Supernova remnants, planetary nebulae and superbubbles: **prospects for new XMM-Newton observations**

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I- Planetary nebulae
II- SNRs
III- Superbubbles

The hot interstellar medium (ISM)

Hot interstellar medium known since more than 30 years generated by supernova explosions and too a less extent by powerful wind.

SN explosions and stellar winds act qualitatively in a similar way:

$\Rightarrow$ **They enhance the ISM metallicity through injection of mass enriched in heavy elements** by the thermonuclear reactions taking place in stars and supernovae.

$\Rightarrow$ **They forge the structure of the ISM through injection of energy:** largely responsible for its multi-phase nature and turbulent state.

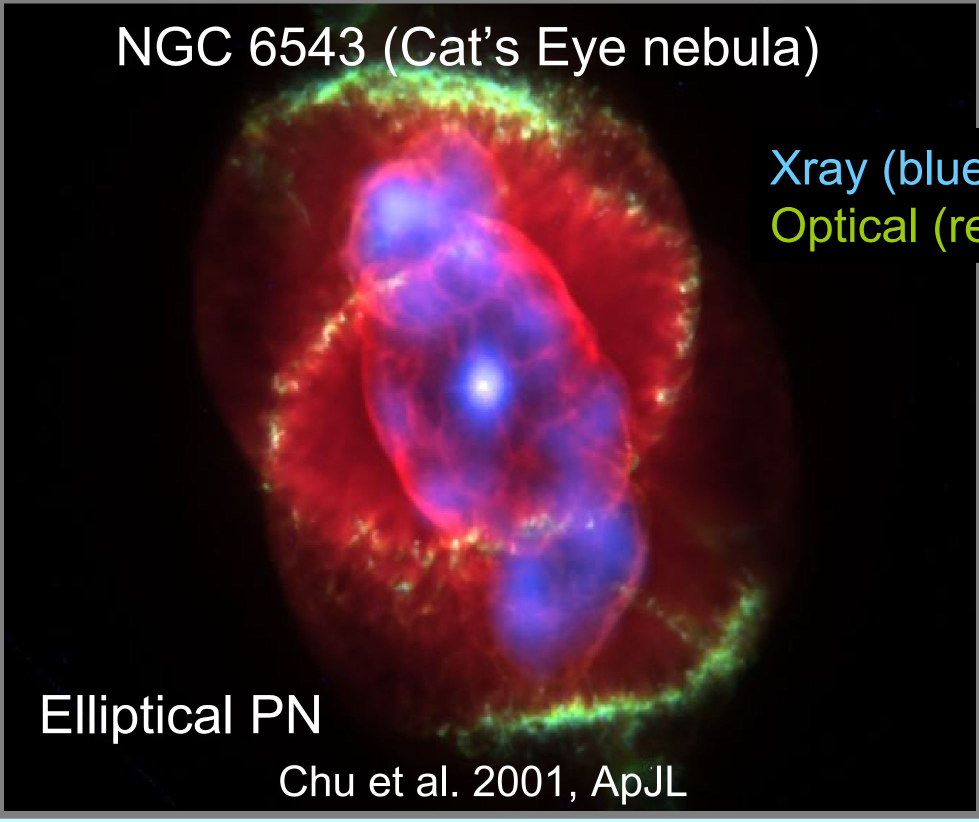
$\Rightarrow$ **They are likely the birth places of Galactic Cosmic Rays and amplification of the magnetic field through particle acceleration at their shocks.**

X-ray observations give access to these sources that shape the large view of galaxies :

Planetary nebulae, stellar winds, supernovae, superbubbles

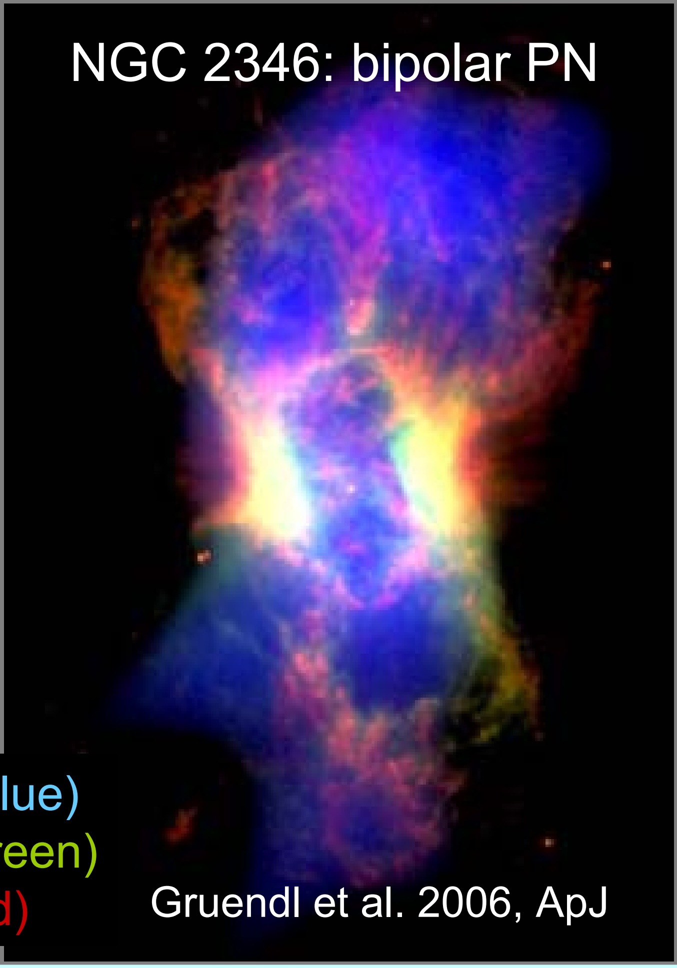
Planetary Nebulae (PNe)

Chandra



Xray (blue-purple)
Optical (red and green)

XMM-Newton



XMM X-ray (blue)
HST [O III] (green)
HST [N II] (red)

PNe formed by the interaction of a copious slow AGB wind with a tenuous fast wind.

⇒ produce the elliptical and bipolar morphologies of PNe.

⇒ give rise to shocks that heat the fast wind material to temperature above 10^6 K.

Elliptical PNe: about 10 observed (XMM-Newton or Chandra), 6 show detectable diffuse X-ray.

Bipolar PNe: many, 3 detected

⇒ X-ray observations shade light on the wind properties and shaping of PNe

Planetary Nebulae

Origin of the X-ray emission and relatively low temperature observed □~ 1-3 10^6 K in PNe ?

Observed velocity of the fast wind V_s ~ 1000 km/s
=> $T_s > 10^7$ K

- Heat conduction (or mixing) at the interface with the cool slow wind material ? It lowers the temperature and increases the density of the shocked fast wind.

- Rapid evolution (weakening) of the fast wind in terms of mass loss.

- Slower moderate velocity wind of ~500 km/s (post-AGB wind) or two opposite jets (collimated fast wind) .

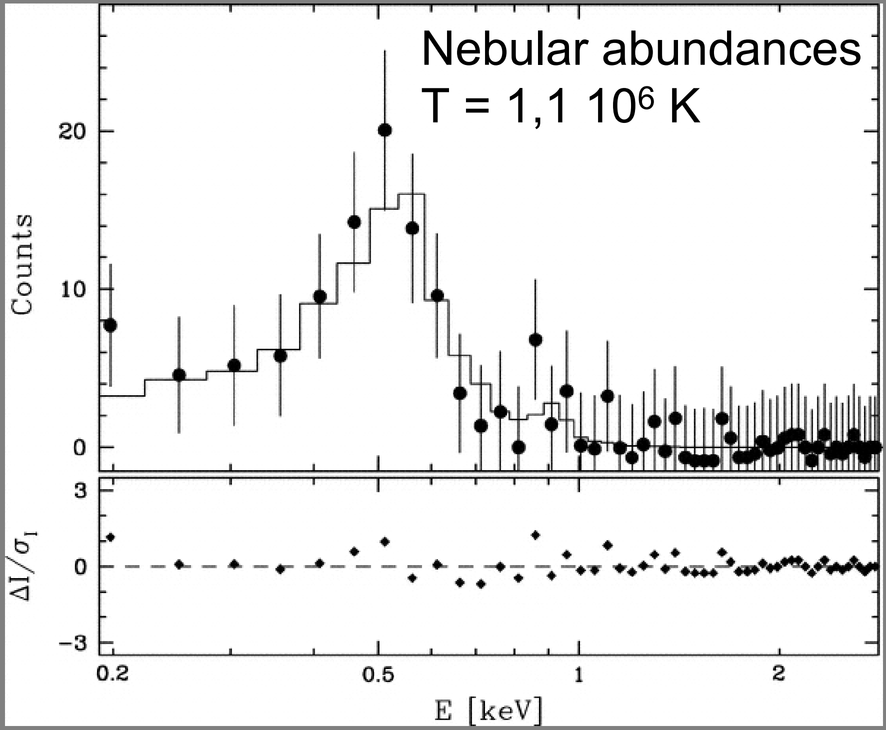
(Akashi et al. 2007)

Composition of the emitting plasma ?

