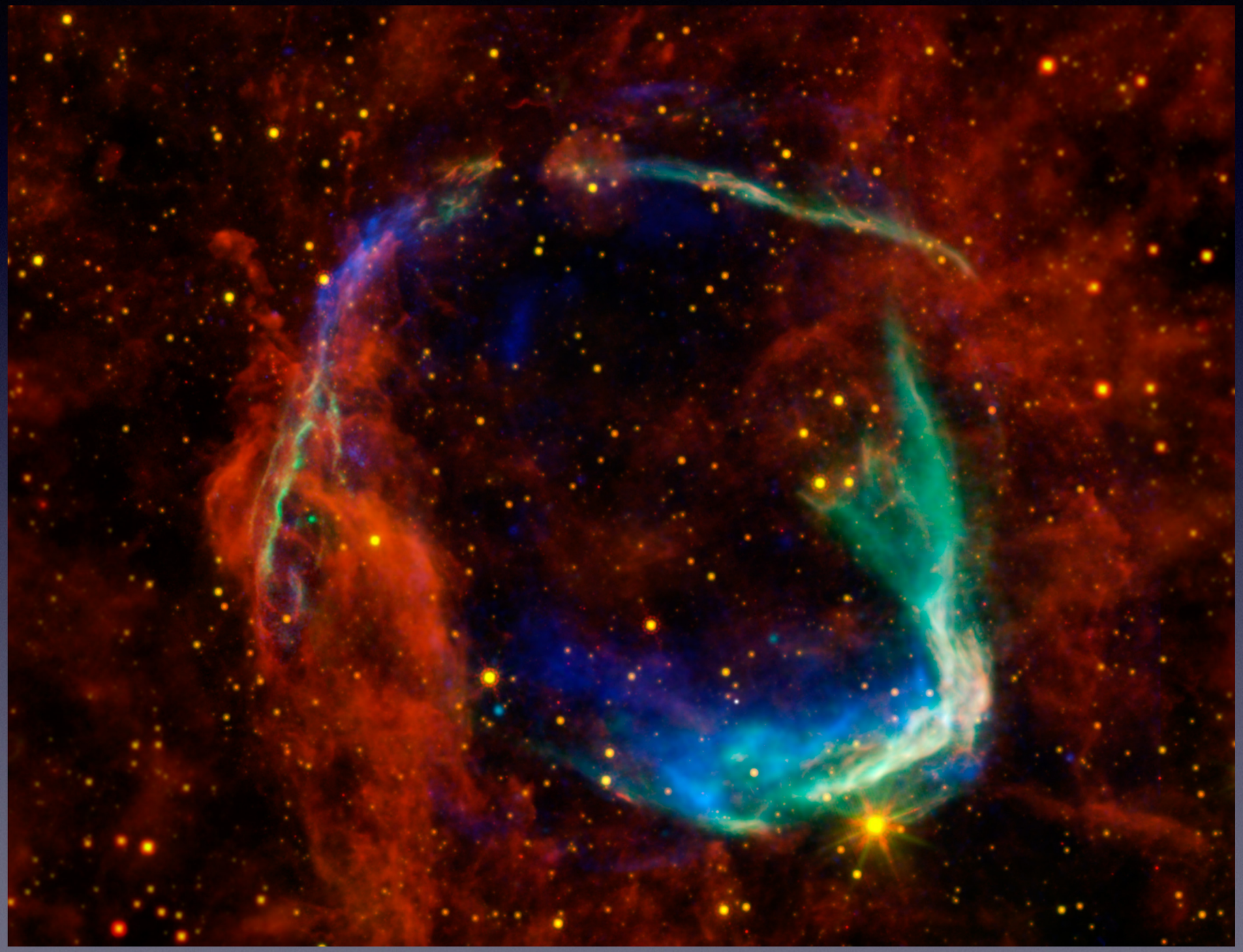
# Highlights from 20 years of XMM-Newton Observations of Supernova Remnants



**Brian Williams**
**NASA GSFC**

RCW 86, as seen by XMM, Chandra, and Spitzer

# One slide on personal reflections of XMM-Newton

**Most of my Ph.D. work was in infrared astronomy. XMM-Newton was the first X-ray telescope that I ever worked with.**

The XMM-Newton ABC Guide:
An Introduction to
XMM-Newton Data Analysis

NASA/GSFC XMM-Newton Guest Observer Facility
Kim Weaver, Lynne Valencic, Brendan Perry, Michael Arida, K.D. Kuntz
With contributions by: Steve Snowden, Ilana Harrus, Stefan Immler,
Rick Shafer, Randall Smith, Martin Still

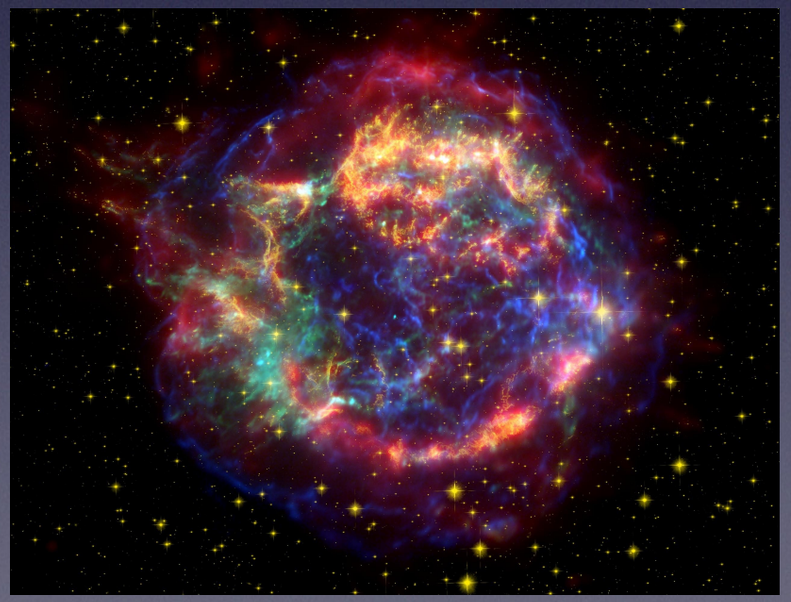
**1 XMM-Newton Lifetime = time to go from high-school student to "mid-career" scientist**

# Disclaimers

- This is a review talk of a very broad topic
- As much as I would love to, I can’t cover everything, and I can’t cite everyone
- If I do cover your work, but I misrepresent it, I apologize (please correct me!)
- I’ve made every attempt to at least misrepresent everyone equally

Stars

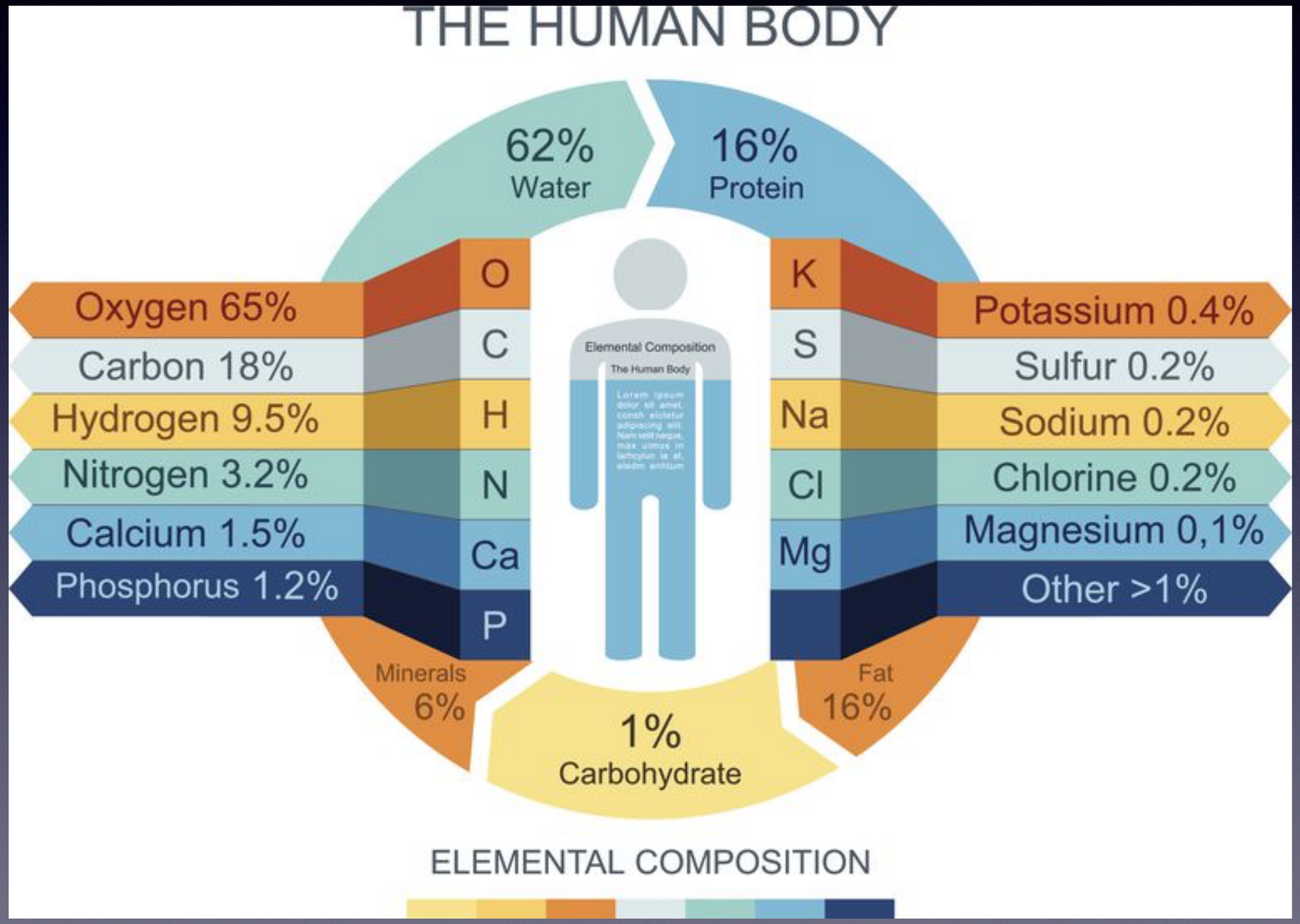
Supernovae

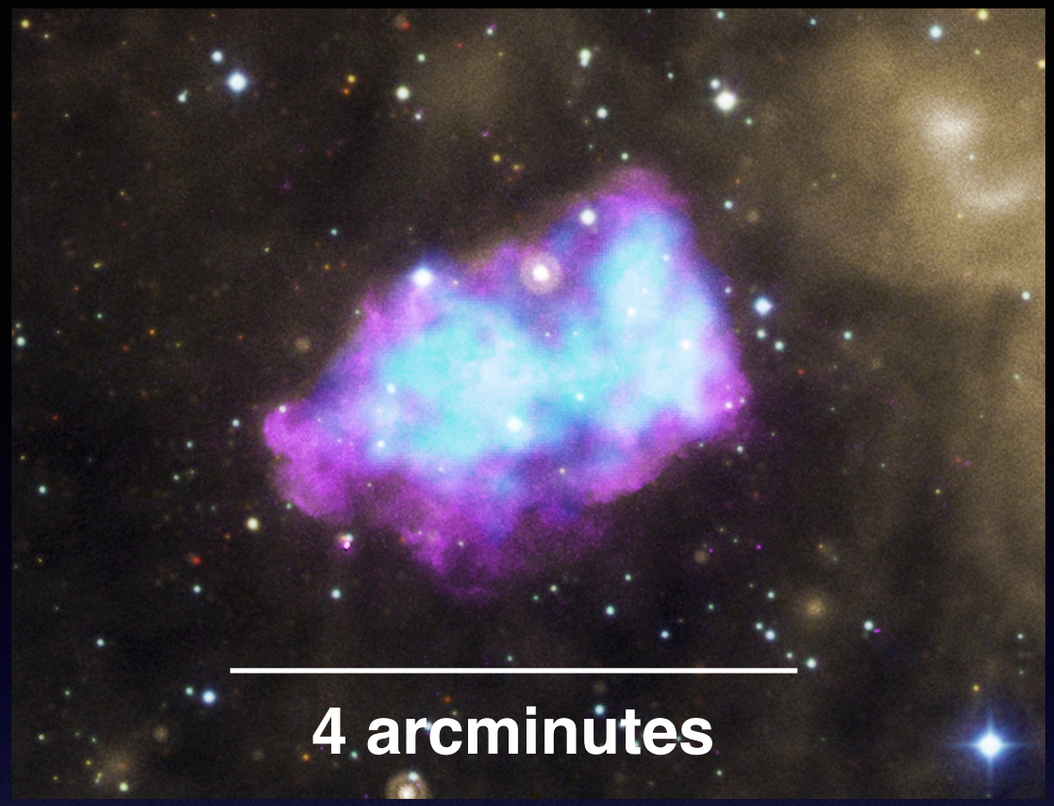


Supernova Remnants

# Q. Why are supernovae important?

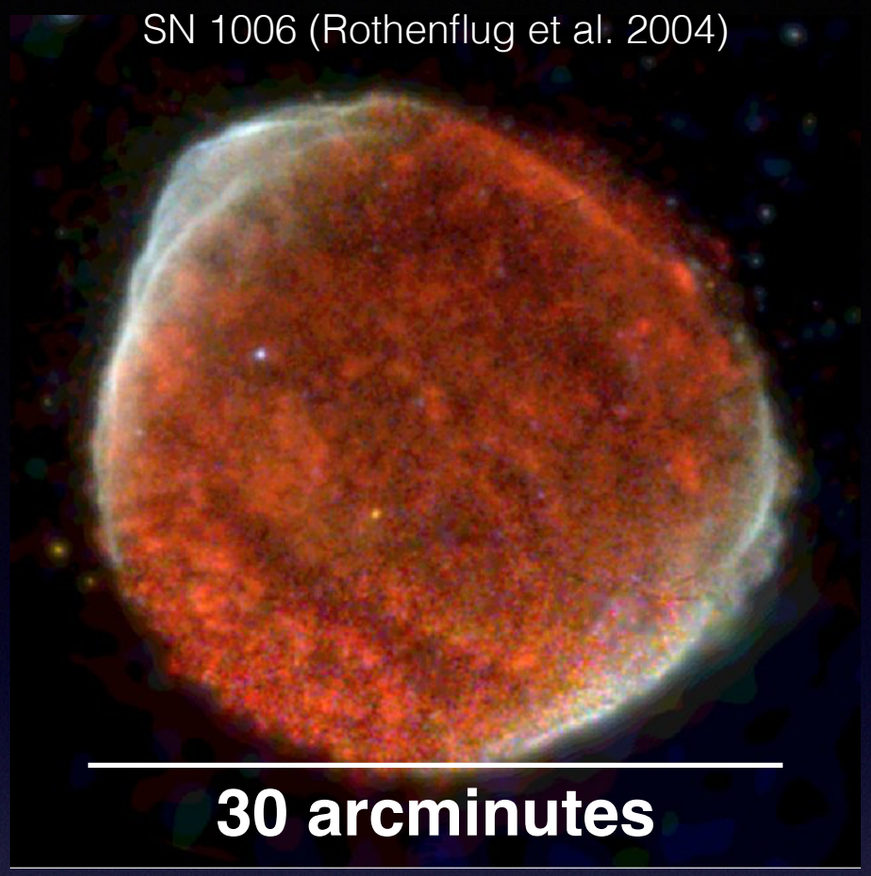
## A. Responsible for seeding cosmos with elements






3C 397 (Yamaguchi et al. 2014)

