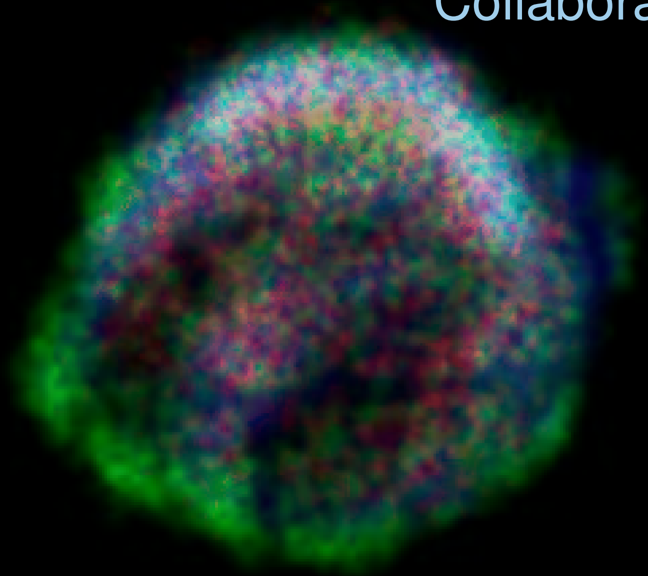
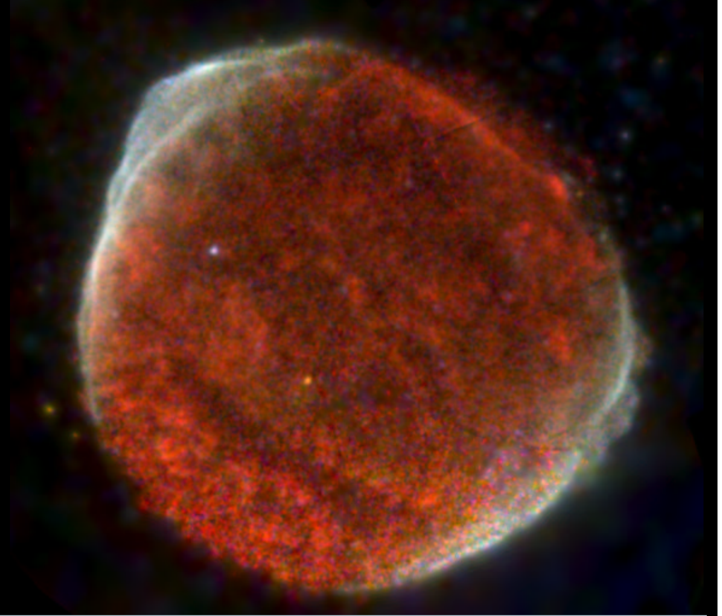
Particle acceleration in Supernova Remnants

Anne Decourchelle
Service d'Astrophysique, CEA Saclay

Collaborators: J. Ballet, G. Cassam-Chenai, D. Ellison



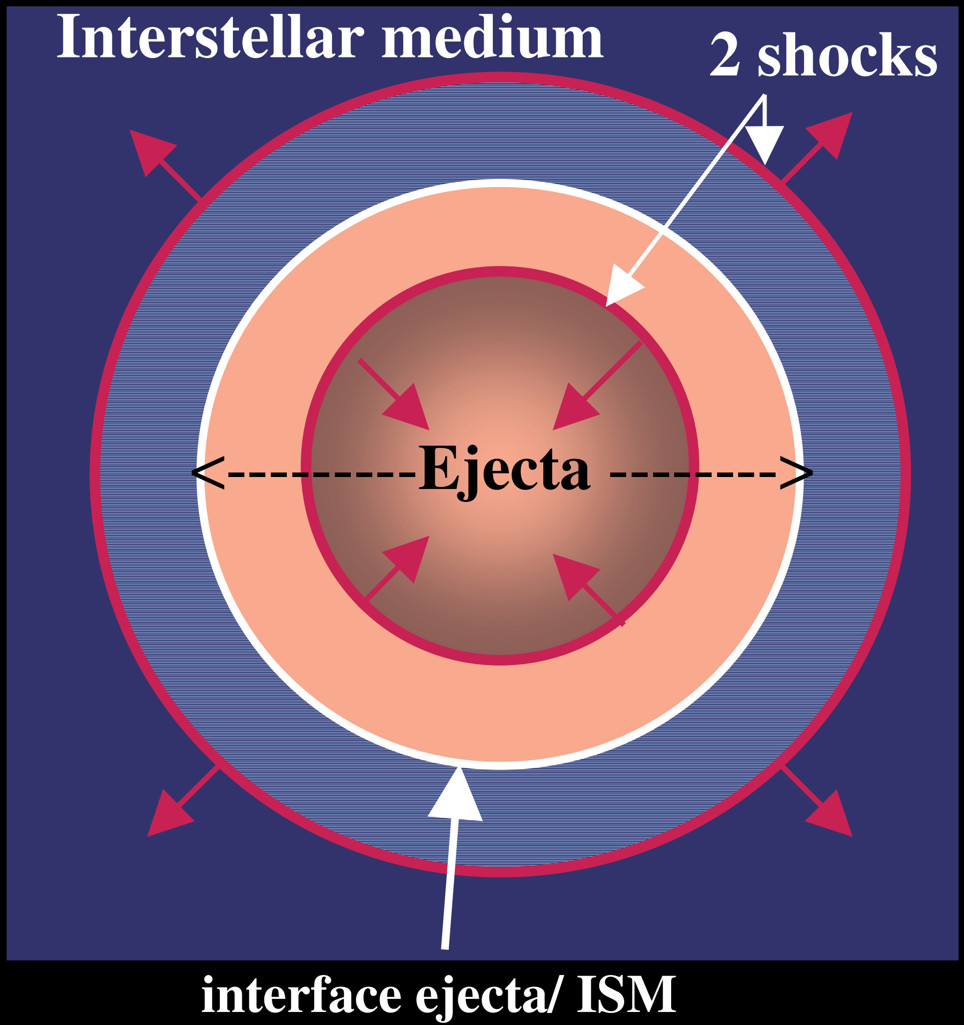


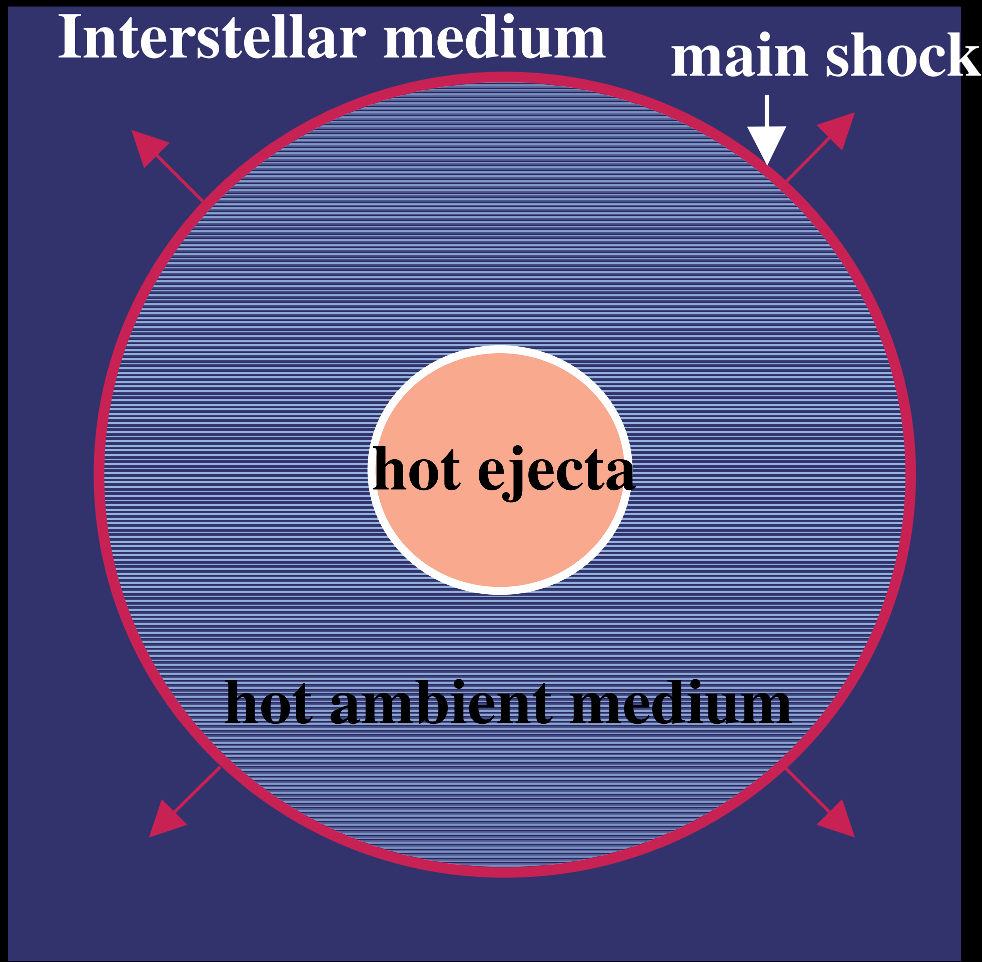
I- Efficiency of particle acceleration at the forward shock in young SNRs:
Tycho, Kepler, Cas A