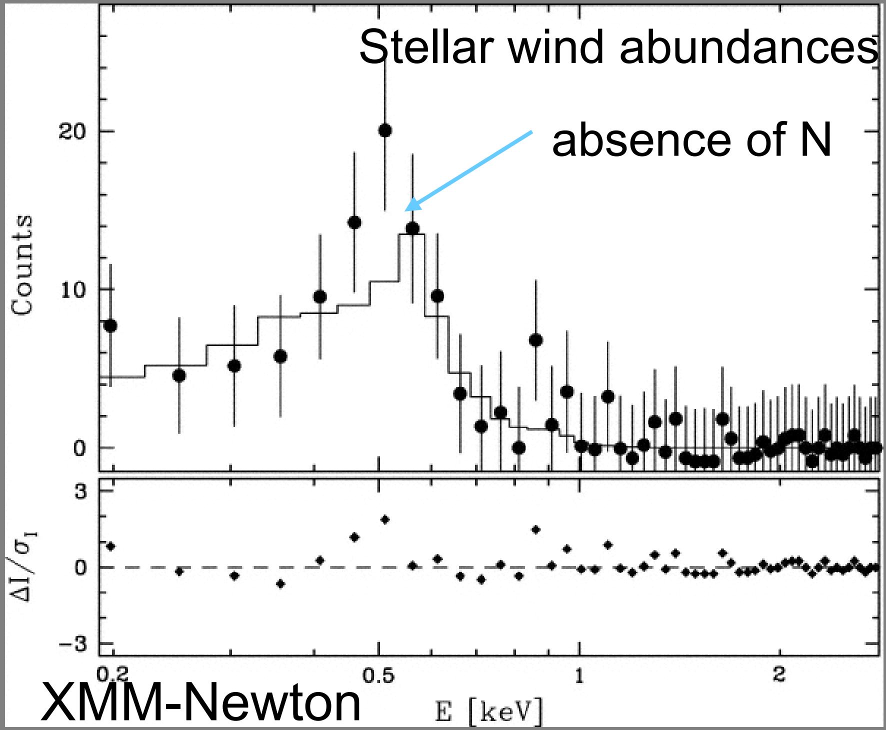
In NGC 7026, better fit with models with nebular abundances than with stellar wind abundances

=> significant mixing of cool nebular material ?

⇒ explanation for the observed low temperature ?



Gruendl et al. 2006, ApJ

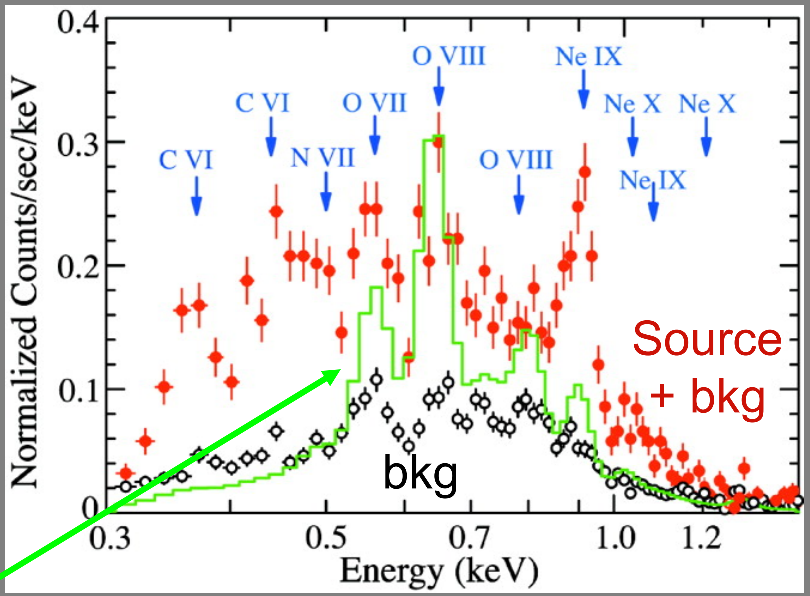


Planetary Nebulae

Fast winds produced during the late evolutionary stage of the central star

⇒ X-ray observations gives access to the late phase products (C,N, O and Ne) synthesized in the CNO cycle and He burning phase and ejected through mass loss.

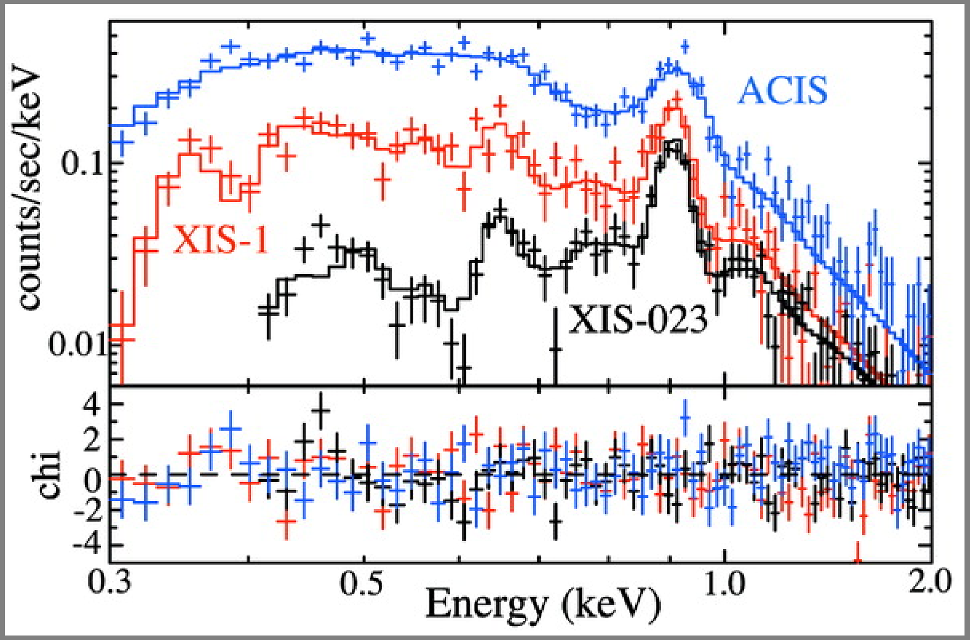
⇒ extreme carbon enhancement over oxygen (by a factor 40) in the brightest X-ray PN BD +30 3639



Solar abundance plasma

BD +30 3639 by Suzaku

Murashima et al. 2006, ApJL



Planetary Nebulae

More than 1500 identified Galactic PNe

The observed X-ray luminosities of PNe are generally much lower than theoretical expectations.

Less than 20 identified as X-ray sources: young elliptical and bipolar PNe, but not from the evolved.

Prospects with XMM-Newton:

- to increase the statistics on the X-ray spectrum of identified PNe.

- to increase the number of observed PNs in X-rays for statistical properties.

Best candidates: fast winds, closed bipolar lobes and young kinematic age (< 1000 years)

X-ray emission => properties of the central fast wind and collimated fast wind

X-ray observations of young SNRs

Tycho (SN 1572)

SN Ia

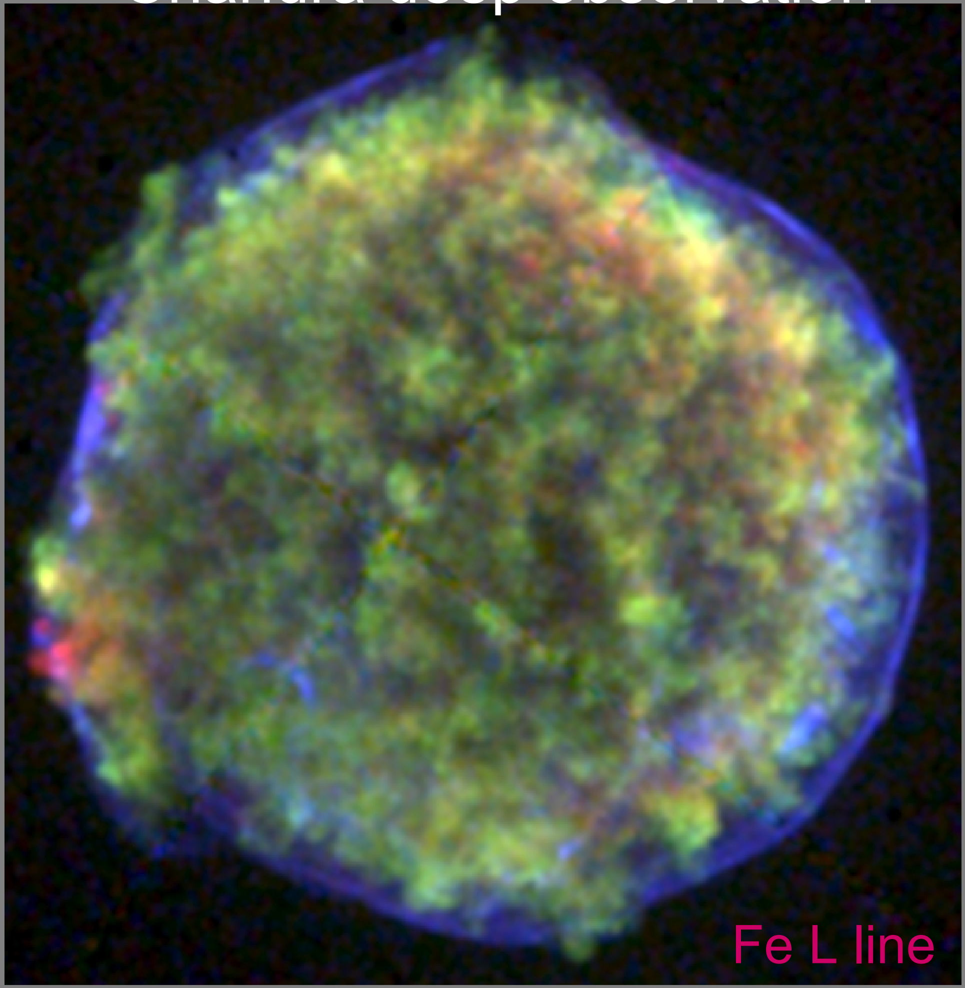
SN material ejected at high velocity

$\Rightarrow$ **Heating of the ejecta and ISM**

Powerful X-ray production usually dominated by:

- thermal emission of the shocked ejecta at ~ 1 keV of optically thin plasma.
- non-thermal emission in the 4-6 keV continuum from accelerated electrons.