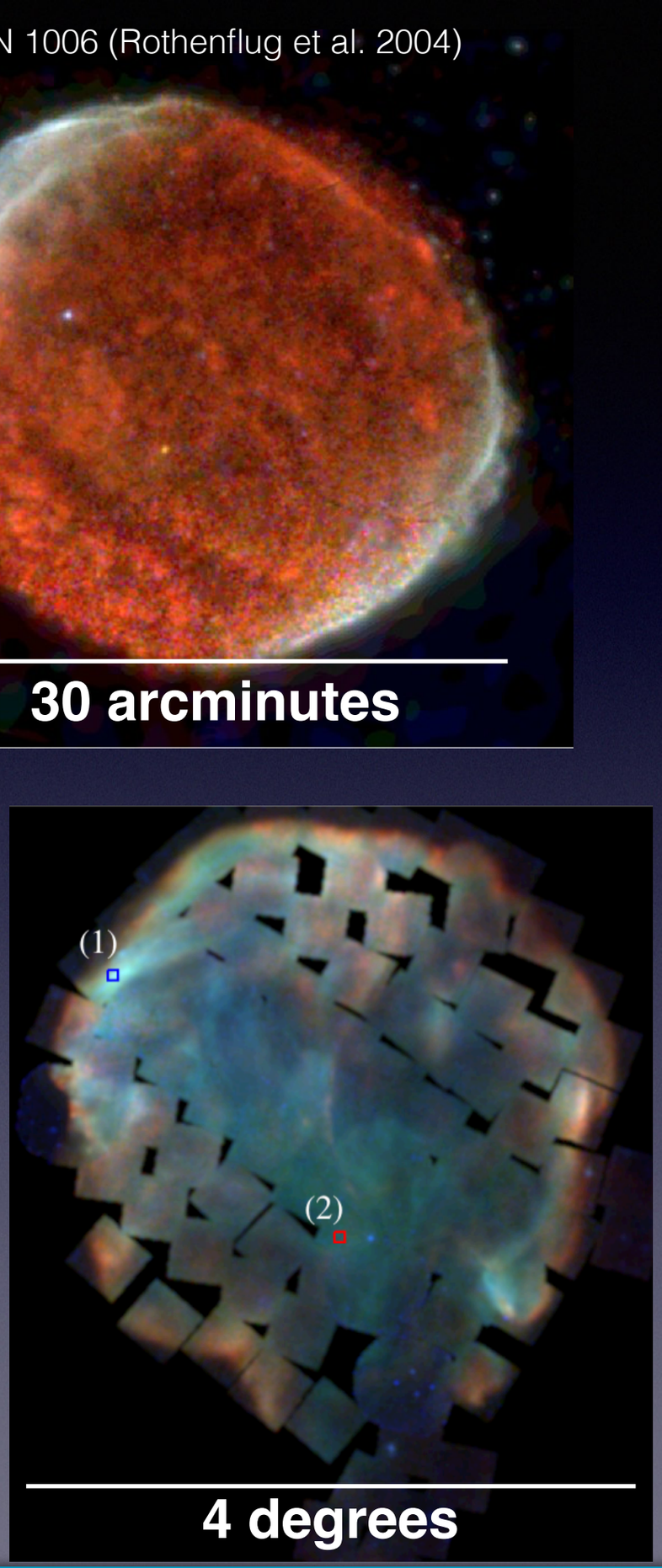
SN 1006 (Rothenflug et al. 2004)



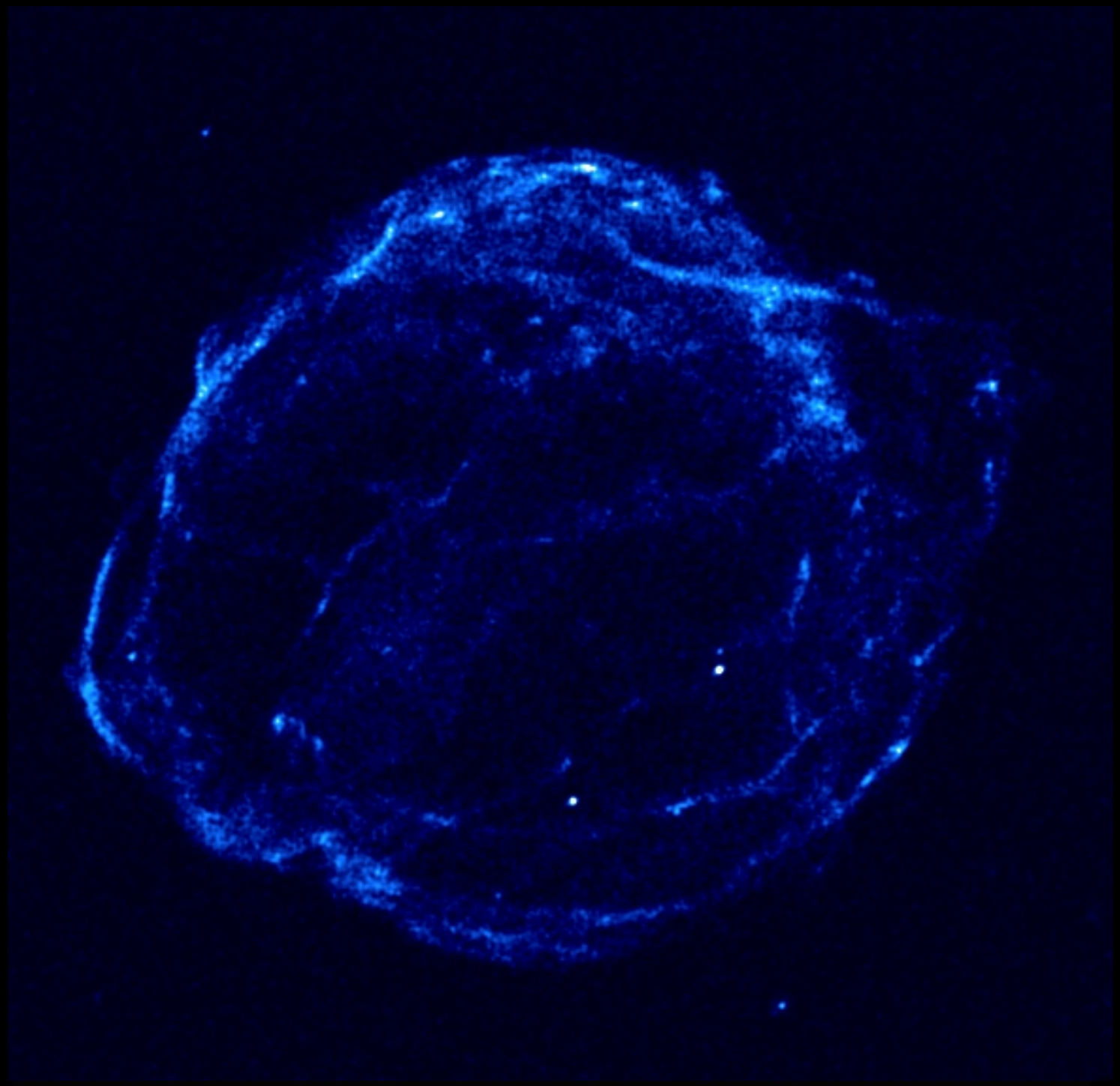


N103B (Williams et al. 2018)

Cygnus Loop
Katsuda et al. (2015)