II- Geometry of the acceleration in the synchrotron-dominated SNR: SN 1006

III- Expectations with Simbol-X

Young and middle-aged supernova remnants

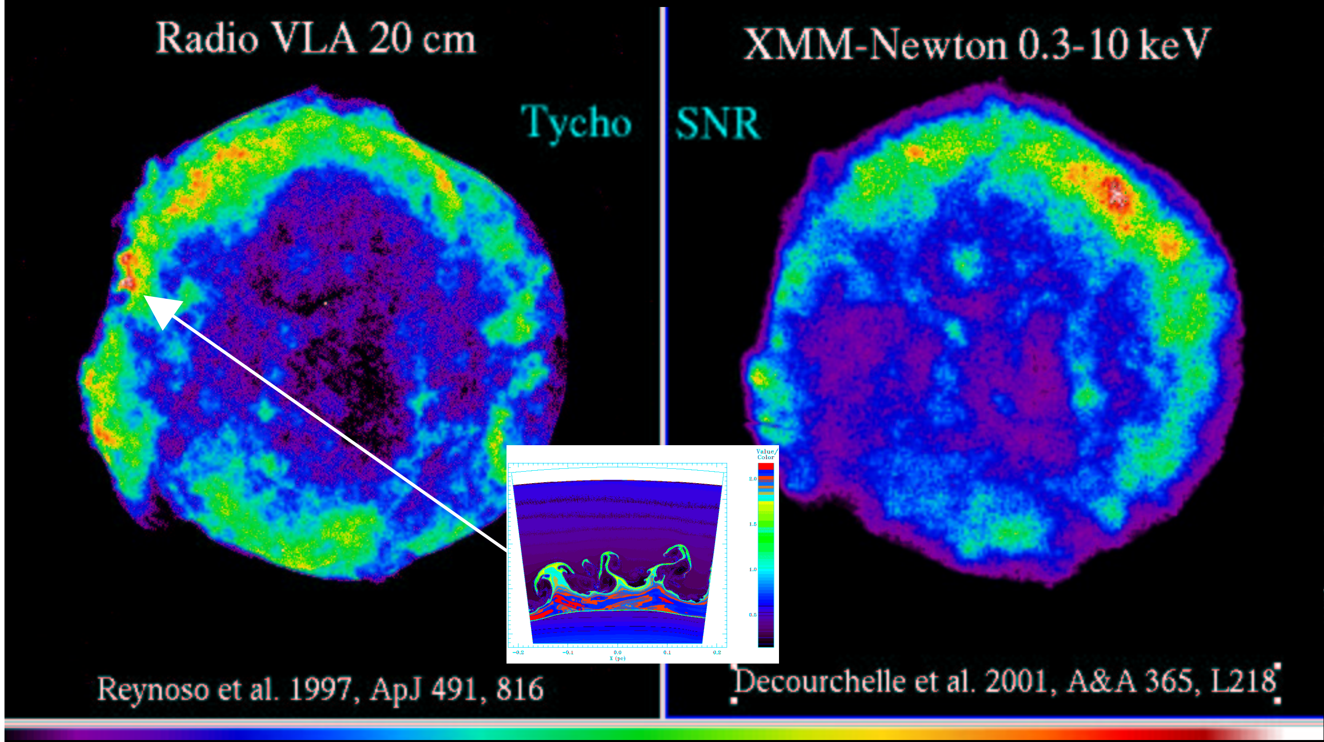




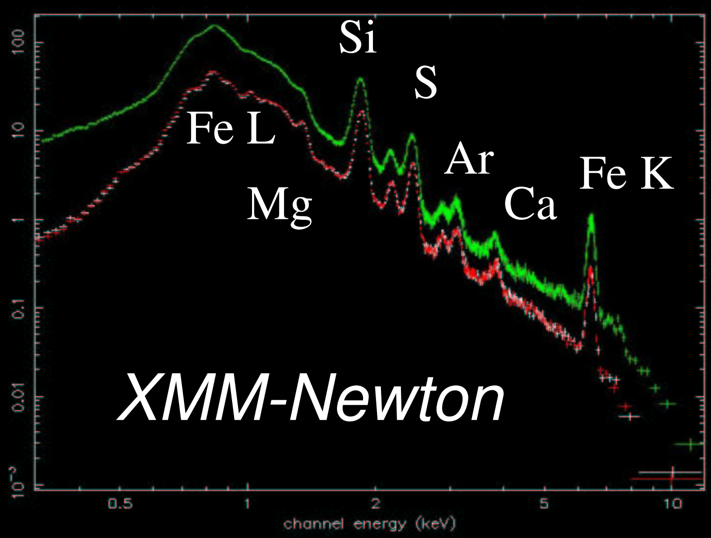
SN material ejected at high velocity
=> Heating of the ejecta and ISM by two shocks: Powerful X-ray production

X-ray emission dominated by the shocked ambient medium: thermal shell emission

Thermal emission



Kepler's SNR (1604)



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

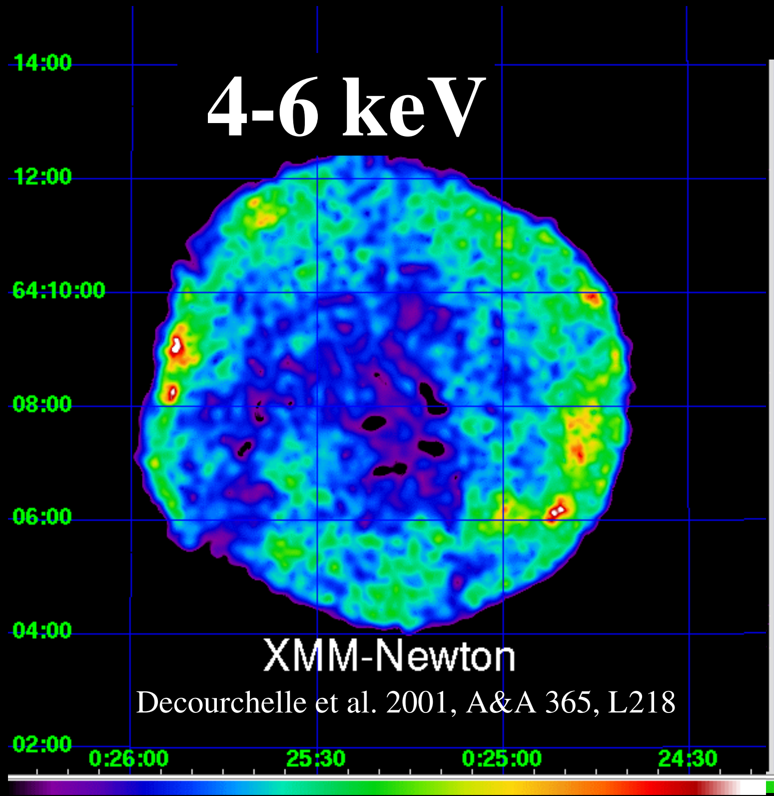
Temperature of a few keV

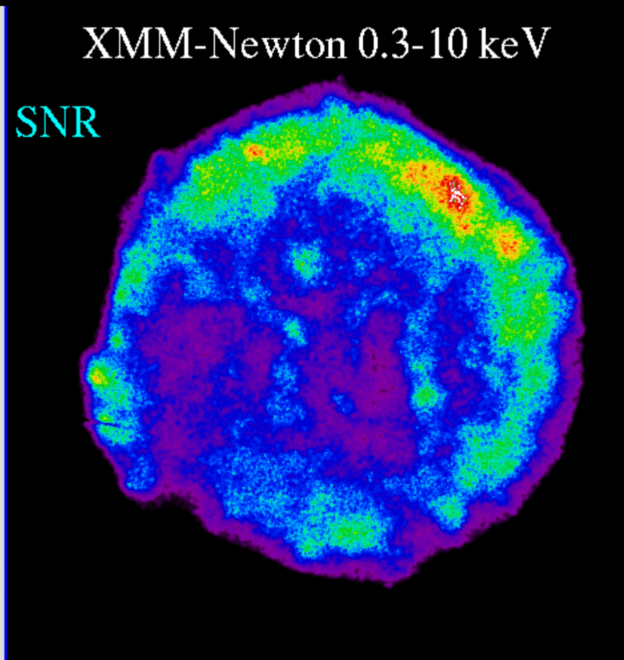
Bremsstrahlung and emission lines (highly ionized non-equilibrium ionisation gas)

Progenitor/supernova: nucleosynthesis products, element mixing, Rayleigh-Taylor instabilities

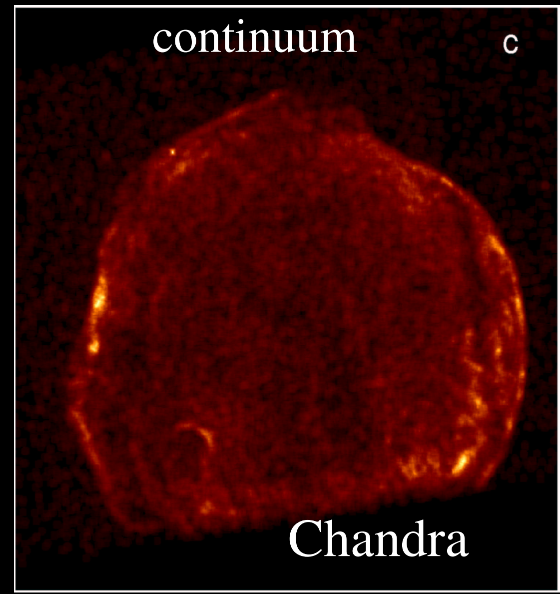
Interaction with the ambient medium: circumstellar wind, interstellar medium and clouds

Non-thermal X-ray emission

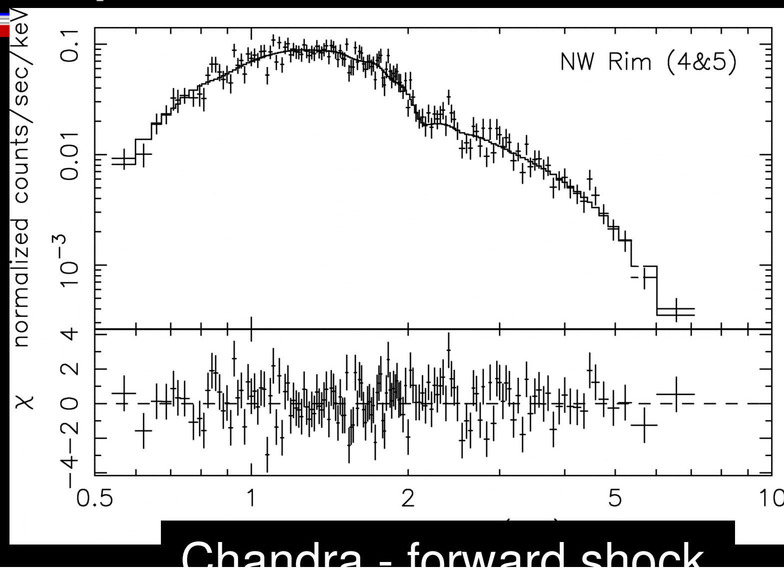




Decourchelle et al. 2001, A&A 365, L218



Hwang et al, 2002, ApJ



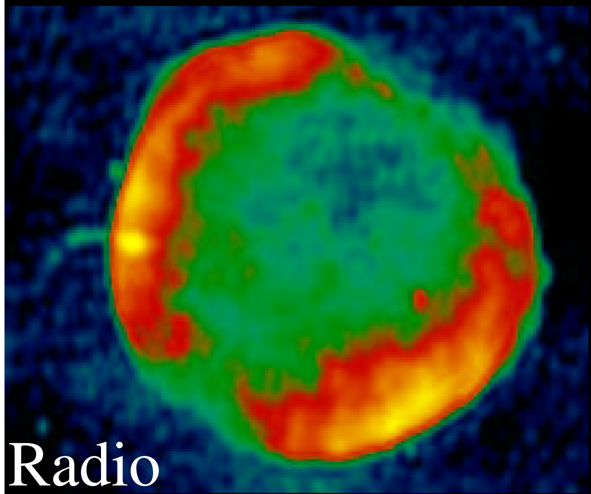
Synchrotron, nonthermal bremsstrahlung
Particle acceleration (TeV electrons)
Interaction with interstellar medium and clouds

Particle acceleration in SNRs

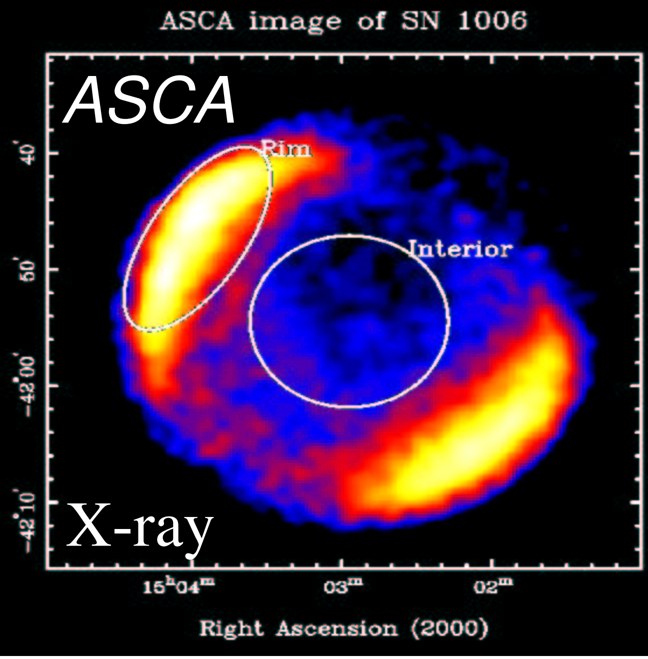
SNRs : main source of cosmic-rays with energies up to 3 10^{15} eV ?