Chandra deep observation



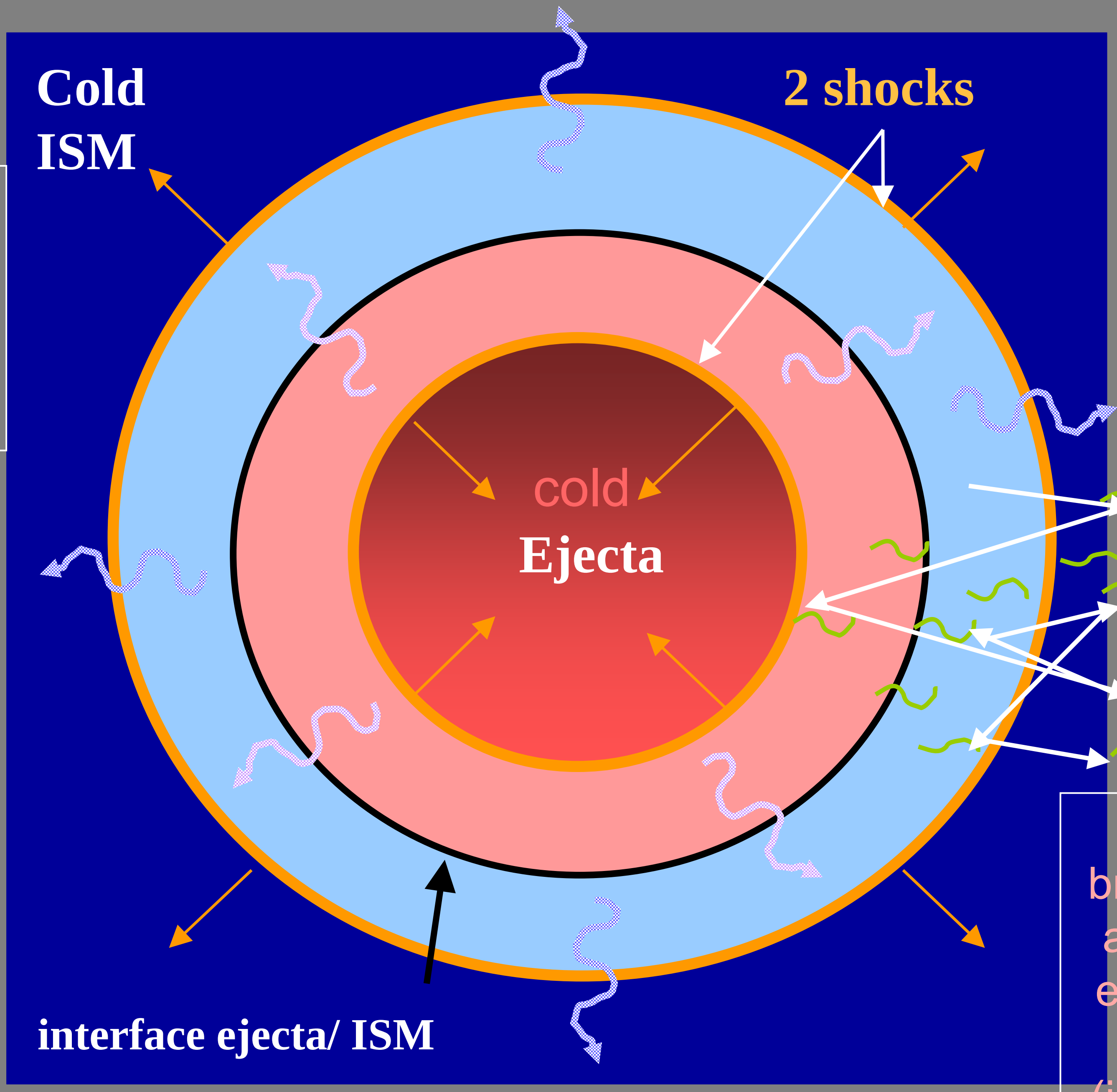
Warren et al. 2005

Si K line

4-6 keV continuum

X-ray emission observed in young SNRs

Thermal X-rays from shocked ejecta



X-ray synchrotron: electrons accelerated by diffusion on magnetic turbulence on both sides of the shock

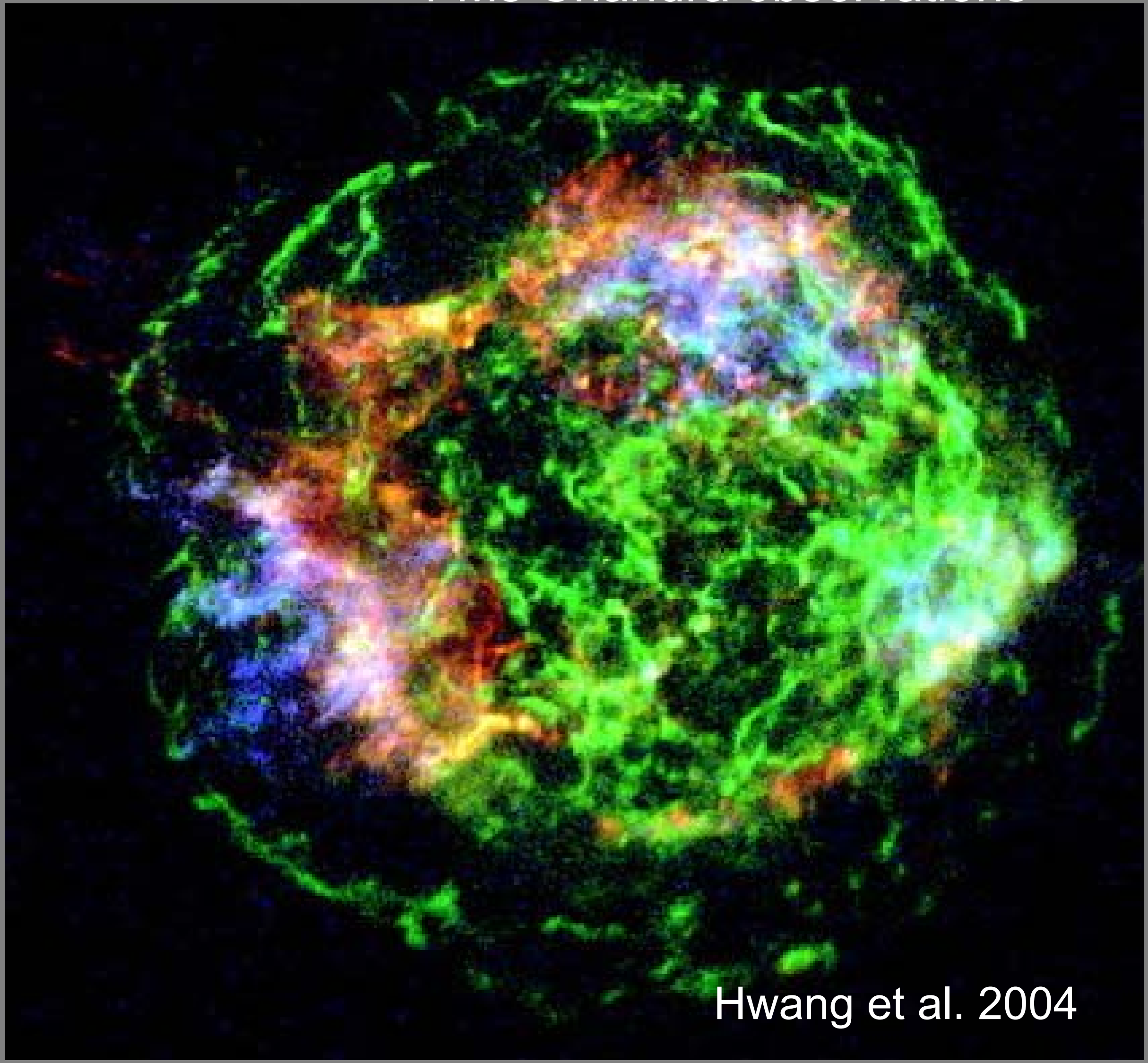
Thermal X-rays from shocked ISM

Non-thermal bremsstrahlung: acceleration of electrons at the interface (in some cases)

1. Nucleosynthesis products

Cas A (~ 1670)

