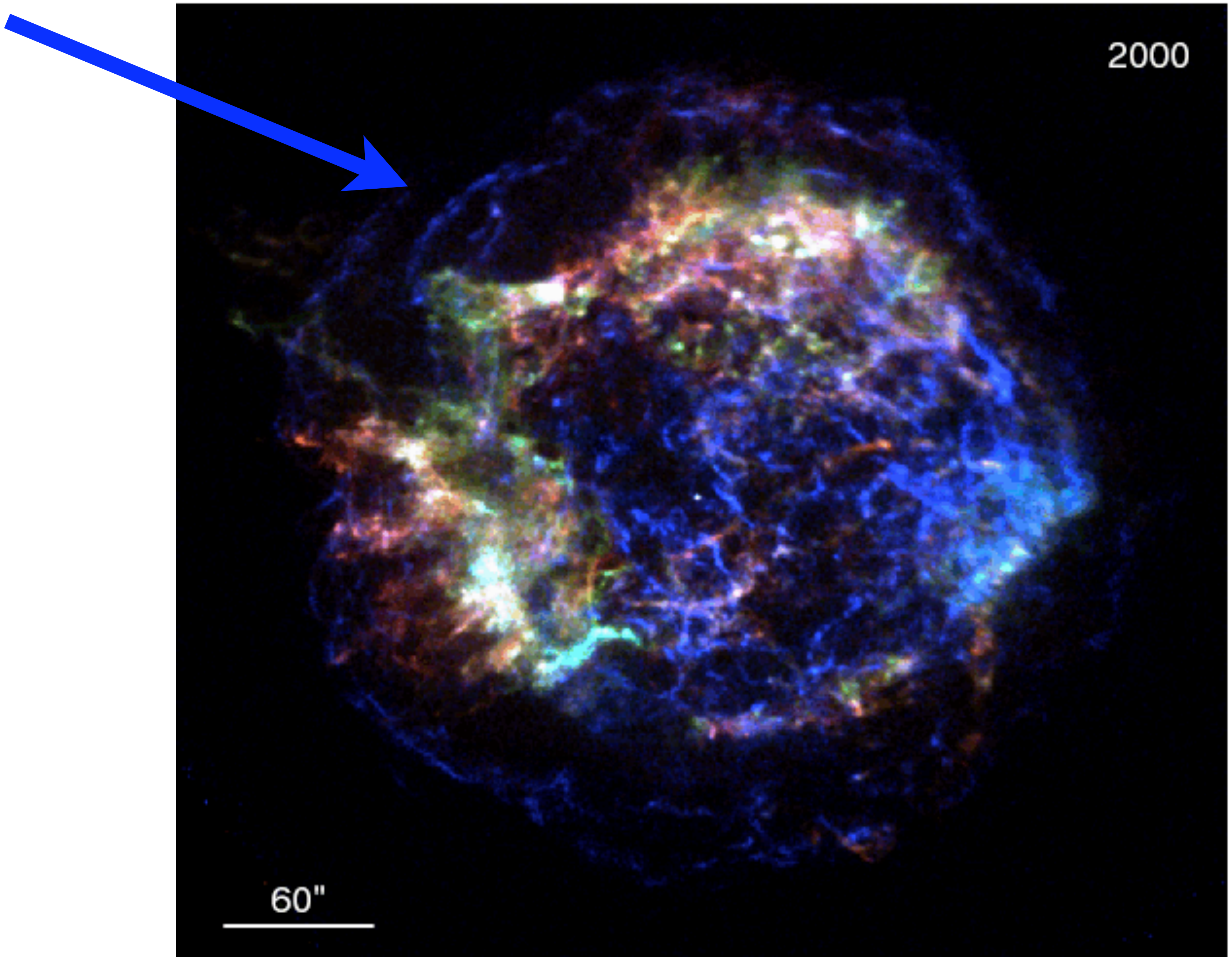
WHAT DO X-RAY OBSERVATIONS OF SNRS TELL US ABOUT THE SN AND ITS PROGENITOR

DAN PATNAUDE (SAO)

ANATOMY OF A SUPERNOVA REMNANT

Forward Shock



Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.

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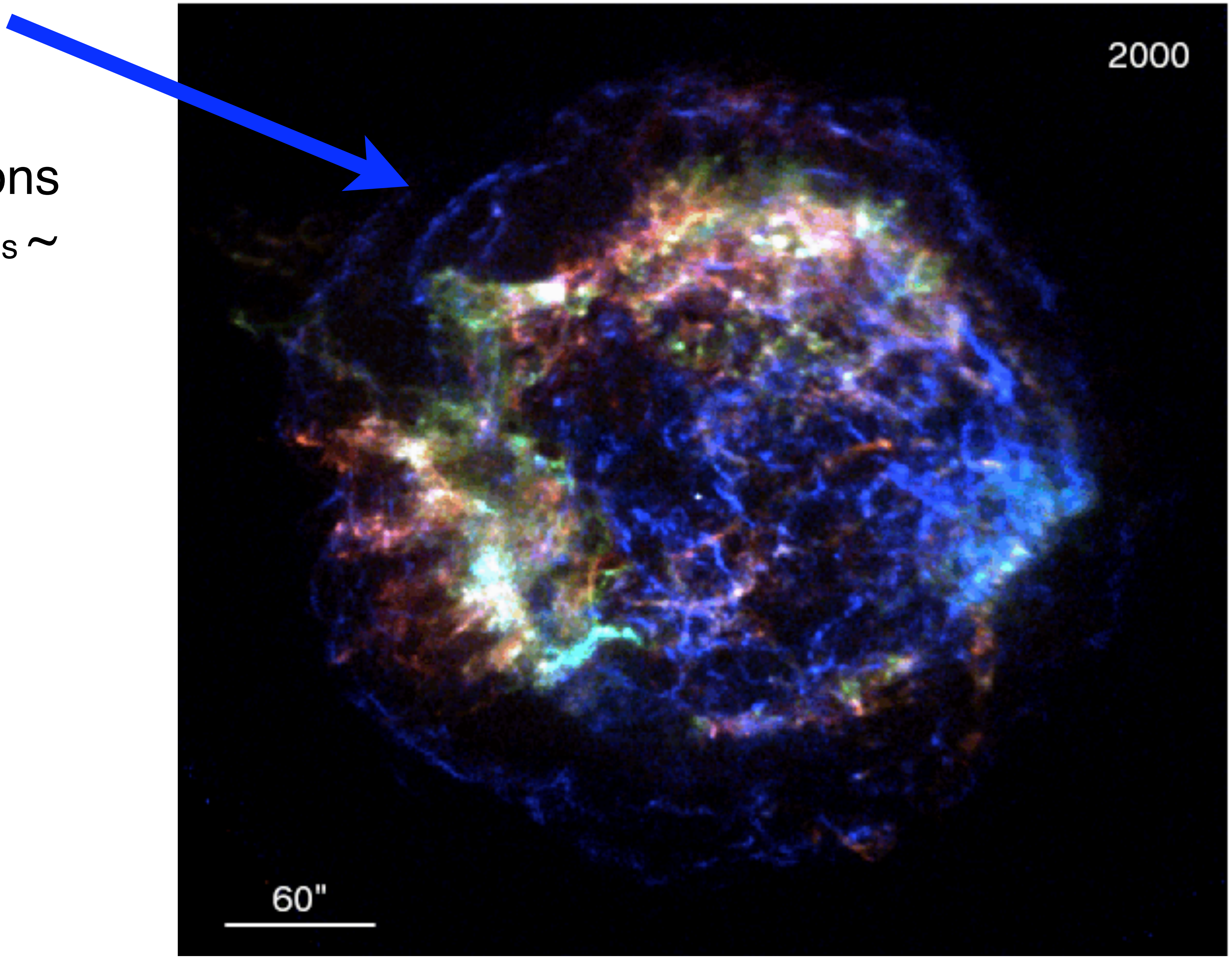
shock accelerated electrons mark the location of the $u_s \sim 5000$ km s^{-1} shock



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ANATOMY OF A SUPERNOVA REMNANT

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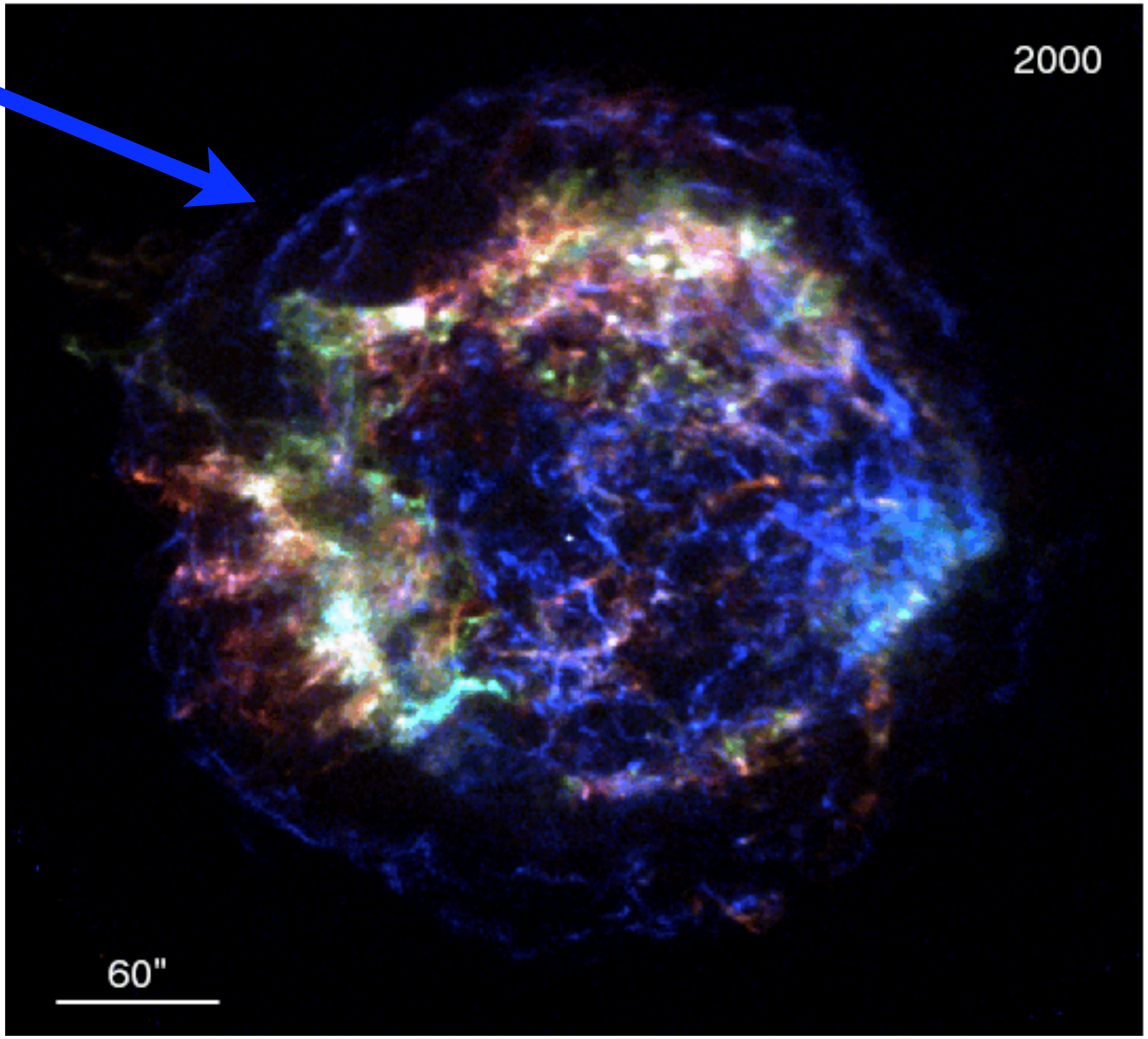
forward shock acts as a probe of the CSM structure and composition



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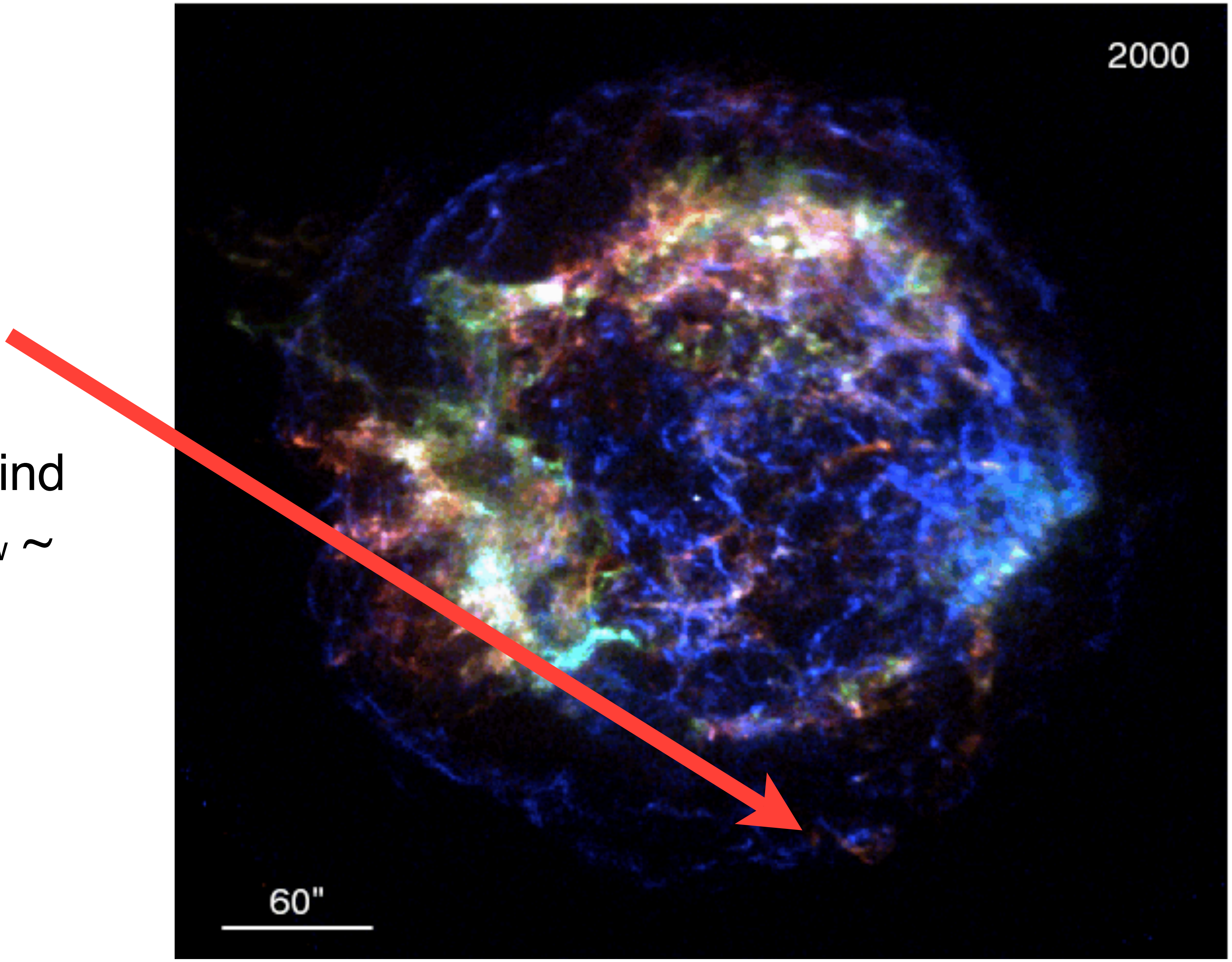
ANATOMY OF A SUPERNOVA REMNANT

Forward Shock

Shocked CSM

CSM consists of a $\rho \propto r^{-2}$ wind with dense clumps with $u_w \sim 20$ km s^{-1}



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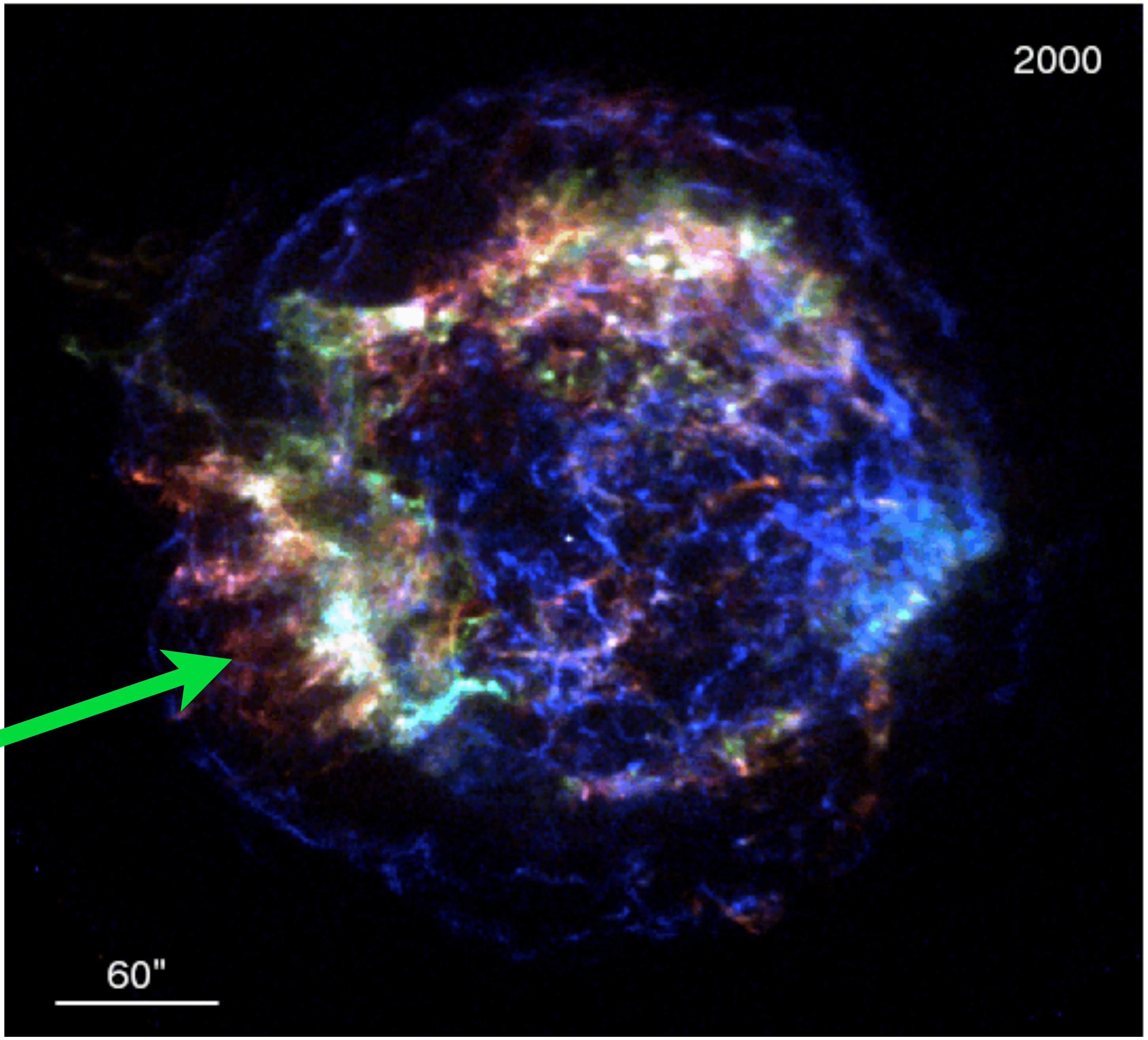
ANATOMY OF A SUPERNOVA REMNANT

Forward Shock

Shocked CSM

Shocked Ejecta

metal rich ejecta shows elevated abundances of explosive nucleosynthesis and sometimes evidence for macroscopic mixing between mass layers



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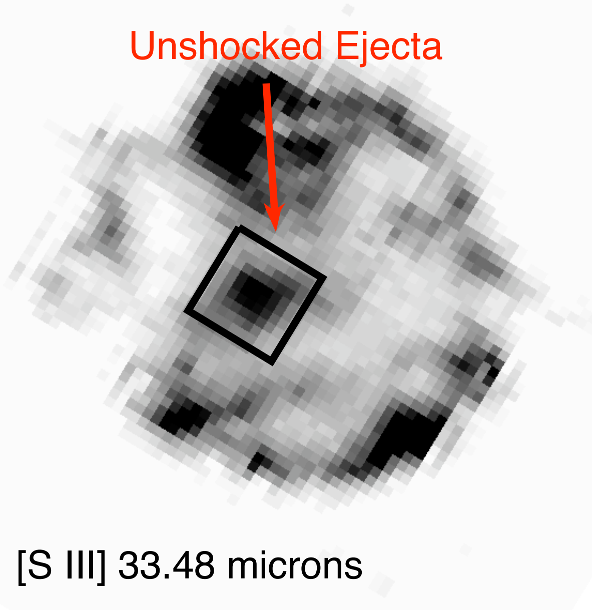
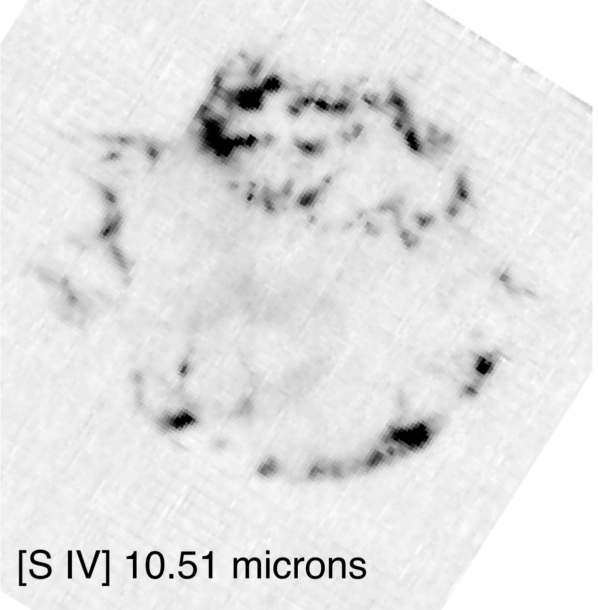
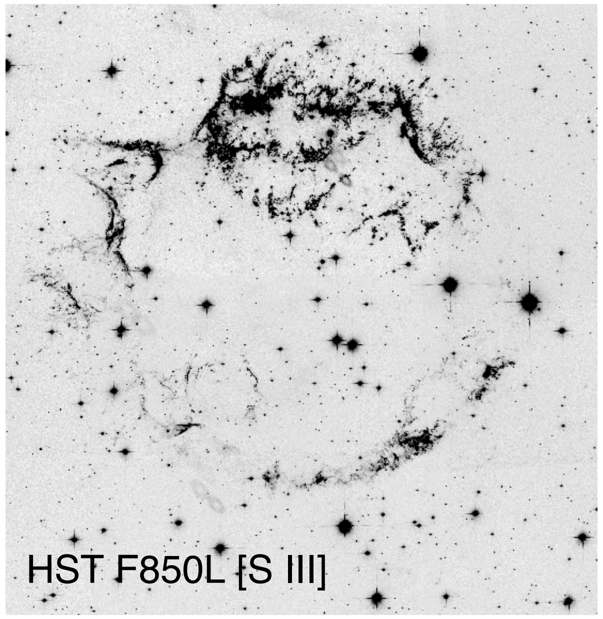
ANATOMY OF A SUPERNOVA REMNANT



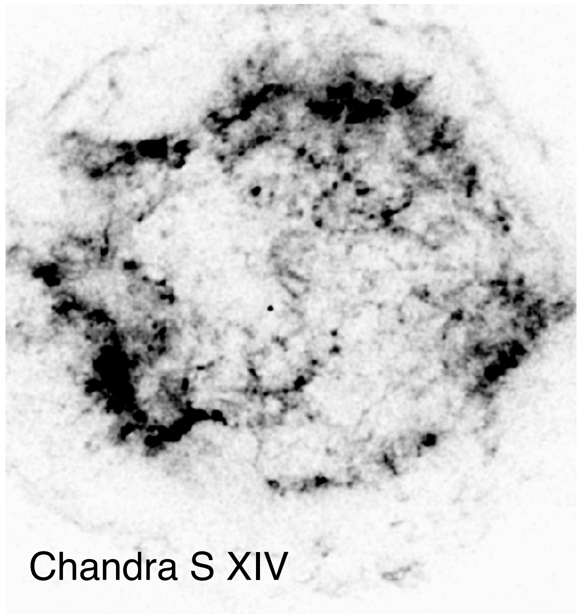
[S III] 33.48 microns



[S IV] 10.51 microns



HST F850L [S III]



Chandra S XIV

Differing wavebands reveal a different evolutionary state of the SNR - X-ray emission reveals the dynamically oldest ejecta

G292.0+1.8: A MASSIVE PROGENITOR IN A DENSE WIND

t_{SNR} ~ 1600 yr

D_{SNR} ~ 4 kpc

shows primarily shock heated CSM - consistent with age estimate

Composite image of G292.0+1.8. (CXC/S. Park)