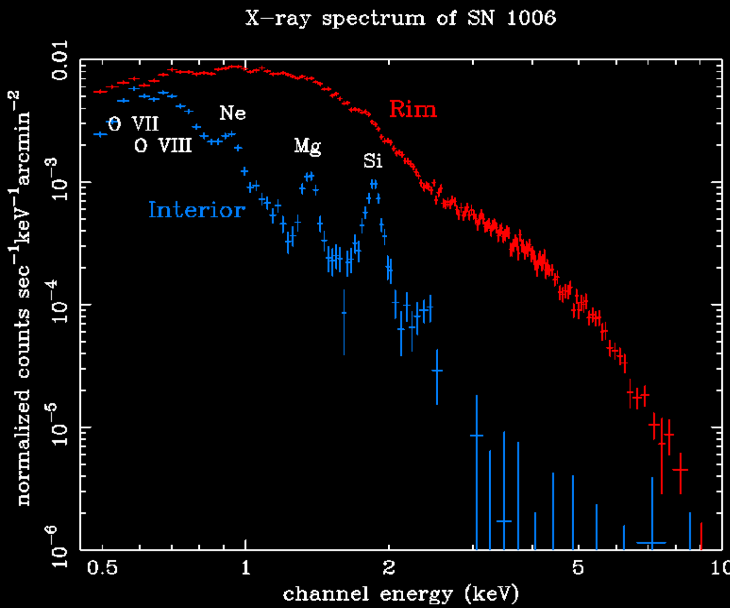
- Strong shocks in SNRs: First-order Fermi shock acceleration
- Radio emission   relativistic GeV electrons
- X-ray observations of synchrotron emission **=> TeV electrons**

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





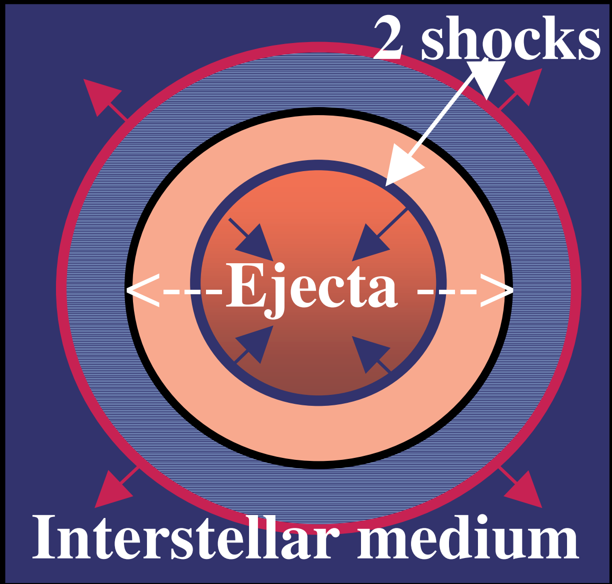
Search for observational constraints on particle acceleration in SNRs

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 ?

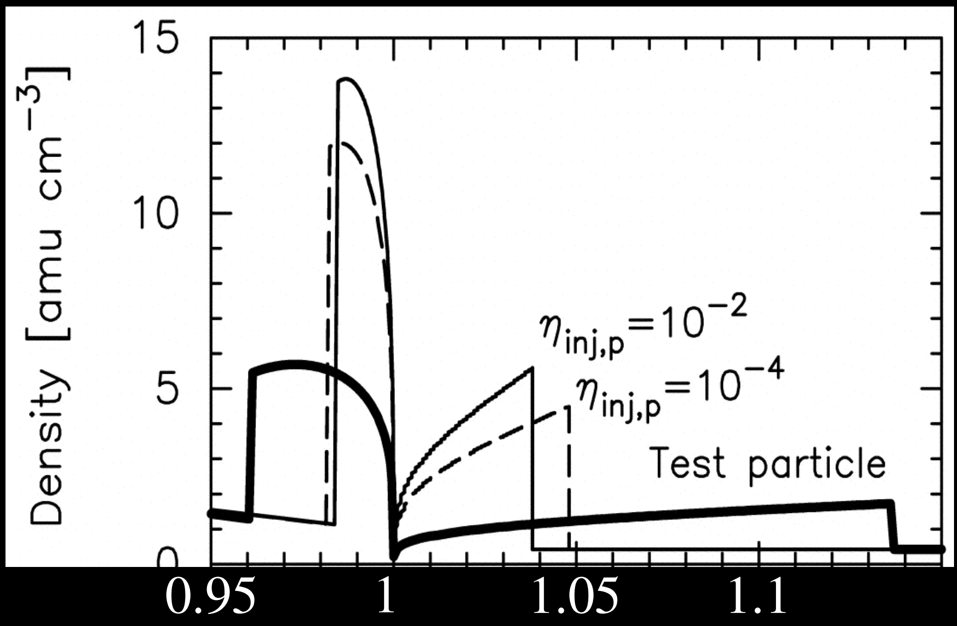
⇒X-ray observations of SNRs with XMM-Newton and Chandra

Efficiency of particle acceleration in young SNRs

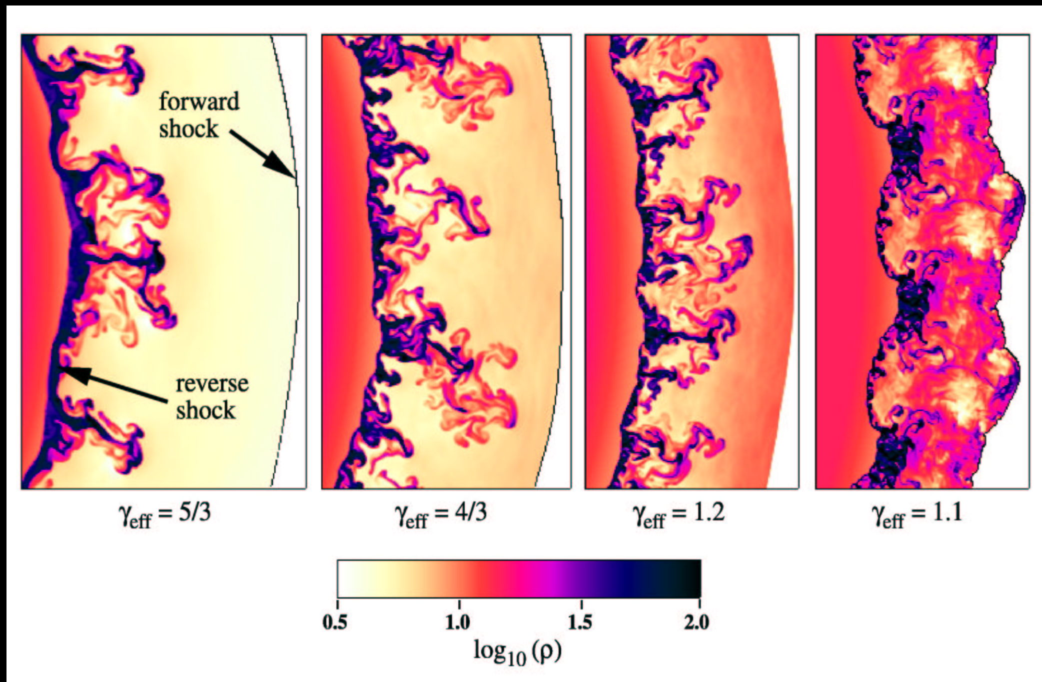


Efficient particle acceleration

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

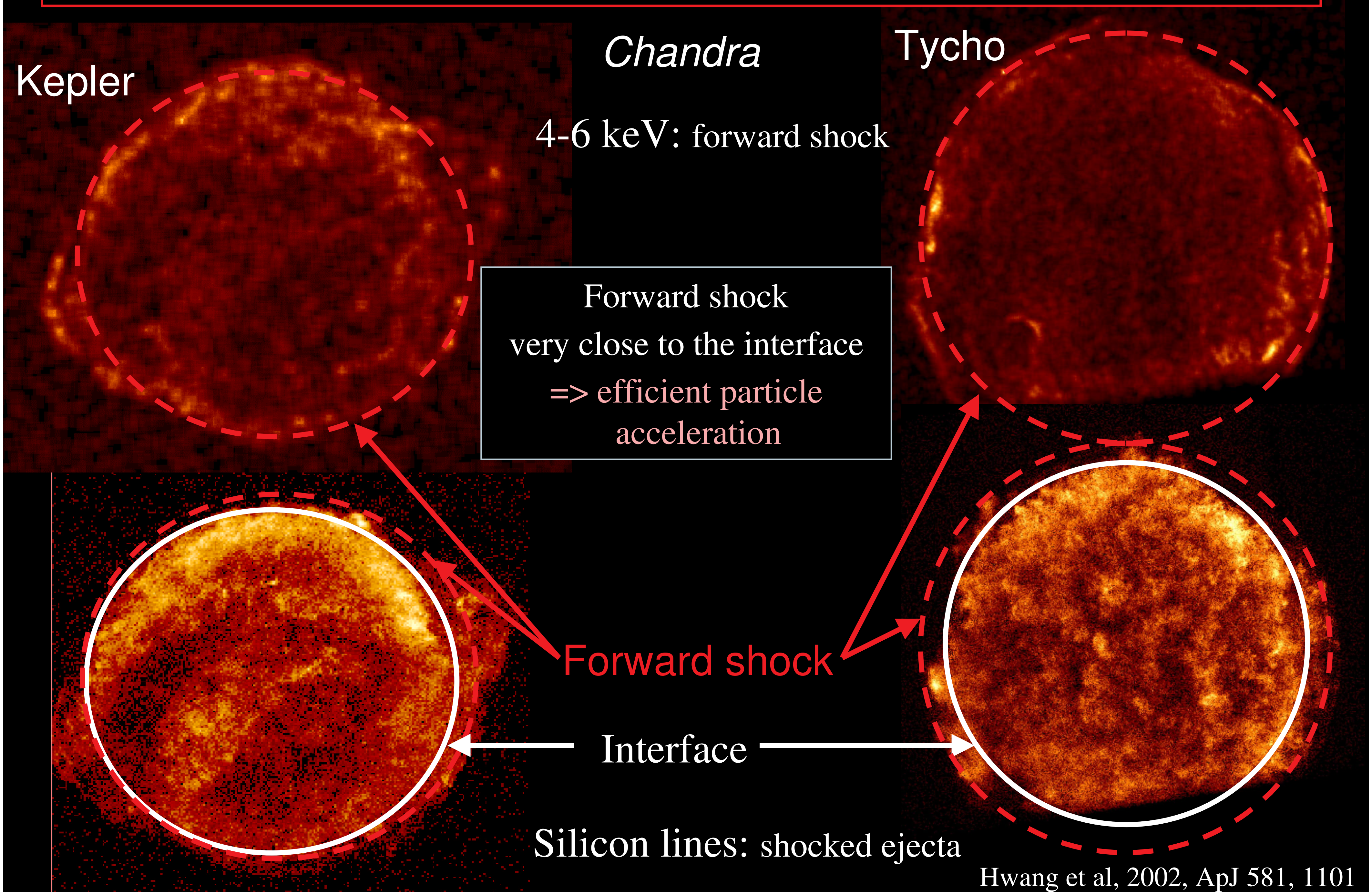


Decourchelle, Ellison, Ballet 2000, ApJ 543, L57
Ellison, Decourchelle, Ballet 2004, A&A 413, 189