1 Ms Chandra observations



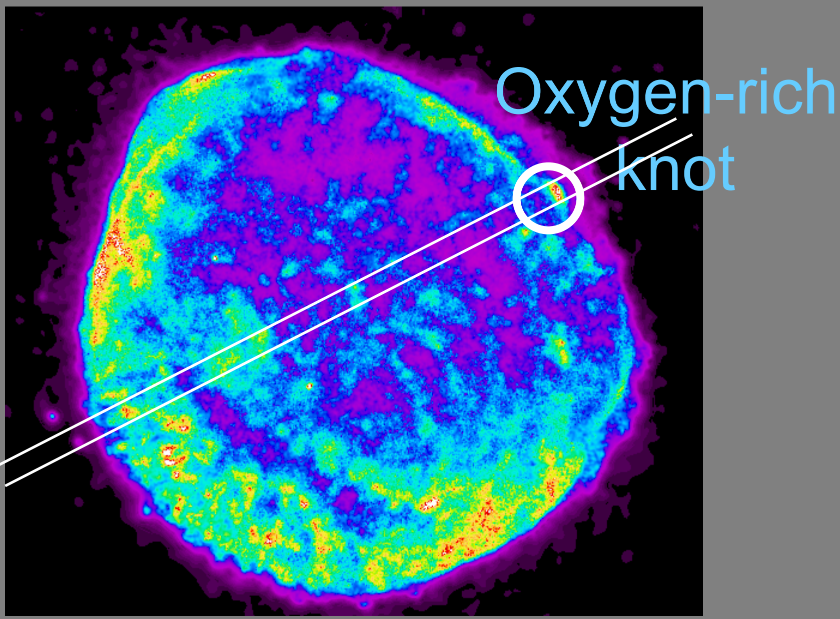
Si He (1.78-2.0 keV) Fe K (6.52-6.95 keV) Continuum (4.2-6.4 keV)

Core-collapse SN

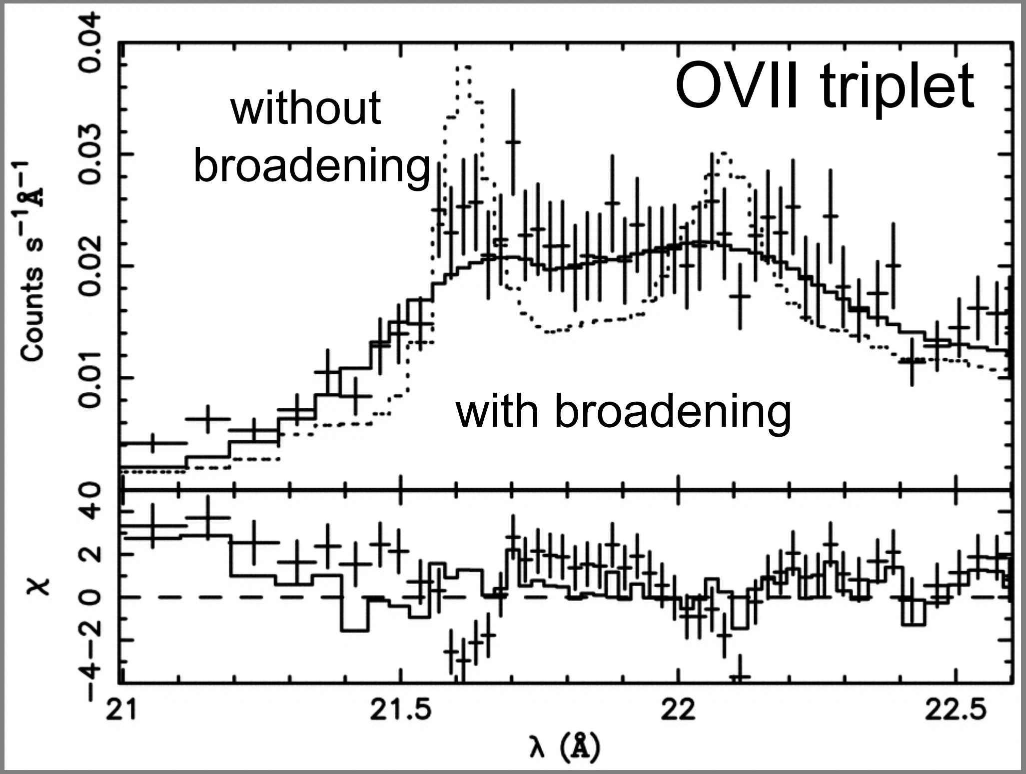
- First unequivocal identification of iron-rich ejecta produced by explosive silicon burning in a young SNR
- Elsewhere in the remnant Si-rich ejecta from explosive oxygen burning
- Fe-rich ejecta lies outside Si-rich ejecta: spatial inversion of a significant portion of the SN core (Hughes et al. 2000, ApJL).

2. Shock physics: Temperature equilibration

XMM-Newton/RGS



O K line band
XMM-Newton



High resolution spectrum of the O knots (NW) with the RGS

=> Doppler broadening of the OVII line measured :

kT_O= 528 ± 150 keV while kT_e = 1.5 keV

⇒ Small degree of electron-ion temperature equilibration (< 5 %)

(Vink et al. 2003, ApJL)

3. Electron acceleration

What is the maximum energy of accelerated particles ?

Electrons are a few % of cosmic rays

but can reveal a lot on the mechanism of diffusive shock acceleration

=> accelerated like protons, so their spectrum is expected to be the same.

X-ray synchrotron emission

- Maximum energy of accelerated particles

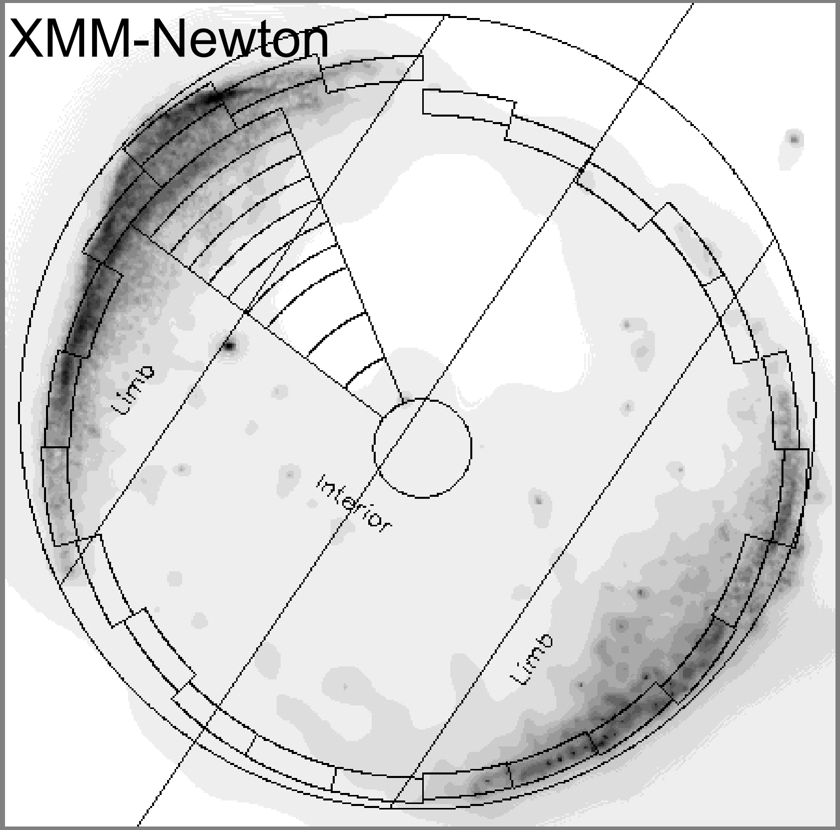
obtained through the measurement of the cut-off frequency of the synchrotron emission, observable in X-rays (if the magnetic field is known)

=> energy on the order of 10 TeV.

- Azimuthal variation of E_{max} along the SNR shock

- spatially resolved spectroscopy required

SN 1006



Rothenflug et al. 2004, A&A 425, 121

Azimuthal variations of the cut-off frequency

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

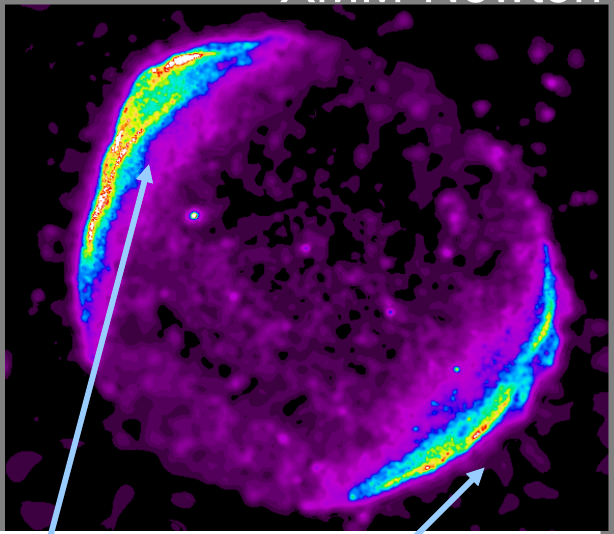
=> Maximum energy of accelerated particles higher at the bright limbs than elsewhere.

