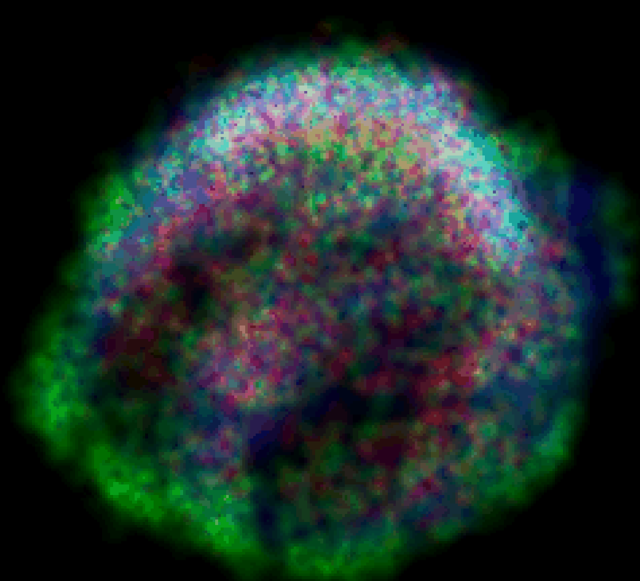
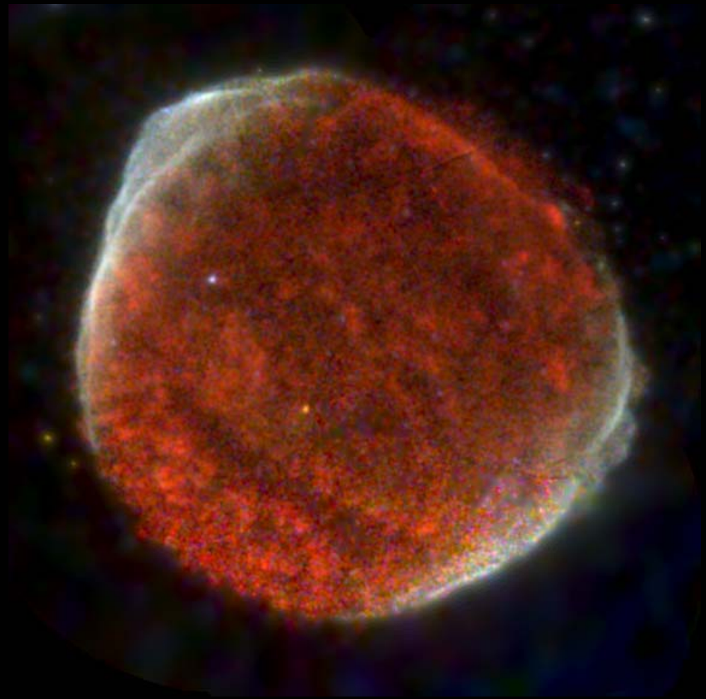
Observations of supernova remnants

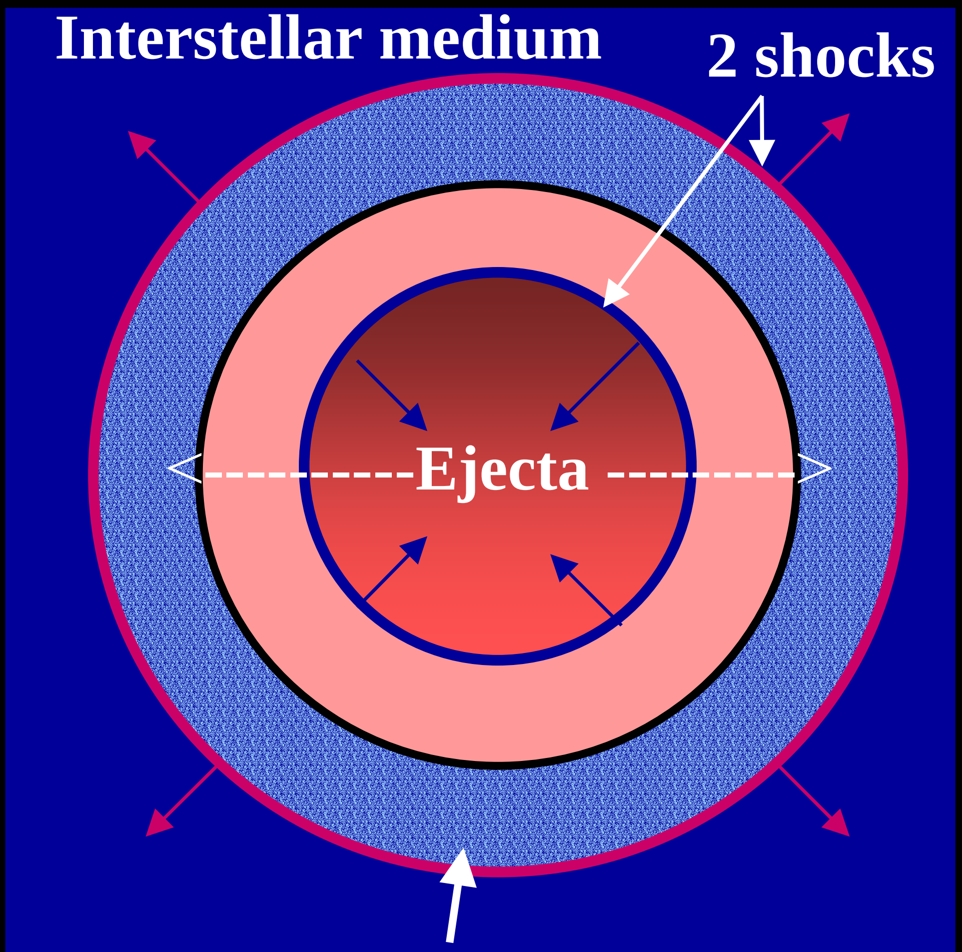
Anne Decourchelle
Service d'Astrophysique, CEA Saclay





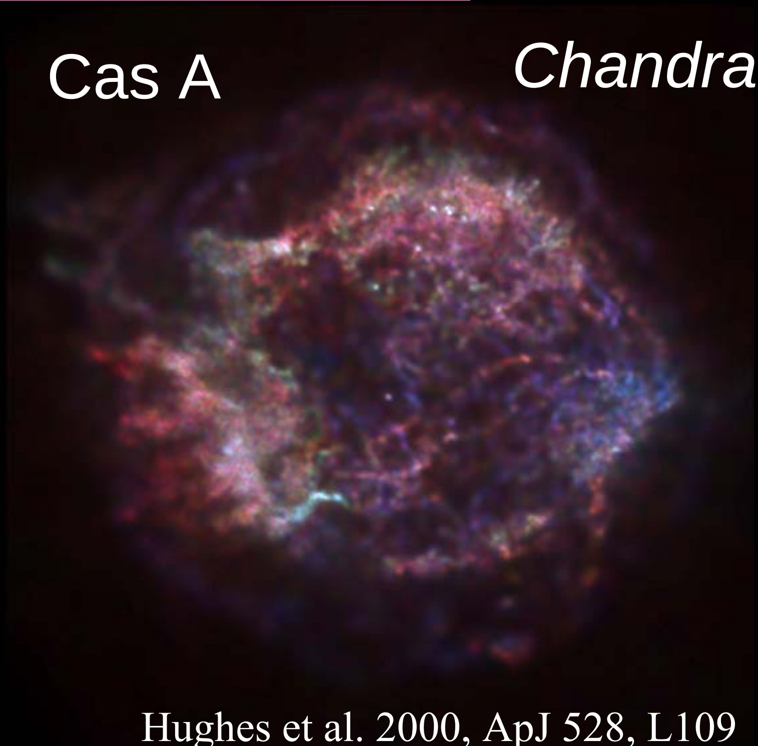
I- Ejecta dominated SNRs: Cas A, Tycho and Kepler
II- Synchrotron-dominated SNRs: SN 1006, G347.3-0.5

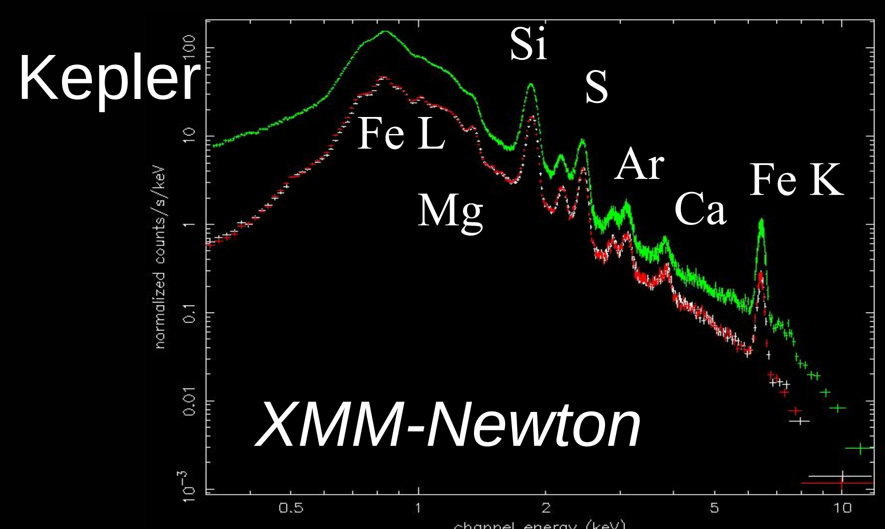
Young supernova remnants



interface ejecta/ ISM

SN material ejected at high velocity
=> Heating of the ejecta and ISM
Powerful X-ray production





Cassam-Chenai et al., 2004, A&A 414, 545

Supernova remnants

X-ray emission

Thermal emission:

bremsstrahlung and lines emission

(highly ionized gas)

Non thermal emission:

synchrotron, nonthermal bremsstrahlung

Progenitor/supernova

nucleosynthesis products, element mixing, rayleigh-Taylor instabilities

Interaction with the ambient medium

(circumstellar wind, interstellar medium and clouds)

Particle acceleration

(TeV electrons)

Radio emission

Thermal emission:

atomic and molecular lines emission

(HI, CO,…)

Nonthermal emission:

Synchrotron emission

Particle acceleration

(GeV electrons)

Interstellar environment

(distribution of HI, CO,… clouds)

Shock interaction with interstellar clouds

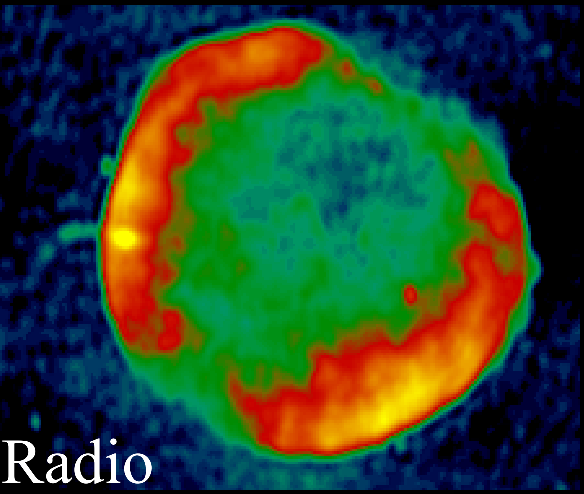
(masers)

Particle acceleration in SNRs

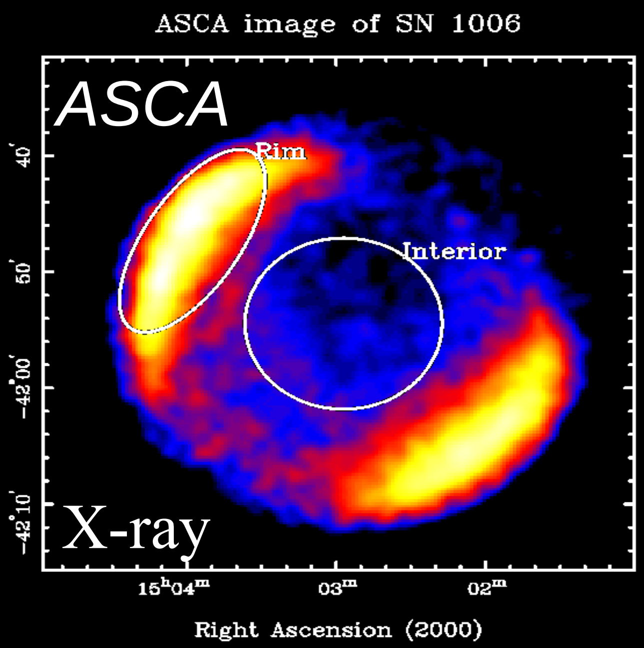
SNRs : main source of cosmic-rays with energies up to 3 10^{15} eV ?

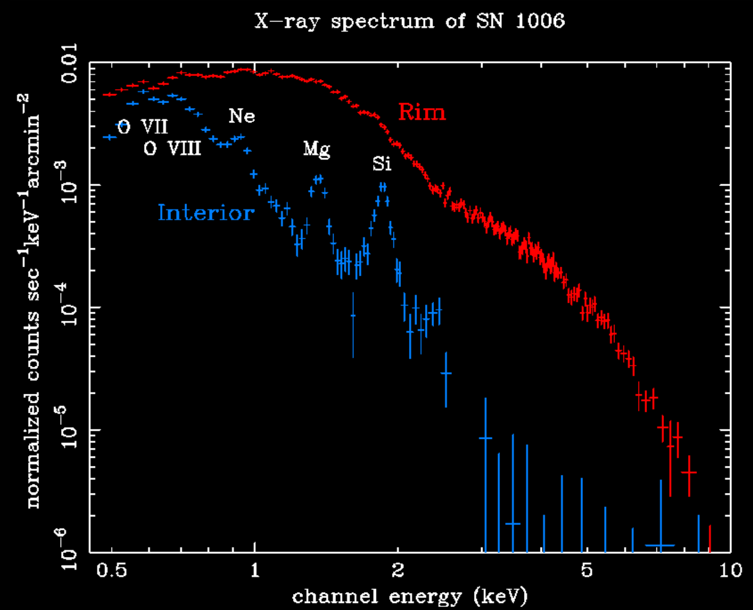
- Strong shocks in SNRs: First-order Fermi shock acceleration
- Radio emission → relativistic GeV electrons
- X-ray observations of synchrotron emission => **TeV electrons**

First evidence of electrons accelerated up to TeV energies in SN 1006:
X-ray synchrotron emission in the bright rims and X-ray thermal emission in the faint areas
(Koyama et al. 1995, Nature 378, 255)



Roger et al. 1988, ApJ 332, 940





Search for observational constraints on particle acceleration in SNRs

Pending questions:

- ❑ How efficient is cosmic-ray acceleration in SNRs ?
- ❑ What is the maximum energy of accelerated particles ?
- ❑ How large is the magnetic field ? Is it very turbulent ?
- ❑ Is it amplified ?
- ❑ Evidence for ion acceleration in SNRs ?