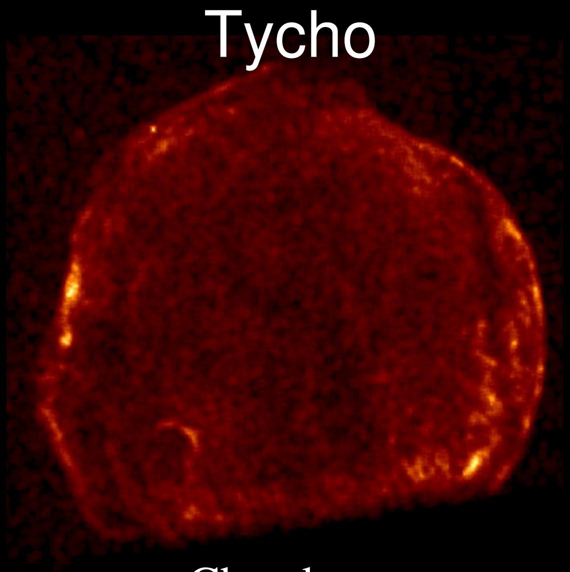


Blondin and Ellison 2001, ApJ 560, 244

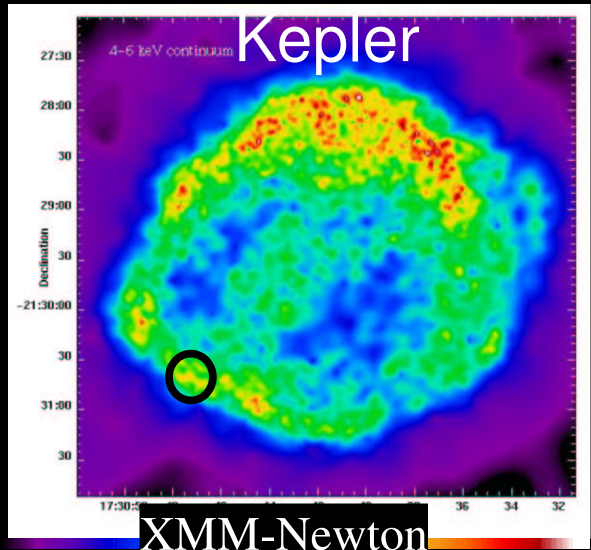
X-ray morphology of the interaction region



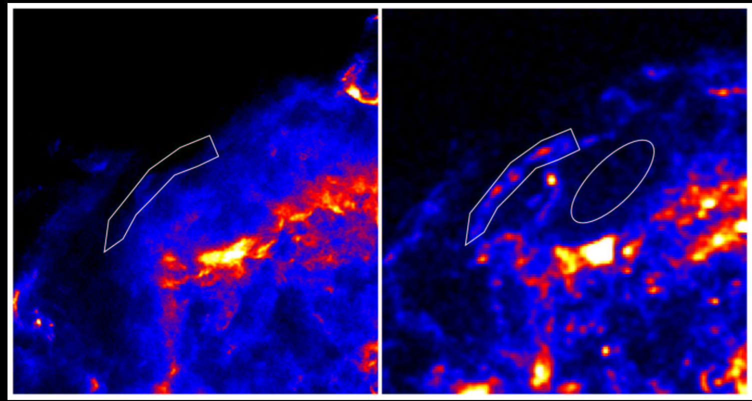
Spectra of the forward shock in ejecta-dominated SNRs



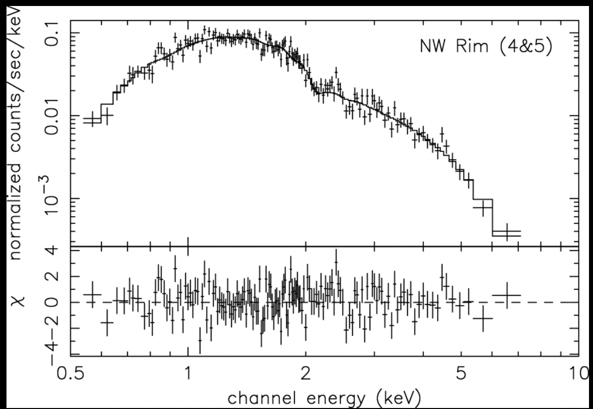
Chandra



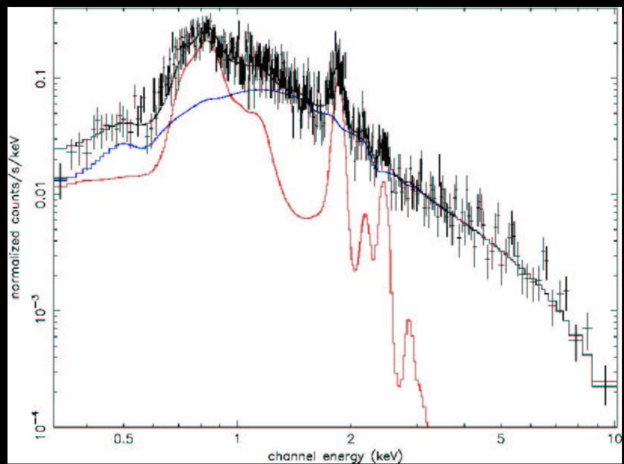
Cas A



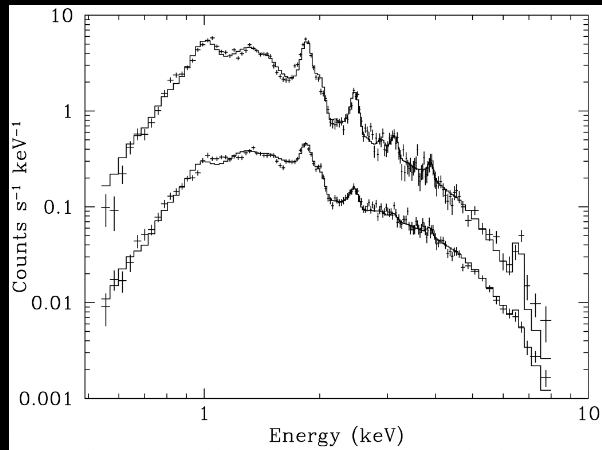
Chandra



Hwang et al, 2002



Cassam-Chenai et al. 2004



Vink and Laming 2003

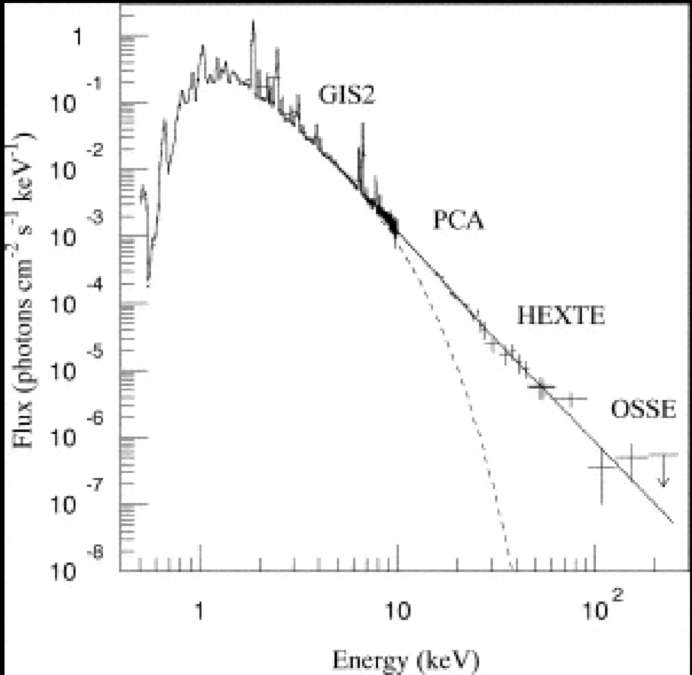
Few or no emission line features !

Thermal: strong ionization delay required but inconsistent with the morphology

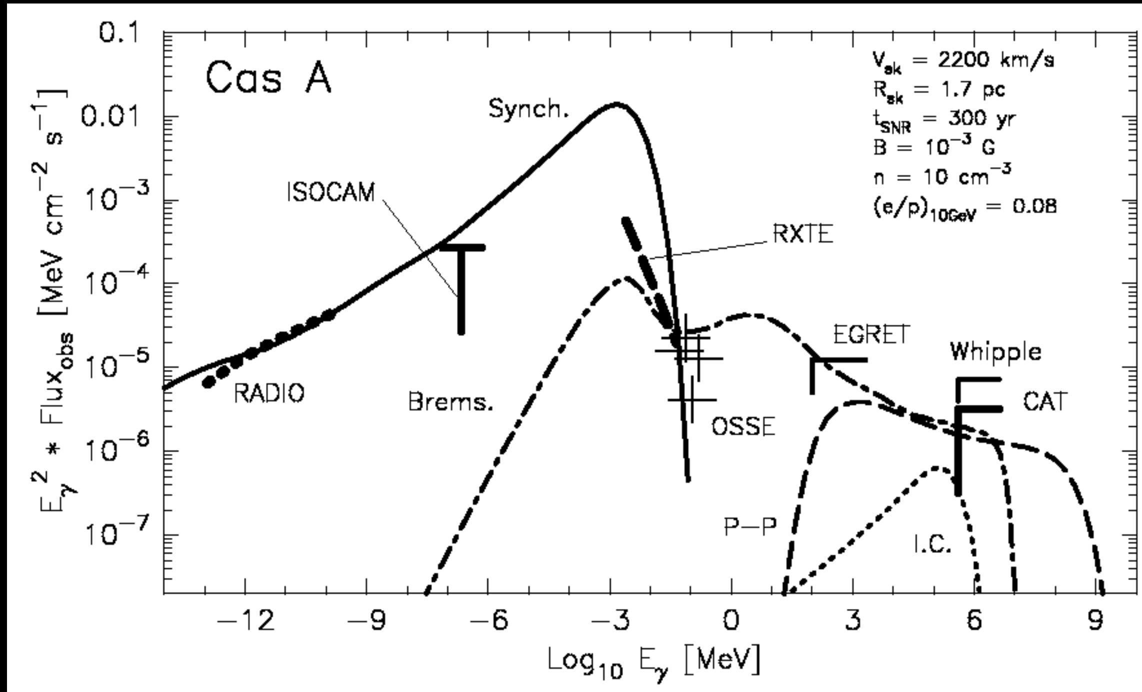
Non-thermal: synchrotron=> maximum electron energies ~ 1-100 TeV

