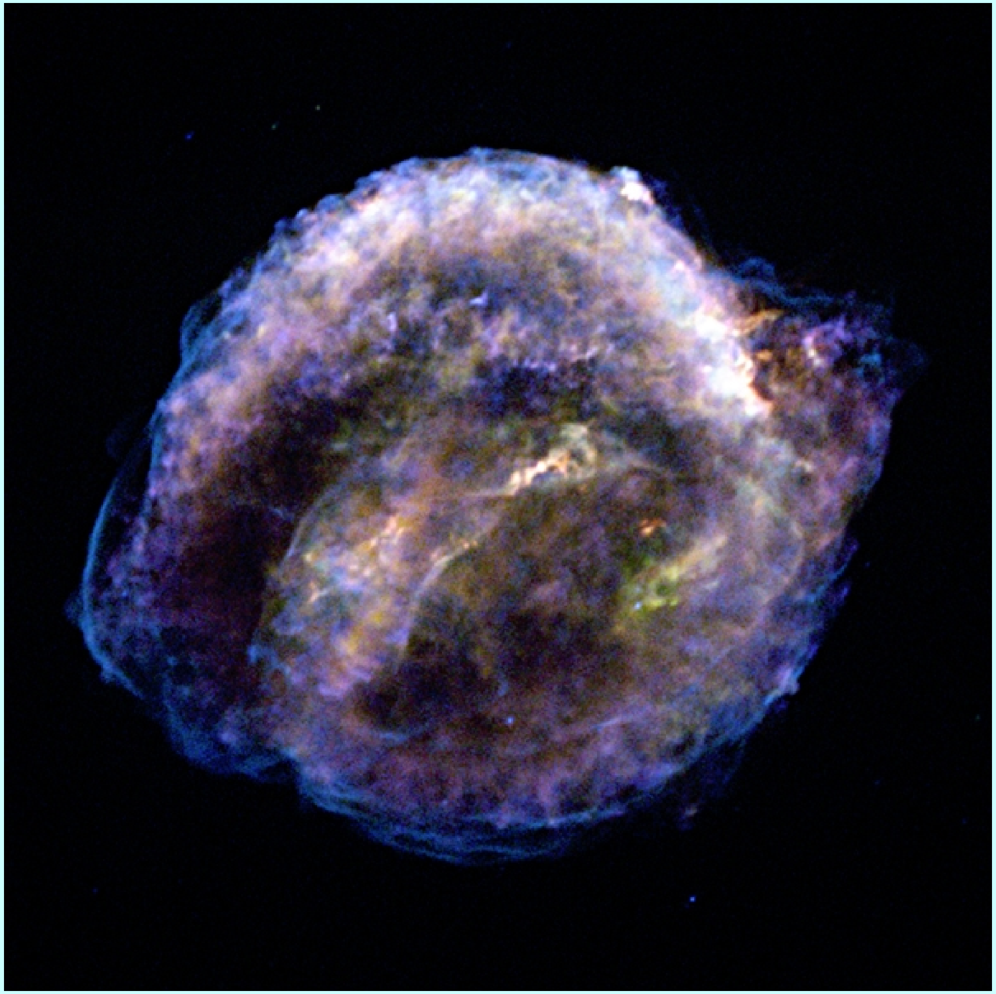
Particle acceleration in supernova remnants

S. P. Reynolds, North Carolina State University



1. Radio inferences
2. Synchrotron X-rays
3. Rolloff frequencies
4. GeV-TeV emission
5. G1.9+0.3
6. Status report

KAW5: Fifth Korean Astrophysics Workshop

November 20, 2009

Supernova remnants as particle accelerators: a brief history

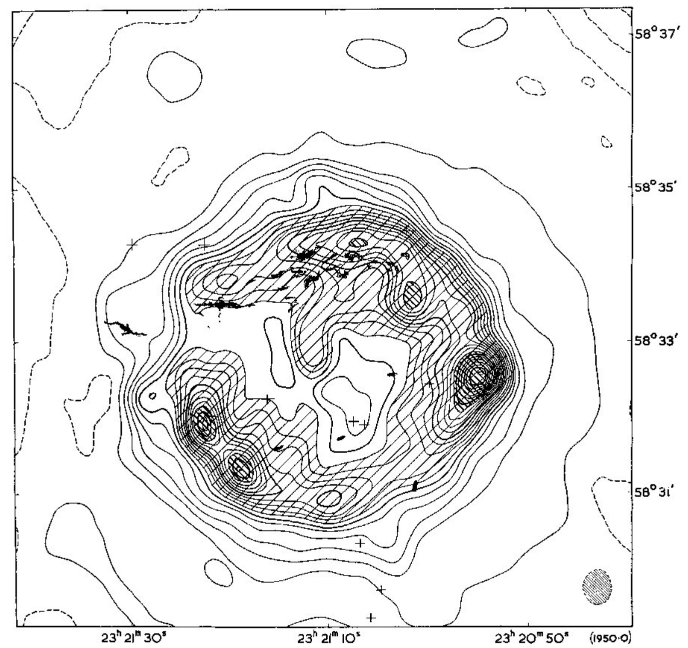


Fig. 5. Contour map of Cassiopeia *A* showing also the main optical filaments. The contour interval is 3,000° K. The positions of some of the brighter stars in the field are indicated by crosses

First interferometric map of Cassiopeia A (Cambridge; Ryle, Elsmore, & Neville 1965)

Cas A: first radio source identified as SNR (Shklovskii 1953; Minkowski 1957).

Shklovskii (1953) proposed **synchrotron radiation** for radio emission:

1. **power-law spectrum** $S_\nu \propto \nu^{-\alpha}$, $\alpha \sim$ 0.5)
2. (later): **Polarization**

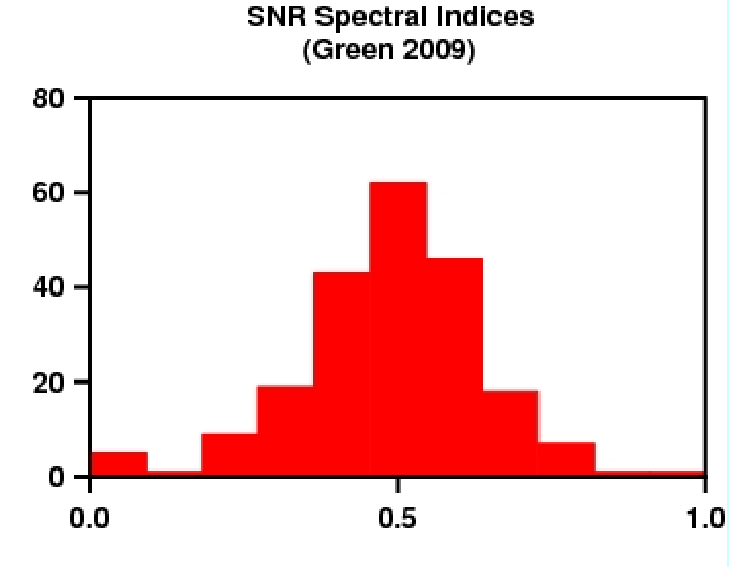
Synchrotron physics: Electron with energy *E* in magnetic field *B* emits peak at

ν = 1.82 x 10^{18} $E^2 B$ Hz or

$E = 15\ (\nu(\mathrm{GHz})/B(\mu\mathrm{G}))^{-1/2}$ GeV ⇒

extremely relativistic electrons.

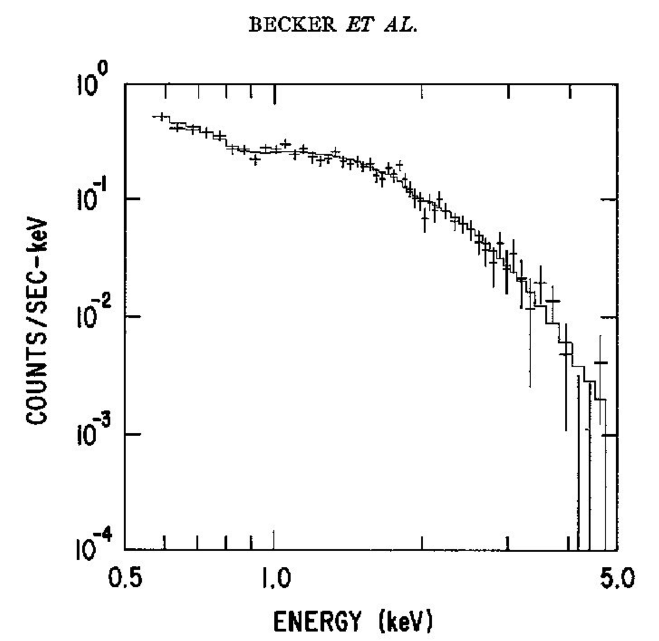
Radio inferences: summary



1. Spectral indices spread by ± 0.2 about 0.5 (among ~250 Galactic SNRs; Green 2009)
2. Young SNRs tend to have steeper spectra (Radio *supernovae*: can have $\alpha \sim 1$!)
3. Some evidence for spectral hardening: prediction of efficient shock acceleration (R & Ellison 1992: infer $B \sim 100\ \mu$G!)
4. Magnetic fields from polarization: mostly disordered in young SNRs, with slight radial preponderance. Older: usually confused, sometimes tangential
5. Minimum nonthermal energies from equipartition: << 10^{51} erg. But young SNRs are too bright to radiate just by compressed ISM: need *new electrons*

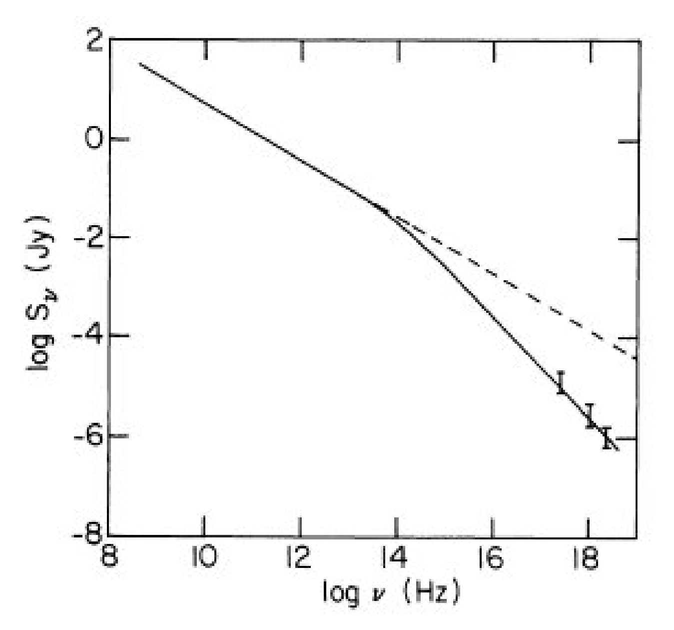
Puzzles: $\alpha < 0.5$? (Thermal contamination?) $\alpha > 0.5$? Not low-compression shocks. Radial *B*?