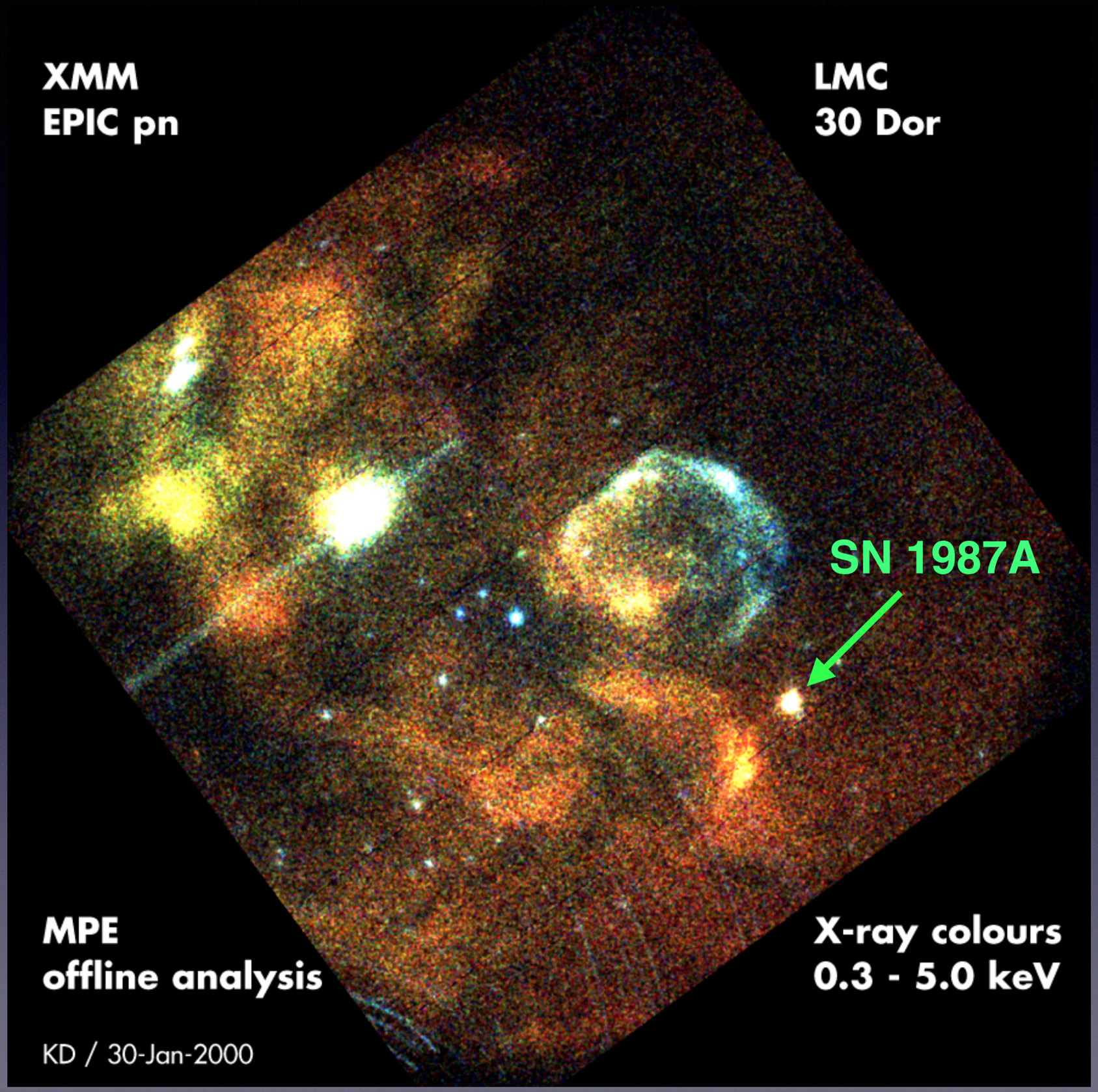
# X-ray Emission from SNRs



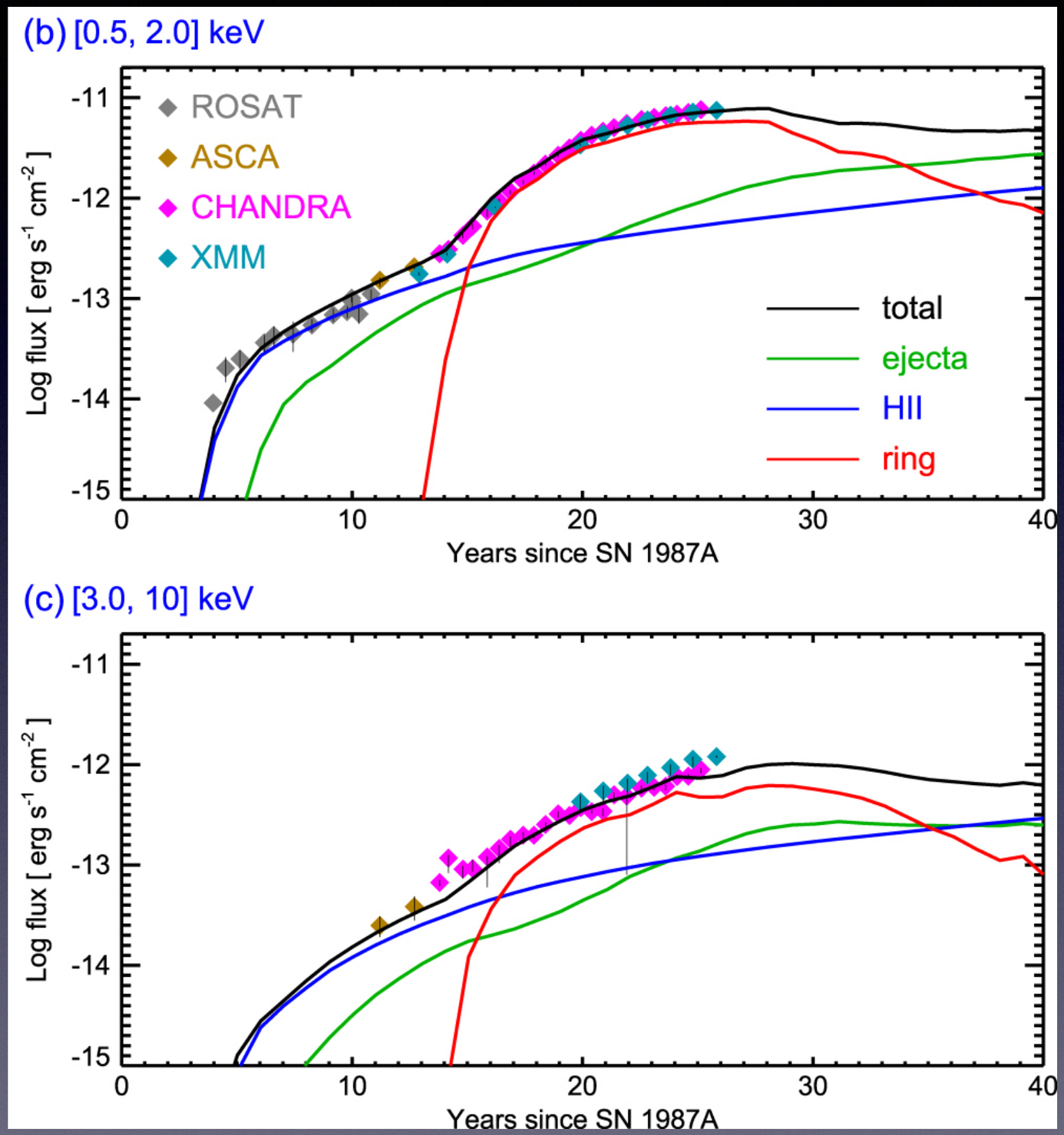
Forward Shock

Reverse-shocked Ejecta

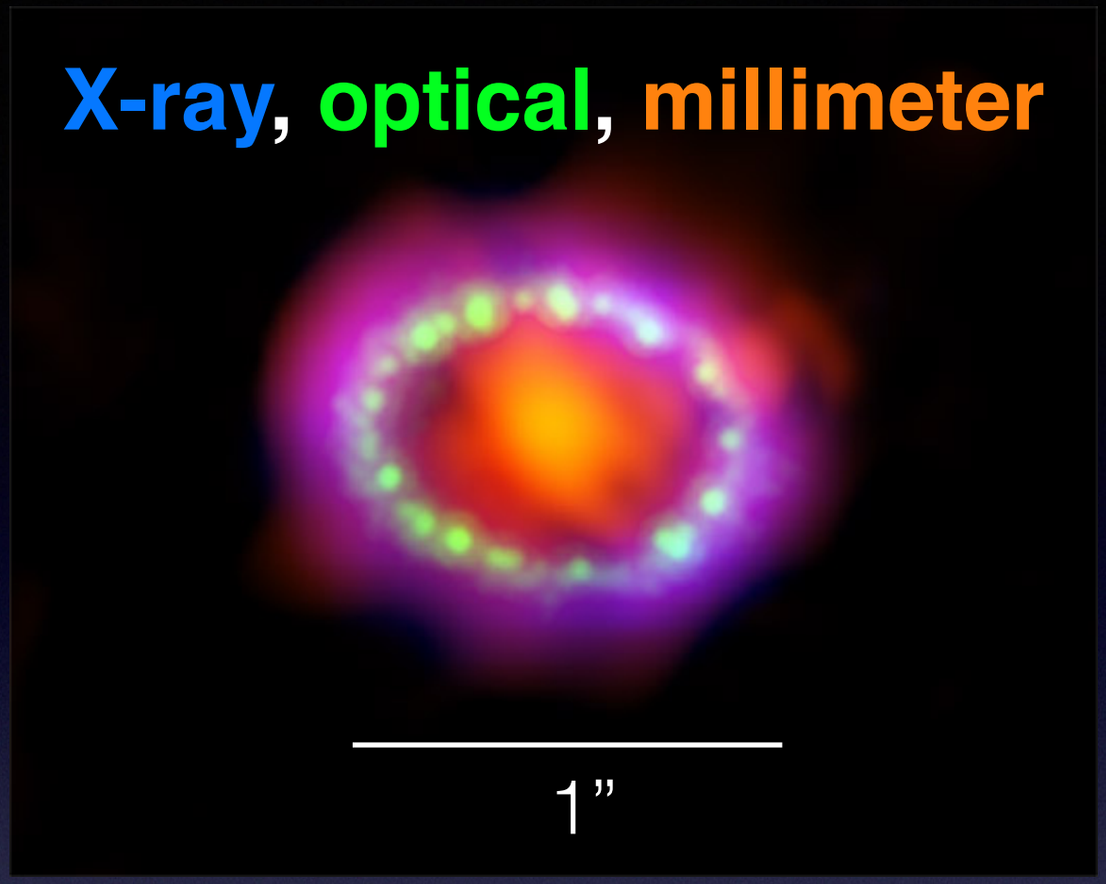
# One of XMM's "First Light" images




HST Image

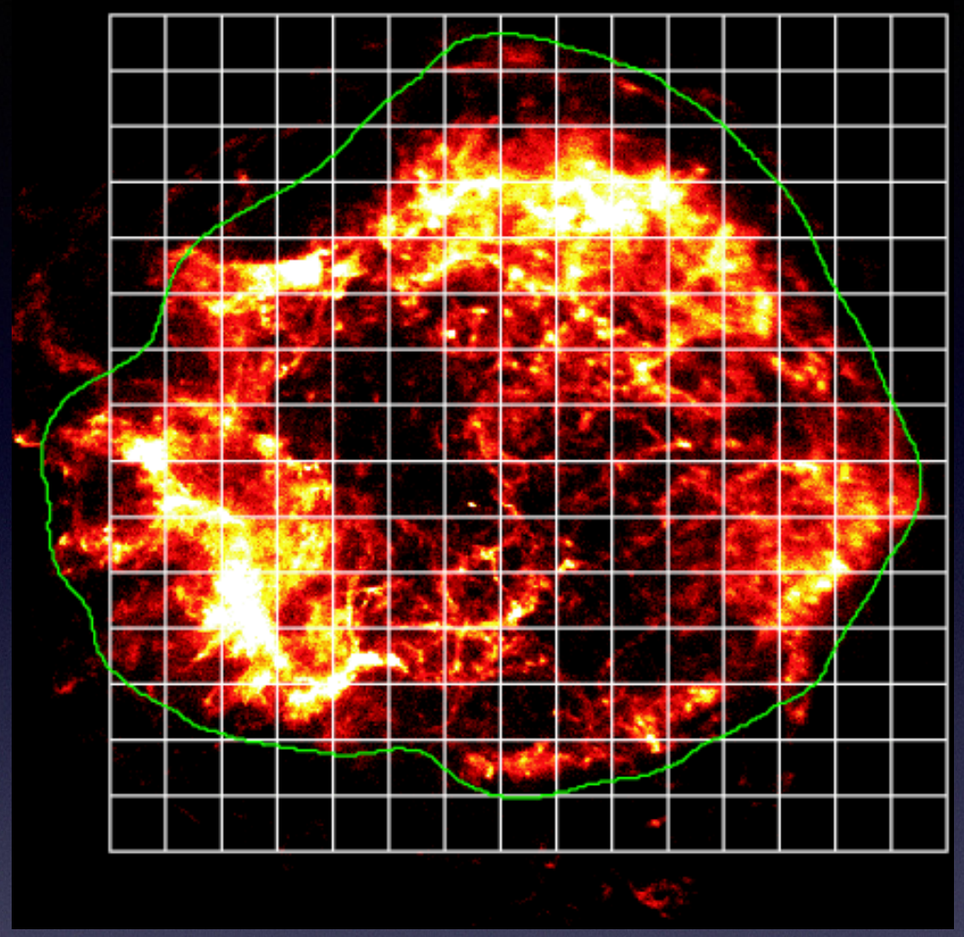



Orlando et al. (2015)

