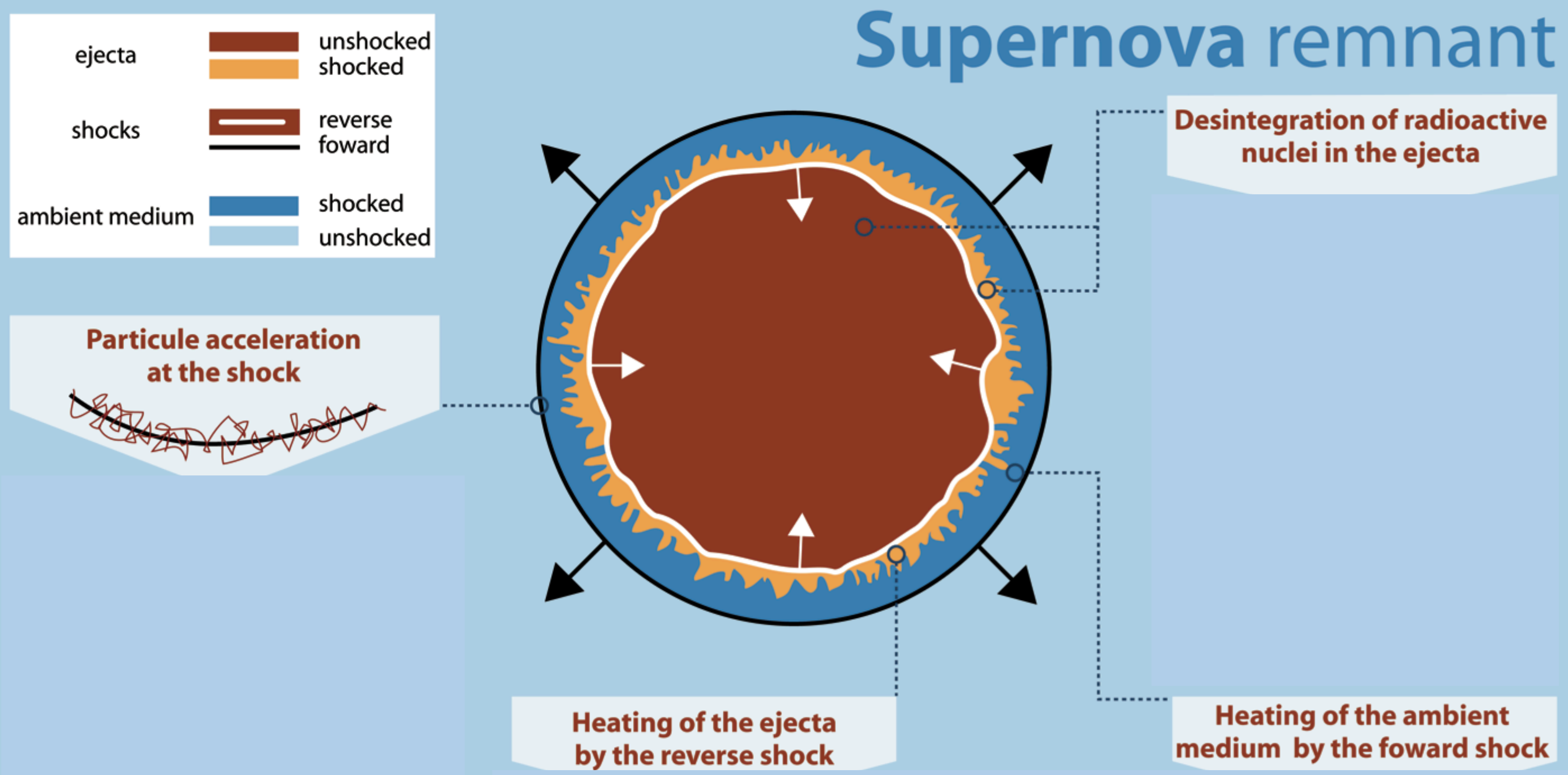
Irfu

Saclay

X-ray Observations of Supernova Remnants

Anne Decourchelle
Service d'Astrophysique
IRFU, CEA Saclay

High energy emission of young supernova remnants



CONTENTS

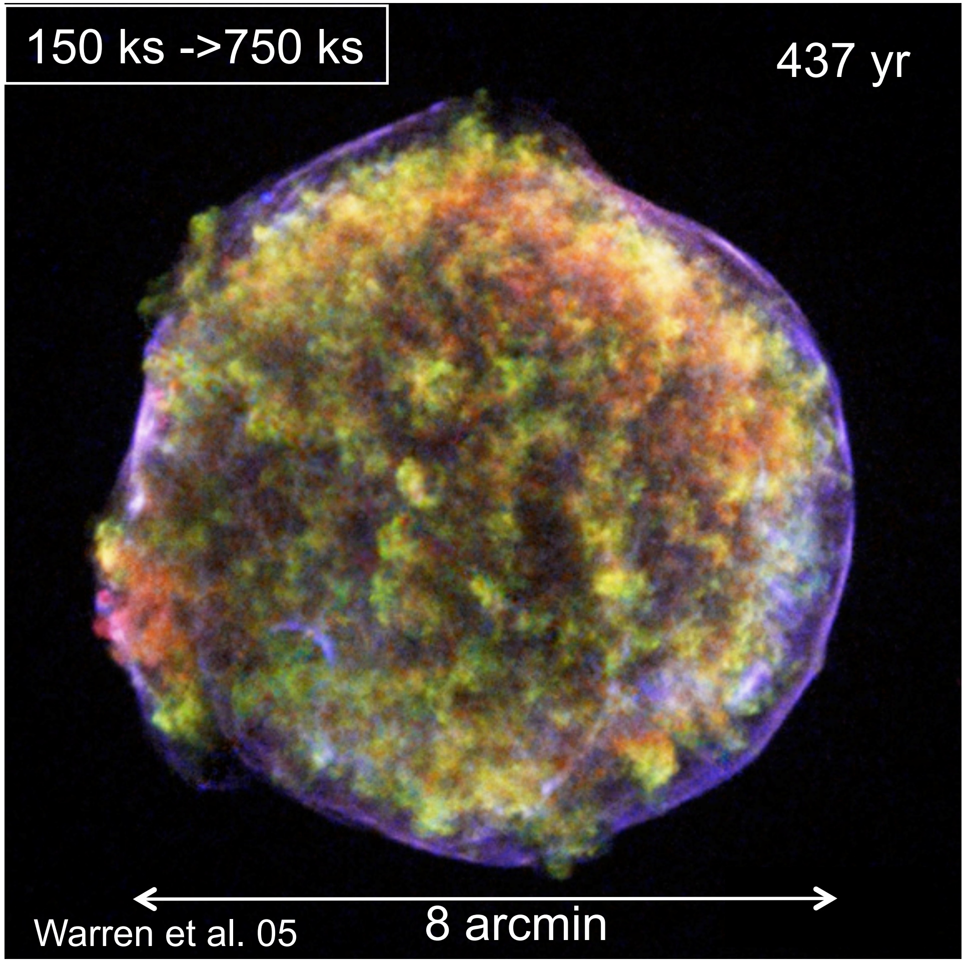
I. SNRs as sites of particle acceleration