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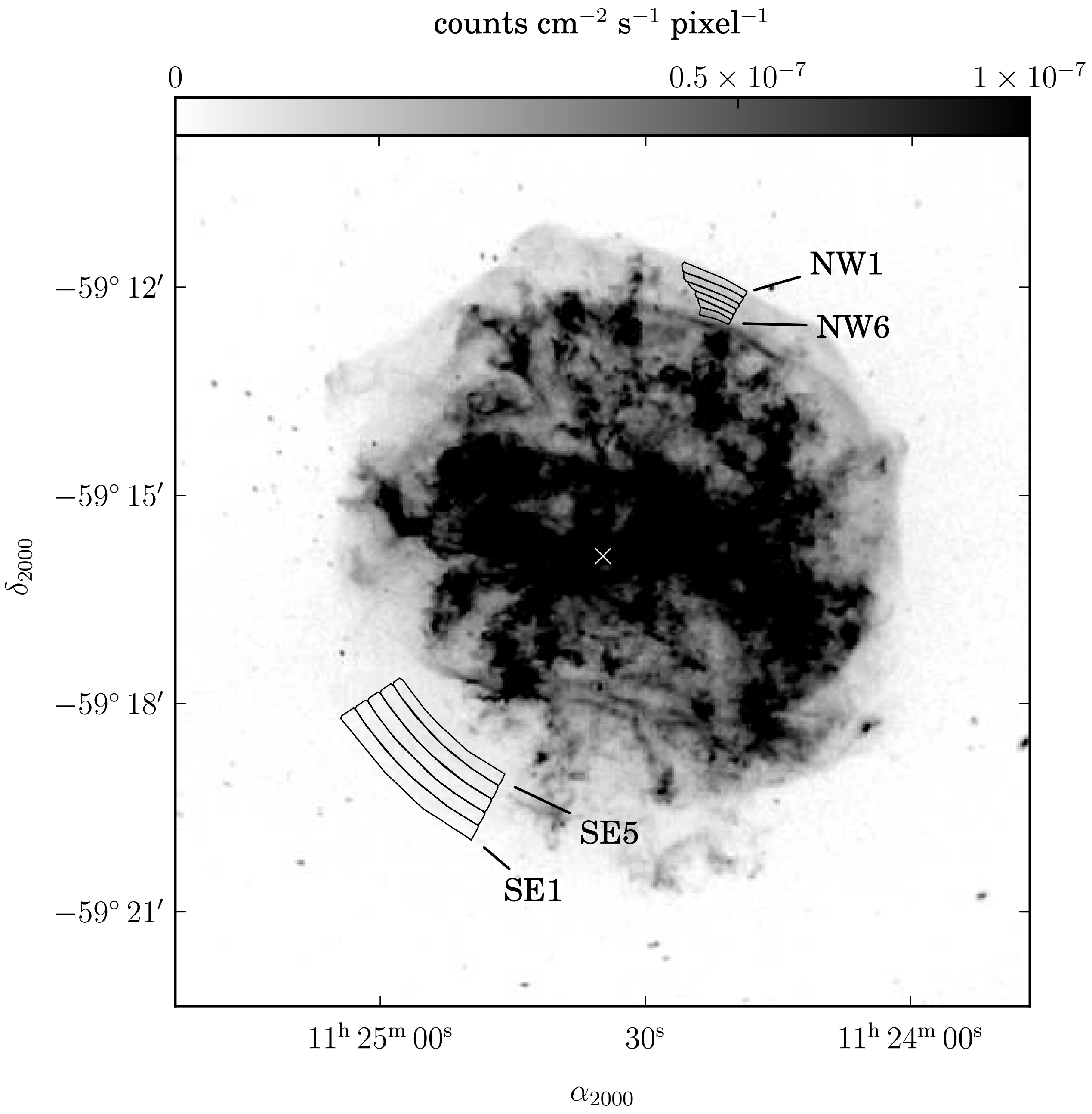

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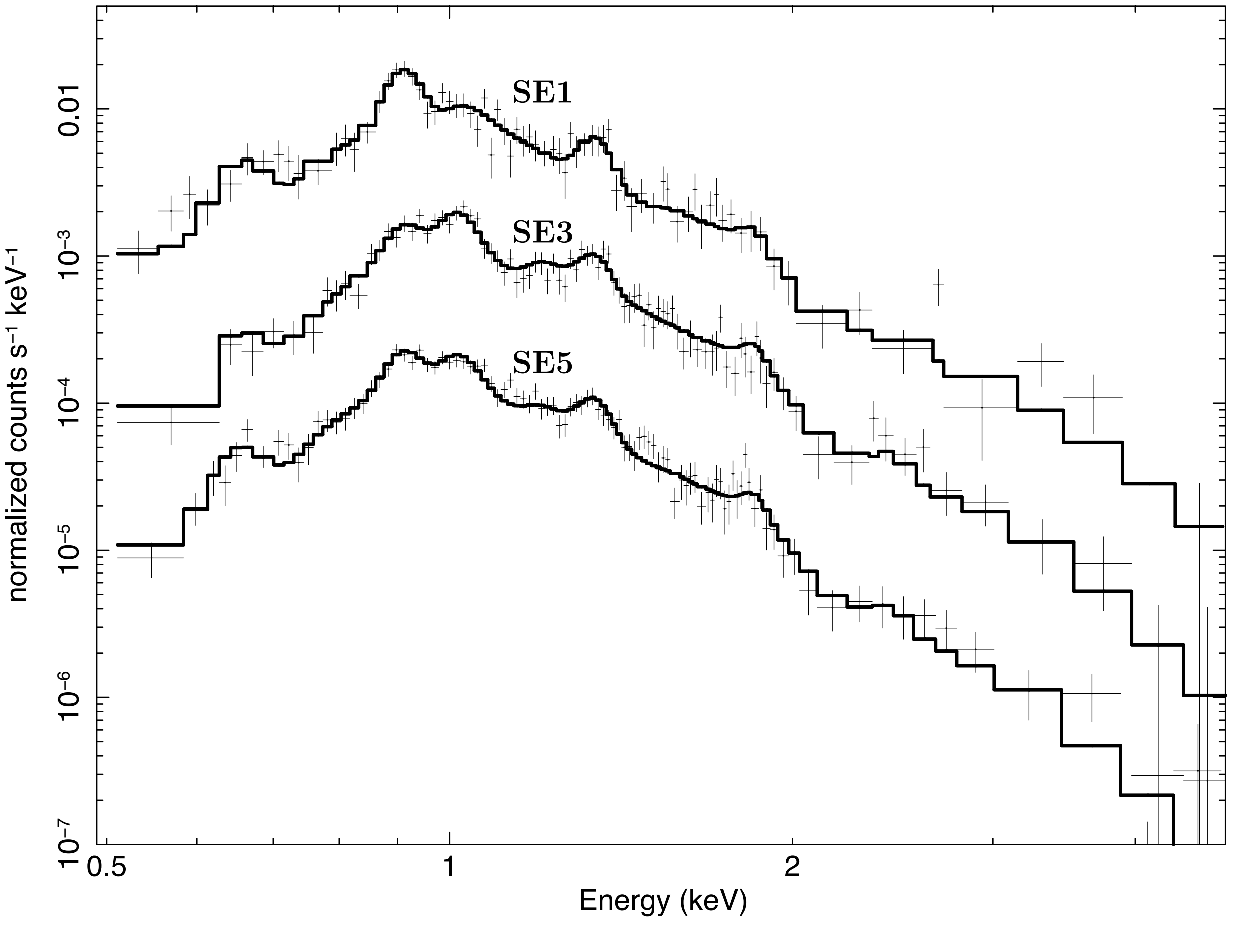

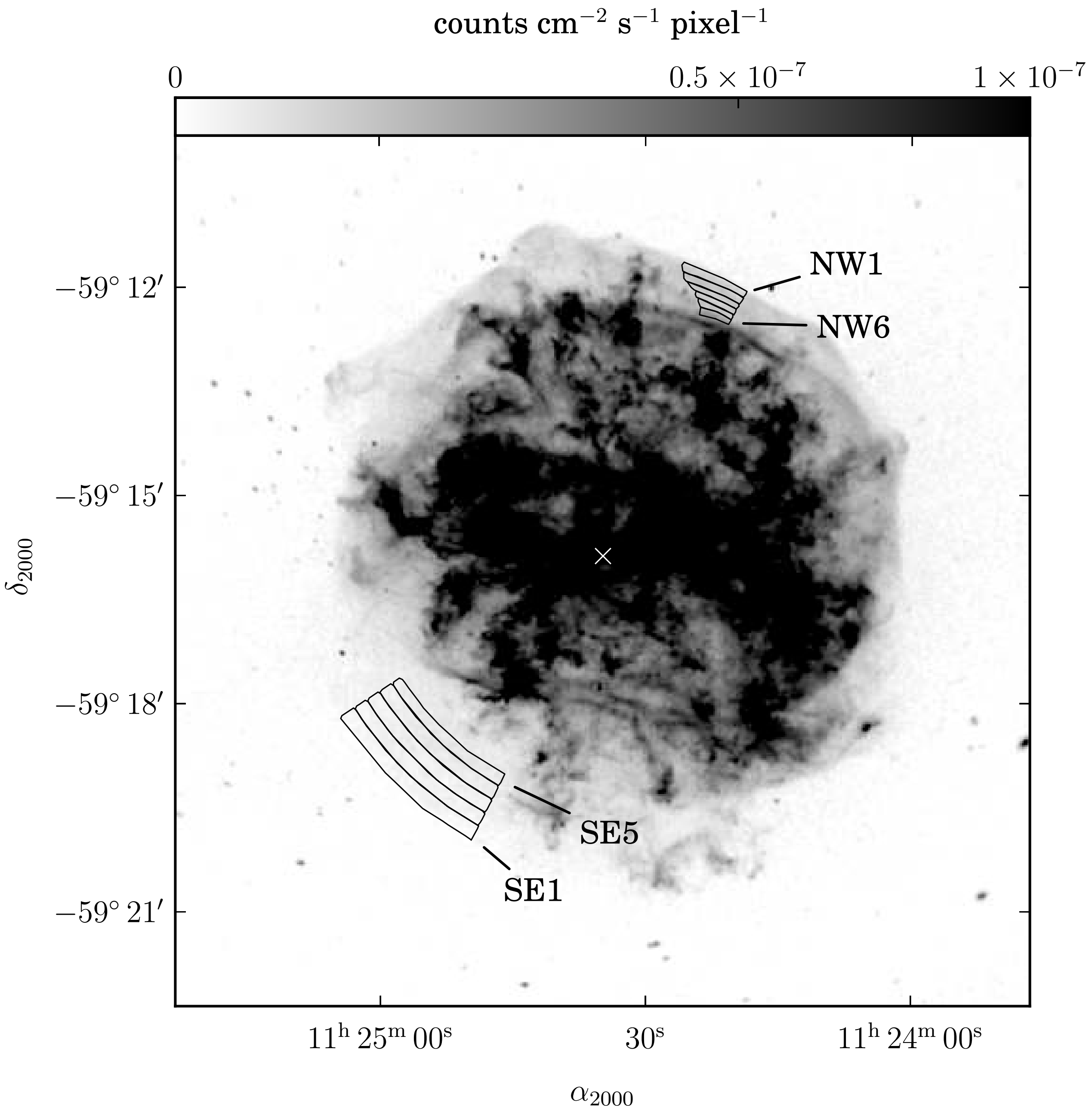

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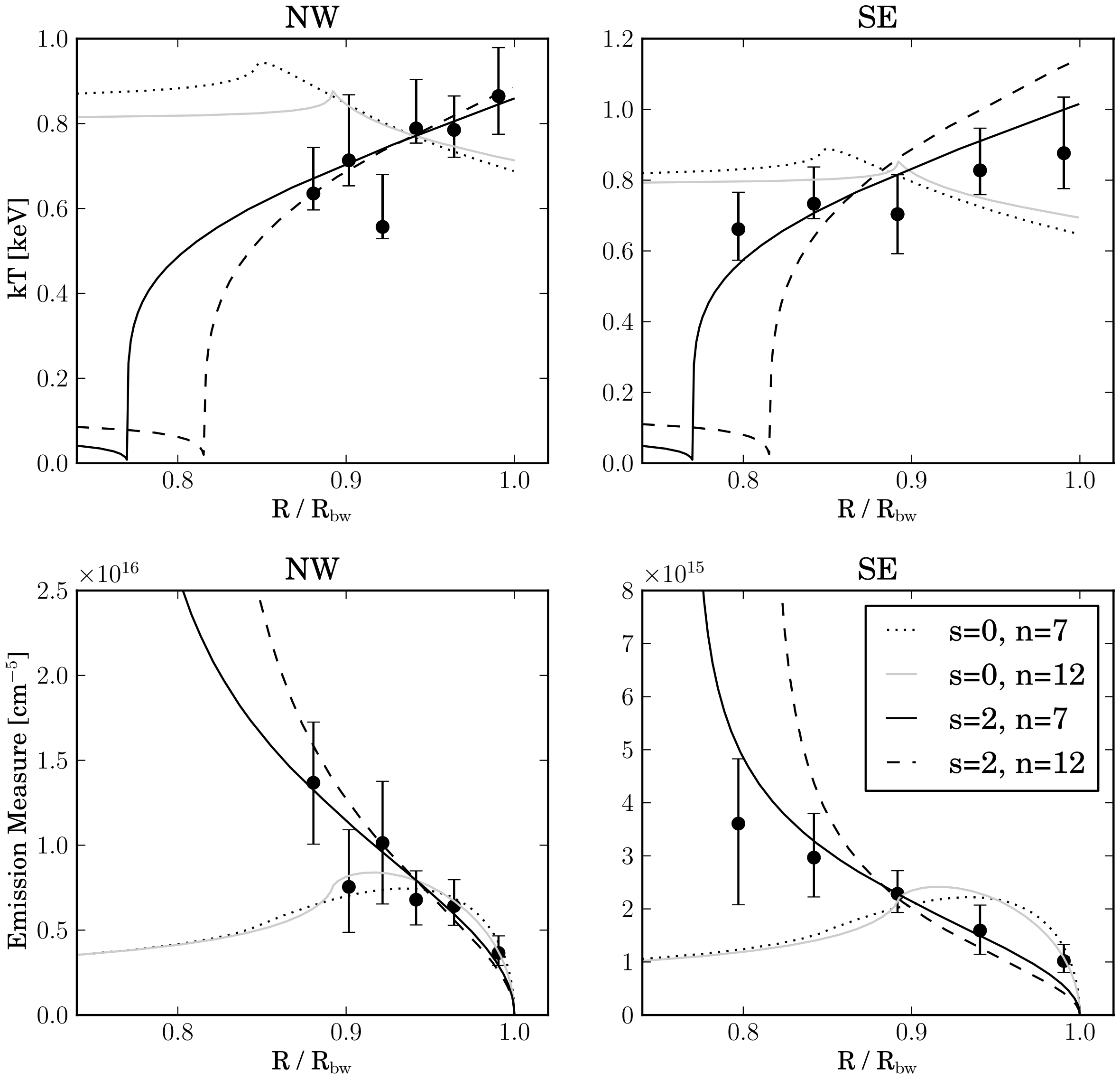

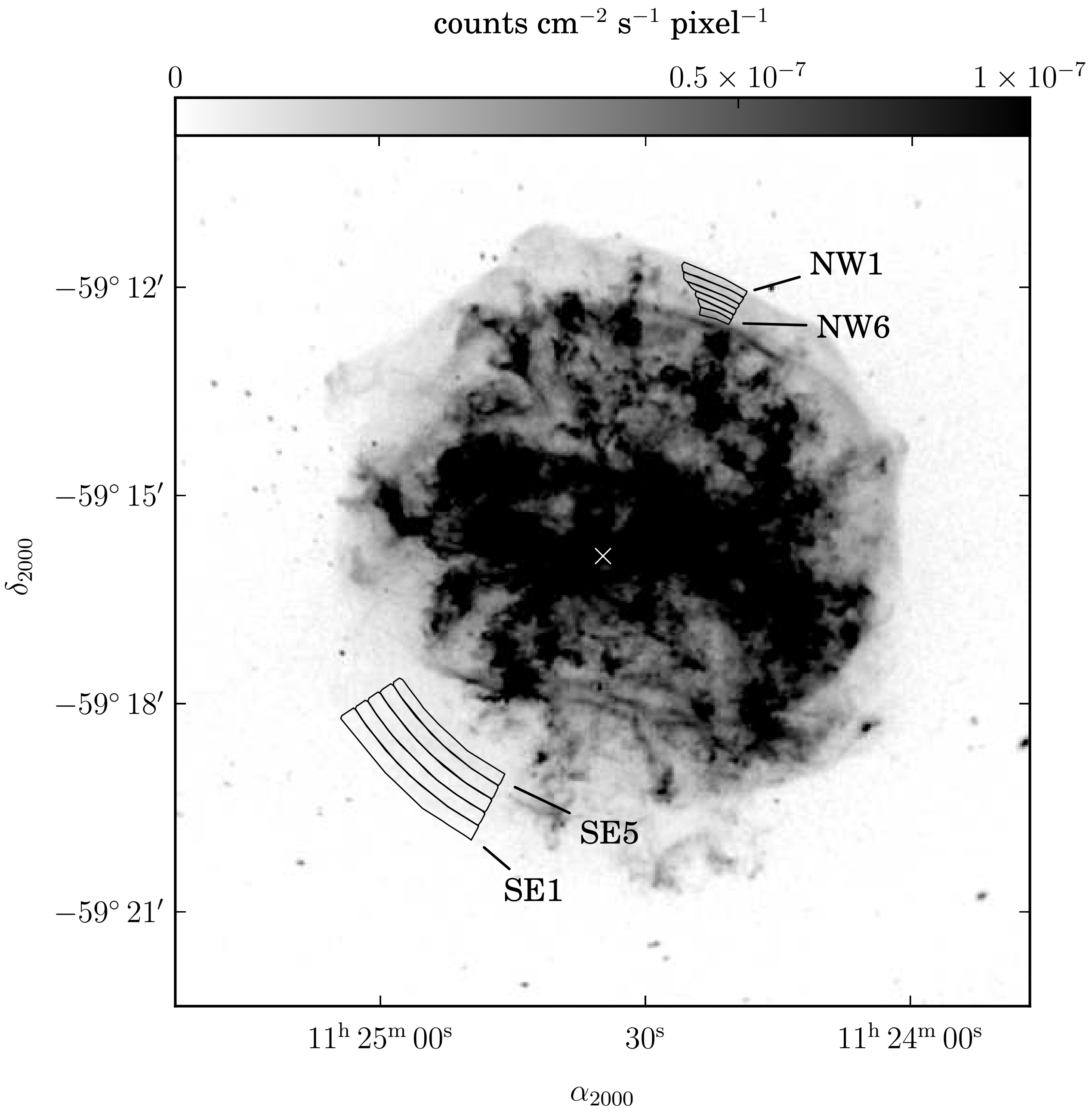

Authors estimate 15-40M$_{sun}$ of wind material swept up by shock

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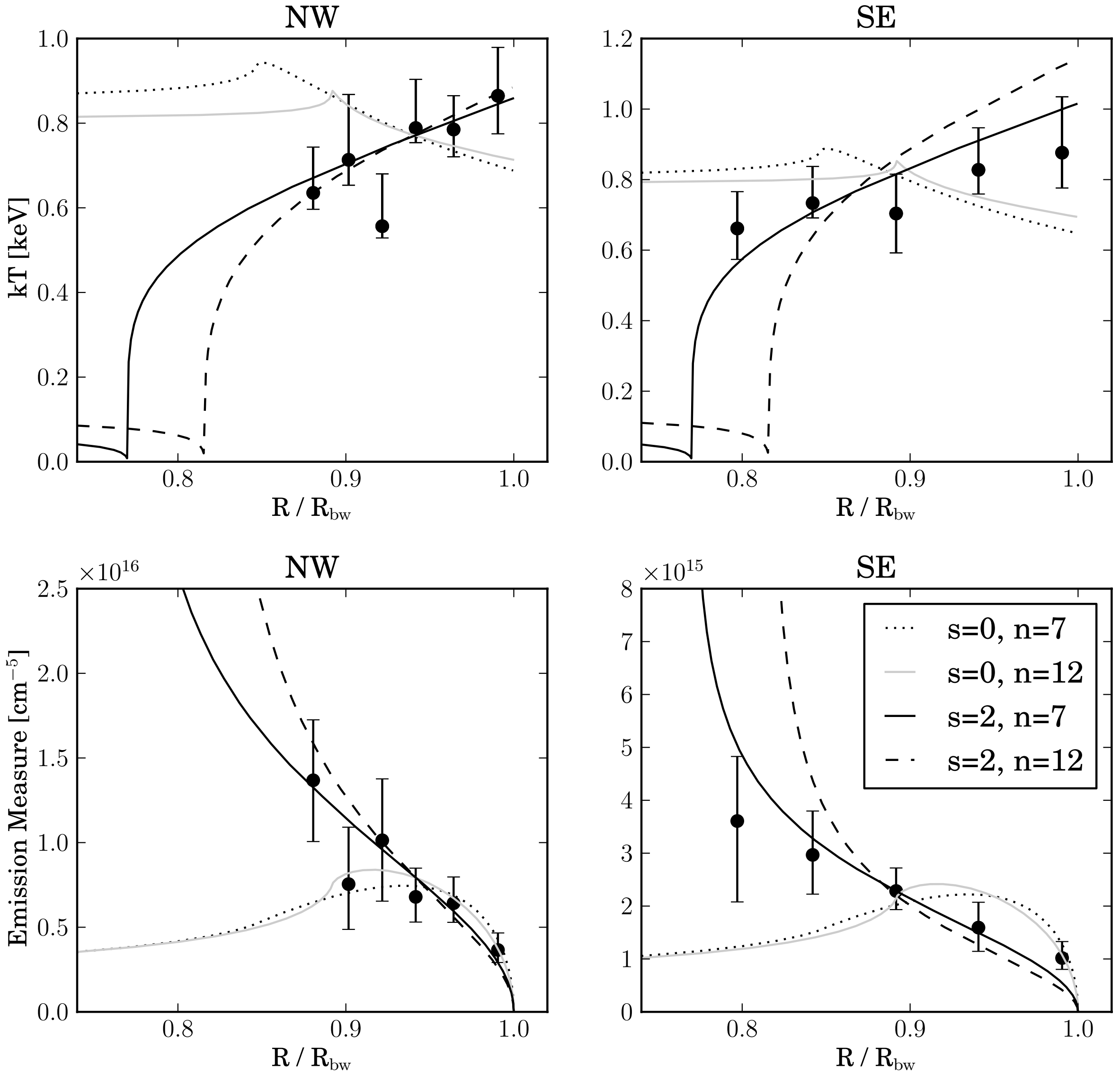

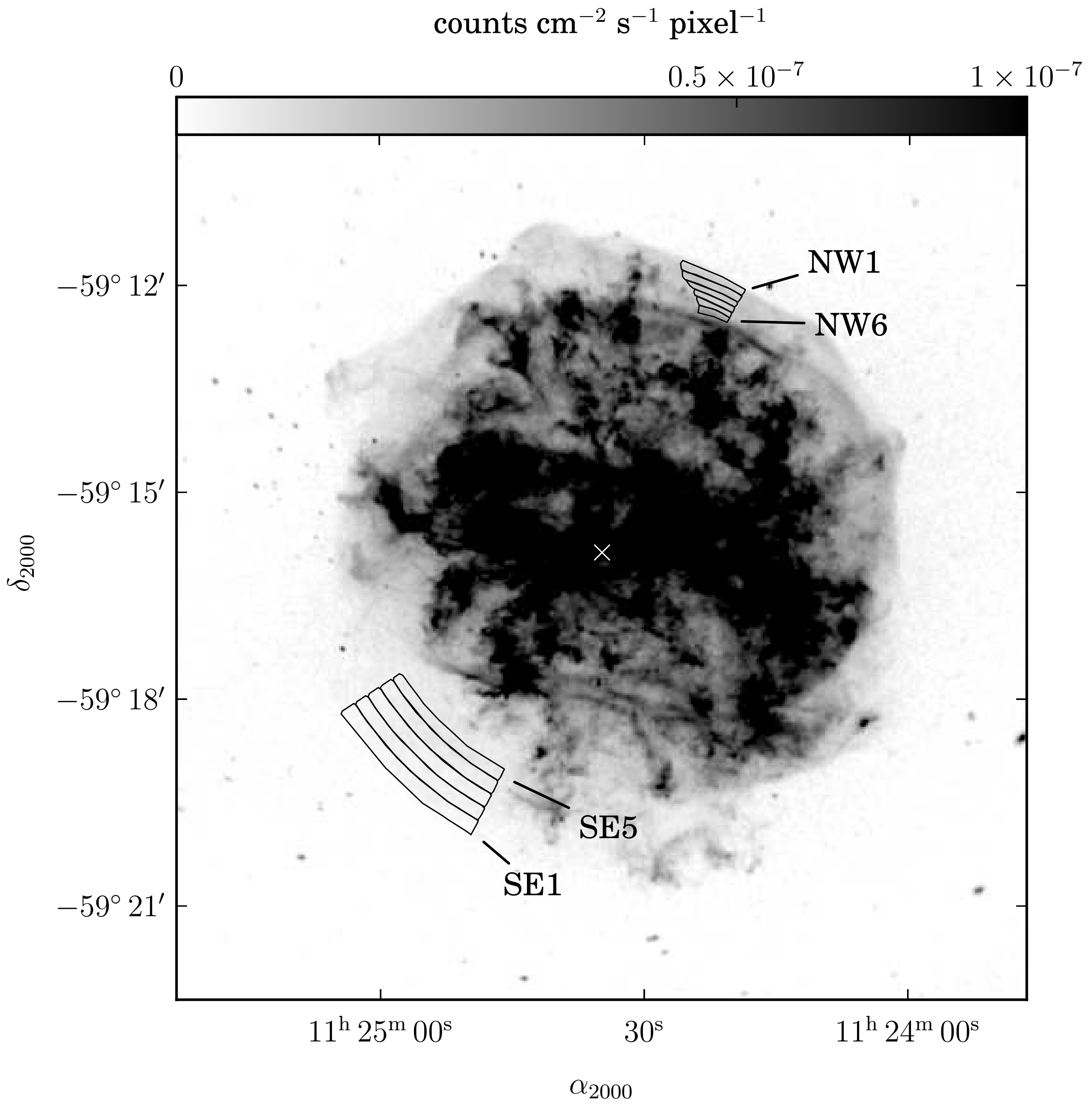

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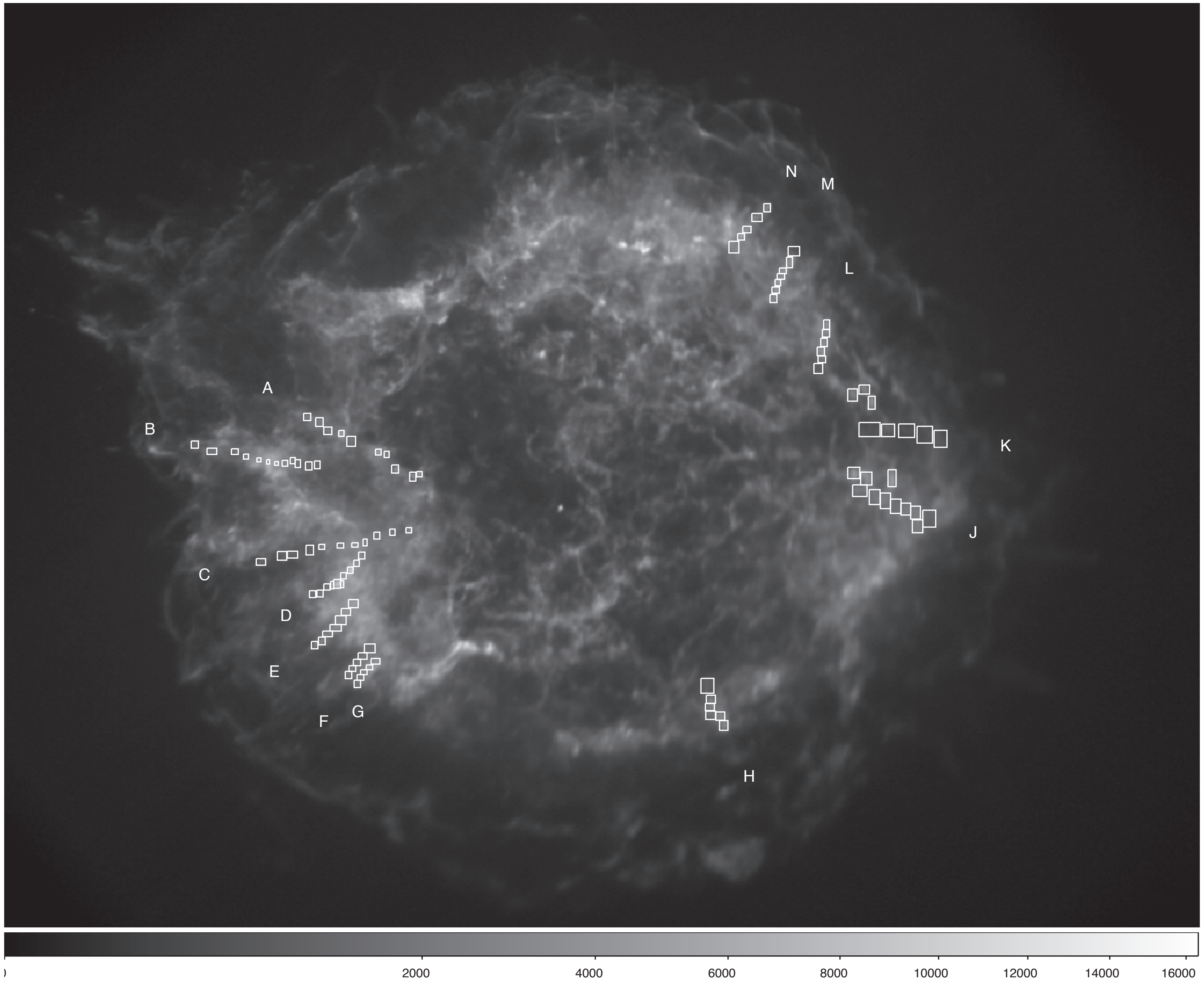
Authors estimate 15-40M_{sun} of wind material swept up by shock

Estimate MS progenitor mass of ~ 25M_{sun}

EJECTA AS A PROBE OF THE CSM AROUND CAS A

emission from shocked ejecta is impacted by structure of CSM

strength of reverse shock determines how much energy is deposited in ejecta...