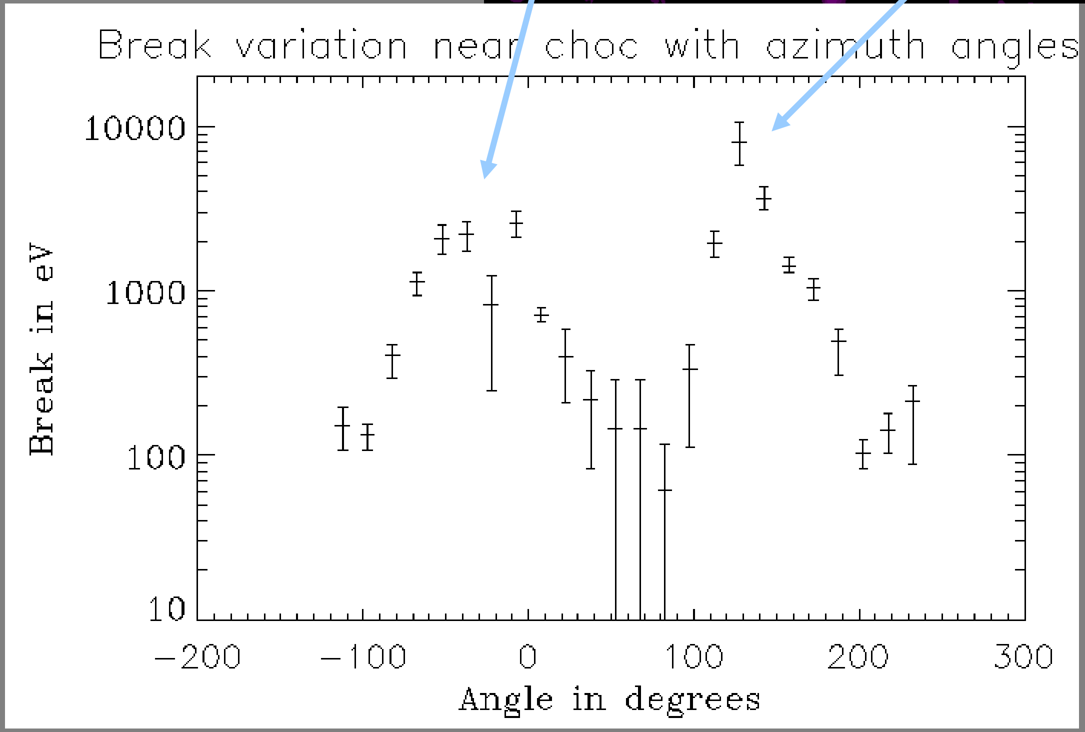
- If B ~ 10 μG, the maximum energy reached by the electrons outside the brights limbs is around 25 TeV.
- If B is amplified at the limbs, E_{max}(protons) is certainly much larger (> 1000 TeV) there.

$$\nu_{cut}\,(\mathrm{eV}) \sim 0.02\, B(\mu G)\, E^2_{cut}\,(\mathrm{TeV})$$

SN 1006: a SN Ia

XMM-Newton





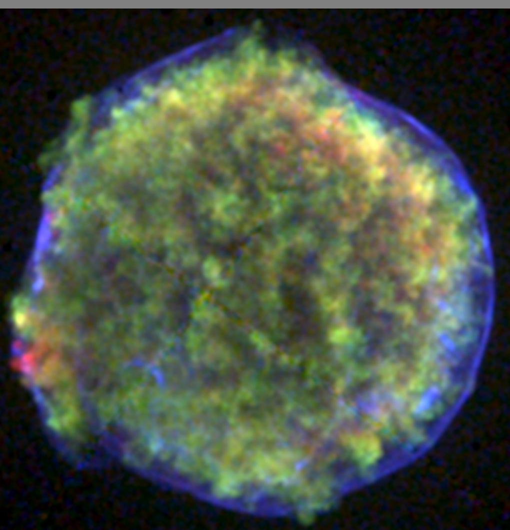
Rothenflug et al. 2004, A&A 425, 121

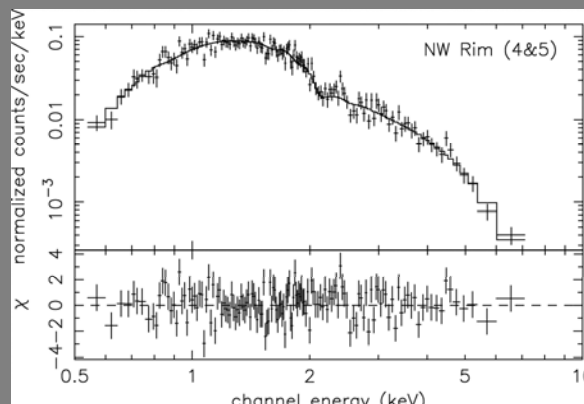
The X-ray geometry of SN 1006 favors cosmic-ray acceleration where the magnetic field was originally parallel to the shock speed (polar caps)

3. Electron acceleration in young SNRs

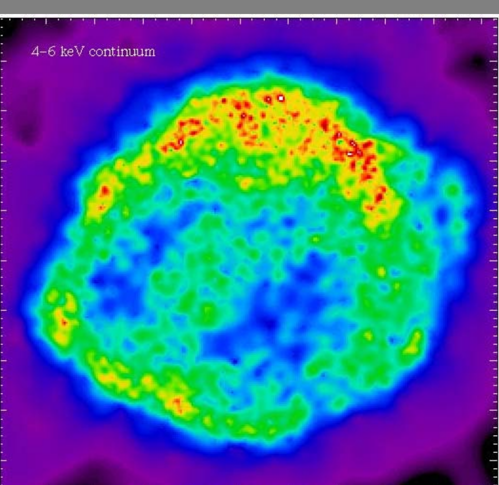
How large is the magnetic field ? Is it very turbulent ? Is it amplified ?

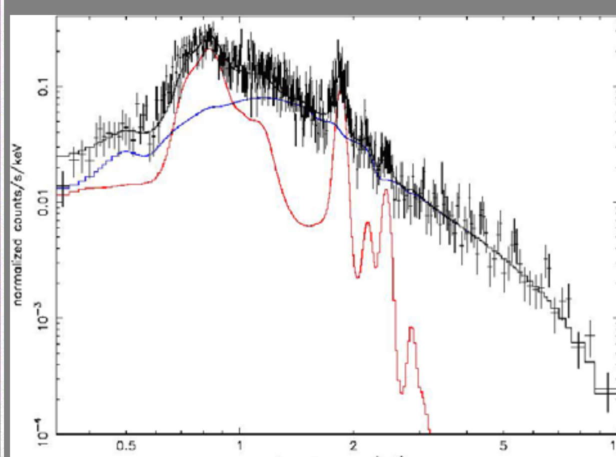
Morphology of the X-ray synchrotron emission:
filamentary emission in thin sheets just behind the blast wave.





Hwang et al, 2002, ApJ 581, 1101





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

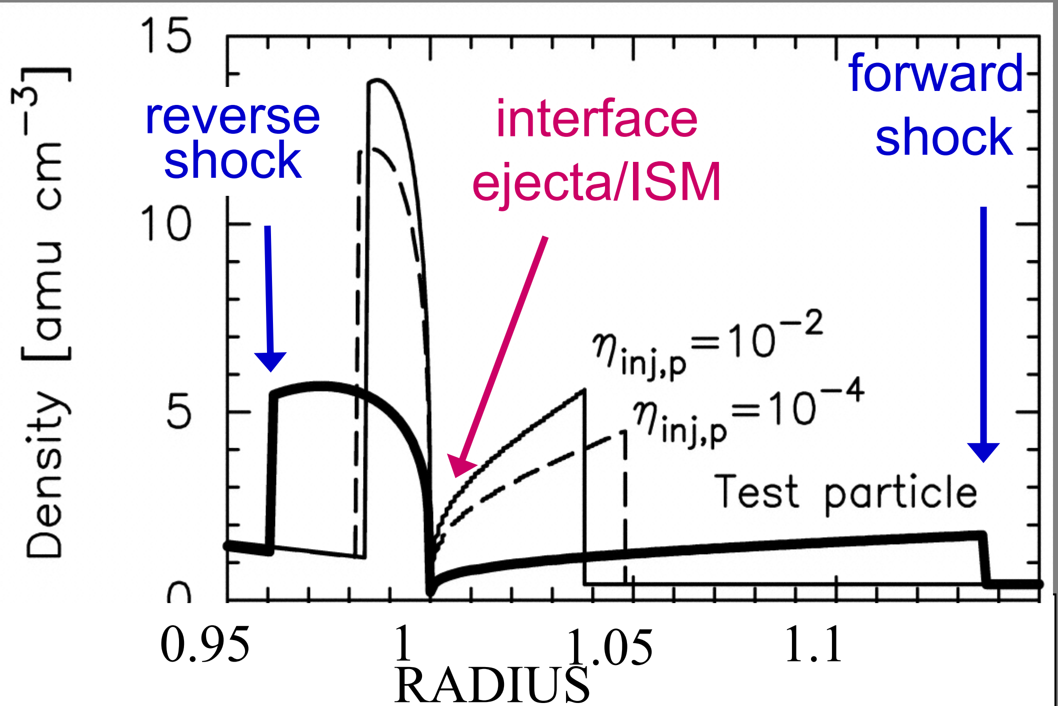
- o Constraints on the magnetic field configuration and intensity
- \- either the magnetic field is large enough (~ 100 μG) to induce strong radiative losses in the high energy electrons (Vink and Laming 2003).
- \- or the magnetic field is damped at the shock (Pohl et al. 2005).

