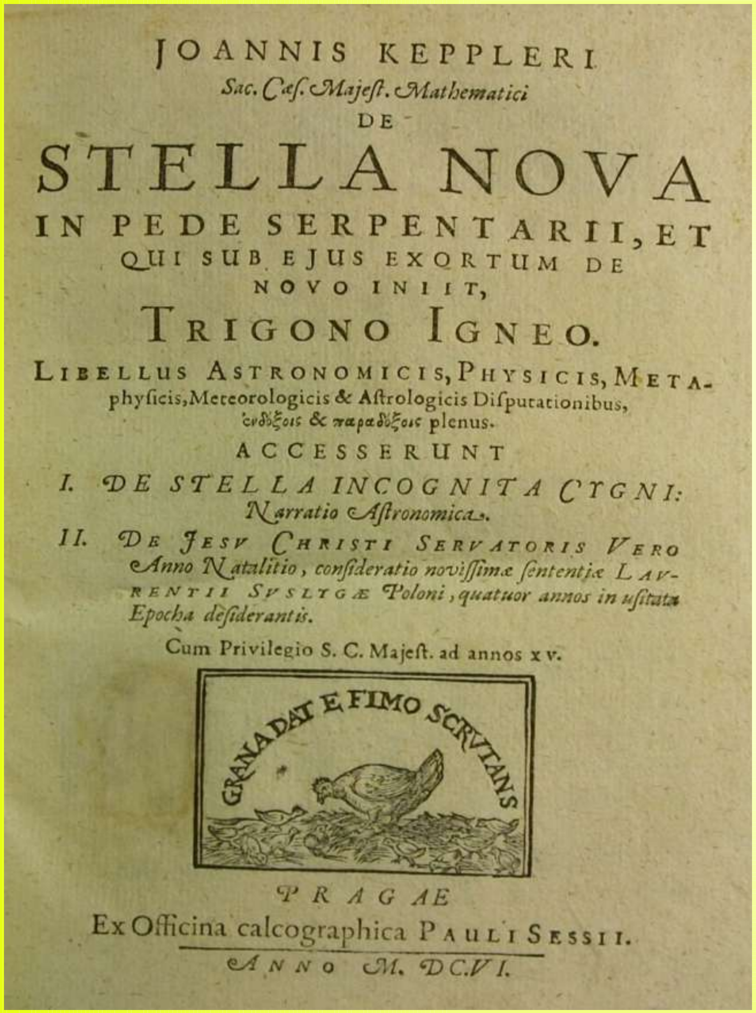
A deep Chandra observation of Kepler's supernova remnant: An anomalous Type Ia supernova

S. Reynolds, K. Borkowski, C. Badenes, J. Hughes, U. Hwang, M. Laming, & J. Blondin

1. A brief history
2. Arcsecond spectroscopy settles the matter
3. Arguments for Ia origin
4. Characterizing the circumstellar medium
5. Implications for Type Ia models and cosmology

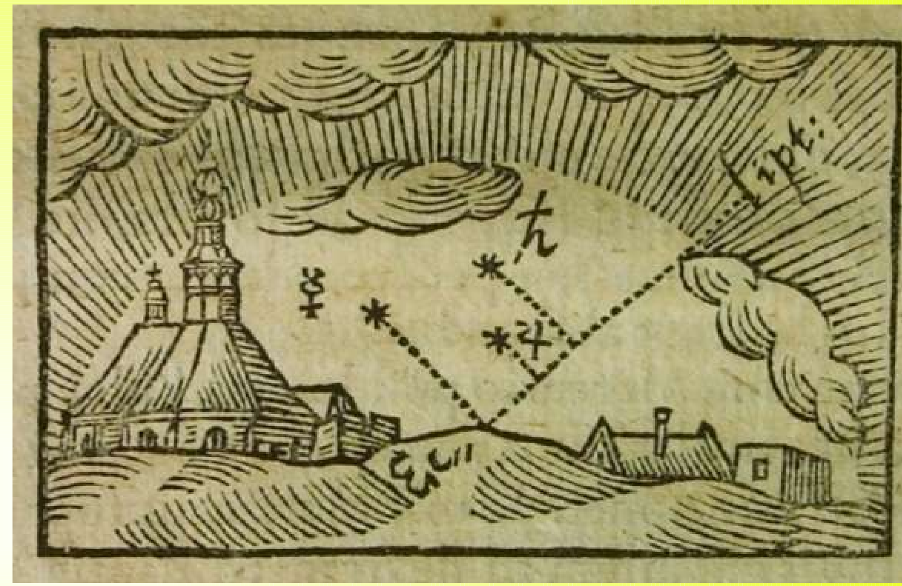
What kind of supernova was Kepler's?



JOANNIS KEPPLERI
Sac. Cæs. Majest. Mathematici
DE
STELLA NOVA
IN PEDE SERPENTARII, ET
QUI SUB EJUS EXORTUM DE
NOVO INIIT,
TRIGONO IGNEO.
LIBELLUS ASTRONOMICIS, PHYSICIS, METAphysicis, Meteorologicis & Astrologicis Disputationibus,
ἐνδόξοις & παραδόξοις plenus.
ACCESSERUNT
I. DE STELLA INCOGNITA CYGNI:
Narratio Astronomica.
II. DE JESV CHRISTI SERVATORIS VERO
Anno Natalitio, consideratio novissimæ sententiæ LAVRENTII SVSLYGÆ Poloni, quatuor annos in usitata
Epocha desiderantis.
Cum Privilegio S. C. Majest. ad annos XV.

GRANA DAT E FIMO SCRVTANS

PRAGAE
Ex Officina calcographica PAULI SESSII.
ANNO M. DCVI.



October 1604: All eyes on a conjunction between Mars and Jupiter in Ophiucus. The new star nearby, “in the serpent's foot,” was carefully observed in Europe and Asia.

Modern recovery of the remnant

NOVA OPHIUCHI OF 1604 AS A SUPERNOVA*

W. BAADE
Mount Wilson Observatory
Received January 11, 1943

ABSTRACT

Nova Ophiuchi of 1604 is one of the earliest well-observed novae. Its position has recently been redetermined by Schlier and Boehme from the original measures of Fabricius and Kepler. The light-curve, derived in the present paper, shows that the star was a supernova of type I, which at maximum reached the apparent magnitude −2.2. A check of the Chinese version of the apparition against the light-curve shows that the Chinese reports about new stars were based on careful observations.

A search for the remnant of the supernova led to the discovery of a small patch of emission nebulosity, which is undoubtedly a part of the masses ejected during the outburst. The investigation of this remnant meets with unusual difficulties because the supernova is behind heavy obscuration. The determination of the distance and the luminosity of the supernova must therefore be left to future observations.