I- Constraints on the efficiency of particle acceleration at the forward shock

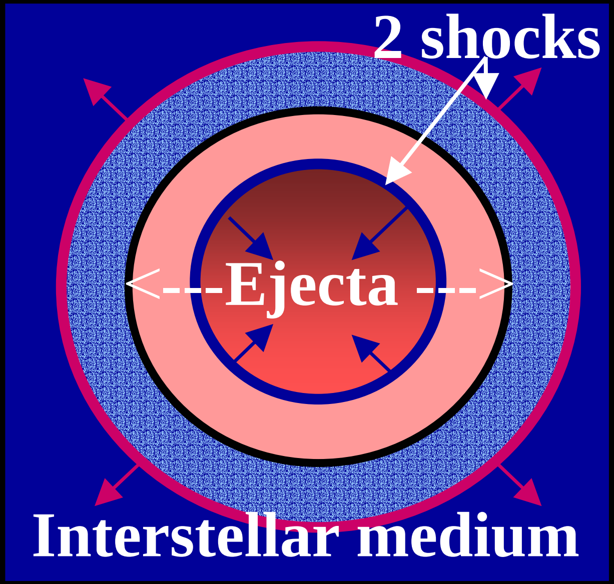
- X-ray and radio morphology
- X-ray spectroscopy

II- Constraints on the efficiency of particle acceleration at the reverse shock

III- Geometry of the acceleration: SN 1006

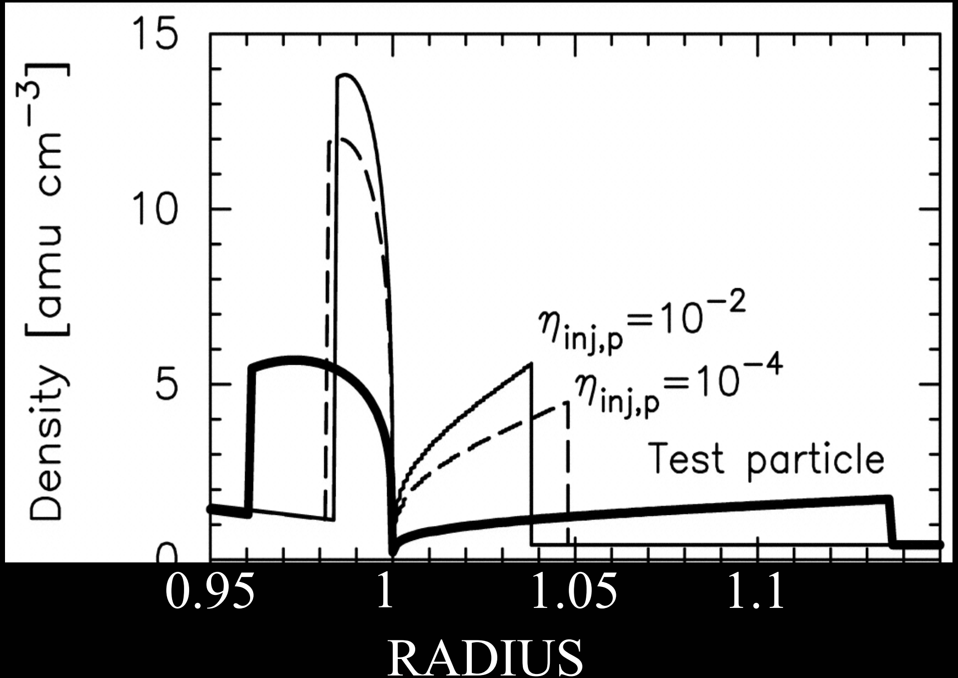
IV- Particle acceleration and interaction with interstellar clouds: G347.3-0.5

Efficiency of particle acceleration in young SNRs

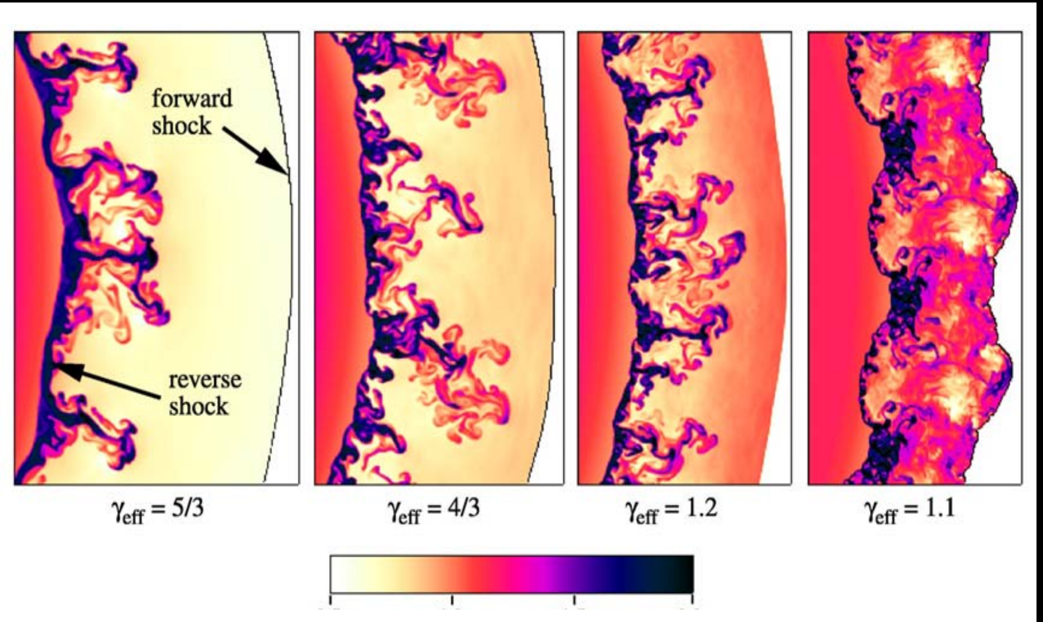


Efficient particle acceleration

=>Modification of the morphology of the interaction region, observable in X-rays, and of the shocked gas temperature

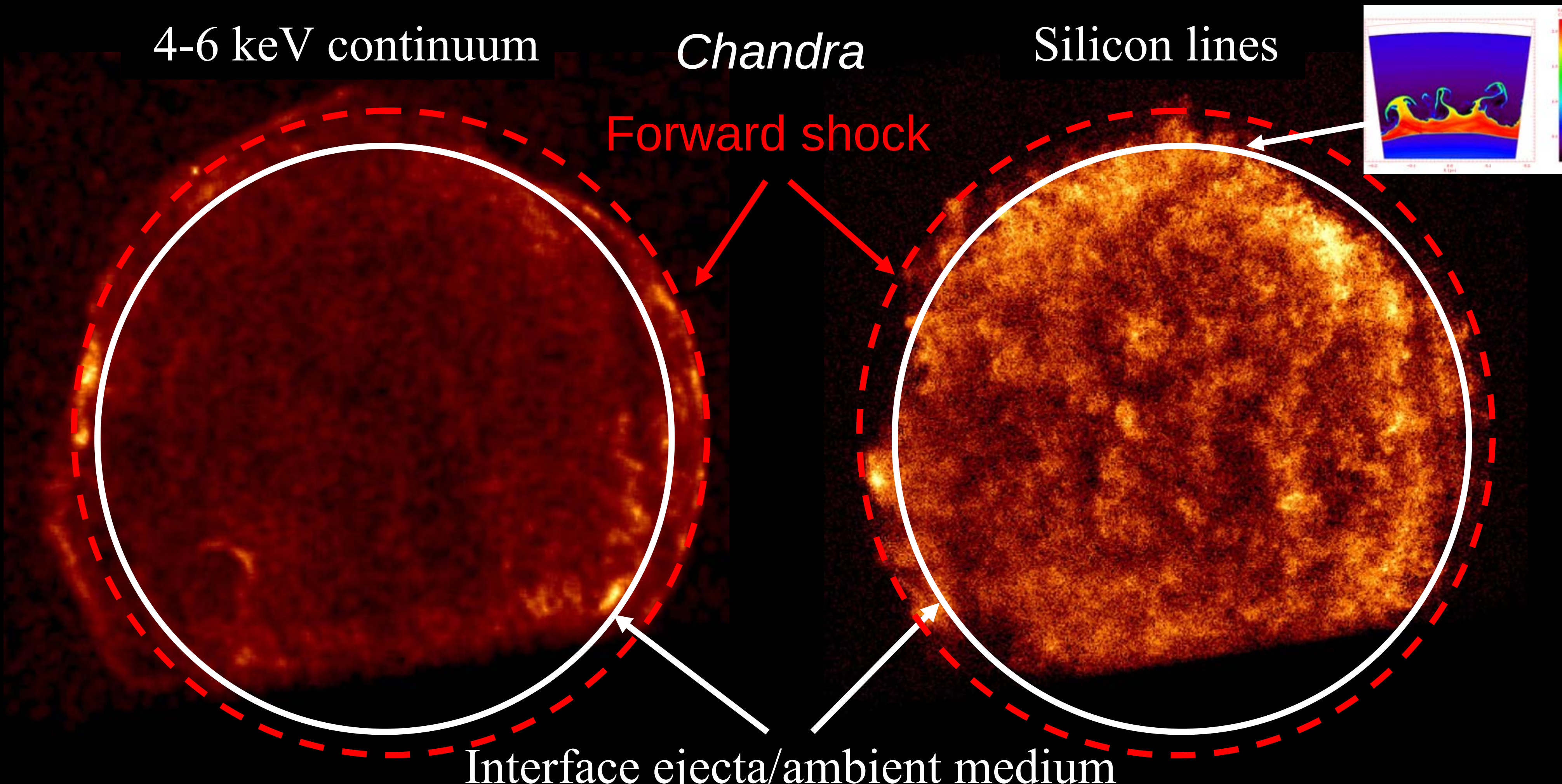


Decourchelle, Ellison, Ballet 2000, ApJ 543, L57
Ellison, Decourchelle, Ballet 2004, A&A 413, 189



Blondin and Ellison 2001, ApJ 560, 244

X-ray morphology of the interaction region in Tycho



Hwang et al, 2002, ApJ 581, 1101

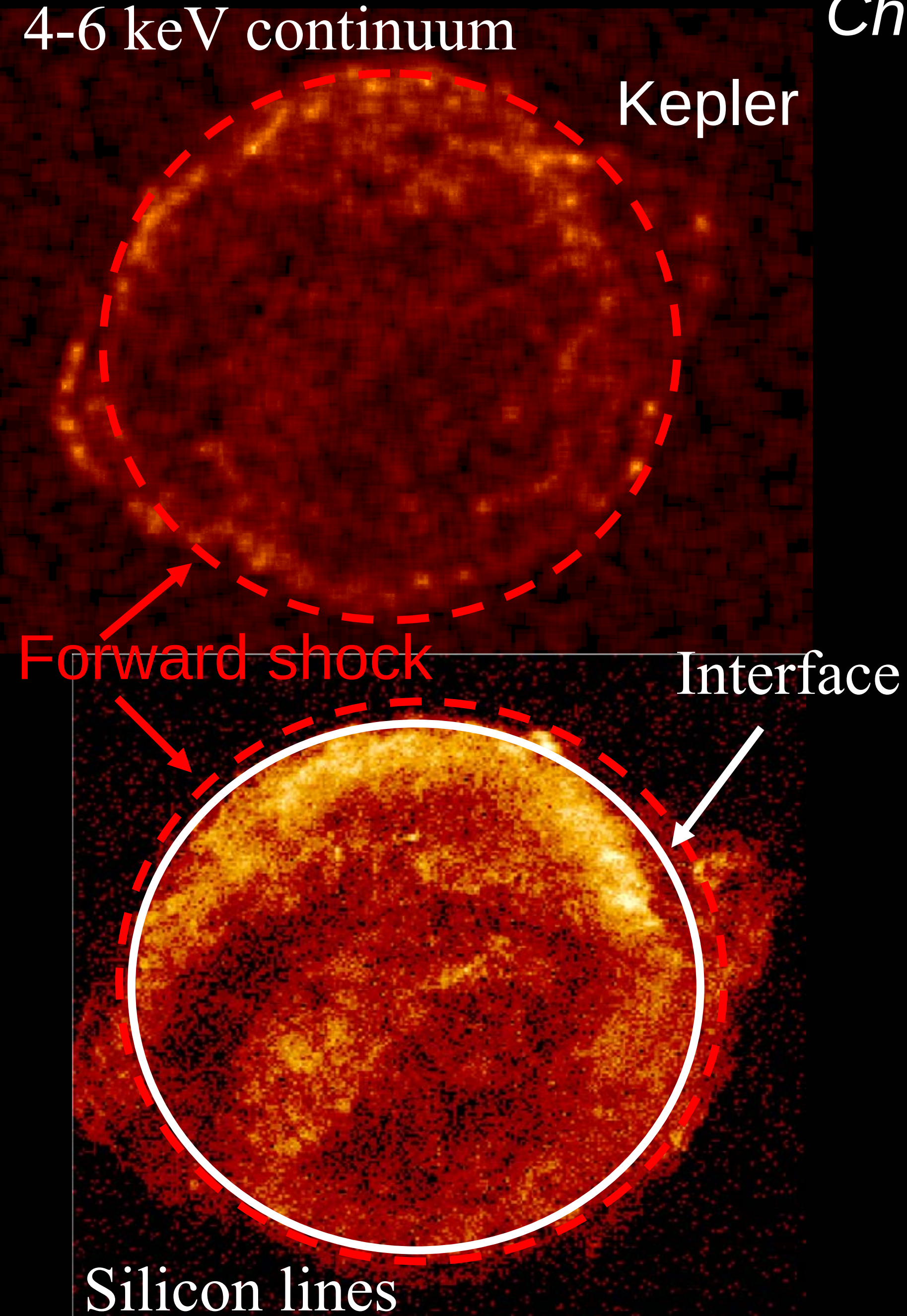
Continuum emission => forward shock; Silicon line emission => shocked ejecta

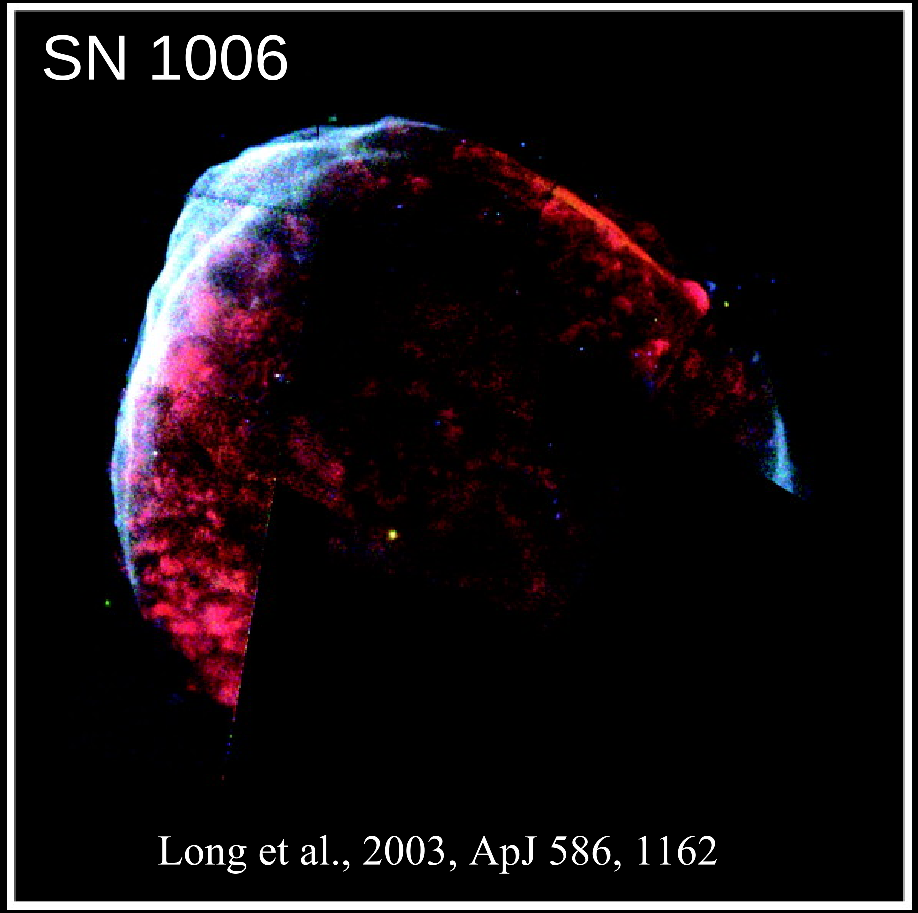
Forward shock very close to the interface ejecta/ambient medium