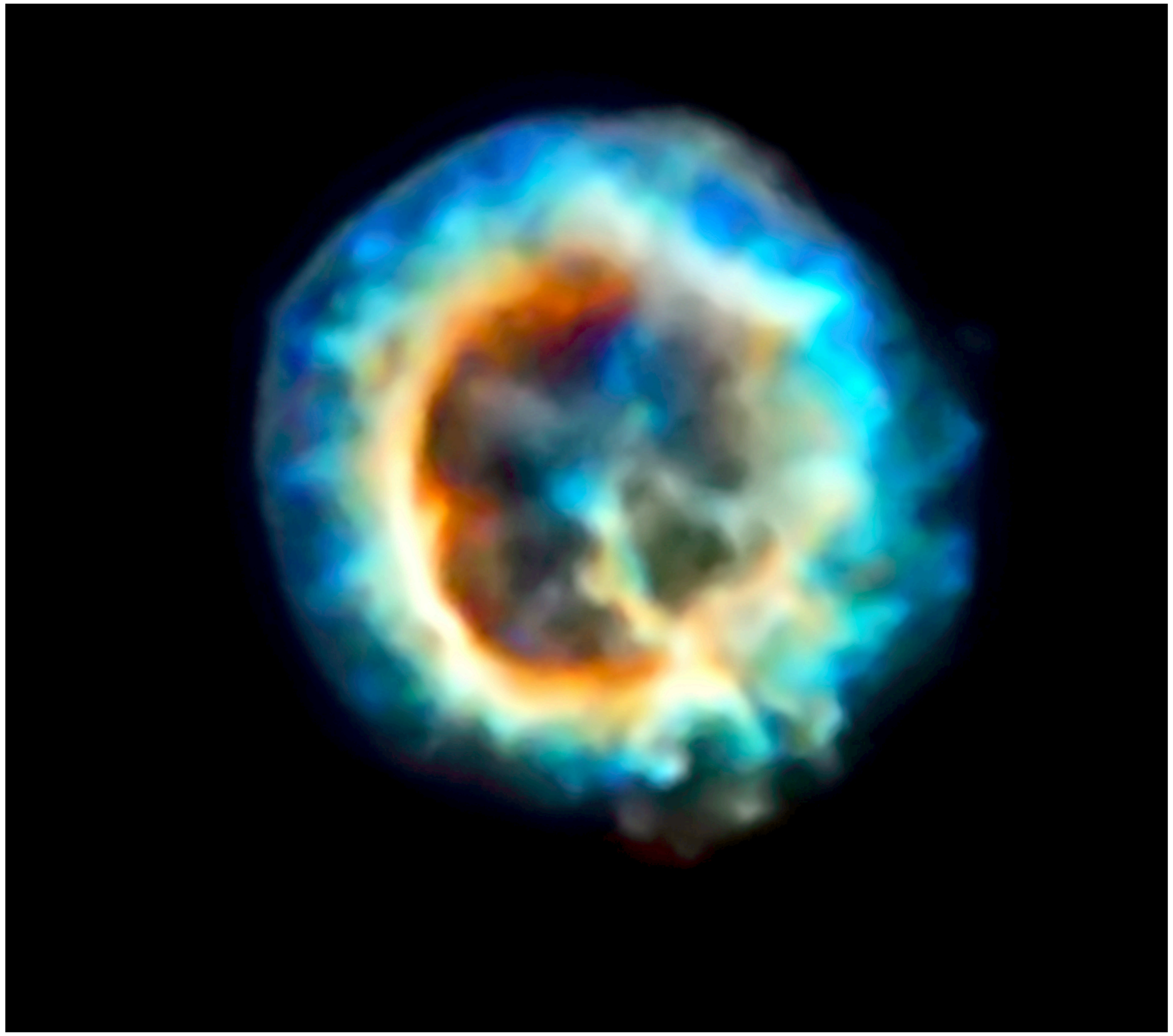


Broadband X-ray image of Cas A (Hwang & Laming 2009)

EJECTA AS A PROBE OF THE CSM AROUND CAS A

emission from shocked ejecta is impacted by structure of CSM

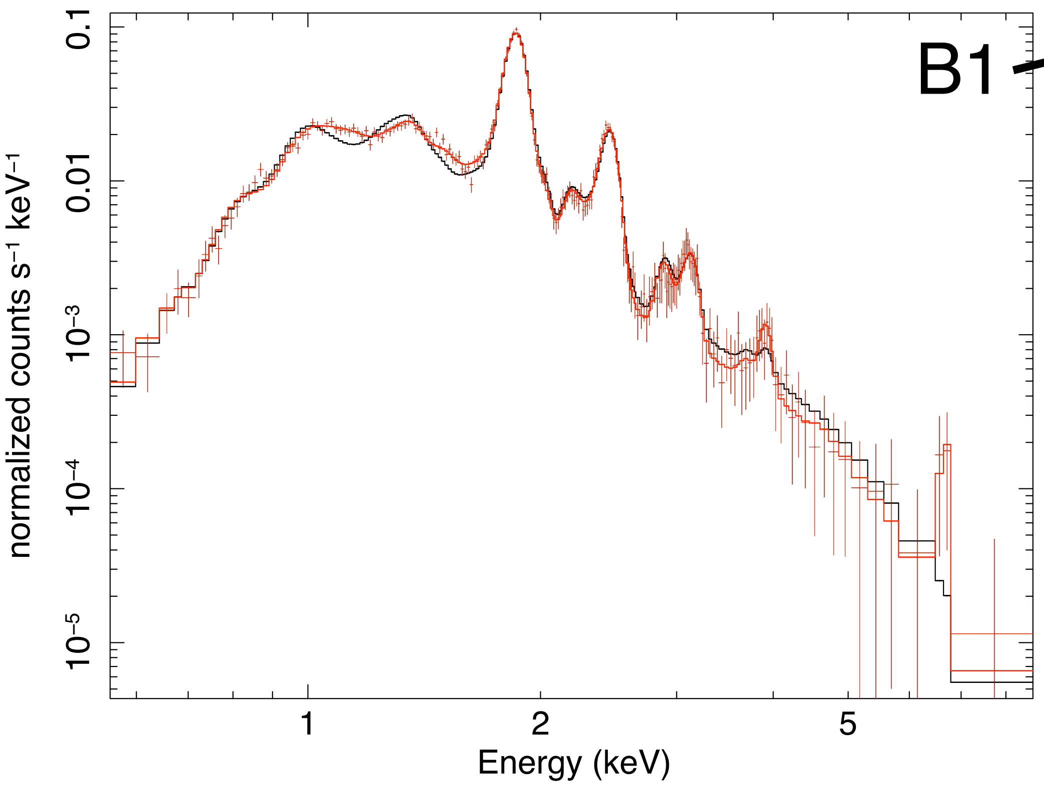
... a low density CSM produces a weak reverse shock that will not penetrate into the deeper layers of ejecta



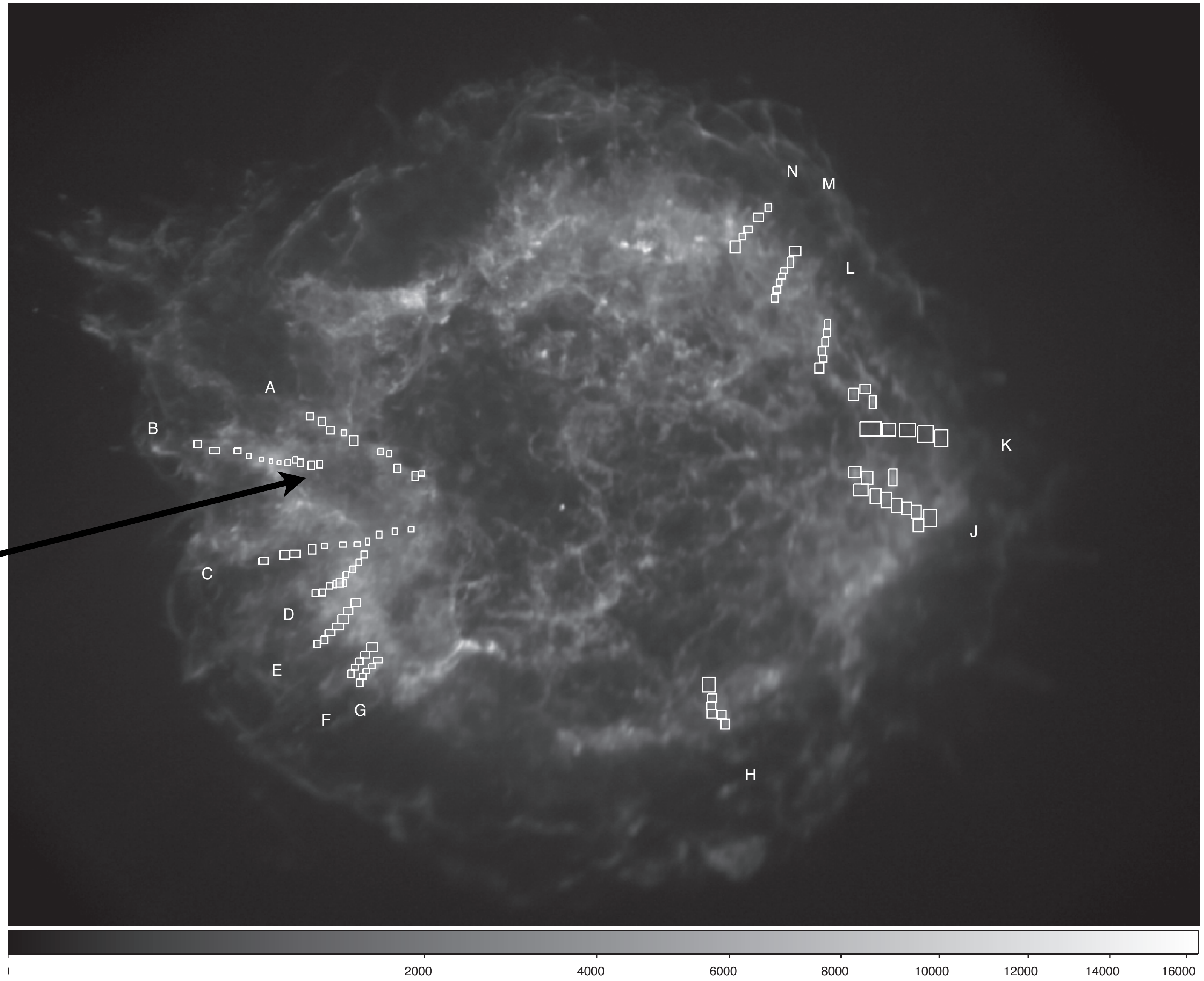
1100 yr old SNR 1E0102.1-7219 shows emission from O, Ne, and Mg only (courtesy CXC)

EJECTA AS A PROBE OF THE CSM AROUND CAS A

ionization balance of silicon rich regions of ejecta suggests a slow wind



Spectrum from Hwang & Laming (2009)



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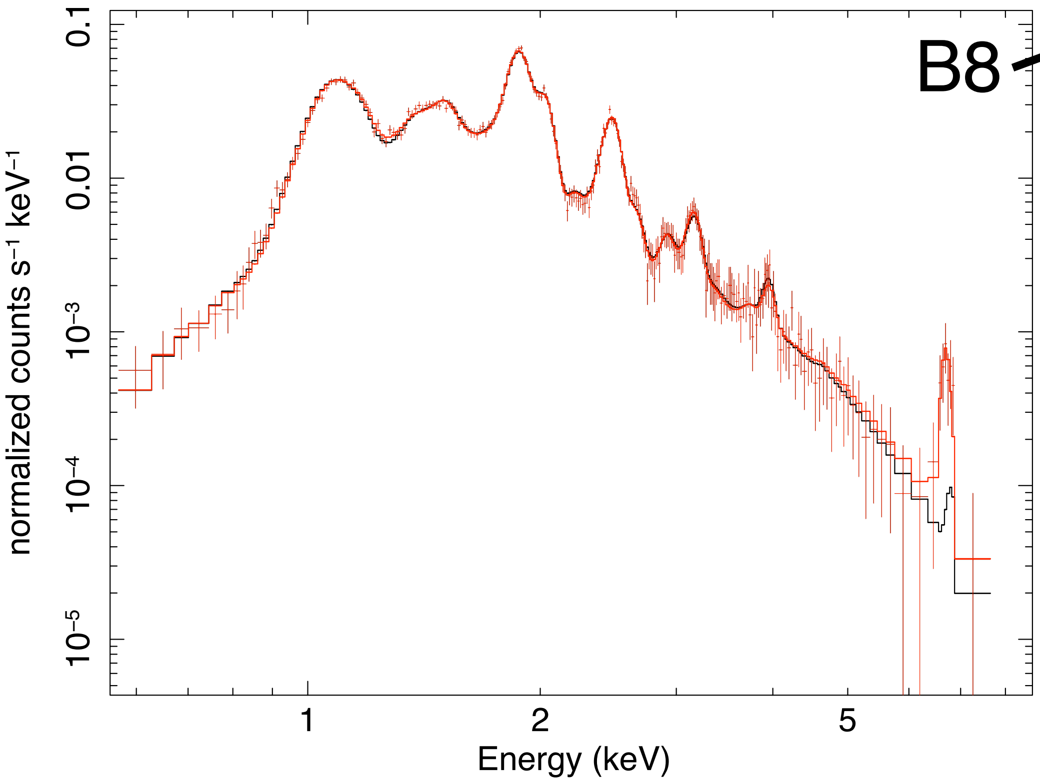

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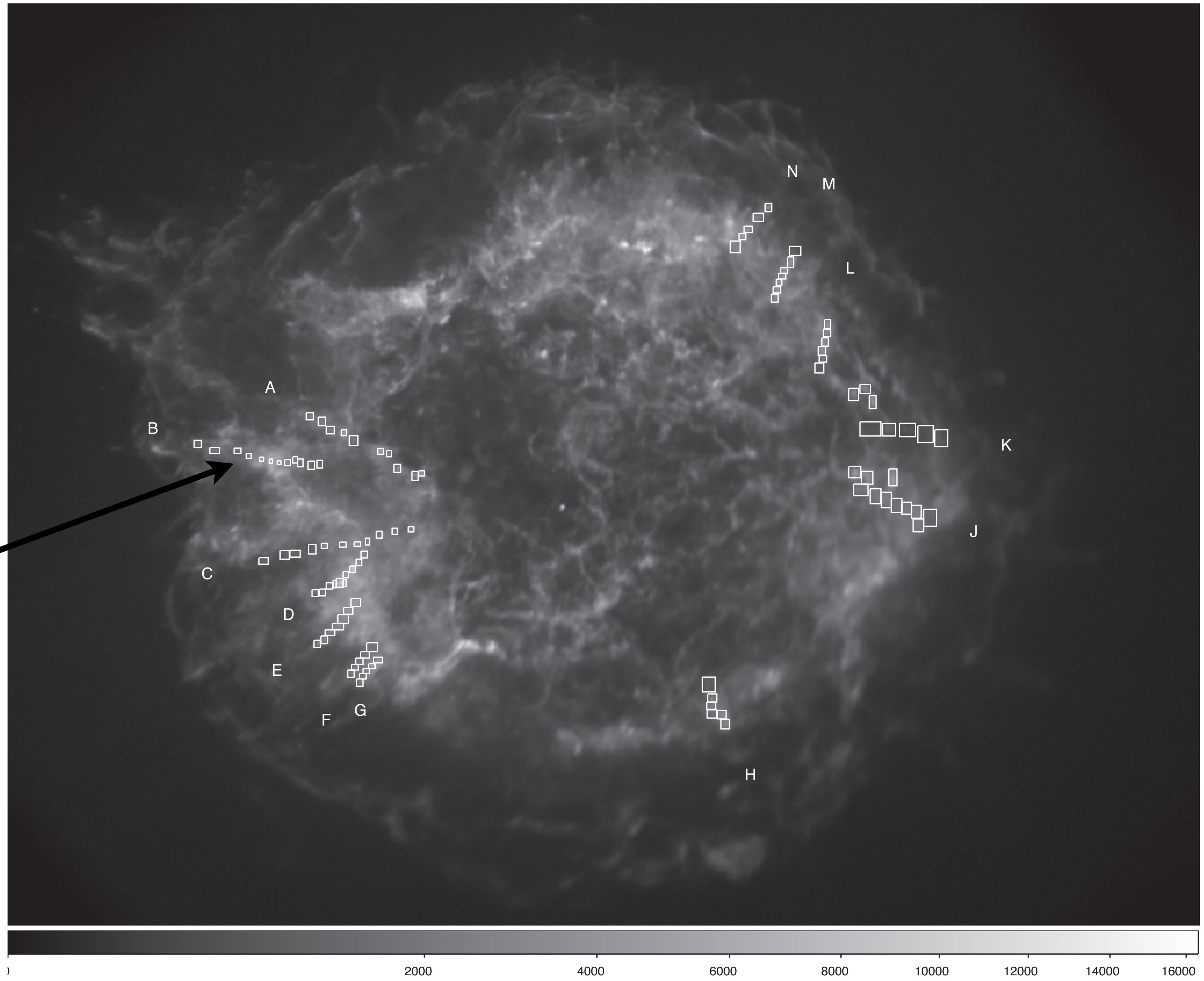

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EJECTA AS A PROBE OF THE CSM AROUND CAS A

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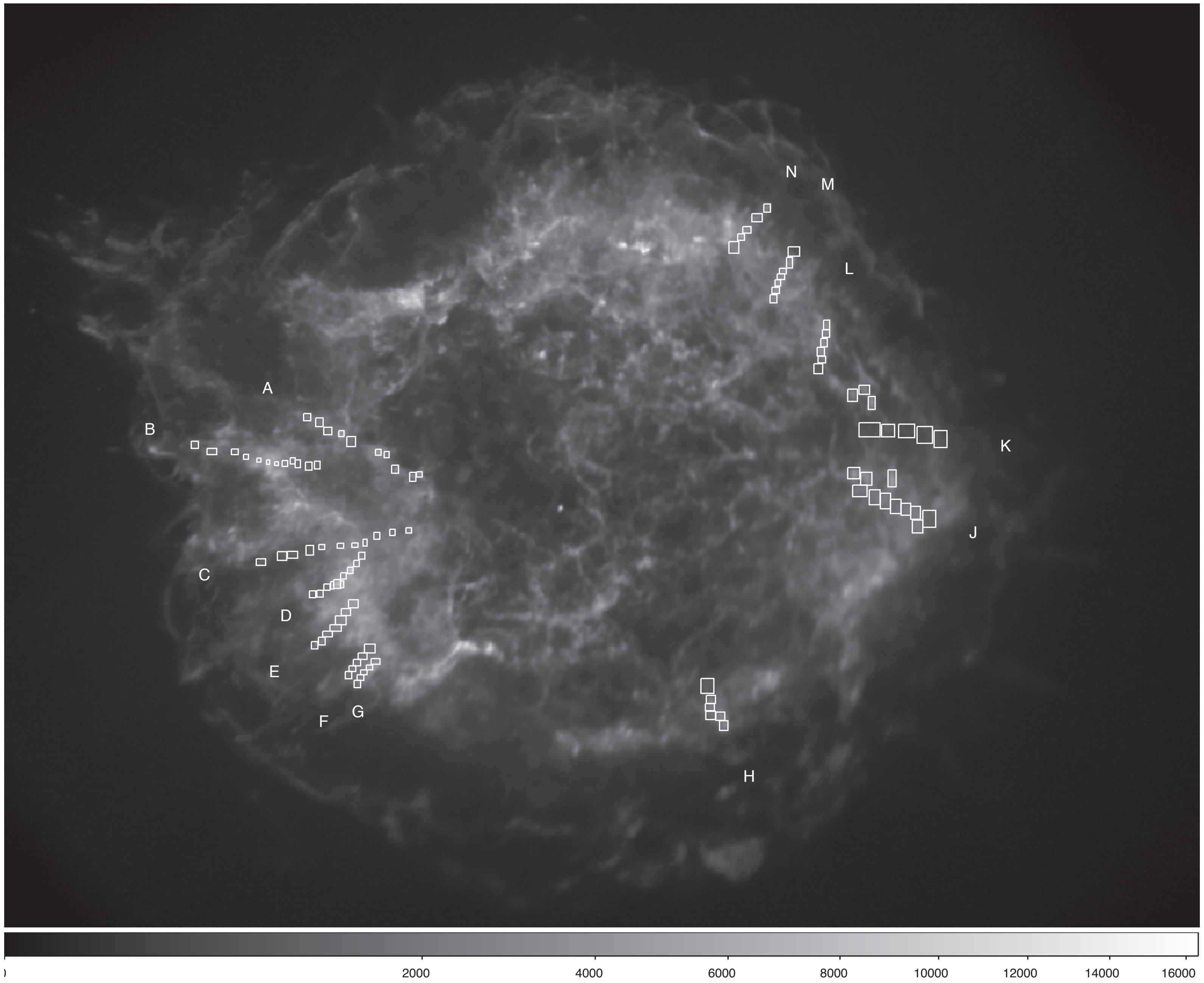
ratio of He-like to H-like ions indicates a 0.2 pc cavity around Cas A prior to the explosion