THE SPECTRUM OF THE NEBULOSITY NEAR KEPLER'S NOVA OF 1604*

R. MINKOWSKI
Mount Wilson Observatory
Received January 11, 1943

ABSTRACT

The spectrum of the nebulosity near Kepler's nova of 1604 consists of the emission lines [*O* III] λ 5007; [*O* I] λ 6300; [*N* II] λ 6584, λ 6548; *Hα*; and [*S* II] λ 6731. The spectrum is very similar to that of the filaments of the Crab nebula, particularly in the low intensity of *Hα* relative to the [*N* II] lines. The intensity of [*O* III] λ 5007, however, is much less than in the Crab nebula; this suggests heavy space reddening corresponding to a color excess of 2.1 mag. The radial velocity, −200 km/sec at the tip and −260 km/sec at the base of the fan-shaped nebulosity, is too high to admit any other interpretation than that the fan-shaped nebulosity is part of an expanding nebula. The results support the opinion that the nebulosity is actually a remnant of Kepler's nova and that this object was a supernova.

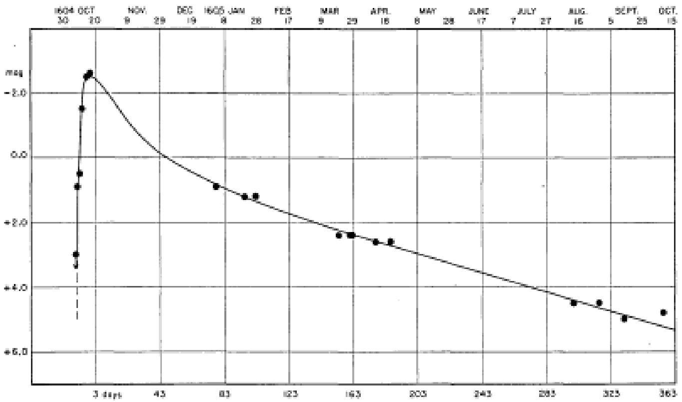


FIG. 1.—Light-curve of Supernova Ophiuchi of 1604. The smooth curve representing the descending branch is the visual light-curve of the recent supernova in IC 4182, properly adjusted.

1943: Baade collects historical light curve: looks like Type I.

Minkowski observes strong [N II], v ~ -200 km/s.

b = +6.8^{o} ; Type I light curve; but dense, N-enriched CSM!

Status as of 2006

Type Ia signs:

-- Nonradiative shocks in optical around much of N rim (Blair et al. 1991) indicate partially neutral medium

-- Integrated X-ray spectrum shows strong Fe (Kinugasa & Tsunemi 1999; Decourchelle & Ballet 1994).

Core-collapse signs:

-- N ~ 3 x solar (Blair et al. 1991)

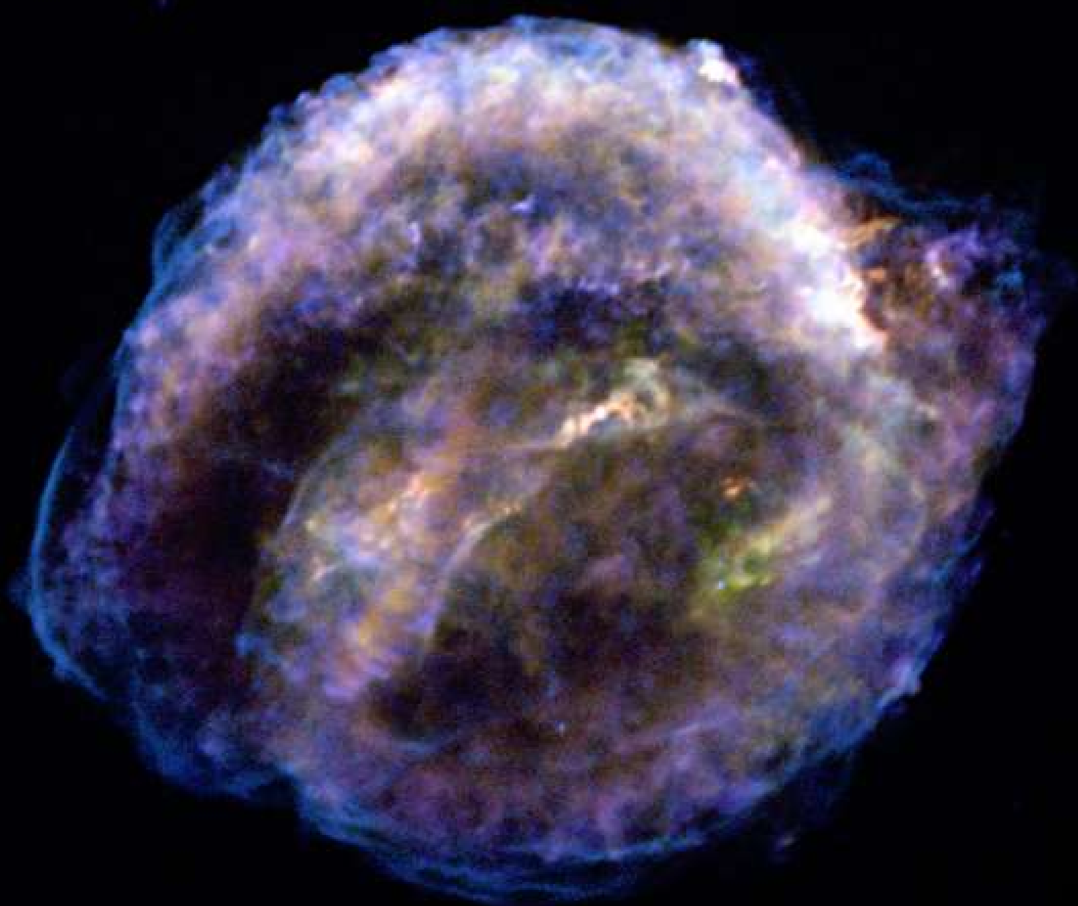
-- Bright N rim requires n ~ several cm^{-3} ; not expected at such b

-- Radial velocity + proper motion ⇒ velocity $\sim$ 300 km/s away from Galactic plane.