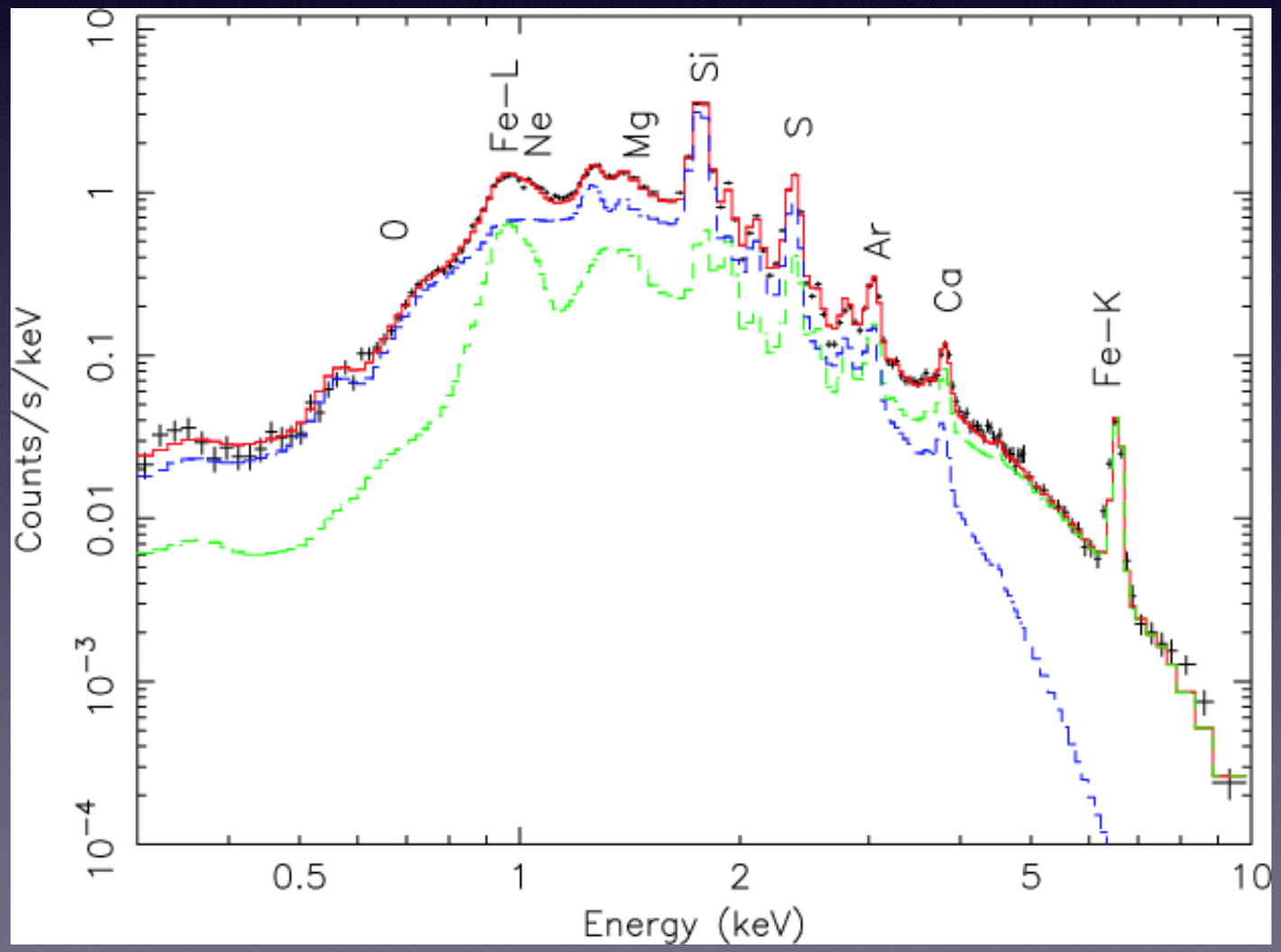



**SN 1987A is the only example where we can watch a SN evolve into an SNR**

# Cas A

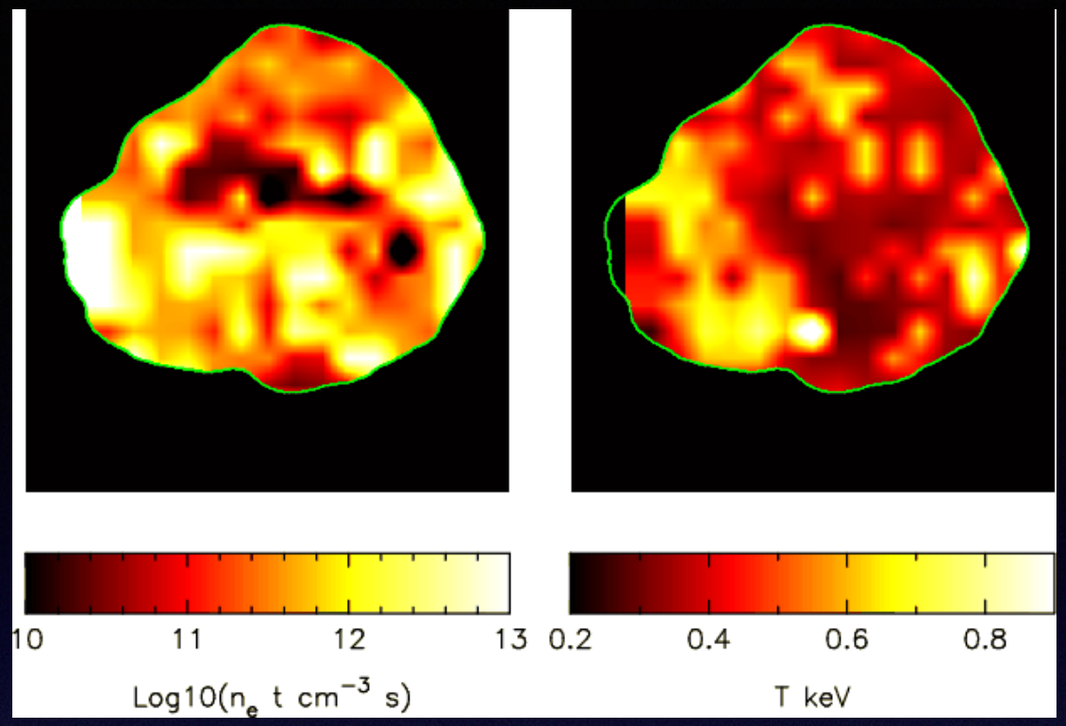


**~330 year old remnant, one of the brighter X-ray and radio sources in the sky**

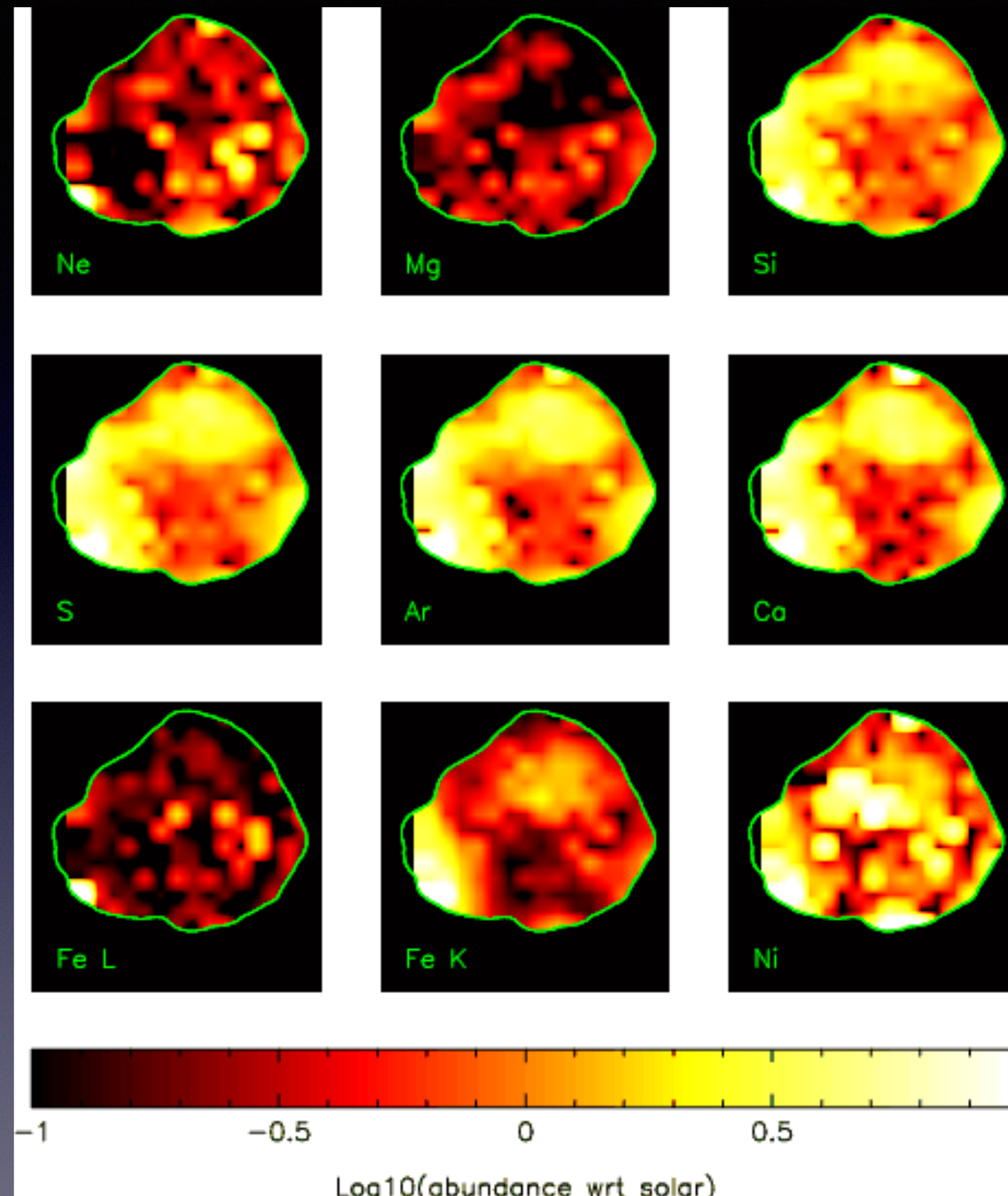



**Willingale et al. (2002) divided 86 ks observation of remnant up into 20” x 20” boxes**

**Spectrum at right is sample spectrum of one box**



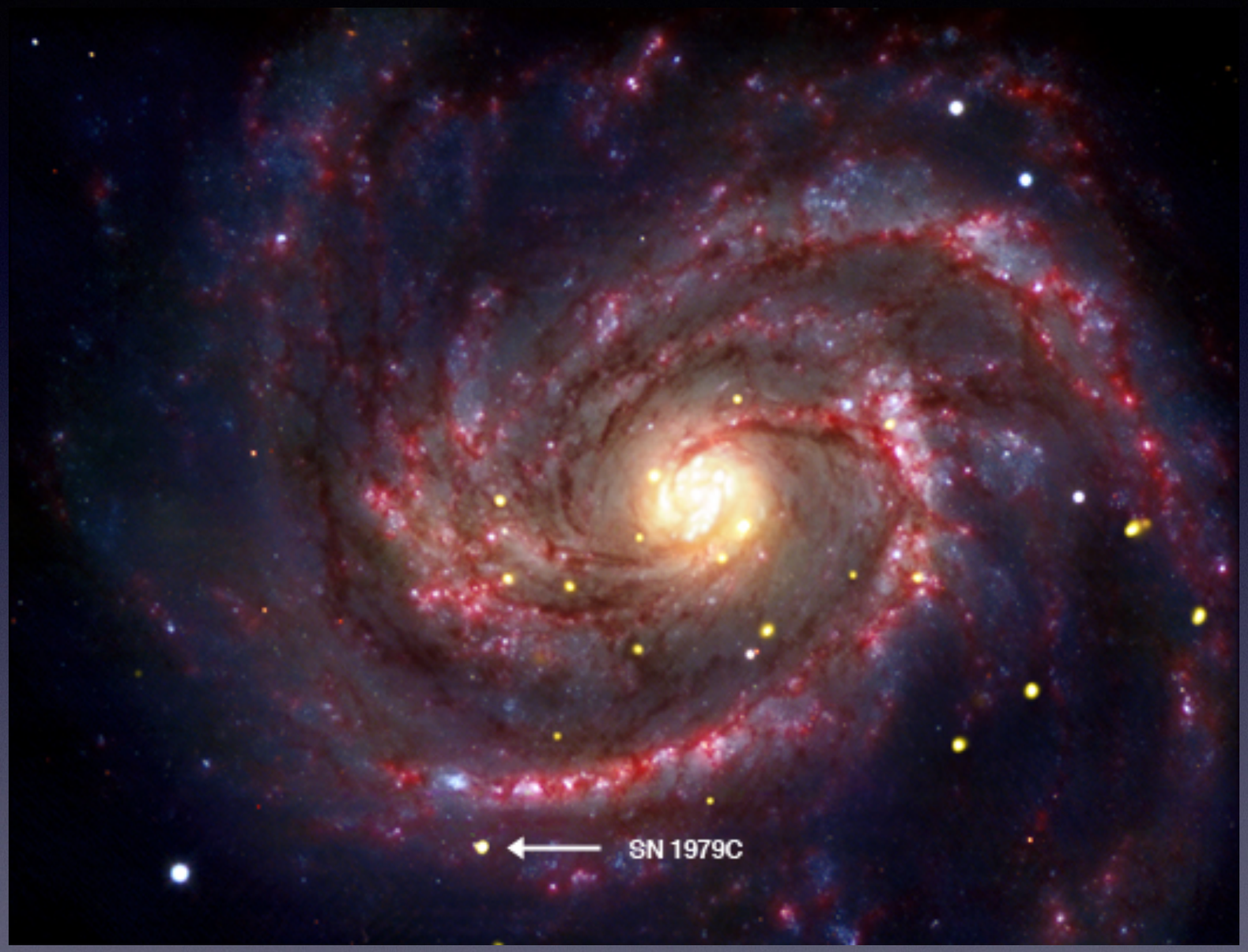

**Maps of ionization state and temperature of the gas**




**Maps of abundances of various elements**

**Willingale et al. (2002)**

# SN 1979C



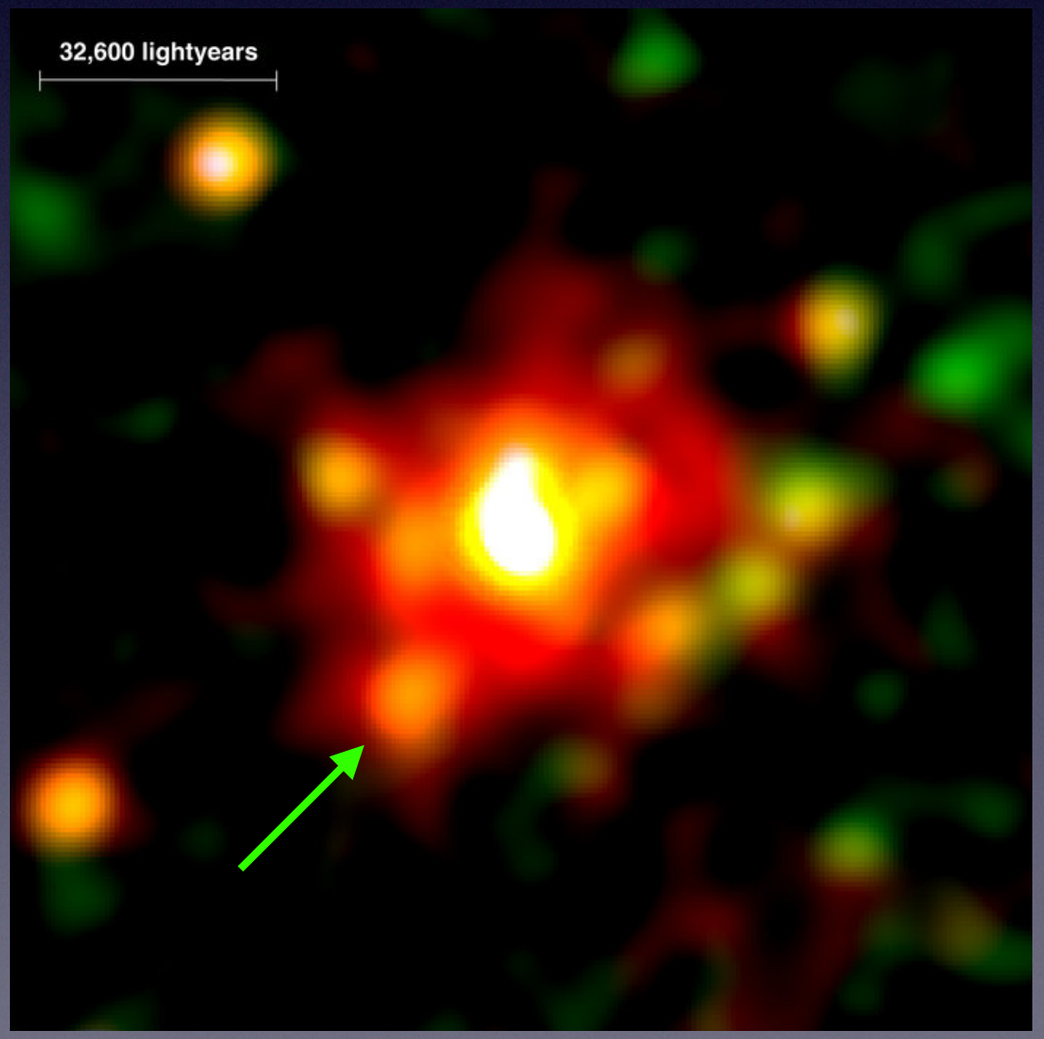

M100 (credit: NASA, ESO)

- discovered by amateur astronomer in western Maryland in April 1979
- categorized as Type IIL
- has a relatively “normal” optical light curve

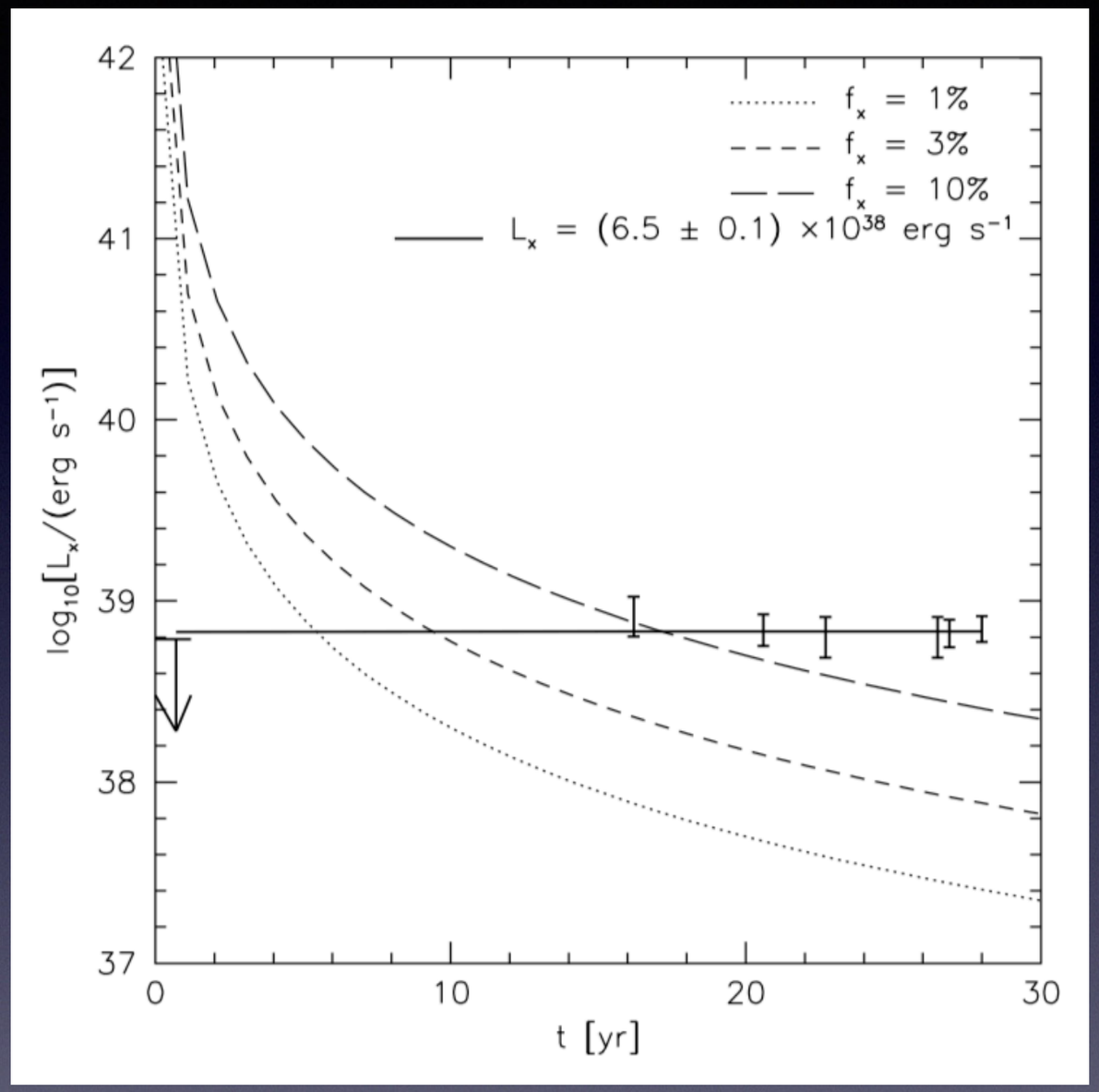

XMM-Newton OM image
(B, U, UVW1)

- Immler et al. (2005) noted that 1979C was still remarkably bright in X-rays, ~25 years post explosion

- If powered by interaction with dense circumstellar material, can derive mass loss rate of progenitor star for >10,000 years pre-explosion




XMM X-ray image




X-ray light curve of SN 1979C

- Patnaude et al. (2011) concluded that stability of light curve could not be caused by CSM interaction
- Proposed two alternatives:
  - 1) stellar-mass black hole steadily accreting material
  - 2) pulsar-wind nebula
- Option 1 would imply perhaps youngest known black hole

- In 185 CE, Chinese astronomers noted a “guest star” in the sky in the modern constellation of Circinus

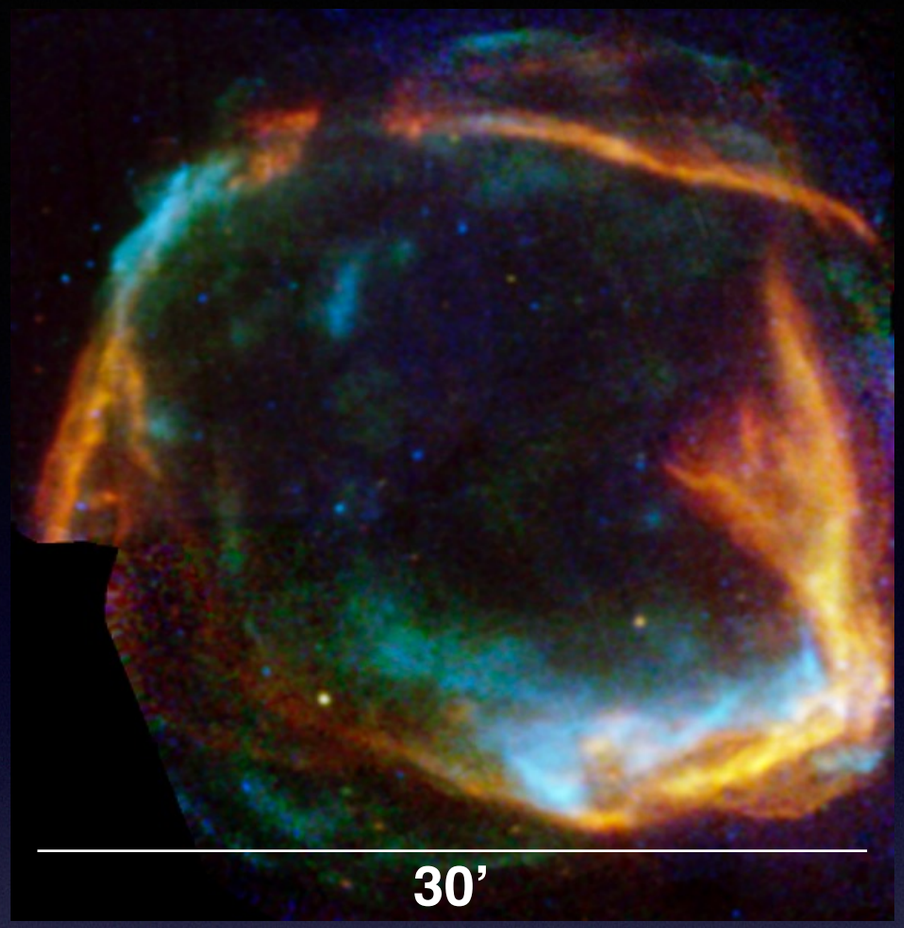
- records show it lasted several months before fading

- did not move (so couldn’t have been comet), too long for most other transient phenomena

- most consistent explanation is a supernova, oldest surviving documentation of such an event; first “historical supernova”