These models predict distinct morphology and spectral shape in X-rays (Cassam-Chenaï et al. 2007).

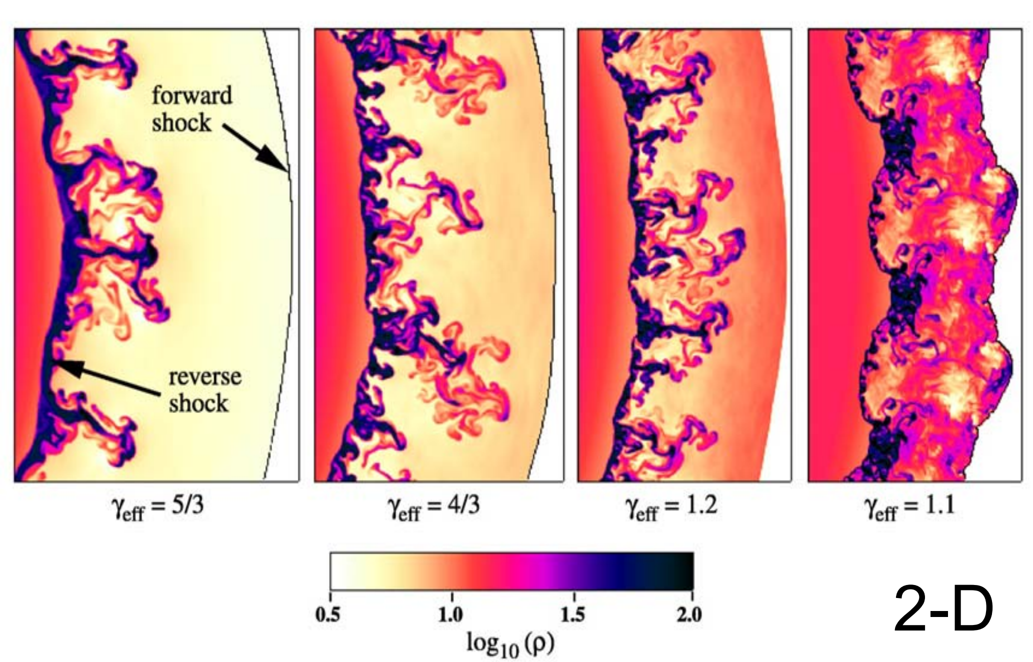
4. Proton acceleration: morphological signature

Evidence for ion acceleration in SNRs ? How efficient is cosmic-ray acceleration ?
What fraction of the shock energy can be tapped by the cosmic rays ?

o Back-reaction of the accelerated particle on the shock and hydrodynamics



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



Blondin and Ellison 2001, ApJ 560, 244

For efficient ion injection, large fraction of energy goes into accelerated particles

- larger compression ratio and lower post-shock temperature (but observed Te < Ti)
- modified hydrodynamics: narrower interaction region, observable in X-rays

Modified hydrodynamics in Tycho's SNR: narrower interaction region

Forward shock very close to the contact discontinuity :

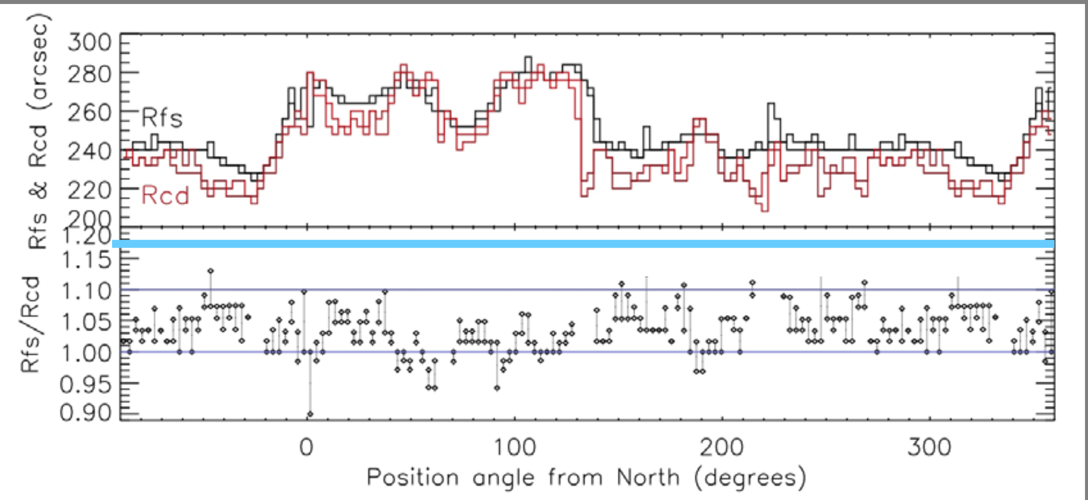
Observed value: $\mathbf{R_{FS}/R_{cd} < 1.1}$

Test-particle value: R_{FS}/R_{cd} ~1.18

=> efficient particle acceleration of protons

Decourchelle 2004, Warren et al. 2005, ApJ 634, 376

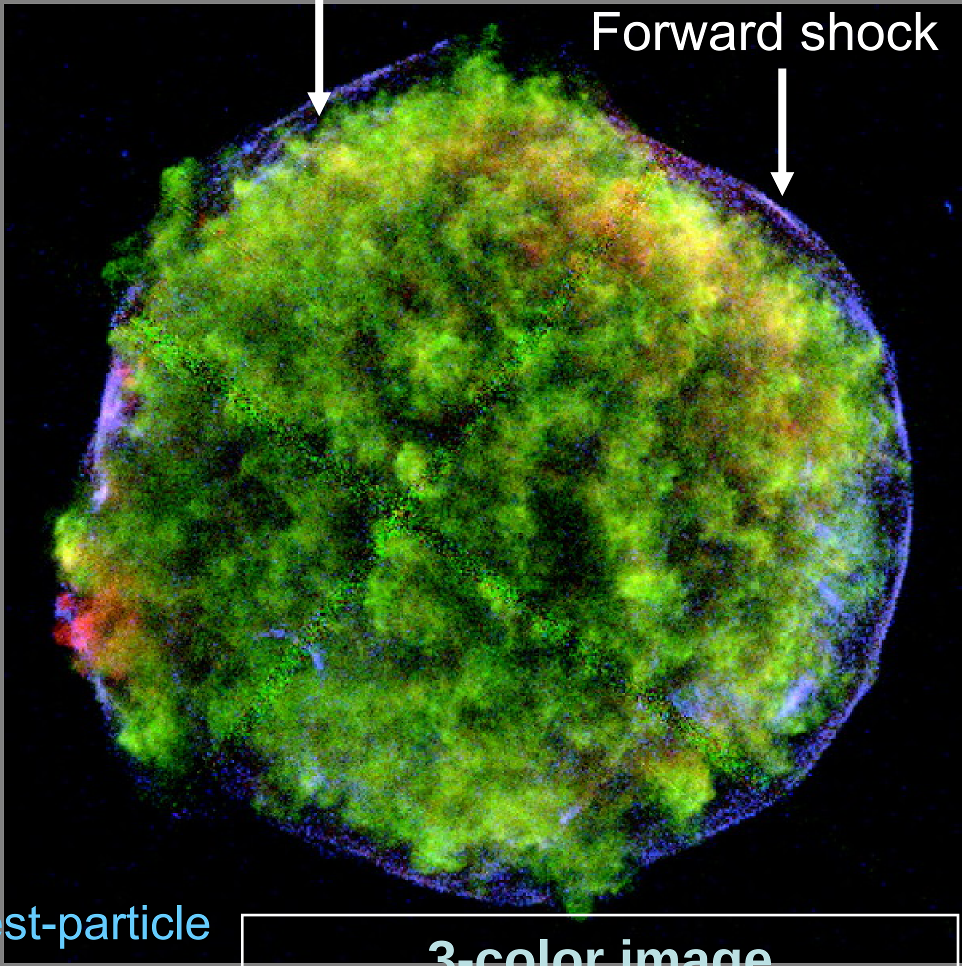
Azimuthal variation of R_{FS}/R_{cd}



Test-particle

Contact discontinuity

Forward shock



3-color image

red = Fe L
green = Si + S K
blue = 4 to 6 keV continuum

4. Proton acceleration: spectral signature at TeV energies

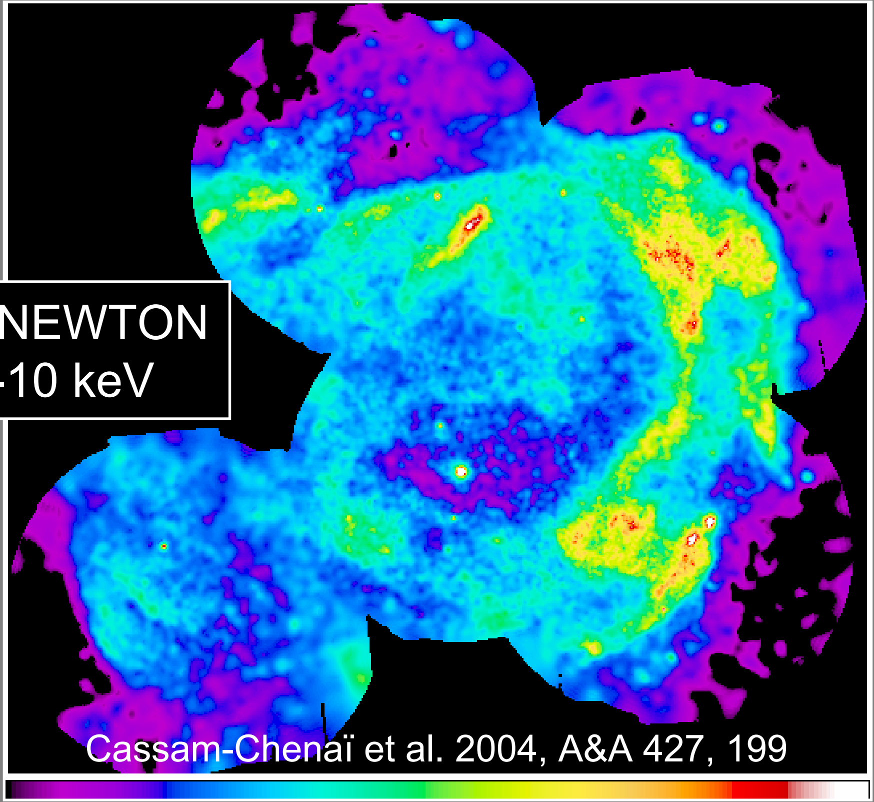
Evidence for ion acceleration in SNRs ?