Could supply CSM with runaway core-collapse progenitor, strong stellar wind (Bandiera 1987) But:

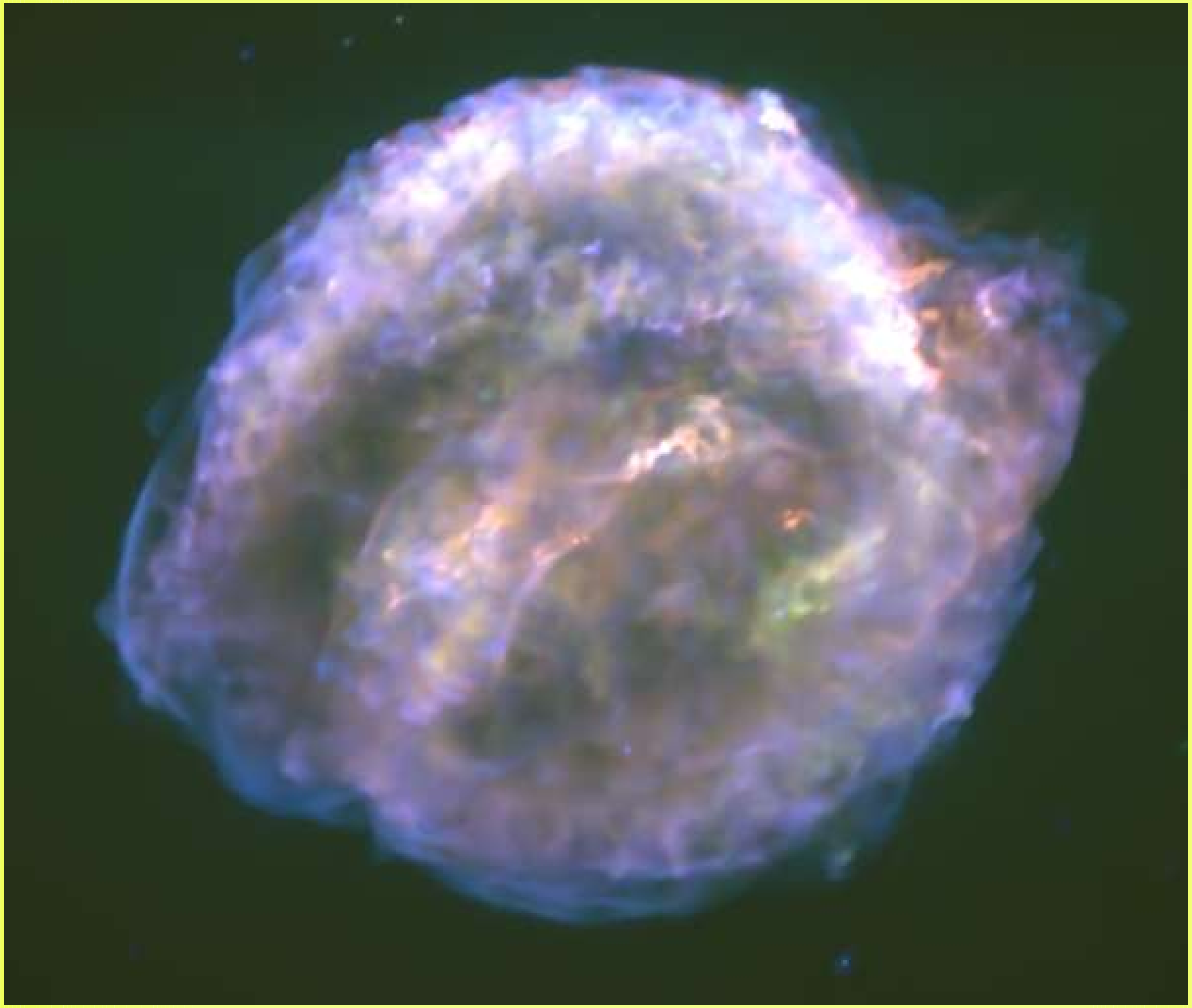
Could Fe be ambient? Neutral ambient material? Type Ia light curve?