II. SNRs as sources of heating of the ejecta and ambient interstellar medium

III. SNRs as radioactive sources

Young supernova remnants : Chandra large programs

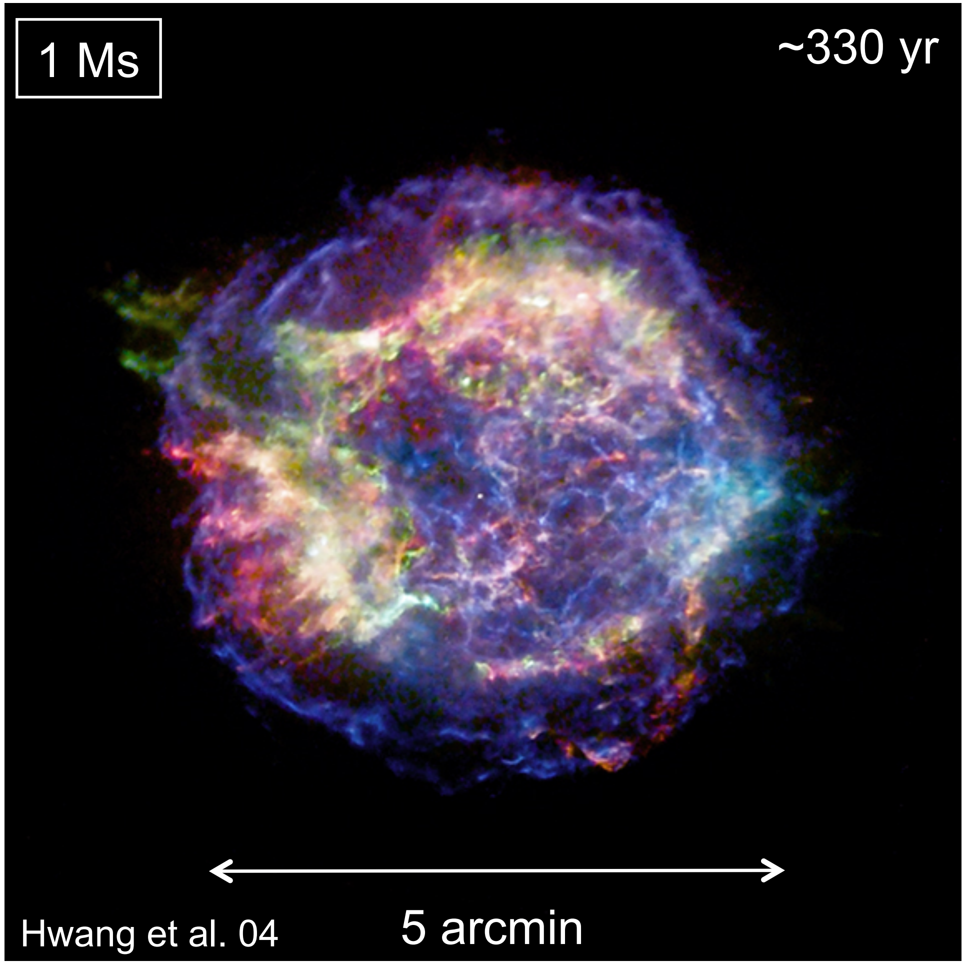
Tycho (SN 1572)
Type Ia



D ~ 2.0 - 4.5 kpc

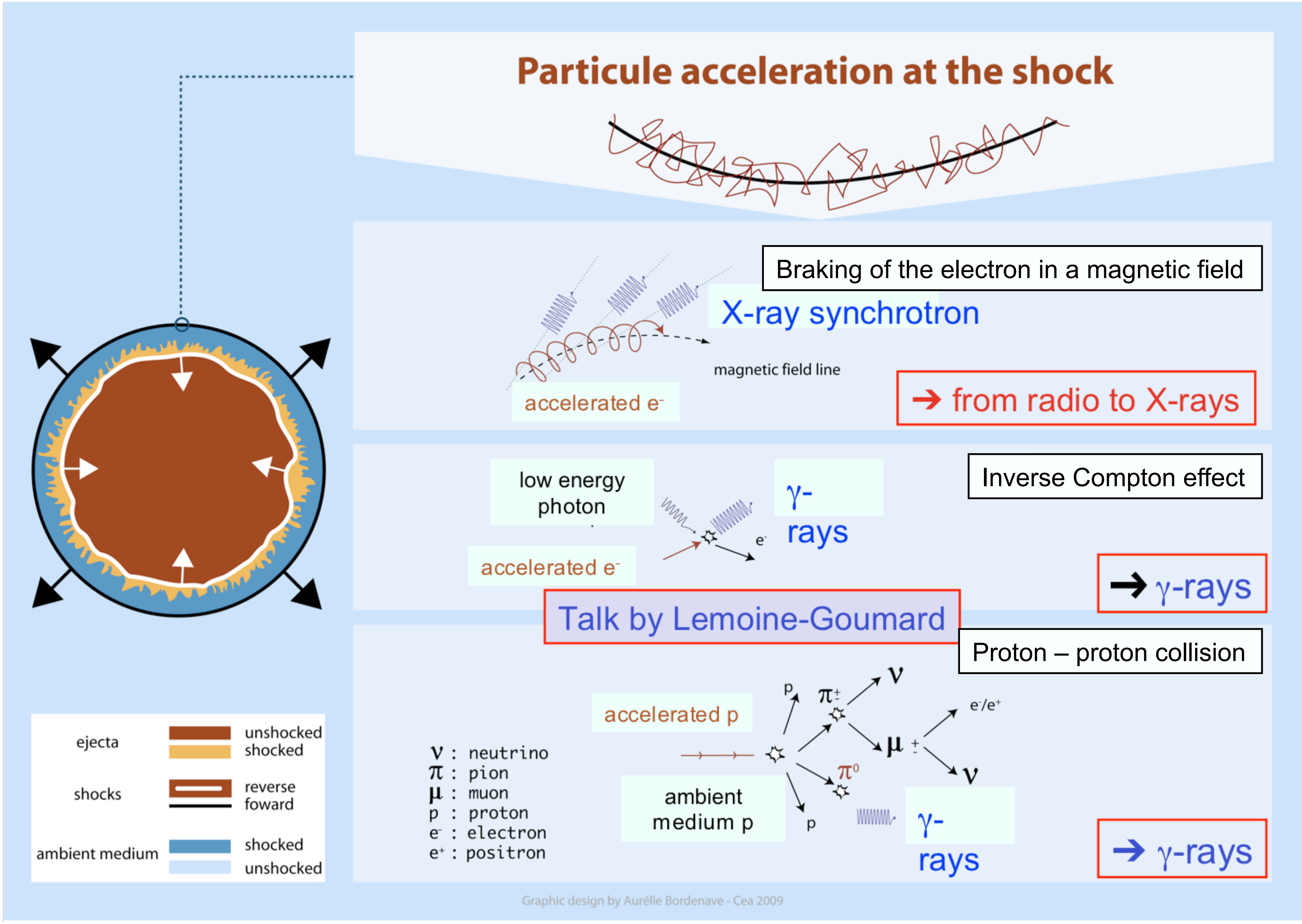
(Krause et al. 08, Ruiz-Lapuente 04, Schwarz et al. 95, Smith et al. 91, Kirshner et al. 87, Albinson et al. 86, De Vaucouleurs 85)