The Book of the Later Han

# RCW 86




XMM-Newton mosaic

THE ASTROPHYSICAL JOURNAL, 648:L33–L37, 2006 September 1


## THE X-RAY SYNCHROTRON EMISSION OF RCW 86 AND THE IMPLICATIONS FOR ITS AGE

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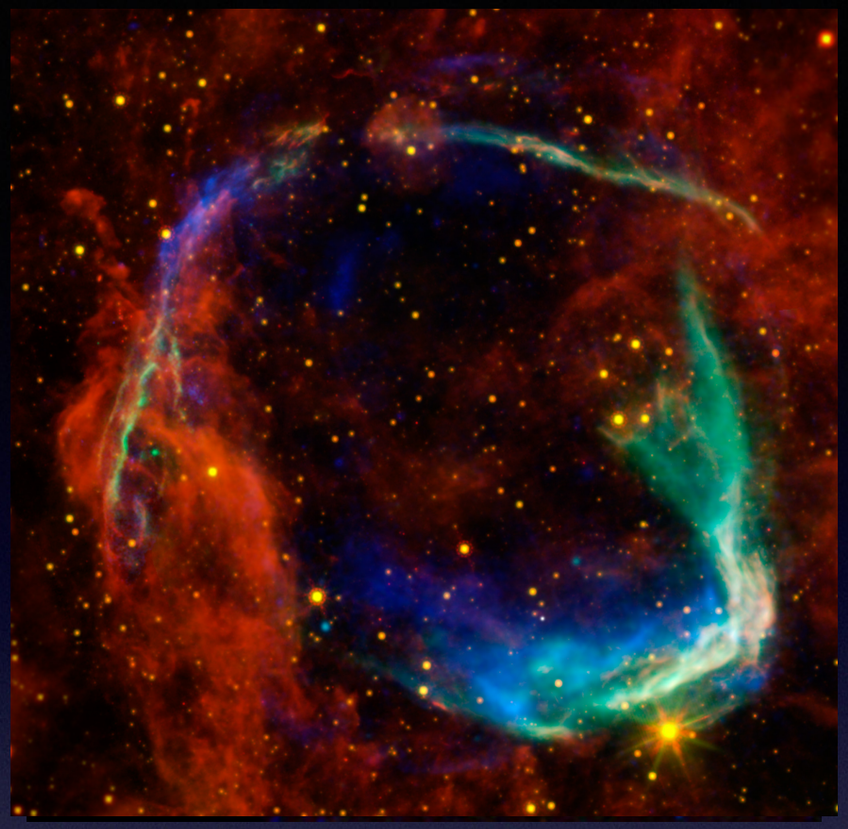
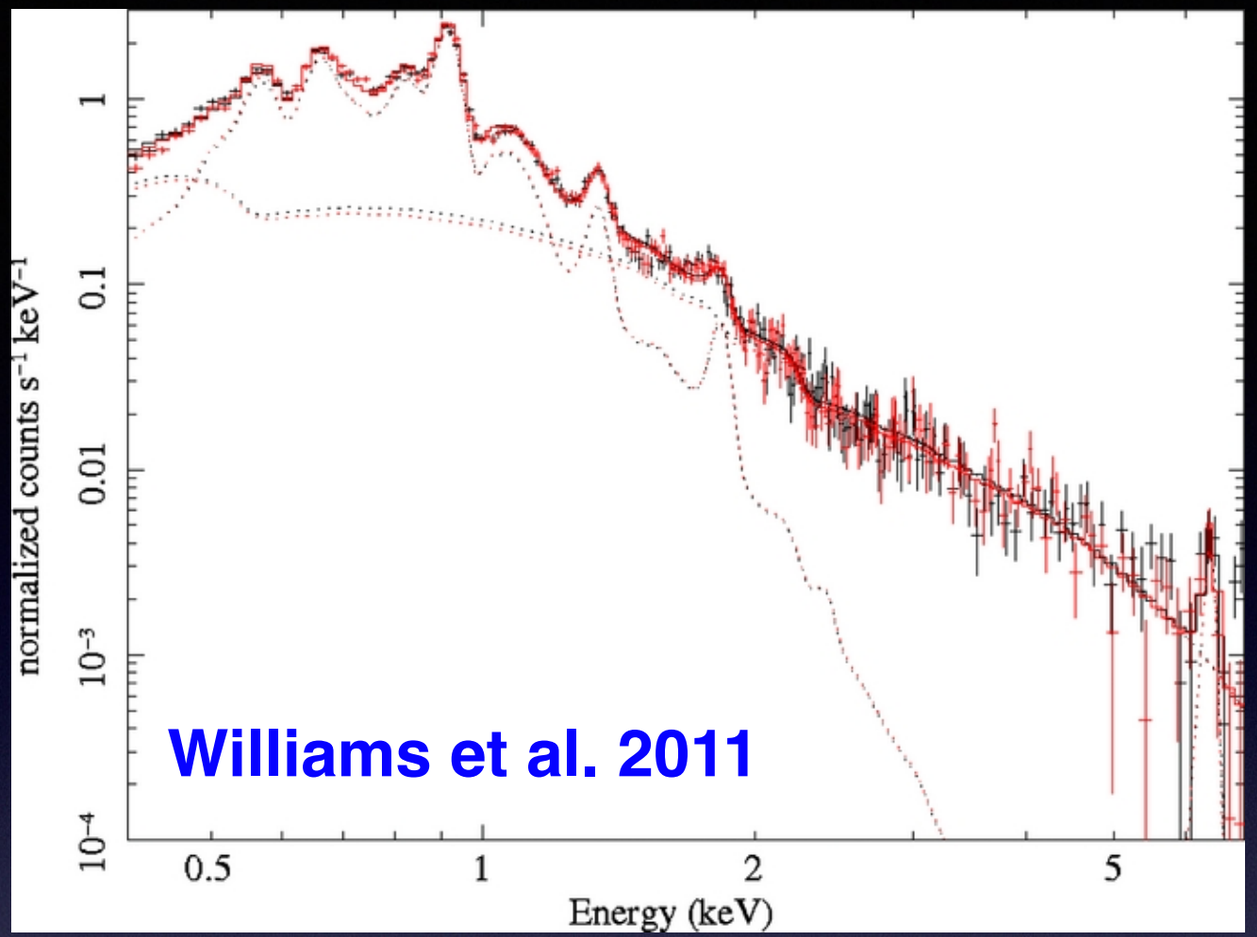
*Received 2006 June 13; accepted 2006 July 13; published 2006 August 14*

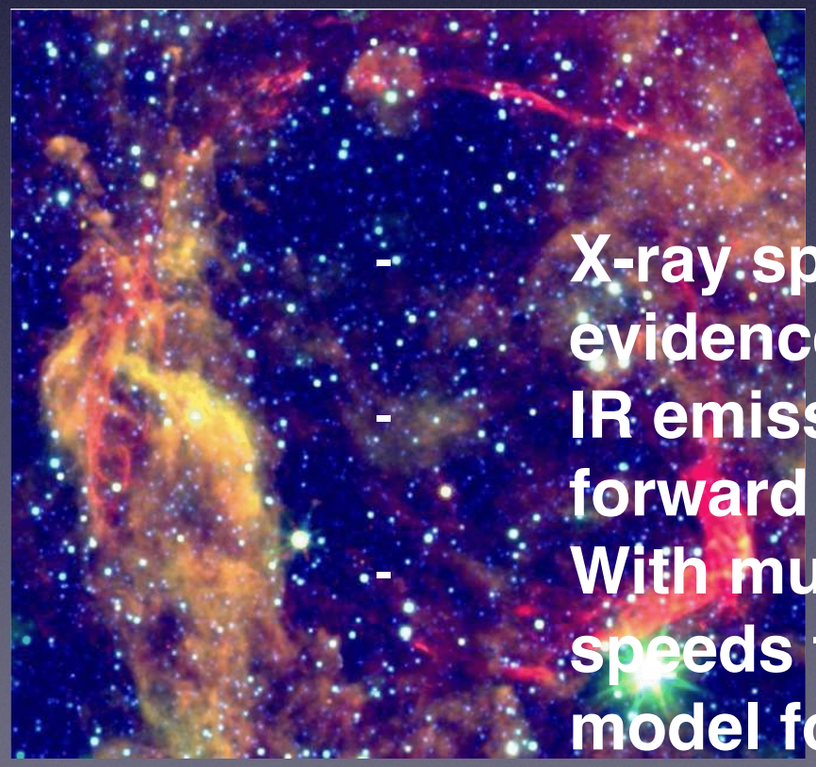
ABSTRACT

We report X-ray imaging spectroscopy observations of the northeastern shell of the supernova remnant RCW 86 using *Chandra* and *XMM-Newton*. Along this part of the shell, the dominant X-ray radiation mechanism changes from thermal to synchrotron emission. We argue that both the presence of X-ray synchrotron radiation and the width of the synchrotron-emitting region suggest a locally higher shock velocity of $V_s \approx 2700$ km s$^{-1}$ and a magnetic field of $B \approx 24 \pm 5$ $\mu$G. Moreover, we also show that a simple power-law cosmic-ray electron spectrum with an exponential cutoff cannot explain the broadband synchrotron emission. Instead, a concave electron spectrum is needed, as predicted by nonlinear shock acceleration models. Finally, we show that the derived shock velocity strengthens the case that RCW 86 is the remnant of SN 185.

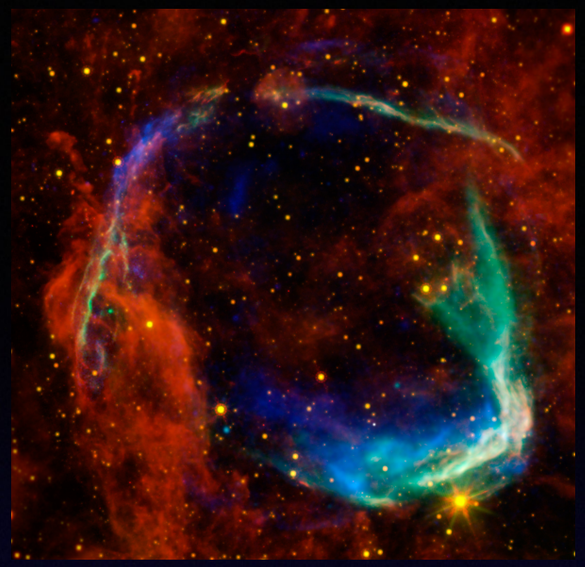





XMM MOS 1&2 spectra of NW shell



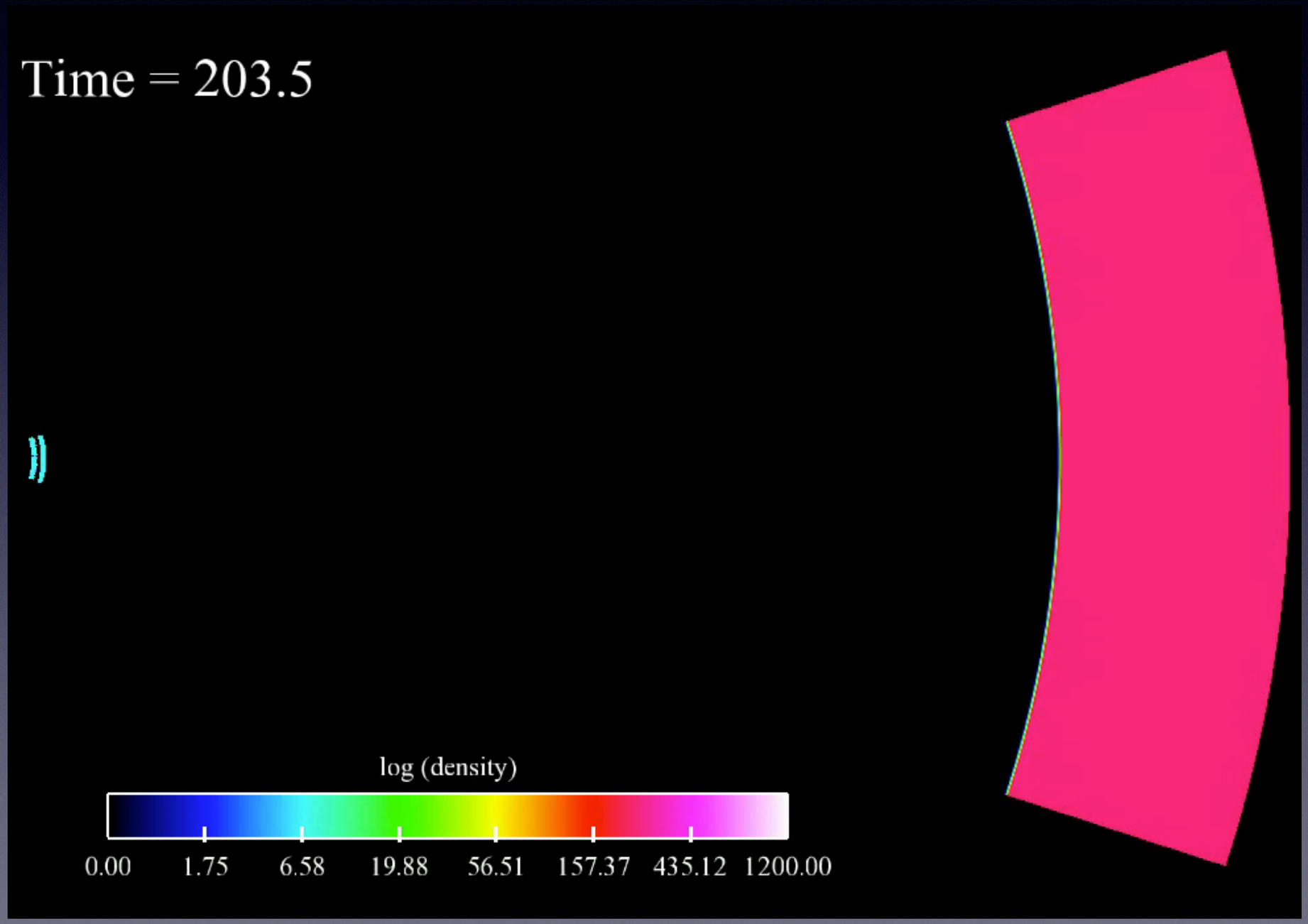
- X-ray spectra show large amounts of Fe in ejecta, no evidence for O (also lots of other evidence for Type Ia SN)
- IR emission places tight constraints on density of ISM forward shock is running into
- With multi-wavelength approach (also proper motion shock speeds from Chandra), we can create a comprehensive model for this remnant



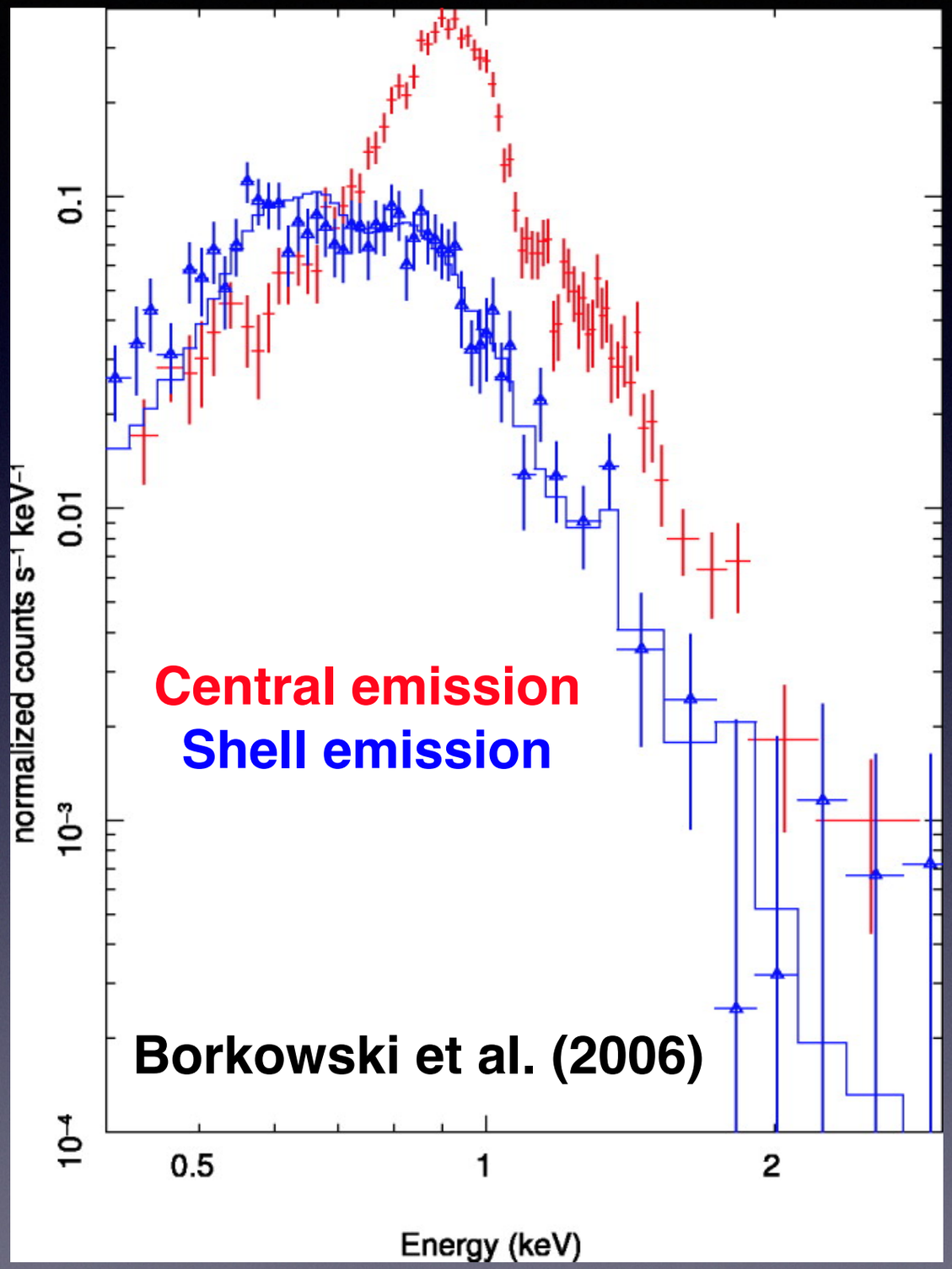
Yes, ***BUT*** it requires an explosion into a wind-blown cavity. Not unusual for Core-Collapse SN, but never seen before for Type Ia (Williams et al. 2011). One mechanism is continuum-driven winds from accreting white dwarfs (Hachisu et al. 1996, Badenes et al. 2007)

Can we construct hydrodynamic model of this remnant that accounts for:

- expansion velocity
- size
- density of ISM
- ionization state of X-ray emitting gas
- age