Solution: 750 ks *Chandra* observation: 30 million counts, arcsec spectroscopy



Four-color press-release image, optimized for visual impact

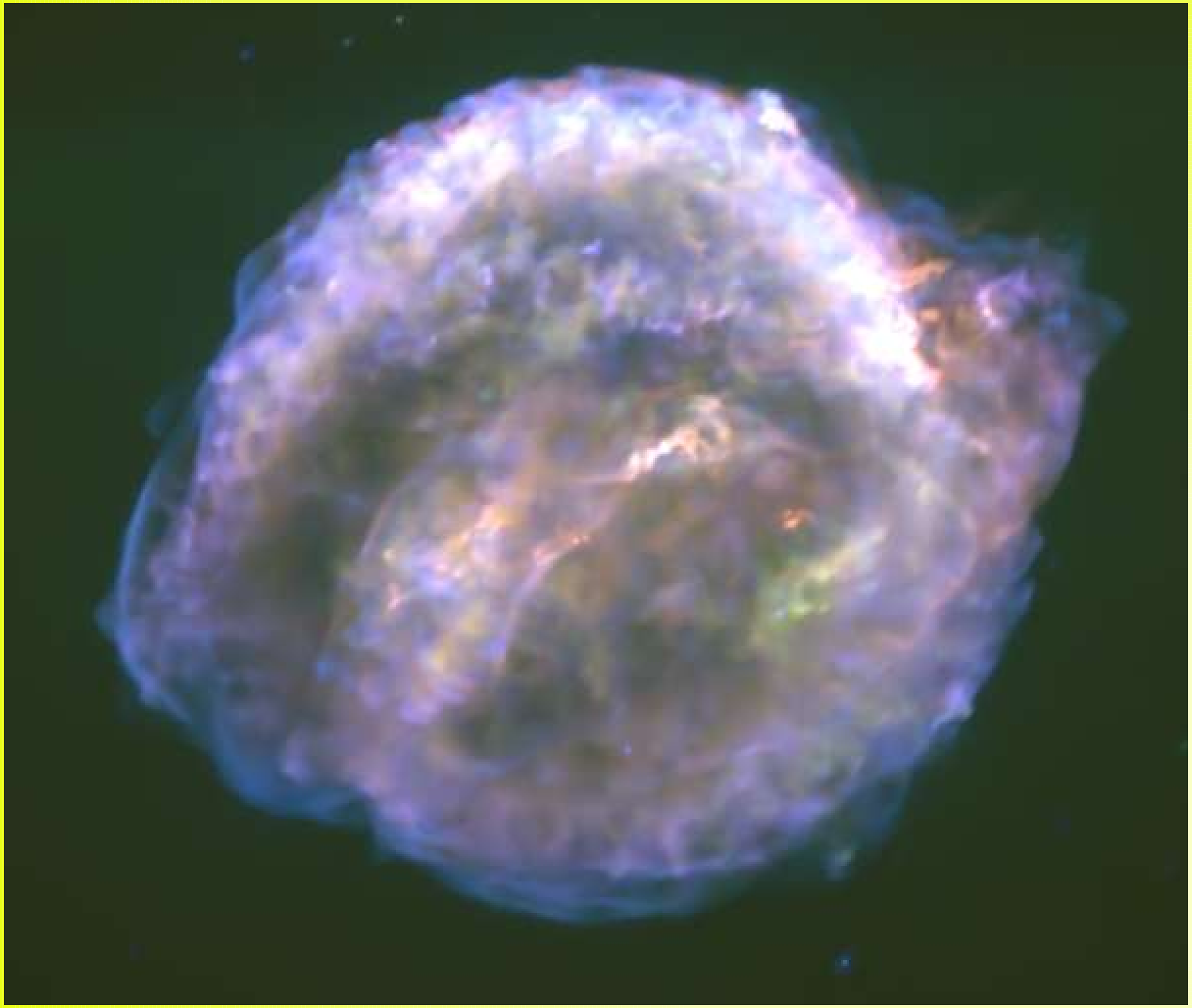
Eyeball spectroscopy

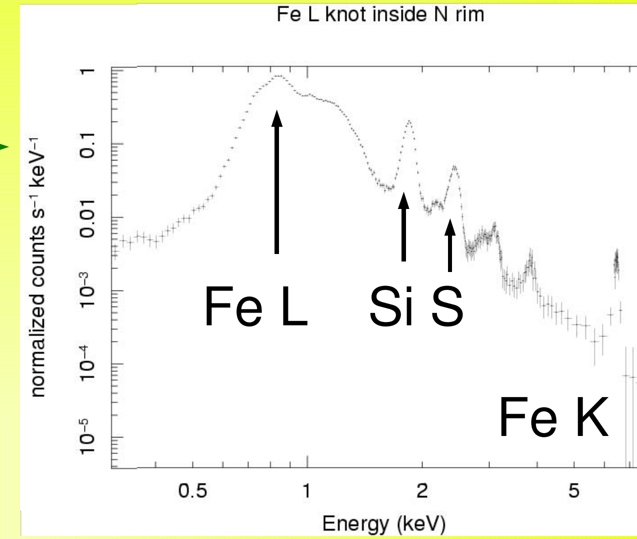


Red: soft + continuum (0.3 – 0.72, 1.5 – 1.7, 2.1 – 2.3, 2.7 – 7 keV)

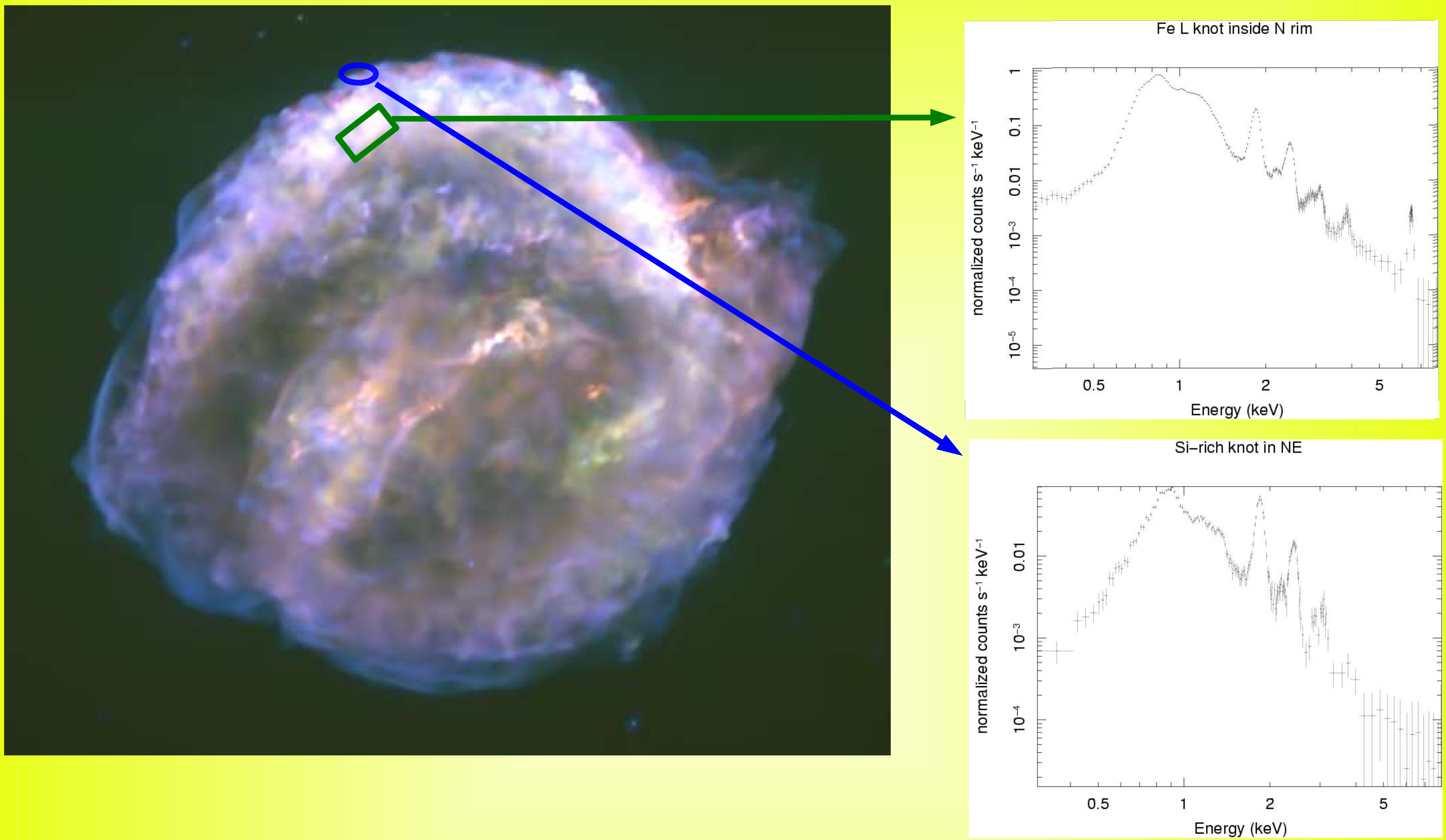
Green: Fe L (0.72 – 1.7 keV)

Blue: mainly Si, S, hard continuum (1.7 – 9 keV; overlaps red)