=> efficient particle acceleration

X-ray morphology of the interaction region in Kepler and SN 1006

Chandra

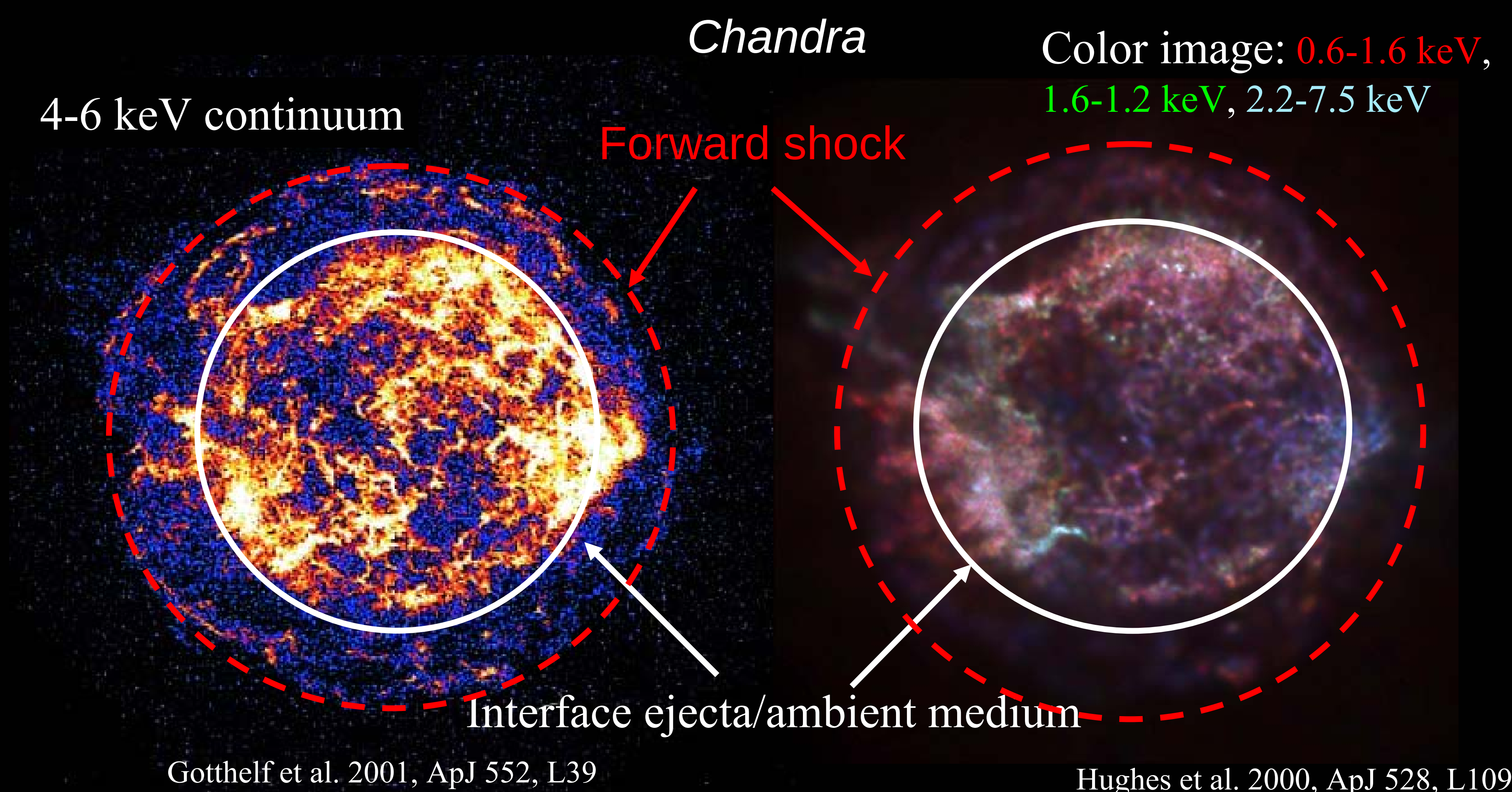




Forward shock very close to the interface ejecta/ambient medium

=> efficient particle acceleration

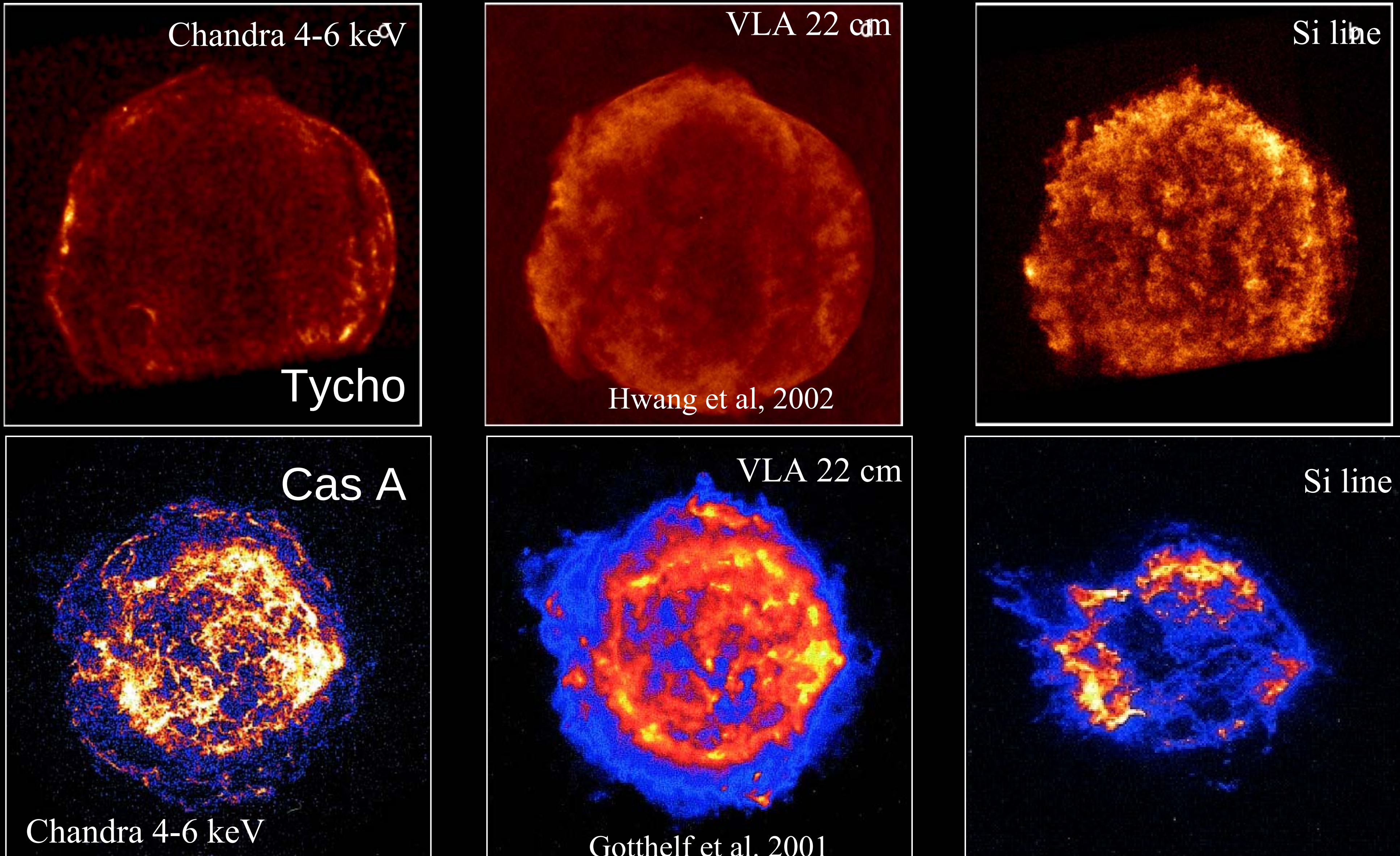
Particularity of Cas A morphology



Strong continuum emission "associated" with the ejecta

Weaker plateau associated with the blast wave

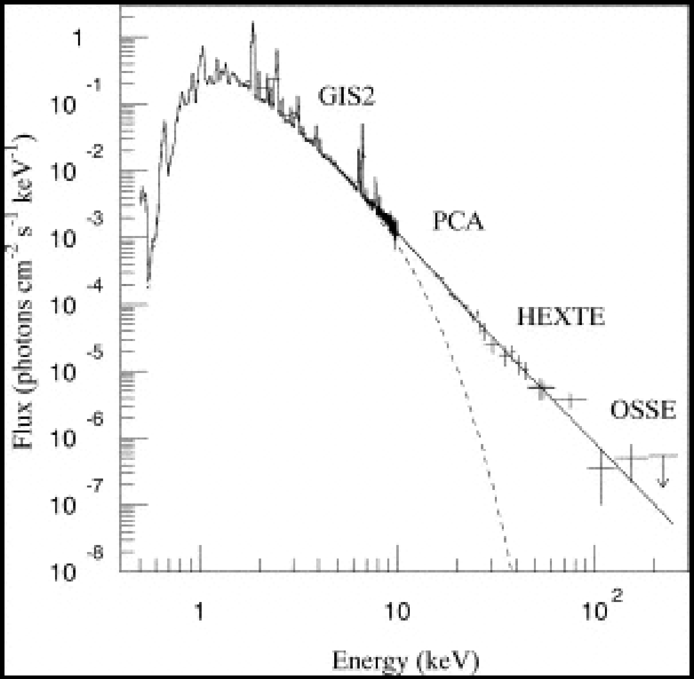
Ambient medium = stellar wind of the progenitor (Chevalier & Oishi 2003, ApJ)



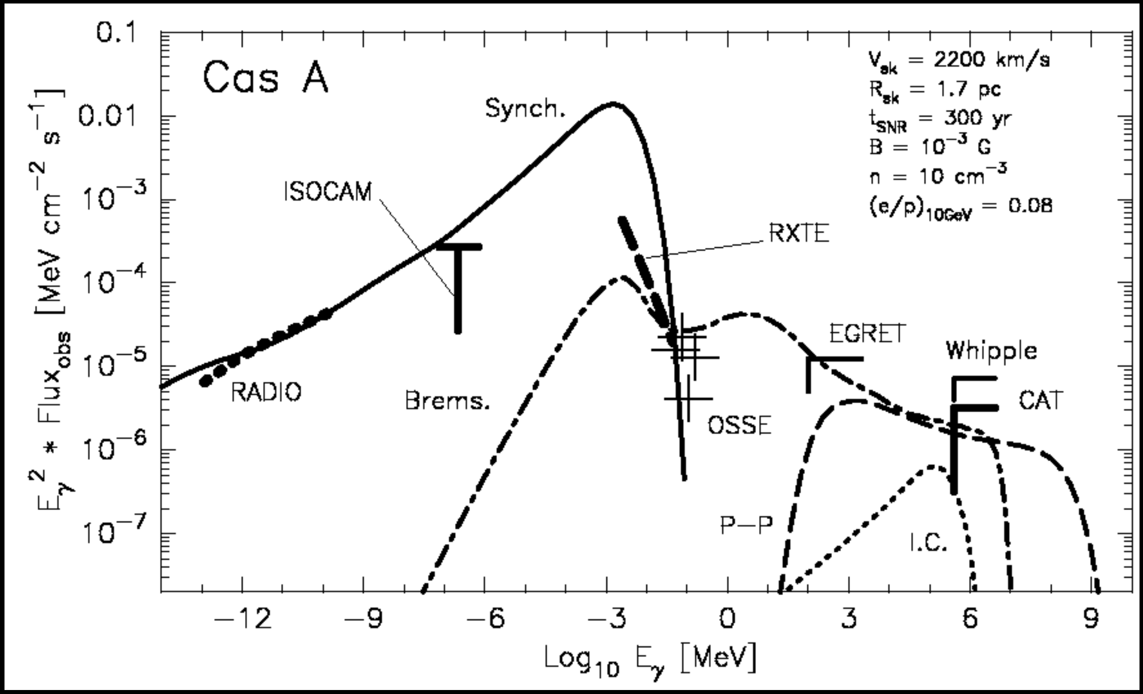
Strong radio emission "associated" with the ejecta interface => **amplified magnetic field** due to R-T instabilities at the interface ejecta/ambient medium (and fast moving knots)

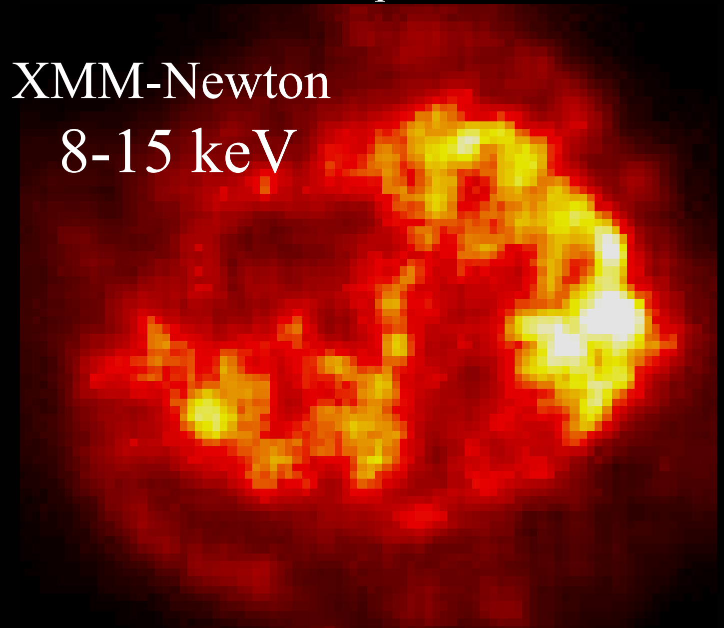
Cas A: **strong X-ray continuum associated with the ejecta !**

Morphology of the high energy X-ray continuum in Cas A



Allen et al. 1997, ApJ 487, L97





Bleeker et al. 2001, A&A 365

Strong radio, weak inverse Compton on IR
⇒ large B ~ 1 mG

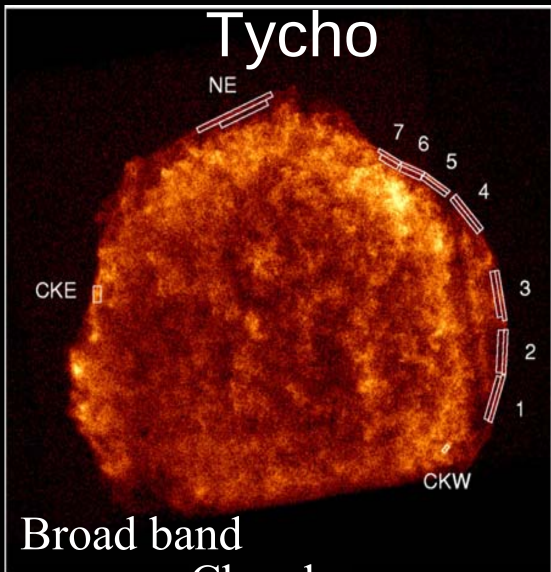
High energy continuum associated with the ejecta
=> inconsistent with X-ray synchrotron

Non-thermal bremsstrahlung at the interface ?

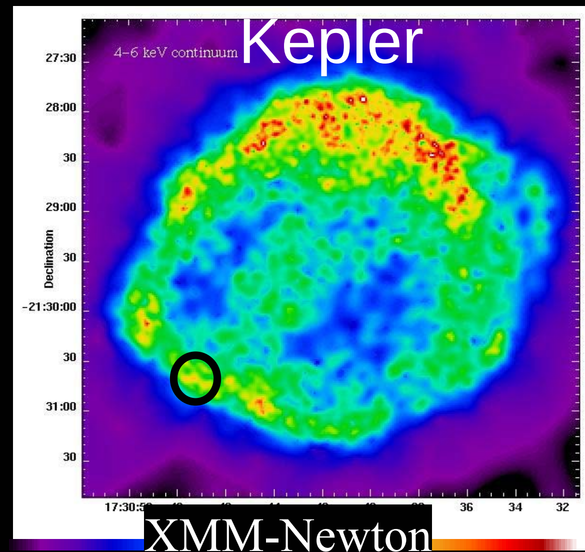
Particle acceleration at secondary shocks ?

(Vink & Laming 2003, ApJ 584, 758)

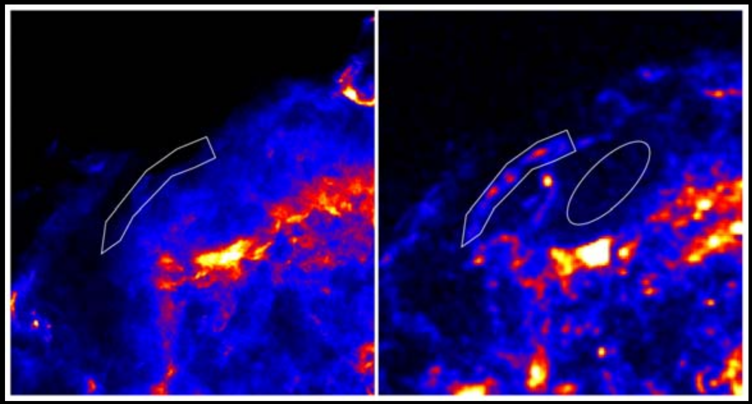
Spectra of the forward shock in ejecta-dominated SNRs



Chandra



Cas A



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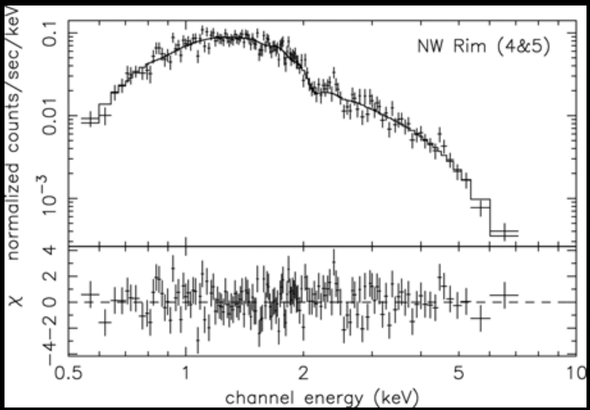
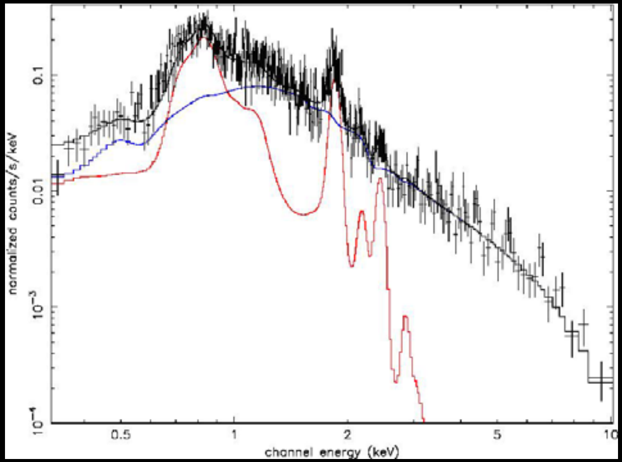
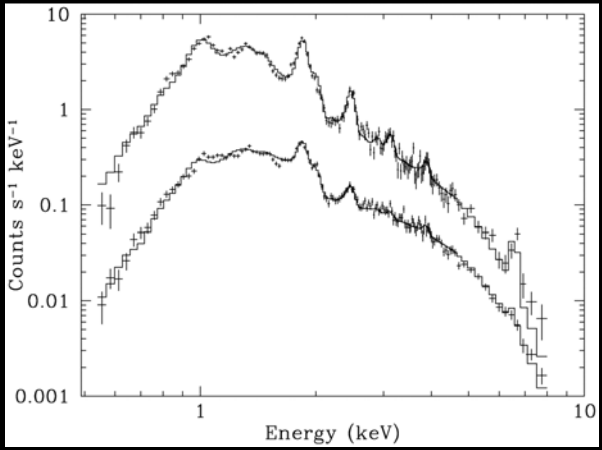


Hwang et al, 2002



Cassam-Chenai et al. 2004, A&A 414, 545



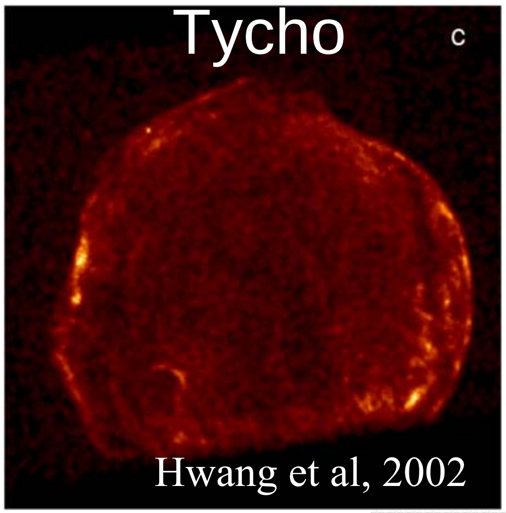
Vink and Laming 2003

Few or no emission line features !