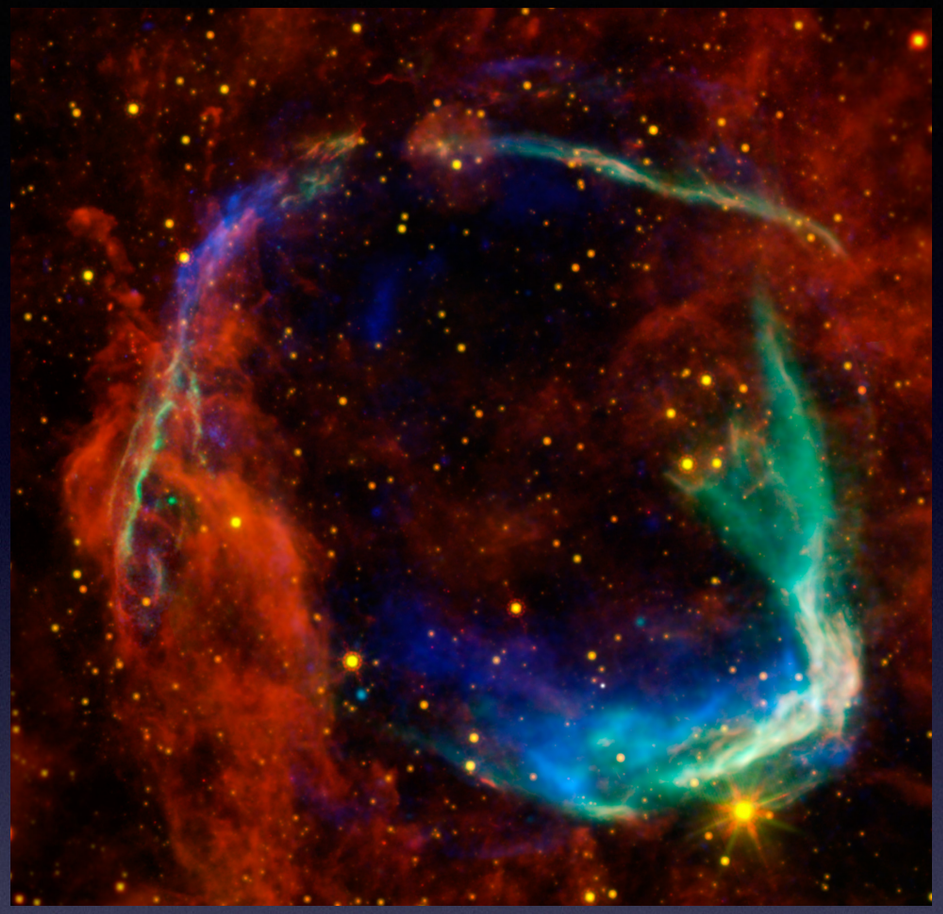


# Prompt SNe Ia?

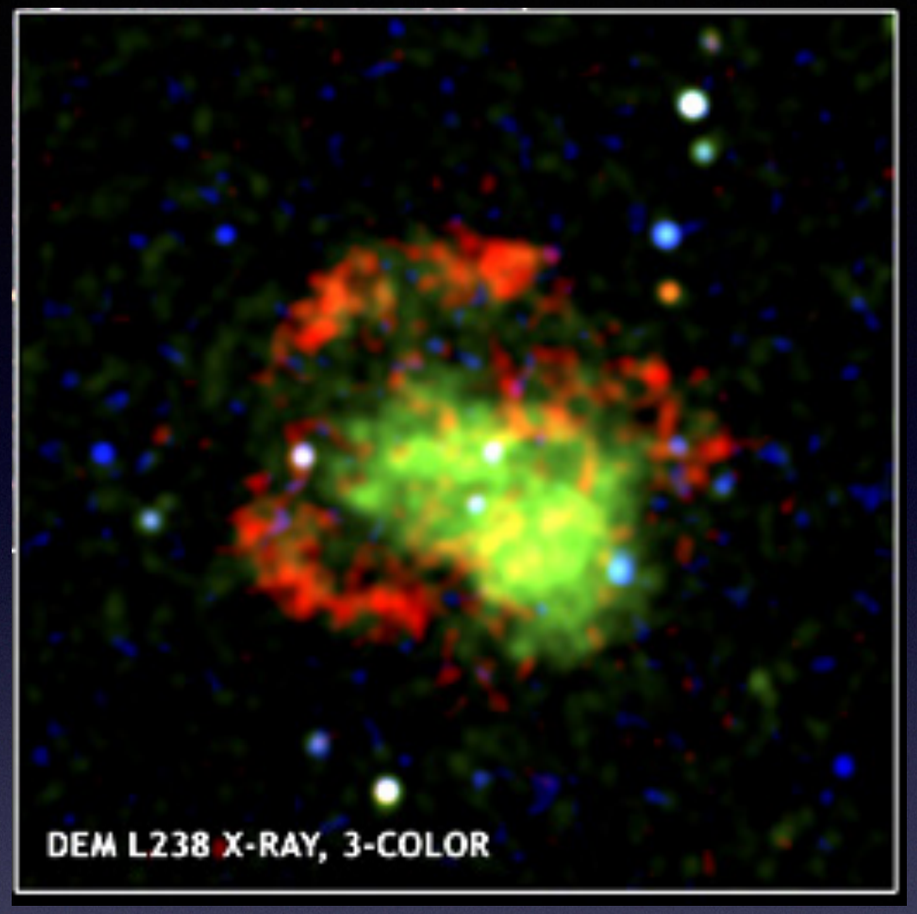

- XMM helped discover a new subclass of Type Ia SNRs
- Fe-rich (not unusual), but with ionization ages order(s) of magnitude higher than the real age
- How? Not sure, but one strong possibility is explosion into dense CSM
- "Prompt" SNe Ia? (Mannucci et al. 2006)
- 2002cx-like? (Li et al. 2003)

## RCW 86



Type Ia SN, consistent with explosion into very low-density medium, created by progenitor wind

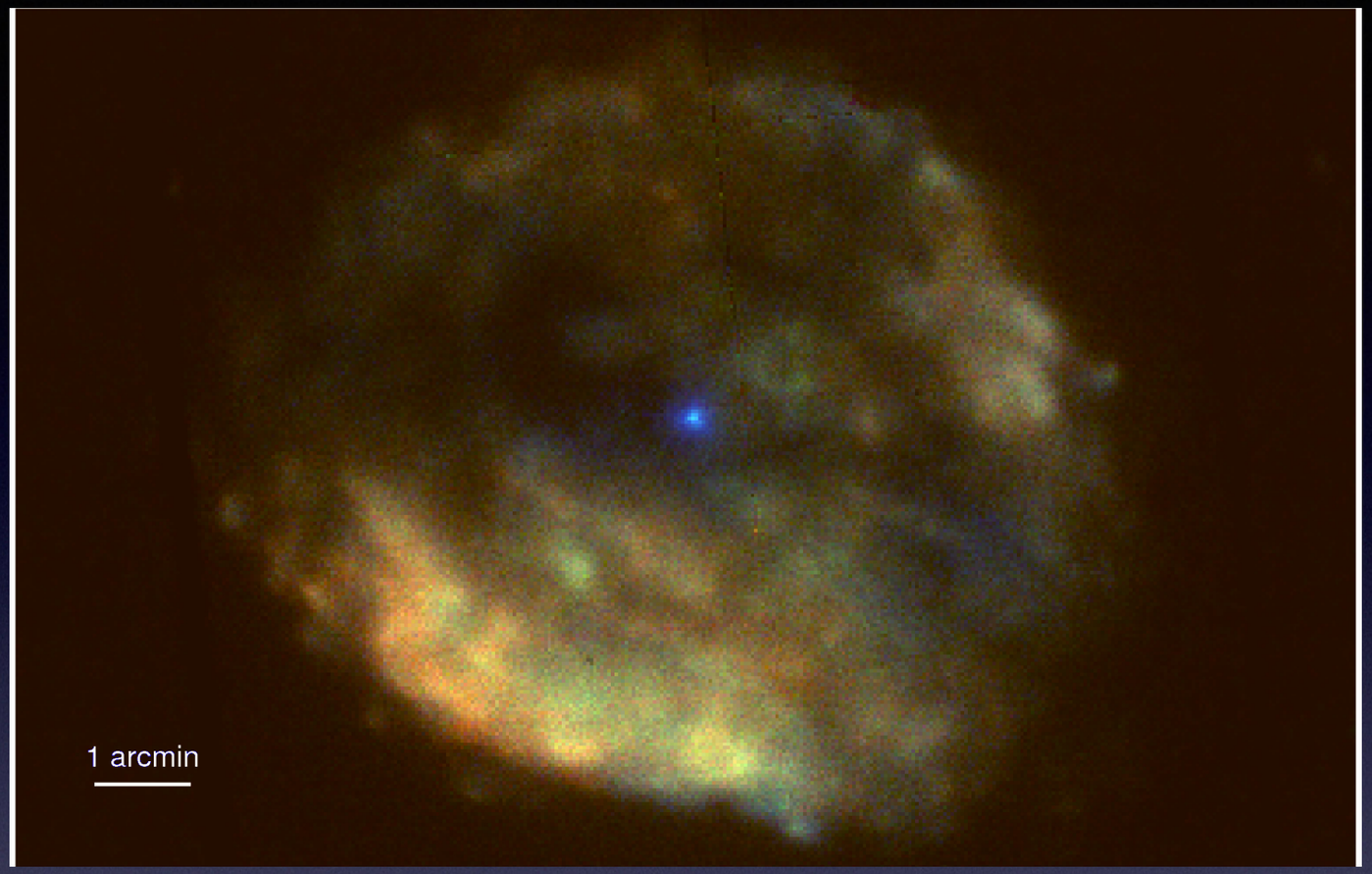
## DEM L238




Type Ia SN, consistent with explosion into very high-density medium, created by progenitor wind

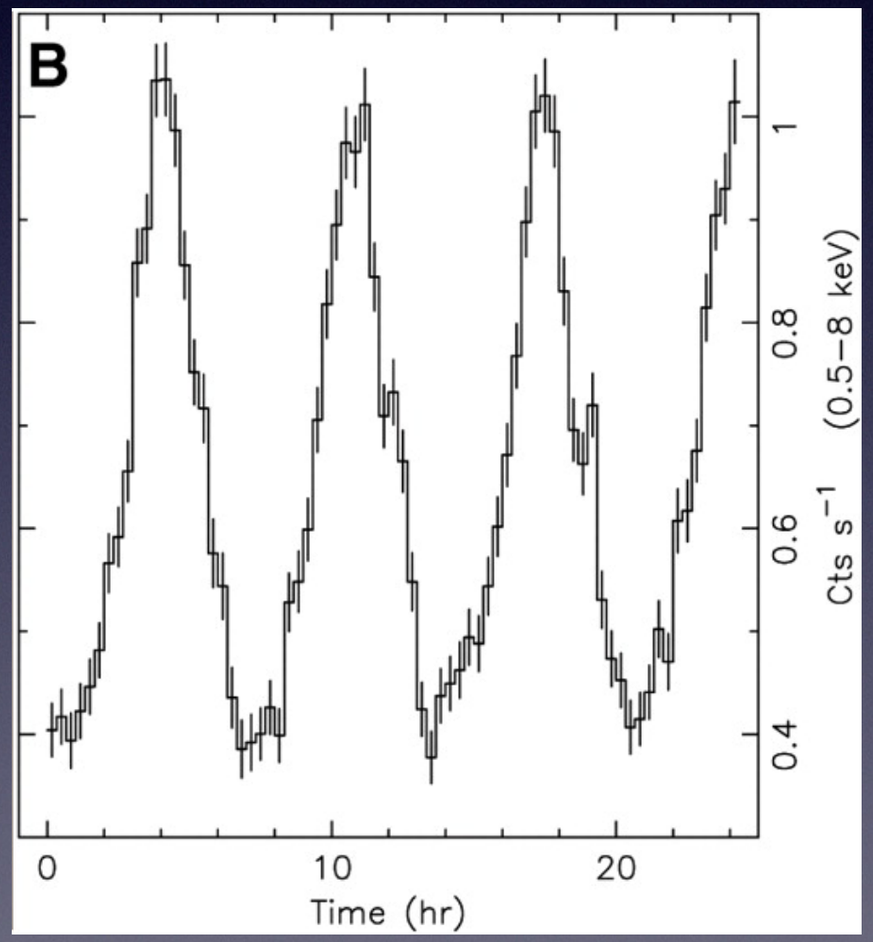
**Most Type Ia SNe just explode into undisturbed ISM. Not only are these two different… they're different from each other. Or are they?**

# RCW 103 and 1E 1613




- central compact object first identified with *Einstein* (Tuohy & Garmire 1980)
- Radio-quiet, no optical emission; no pulsations had been detected in X-rays until XMM-Newton