Cas A
Core collapse



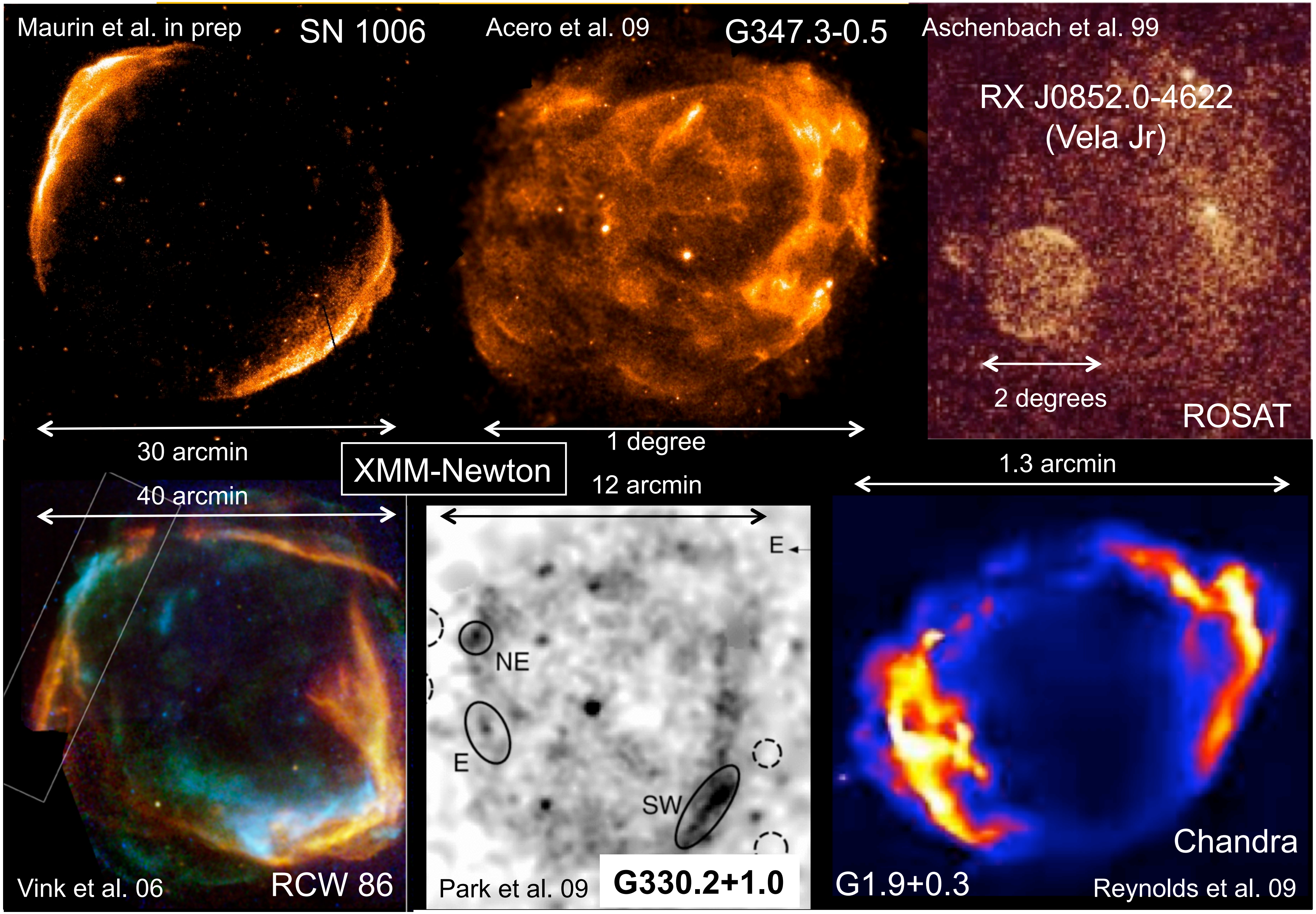
D ~ 3.3-3.7 kpc

(Reed et al. 95)



Particule acceleration at the shock
Braking of the electron in a magnetic field
X-ray synchrotron
magnetic field line
accelerated e-
➔ from radio to X-rays
Inverse Compton effect
low energy photon
γ-rays
e-
accelerated e-
➔ γ-rays
Talk by Lemoine-Goumard
Proton – proton collision
ν
p
π±
e-/e+
accelerated p
μ±
ν : neutrino
π : pion
μ : muon
p : proton
e- : electron
e+ : positron
π0
ν
ambient medium p
p
γ-rays
➔ γ-rays
ejecta
unshocked
shocked
shocks
reverse
foward
ambient medium
shocked
unshocked
Graphic design by Aurélie Bordenave - Cea 2009

Synchrotron-dominated supernova remnants



Particle acceleration at shocks in SNRs

Objective : to understand the process of particle acceleration and the origin of Galactic cosmic rays

- What is the level of magnetic field amplification at the shock ?
- What is the maximum energy of the accelerated particles ?
- What is the efficiency of particle acceleration ?
- …

Why are X-rays crucial to investigate particle acceleration ?