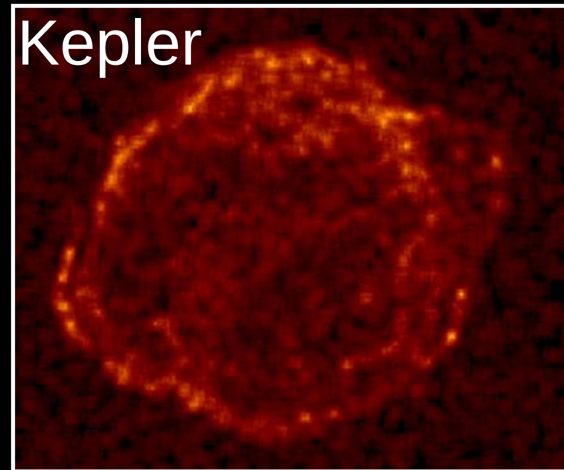
Thermal interpretation requires strong ionization delay: inconsistent with the morphology

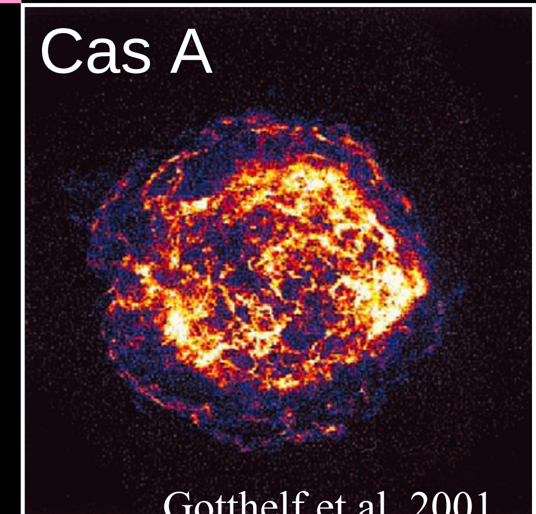
Non-thermal interpretation: synchrotron=> maximum electron energies ~ 1-100 TeV

Sharp rims at the forward shock



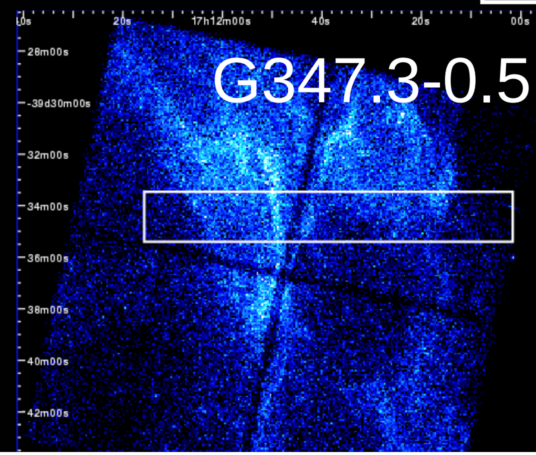
Hwang et al, 2002





Gotthelf et al. 2001

Long et al. 2003, ApJ 586, 1162
Bamba et al. 2003, ApJ 589, 827



Uchiyama et al. 2003, A&A 400, 567
Lazendic et al., 2004, ApJ in press

Sharp filaments observed at the forward shock: **synchrotron emission**

- all along the periphery in the 3 young ejecta-dominated SNRs: Tycho, Kepler, Cas A
- in bilateral limbs in SN 1006
- irregularly along the periphery in G347.3-0.5

=> width of the filament determined by synchrotron losses of ultrarelativistic electrons

Sharp rims at the forward shock. Radiative ?

Synchrotron emission:
width determined by synchrotron losses of ultrarelativistic electrons

Time to move out $\Delta t = \Delta r / u_{gas}$ with $u_{gas} = 1/R*V_{sh}$, R: compression ratio

Equating t_{loss} and Δt gives B.

Tycho: D = 2.3 kpc, Vsh~ 4600 km/s, 4”, $\Delta t = 1.65\times10^9$ s **=> B ~ 75 μG**

Cas A: D = 3.4 kpc, Vsh~ 5200 km/s, <4", $\Delta t < 1.56\times10^9$ s **=> B ~ 60-100 μG**

Vink and Laming 2003, ApJ

Kepler: D = 4.8 kpc, Vsh~ 5400 km/s, 3”, $\Delta t = 1.59\times10^9$ s **=> B ~ 60 μG**

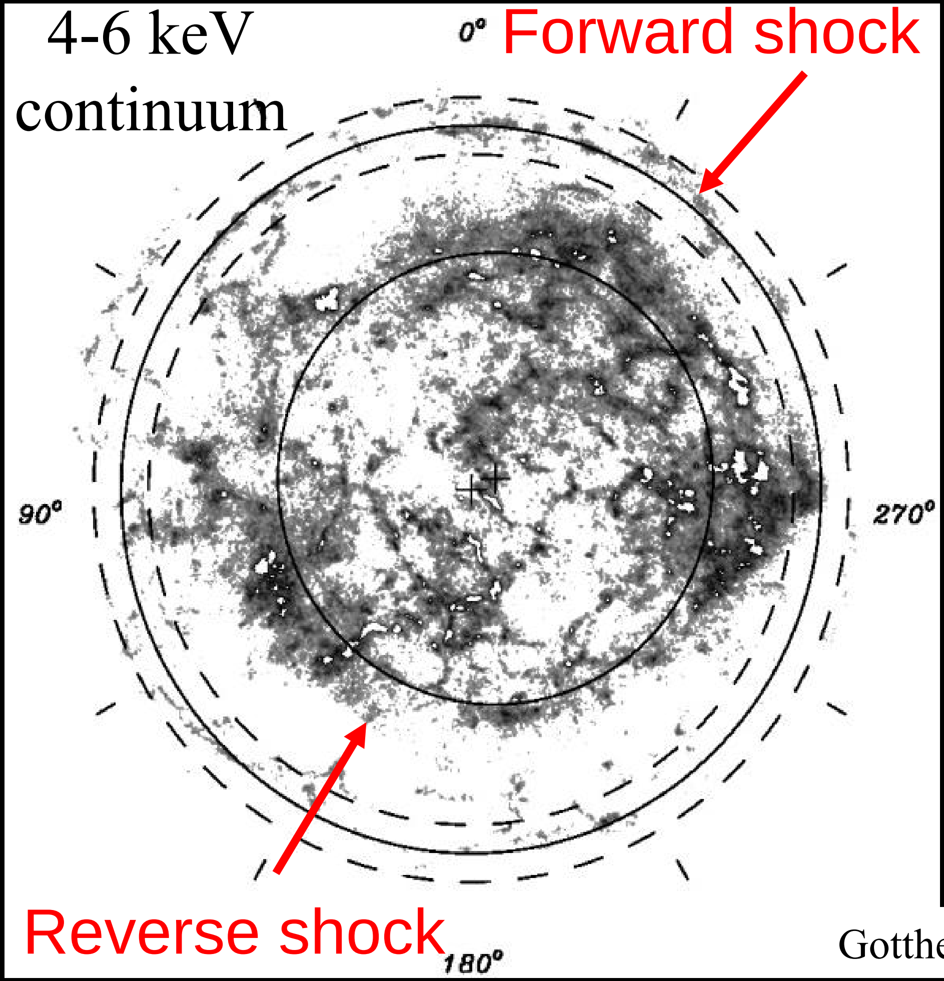
Intrinsic width expected to be even smaller

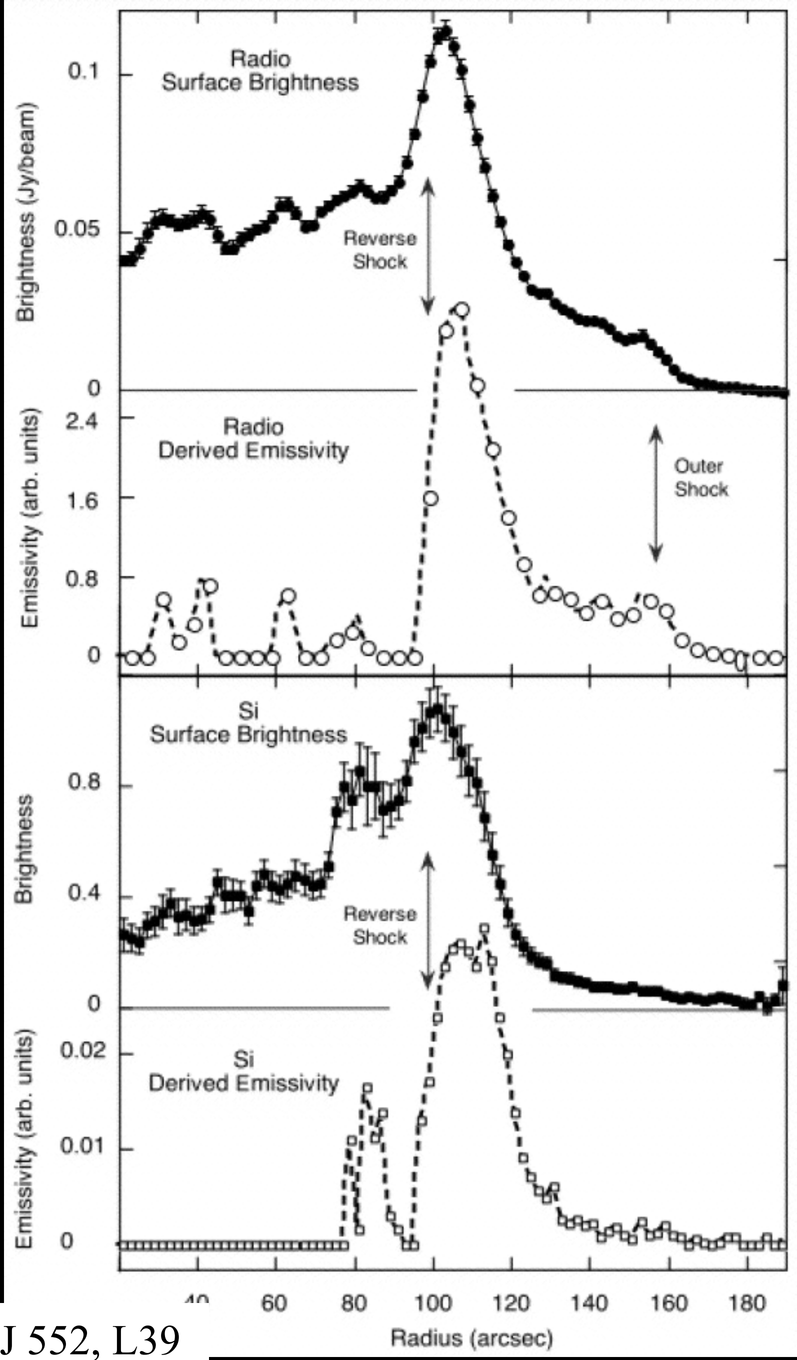
Requires nonlinear particle acceleration
and/or magnetic field amplification (Lucek and Bell 2000, MNRAS 314,65)

Maximum energy of accelerated ions much larger than that of electrons

Particle acceleration at the reverse shock ?

Ejecta: vast dilution of the B field from the progenitor
=> Reverse shock not expected to produce relativistic particles
If radio/X-ray synchrotron emission at the reverse shock
=> strong amplification of the ejecta magnetic field

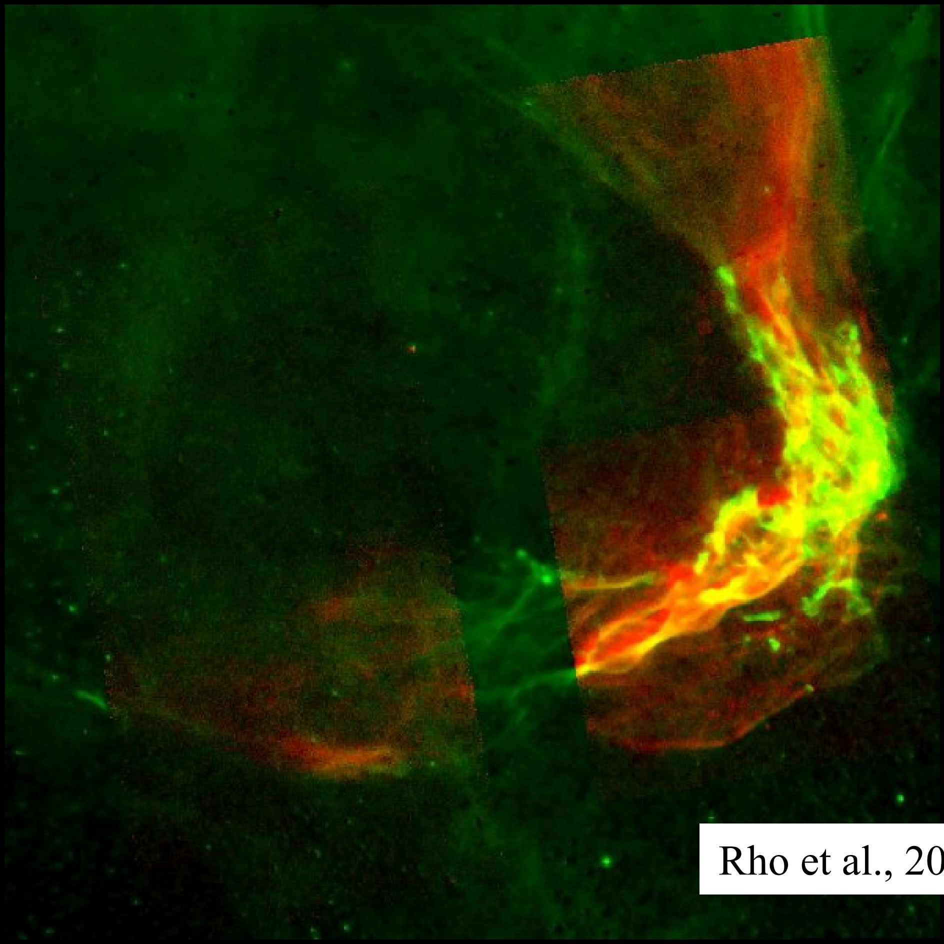




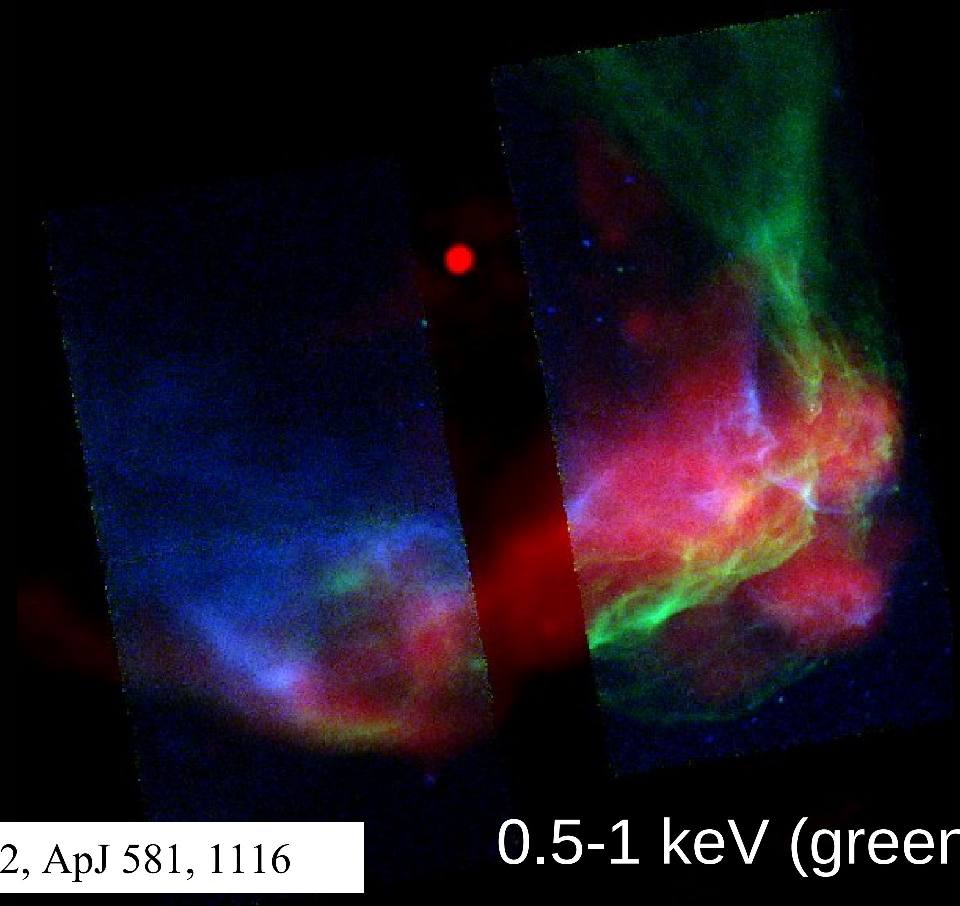
Gotthelf et al. 2001, ApJ 552, L39

RCW 86

Soft X-rays (red) / Hα (green)