New frontier: synchrotron X-rays?



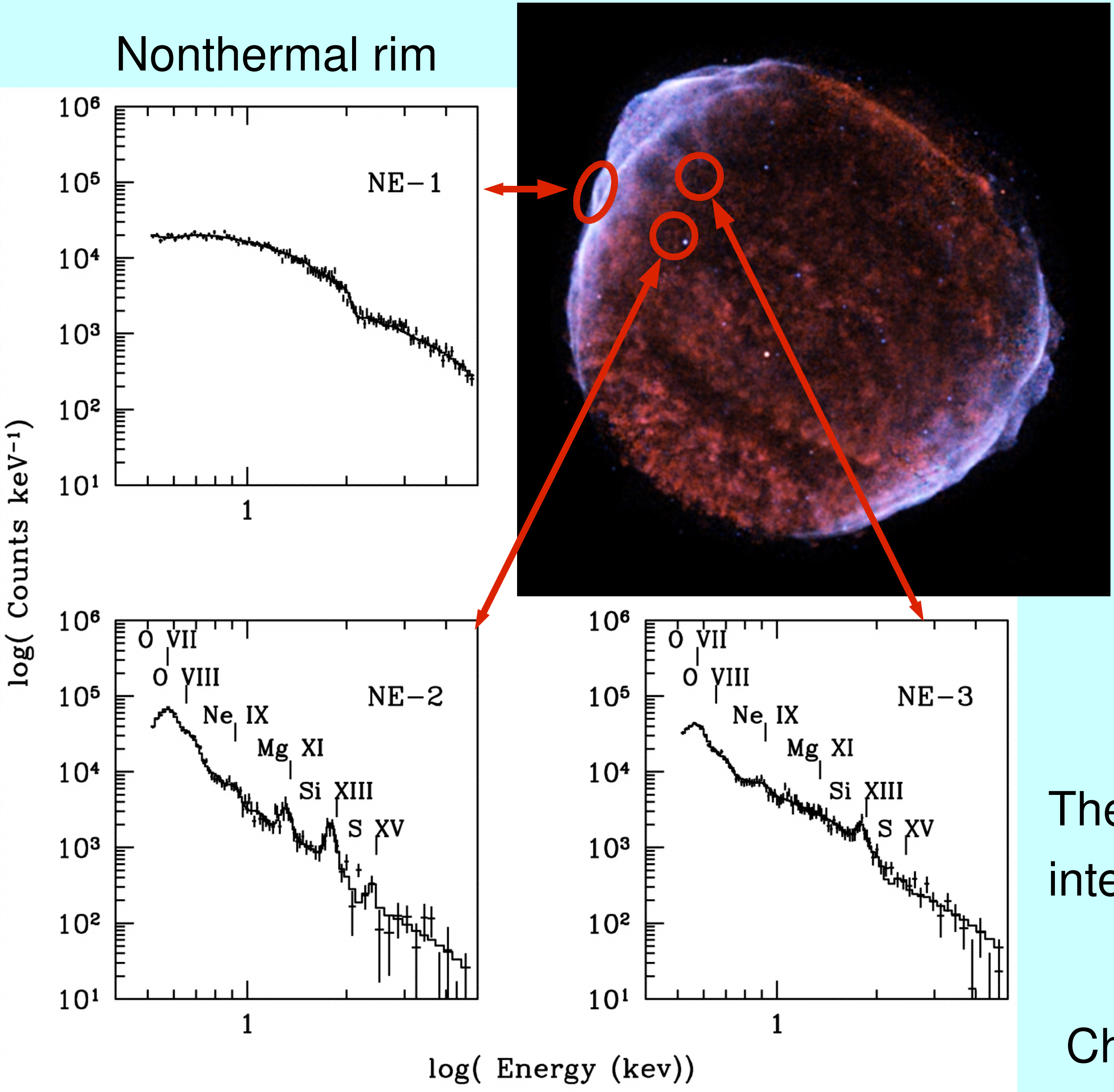
Observations: Becker et al. (1980), Einstein SSS. Report $\Gamma \simeq$ 2.2 (photon index) --but background, confusion problems with Lupus Loop

Theory: RC81. $\Gamma \simeq 2.2 \Rightarrow \alpha \simeq 1.2$, about 0.5 steeper than radio ($\alpha \simeq 0.6$): synchrotron losses! Except assume instantaneous acceleration to E_{max} before synchrotron losses occur.



Requirement: Spatial resolution

Nonthermal rim



Bright rims:
featureless
power-laws

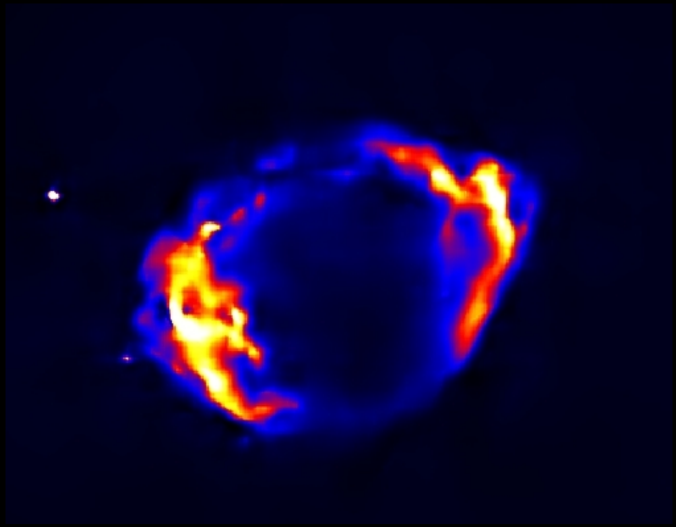
Interior: thermal spectrum (prominent O; ejecta. Most Fe not shocked yet)

Thermal
interior

Chandra. Long et al. 2003

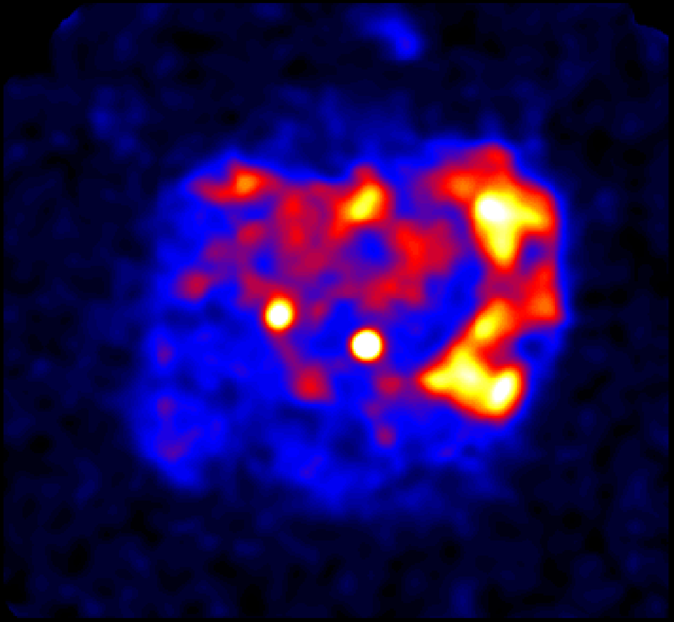
The Big Four: synchrotron X-ray dominated

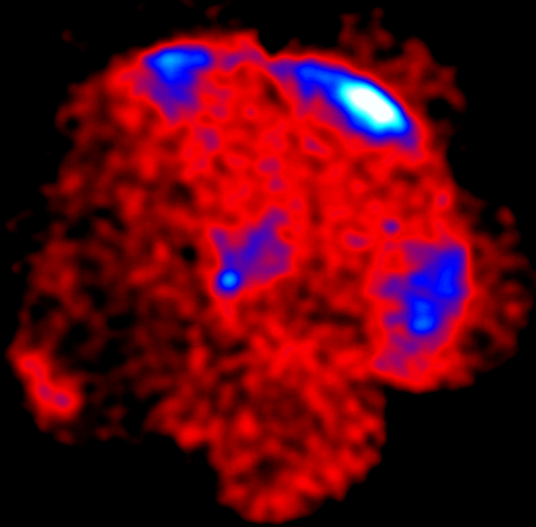
G1.9+0.3:
youngest
SNR!
(Chandra;
Reynolds
et al. 2008)



SN 1006
(Chandra;
CXC)

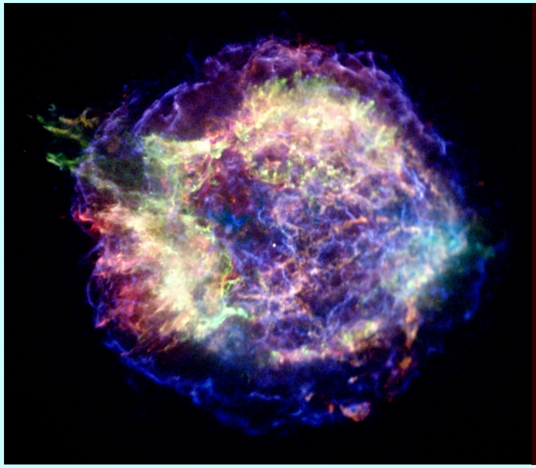
G347.3-0.5
(RX J1713.7-
3946) (ROSAT;
Slane et al.
1999)



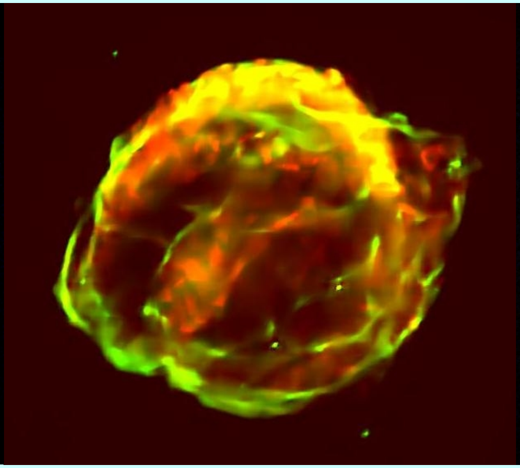


G266.2-1.2
(“Vela Jr.”)
(ASCA;
Slane et al.
2001)

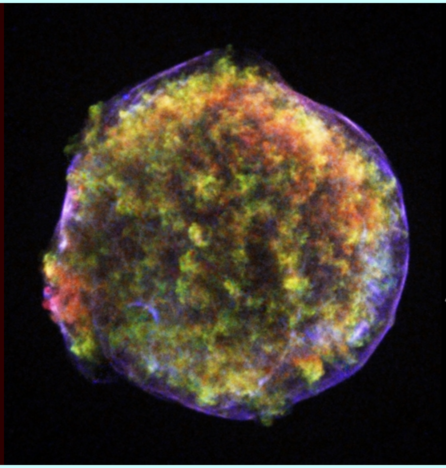
Thin rims, synchrotron components in other SNRs