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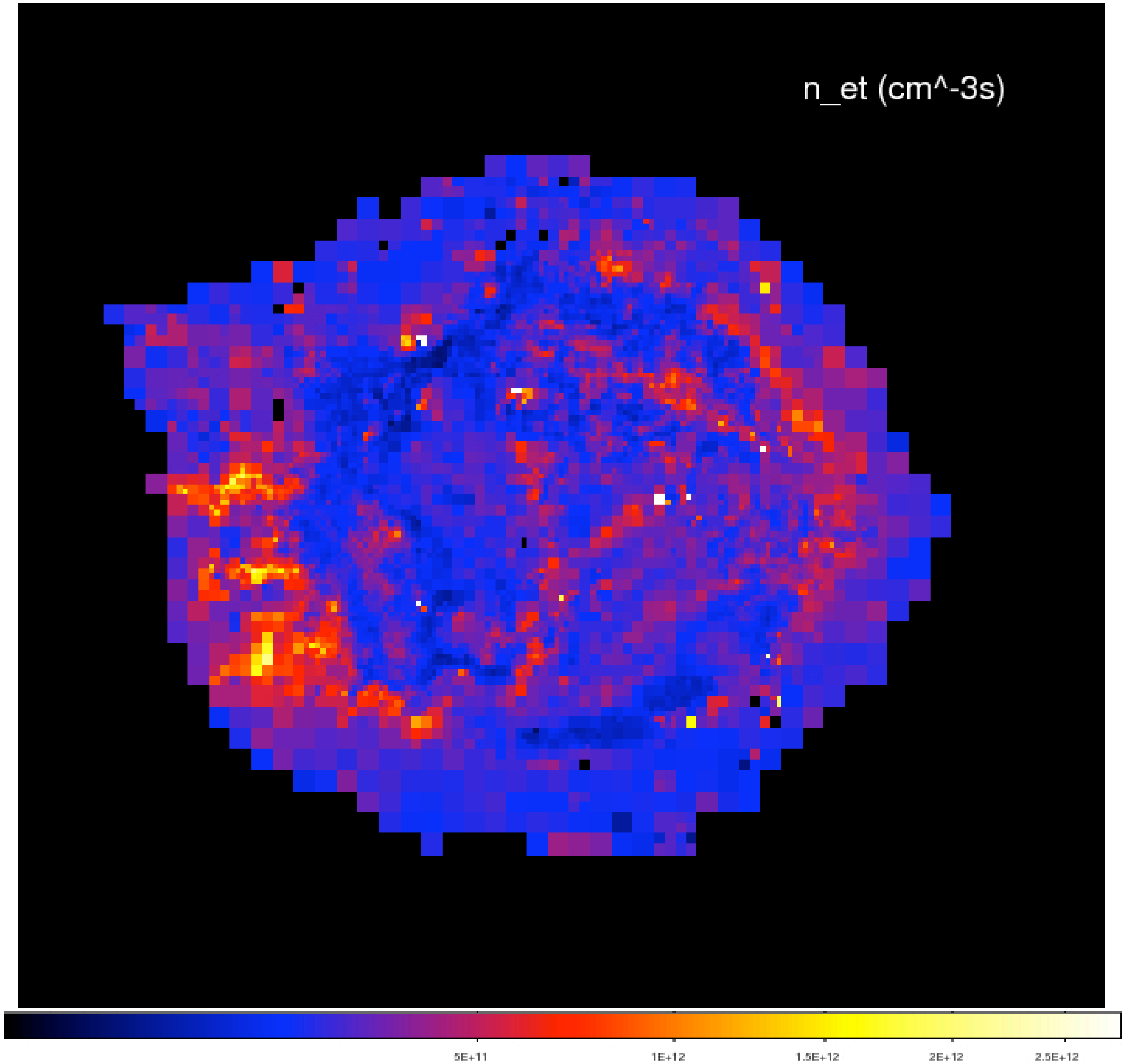
X-RAY EMISSION AS A PROBE OF EJECTA COMPOSITION



Ionization parameter vs position in Cas A (Hwang & Laming 2012)

fitted ionization age (n_et) indicates that most X-ray bright regions were shocked ~ 20-200 yr ago

Region with highest ionization age corresponds to Fe-rich region - supports theory that Fe-rich plumes overturned during explosion

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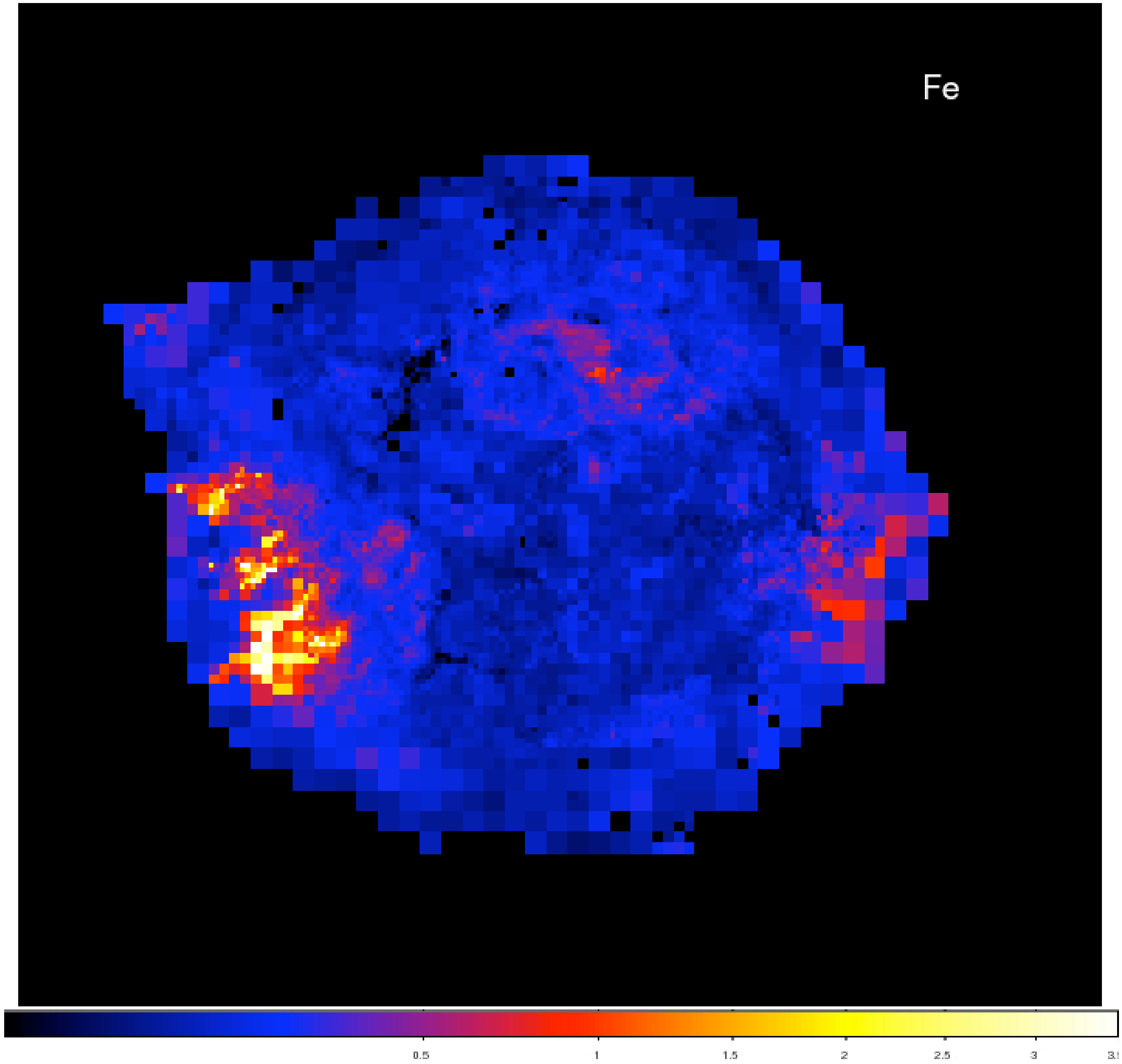

Iron abundance relative to solar in Cas A (Hwang & Laming 2012)

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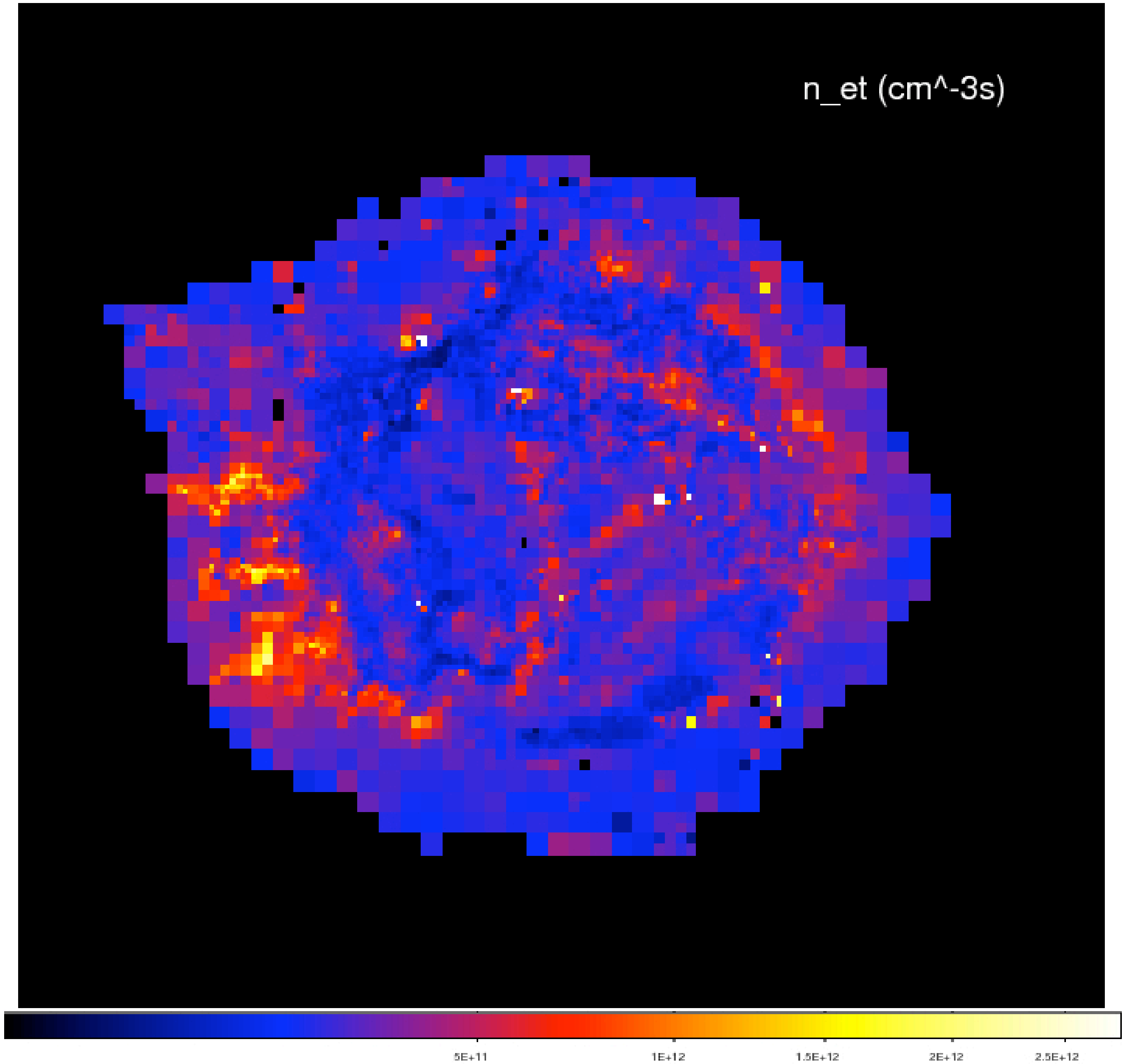

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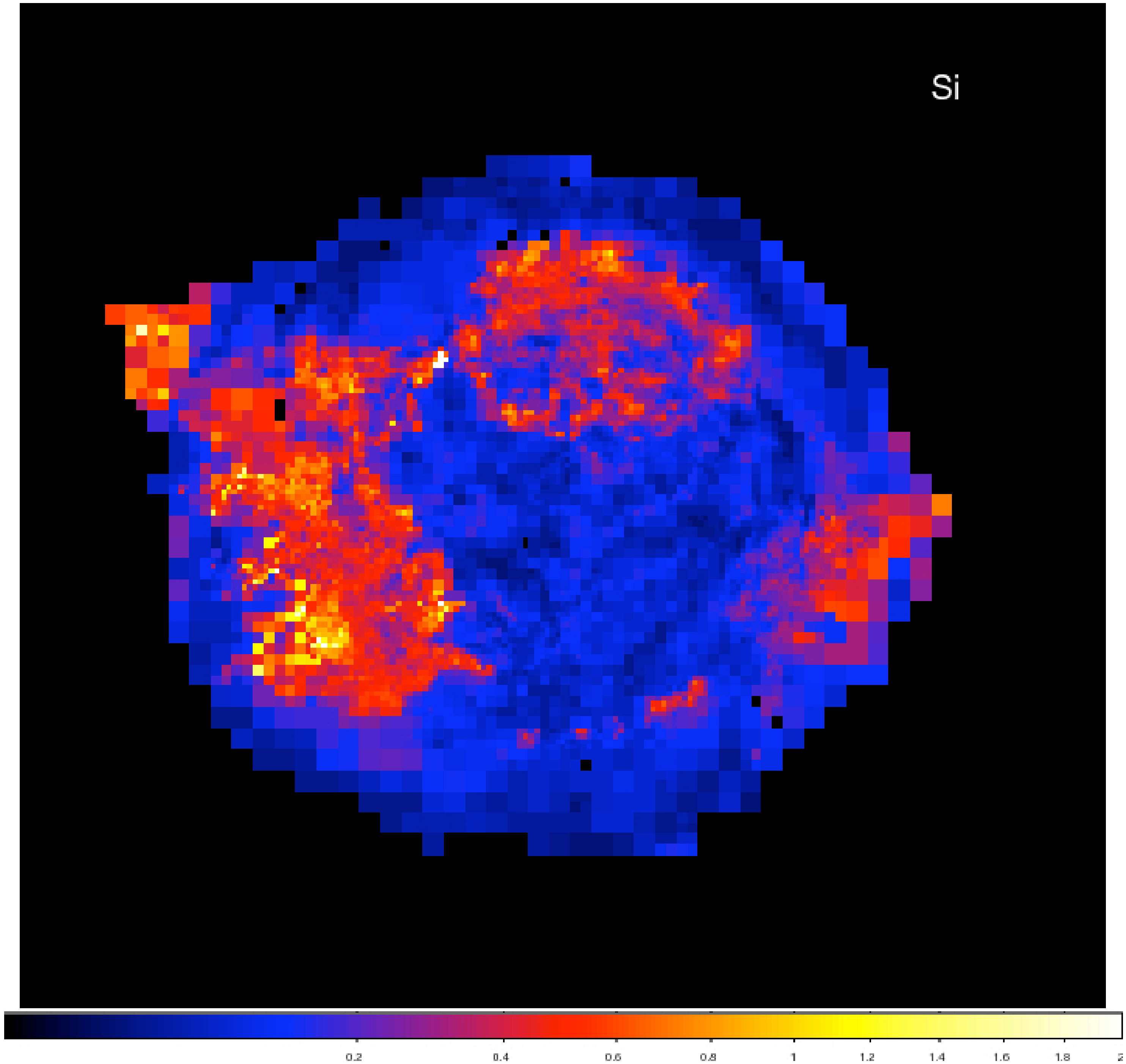

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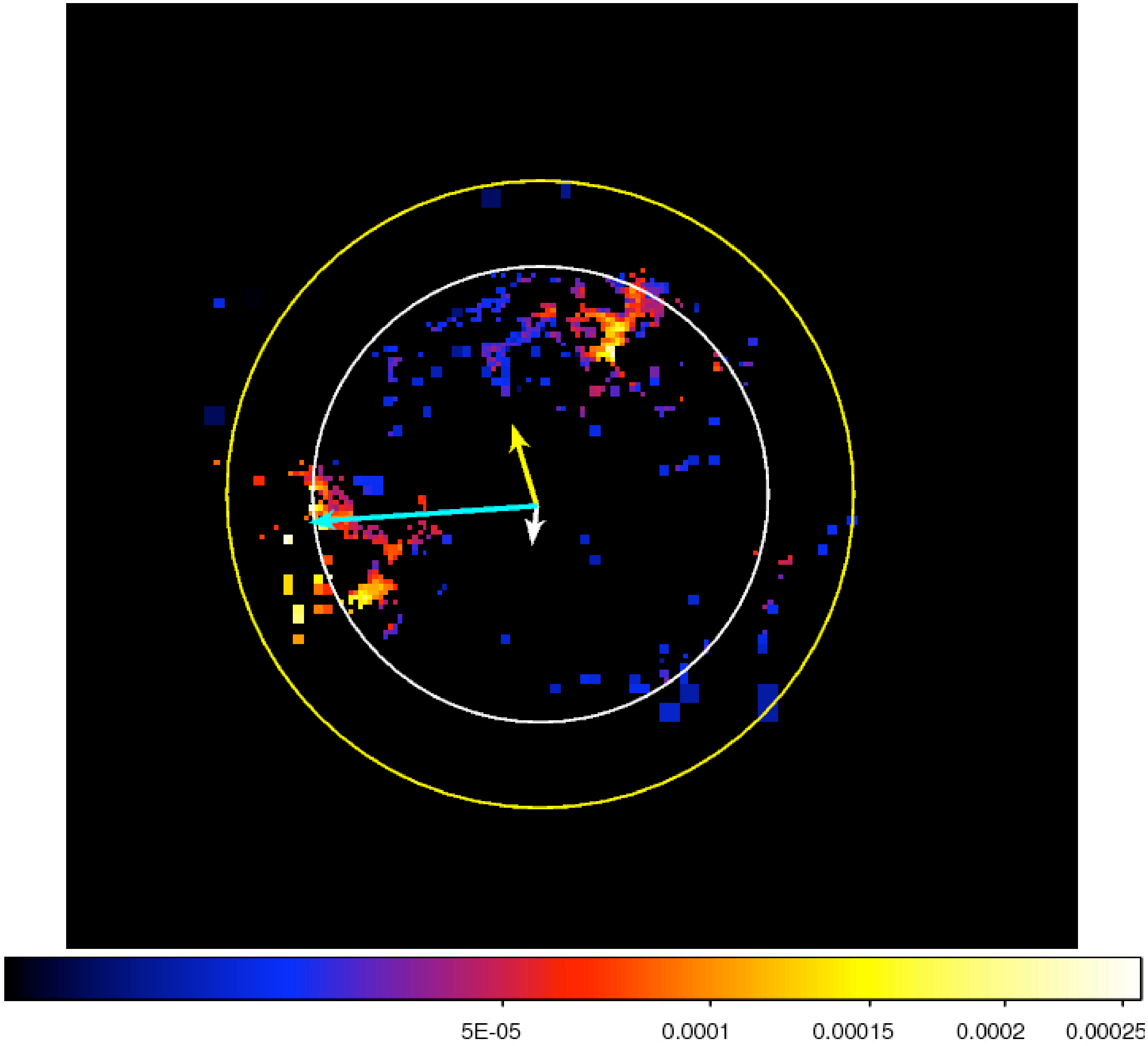


Distribution of “pure” Fe ejecta in Cas A (Hwang & Laming 2012)

Find $M_{Fe} = 0.09\text{-}0.13 M_{sun}$

ALL Fe produced in Cas A explosion has now been shocked

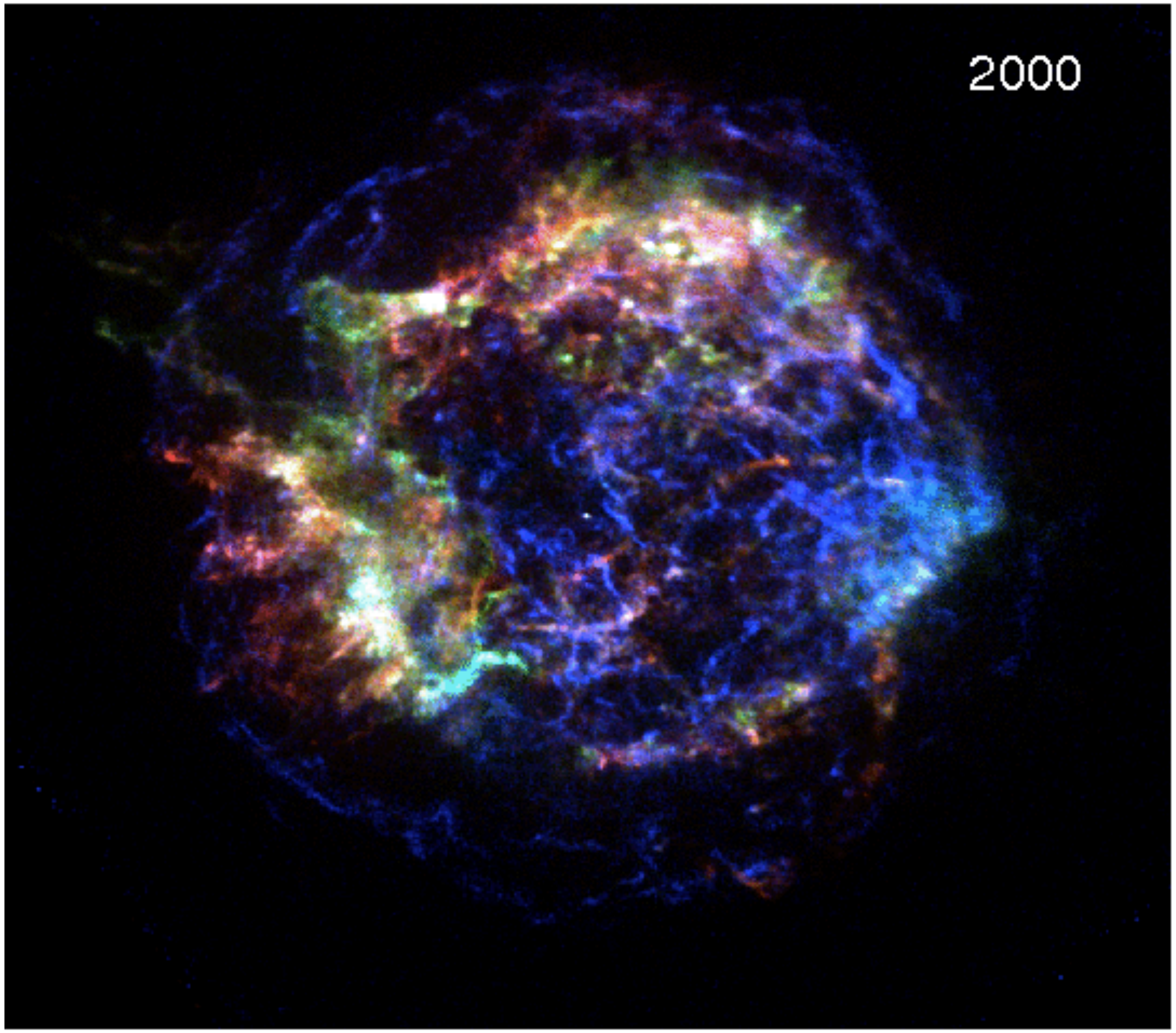
$$\begin{aligned} \mathrm{Fe}_{Si} &= 0.075 - 0.11 \ \mathrm{M}_\odot \\ \mathrm{Fe}_{\alpha} &= 0.023 - 0.03 \ \mathrm{M}_\odot \end{aligned}$$

Consistent with Cas A NS atmosphere being composed of carbon

TEMPORAL VARIATIONS

multiepoch observations reveal fading and brightening of thermal and nonthermal emission

rise time in X-ray emission from any particular feature is dependent upon the density of the emitting material - reveals anisotropy in expanding ejecta (Patnaude & Fesen 2007)



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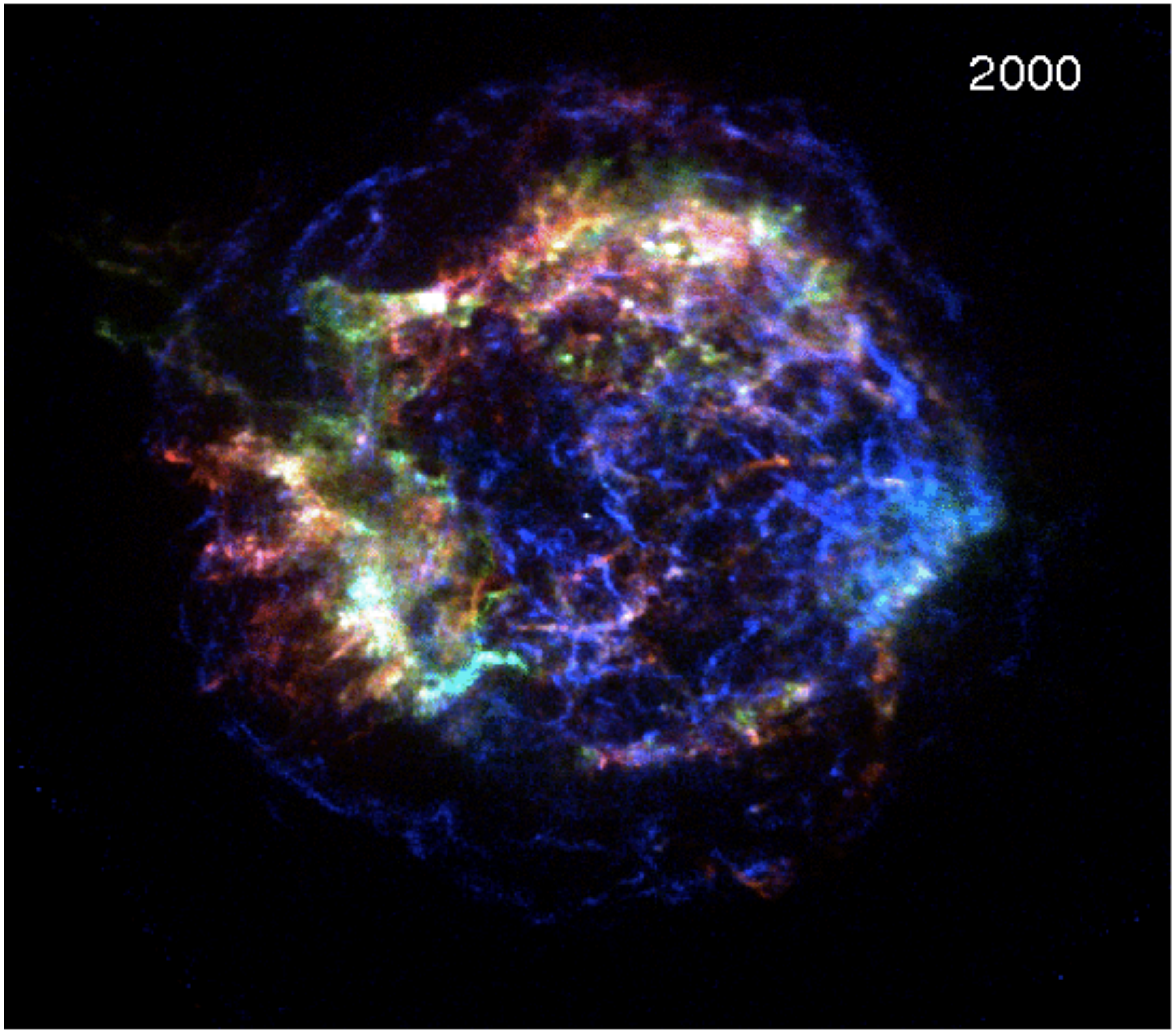
TEMPORAL VARIATIONS

multiepoch observations reveal fading and brightening of thermal and nonthermal emission