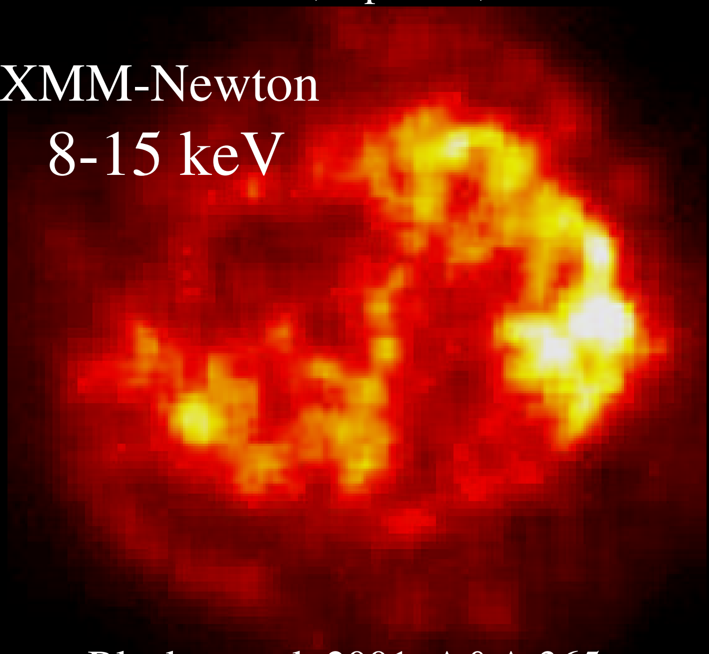
Sharp rims: limited lifetime of the ultrarelativistic electrons in the SNR => B ~ 60-100 μG

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
$\Rightarrow$ large B ~ 1 mG

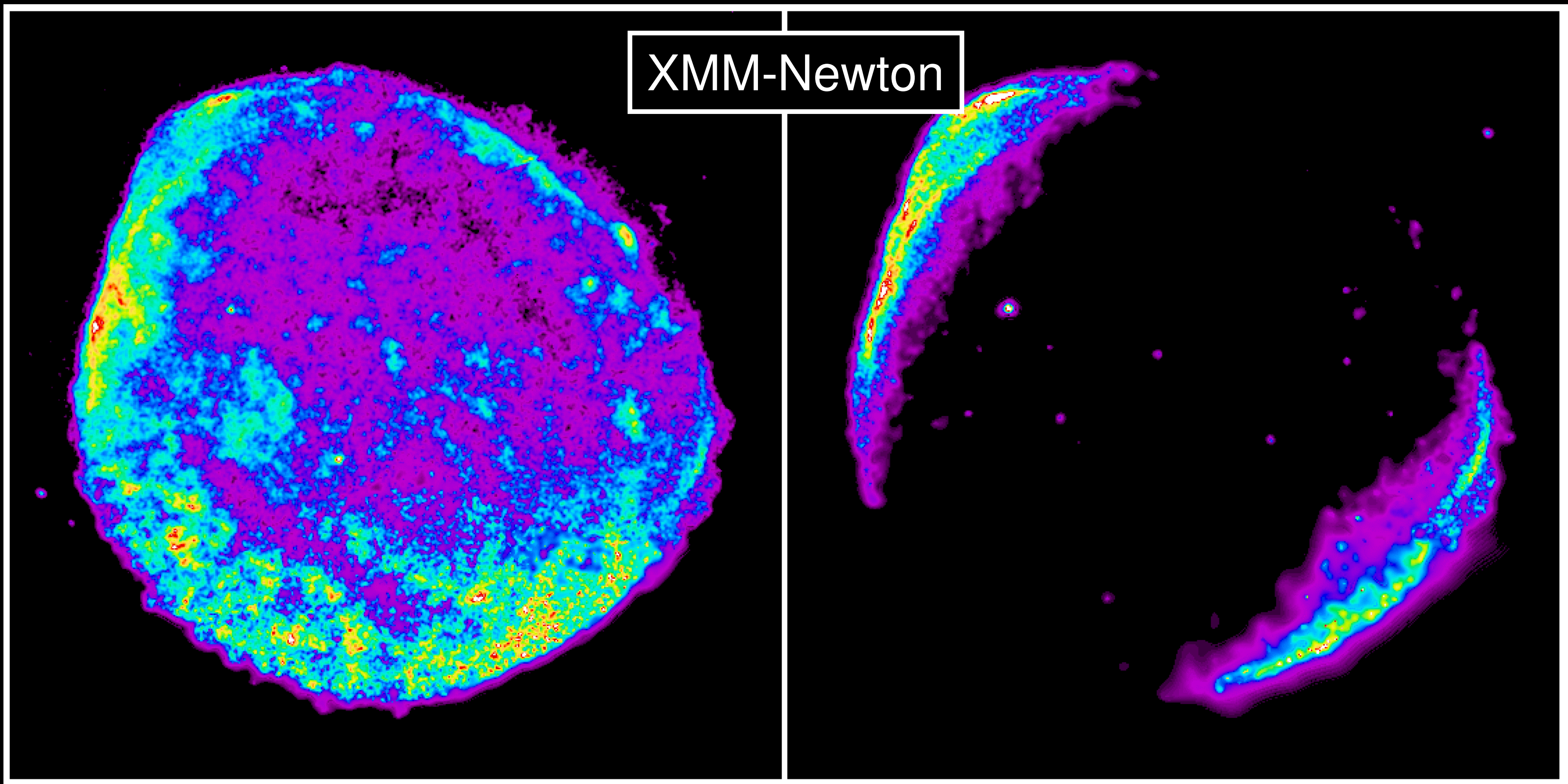
High energy continuum associated with the ejecta
=> inconsistent with X-ray synchrotron

Non-thermal bremsstrahlung at the interface ?

Particle acceleration at secondary shocks ?

(Vink & Laming 2003, ApJ 584, 758)

SN 1006 with XMM-Newton : Geometry of the acceleration



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

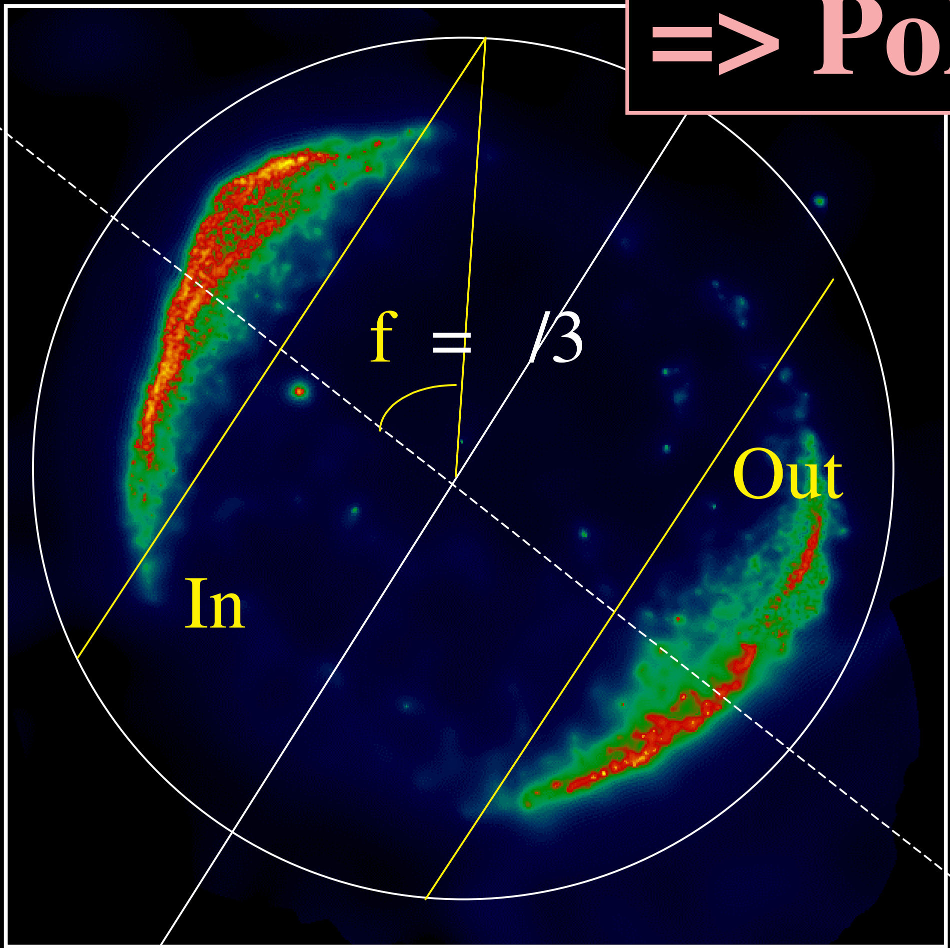
2 – 4.5 keV band : **Non-thermal emission**