Hard X-rays (blue) / radio (red)



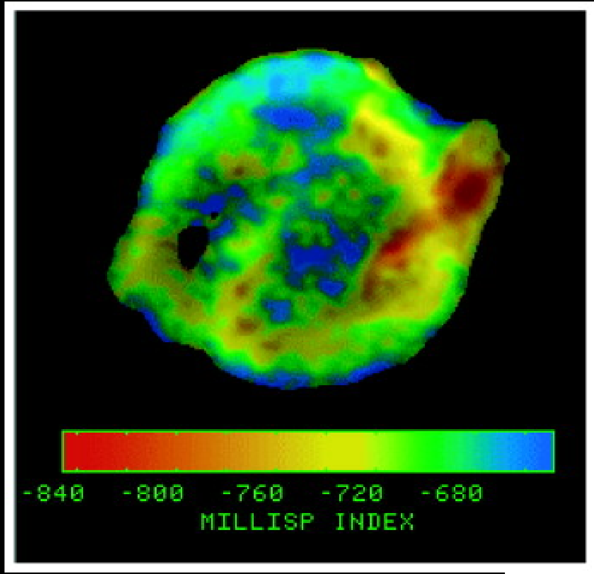
0.5-1 keV (green)

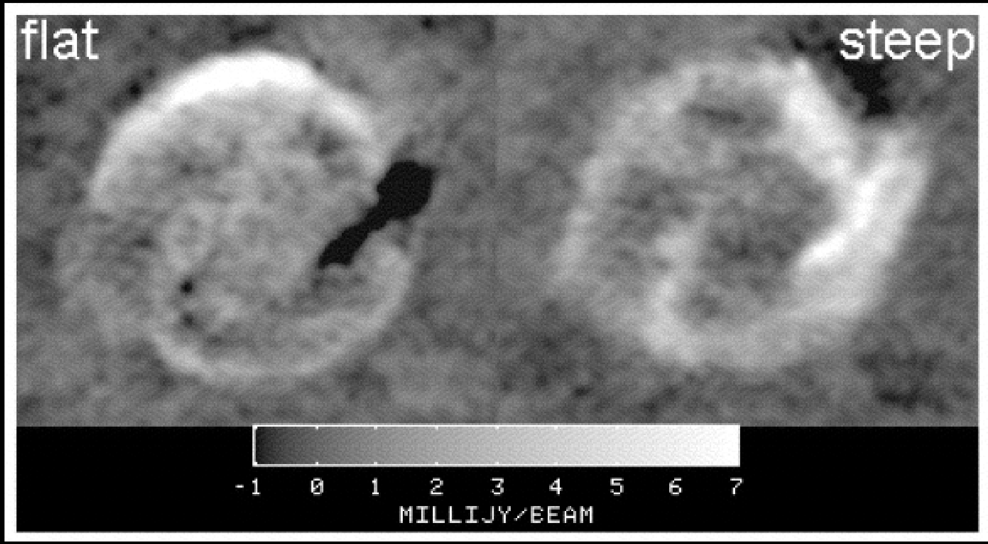
Rho et al., 2002, ApJ 581, 1116

X-ray synchrotron emission from the ejecta:
acceleration at the reverse shock ?

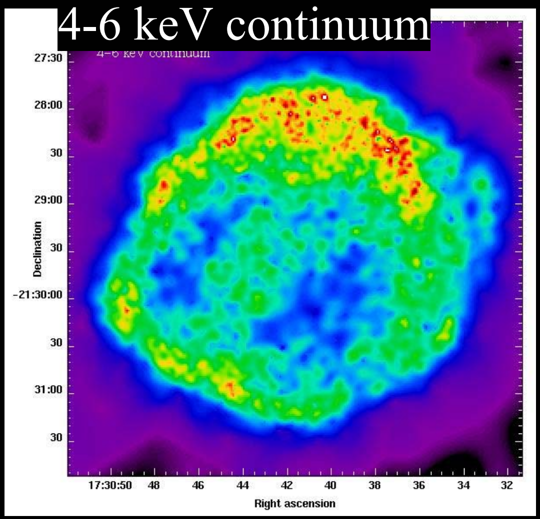
Radio observations of Kepler

Spectral index between 6 and 20 cm





DeLaney et al., 2002, ApJ 580, 914

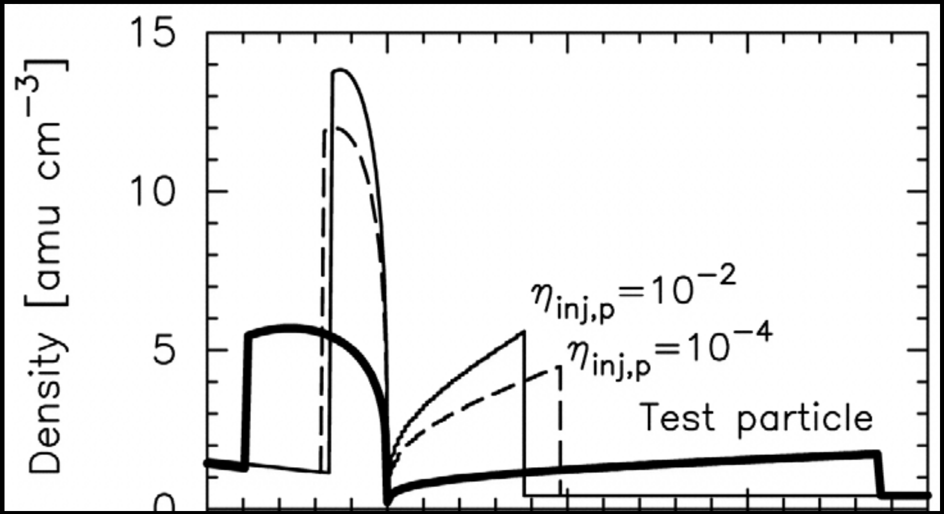


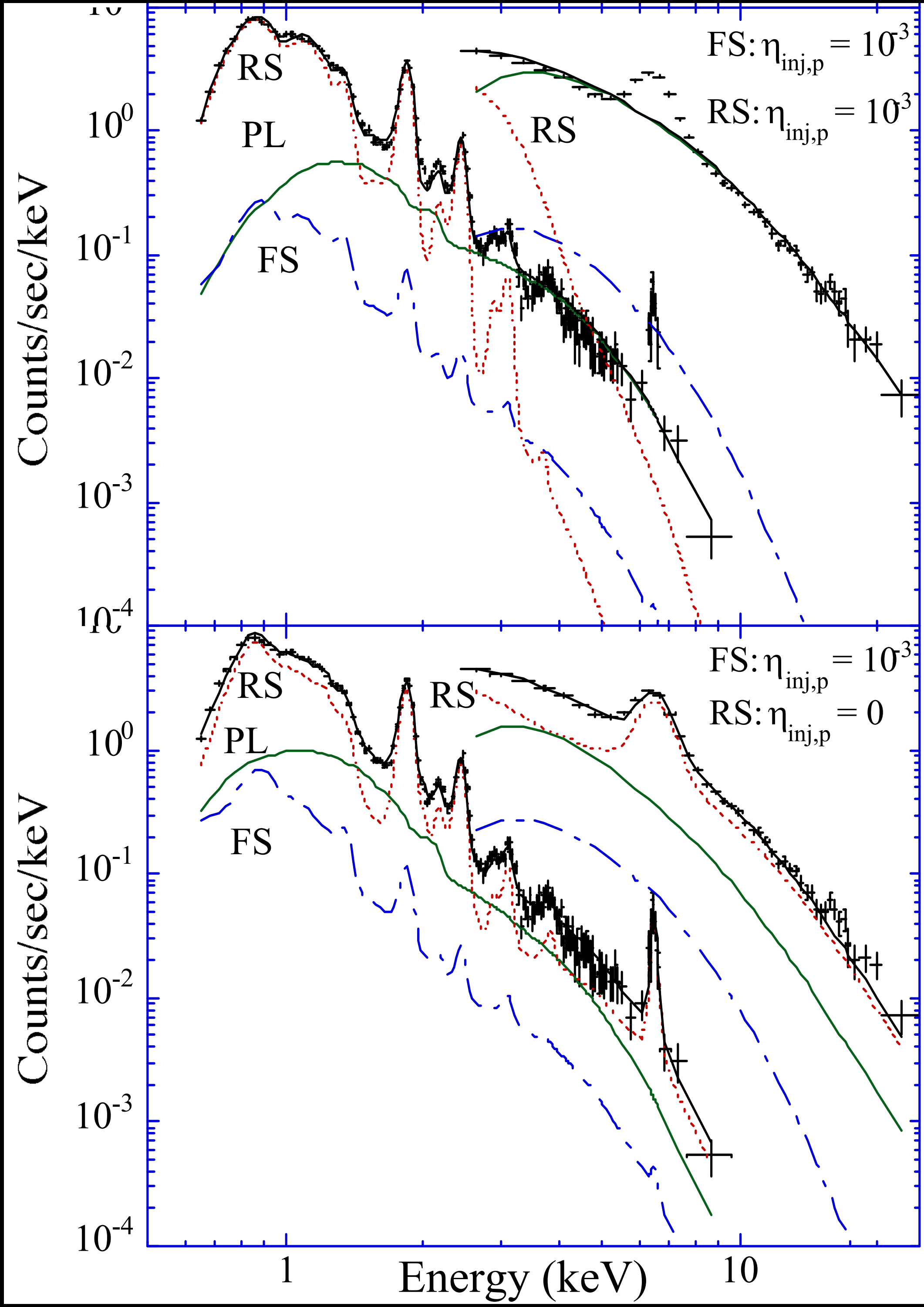
Cassam-Chenai et al., 2004, A&A 414, 545

Flat spectral index:
associated with the forward shock

Steep spectral index:
associated with the ejecta ?

Thermal X-ray emission : constraints on the proton acceleration efficiency

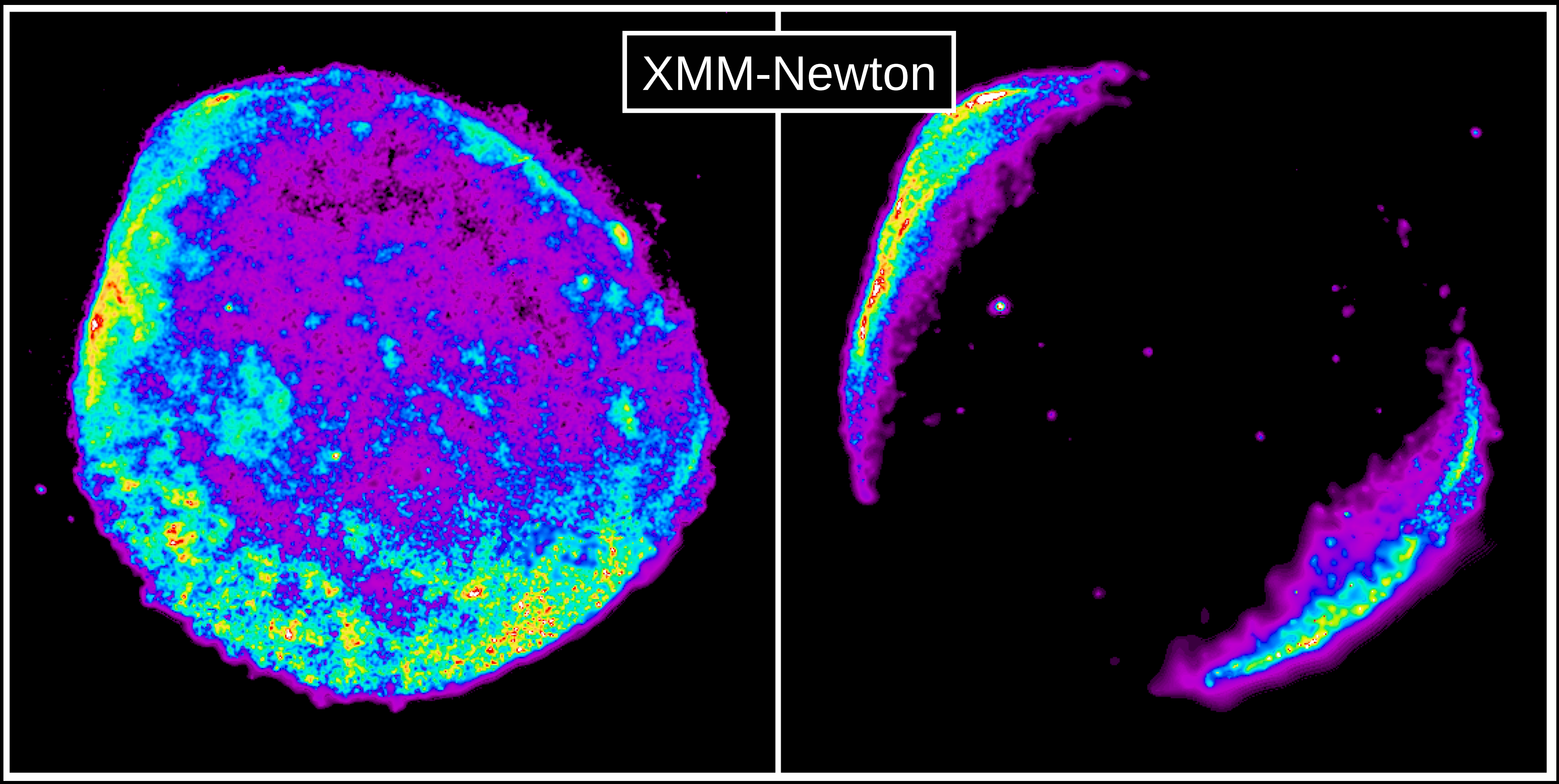




Inefficient acceleration at the reverse shock to produce the iron K-line at 6.5 keV => high temperature required

Decourchelle, Ellison & Ballet 2000, ApJL 543, 57

SN 1006 with XMM-Newton : Geometry of the acceleration



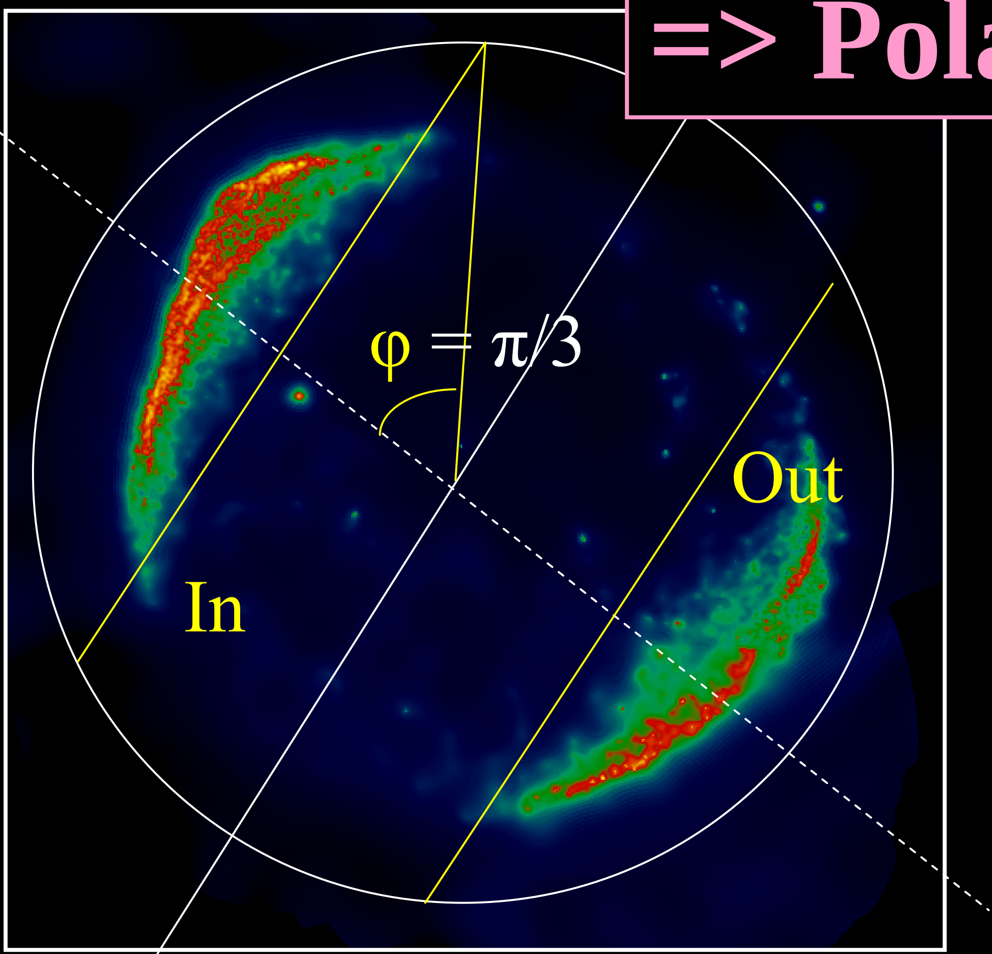
Oxygen band (0.5 – 0.8 keV) : **thermal emission**