$\chi \sim 2\text{-}4$ between X-ray bright knots and diffuse X-ray component - “knots” are not really knots (ΔEM between knots and diffuse component = 4-16)



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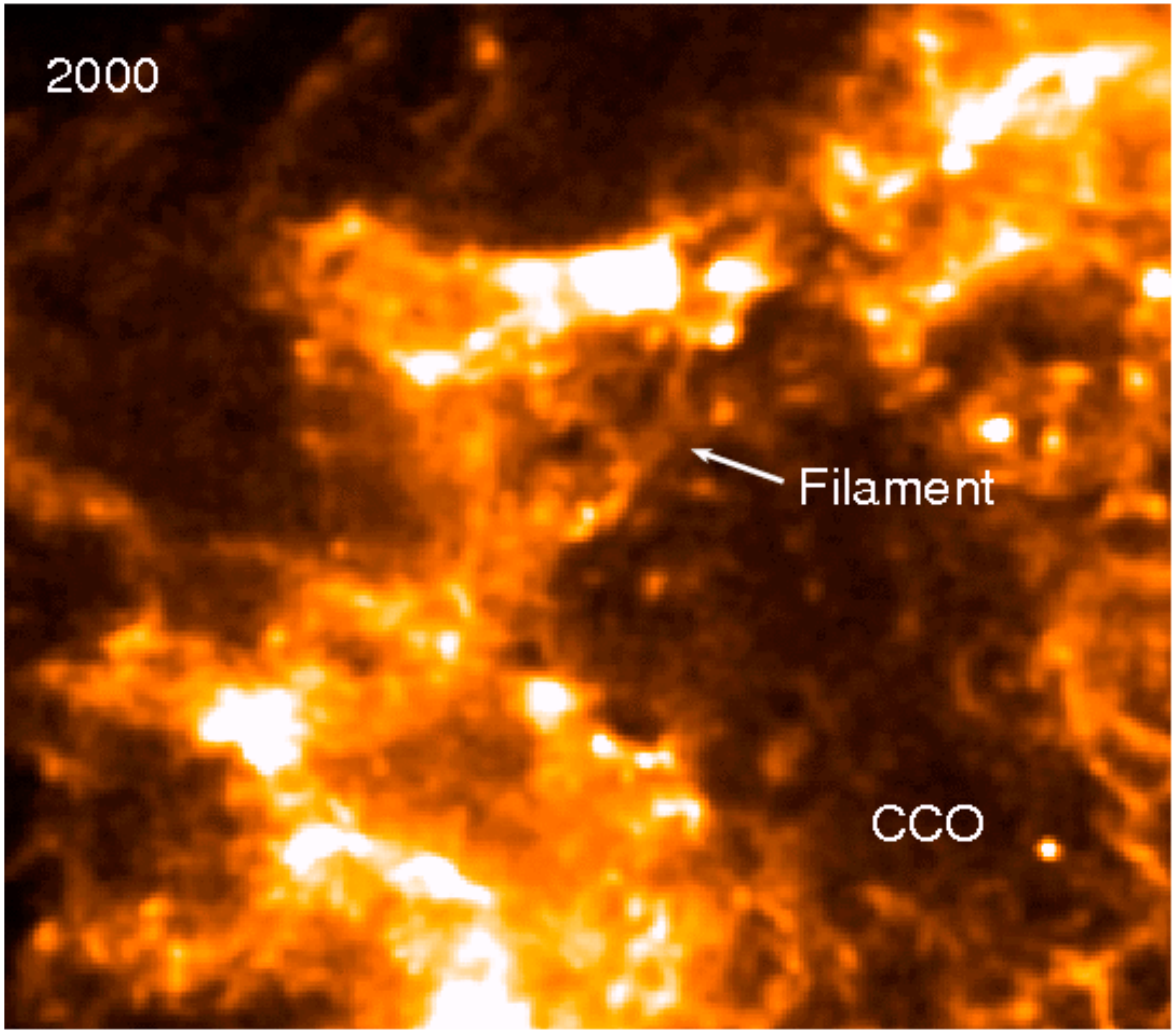
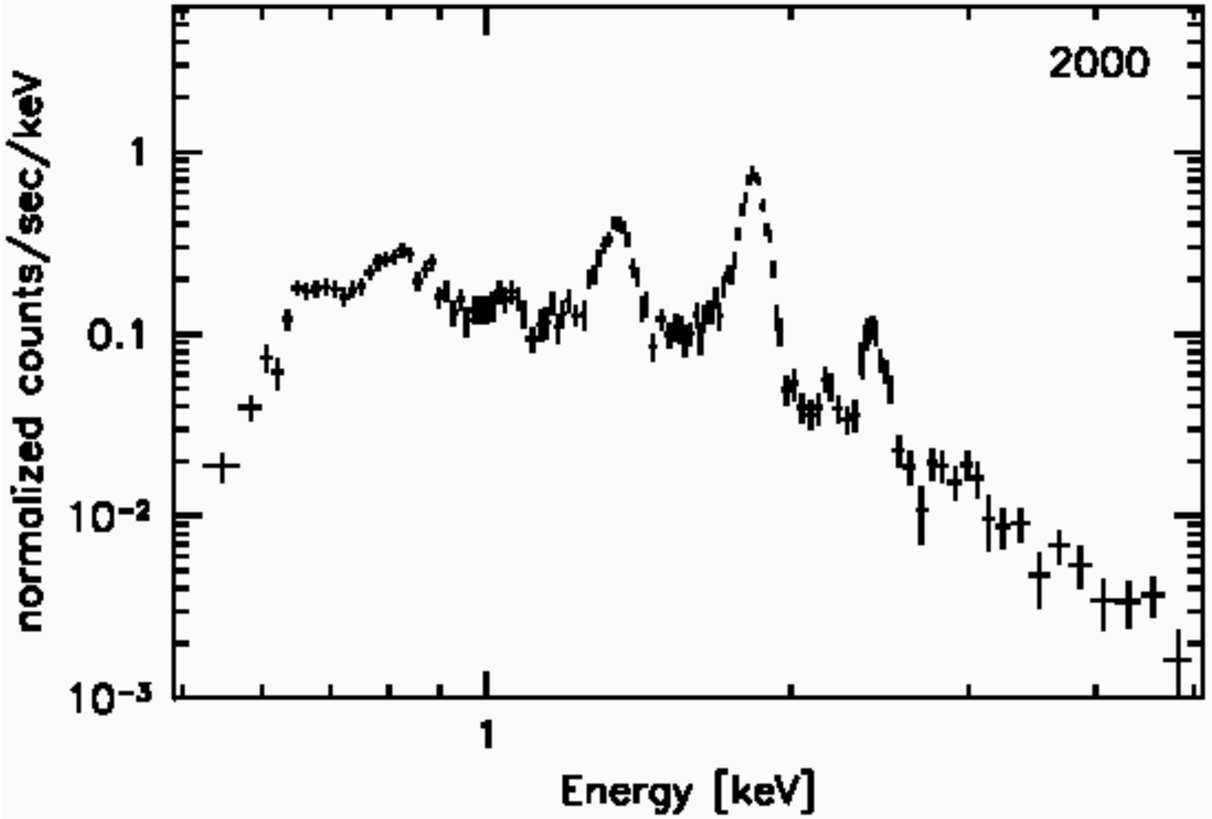
TEMPORAL VARIATIONS - CAS A - EJECTA



Si-bright filament at base of NE jet in Cas A

Brightening of filament marks the location of the reverse shock



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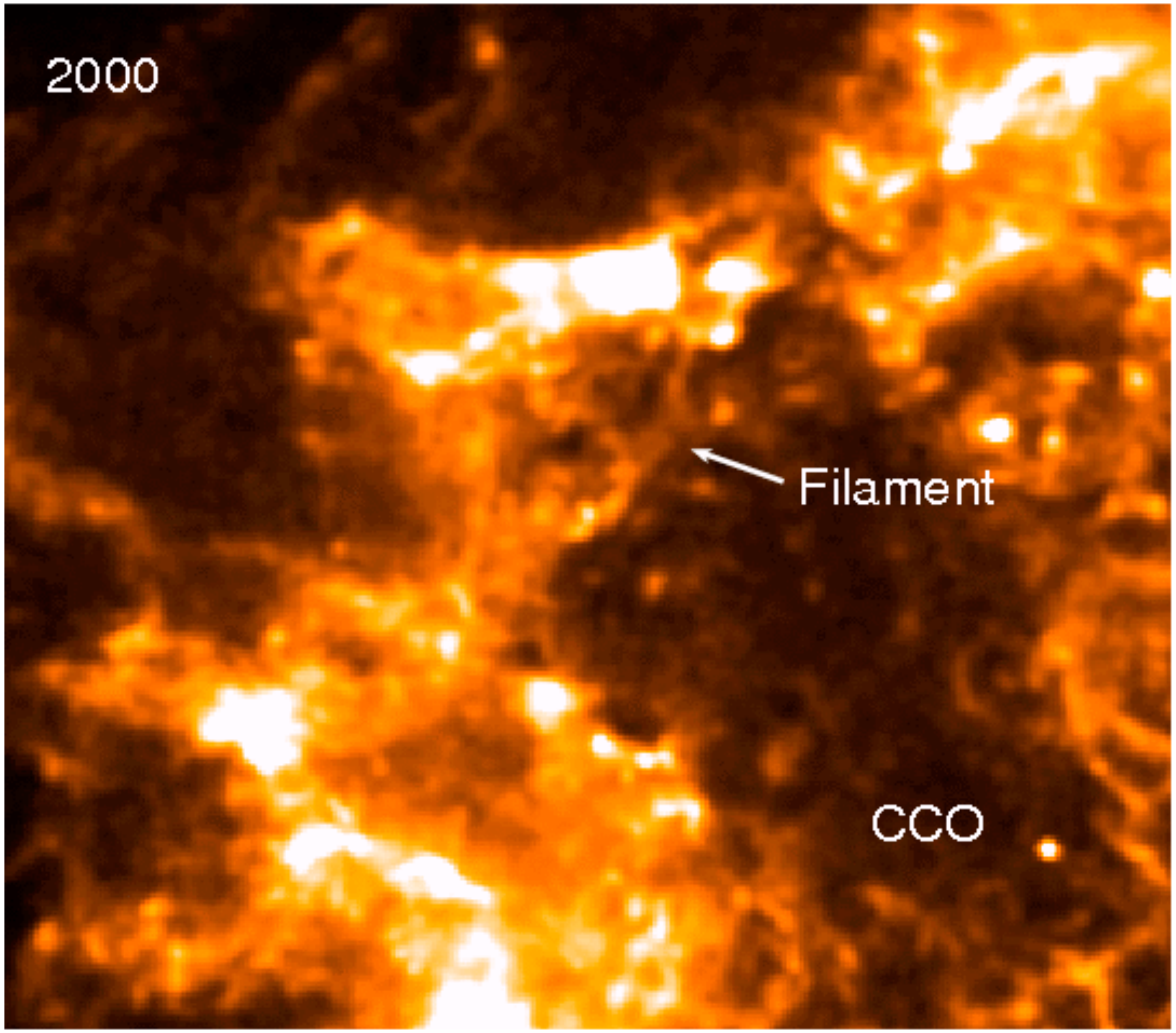
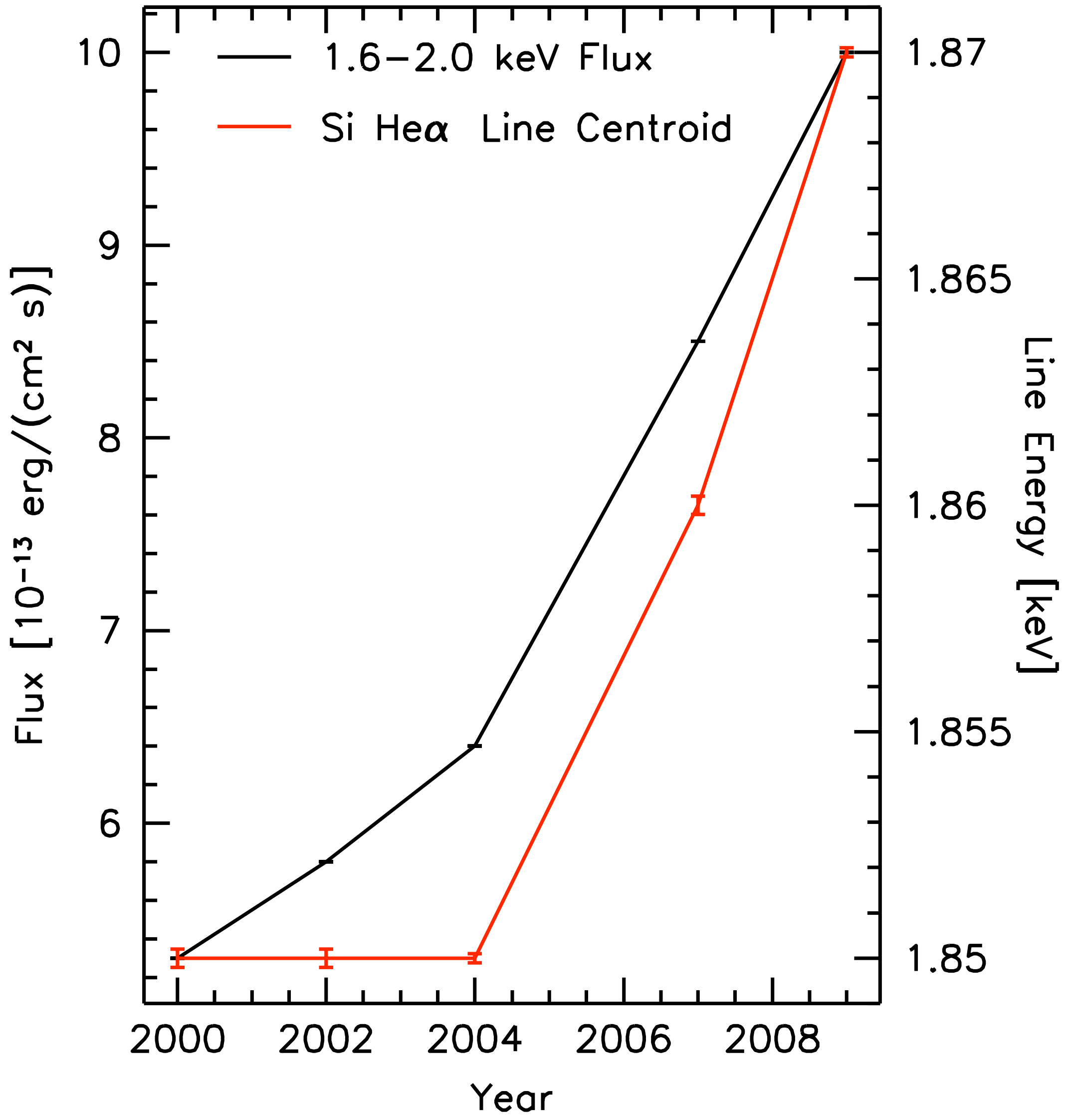


Si-bright filament at base of NE jet in Cas A

Rate at which plasma reaches ionization equilibrium is related to ρ and $\mathcal{E}$ - relates back to explosion energetics

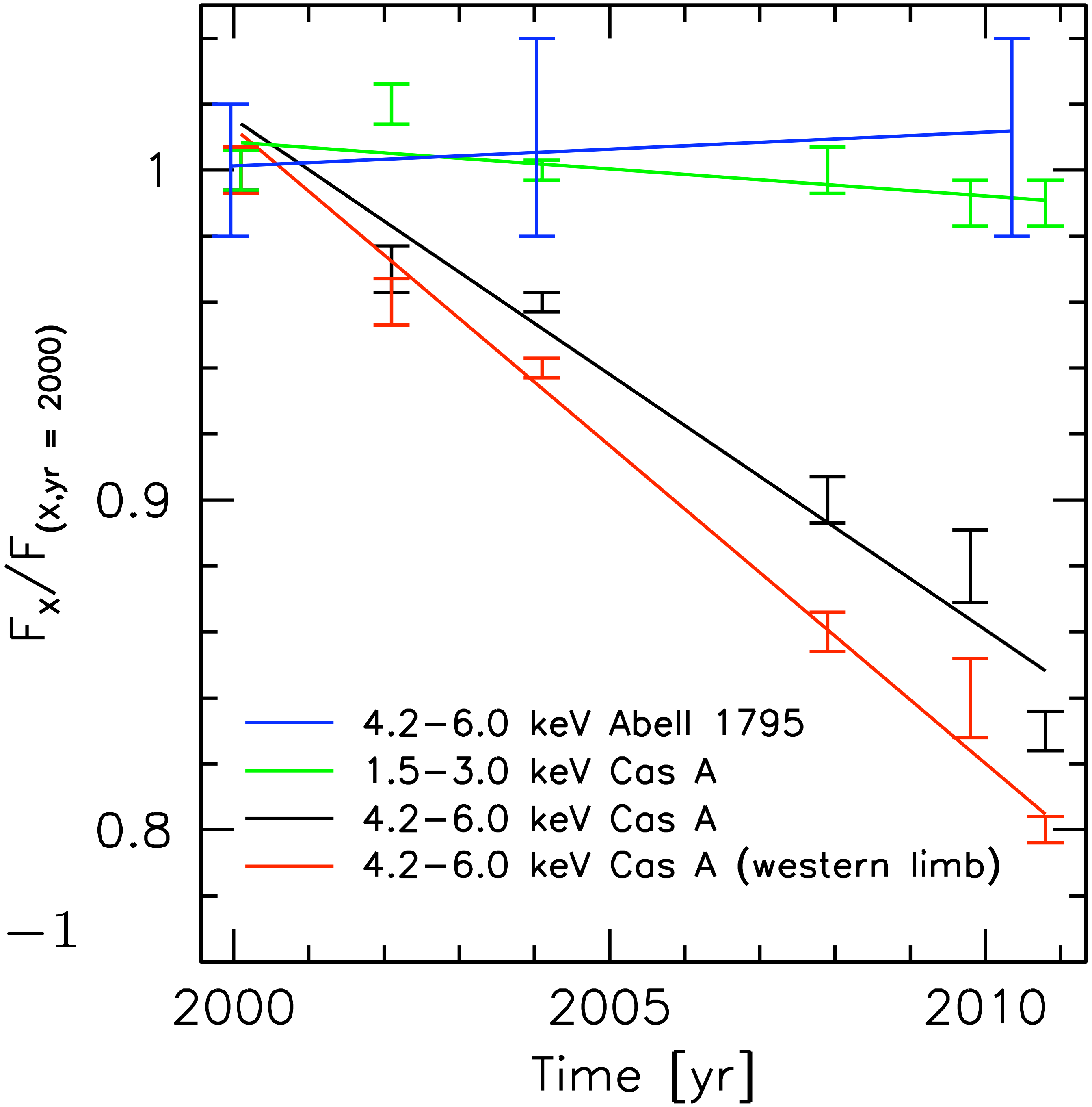


TEMPORAL VARIATIONS - CAS A - SYNCHROTRON EMISSION

$$\frac{1}{F_X}\frac{dF_X}{dt} \sim -2\% \ \mathrm{yr}^{-1}$$

decline in nonthermal emission suggests loss of energy to efficient cosmic ray acceleration

$$\frac{dV_s}{dt} \propto \frac{dE_c}{dt} \approx -20 \ \mathrm{km\ s}^{-1}\,\mathrm{yr}^{-1}$$



Integrated emission from Cas A vs time, showing decline in nonthermal emission, but constant thermal emission (Patnaude et al. 2011)

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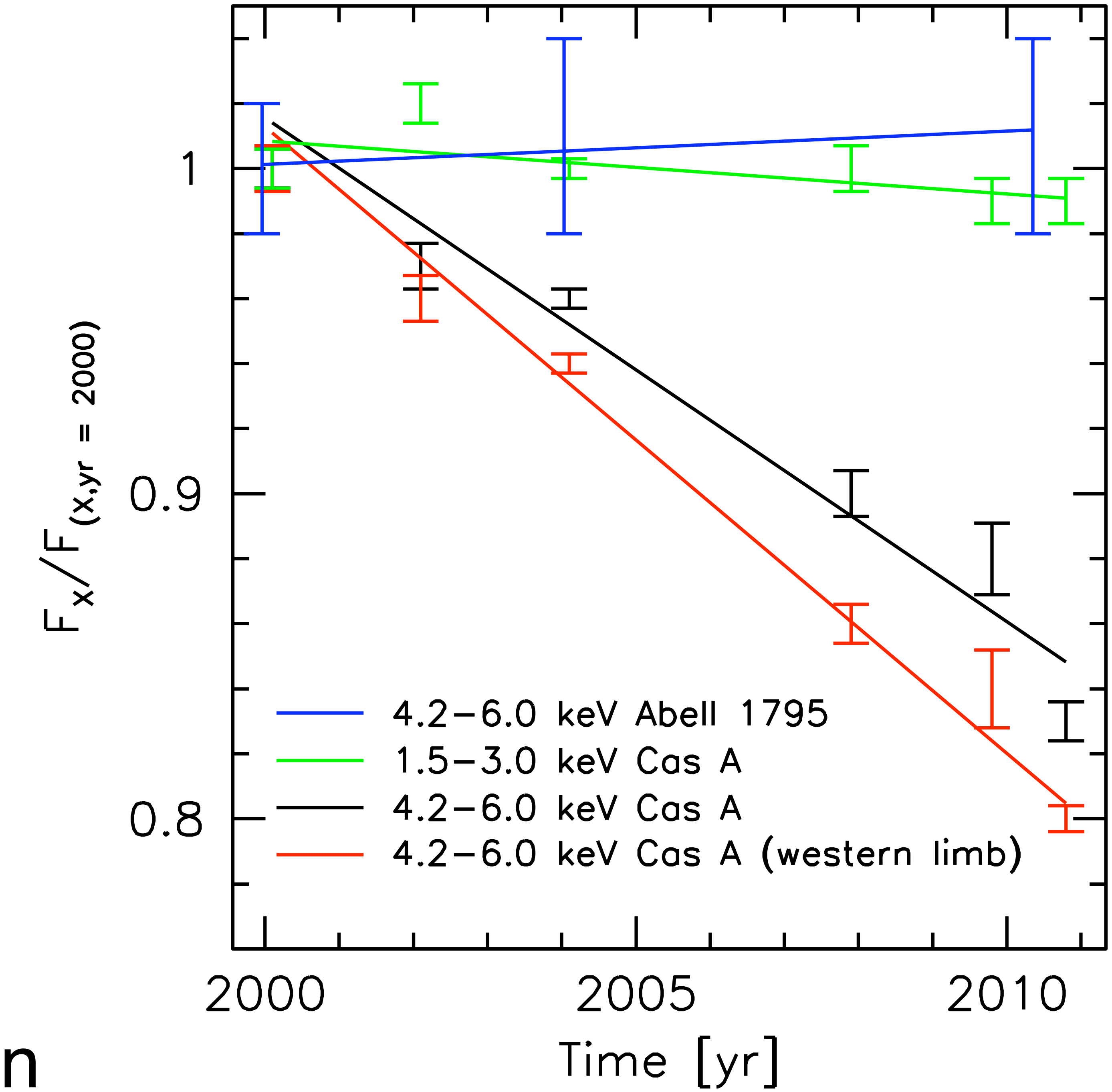
location of nonthermal emission (RS vs FS) may depend on nucleosynthesis processes during explosion (e.g. Zirakashvili & Aharonian 2011)



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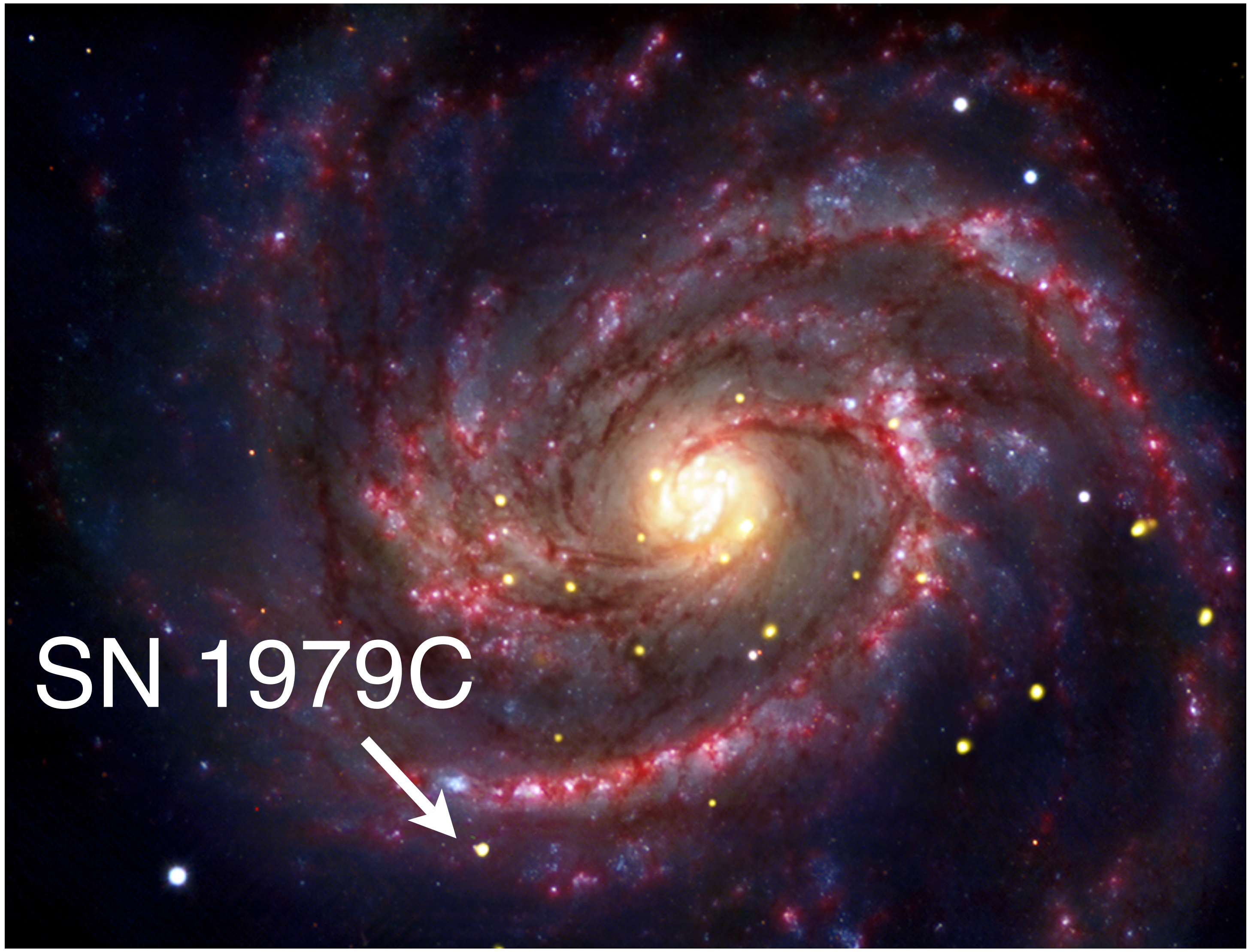
DETECTION OF CENTRAL COMPACT OBJECTS