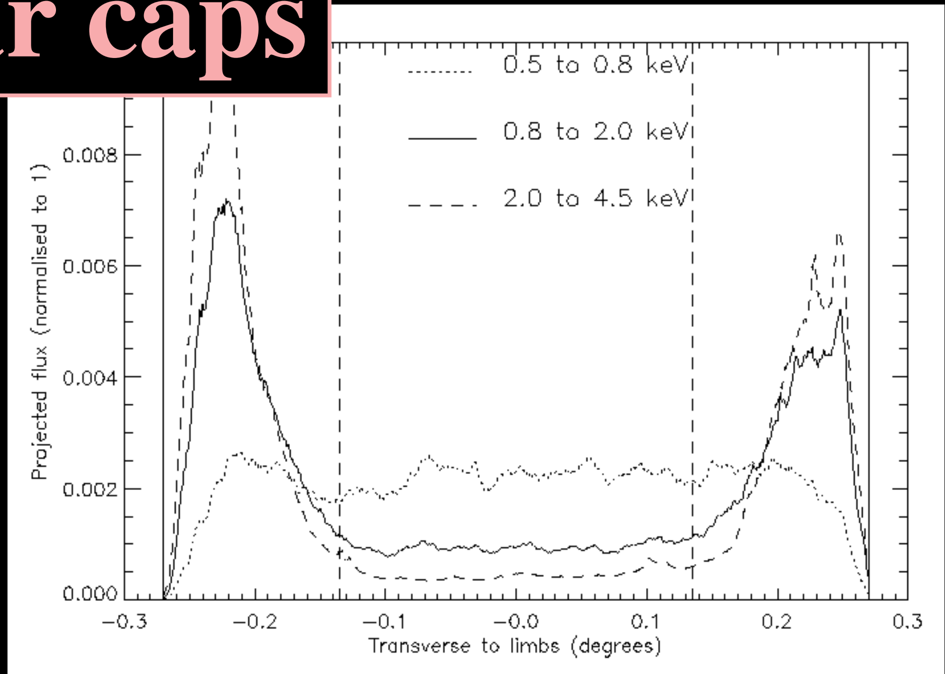
Transverse profile: principle

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: $F_{in}/F_{out} > 0.5$

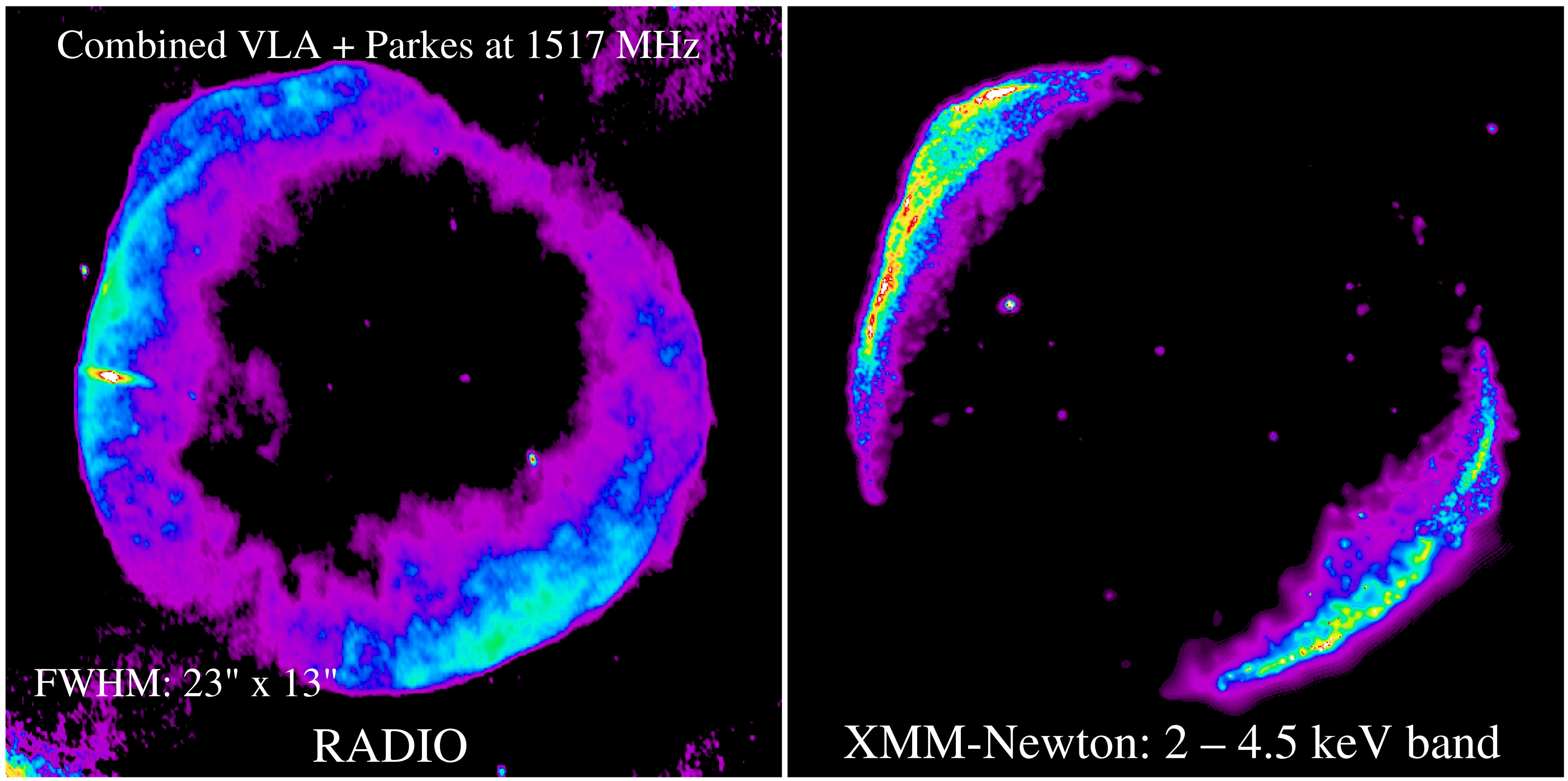
Observed: 0.8-2 keV: 0.300 ± 0.014

2-4.5 keV: 0.127 ± 0.074

$F_{in}/F_{out} > p/2 - 1 = 0.5$

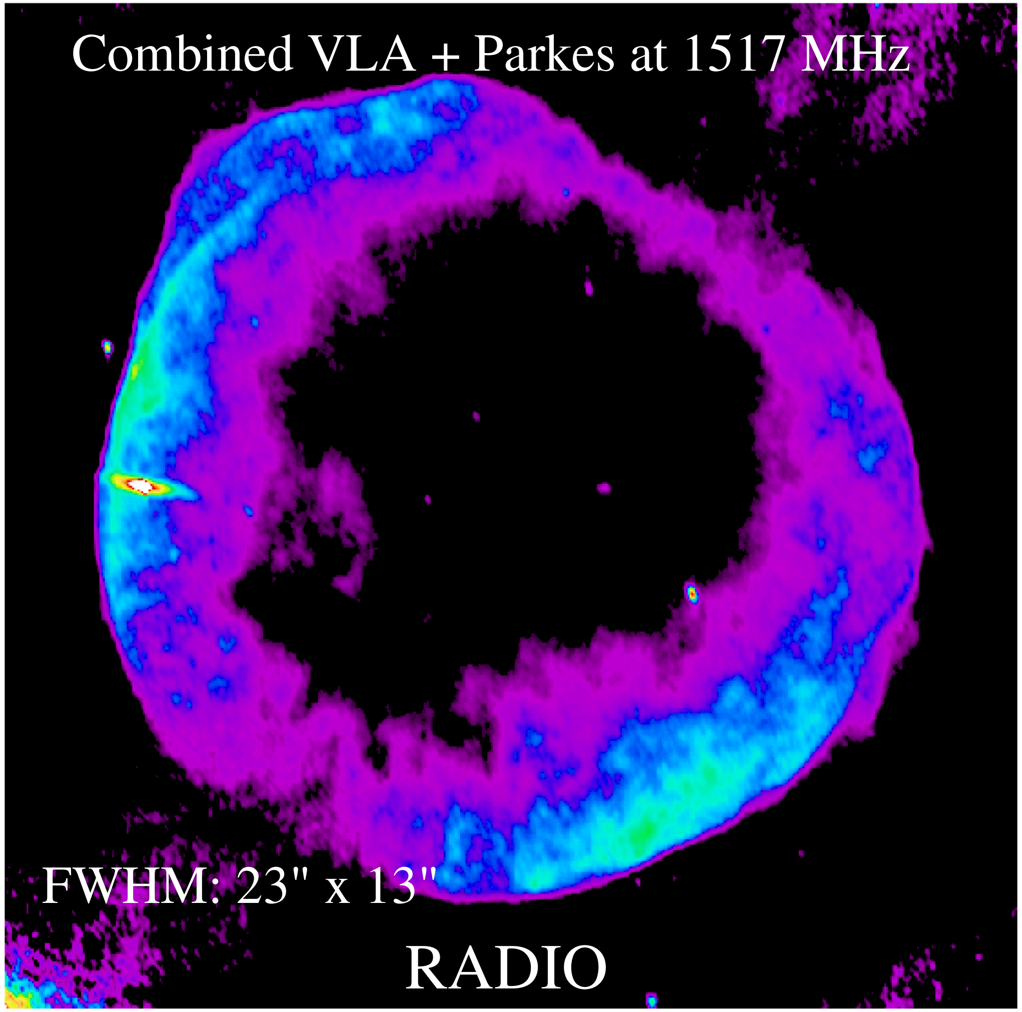
Rothenflug et al., 2004, A&A submitted

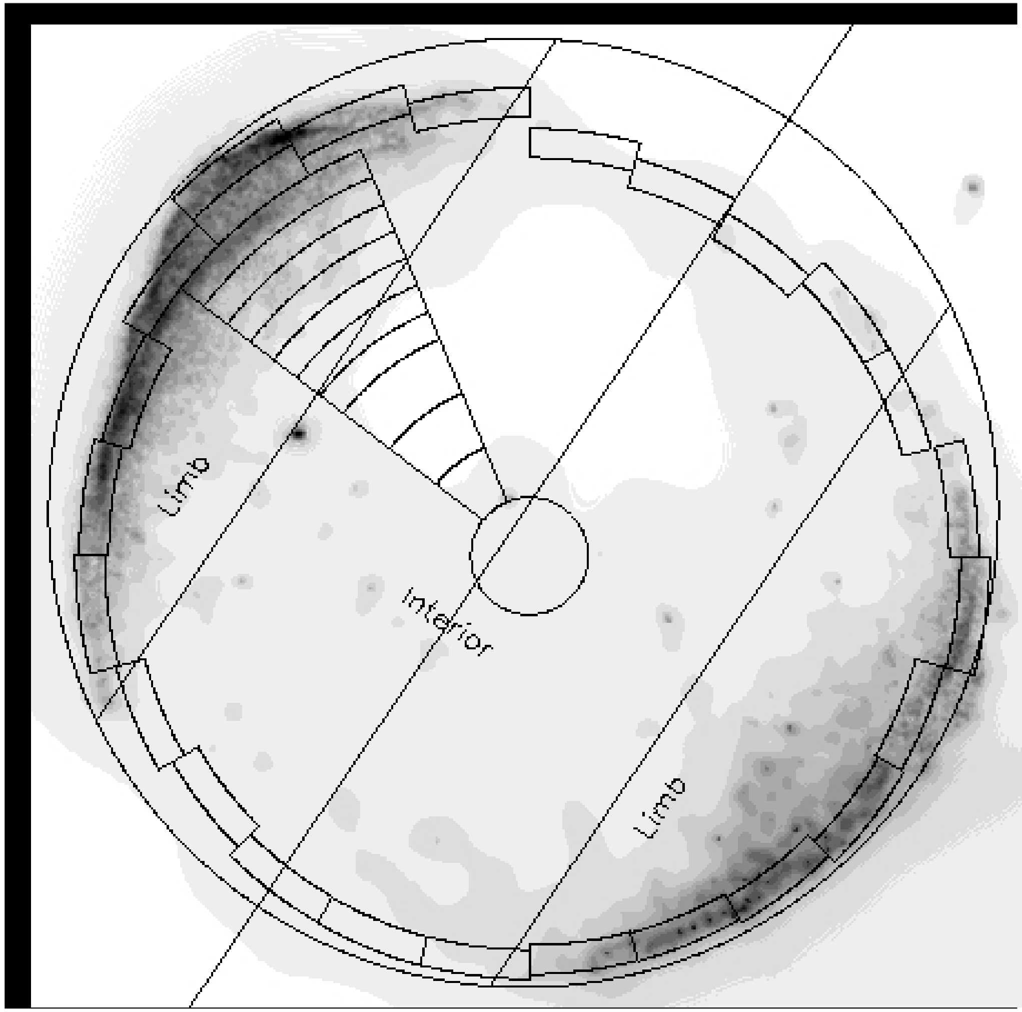
Radio/X-ray comparison



Rothenflug et al., 2004, A&A submitted

Radio/X-ray comparison





Rothenflug et al., 2004, A&A submitted

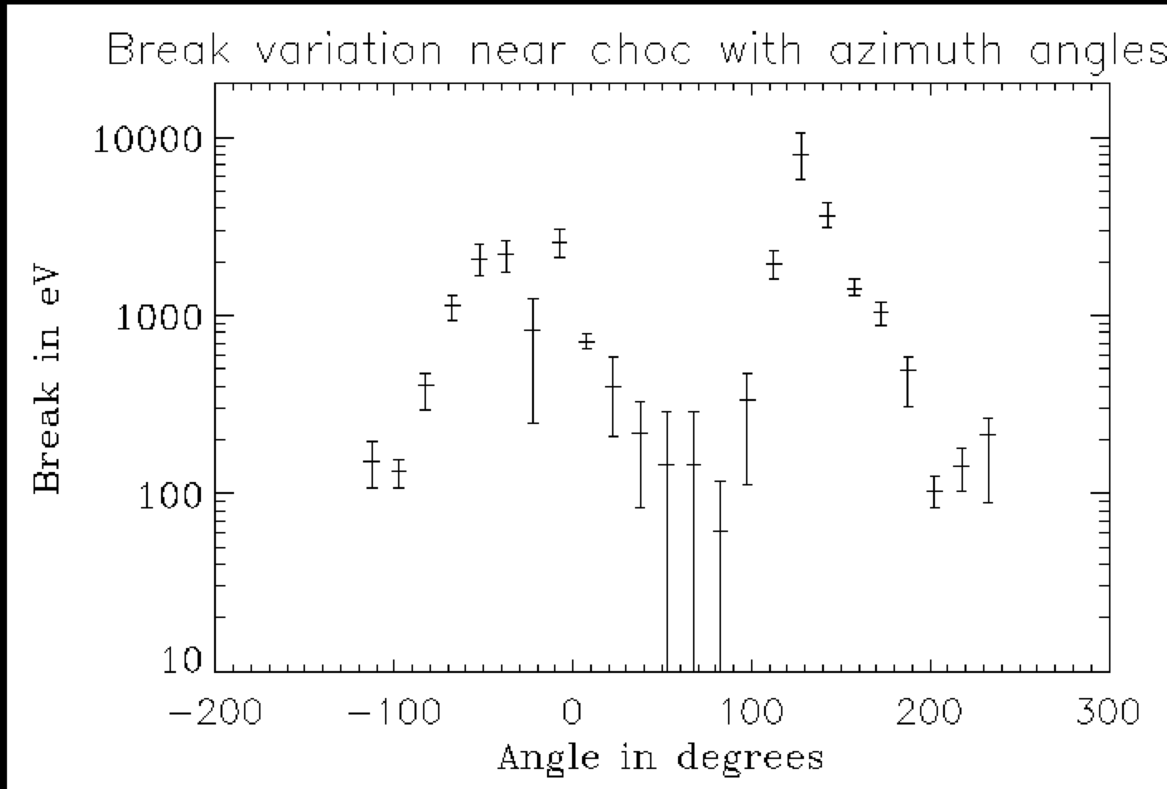
Fit: **synchrotron** from a cut-off electrons power law (SRCUT) plus thermal NEI emission
Normalisation of the synchrotron component fixed using the radio data
Only the cut-off frequency was left free.

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 G, 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)

Objectives with Simbol-X

Particle acceleration in SNRs

a new observational field opened with XMM-Newton and Chandra satellites