**XMM discovered that neutron star pulses with period of 6.7 hr!**

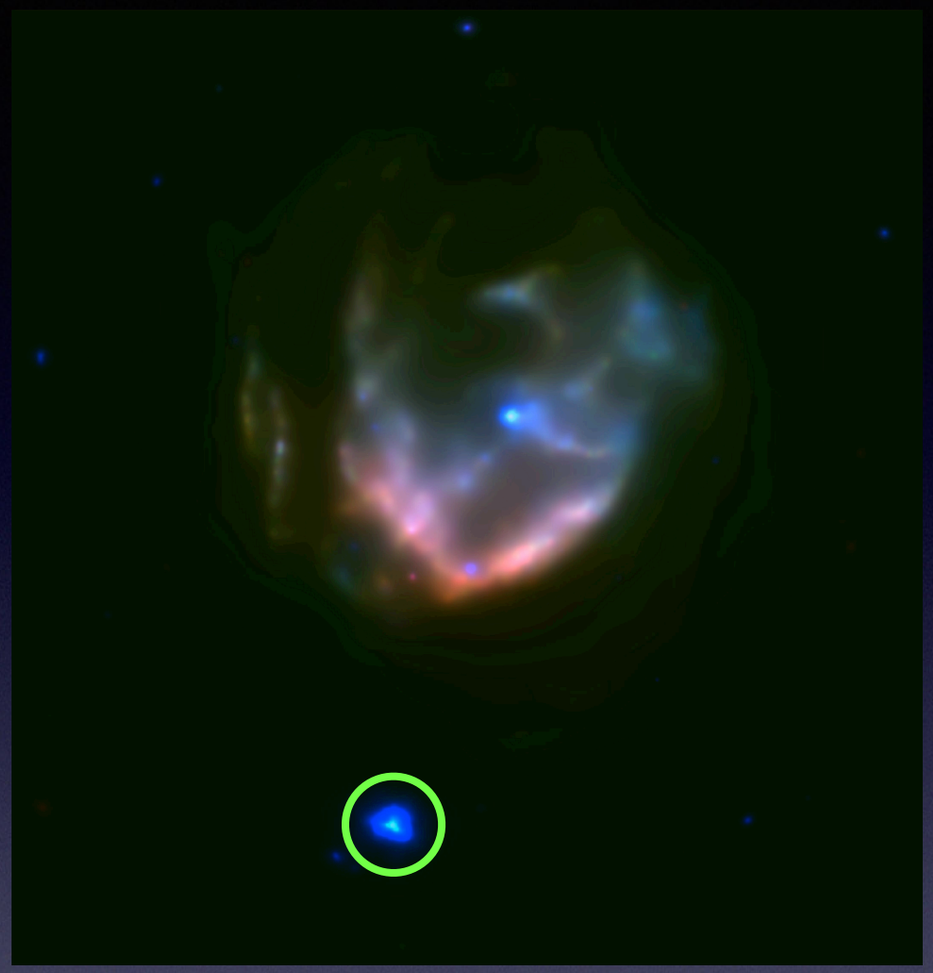


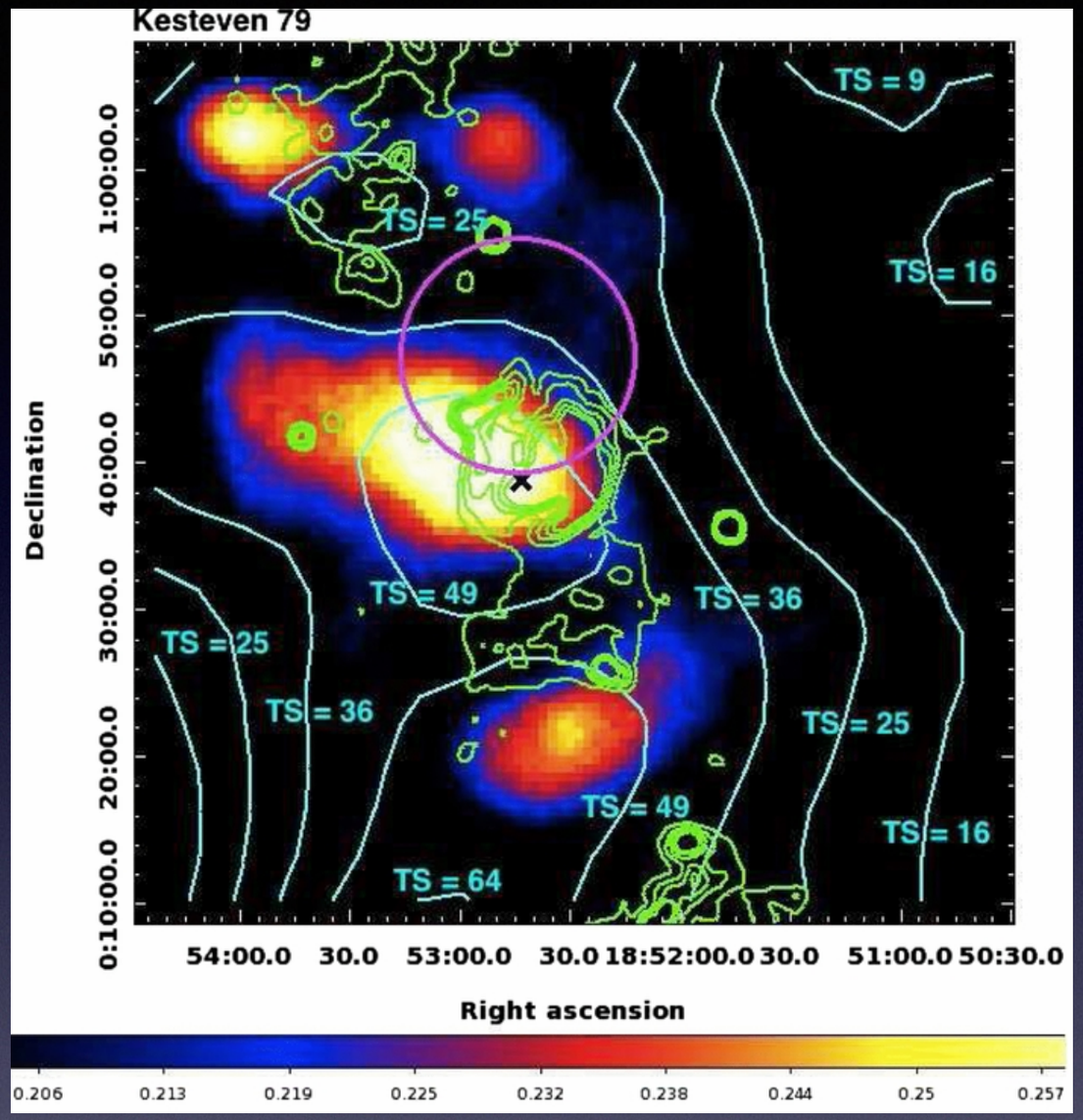

De Luca et al. (2006)

Magnetar? Binary system? ¯_(ツ)_/¯

On June 22nd 2016, Swift BAT detected an X-ray burst from this object, and subsequent follow-up with Chandra and NuSTAR showed emission favored magnetar interpretation (Rea et al. 2016). Perhaps fallback accretion of material is responsible for slowing by orders of magnitude.

# Kes 79



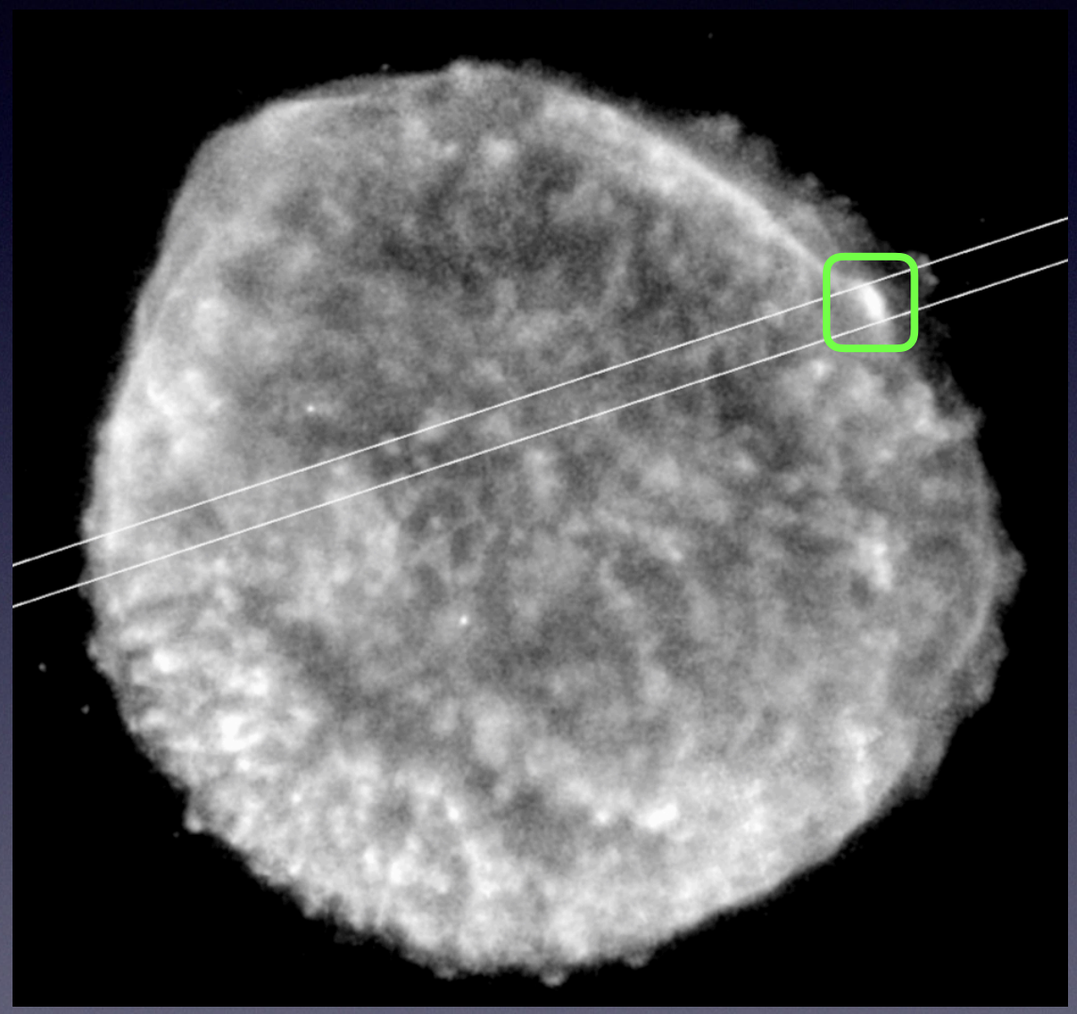



**Serendipitous discovery of > 1 Myr old flaring magnetar in 2014 observations (Zhou et al. 2014)**

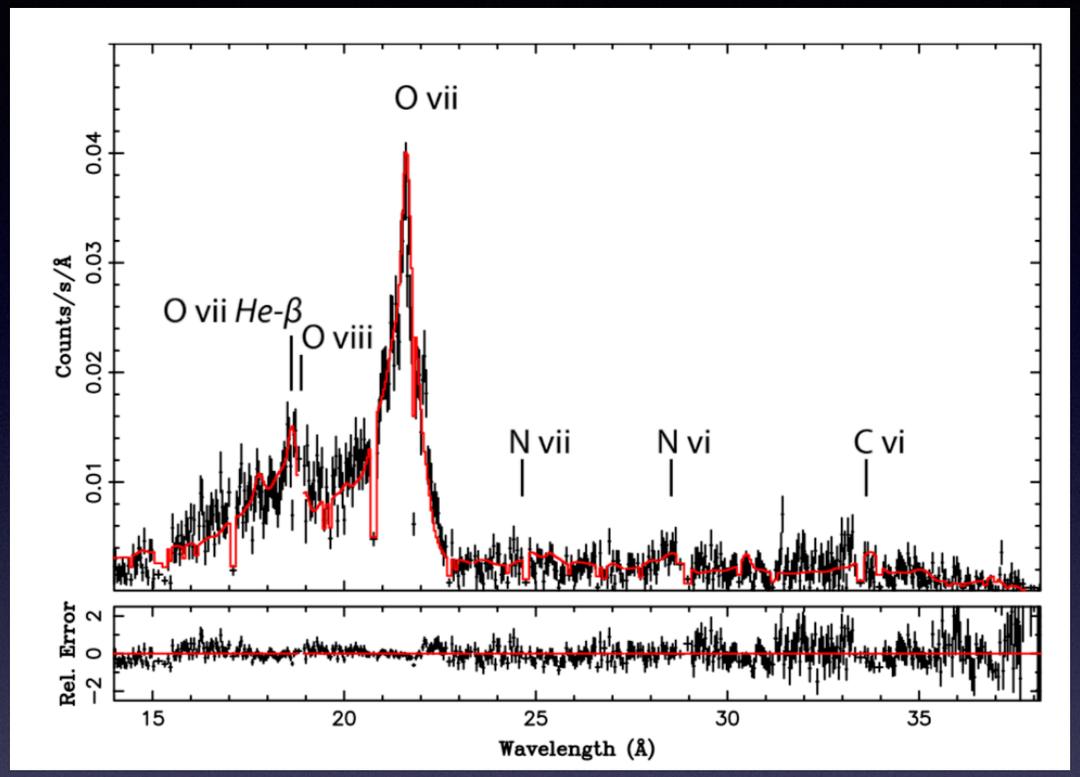
**Fermi image from Auchettl et al. (2015), who modeled emission from radio, X-rays, and gamma-rays, and found that source of gamma-rays is consistent with "hadronic" interpretation**

# What about RGS?

Difficult to use RGS for extended, spatially-varying sources like SNRs



Vink et al. (2003), Broersen et al. (2015)

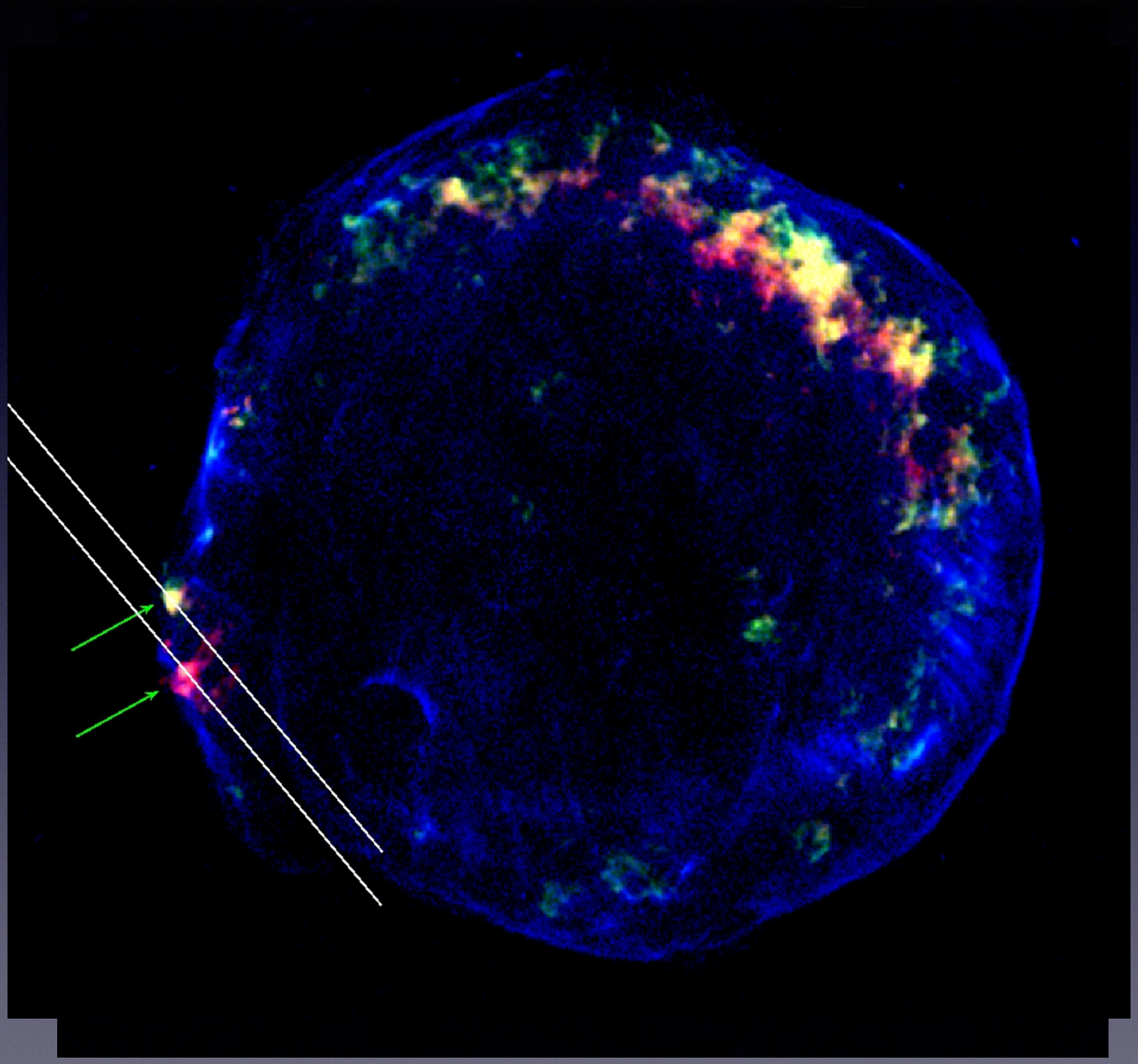



**RGS spectrum of bright emission knot in SN 1006 from ~3,000 km/s shock plowing into ISM. Widths of lines correspond to temperatures of ions.**