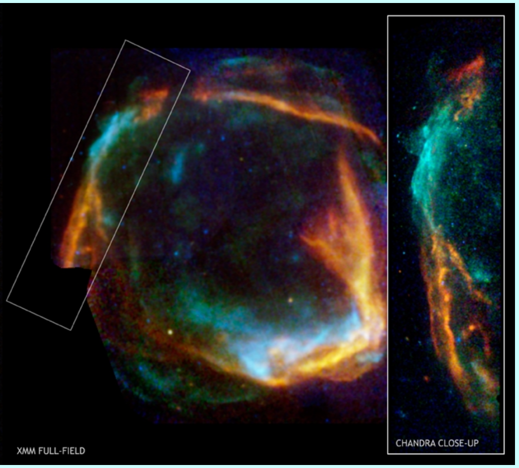
Cas A (SN ~1680)
(Stage et al. 2006)



Kepler (SN 1604)
(Reynolds et al. 2007)

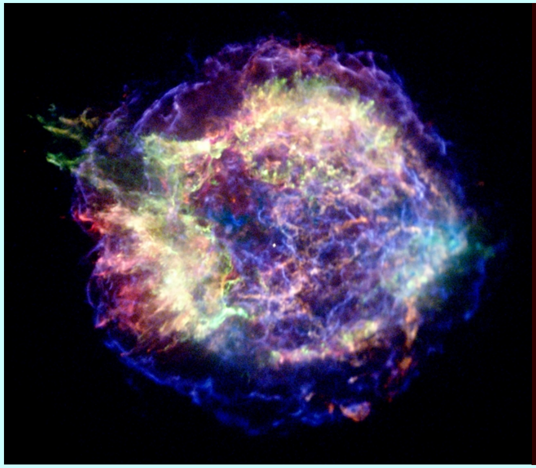


Tycho (SN 1572)
(Warren et al. 2005)



RCW 86 (SN 185?)
(Vink et al. 2008)

Thin rims, synchrotron components in other SNRs



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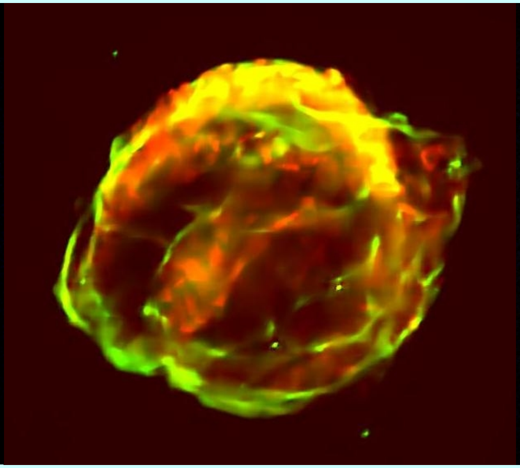

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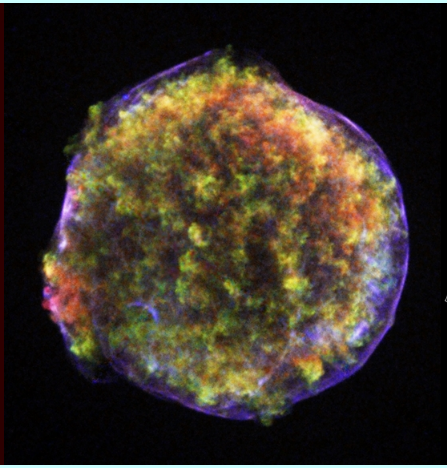
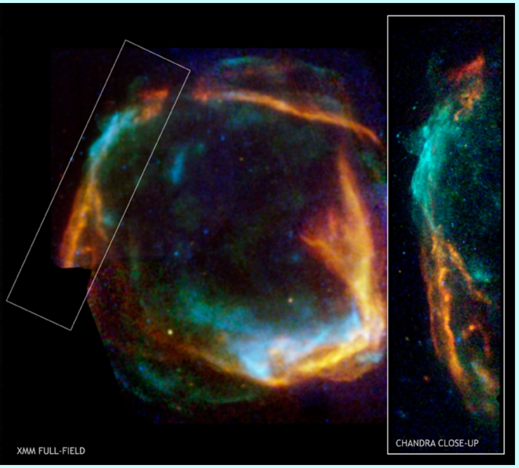


Tycho (SN 1572)
(Warren et al. 2005)



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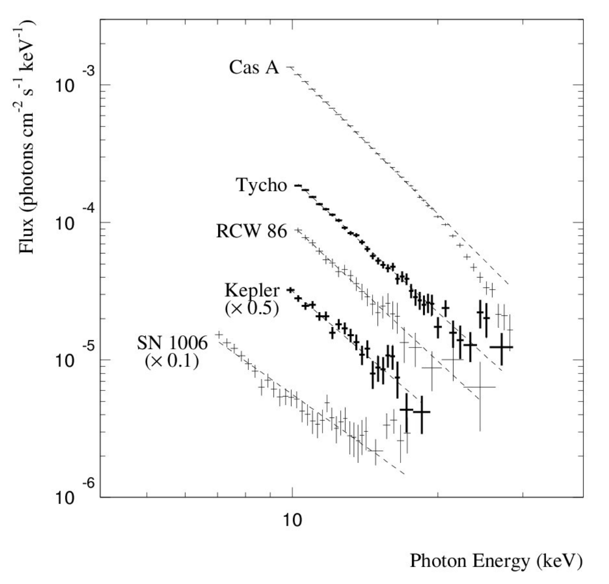


Integrated spectra from RXTE PCA of 5 shell SNRs: all show ~ power-law continua above 10 keV (Allen et al. 1999)

How can we be sure it's synchrotron emission?

- What's the alternative?
  - Nonthermal bremsstrahlung: electrons emitting 2 keV photons have ~6 keV energy; would excite lines
  - Inverse-Compton: observed spectrum far too steep
  - Underionized thermal emission: lines should begin to appear
- Flux lies on rolling-off extrapolation of radio spectrum for sensible parameters. Prediction: spectral steepening

What can we conclude?

- Synchrotron X-rays at 1 keV require electrons with $E = 72\ (h\nu/1\ \mathrm{keV})^{1/2}(B/10\ \mu\mathrm{G})^{-1/2}$ TeV
- Spectrum is not the unbroken extension of radio spectrum: rolling off
- Spectral cutoff could be due to finite age (or size) of remnant, lack of turbulence to scatter particles, or (affecting electrons only) radiative energy losses

Maximum energies

Diffusion: $\kappa \propto$ mfp = ηr_g commonly assumed, so $\kappa \propto 1/B$.
Acceleration time to momentum $p \propto \kappa(p)/u(\mathrm{shock})^2$ so rapid acceleration for high B, u(shock). Cutoffs:

1. age (or size) of remnant: $E_{\mathrm{max}} \propto t\, u(\mathrm{shock})^2 B \eta^{-1}$
2. lack of scattering above some λ(MHD): $E_{\mathrm{max}} \propto \lambda B$
3. radiative losses: $E_{\mathrm{max}} \propto u(\mathrm{shock})\, \eta^{-1/2} B^{-1/2}$

In all cases, easily reach 10 – 100 TeV.

So observing frequency at which spectrum rolls off gives information on remnant properties.

Rolloff frequencies

$$h\nu_{\rm roll}({\rm age}) \sim 0.4 \left(\frac{u_{\rm sh}}{3000 \ {\rm km \ s^{-1}}}\right)^4 \left(\frac{t}{1000 \ {\rm yr}}\right)^2 \left(\frac{B}{10 \ \mu{\rm G}}\right)^3 (\eta R_J)^{-2} \ \text{keV}$$

$$h\nu_{\rm roll}({\rm loss}) \sim 2 \left(\frac{u_{\rm sh}}{3000 \ {\rm km \ s^{-1}}}\right)^2 (\eta R_J)^{-1} \ \text{keV} \quad \textit{independent} \text{ of } B!$$

$$h\nu_{\rm roll}({\rm esc}) \sim 2 \left(\frac{B}{10 \ \mu{\rm G}}\right)^3 \lambda_{17}^2 \ \text{keV}$$

Here $R_J(\theta_{\rm Bn}, \eta, r) \equiv \tau_{\rm acc}(\theta_{\rm Bn})/\tau_{\rm acc}(\theta_{\rm Bn} = 0^\circ)$.

Operative value from loss mechanism giving lowest $E_{\rm max}$

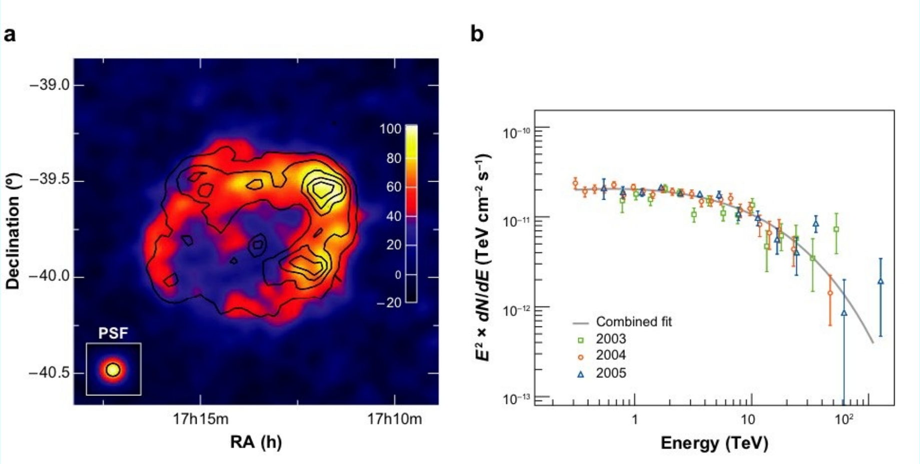
Radiation mechanisms, keV to TeV

1. Hadronic: inelastic p+p collisions produce π^0 's which decay to gamma rays (E > 70 MeV). Same spectrum as ions.

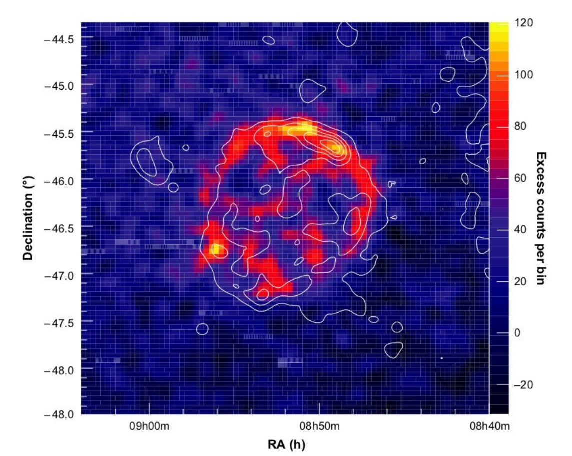
2. Leptonic:
   a. Synchrotron (require > 10 TeV electrons for few keV photons). See only in cutoff regime.
   b. Nonthermal bremsstrahlung: same spectrum as of electrons of similar energies (so up to TeV photons)
   c. Inverse-Compton from ambient radiation (UVOIR) or CMB: hard spectrum (same as radio) up to cutoff, ~ tens of TeV

Direct evidence for cosmic-ray *ions*: need to be sure hadronic process is operating. Best: 70 MeV “bump.”