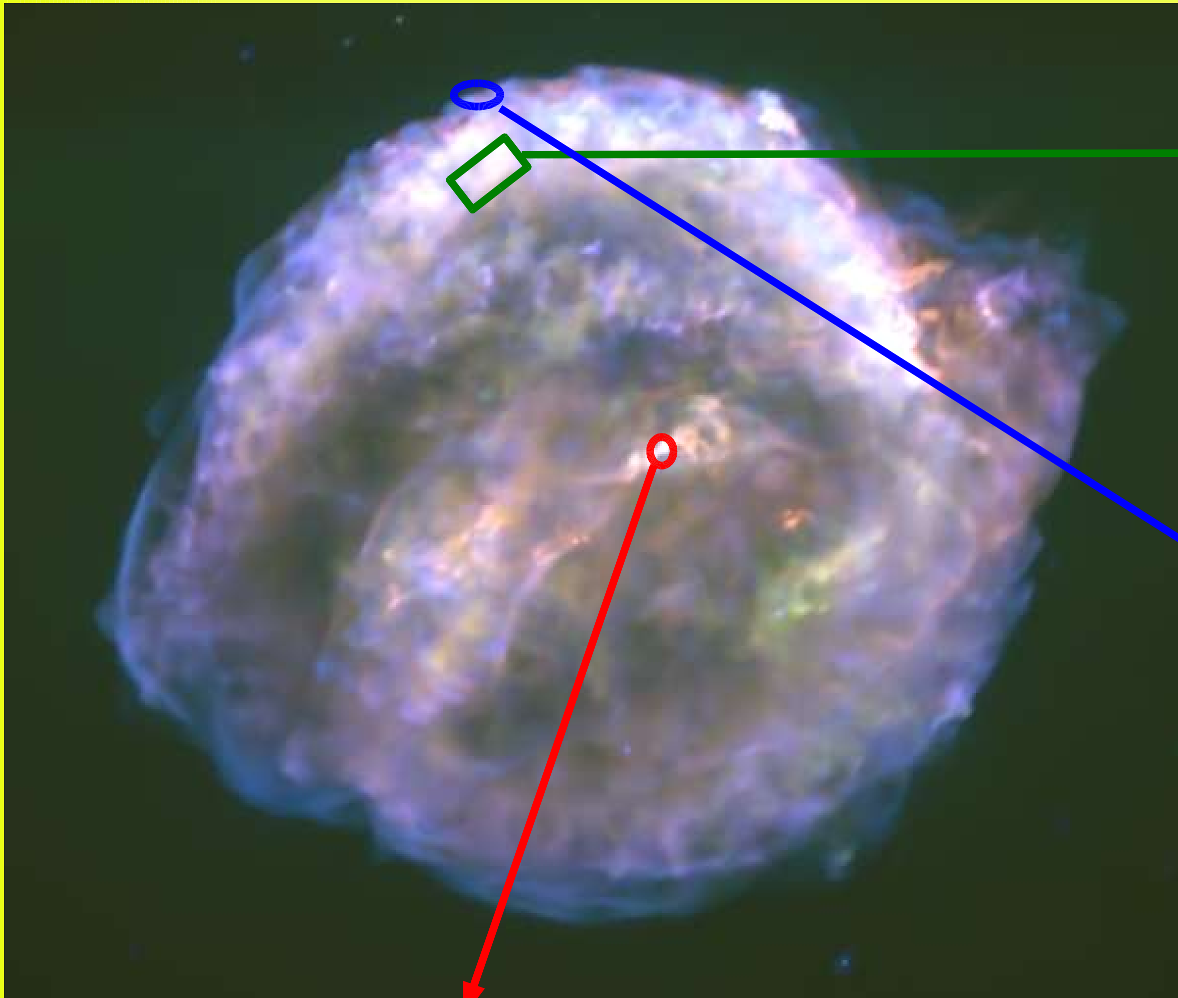


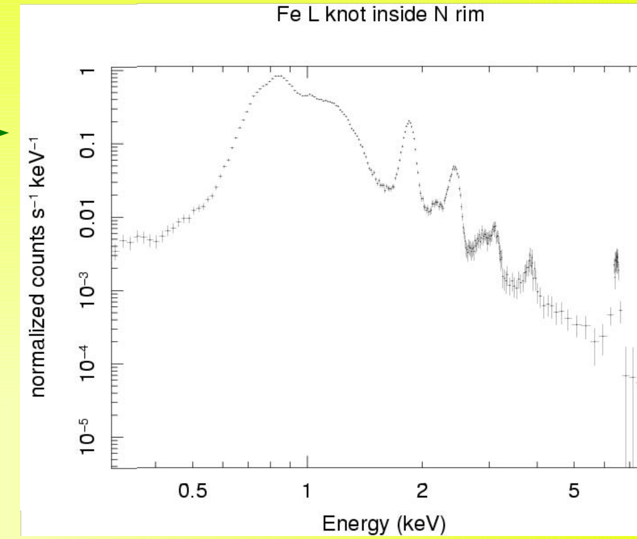


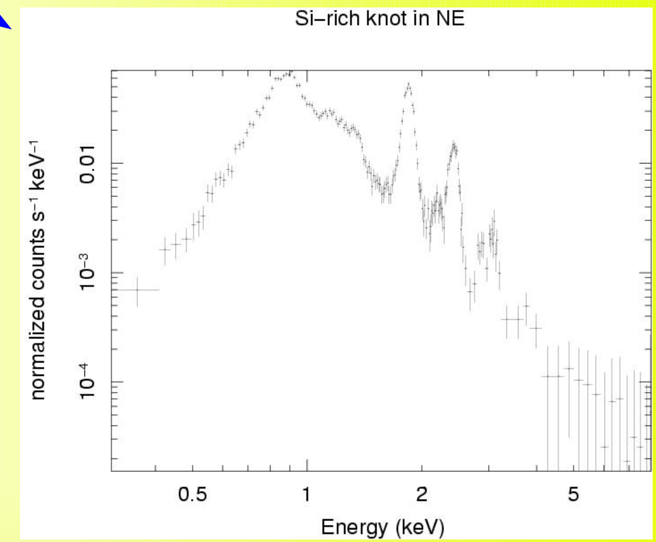
Fe L-shell-dominated region
(similar to integrated spectrum)

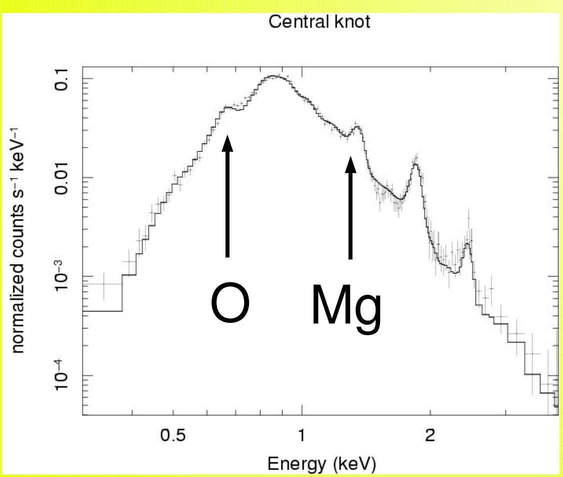


Si-rich knot (higher Si/Fe L)