Some Type IIL SNe (79C, 80K, 85L could be powered by the formation of a magnetar (Kasen & Bildsten 2010; Woosley 2010):

$$L_p = 2 \times 10^{42} B_{14}^2 (\mathrm{t/yr})^{-2} \mathrm{erg\ s}^{-1}$$

at late times, the X-ray emission from the central object might be observed



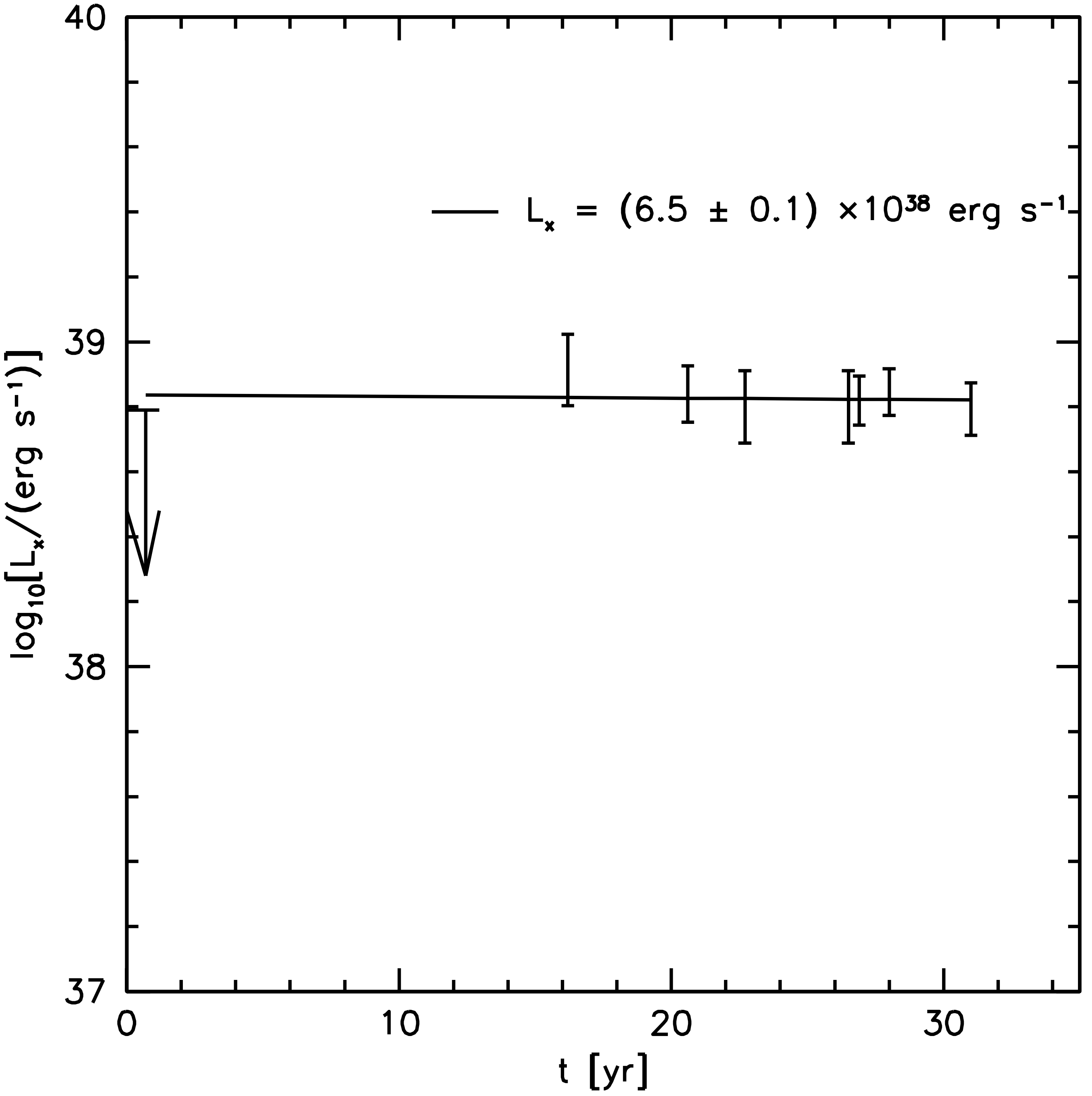
Composite image of M100 with data from Spitzer (red), VLT (blue), and Chandra (yellow) (CXC/Patnaude)

SN 1979C:

- observed with every X-ray satellite since *Einstein*

- X-ray emission has remained constant with time. Expect that:

$$L_X \propto t^{-n}$$

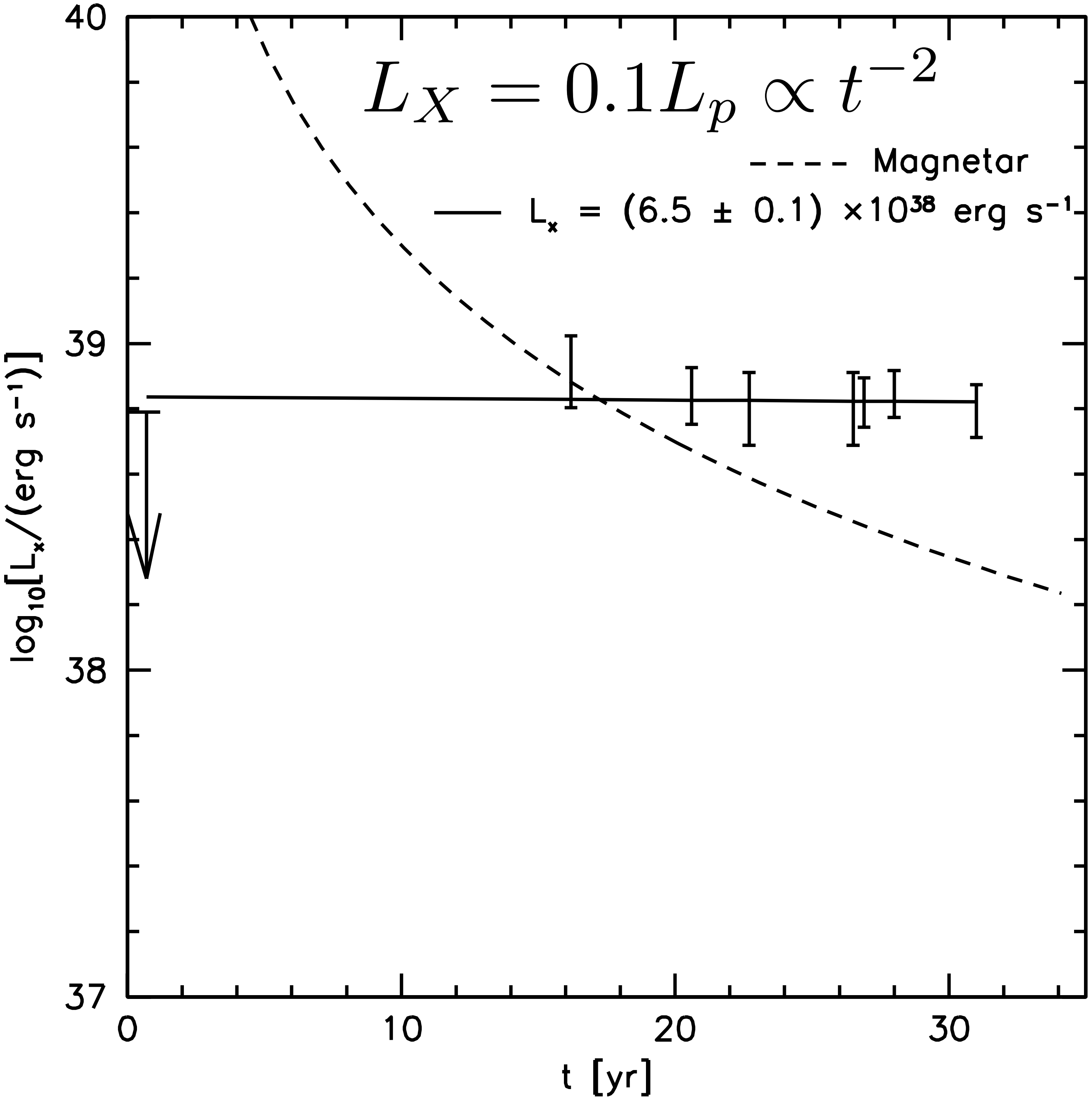


X-ray lightcurve of SN 1979C (Patnaude et al., 2011)

SN 1979C:

- model the X-ray emission as some fraction of magnetar spin down luminosity

- ROSAT and early CXO observations are consistent with this scenario, but quickly diverge



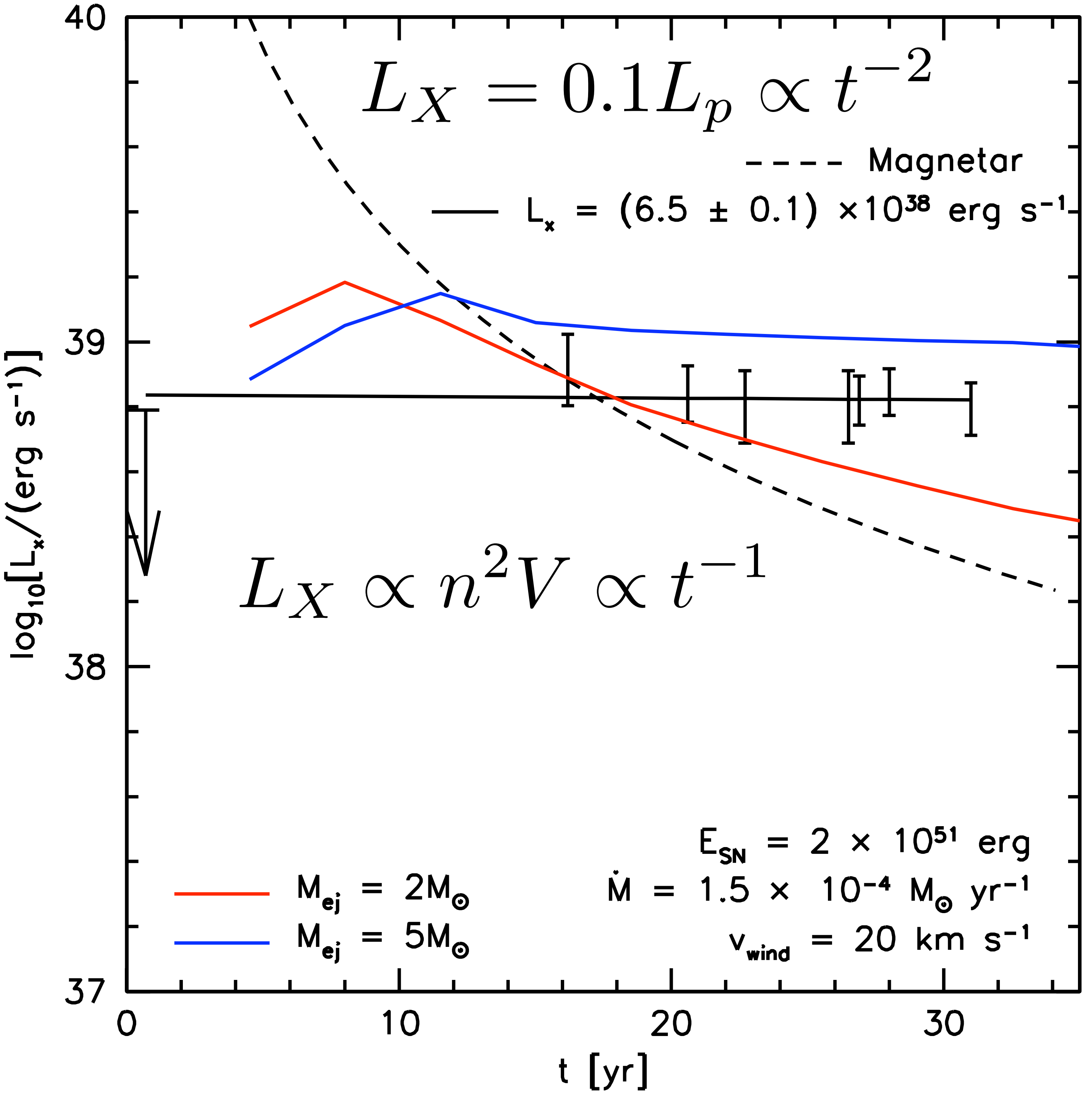
X-ray lightcurve of SN 1979C (Patnaude et al., 2011)

SN 1979C:

- In reality, X-ray emission is probably some combination of emission from shocked material and any central object

- after an inital rise time, X-ray emission from shocked material:

$$L_X \propto t^{-1}$$



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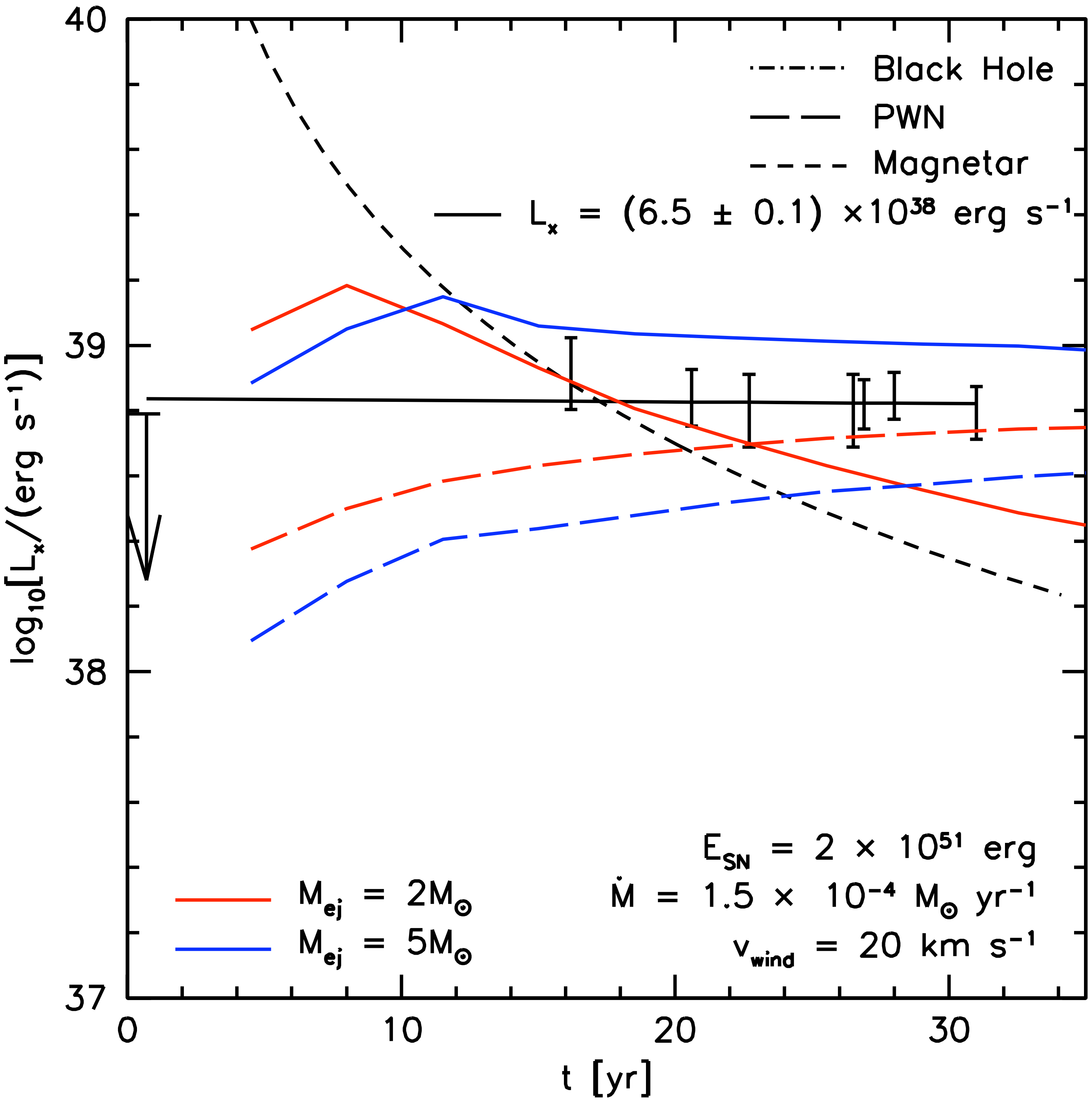
SN 1979C:

in ejecta:
  τ<< 1 after ~ 10 yr

model a central compact object:

  Luminous Crab-like PWN with t_P ~ 1000 yr?



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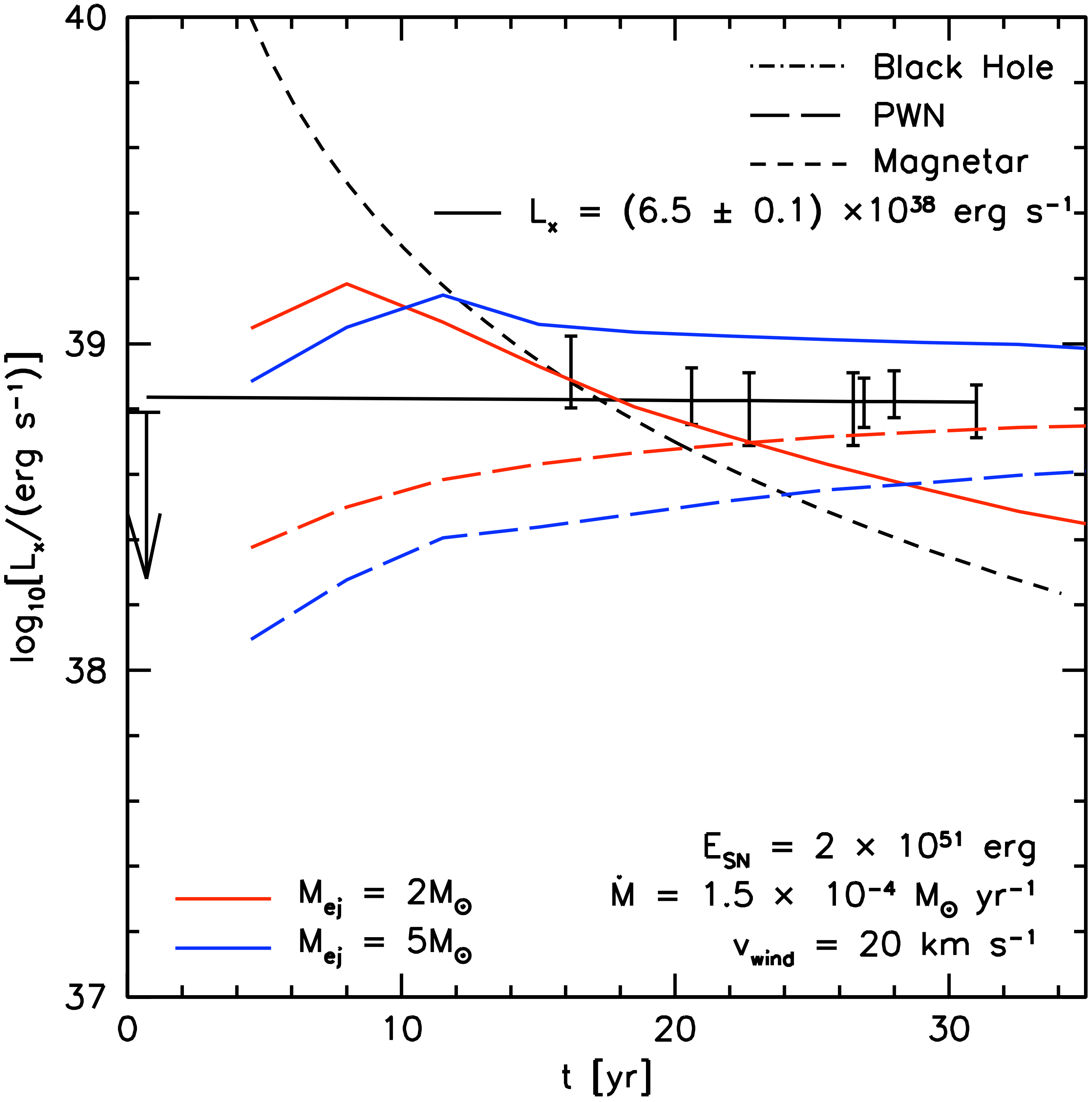
model a central compact object:

Luminous Crab-like PWN with t_P ~ 1000 yr?

L_X (Crab) ~ $10^{37.4}$ erg s^{-1}

PWN in 79C would be 25x more luminous than the Crab!



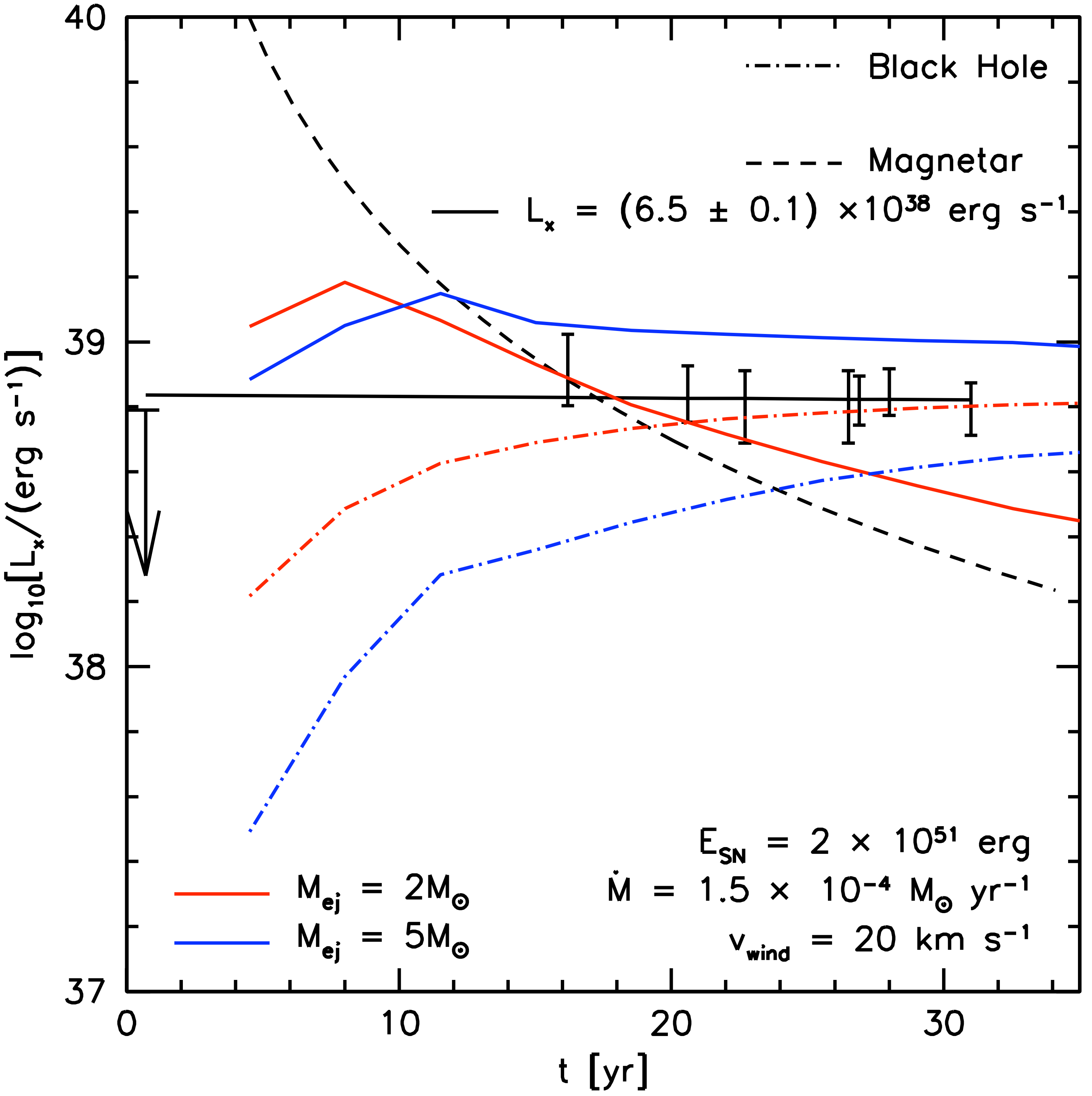
X-ray lightcurve of SN 1979C (Patnaude et al., 2011)

SN 1979C:

in ejecta:
$\tau \ll 1$ after ~ 10 yr

model a central compact object:

BH accreting near Eddington Limit?