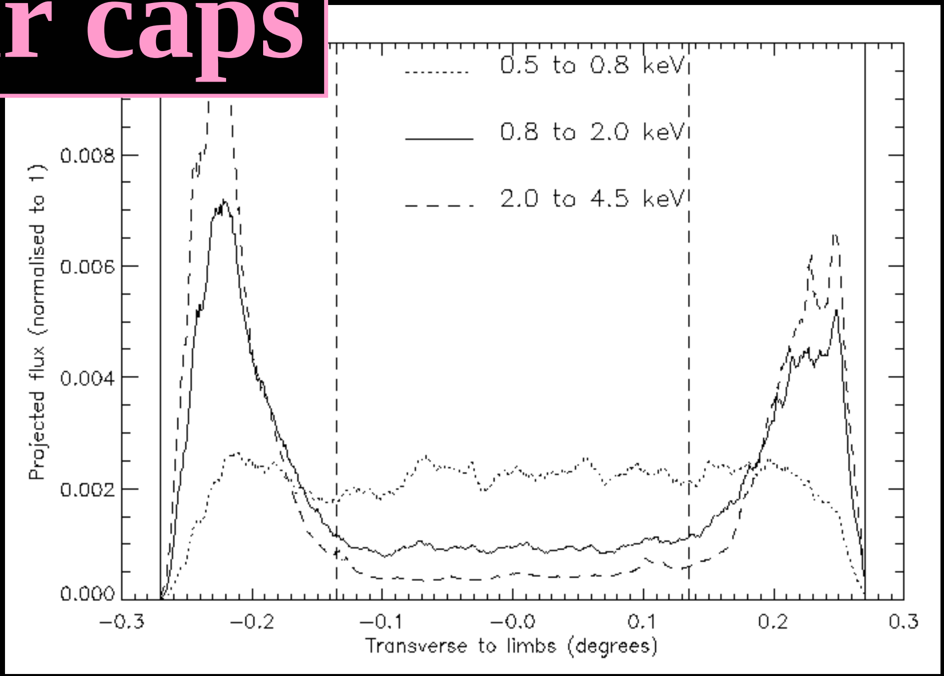
2 – 4.5 keV band : **Non-thermal emission**

Transverse profile: principle

How is the magnetic field oriented ?
Symmetry axis running from south-east to north-west, BUT if the bright limbs were an equatorial belt, non-thermal emission should also be seen in the interior

=> Polar caps



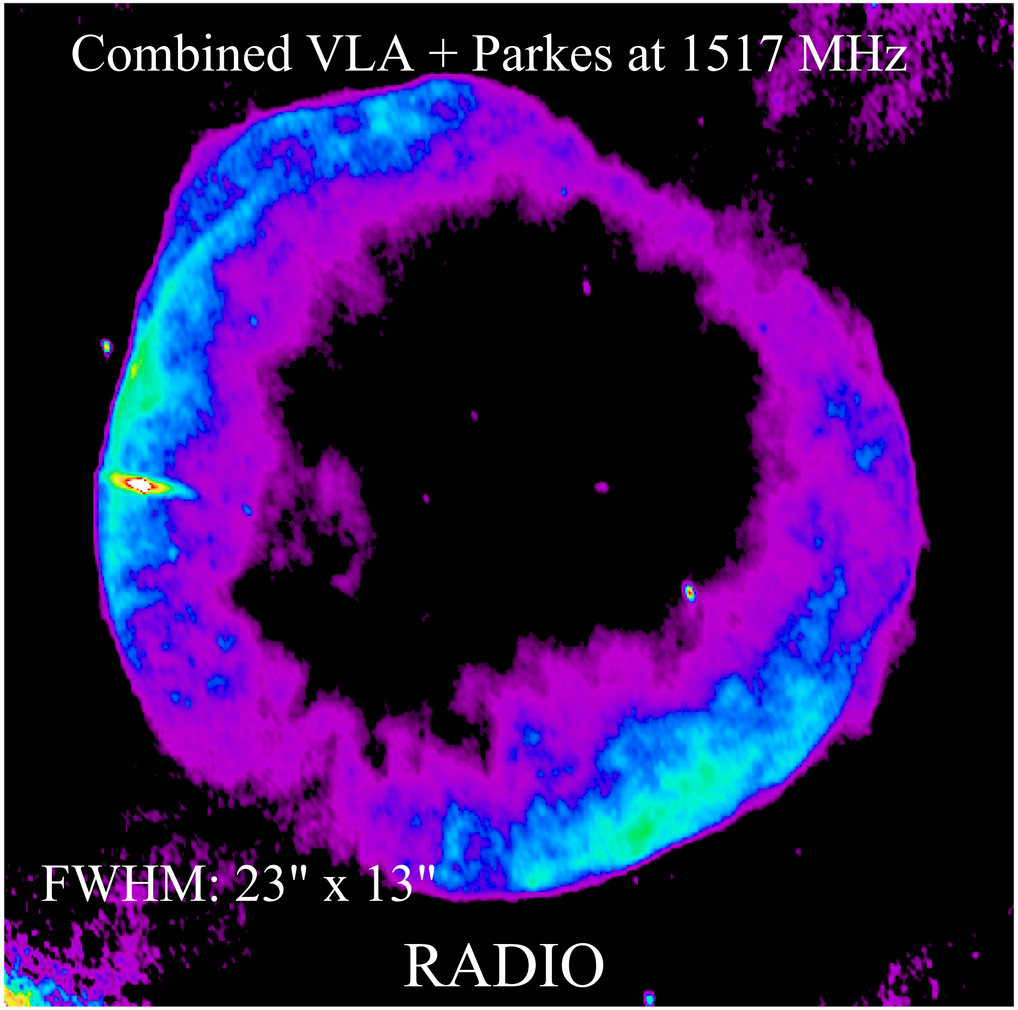


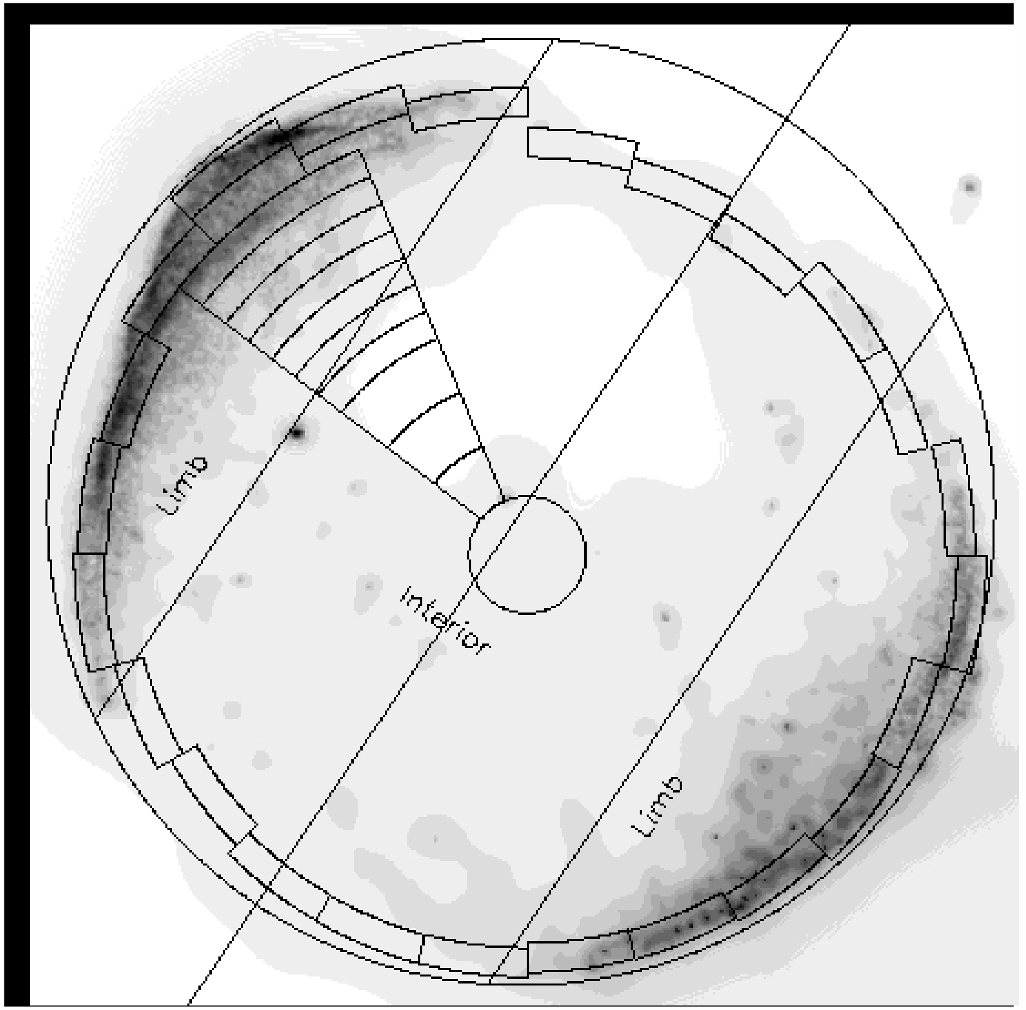
If equatorial belt: $F_{in}/F_{out} > 0.5$
Observed: 0.8-2 keV: 0.300 ± 0.014
2-4.5 keV: 0.127 ± 0.074

$F_{in}/F_{out} > \pi/2\varphi - 1 = 0.5$

Rothenflug et al., 2004, A&A submitted

Radio/X-ray comparison





Rothenflug et al., 2004, A&A submitted

Fit: **synchrotron** from a cut-off electrons power law (SRCUT) plus thermal NEI emission
Normalisation of the synchrotron component fixed using the radio data

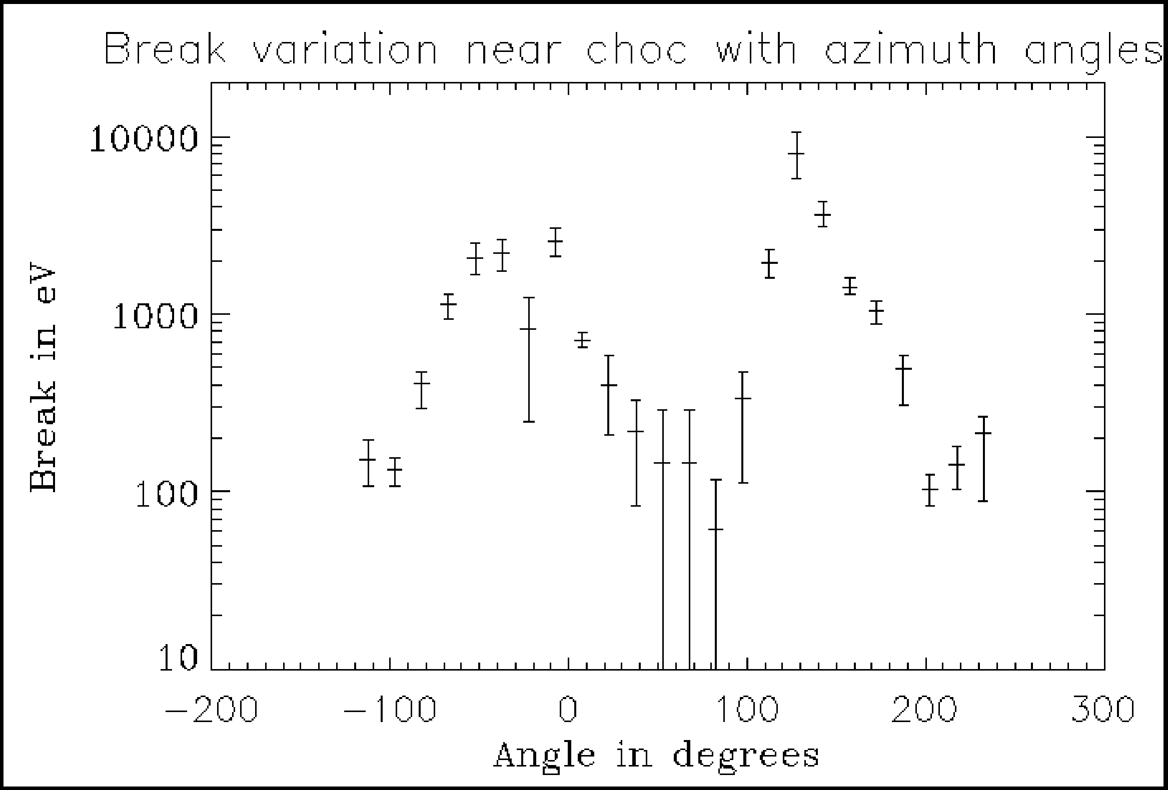
Only the cut-off frequency was left free.

Azimuthal variations of the cut-off frequency

- Very strong azimuthal variations, cannot be explained by variations of the magnetic compression alone.

=> Maximum energy of accelerated particles higher at the bright limbs than elsewhere.

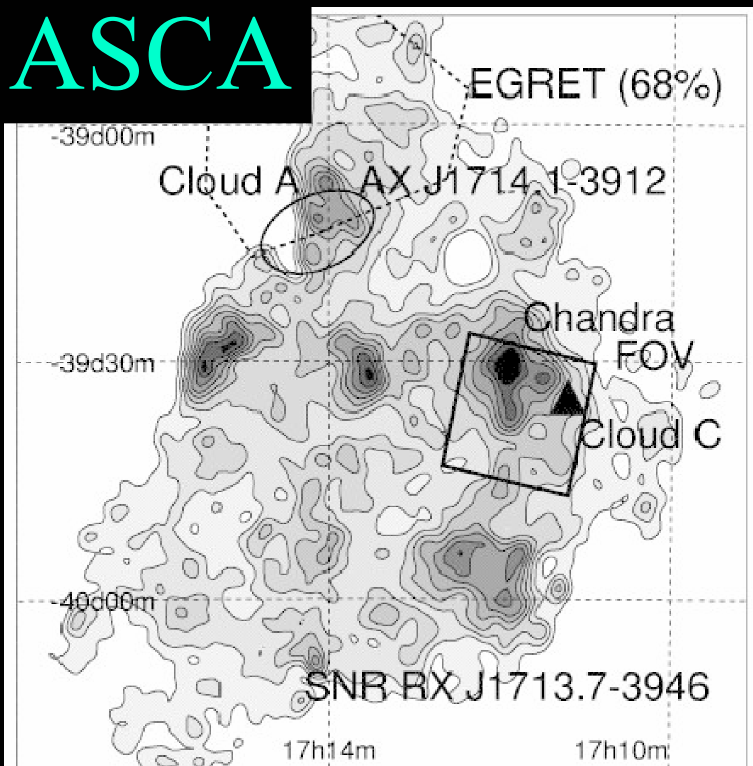
- If B ~ 50 μG, the maximum energy reached by the electrons at the bright limb is around 100 TeV.



