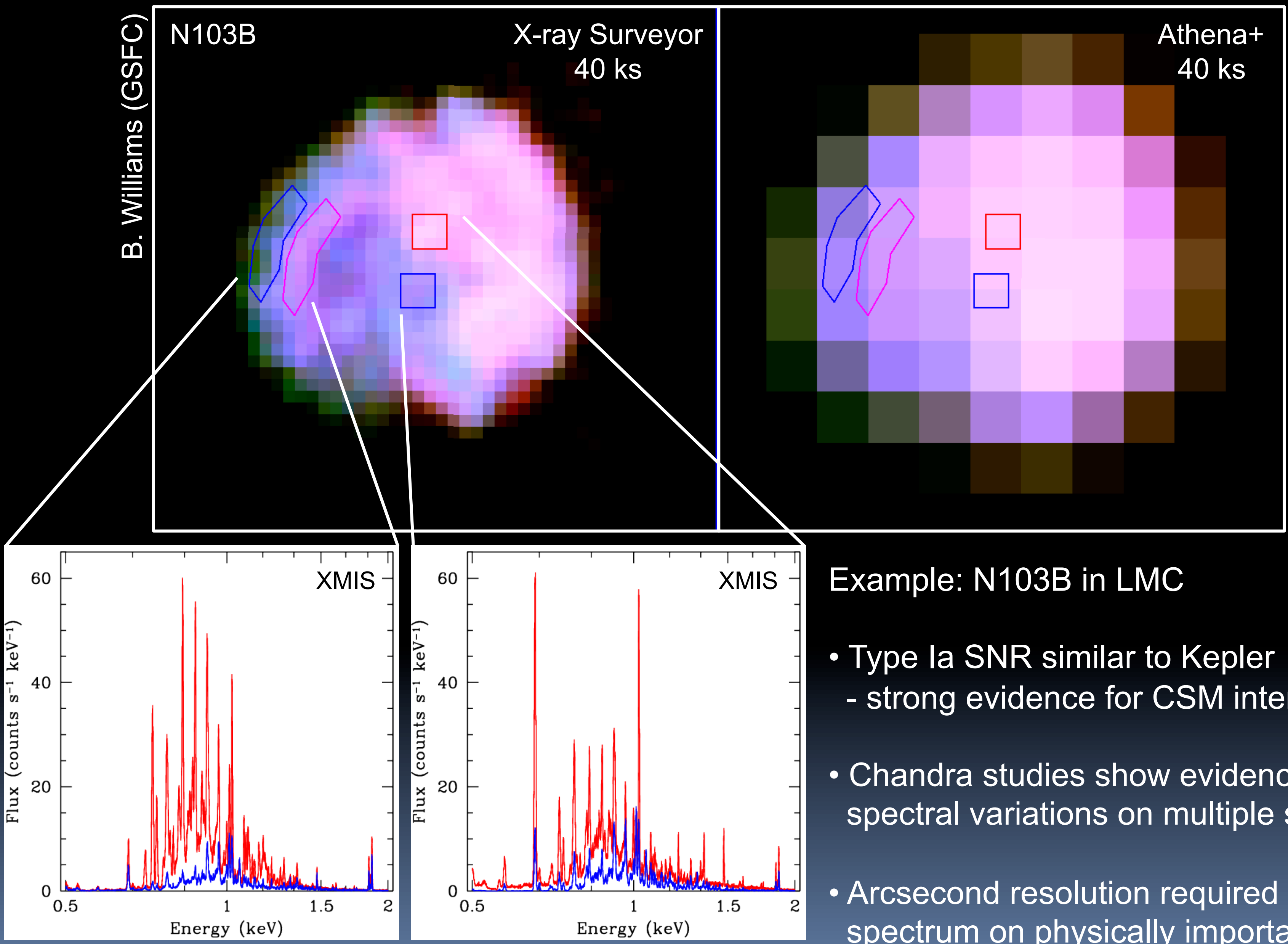




Example: N103B in LMC

- 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.