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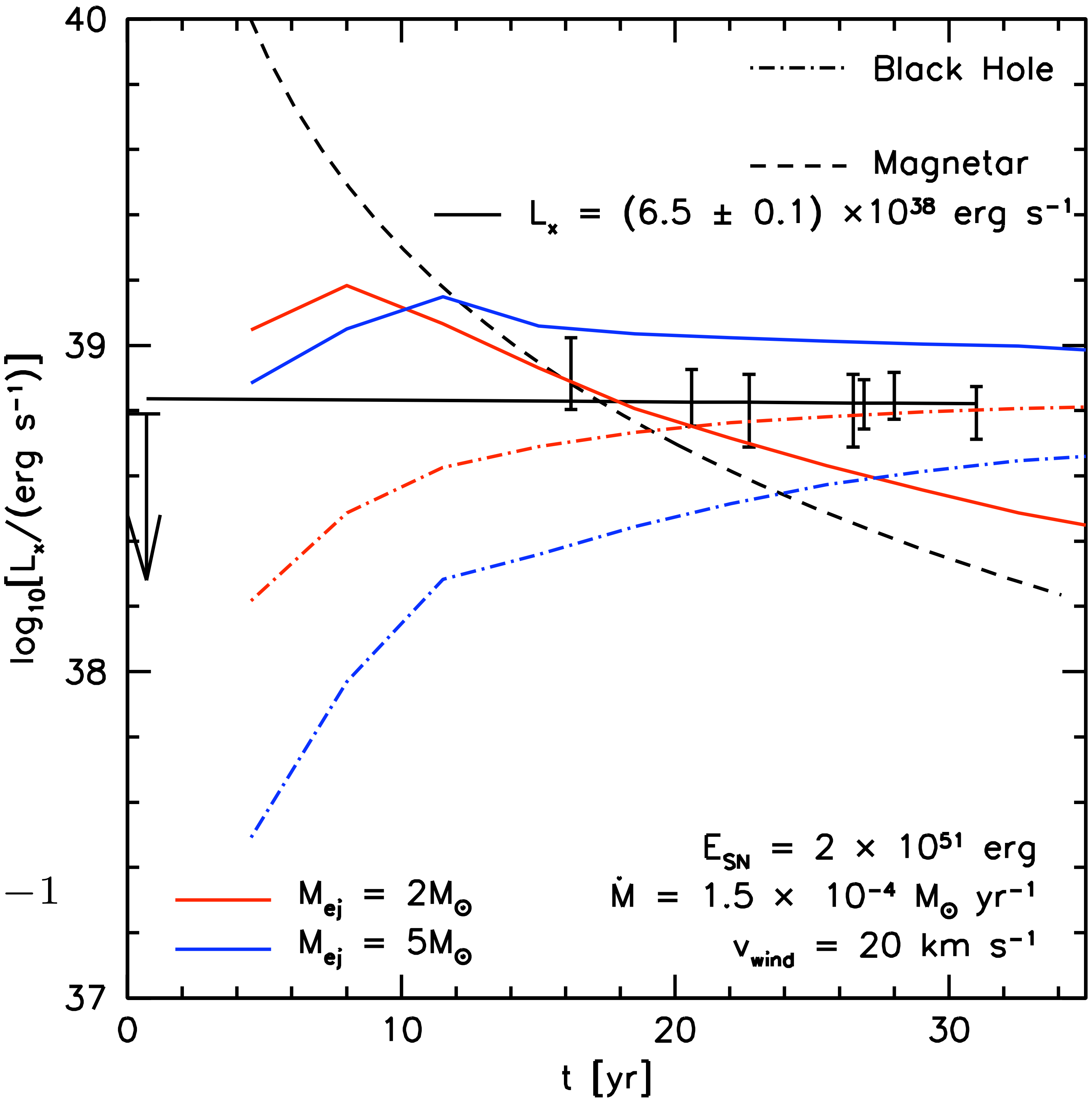
BH accreting near Eddington Limit?

$$L_{\mathrm{Edd}} = 1.4 \times 10^{38} \left(\frac{M_x}{M_\odot} \right) \ \mathrm{erg\ s^{-1}}$$

$\Rightarrow M_{\mathrm{BH}} \approx 5M_{\mathrm{Sun}}$



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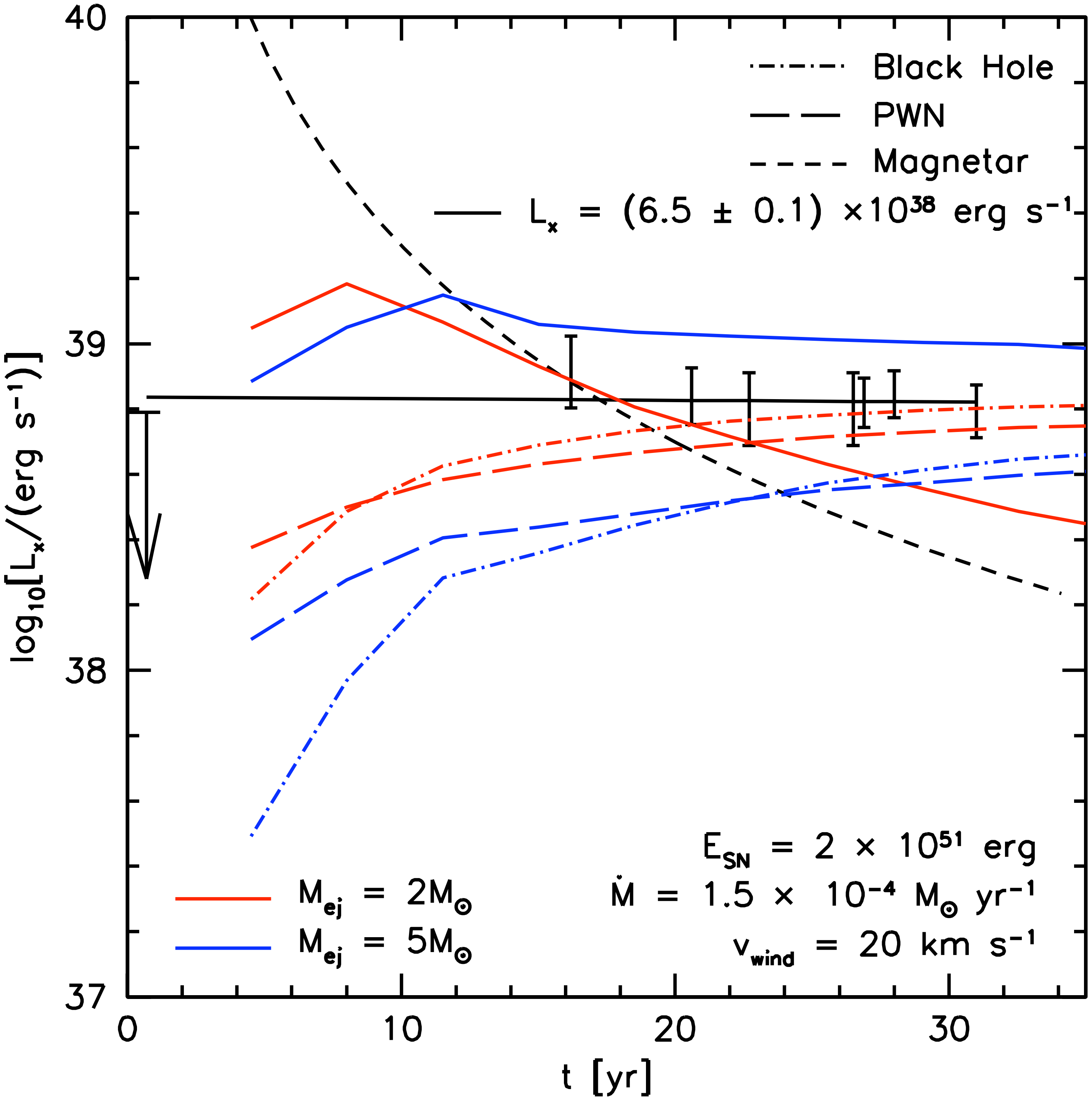
SN 1979C:

in ejecta:
  $\tau << 1$ after ~ 10 yr

High mass ejecta model overpredicts X-ray emission, while low mass model underpredicts the emission

the answer is probably somewhere in the middle, with a combination of emission from shocked material and a central object



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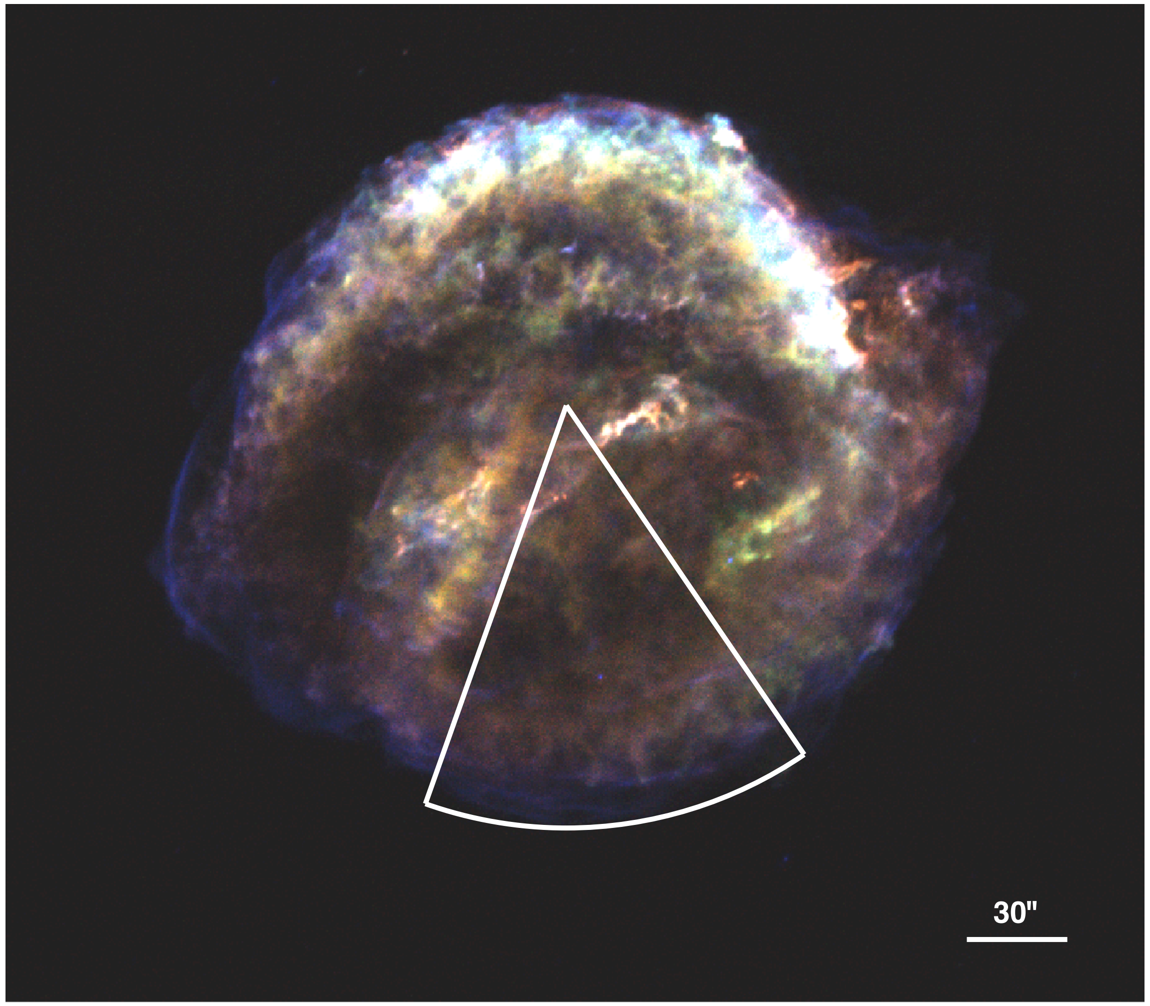
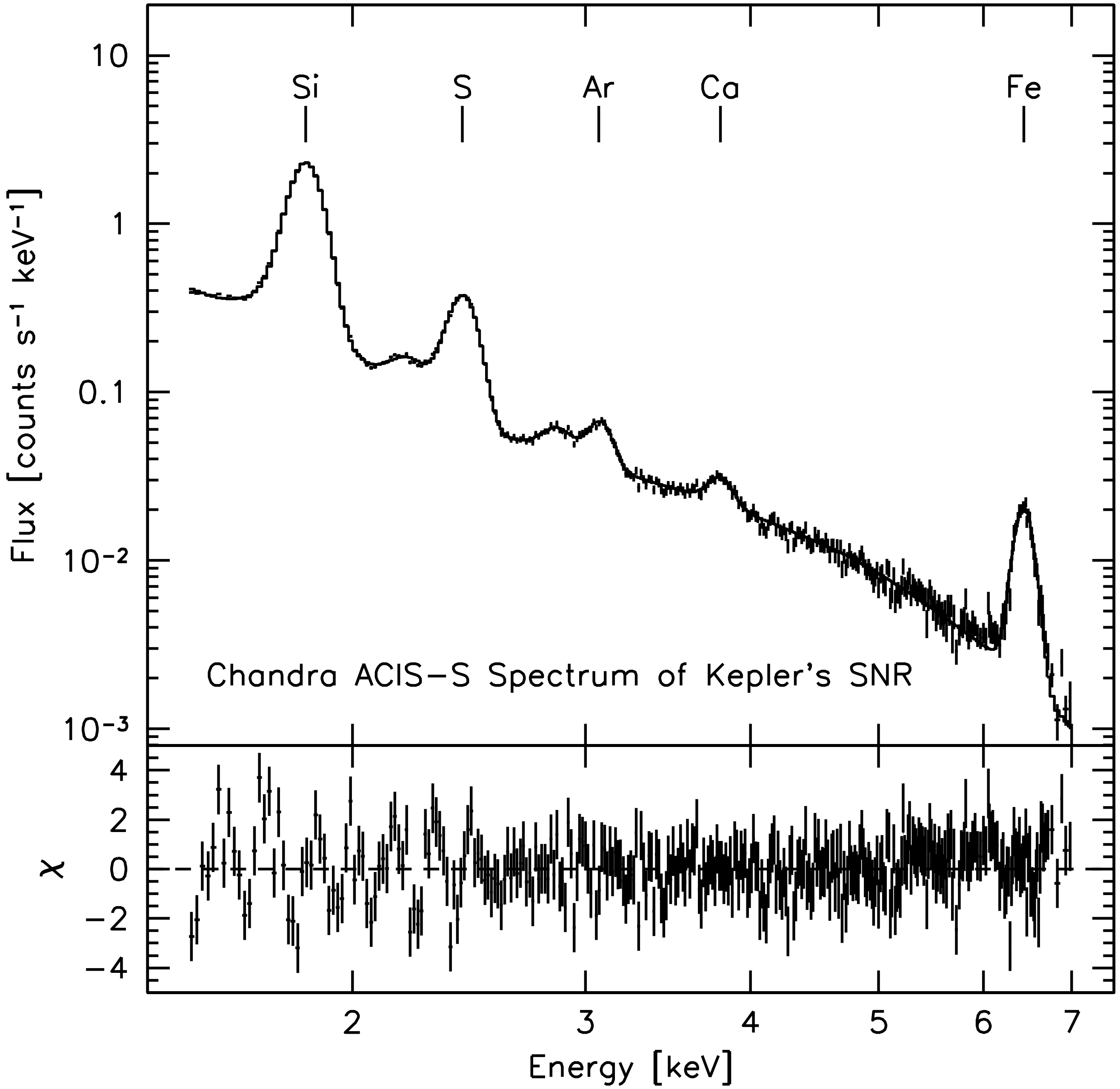
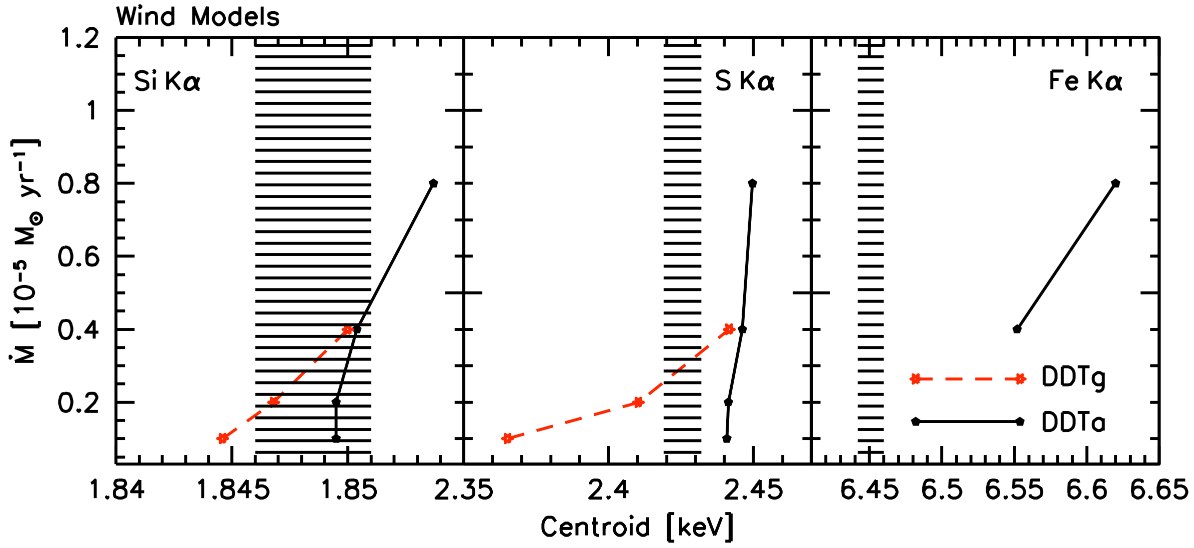
BULK PROPERTIES OF SNR - CONNECTIONS TO THE SNE AND PROGENITOR



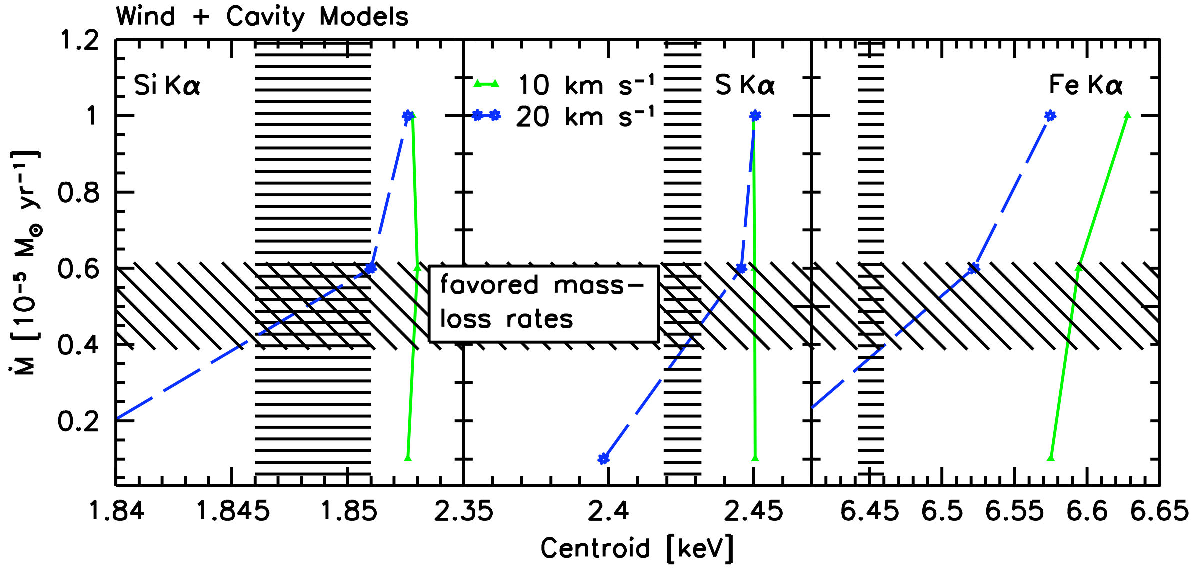
Analysis of SN Ia X-ray spectra compare directly to SN Ia models (Badenes et al. 2006, 2008; Patnaude et al. 2012)

Can use the properties of the X-ray spectrum to constrain the progenitor type and it's evolution

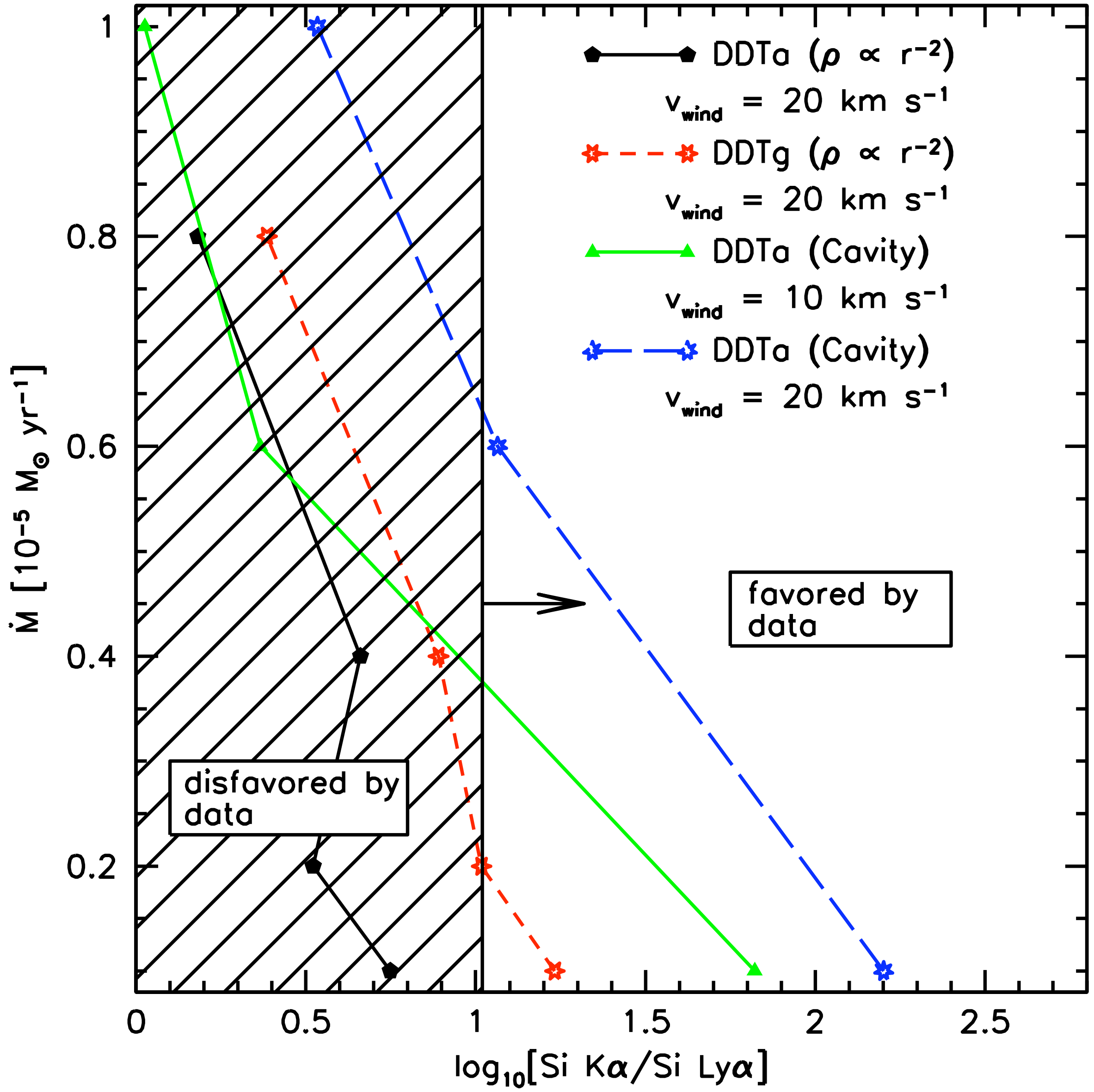




Line centroids and flux ratios suggest that the progenitor's companion had typical AGB mass loss parameters, and a small cavity was located around the progenitor prior to the SN



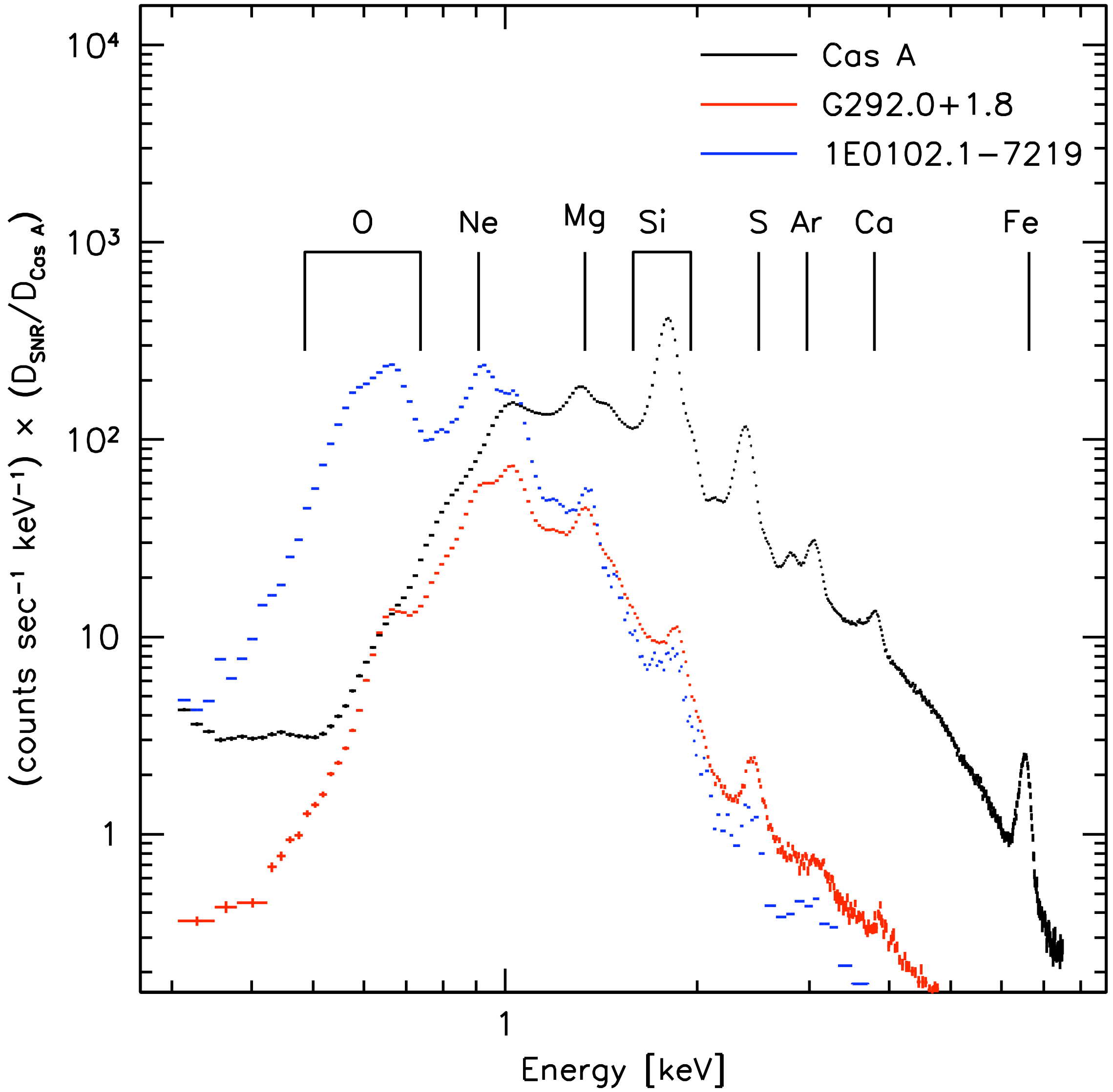
X-ray spectrum indicates a solar mass of ^{56}Ni was synthesized, suggesting that Kepler's SNR was a 1991T like event



FOR SN IA, BULK PROPERTIES TEACH US ABOUT THE EXPLOSION AND PROGENITOR HISTORY

CAN THE SAME TECHNIQUES BE USED FOR MORE COMPLICATED CCSNE?