- o Pion decay (TeV observations with HESS, GLAST,…)

=> knowledge of the contribution of the IC emission required

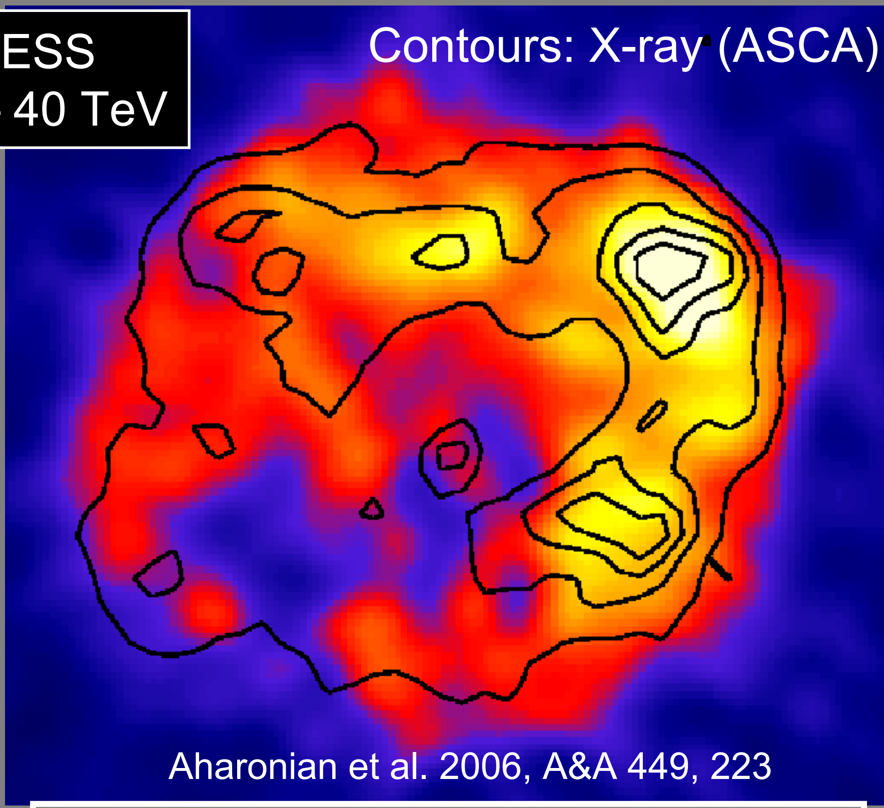
G347.3-0.5: a core collapse supernova

XMM-NEWTON
0.5-10 keV



Cassam-Chenaï et al. 2004, A&A 427, 199

HESS
0.3 – 40 TeV



Aharonian et al. 2006, A&A 449, 223

Large nearby remnant (1° diameter) with only synchrotron emission
Brighter emission, softer spectrum (cloud interaction)

First resolved TeV source
First shell SNR detected in γ-rays
Good correlation with X-ray emission

SNRs: **Prospects with XMM-Newton**

Thanks to its high sensitivity, reasonable spatial resolution and large field of view, there are a large number of projects to be carried out on SNRs:

1. Nucleosynthesis products: extended SNRs (nearby or middle-aged, see Miceli’s talk)
2. Shock physics: deep RGS observation of specific remnants or regions
3. Electron acceleration: deep spatially resolved spectroscopy in extended SNRs (SN 1006, G347.3-0.5, Vela Junior)
   - maximum energy of accelerated particle
   - azimuthal variations
   - density of the thermal plasma
4. Proton acceleration
   - morphological constraints from X-rays on the hydrodynamics
   - estimate of the IC contribution to the TeV emission (see Pühlhofer’s talk)

Others:
- interaction with interstellar clouds (Cygnus Loop, Vela, etc…)
- statistical properties of galactic SNRs (Green’s catalog)

Superbubbles

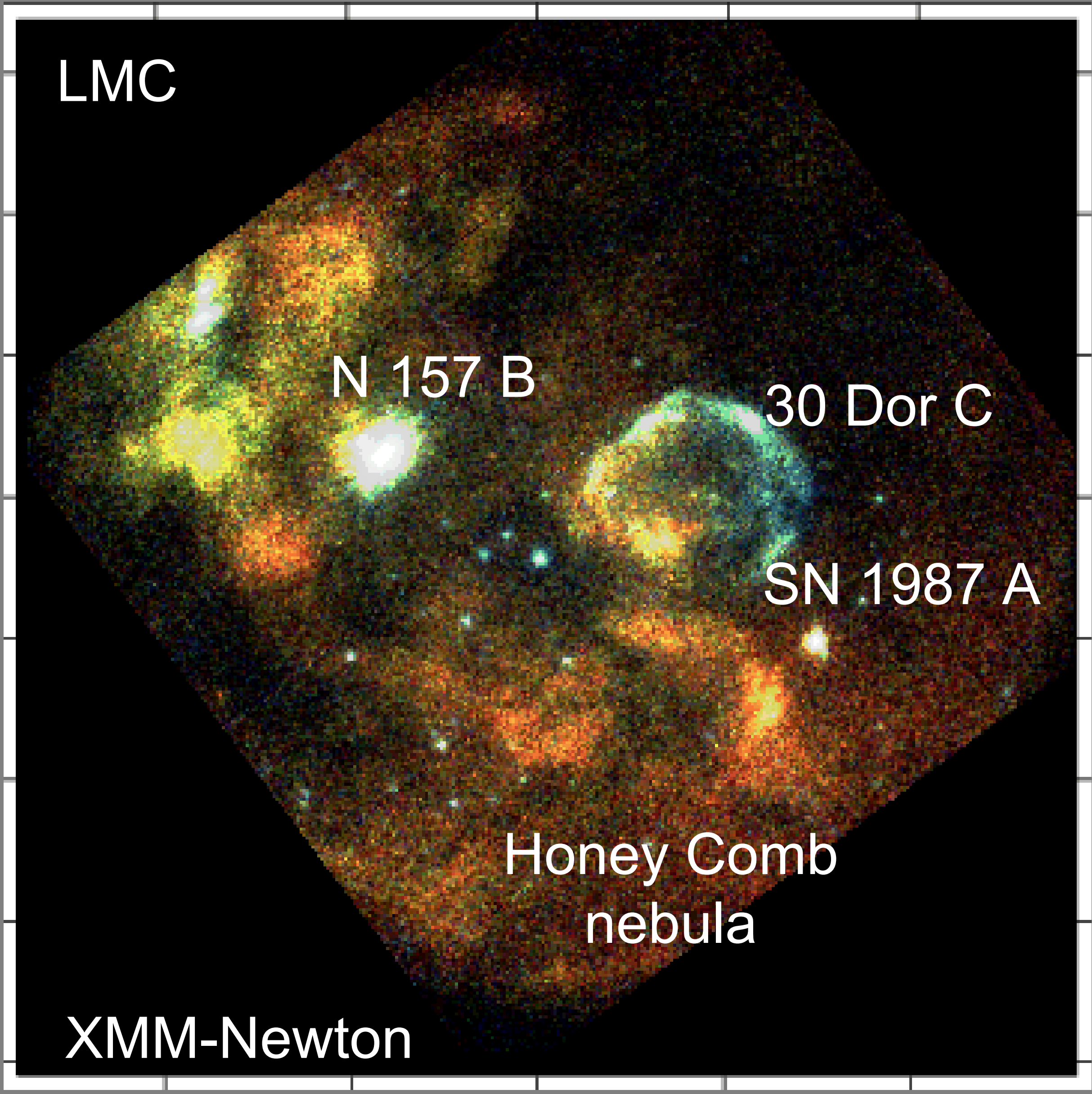
Majority of O and B stars grouped in associations: 60 % of all type II SNe (core collapse) are clustered.

Winds and SNe act collectively to engender superbubbles.

About 15-20 % of the total energy input is provided by the stellar winds, more than 80 % by SNe.

In a SB ~ 4-1000 clustered SN II (average of 30).