- Physics of the synchrotron emission of the electrons accelerated at the highest energy
- Physics of the thermal gas
    - Global parameters of the remnant : => downstream density => ambient density
    - Back-reaction of accelerated ions (protons)
- Capability of performing spatially-resolved spectroscopy at small scale (< 10 arcsec)

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

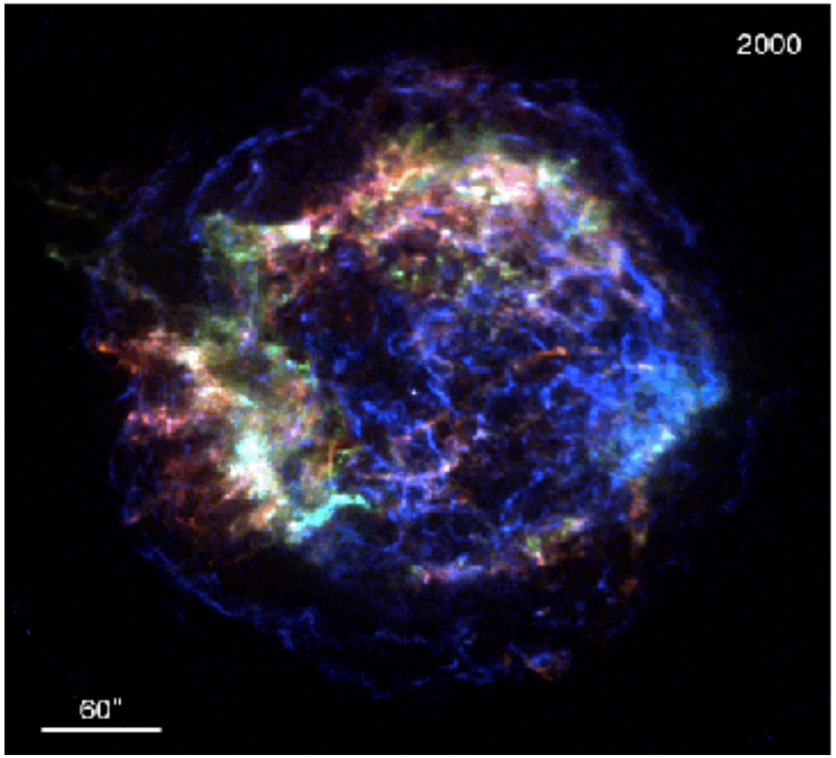
The magnetic field is a crucial parameter :

- for understanding particle acceleration
- for deriving the maximum energy of accelerated particles
- for interpreting the origin of TeV γ-rays : leptonic versus hadronic

Morphology and variability of the synchrotron emission

- Sharp filaments observed at the forward shock : width determined by synchrotron losses of ultrarelativistic electrons
  (Park et al. 09, Parizot et al. 06, Bamba 05, 04, 03, Vink & Laming 03,…*)*
- Fast variability of the brightness of these filaments
  (Patnaude et al. 09, Uchiyama et al. 08, 07)
- Broad band modeling of the nonthermal emission
  (Berezhko et al. 09,Voelk et al. 08,...)

=> high value of $B_{downstream}$(~ 50-500 μG) which implies large magnetic field amplification



Patnaude et al. 09

Maximum energy of electrons and protons

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, except for the radiative losses

Spectrum of the synchrotron emission (radio + X-rays)

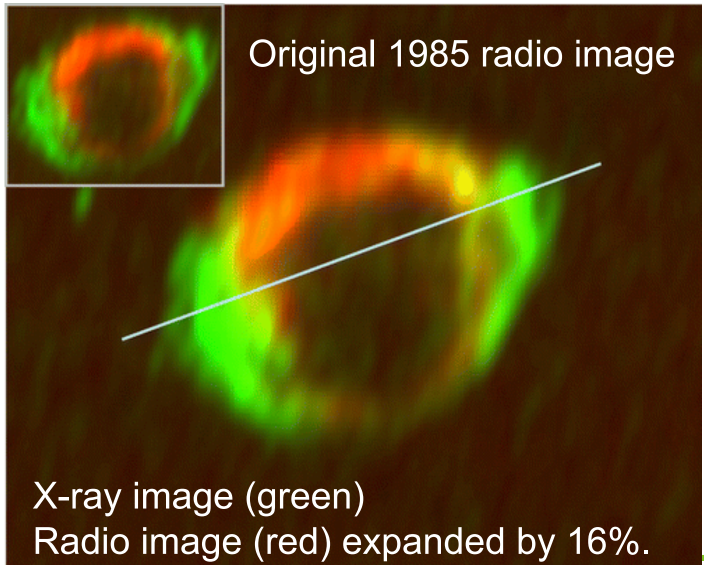
- **Measurement of the rolloff photon energy $h\nu_{roll}$**, observable in X-rays

+

- Estimate of downstream magnetic field

⇒ Estimate of the maximum energy of accelerated electrons :

$E_{max} = 39\,(h\nu_{roll} / B_{10})^{1/2}$ TeV **~ few 10 TeV**



G1.9+0.3: the youngest observed galactic SNR
(Reynolds et al. 08, 09, Green et al. 08)

Expansion by 16 % between 1985 and 2007

=> Vs ~ 14000 km/s for D ~ 8.5 kpc, age ~100 yr

$h\nu_{roll}$ ~ 2.2 keV, among the highest reported

E_{max} ~ 70 TeV assuming B ~10 μG

Variation of the E_{max} along the shock

How does E_{max} and hence particle acceleration vary with B orientation ?

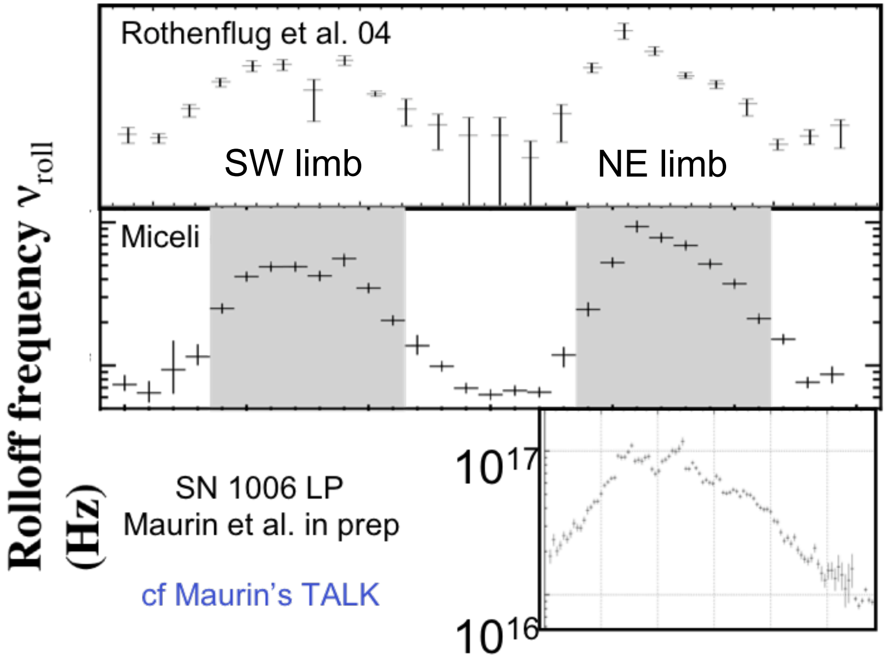
High latitude SNRs evolving in a uniform interstellar magnetic field, like SN 1006, offer the possibility to investigate this dependence.