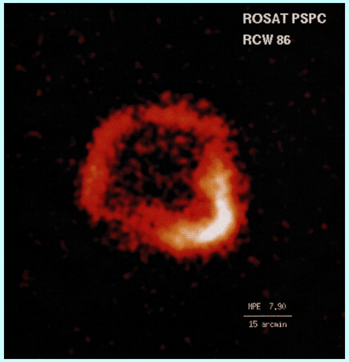
H.E.S.S. observes 4 shell SNRs at TeV energies



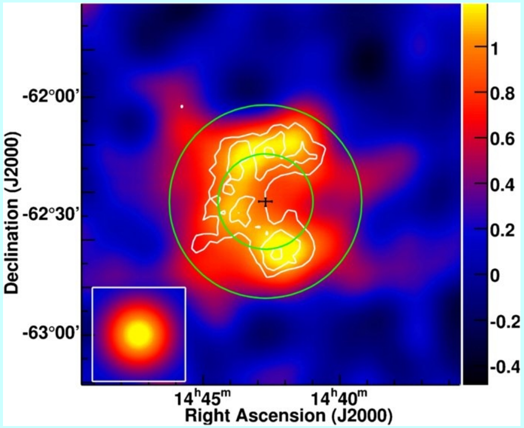
G347.3-0.5



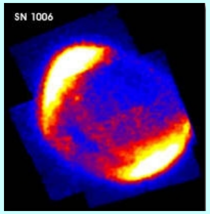
Vela Jr.



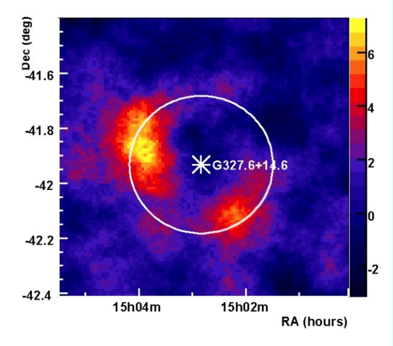
ROSAT



RCW 86

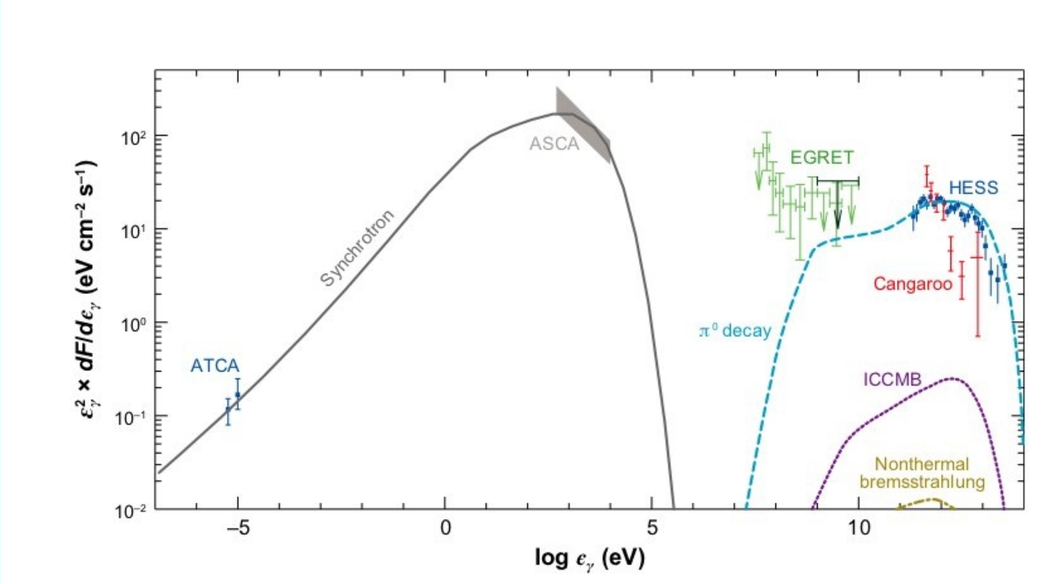


ASCA

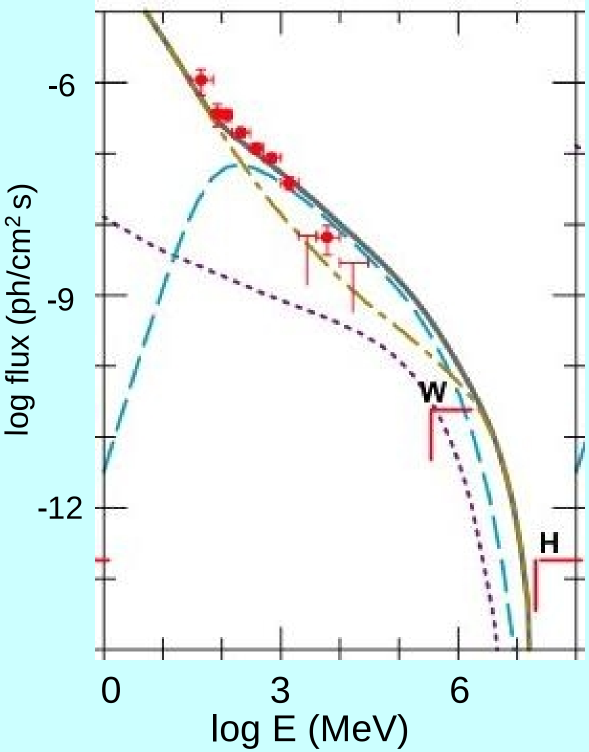


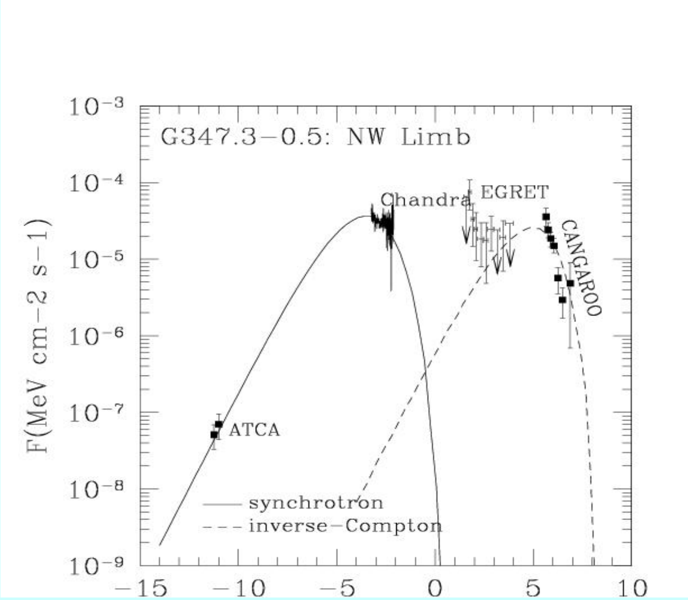
SN 1006

High-energy emission modeling



G347.3-0.5: Berezhko & Völk 2006. TeV emission from π^0-decay.

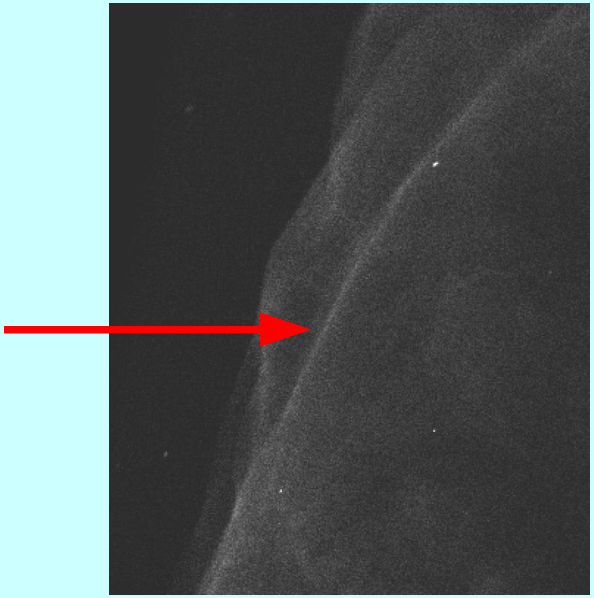




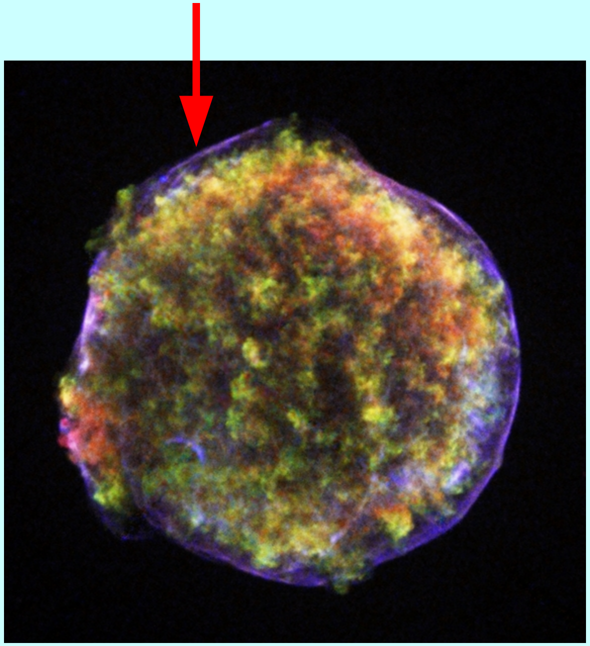
G347.3-0.5: Lazendić et al. 2004. TeV emission from IC/CMB.