Main questions :

What is the maximum energy of accelerated particles ?

What is the spectrum of these high energy electrons ?

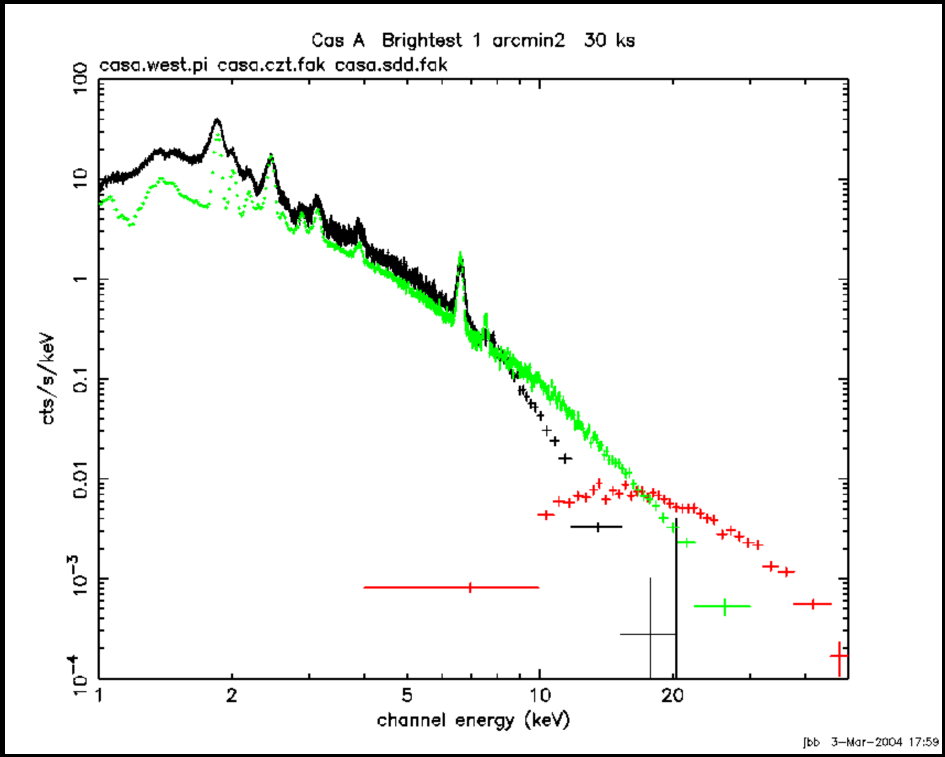
In thermal SNRs, 3 possible components at high energy:

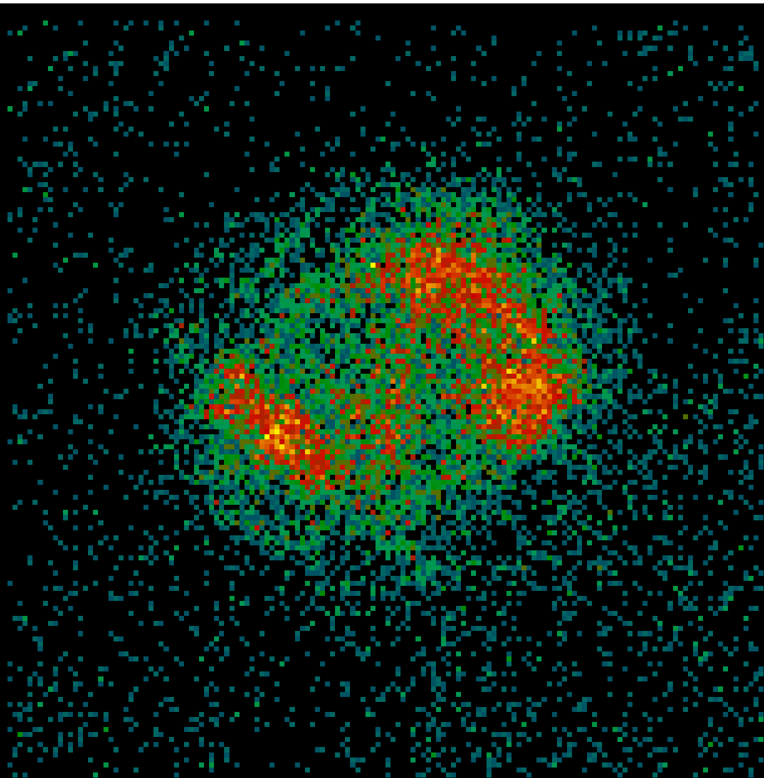
- thermal bremsstrahlung
- non-thermal bremsstrahlung from Low Energy electrons (< 1 MeV)
- synchrotron from electrons accelerated at very high energy (>10 TeV).

=> spatially resolved spectra above 10 keV to disentangle the different components and characterize the spectrum of the highest energy electrons

Cas A (1670): the youngest and brightest known galactic SNR

Suprathermal electrons accelerated at the interface or relativistic electrons accelerated at the forward shock ?



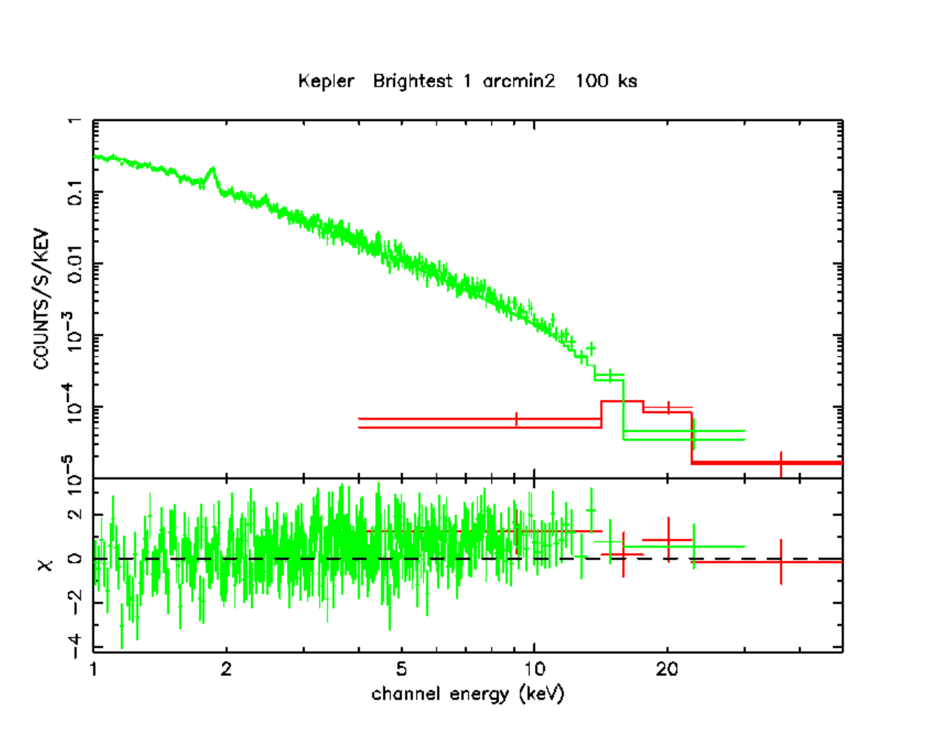


Simulation with SIMBOL–X: bright region and relatively hard spectrum region in the west.Tobs = 30 ks

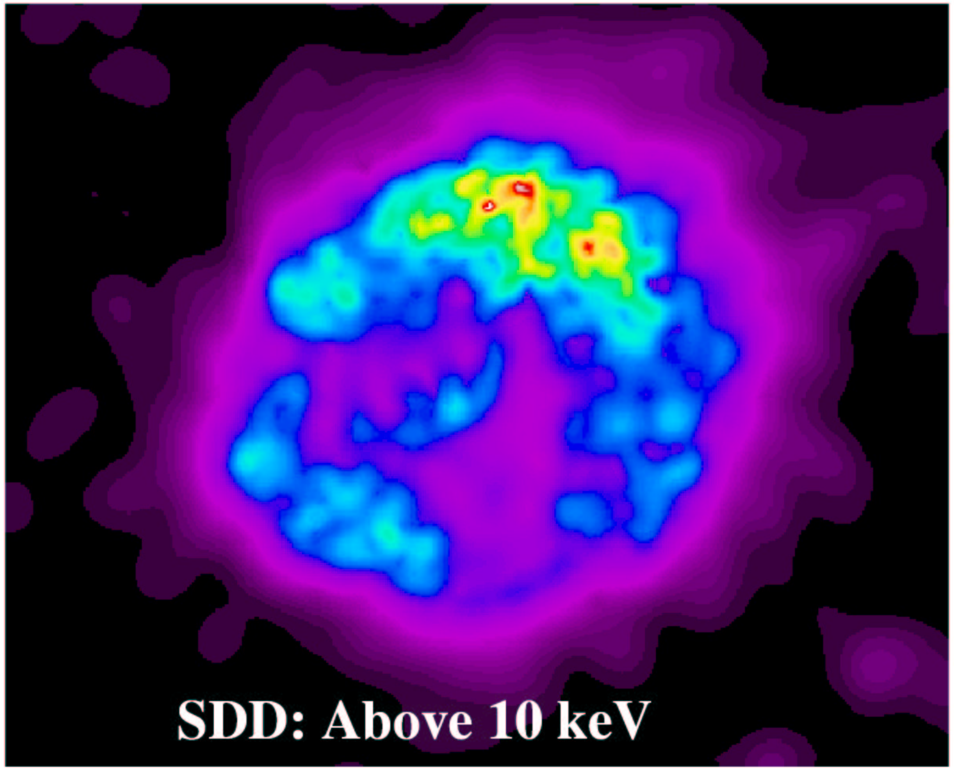
SIMBOL–X > 20 keV
Field of 10 x 10 arcmin2
Total exposure time = 100 ks