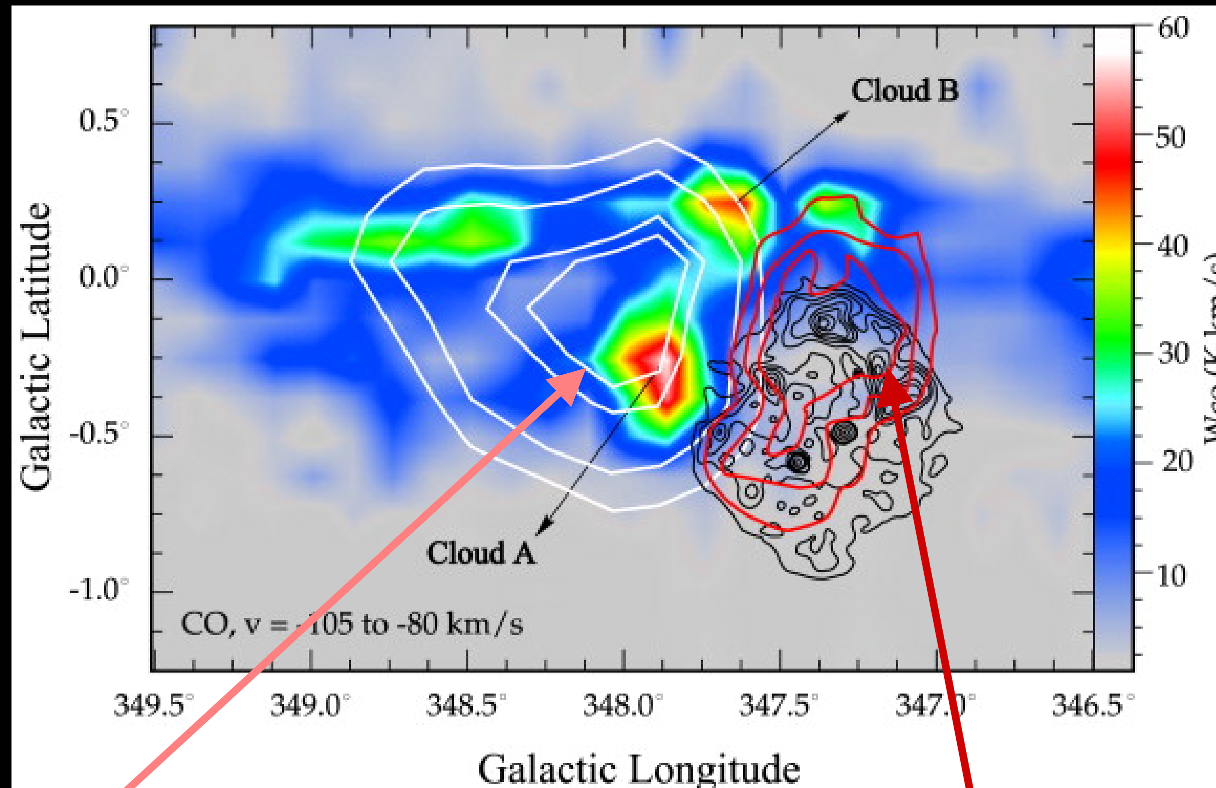
The X-ray geometry of SN 1006 favors cosmic-ray acceleration where the magnetic field was originally parallel to the shock speed (polar caps)

An extreme case of synchrotron-dominated SNR: G347.3-0.5 (also RX J1713.7-3946)

ASCA



Uchiyama et al. 2002, PASJ 54, L73

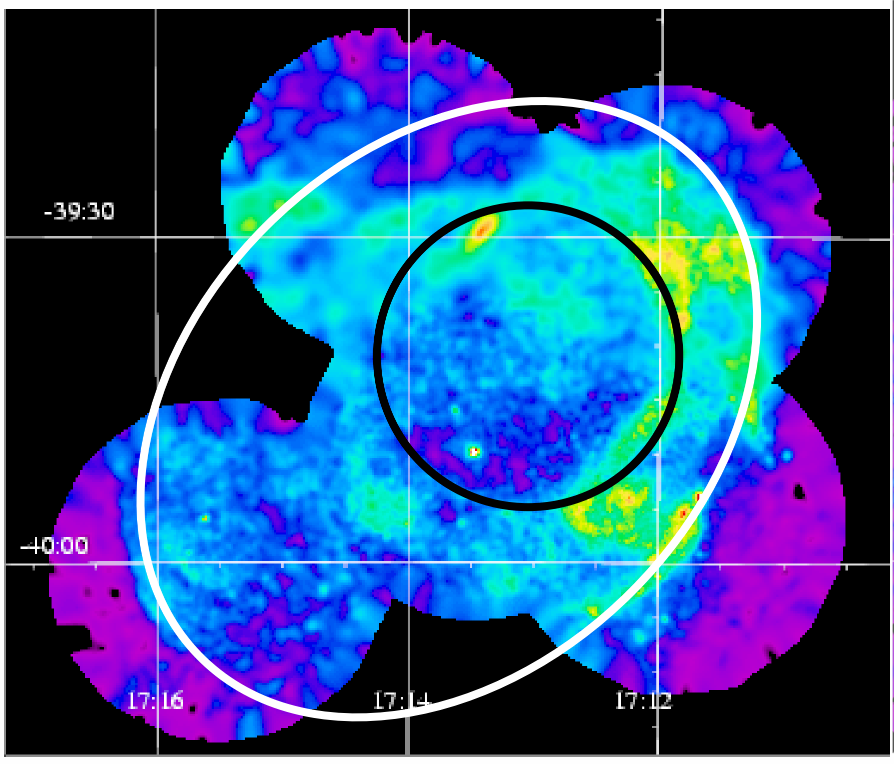


Distance of 6 kpc
(Slane et al. 1999, ApJ, 525, 357)
GeV emission (EGRET) associated with cloud A ?
(Butt et al. 2001, ApJ, 562, L167)

TeV emission (CANGAROO) in the NW:
Inverse compton or π^0 decay process ?
Muraishi et al. 2000, A&A, 365, L57, Enomoto et al. 2002, Nature, 416, 25, Reimer & Pohl 2002, A&A, 390, L43

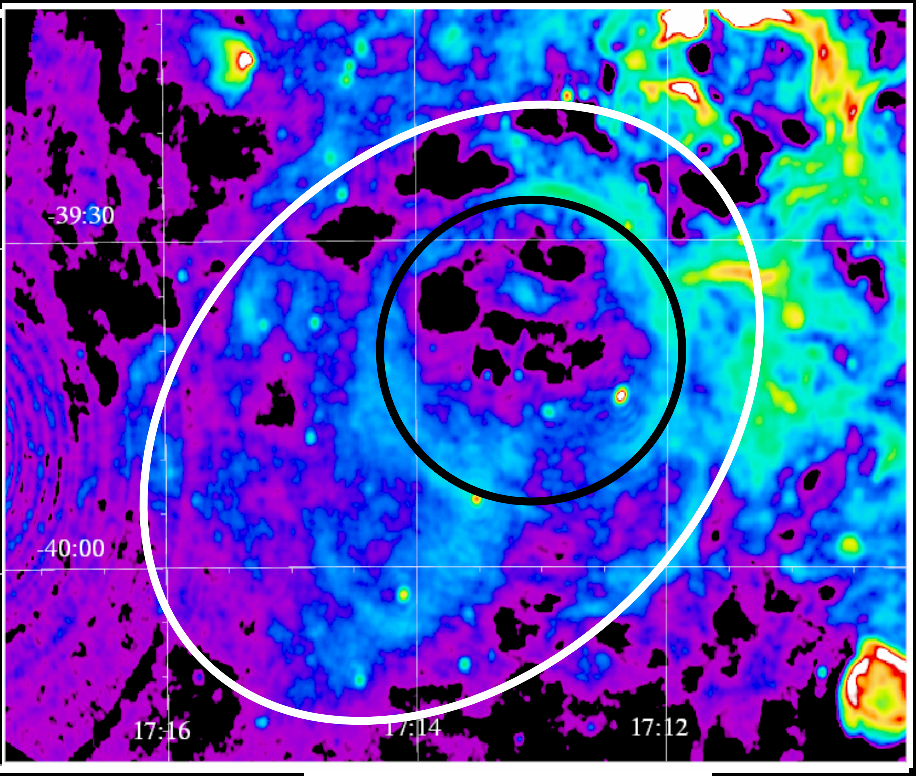
Morphology of the X-ray continuum: G347.3-0.5

In any place, X-ray spectrum entirely dominated by nonthermal emission



XMM-Newton

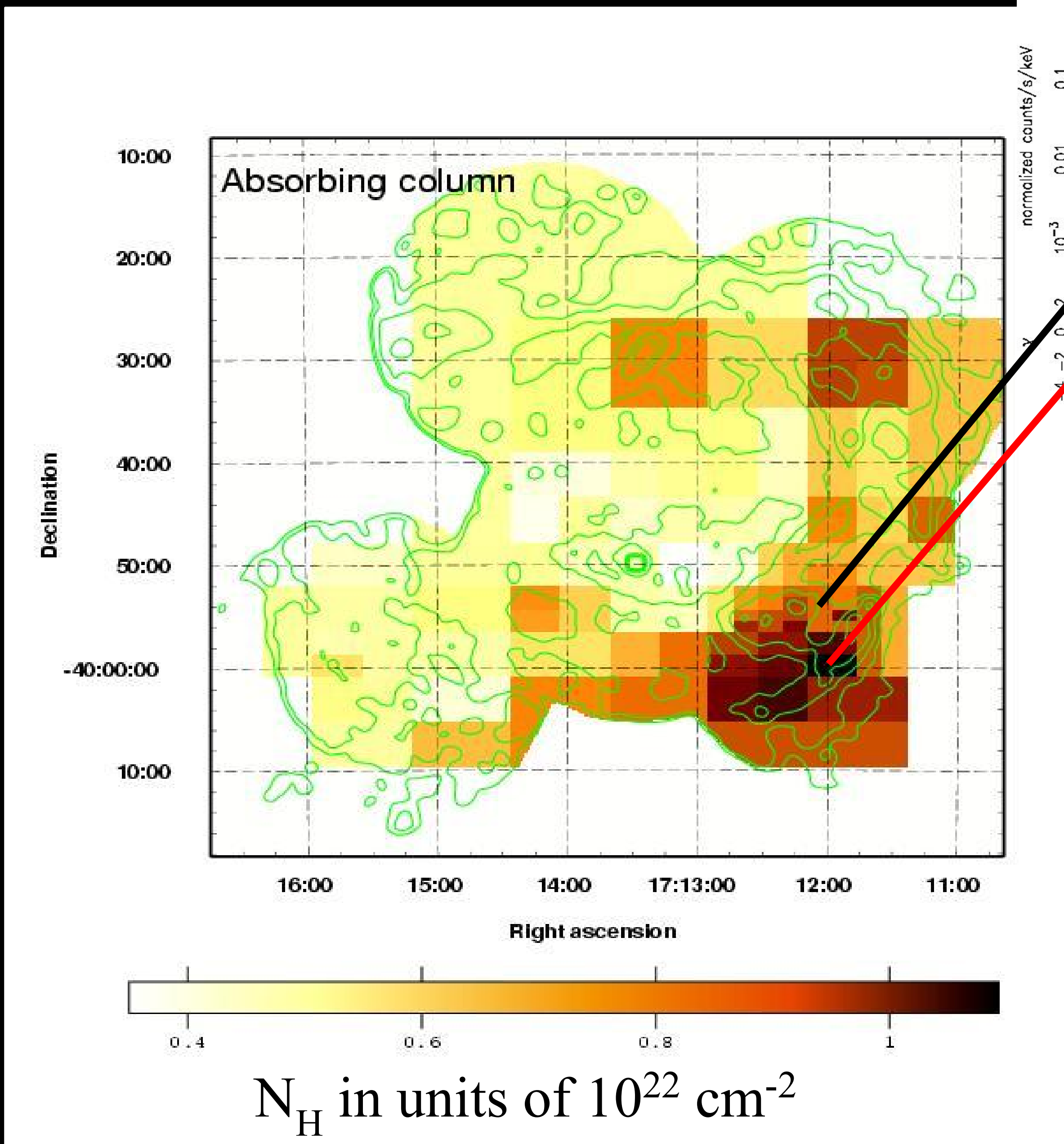
Cassam-Chenaï et al., 2004, in prep

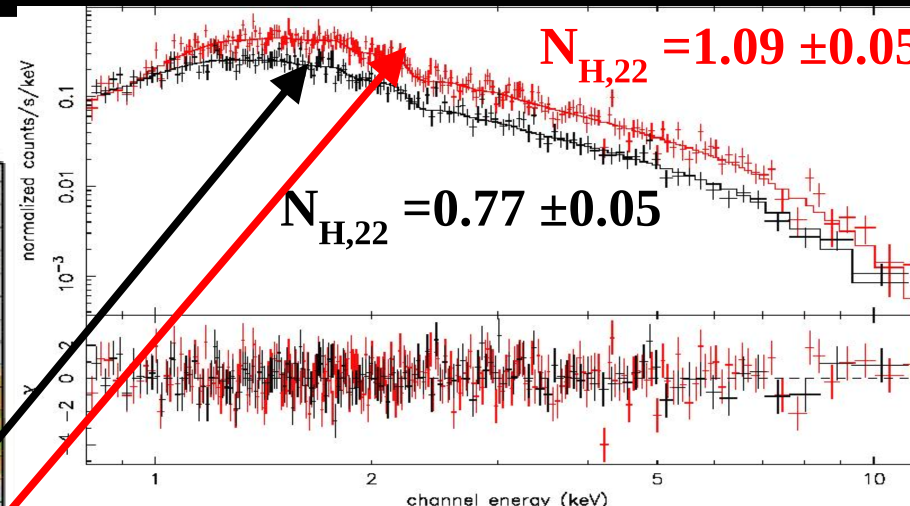


Radio ATCA

Lazendic et al., 2004, ApJ in press

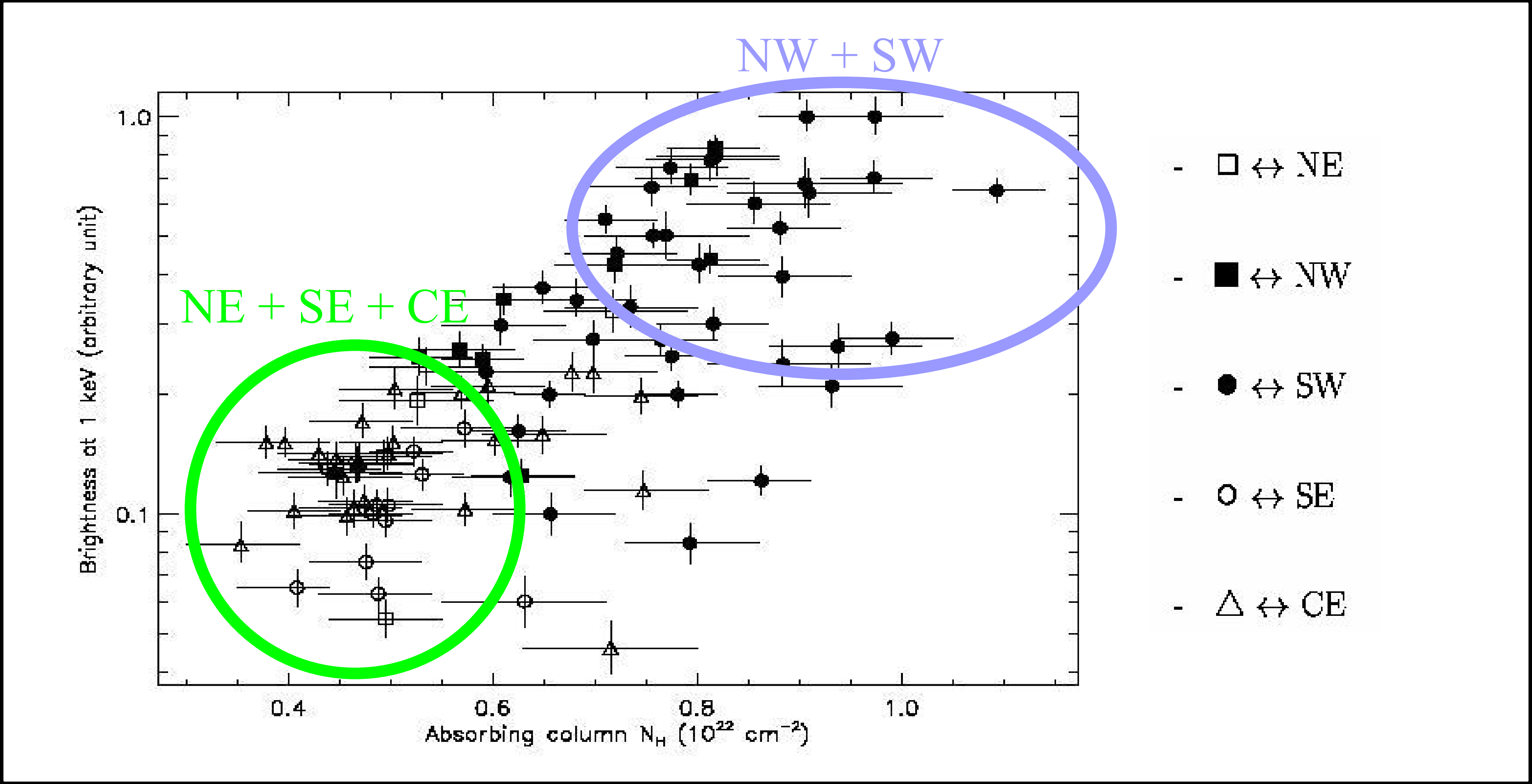
Variation of absorbing column over the SNR





- Adaptive grid (point sources removed)
- Fit using a simple power law
- Mean relative error on the absorbing column in each pixel grid: 8.5% (Max=16%)
- Strong N_H in the W
- Weak N_H in the SE