IC443: Baring et al. 1999. GeV emission from sum of brems, π^0-decay, IC/CMB

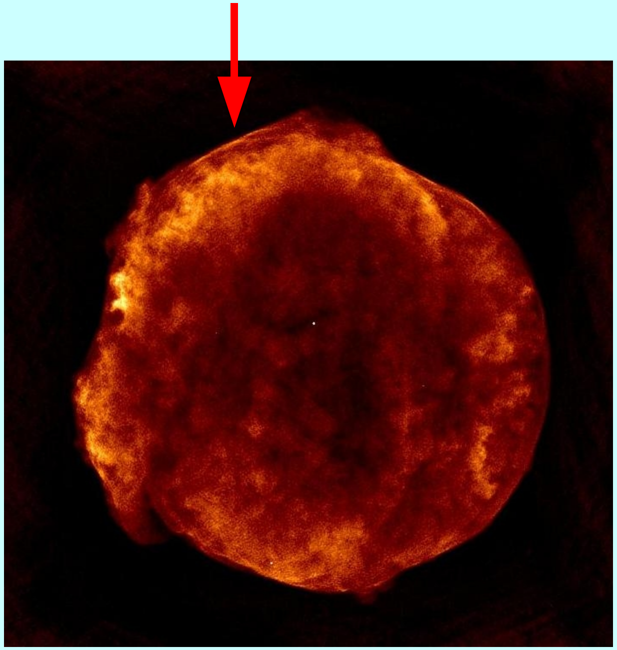
Thin X-ray rims: magnetic-field amplification



SN 1006 (Chandra)



Tycho (Chandra)

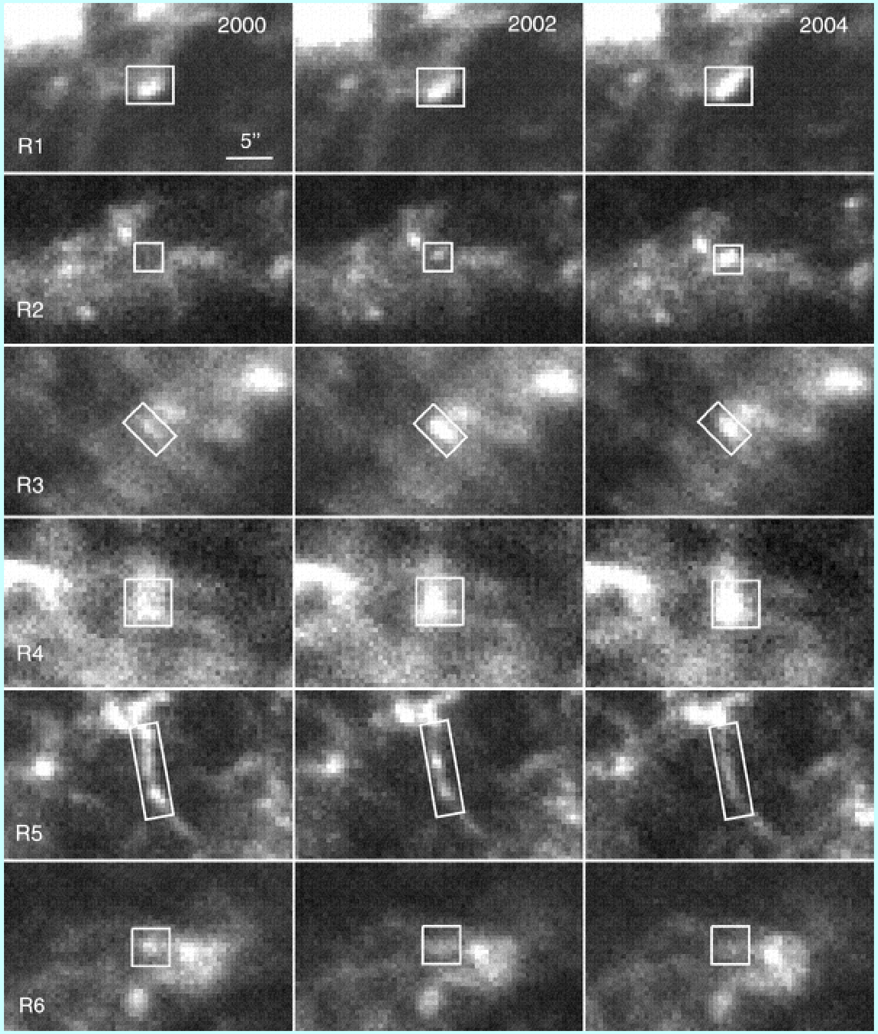


Tycho (radio; VLA)

If thickness of rims is due to synchrotron losses, electrons must be depleted rapidly: for observed rim widths w ~ 0.01 pc, need $\mathbf{B > 200\,(v_{shock}/1000\ km/s)^{2/3}\,(w/0.01\ pc)^{-2/3}\ \mu G}$ (without some amplification process, just expect to compress typical interstellar B ~ 3 μG by compression ratio r ~ 4).

Similar rims seen in other SNRs (but some rims are thin in radio as well!)

Rapid X-ray variability



Chandra observations of Cas A (Patnaude & Fesen 2007)

Small features seen to brighten or fade in ~ 1 yr in Cas A (Patnaude & Fesen 2007), G347.3–0.5 (Uchiyama et al. 2007)
If this is timescale of particle acceleration, need high *B*:

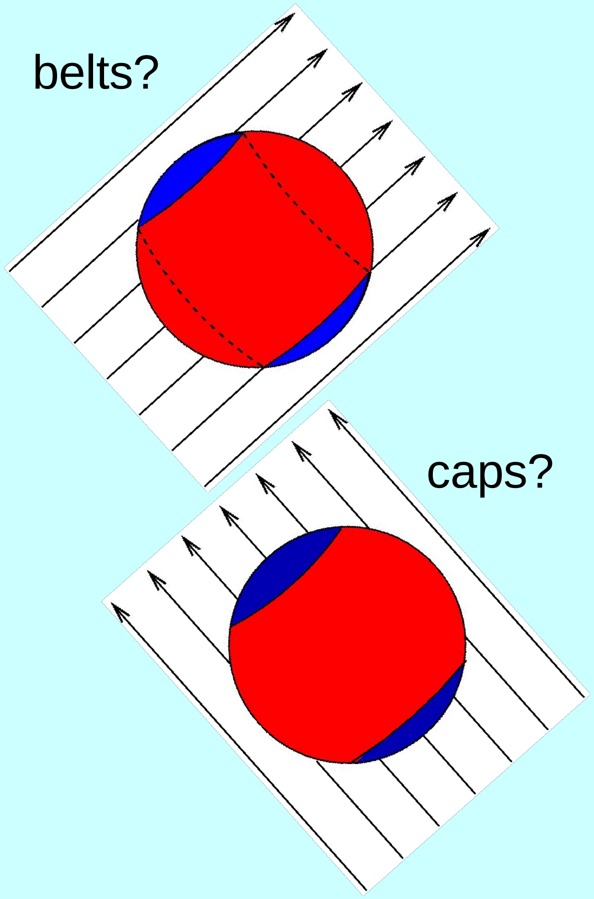
$$\tau_{\text{accel}} \propto \kappa/(v_{\text{shock}})^2$$

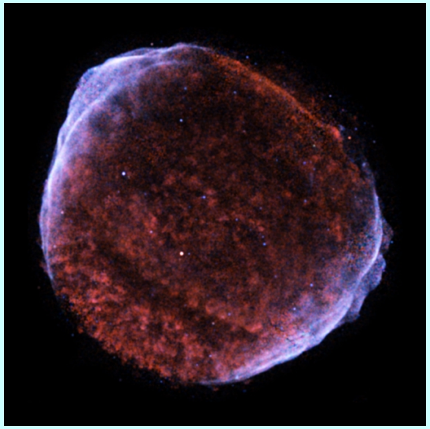
where κ is diffusion coefficient, $\kappa \propto 1/B$

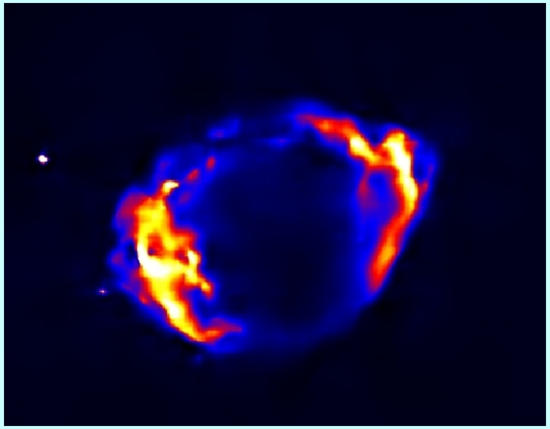
Get *B* ~ 1 mG (Uchiyama et al. 2007)

If fading is due to synchrotron losses, similar result. -- But *B* may be turbulent; see “twinkling” of temporary regions of very high *B* (Bykov et al. 2008, 2009)

Obliquity dependence: caps or belts?



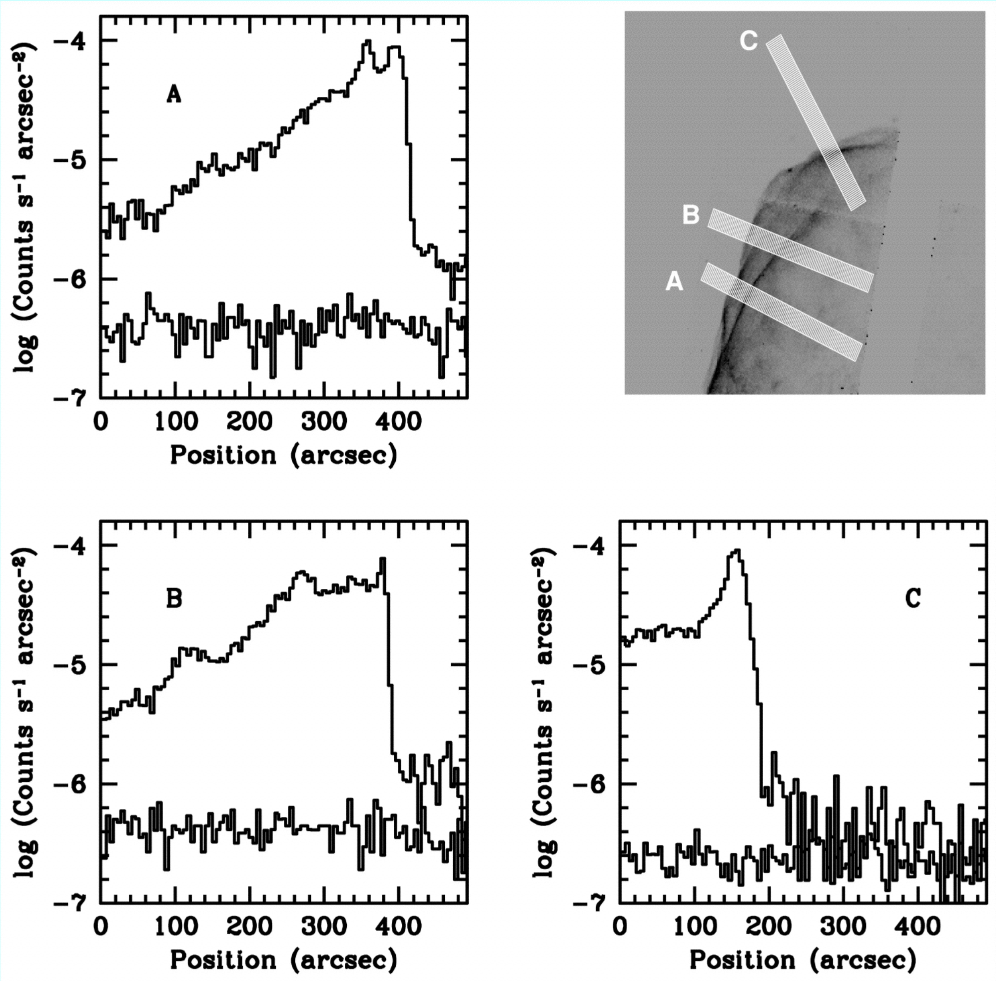




Are bright rims in SN 1006 and G1.9+0.3 due to variations in θ_{Bn} , obliquity angle between shock normal and upstream (undisturbed! ⇒ Type Ia?) magnetic field? If so, are rims caps (θ_{Bn} ~ 0, parallel shocks) or belts (θ_{Bn} ~ 90˚, perpendicular)?