Spatially resolved spectroscopy of the synchrotron emission

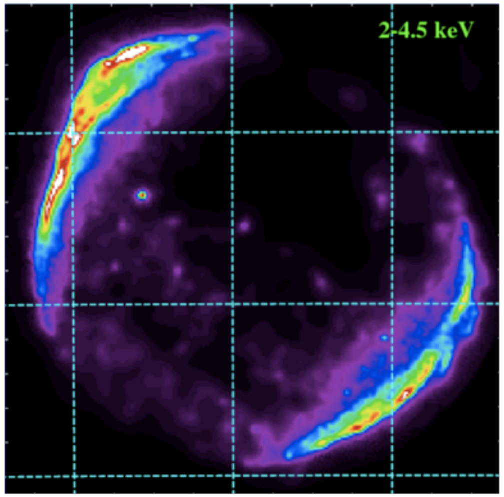
⇒ Measurement of the azimuthal variation of ν_{roll} along the SNR shock

SN 1006: very strong variations ($h\nu_{roll}$ up to 5 keV), which cannot be explained by variations of the magnetic compression alone.

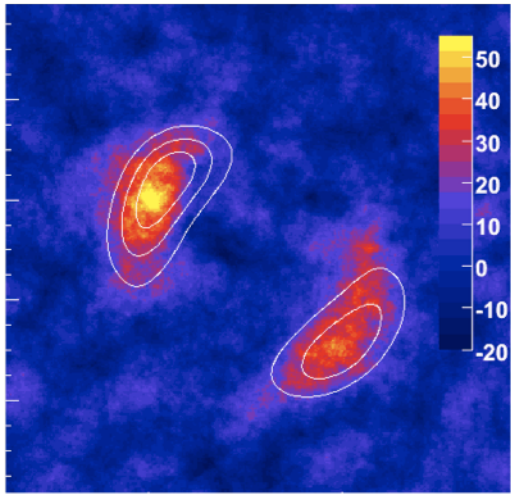
=> Maximum energy of accelerated particles must be higher at the bright limbs than elsewhere



XMM-Newton



XMM-Newton
Miceli et al. 09



HESS
Naumann-Godo et al. 09

Efficiency of particle acceleration

What fraction of the shock energy can be tapped by the cosmic rays ?

Evidence for ion acceleration in SNRs ?

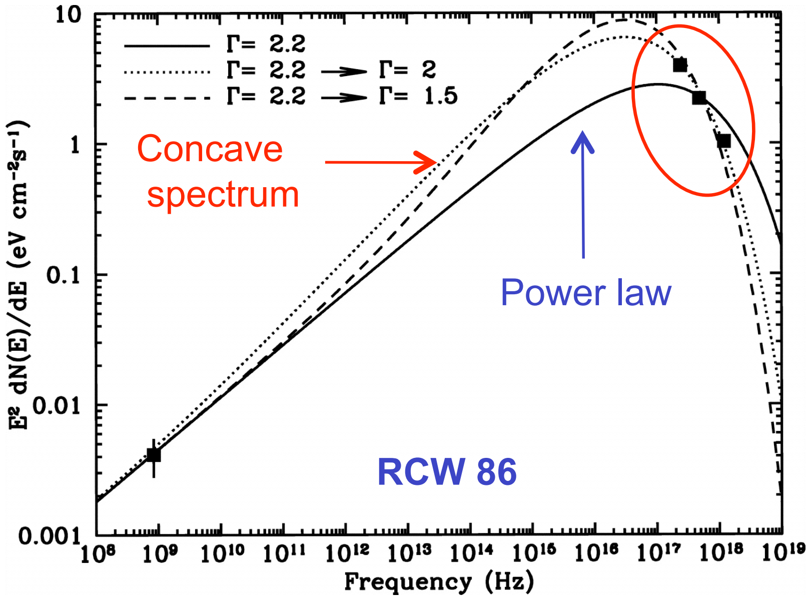
NL diffusive shock acceleration

- Curvature of the particle spectra (Berezhko & Ellison 99, Ellison & Reynolds 91,...)
- Lower post-shock temperature (Ellison et al. 00, Decourchelle et al. 00)
- Shrinking of the post-shock region (Decourchelle et al. 00)

Curvature of the spectrum :

indications in a few SNRs

- **SN 1006**: combining radio and X-ray data (Allen et al. 08)
- **RCW 86:** combining radio and X-ray data (Vink et al. 06)
- **Cas A**: from infrared data (Jones et al. 03)
- **Tycho and Kepler**: from radio data (Reynolds & Ellison 92)



Vink et al. 06

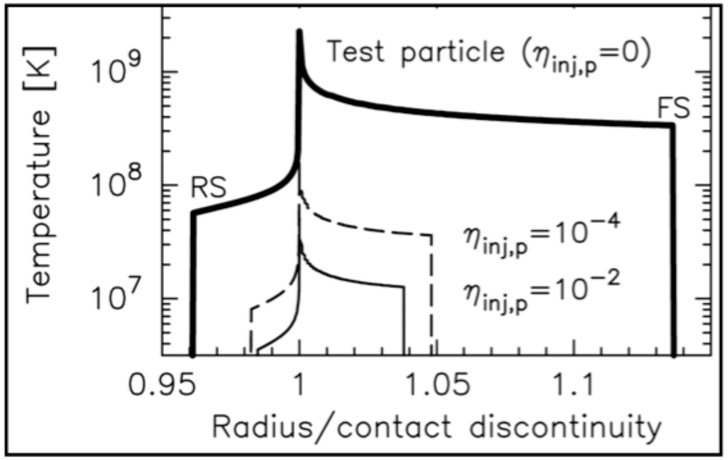
Post-shock conditions

If efficient ion diffusive shock acceleration

- larger compression ratio
- lower post-shock temperature

than for test-particle case

(Chevalier 83, Ellison et al. 00, Decourchelle et al. 00)