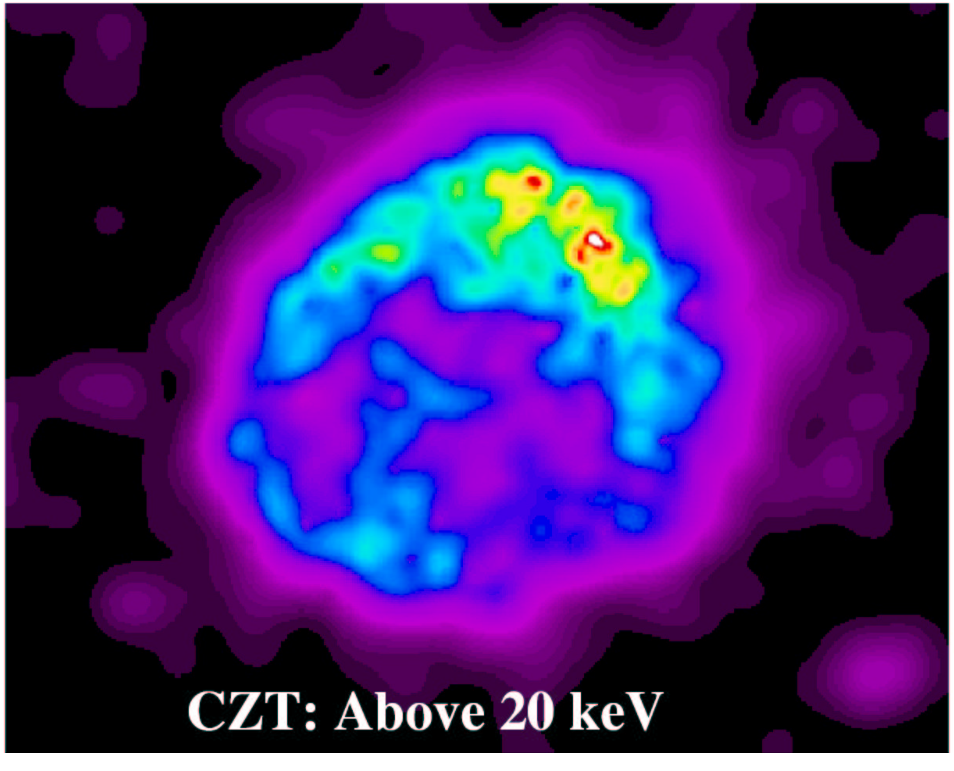
Kepler (1604)

Spectrum and maximum energy of the electrons accelerated at the forward shock ?Azimuthal variations ?



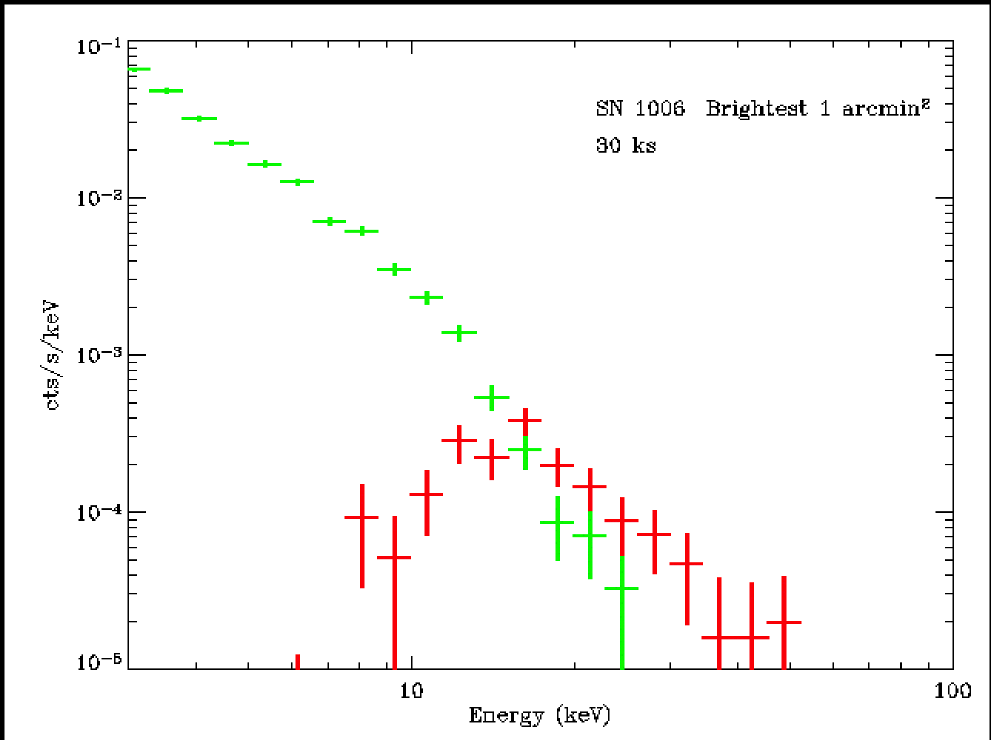
Simulation with SIMBOL–X
Bright and relatively hard region of 1 arcmin2, Tobs = 100 ks



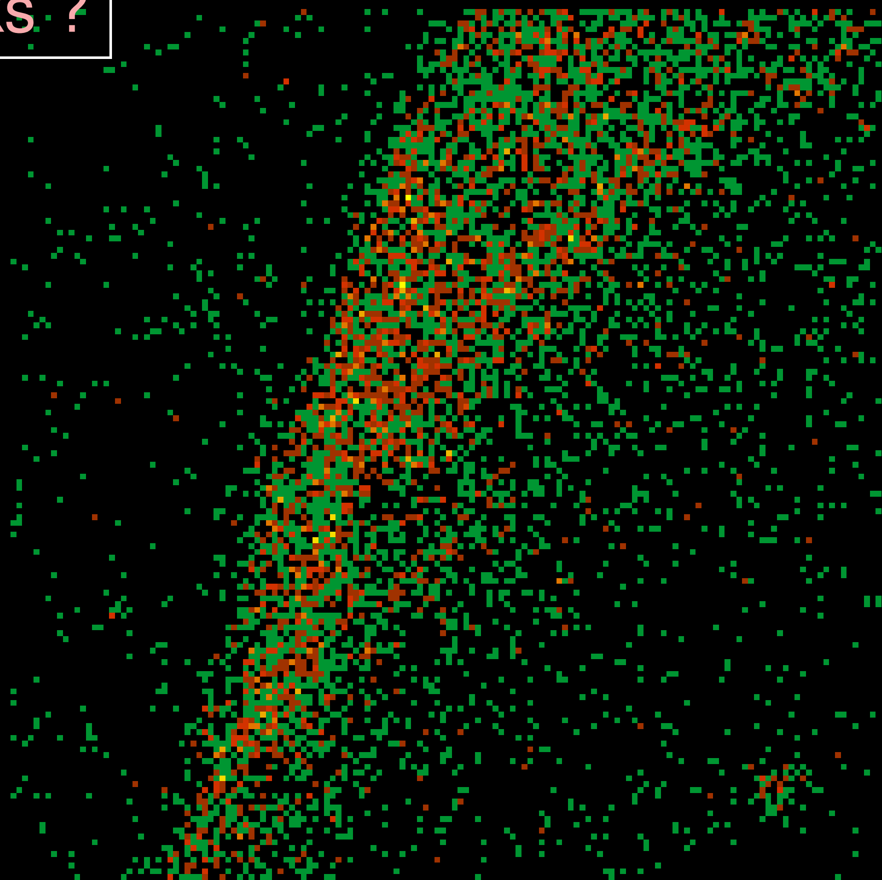


SN 1006

Spectrum and maximum energy of the electrons accelerated at parallel shocks ?



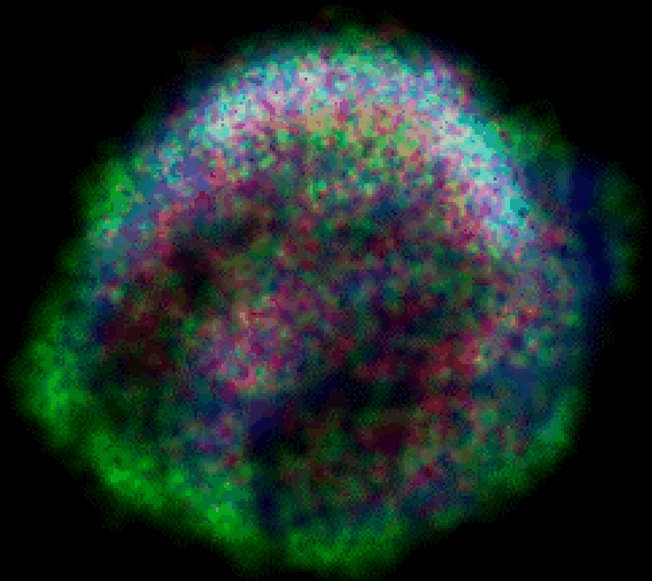
Simulation with SIMBOL–X
Bright and relatively hard region of 1 arcmin2, Tsimul = 30 ks



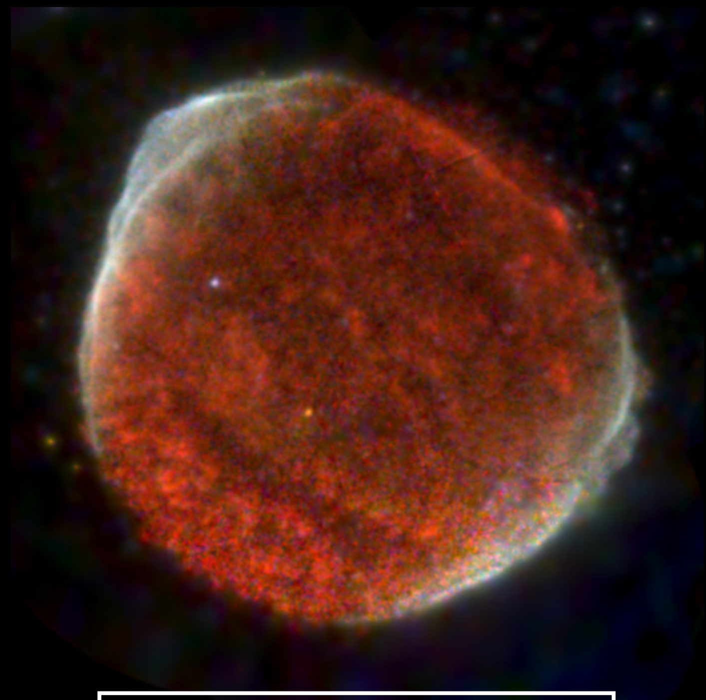
Simulation with SIMBOL–X > 10keV
Field of 10 x 10 arcmin2
Total exposure time = 100 ks

CONCLUSION

Supernova Remnants await SIMBOL-X
to reveal the physics of particle acceleration at the highest energy
via their morphology and spatially resolved spectroscopy



Kepler



SN 1006