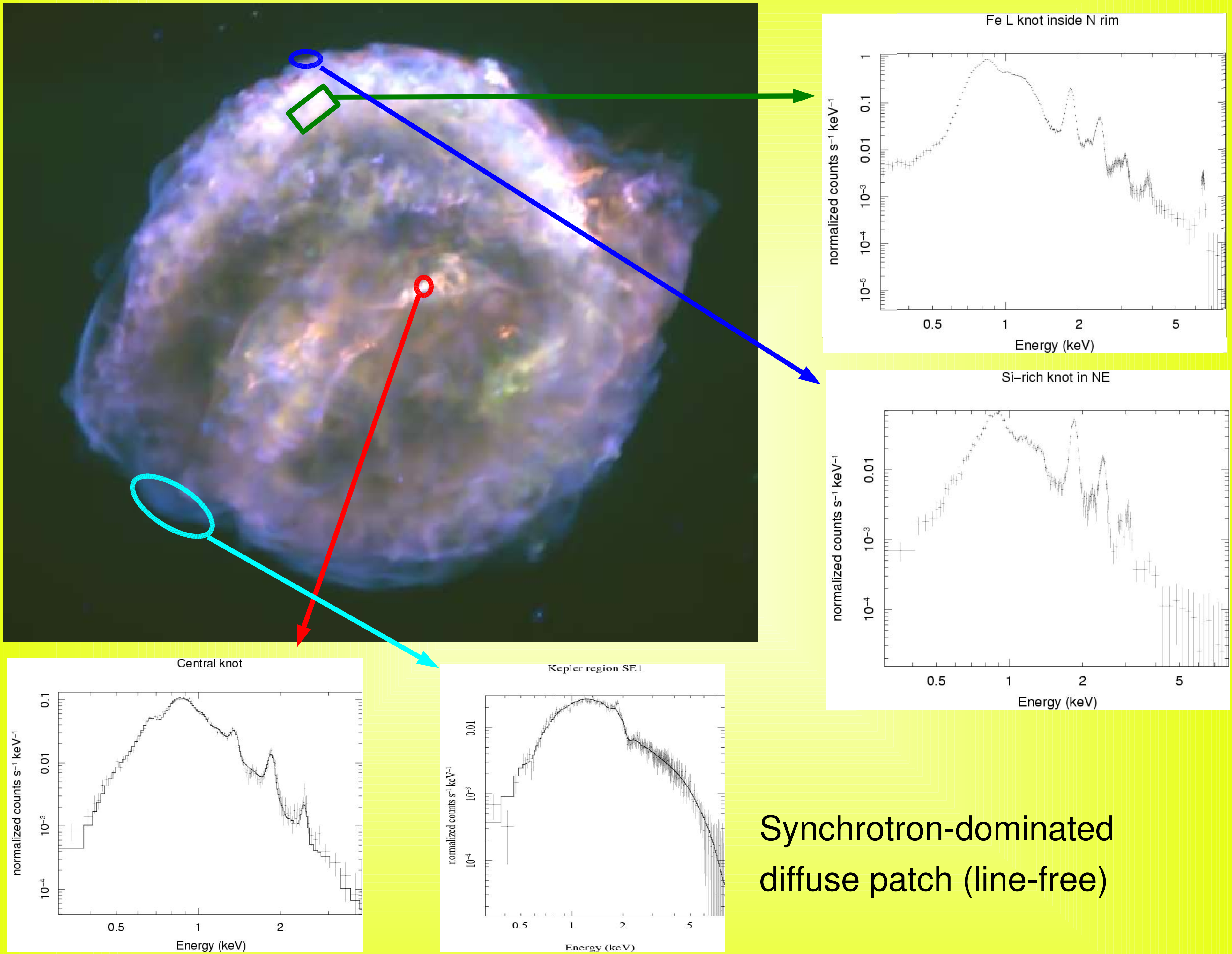






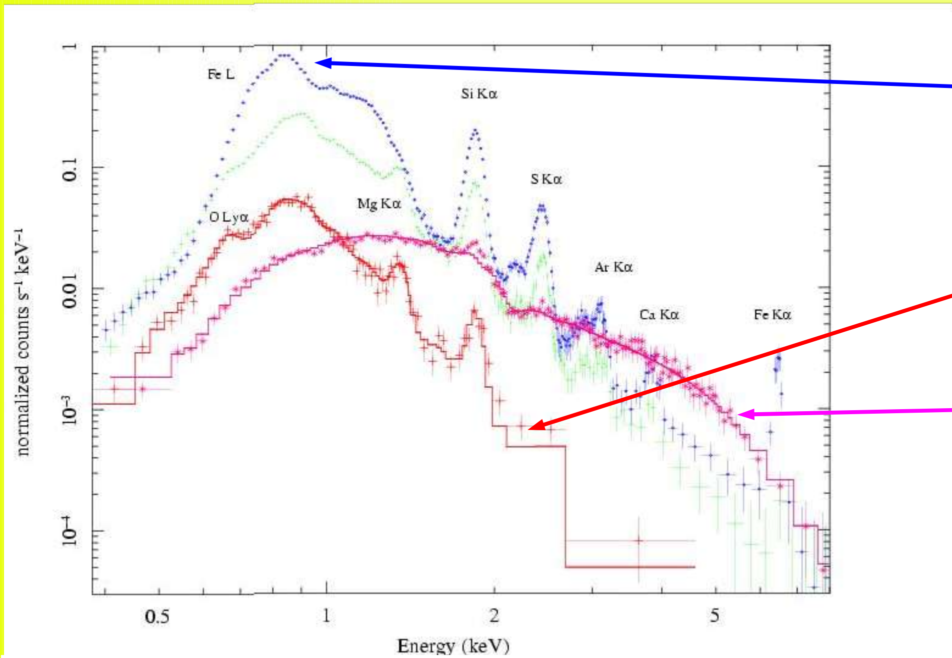


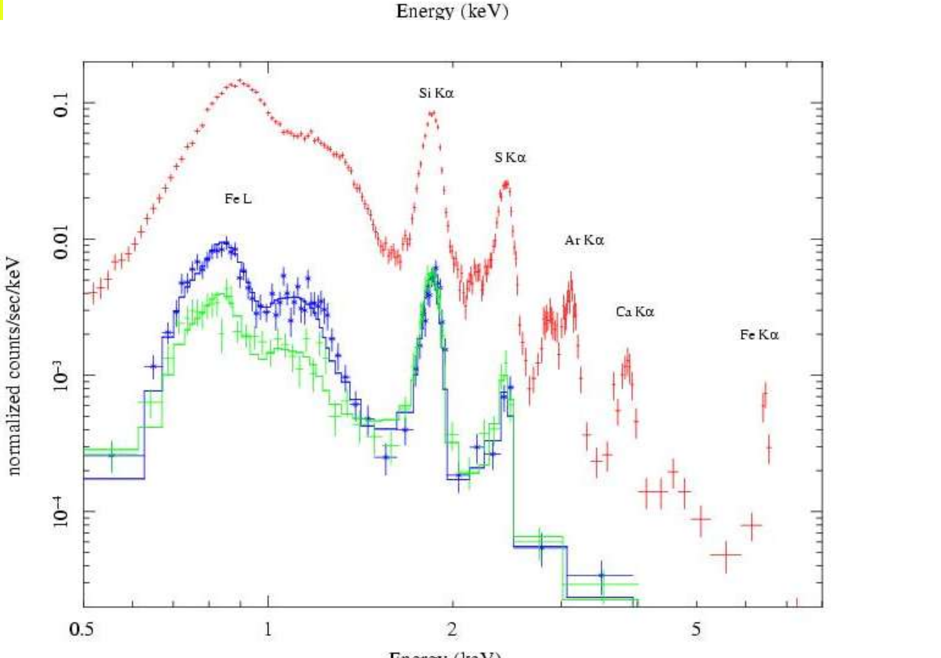
Soft-spectrum central knot (local background subtracted)



Synchrotron-dominated diffuse patch (line-free)

Summary: spectra of 100 small regions



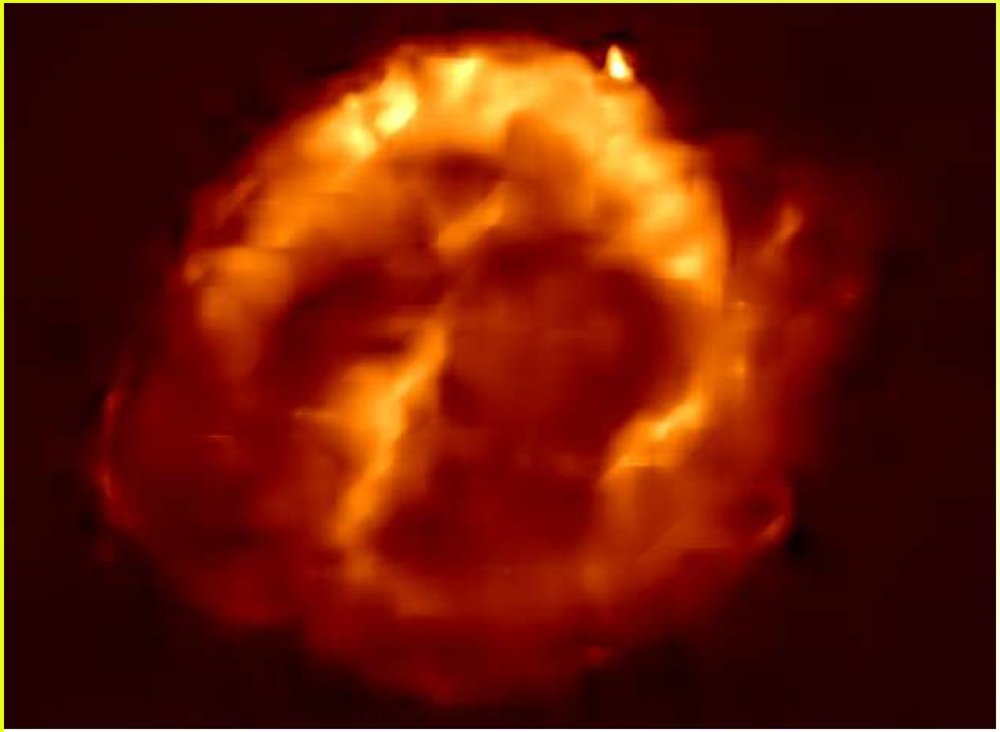


1. Vast majority: Strong Fe L, Si, S. No O, Mg. Often Fe K.