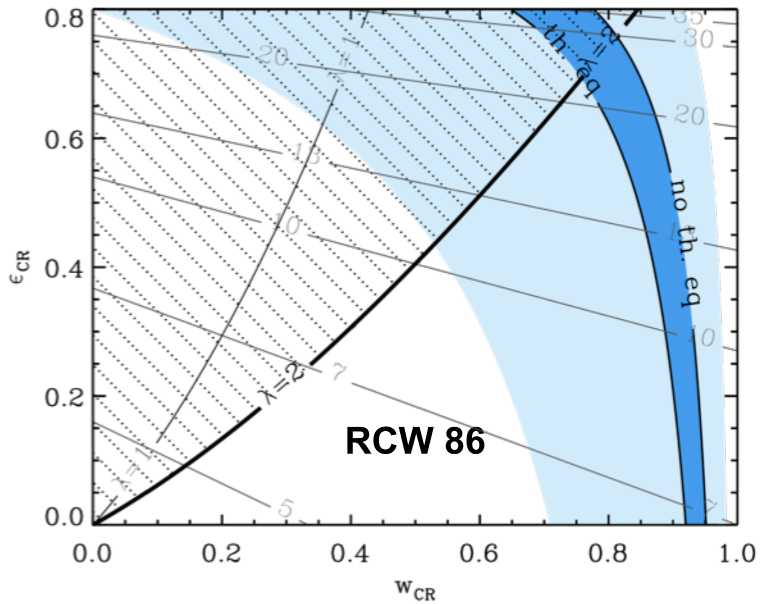
Decourchelle et al. 00

Indication of strong back reaction in young SNRs

- **1E0102**: post-shock electron temperature from X-rays and shock velocity from X-ray proper motion (Hughes et al. 00)
- **RCW 86**: post-shock proton temperature from Hα broad line and shock velocity from X-ray proper motion (Helder et al. 09)

No back-reaction in the older SNR

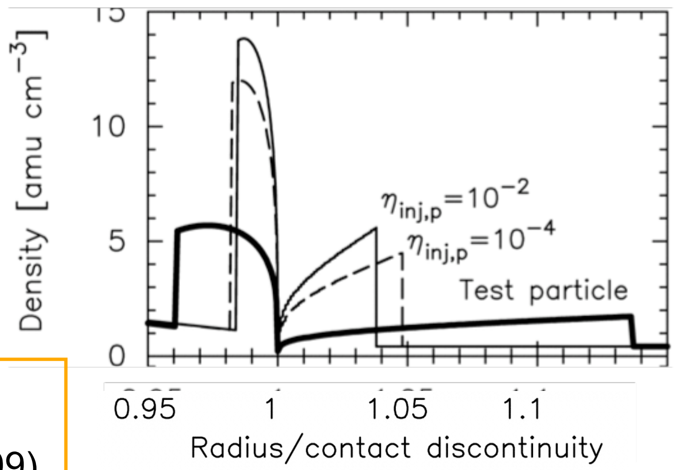
- **Cygnus Loop** : post-shock electron temperature from X-rays and shock velocity from optical proper motion (Salvesen et al. 09)



50 % post-shock pressure in relativistic particles
Helder et al. 09

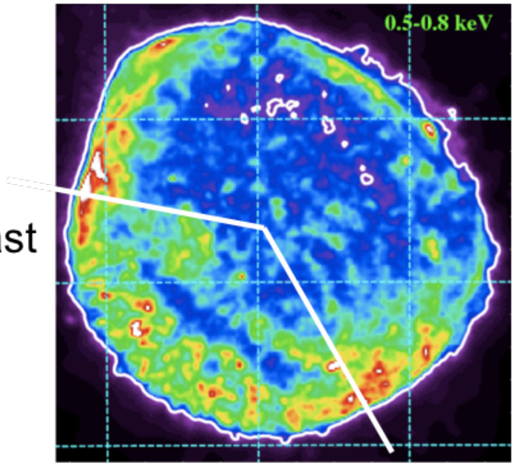
Shrinking of the shocked region

If efficient ion diffusive shock acceleration
modified hydrodynamics
=> narrower shocked region than test-particle case
(Decourchelle et al. 00, Chevalier 83)

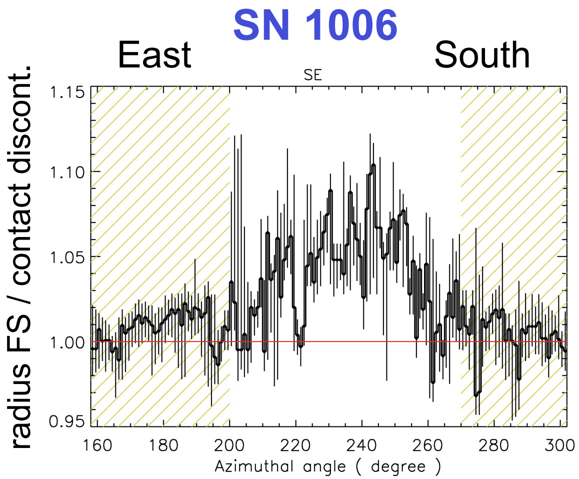


Indication of strong back reaction in young SNRs

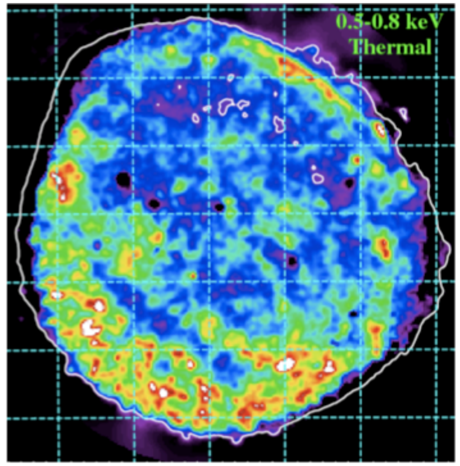
- **Cas A**: X-ray proper motion and morphology (Patnaude et al. 09)
- **SN 1006:** morphology (Miceli et al. 09, Cassam-Chenaï et al. 08)
- **Tycho:** morphology (Warren et al. 05, Decourchelle et al. 04)