**$kT_{Oxygen}$ = 275 keV**

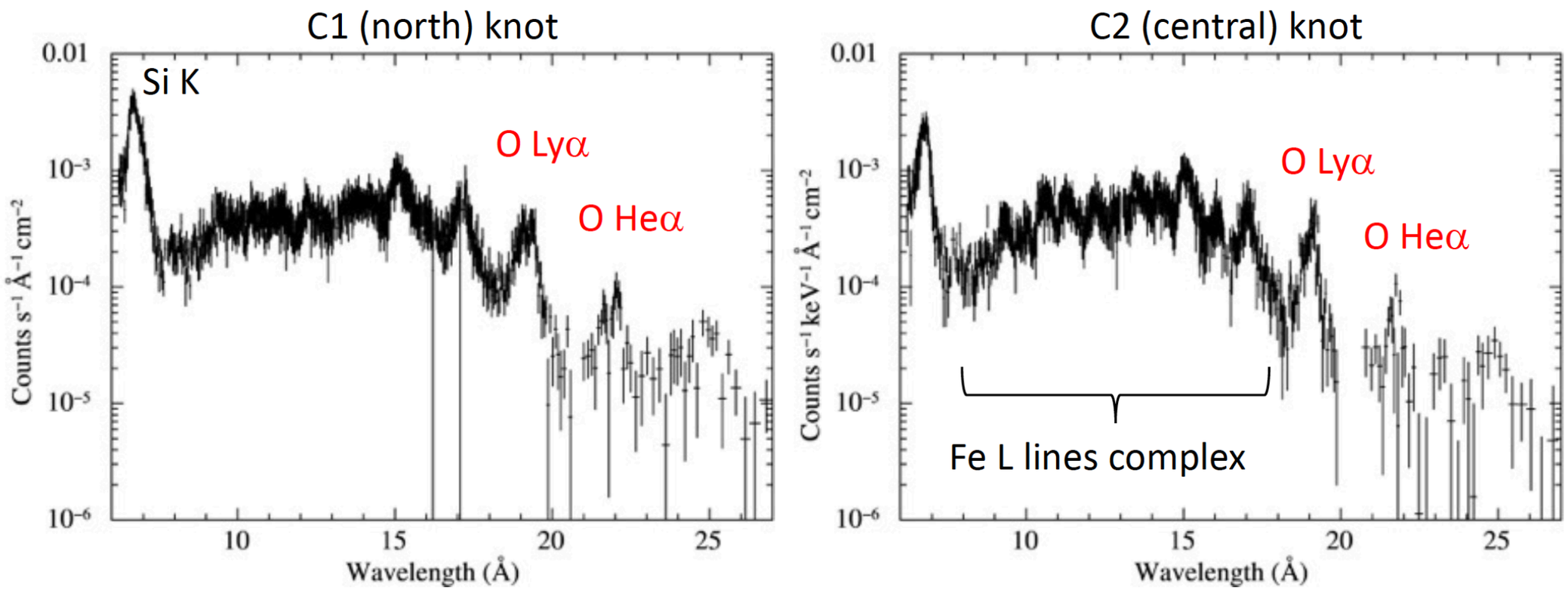
**$kT_{electron}$ = 1.35 keV**

# RGS Observations of Tycho's SNR



Fe L
Si Ka
Continuum

# RGS Spectra



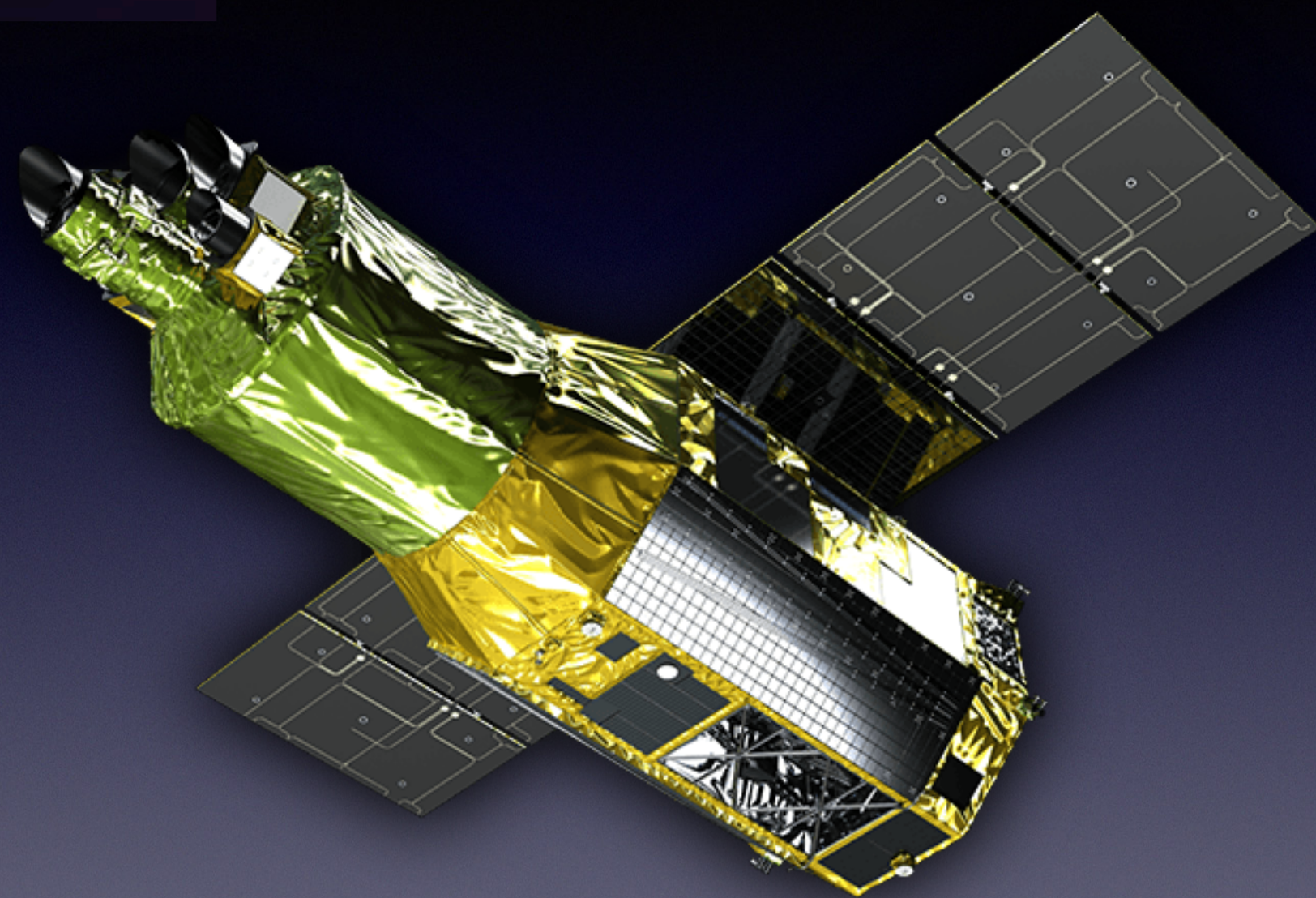

**Williams et al. ~~2019~~ 2020, in prep**

**First clear detection of O K lines in Tycho's SNR**
**$kT_O$ = 400 +/- 50 keV**

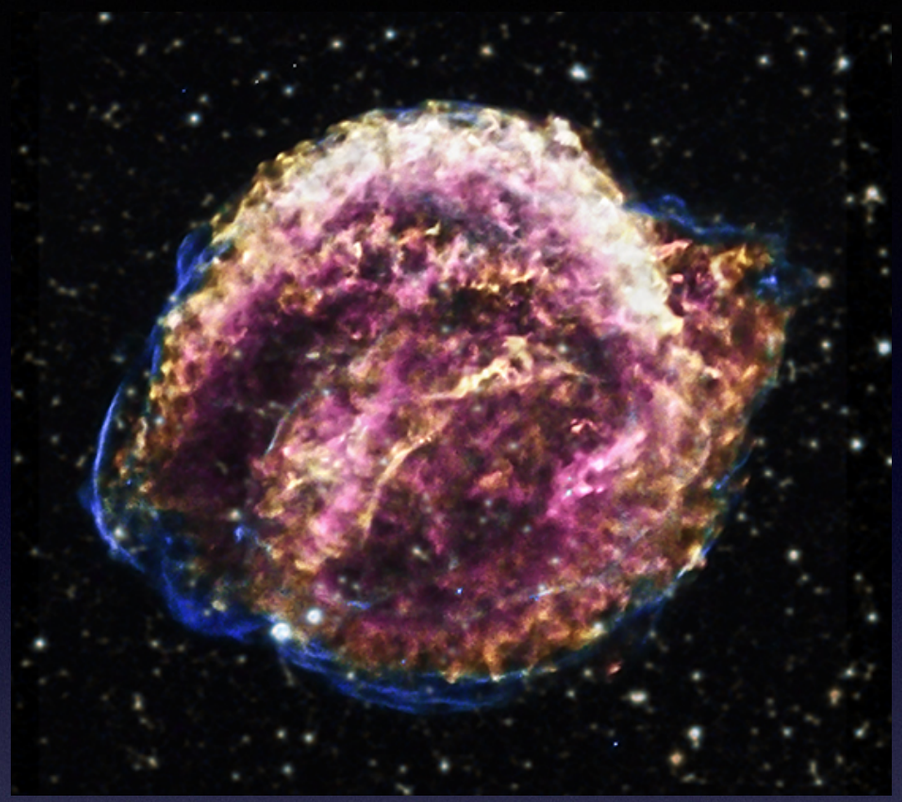
**High, but not as high as expected, given extremely fast shock speeds in that part of the remnant. Must be heated by slower reverse shock; Oxygen must be coming from SNR ejecta**

XRISM X-Ray Imaging and Spectroscopy Mission

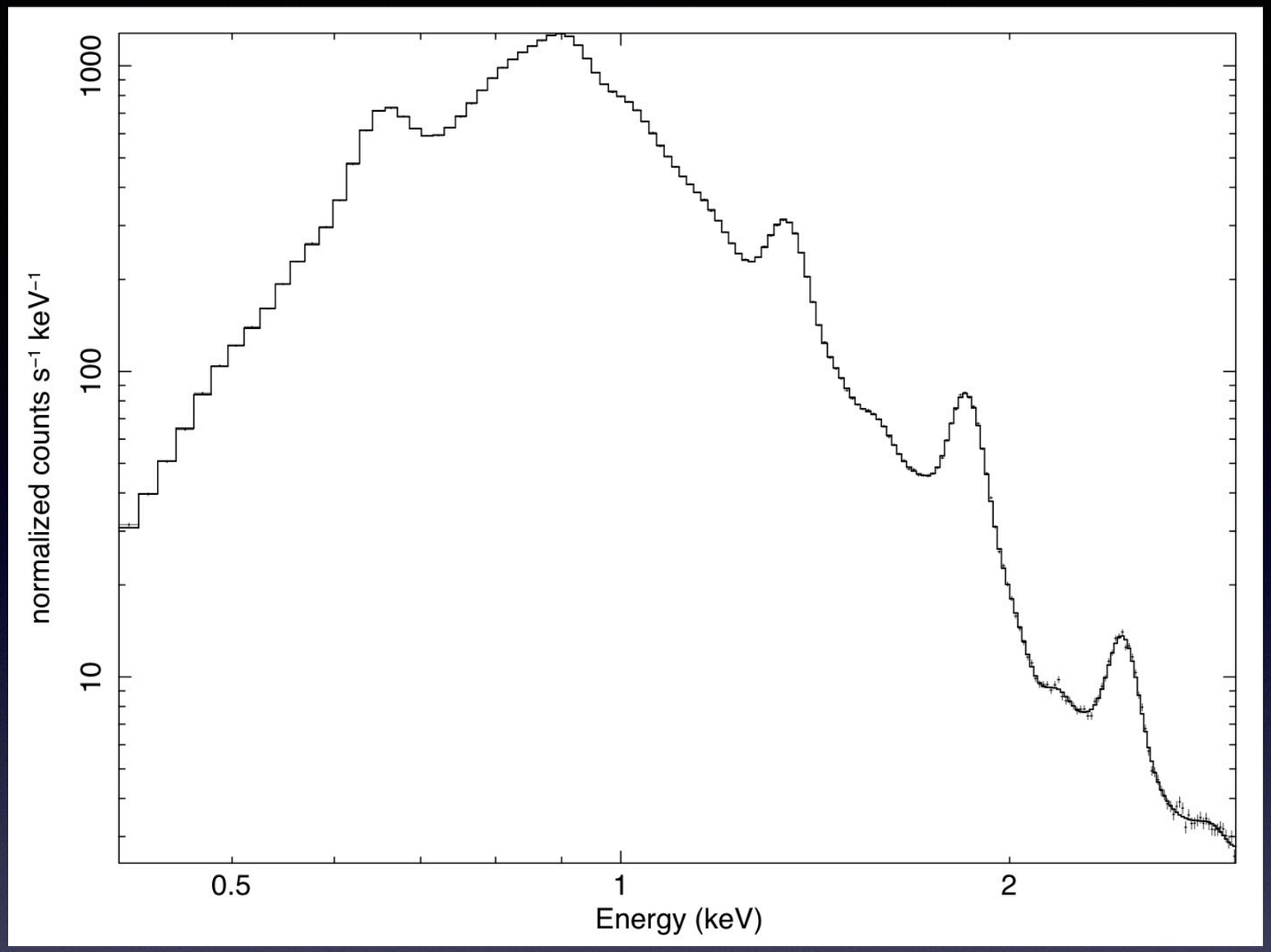
# Supernova remnants beyond XMM…



**Non-dispersive high resolution X-ray spectroscopy**



Kepler's SNR (from Chandra)




Thermal emission from a ~1 keV shocked plasma

**XRISM will enable:**

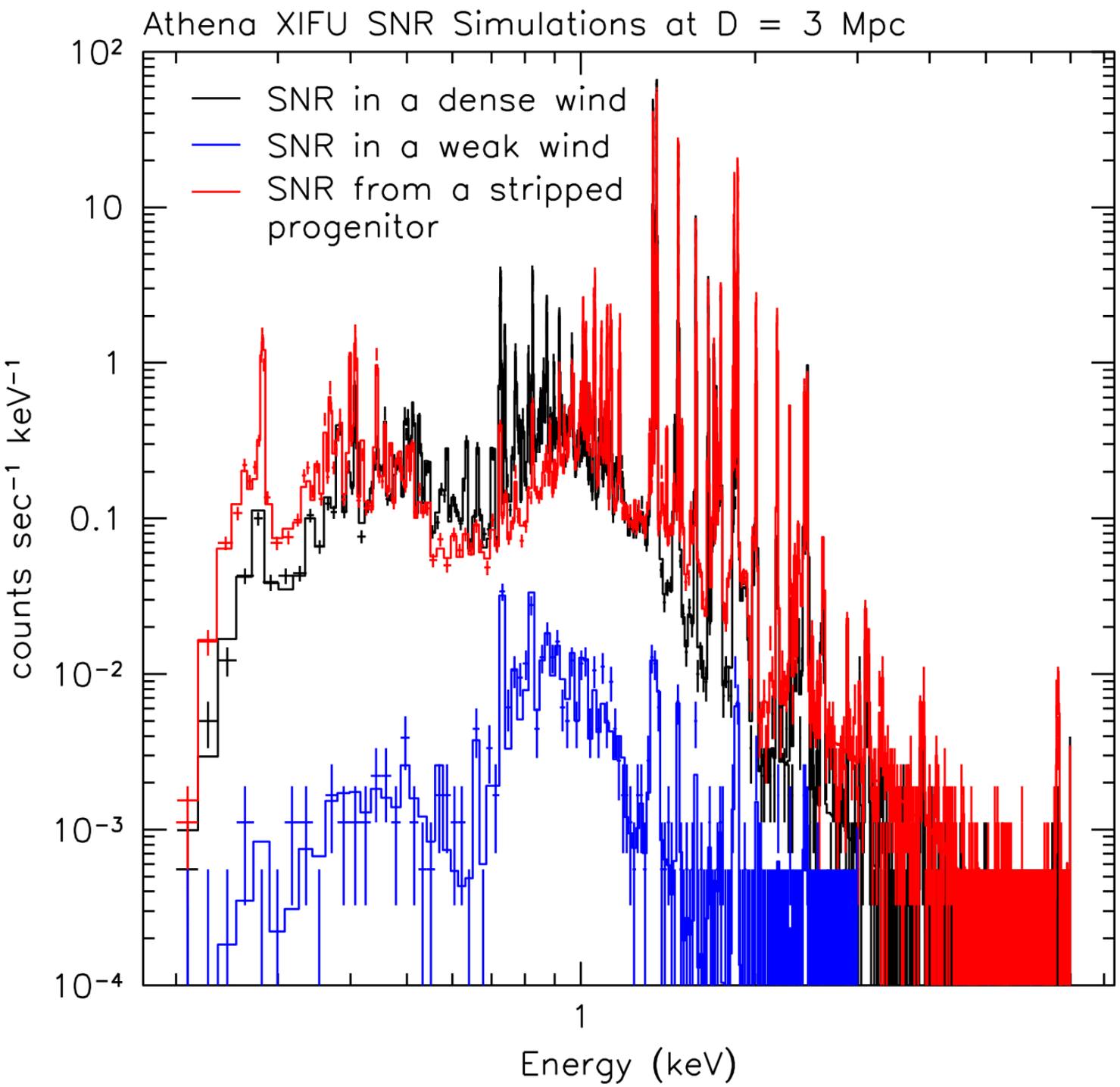
- line diagnostics to constrain atomic physics
- detection of faint emission lines (high-Z elements)
- precise measurements of velocity structure
- and much more!

# XRISM Top-Level Performance Requirements

| Parameter | Requirement | Hitomi Values |
|---|---|---|
| Energy resolution | 7 eV (FWHM) | 5.0 eV |
| Energy scale accuracy | ± 2 eV | ± 0.5 eV |
| Residual Background | $2 \times 10^{-3}$ counts/s/keV | $0.8 \times 10^{-3}$ counts/s/keV |
| Field of view | 2.9 x 2.9 arcmin | same, by design |
| Angular resolution | 1.7 arcmin (HPD) | 1.2 arcmin |
| Effective area (1 keV) | > 160 $cm^2$ | 250 $cm^2$ |
| Effective area (6 keV) | > 210 $cm^2$ | 312 $cm^2$ |
| Cryogen-mode Lifetime | 3 years | 4.2 years (projected) |
| Operational Efficiency | > 90% | > 98% |

**Scheduled to launch in early 2022**

Imaging and
oscopy Mission




**See Astro2020 white paper: "Future X-ray Studies of Supernova Remnants" by B. Williams**

# Final Thoughts...

- Thank you to the organizers for giving me the privilege (and significant workload) of trying to review such a broad topic

- I can only scratch the surface of the work that has been done by many, many people

- Let’s go have a celebratory drink to XMM-Newton!