Variation of absorbing column over the SNR

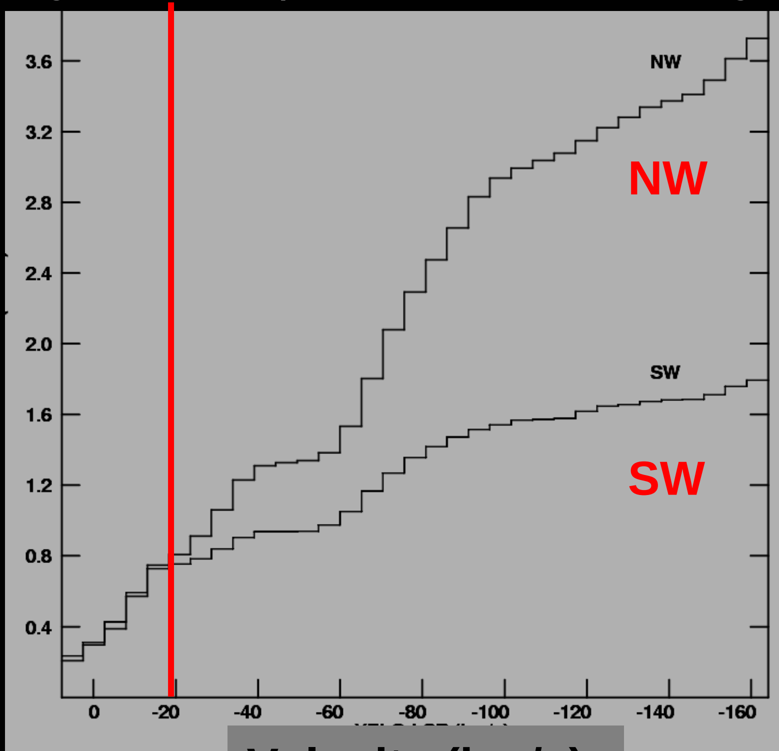


Absorbing column the highest where the X-ray brightness is the strongest (SW and NW)

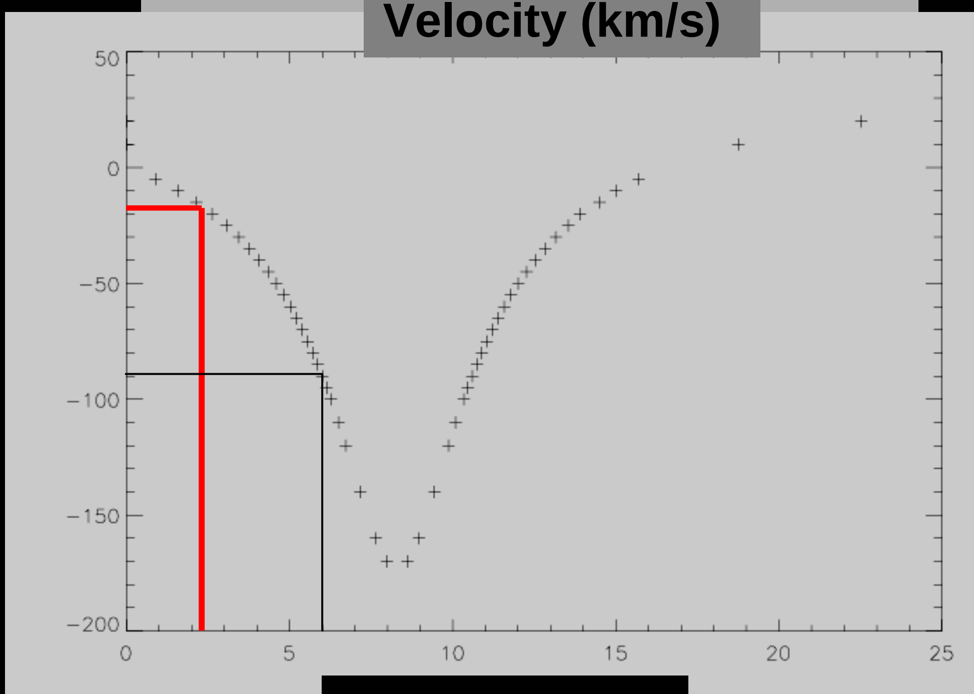
=> interaction of the SNR with dense material in the brightest regions

(50 part cm^{-3} at D = 6 kpc or 300 part cm^{-3} at D= 1 kpc)

Integrated CO profile in the line of sight

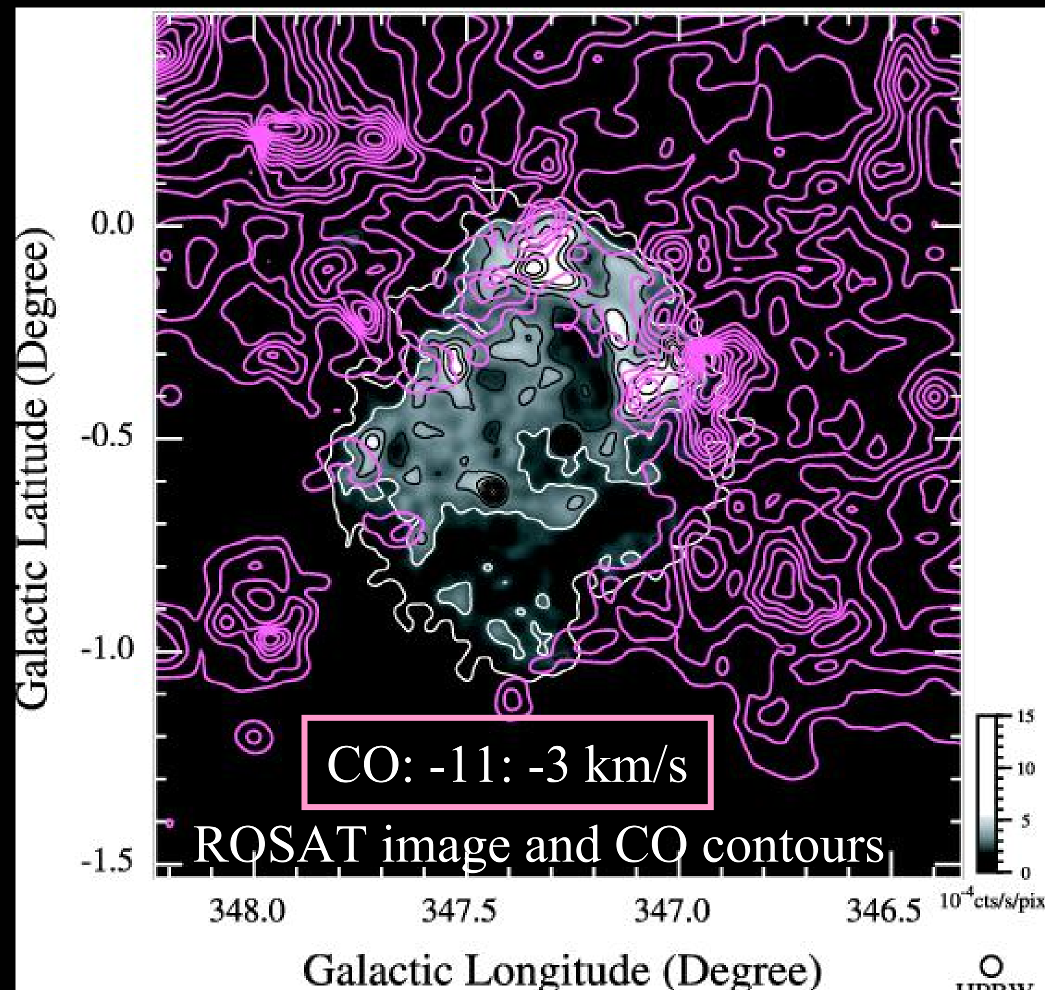


Velocity (km/s)



Distance (kpc)

In X-rays $N_H(NW) < N_H(SW)$
⇒Much lower distance of the remnant

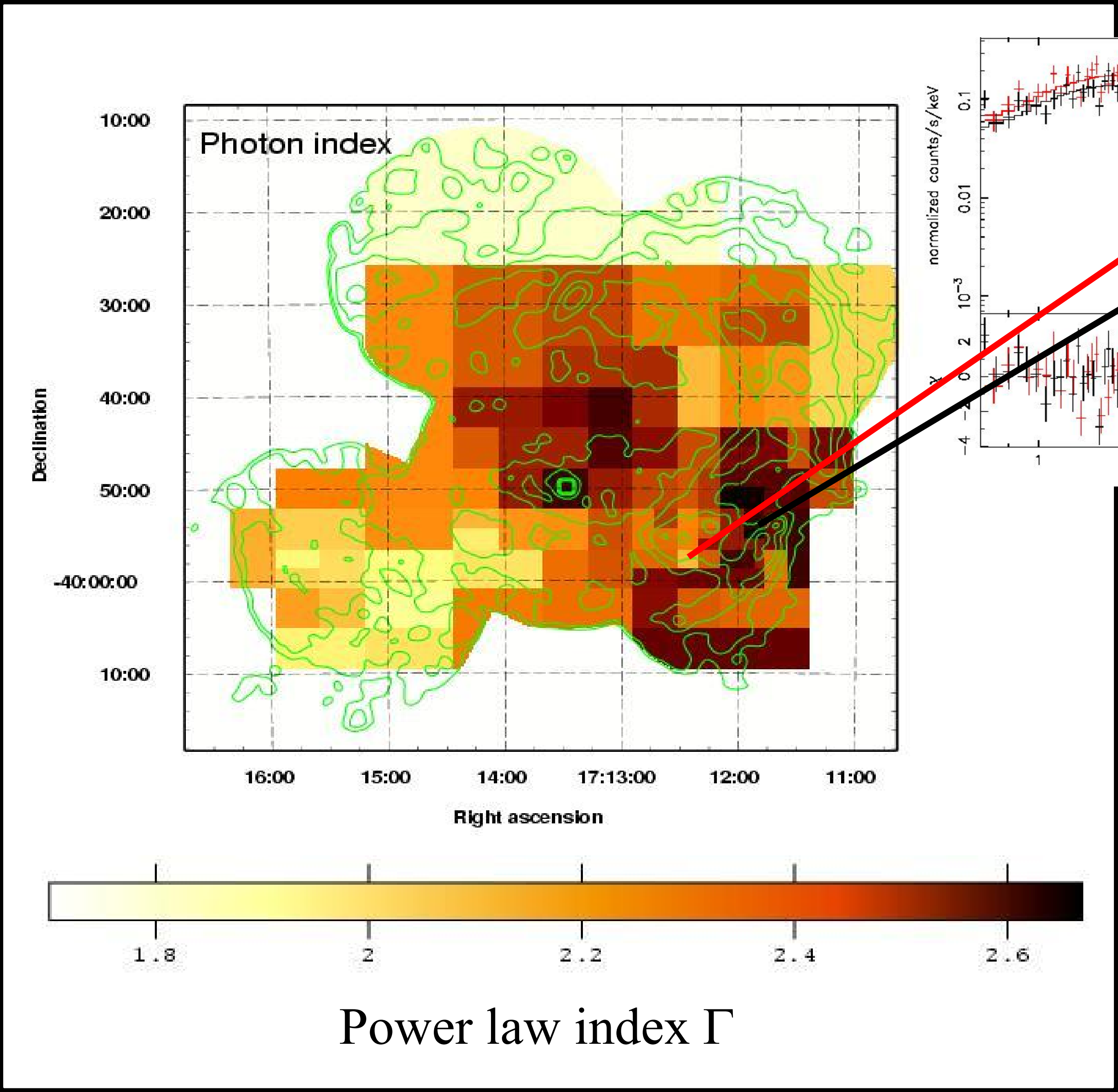


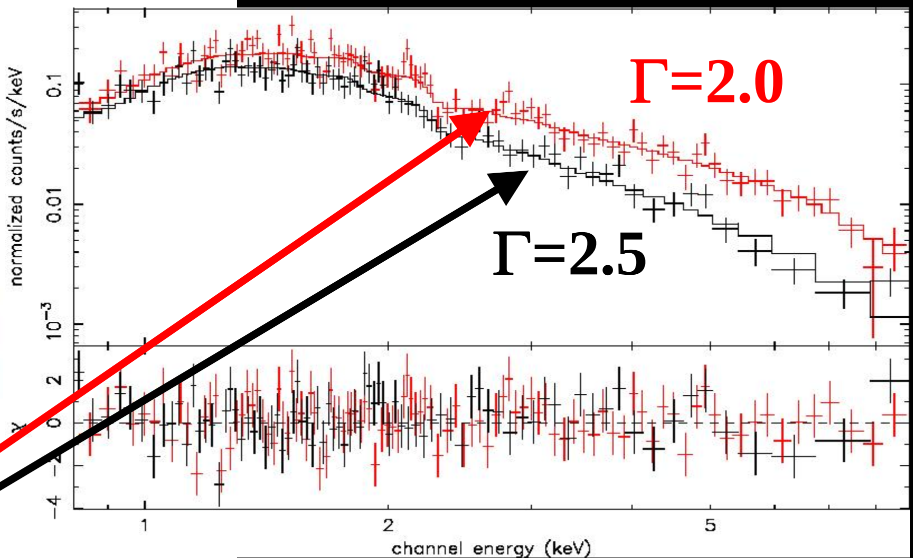
Fukui et al., 2003, PASJ 55, L61

Revised distance of the SNR:

~ 1 kpc

Variation of the Photon Index over the SNR





- At the shock:
  - Flat spectrum in the faint SE
  - Steep spectrum in the brightest regions (SW). Inverse situation to that of SN 1006 .
- In the interior, steep spectrum.
- Mean relative error on the photon index in each pixel grid: 3.8% (Max=4%)

CONCLUSIONS

- Ejecta interface close to the forward shock => nonlinear particle acceleration at the forward shock with shock modification

- Sharp rims due to the limited lifetime of the ultrarelativistic electrons in the SNR => large magnetic field values ~ 60-100 μG

Shock modification with large compression ratio and/or magnetic field amplification

⇒ Maximum energy of protons much higher than that of electrons

SN 1006

Bright limbs: polar caps, where particle injection is easier.

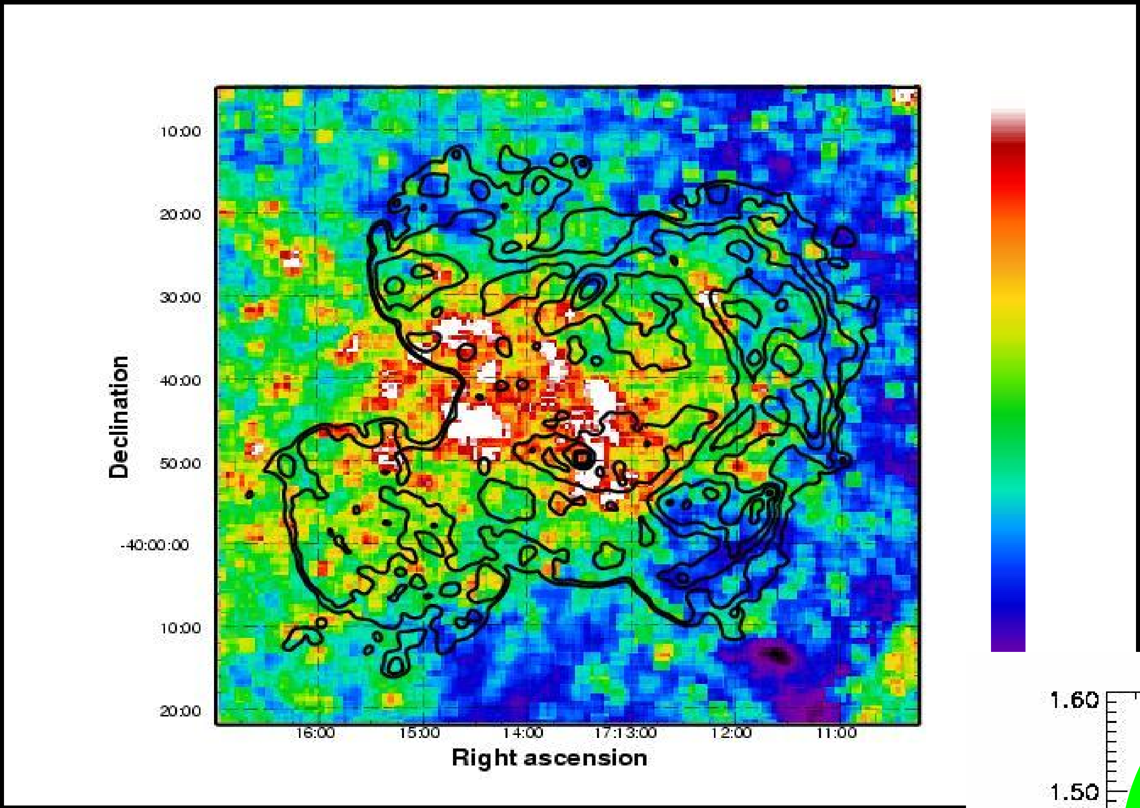
Accelerated particles reach higher energy there

G347.3-0.5

Regions interacting with molecular material: brighter and steeper spectrum than elsewhere

=>Revised distance of the SNR < 1 kpc

Variation of absorbing column over the SNR



Smoothed optical image (DSS2 in red color) overlaid with X-ray contours

Correlation between the optical brightness and the absorbing column

What is interacting with the SNR?

- Molecular clouds? Evidence for such an interaction but at a smaller distance

(Fukui et al., 2003, PASJ 55, L61)

- HI region? YES

(Koo et al. 2004, IAU symposium, Vol. 218)