East


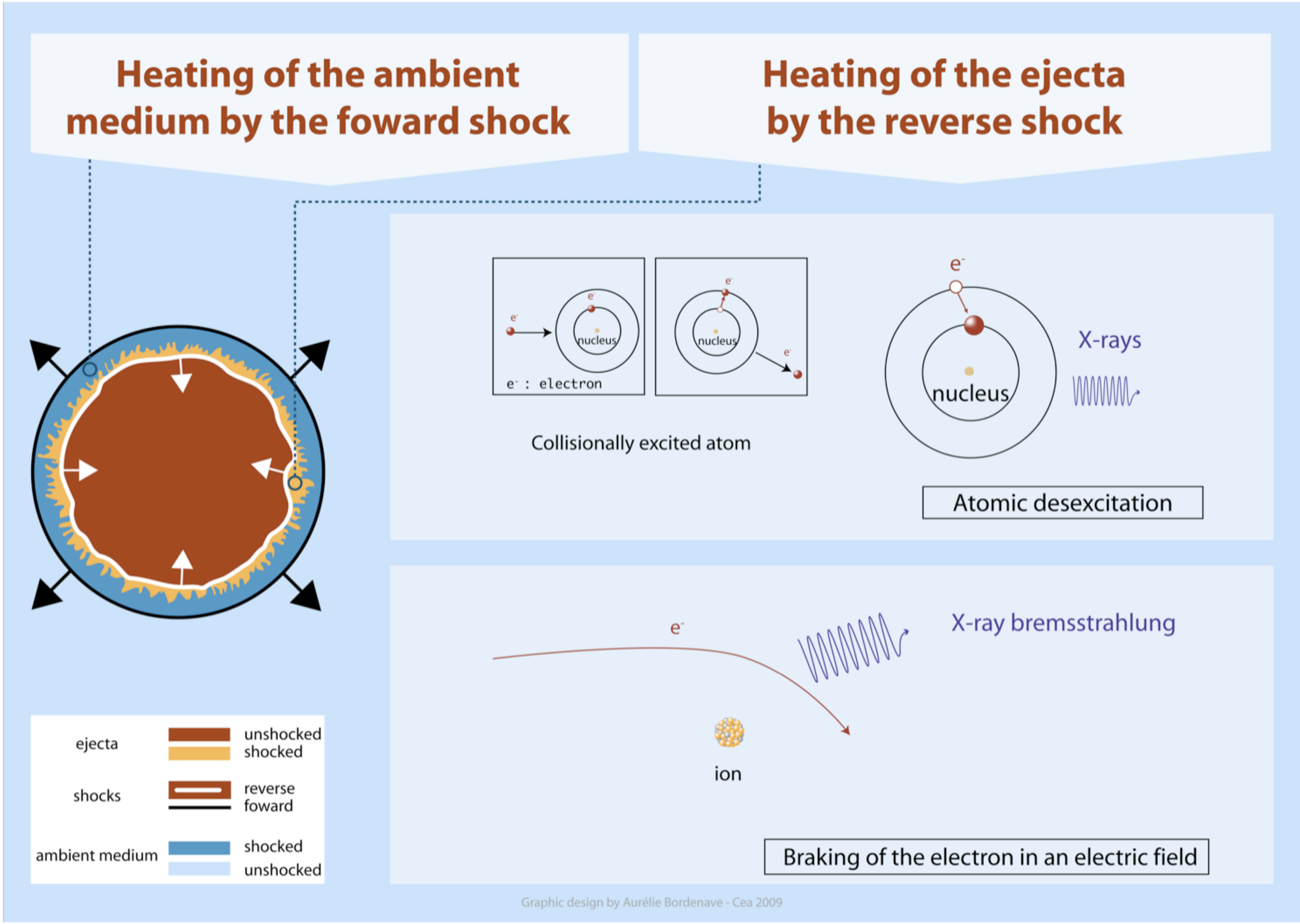
South



Cassam-Chenaï et al. 08



Miceli et al. 09
Cf Miceli's talk


Heating of the ambient medium by the foward shock
Heating of the ejecta by the reverse shock
e-
e-
nucleus
e- : electron
e-
nucleus
e-
Collisionally excited atom
e-
nucleus
X-rays
Atomic desexcitation
e-
X-ray bremsstrahlung
ion
Braking of the electron in an electric field
ejecta
unshocked
shocked
shocks
reverse
foward
ambient medium
shocked
unshocked
Graphic design by Aurélie Bordenave - Cea 2009

Thermal emission from the shocked ambient medium

Access to the global properties of the remnant

- ambient medium: density, composition
- supernova: shock velocity and radius => age, SN energy and ejected mass
- shock physics: particle acceleration (Spitkovski), collision-less e^- and ion heating (Laming)

Shock physics

- **High post-shock oxygen temperature** in SN 1006 (XMM-Newton/RGS, Vink et al. 03)

$kT_O \sim 528 \pm 150$ keV and $kT_e \sim 1.5$ keV => small degree (5%) of e^-/ion equilibration at the shock

Low density ambient medium for

- **the SN Ia remnants:**

✓ G330.2+1.0: $n_0 \sim 0.1$ cm^{-3}, Park et al. 09
✓ SNR 0509-67.5 $n_0 < 0.6$ cm^{-3}, Kosenko et al. 08
✓ Tycho: $n_0 < 0.6$ cm^{-3}, Cassam-Chenaï et al. 07
✓ SN 1006: $n_0 < 0.05$ cm^{-3}, Acero et al. 07

- **the core collapse remnant** RXJ1713.7-3946: $n_0 < 0.02$ cm^{-3}, Cassam-Chenaï et al. 04b

=> impact the level of pion decay emission in the TeV range due to proton-proton collisions

- **Stellar wind environment** for the core collapse SNR Cas A: proper motion and morphology, Patnaude et al. 09
- **Sub-solar abundances in the Magellanic clouds** (Borkowski et al. 06, 07, …)

Thermal emission from the shocked ejecta

Access to the elements synthesized by the supernovae => keys to the determination of the SN type of the remnant

A new class of Type Ia supernova ?

- **Dense Fe-rich ejecta** in DEM L238 and DEM L249 in the LMC

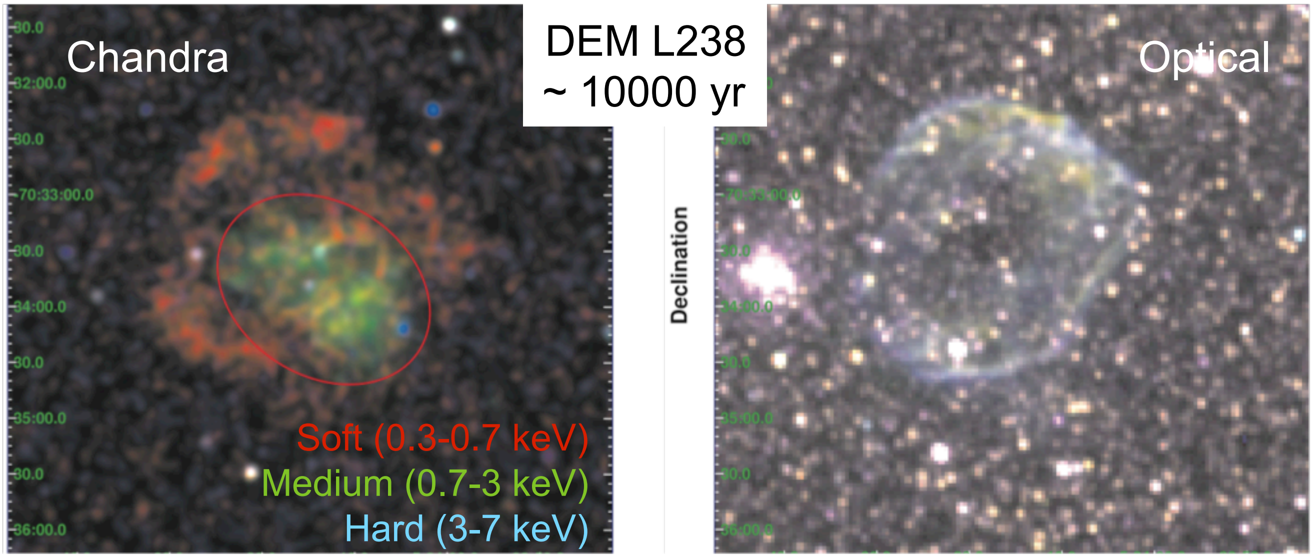
  ⇒ substantial amounts of CSM ? Remnant of prompt Type Ia SN with young progenitors ?