2. Very few: soft spectrum, O Lyα, Mg K.
3. A few regions at edge: no lines (synchrotron)

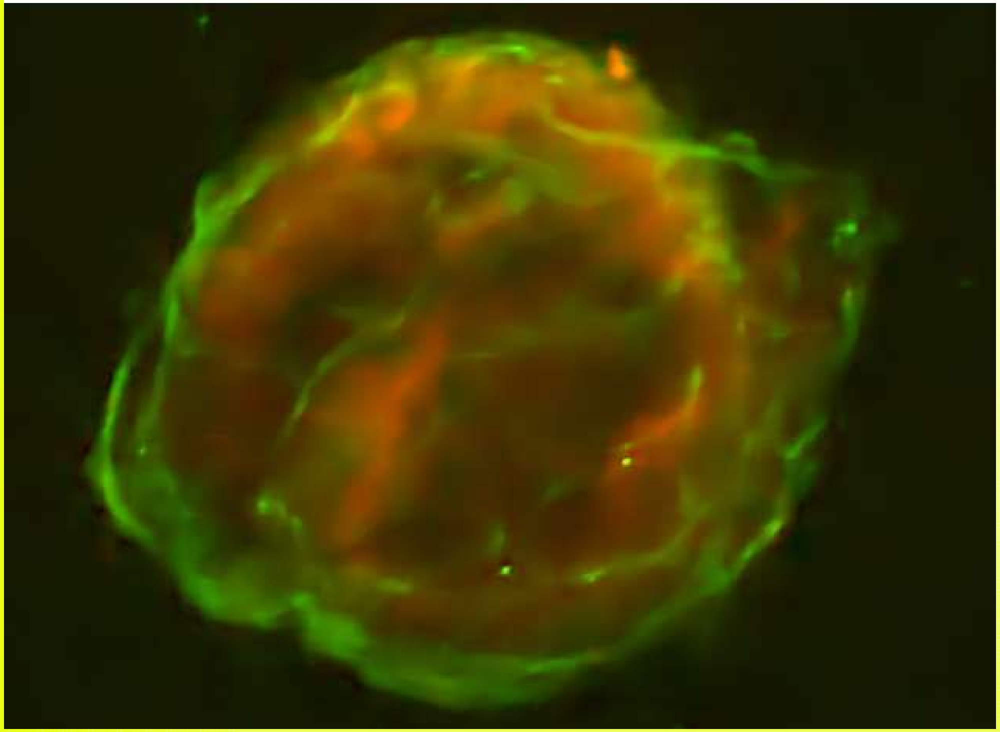
Detailed spectral fitting will require better tools (Fe data, heavy-element ejecta codes, multi-T)

Regions at extreme edge still show substantial Fe, but Si/Fe larger.
Clues to explosion mechanism.