30 Dor C : massive star-forming region with possible recent core-collapse SNe in the superbubble.



Dennerl et al. 2001, A&A

Superbubbles

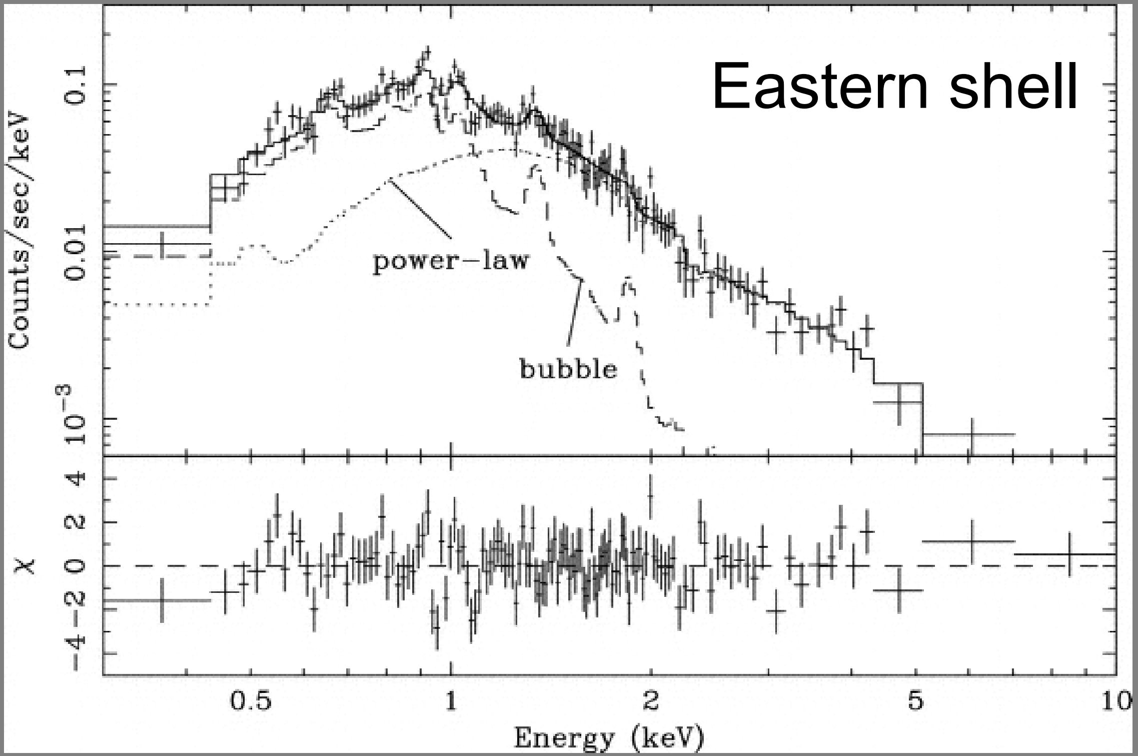
- Origin of the bright X-ray regions:

Region of thermally evaporated material or superbubble shell shocked by SNe ?

- Energy budget:

Amount of energy currently present in SBs (30 Dor C, N51D…) significantly less than the expected energy input from the enclosed massive stars over their lifetime.

XMM-Newton



30 Dor C

Group of alpha-process elements (O, Ne, Mg, Si, S, Ar, Ca) ~ 1.6 ± 0.5 solar

O/H mass ratio = 0.022 for the X-ray emitting gas

O/H mass ratio = 0.0067 for the LMC (Russel and Dopita 1992).

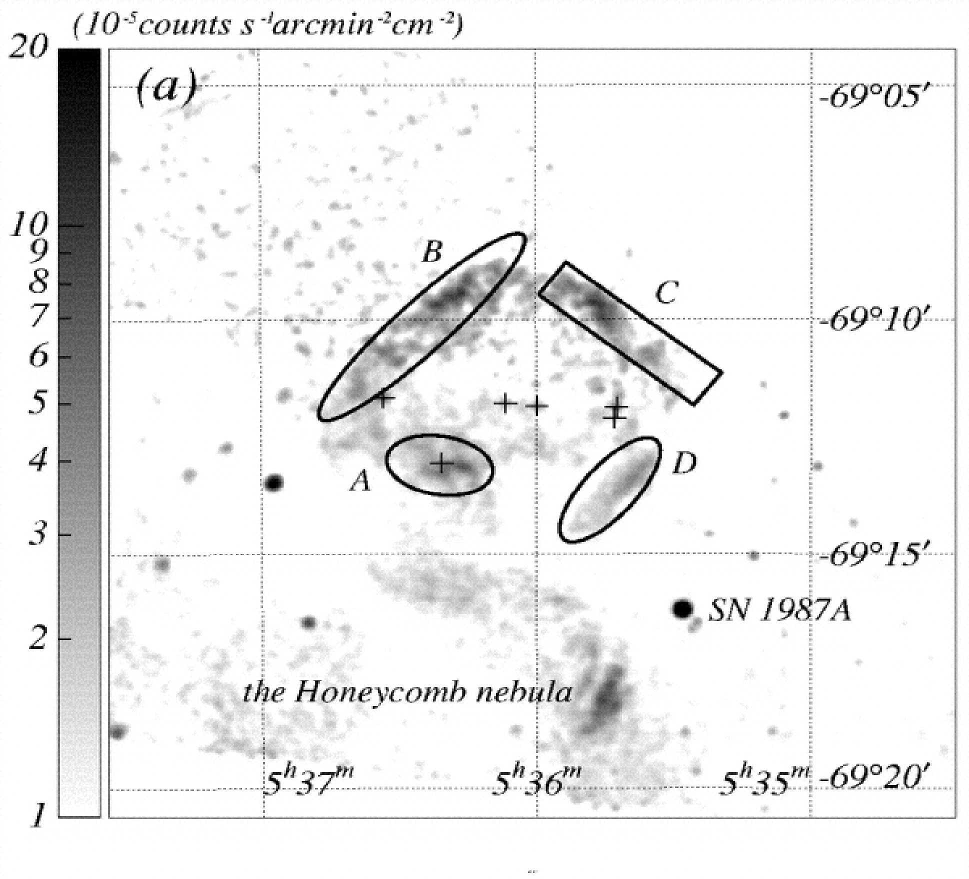
=> The bubble has been enriched by 5 M_{sol} of oxygen, requiring 2-3 high mass (> 20 M_{sol}) core collapse SNe.

Group of Fe-like elements ~ 0.5 solar (appropriate for the LMC)

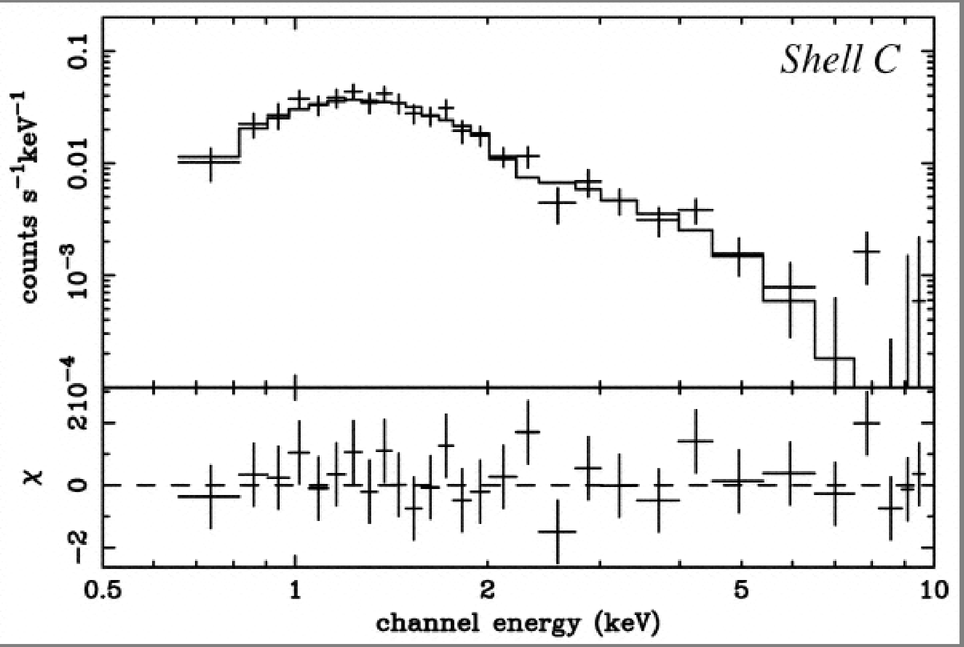
(Smith and Wang 2004)

Superbubbles

30 Dor C in the LMC



XMM-Newton



Bamba et al. 2004

- Origin of the nonthermal emission:

Synchrotron, IC or NT bremsstrahlung ?(Smith and Wang 2004)

- Are superbubbles the main sources of GCR ?

Superbubbles

Perspectives with XMM-Newton:

LMC: ideal laboratory for observing superbubbles in X-rays

About 20 SBs in the LMC: known distance, faint interstellar absorption.

$\Rightarrow$ deep exposures required to characterize the abundances of the thermal gas and the spectral characteristics of the observed nonthermal component.

$\Rightarrow$ large field of view required to cover a large number of superbubbles.

$\Rightarrow$ path finder for long dedicated observations on specific superbubbles.

XMM required for a quantitative view of all superbubbles in the LMC