Morphological evidence (Rothenflug et al. 2004, Orlando et al. 2009) supports caps for SN 1006. (But what would end-on view look like?) Both SN 1006 and G1.9+0.3: higher rolloff frequencies in caps. What increases acceleration rate for electrons? (Frequency radiated by electrons with loss-limited E_{max} is independent of *B*!)

Synchrotron halos: where is the precursor?

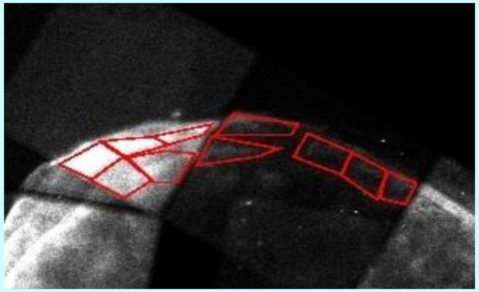


SN 1006: X-rays drop by > 70 within < 20″ of sharp edge ($\Delta R/R < 0.02$). (Perhaps see ~ 2 x blank-sky background, but could be dust scattering too)

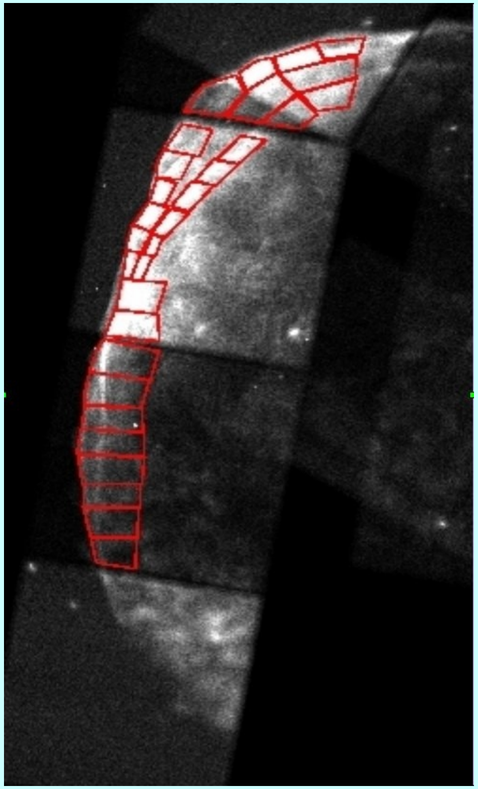
Modified shock: both *B*, cr's continuous at shock. Upstream diffusion scale must be < 0.02 R.

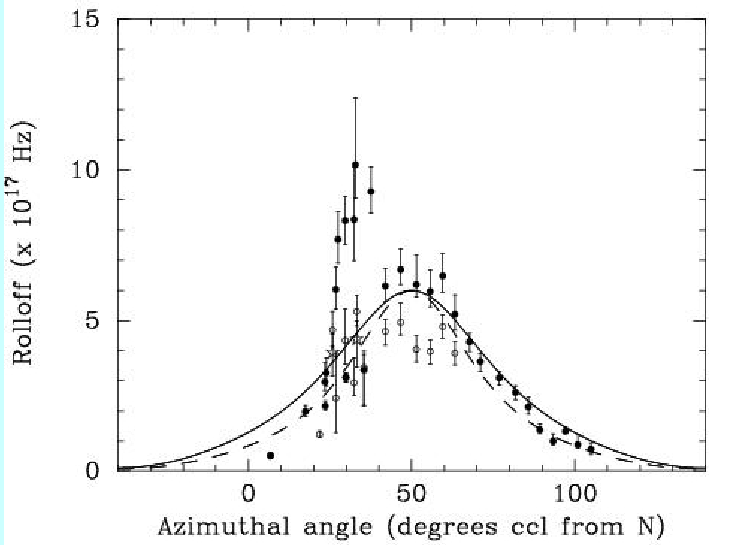
Chandra: Long et al. 2003

Modeling azimuthal variations in SN 1006



SN 1006: dependence of rolloff frequency on azimuthal position (McFarland, SPR, Borkowski, 2004 HEAD)





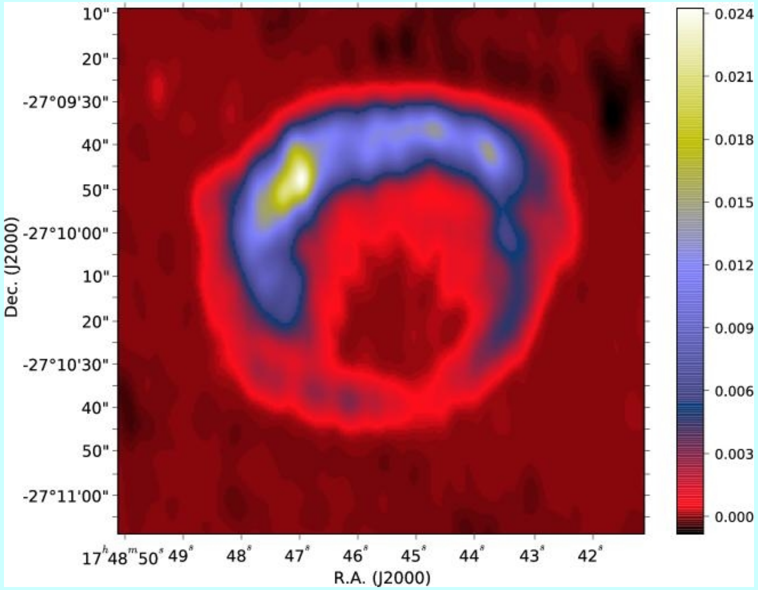
Filled circles: outer rim. Open circles: inner filaments.
Open stars: intermediate regions.
Loss−limited models: solid line, η = 2; dashed, η = 3

Models: loss-limited, more rapid acceleration where shock is perpendicular. Describes inner shell well.

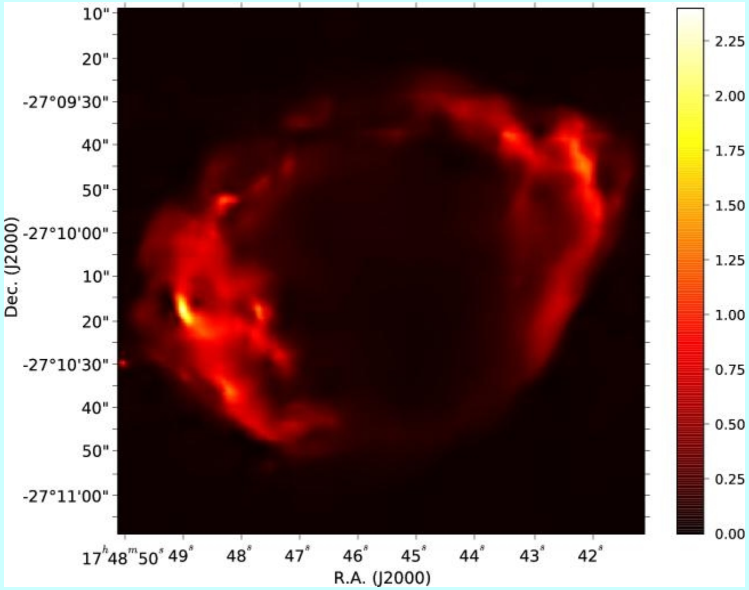
NE “extension”: higher rolloff values

Loss-limited acceleration: rolloff frequency is *independent* of *B*

G1.9+0.3: the youngest Galactic SNR



Radio (VLA 1985)



Chandra (2007) (platelet smoothed)

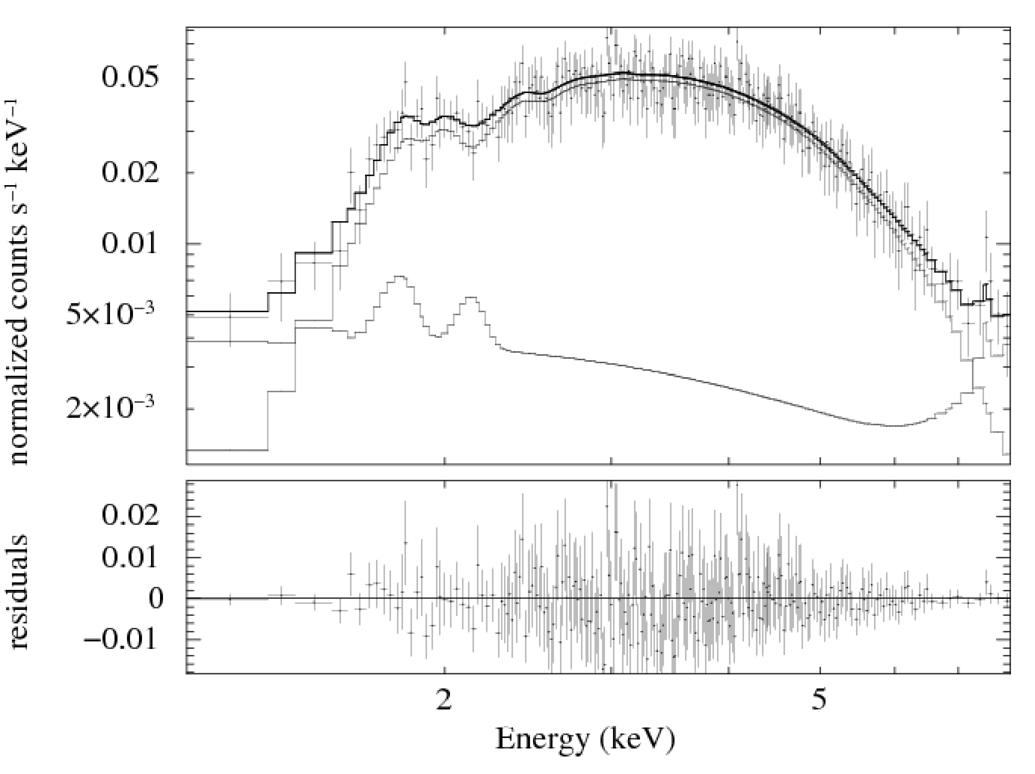
Angular diameter ~ 100". Radio flux (1 GHz) ~ 0.9 Jy; $\alpha \sim -0.65$.

Discovered in search for young SNRs (Green & Gull 1984).