CCSNe show wealth of asymmetry and macroscopic mixing

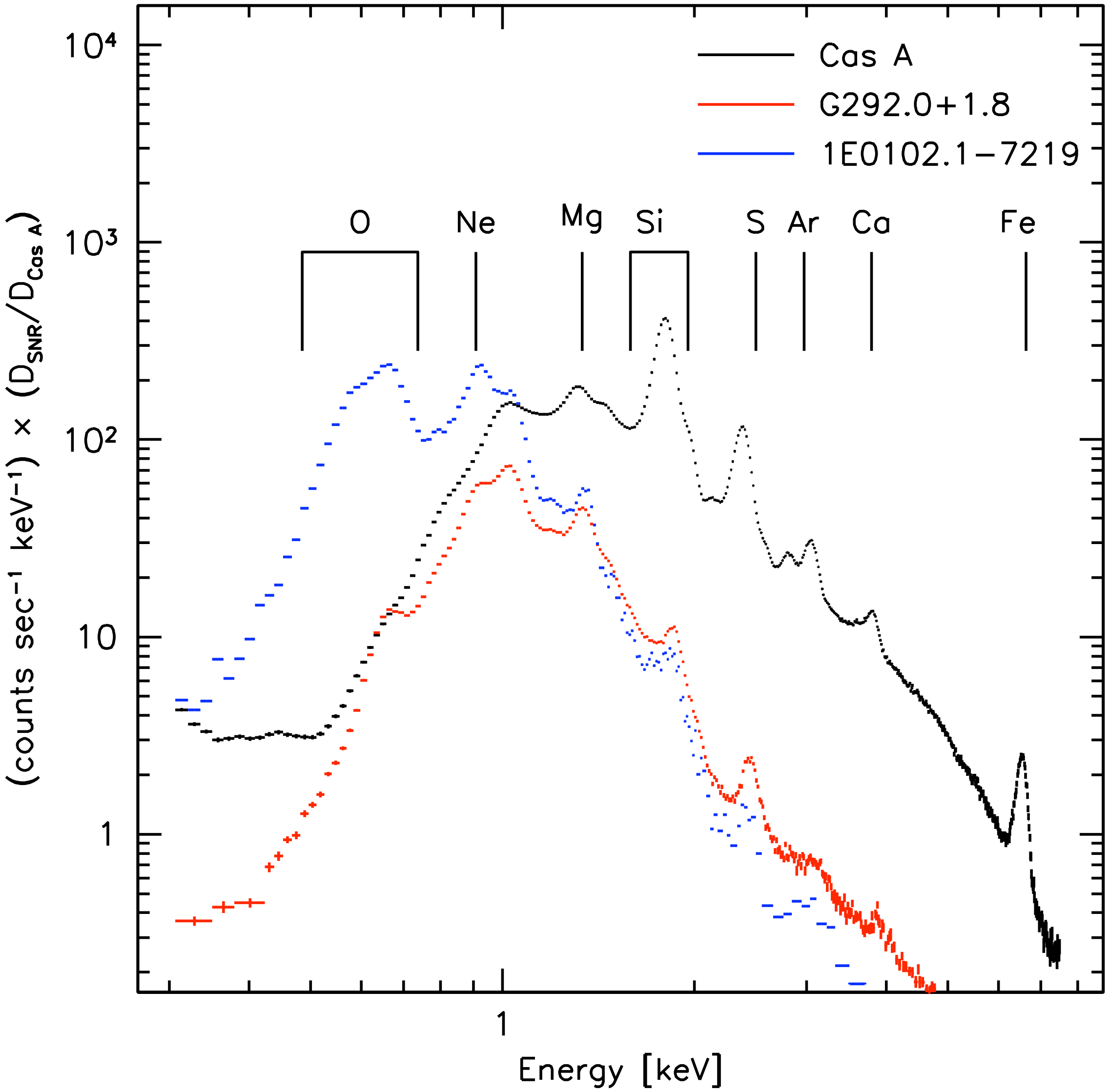


Integrated X-ray spectra from 3 CCSNe scaled to 3.4 kpc

CAN THE SAME TECHNIQUES BE USED FOR MORE COMPLICATED CCSNE?

CCSNe show wealth of asymmetry and macroscopic mixing

Current studies only focus on piecewise studies of emission (e.g., Lee et al.; Hwang & Laming) to infer CSM or explosion properties

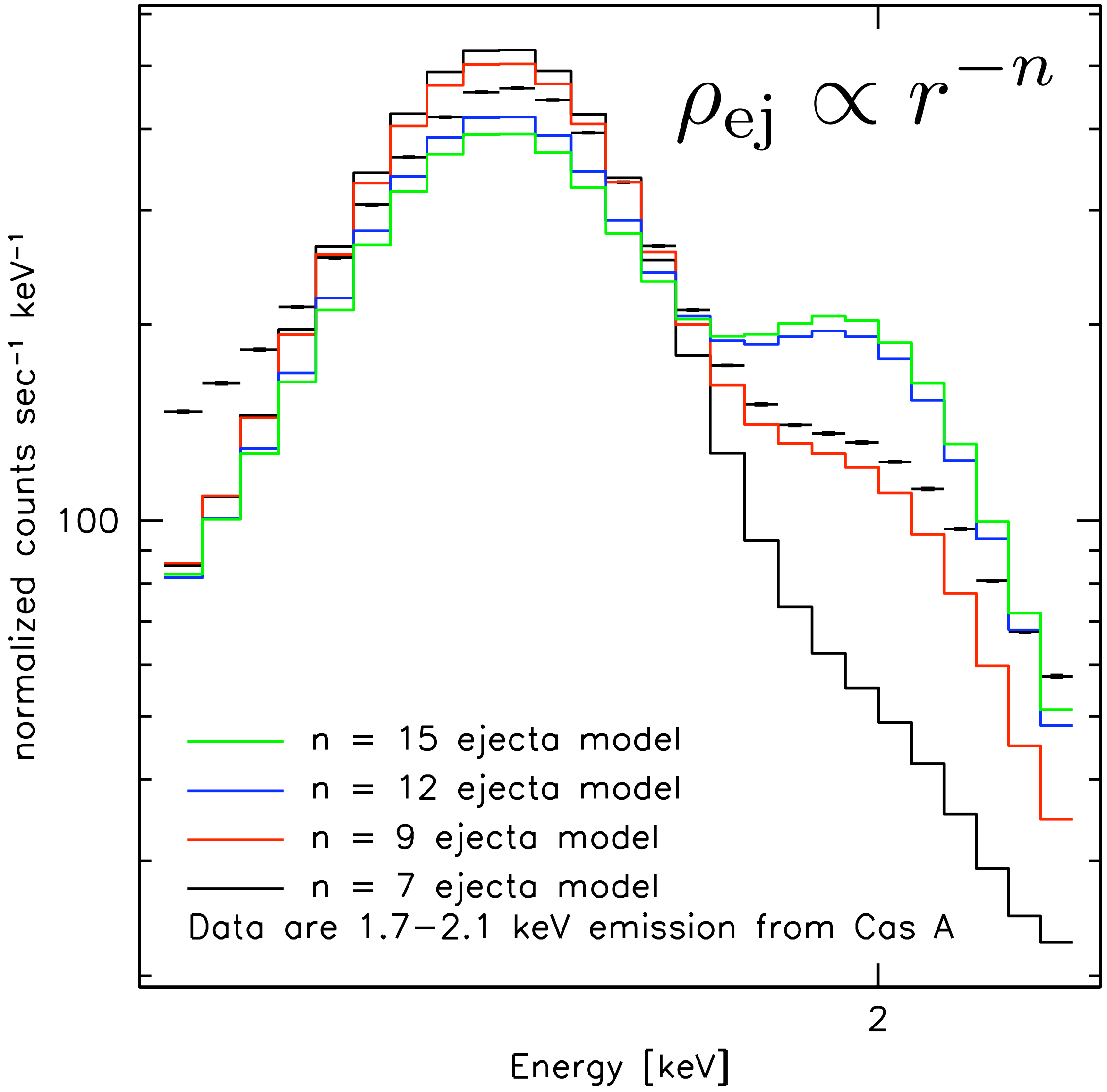


Integrated X-ray spectra from 3 CCSNe scaled to 3.4 kpc

CAN THE SAME TECHNIQUES BE USED FOR MORE COMPLICATED CCSNE?

CCSNe show wealth of asymmetry and macroscopic mixing

Simple self-similar models with composition derived from spectral fits show reasonable agreement with data (there's hope!)

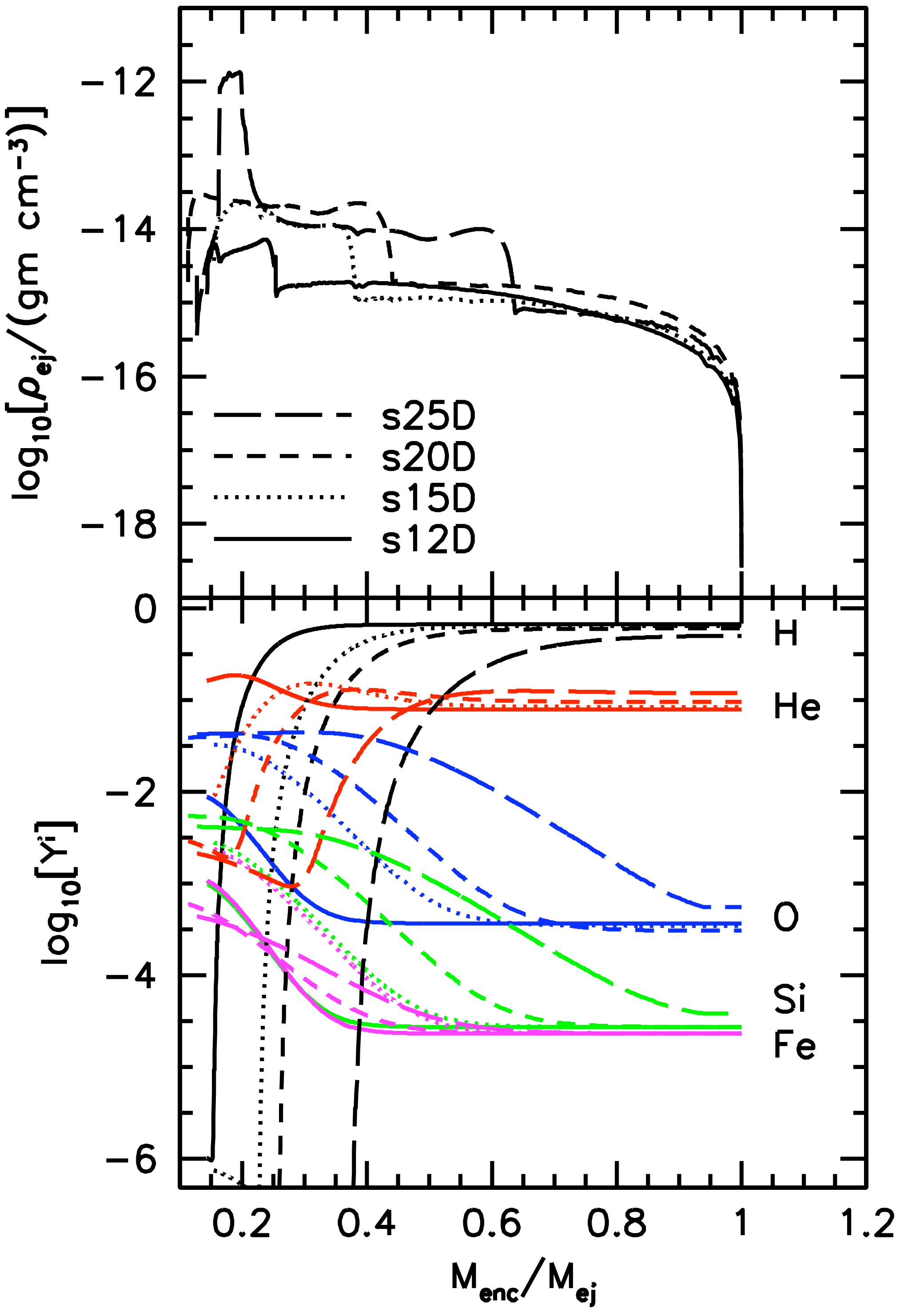


Integrated silicon emission from Cas A

CAN THE SAME TECHNIQUES BE USED FOR MORE COMPLICATED CCSNE?

CCSNe show wealth of asymmetry and macroscopic mixing

Evolve Woosley & Heger (2007) models from ages of ~ 100 days to 1000 yrs

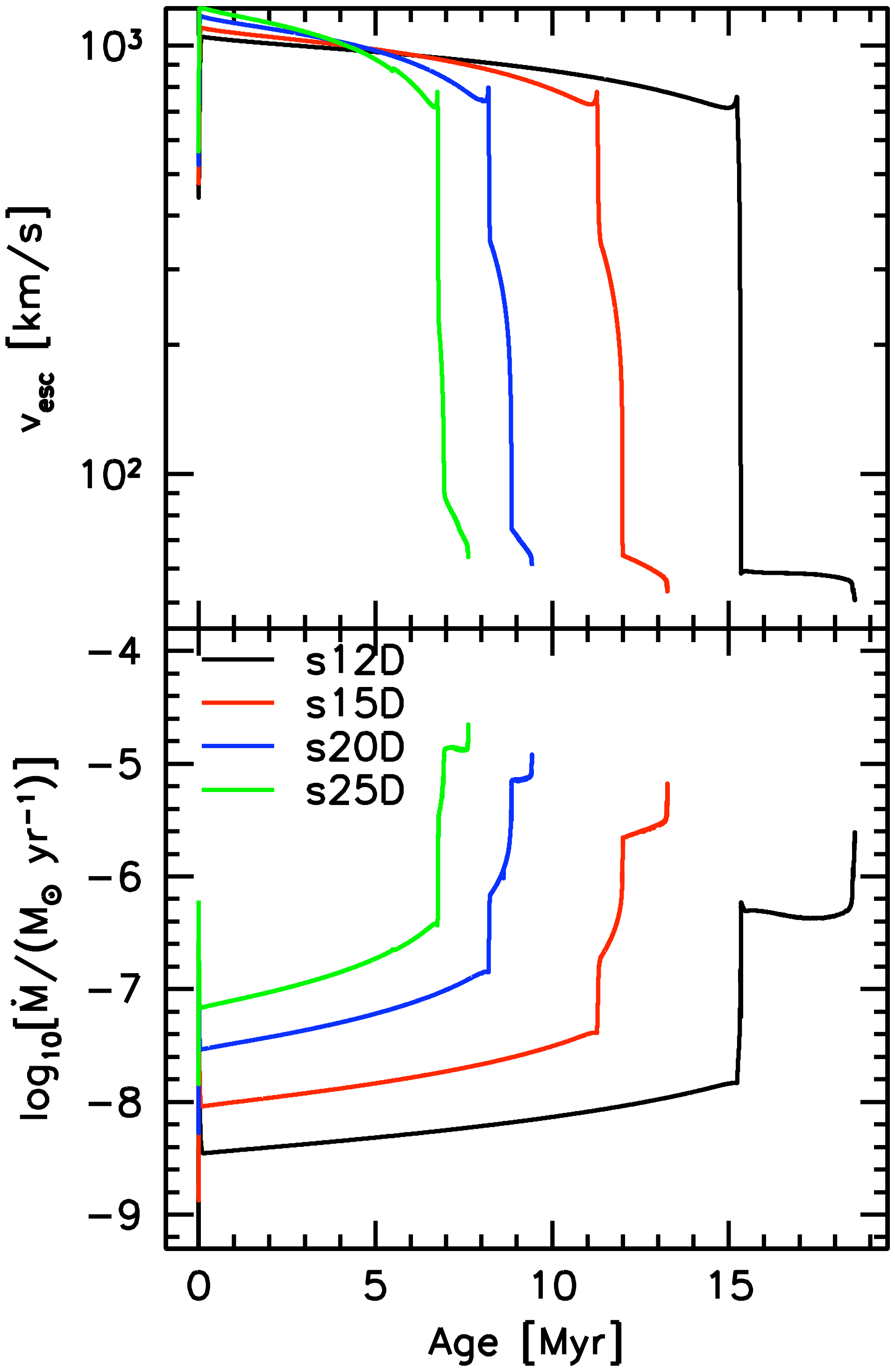


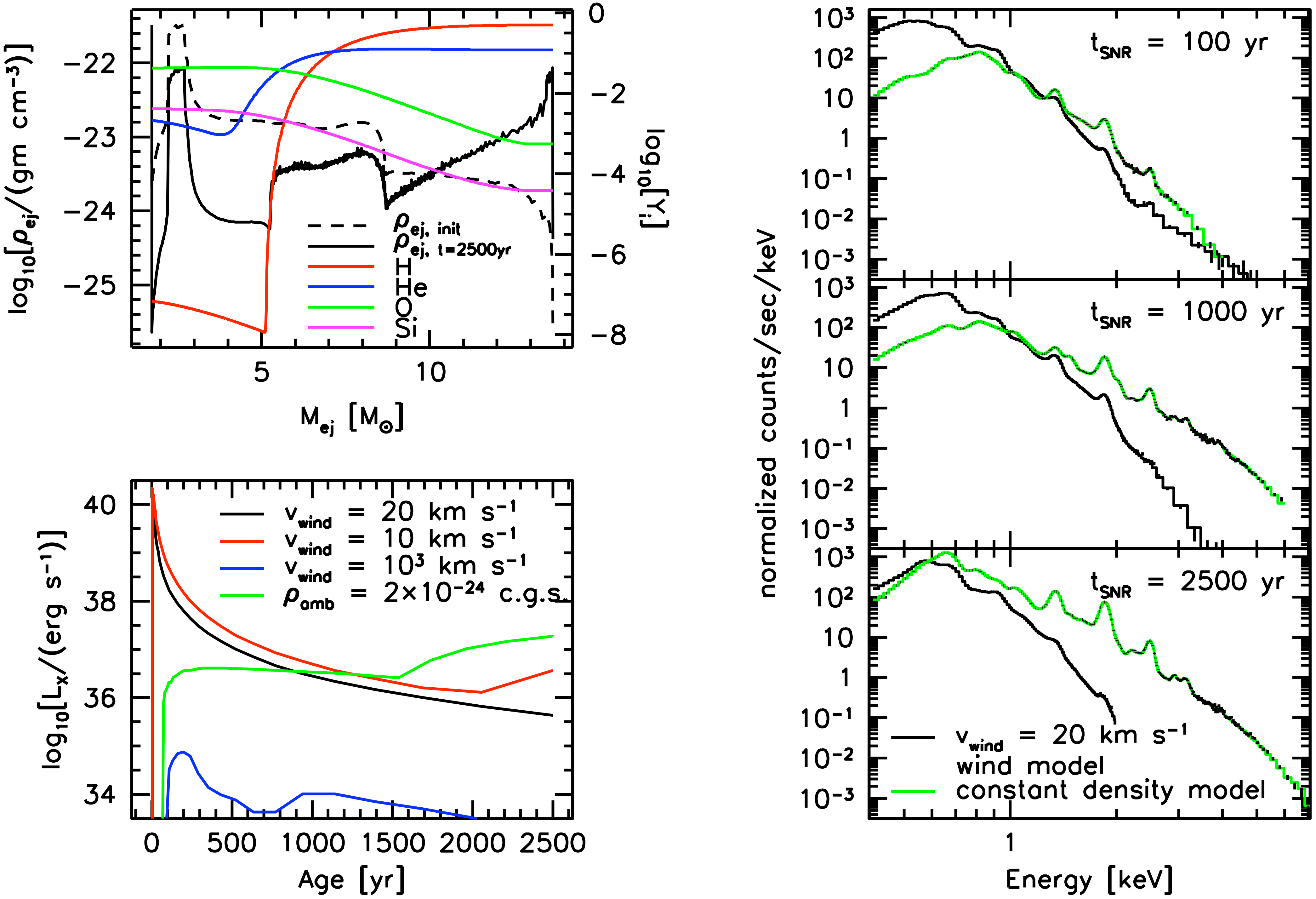
CAN THE SAME TECHNIQUES BE USED FOR MORE COMPLICATED CCSNE?

CCSNe show wealth of asymmetry and macroscopic mixing

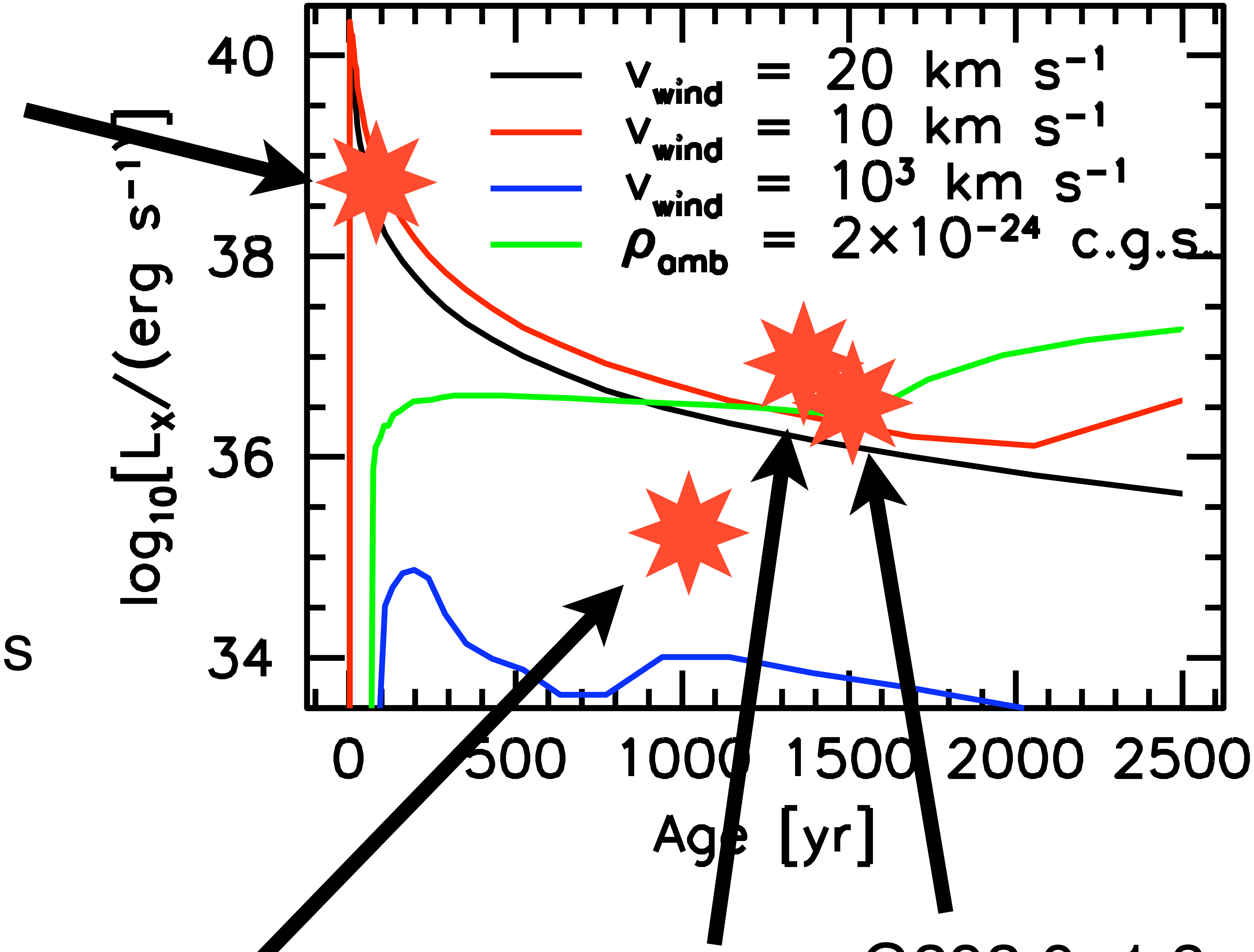
Evolve Woosley & Heger (2007) models from ages of ~ 100 days to 1000 yrs

Include presciption for mixing as well as integrated mass loss history of progenitor





s25D model evolved to t_{SNR} = 2500 yr in multiple CSM environments qualitatively, the evolution of s25D SN ejecta models match observations of young SNR



NGC 4449-1

1E 0102.1-7219

N132D

G292.0+1.8

Comparison between models and observations of SNR (data from Patnaude & Fesen 2003)

CONCLUSIONS

- X-ray emission from swept up CSM and shocked ejecta can be used to constrain progenitor mass and mass loss history
- X-ray observations show that the bulk of Fe produced in Cas A is already shocked
- Bulk properties of CCSN progenitor models can be compared directly to X-ray observations of young SNRs