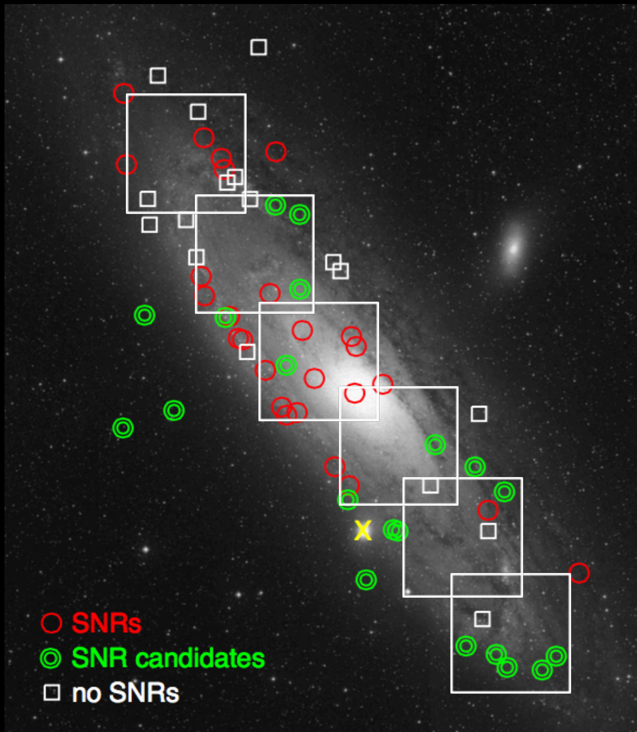
# Magellanic Cloud SNRs




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.

# Extragalactic SNRs



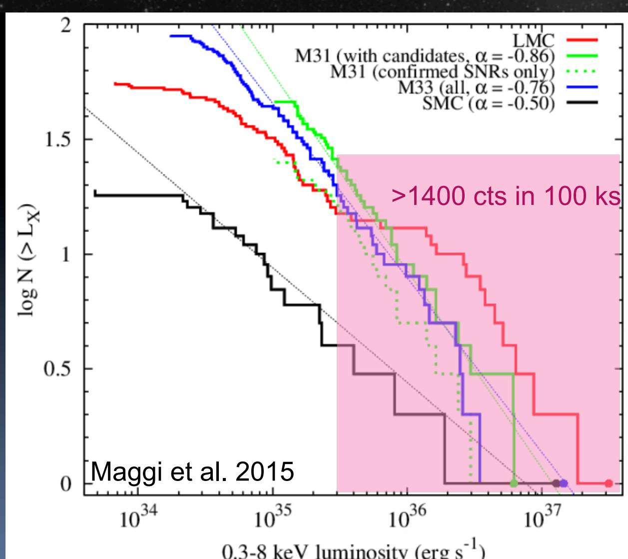

- Samples at known distance provide probe of intrinsic differences between SNRs
  - Probe properties for SNRs in arm/inter-arm/bulge regions
  - Compare properties and demographics between galaxies
    - ▹ Star formation rates ▹ Metallicities ▹ Masses

- For nearby galaxies, Surveyor can resolve most SNRs
  - Compare XMM: 80% EER ≈ 25"
  - $L_x = 10^{35}$ erg/s → $R_{HDXI} \approx 7$ ct/ks for middle-aged SNR spectrum

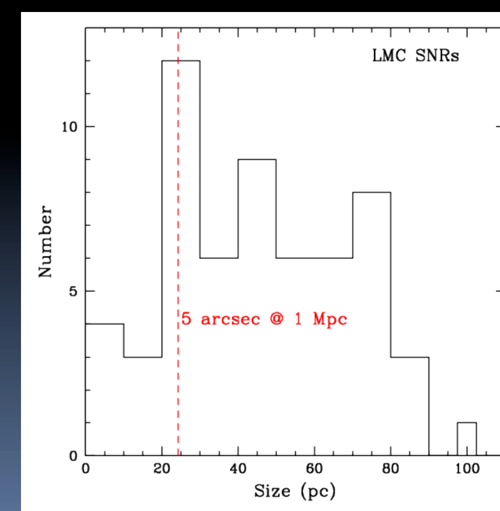
25" at LMC = 1" at 1.25 Mpc

Examples:

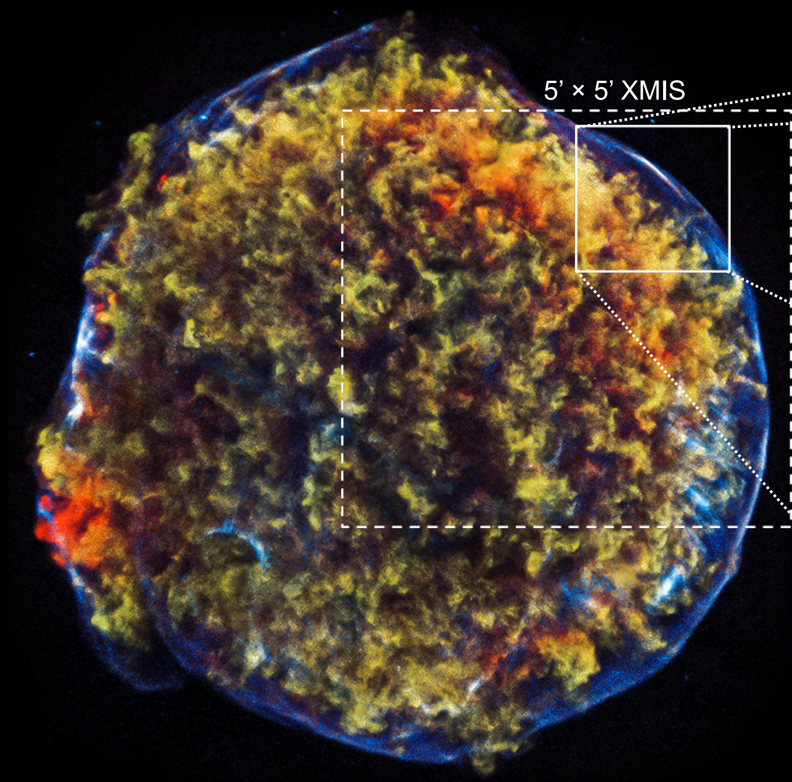
| Galaxy | D (Mpc) | Type |
|---|---|---|
| M33 | 0.8 | SA |
| M31 | 0.8 | SA |
| NGC 6822 | 0.5 | IB |
| NGC 1613 | 0.7 | IB |