2007 Chandra observation compared with 1985 radio observation:

X-ray size larger by 16%! Age < 140 yr (~ 100 yr with deceleration)!

G1.9 integrated spectrum



Chandra: Reynolds et al. 2009

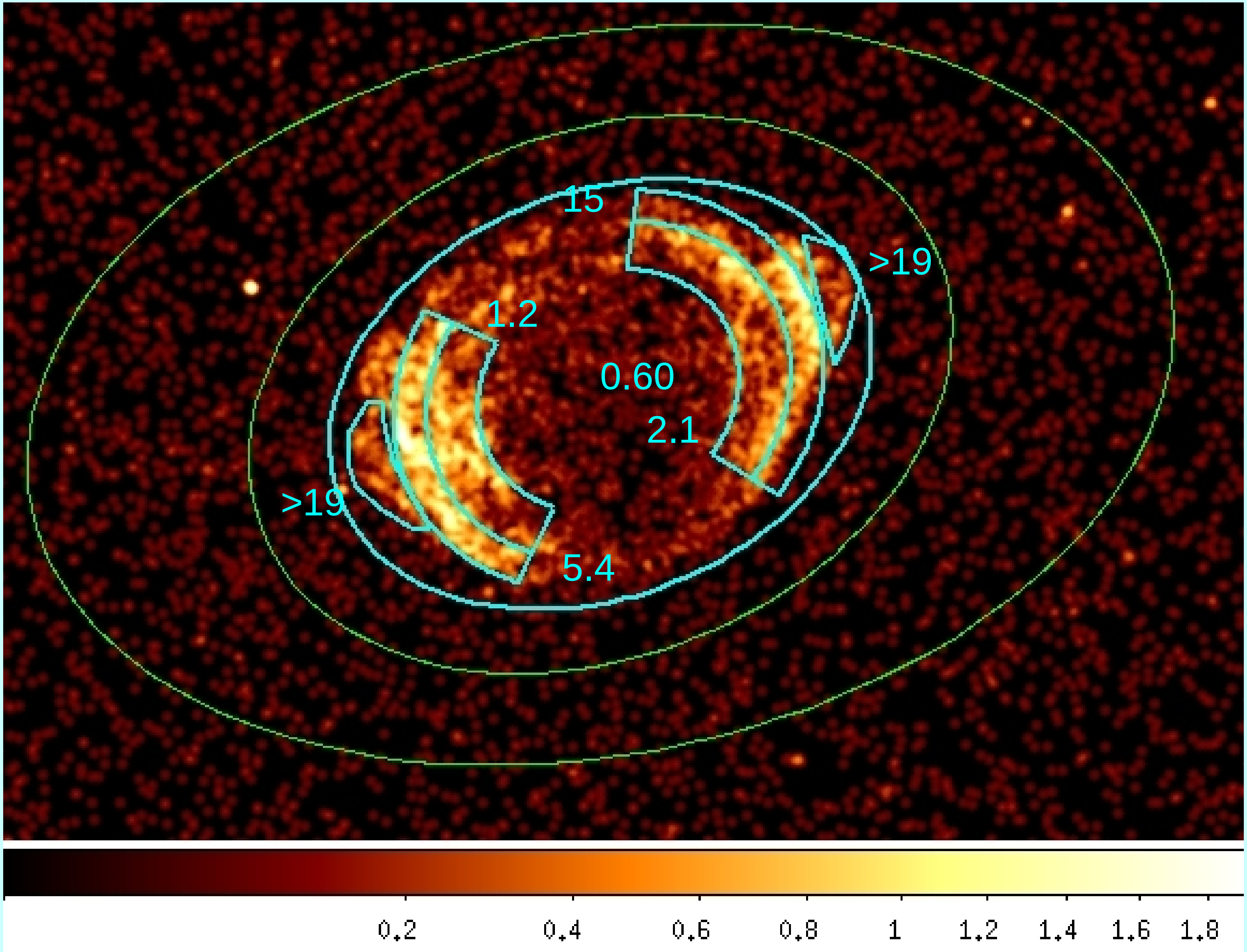
Featureless spectrum, well fit with srcut model

Rolloff frequency **2.2 keV**

Dust scattering is important (N_H ~ 6 x 10^{22} cm^{-2} !)

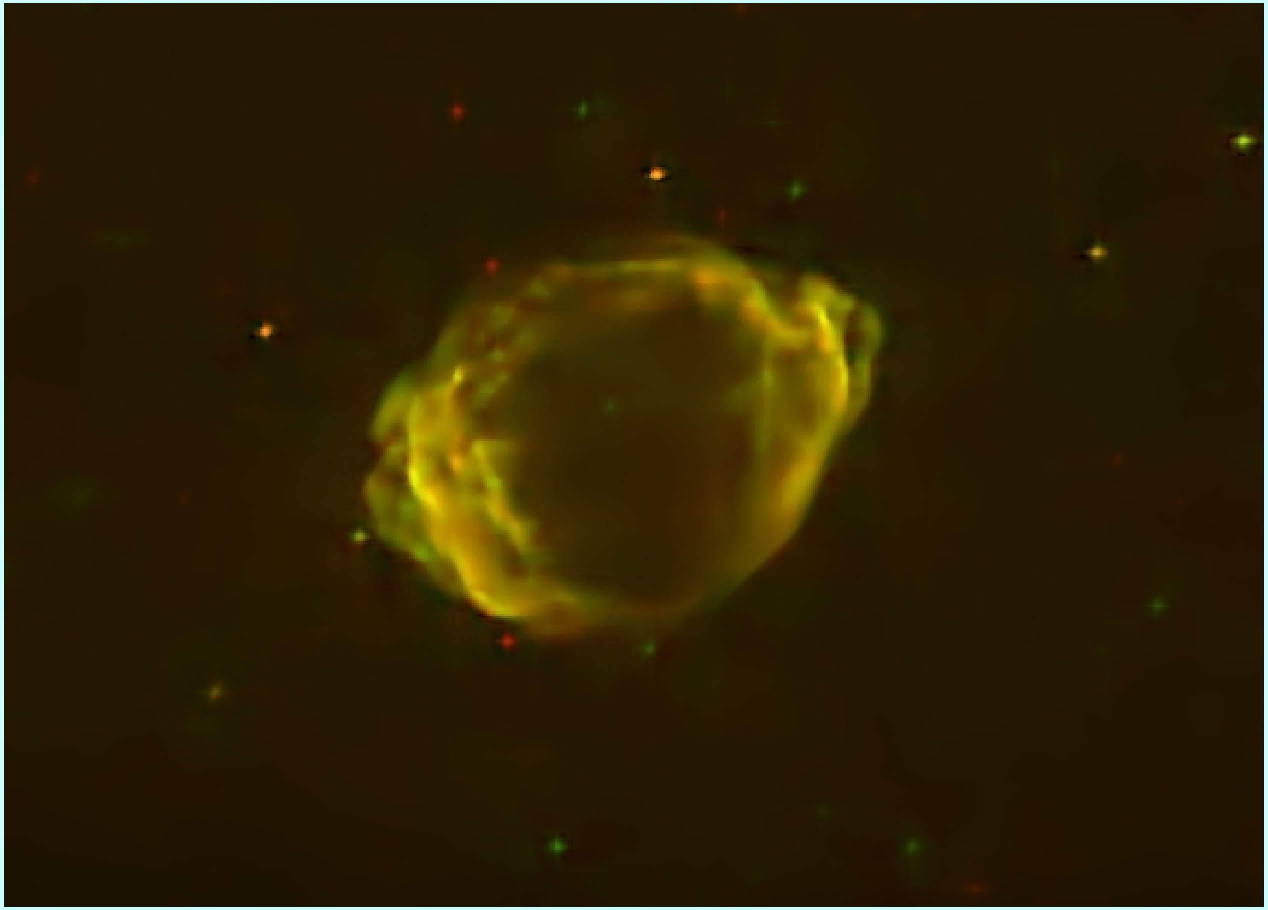
Faint hint of thermal emission near Si line

X-ray Spectral Variations



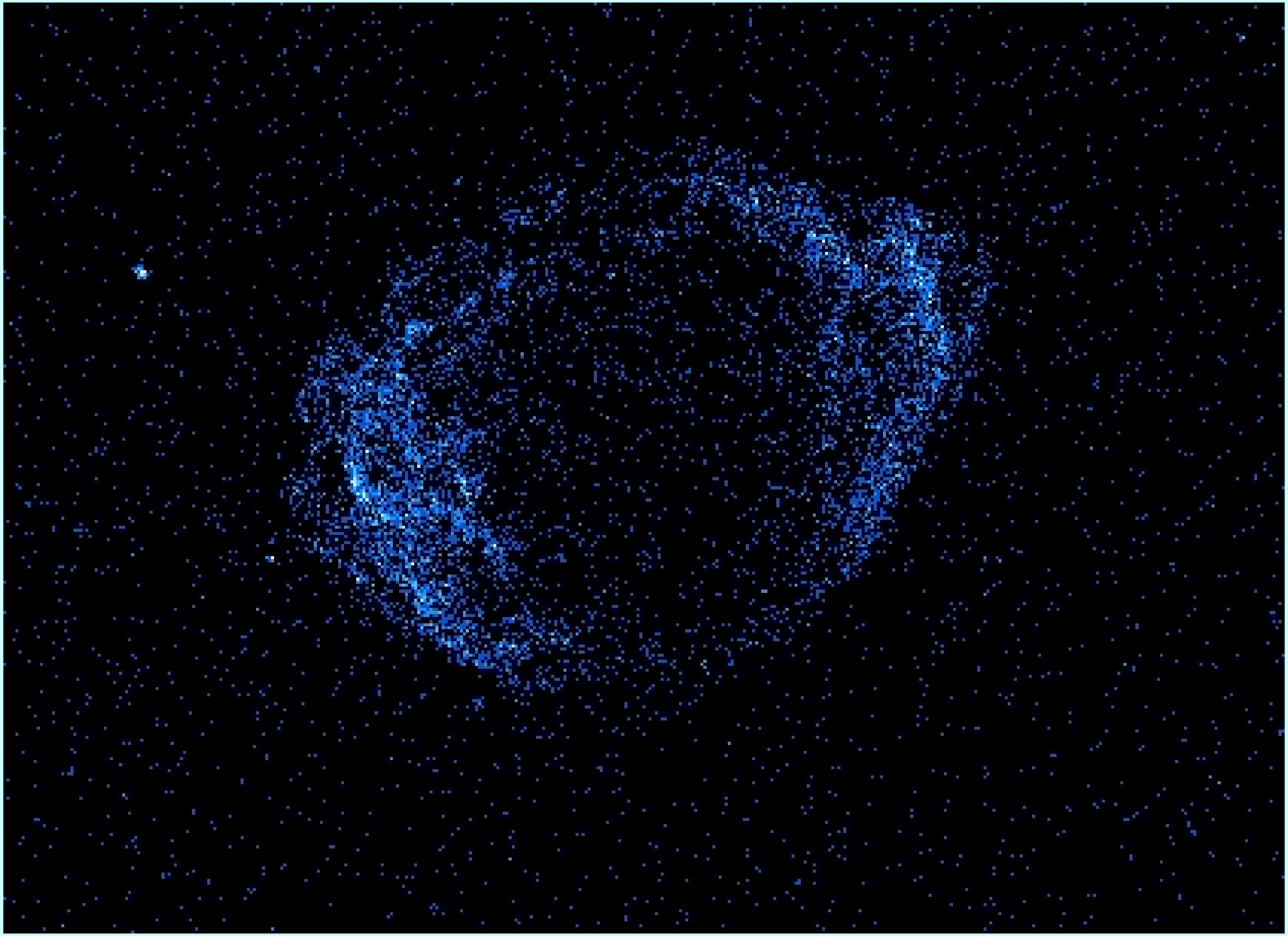
Break frequency increases outward along the bipolar X-ray axis