Iron is everywhere!



Fe K image (6.2 – 6.8 keV)



Fe K + broad continuum (4.5 – 6.2 keV, mainly synchrotron. Shows blast wave.)

Both smoothed with “platelets” (Willett 2007)

It was a Ia event!

1. Integrated spectrum: Strong Fe, Si, S: ejecta emission. Resembles Tycho, not Cas A
2. Almost no O, except in a few soft-spectrum knots where O/Fe is solar. Values near 70 are ruled out.
3. No point source (< 10^{-2} x Cas A CCO)
4. Nonradiative shocks. CC events ionize entire CSM
5. Light curve still looks like Ia (and $M_{max} \sim -19^{m}$)

Properties of circumstellar medium (CSM)

1. High density, to north at least. (Modeling *Spitzer* fluxes: $n_e \sim 20$ cm^{-3} in N rim; Blair et al. 2007).

2. Large N/S density contrast, at least 5 (Blair et al. 2007)

3. Nitrogen rich. (Optical: Blair et al. 1991. Our *Chandra* data are also best fit with N ~ 3 x solar, but with large uncertainties.)

4. Solar O/Fe. Neither CC nor Type Ia ejecta.

5. Partially neutral. (Blair et al. 1991)

6. Total mass ~ 1 $M_\odot$ (Blair et al. 2007).

Results, and questions

1. Kepler's SNR resulted from a thermonuclear supernova.
2. -- but is also interacting with dense, enriched CSM.
   What Ia progenitor system produces such CSM?

3. How did it get to z = 470 pc (for d = 4 kpc; Sankrit et al. 2005), with peculiar velocity ~ 300 km/s? -- but Pop I abundances??
   Kinematics are unlike almost any Pop I objects.

4. Fe-rich ejecta are seen to largest distances.
   Consistent with Ia explosion models? (Detonation?)

Cosmological implications

CSM suggests more massive progenitor system. Related to "prompt" Ia's (Mannucci et al. 2006, Sullivan et al. 2006, etc.)?

Prompt Ia's (delays < 100 Myr) have obvious serious implications for chemical evolution of galaxies, use of Ia's for cosmology: Prompt/"normal" Ia ratio will be redshift-dependent.

Is Kepler the nearest "massive Ia" example?

Ia modeling implications

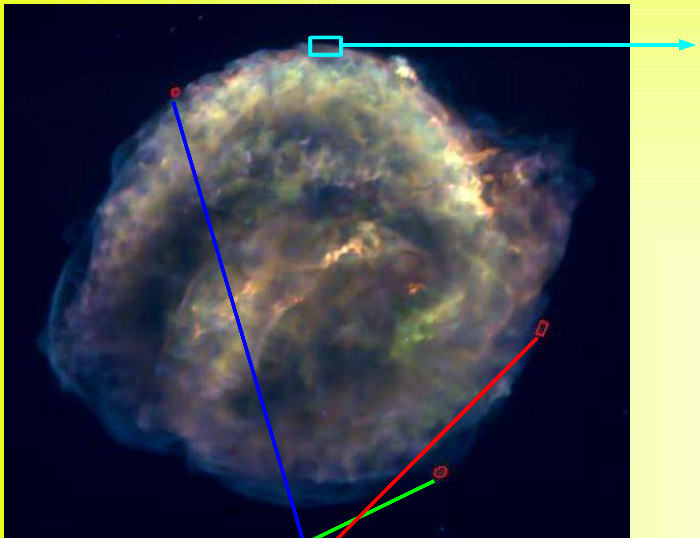
Progenitor

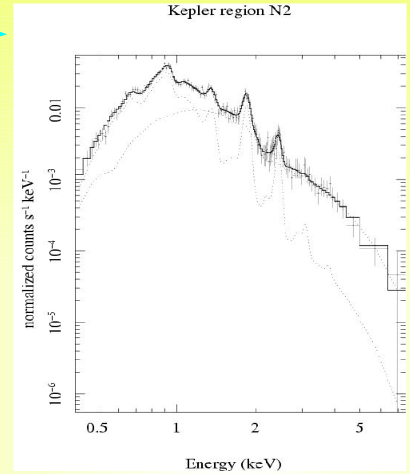
1. More massive than standard single-degenerate picture?
2. Mass loss: from WD, companion, WD progenitor? (Anisotropy?)
3. How did progenitor system get here? (~ 3 Myr from $z = 0$ at observed speed; but how get a *binary* to 300 km/s??)

Explosion mechanism

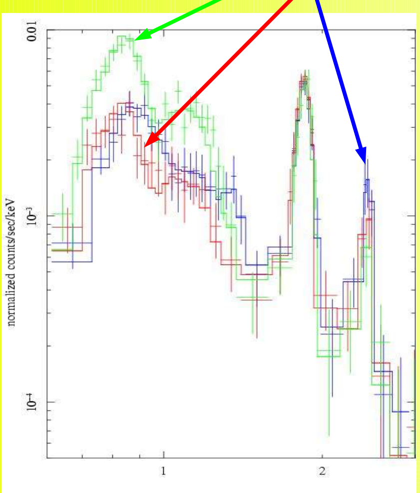
1. Detonation predicts some Si beyond most Fe. Do we see this? (Outer knots have 6% and 25% Fe by mass; are there some with less?)
2. Lack of ejecta O even at large radii: Require almost complete burning.
3. Ejecta are extremely clumpy; some clumps beyond the mean blast wave radius. Ni bubble effect?

A mine of information

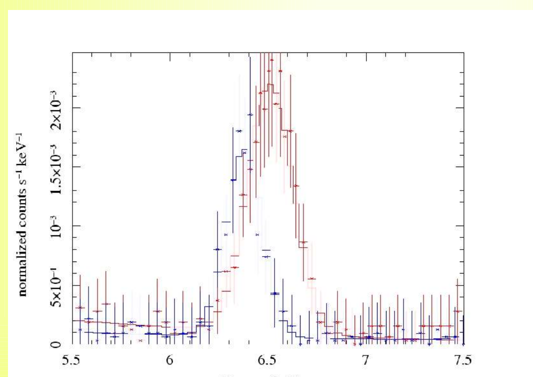




Thermal + nonthermal blends



Contrast 3 distant knots



Fe K line profiles:
map kinematics

This investment of *Chandra* time will yield scientific benefits for years to come.