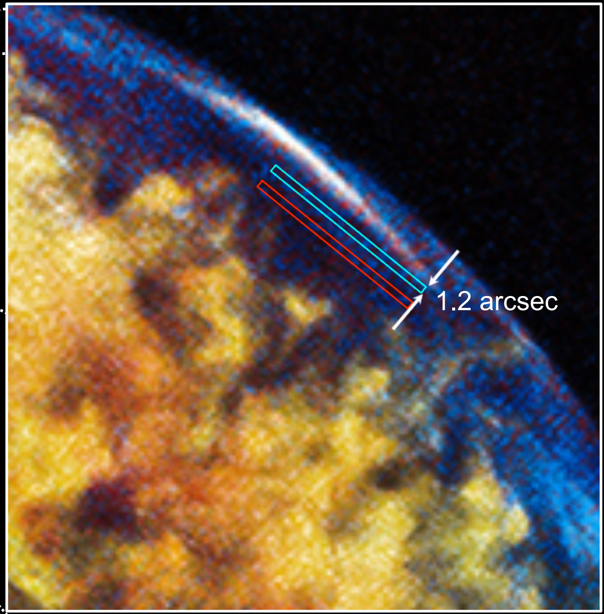


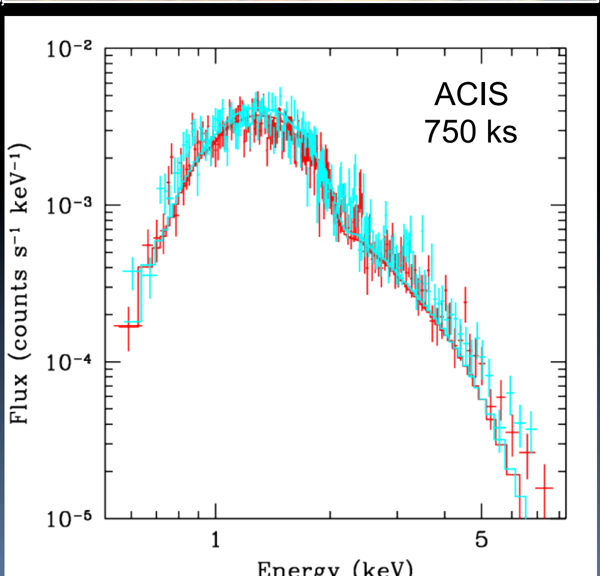

- Based on SNR size distribution in LMC, many in nearby galaxies would provide spatially-resolved spectral characterization with Surveyor.
  - identify SNR types for much of sample
  - identify ejecta, nonthermal emission, PWNe for many