Two-color 2009 Chandra Image



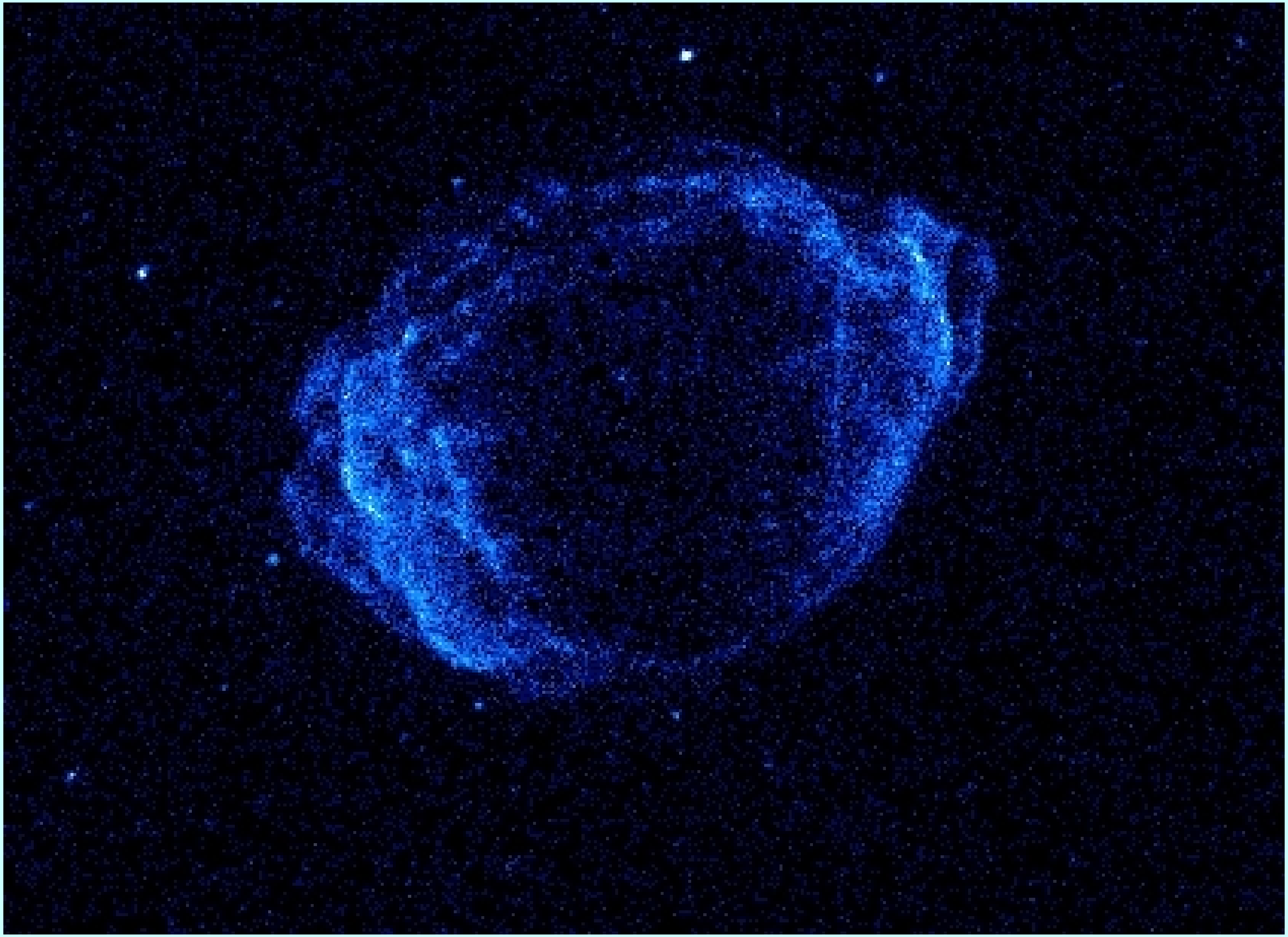
Red: 1-3.5 keV, Green: 3.5-7 keV. Spectral variations are apparent

2007



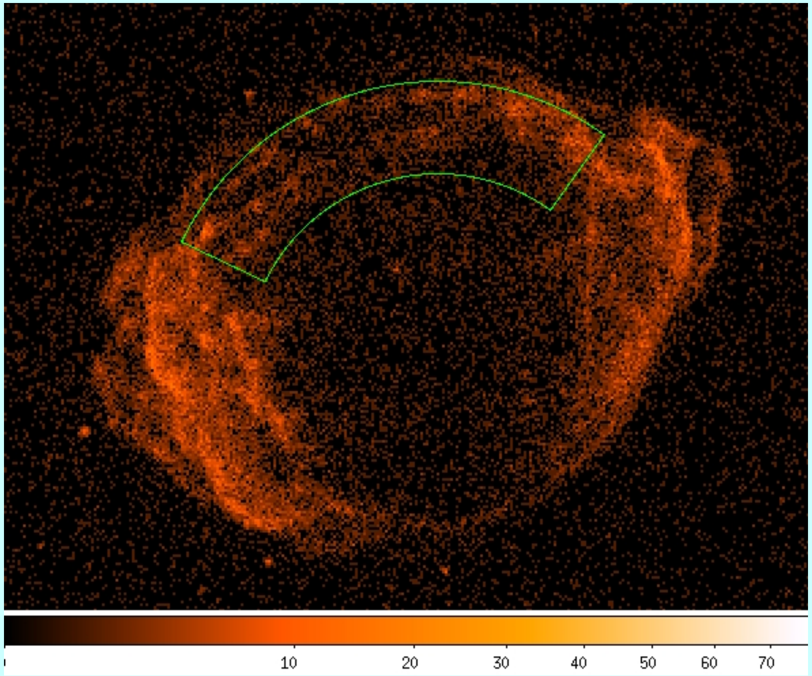
smaller

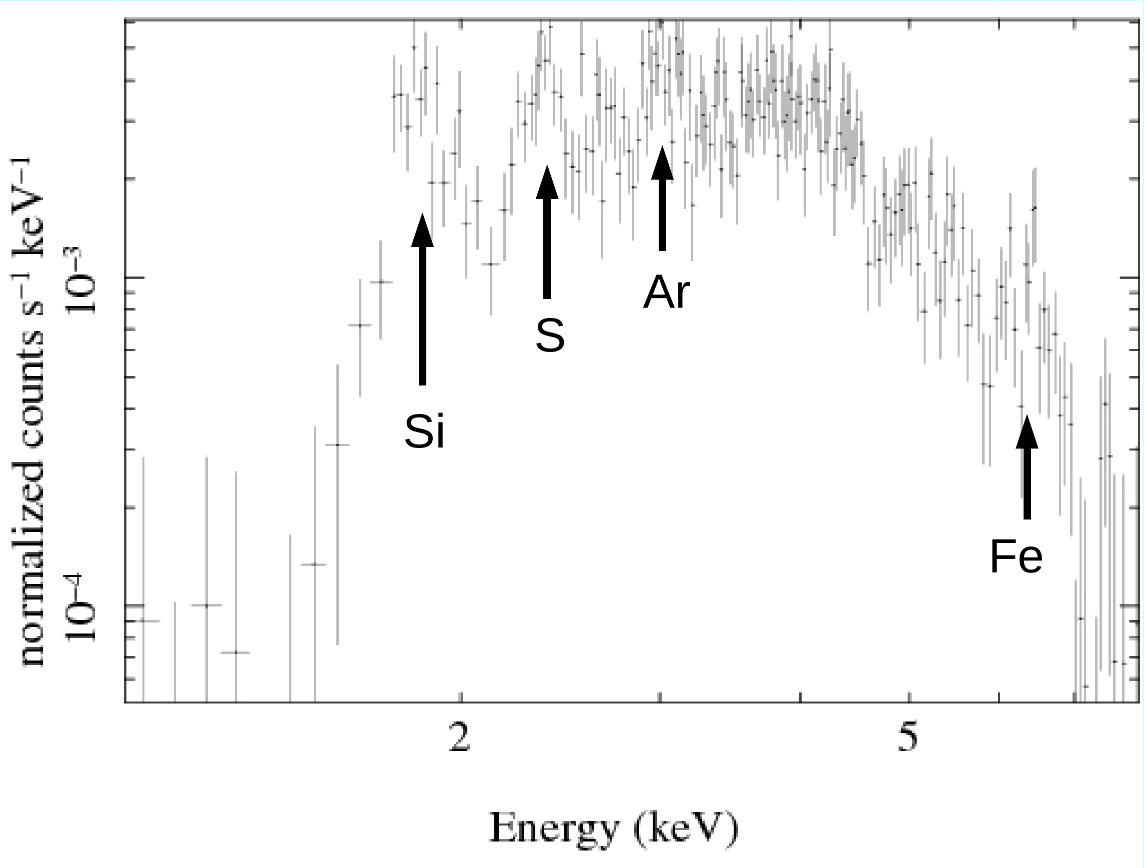
2009



bigger

Thermal X-ray emission: powerful diagnostics





See He-like states of Si, S, Ar, Ca. Very strong Fe K: width 26,000 km/s!

Deeper observations can further constrain shock velocity, density

Puzzles: summary

1. **Synchrotron halos** in precursors are still missing.
2. SN 1006 and G1.9+0.3: large-scale **obliquity effects** seem required, but shock is turbulent locally. Variations of rolloff energy with position demand variations in acceleration rate by ~ 10 (not just in *B* if loss-limited). Variations in radio intensity may require injection effects.
3. **Thin *radio* filaments** seem to require disappearing B, but some X-ray filaments do *not* have thin radio counterparts.
4. Some X-ray synchrotron edges are not thin filaments.

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5. Needs: Fermi observations; more TeV observations; modeling of particle injection, obliquity-dependence, B amplification. Model radio observations too! Watch G1.9+0.3 evolve. Monitor twinkling!