# Cosmic Ray Acceleration in SNRs



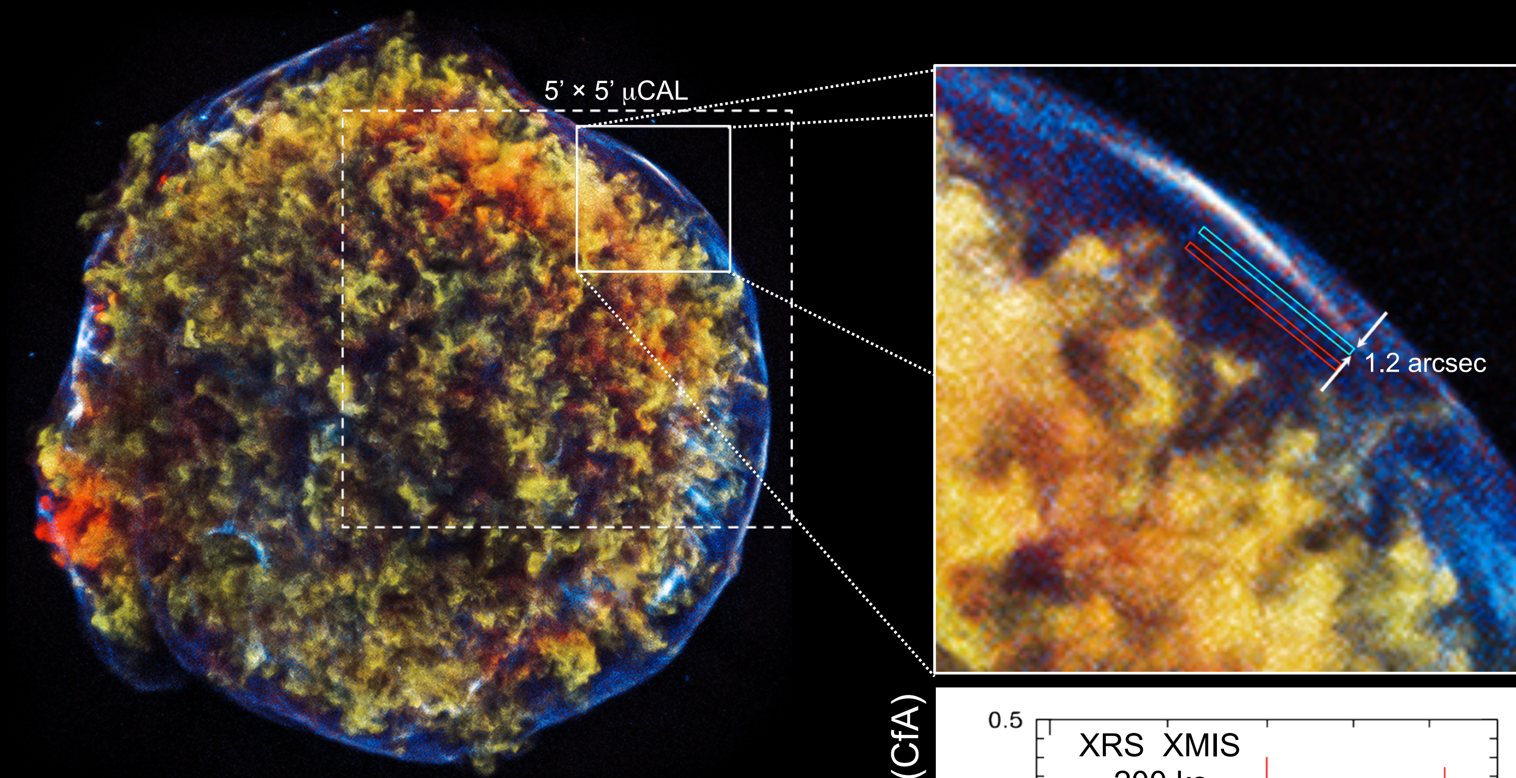



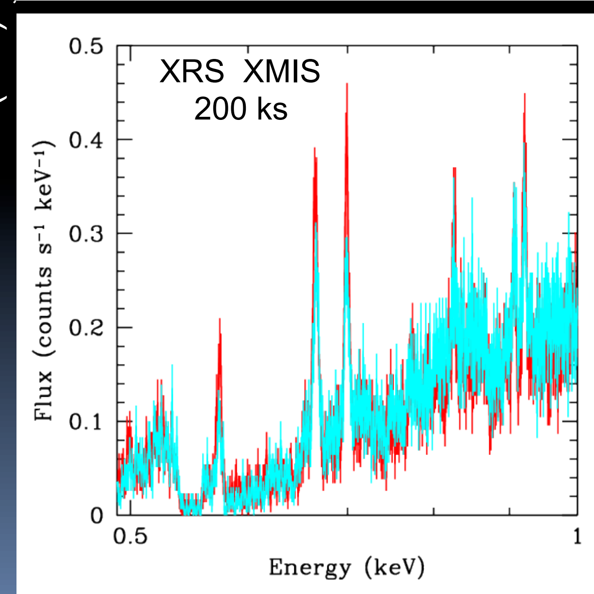

Slane et al. 2015

- CR acceleration changes shock compression ratio
  - temperature, density, and ionization of downstream gas is modified
  - modeling plasma properties self-consistently with observed nonthermal emission is crucial
  - high spectral/angular resolution and large area required to probe shocked CSM/ISM

# Cosmic Ray Acceleration in SNRs

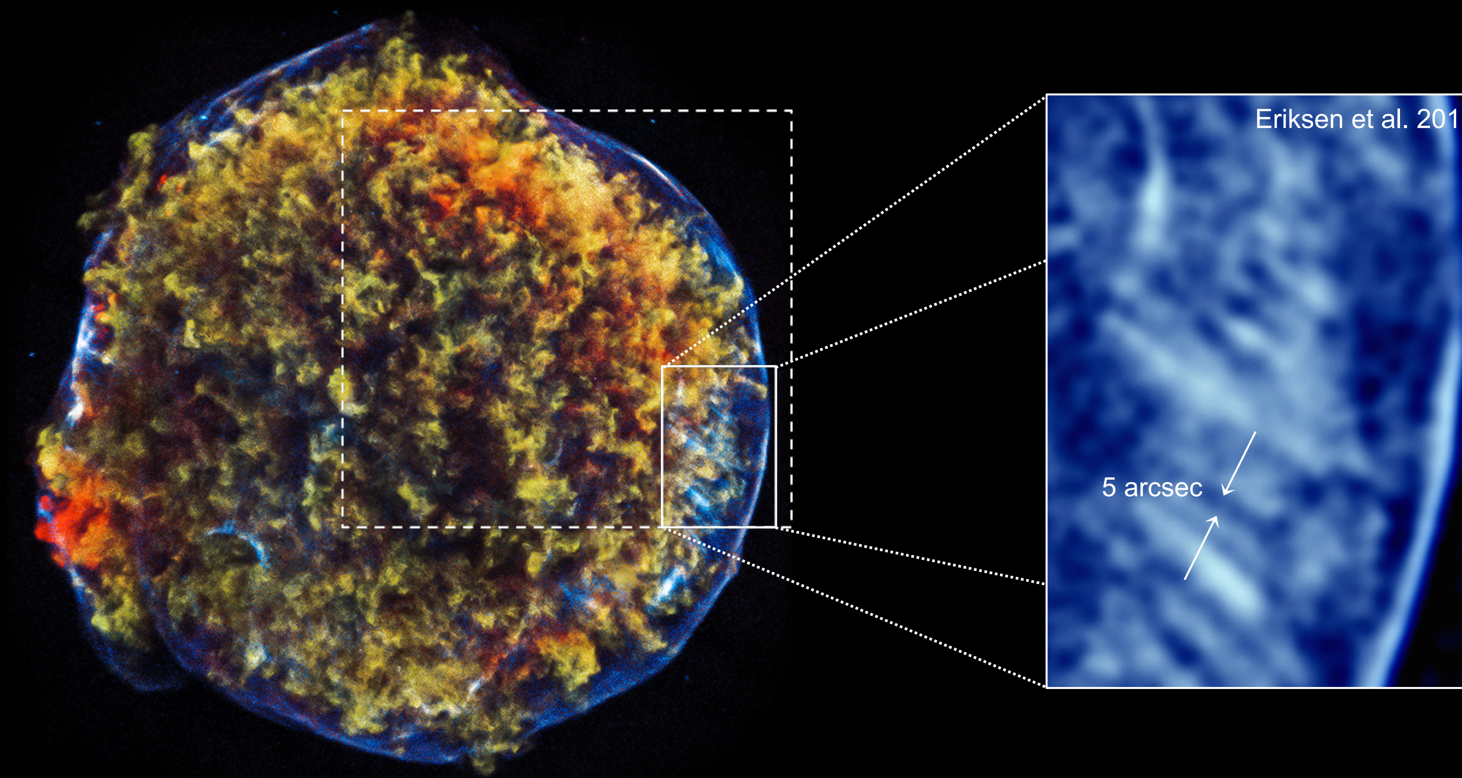



P. Slane (CfA)




- CR acceleration changes shock compression ratio
  - temperature, density, and ionization of downstream gas is modified
  - modeling plasma properties self-consistently with observed nonthermal emission is crucial
  - high spectral/angular resolution and large area required to probe shocked CSM/ISM

# Cosmic Ray Acceleration in SNRs




- Thin synchrotron rims constrain particle diffusion and magnetic fields
- Magnetic “stripe” features in Tycho may be signatures of instabilities or cascading turbulence on spatial scales associated with gyroradius of highest energy ions
  - crucial for understanding maximum acceleration energies in SNRs
- Spectra indicate these structures have higher cut-off energies than other nonthermal emission regions
  - Better spectra, and more examples, are needed to understand formation process
  - High angular resolution and large area required

# Summary

Current studies are producing new constraints on a broad range of topics in supernova physics. These demonstrate need for large collecting area with high spatial and spectral resolution, as would be provided by X-ray Surveyor:

- Typing SNRs in external galaxies; producing modest spatially-resolved spectra
- Measuring expansion and line-of-sight velocities to obtain 3D mapping of ejecta
- Studying ion heating in shocks and turbulence scales in ejecta
- Identifying explosion asymmetries and connecting with neutron star properties
- Probing mass loss on scales of tens of years to K-H timescale for progenitor
- Obtaining high-quality spatially-resolved spectra for Magellanic Cloud SNRs
- Constraining cosmic-ray acceleration in supernova remnants