  (Borkowski et al. 06)

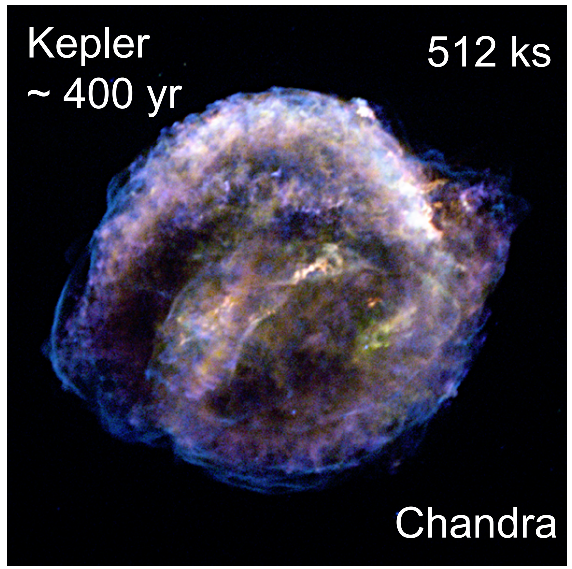
- **Kepler's SNR:** iron emission, absence of oxygen and optical evidence of CSM.

  ⇒SN Ia explosion in a more massive progenitor ?

  (Reynolds et al. 07)



Borkowski et al. 06

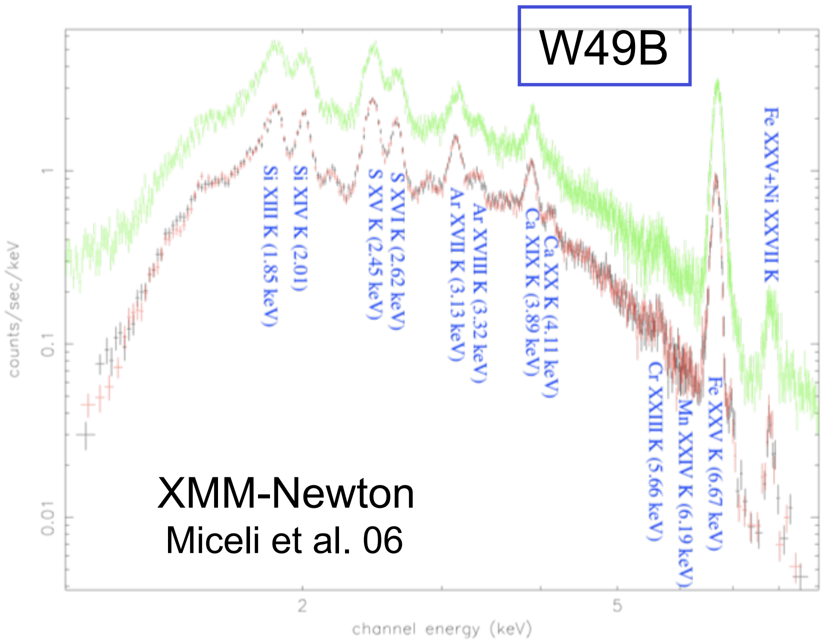


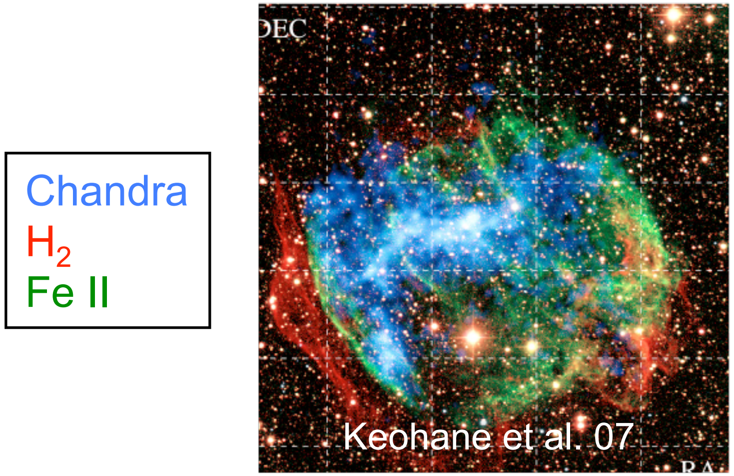
Reynolds et al. 07

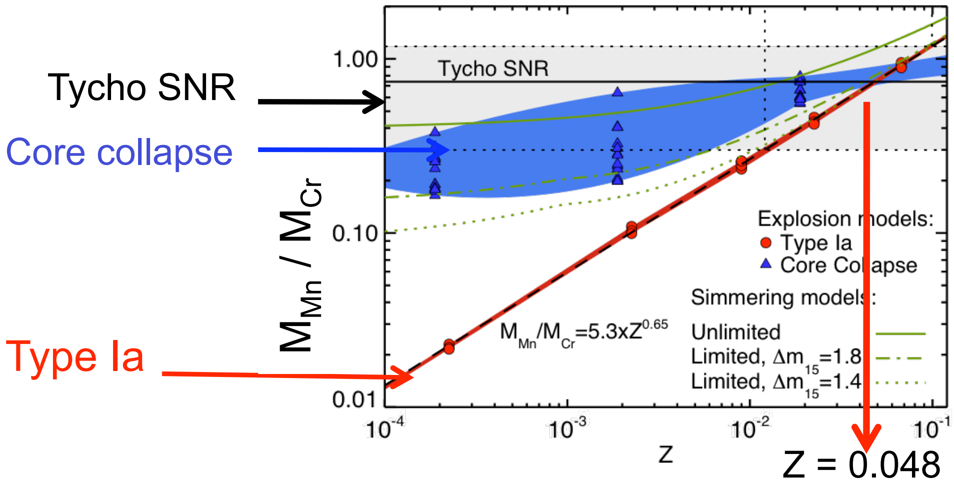
Thermal emission from the shocked ejecta

Presence of Cr and Mn Kα lines in the X-ray spectrum of young SNRs

- W49 B (ASCA, Hwang et al. 00, XMM-Newton Miceli et al. 06)
- Tycho (Suzaku, Tamagawa et al. 09)
- Cas A, Kepler (Cr only, Chandra, Yang et al. 09)







⇒For type Ia, Mn / Cr is a promising tracer of progenitor metallicity (Badenes et al. 08, 09)

⇒cf Badenes's talk

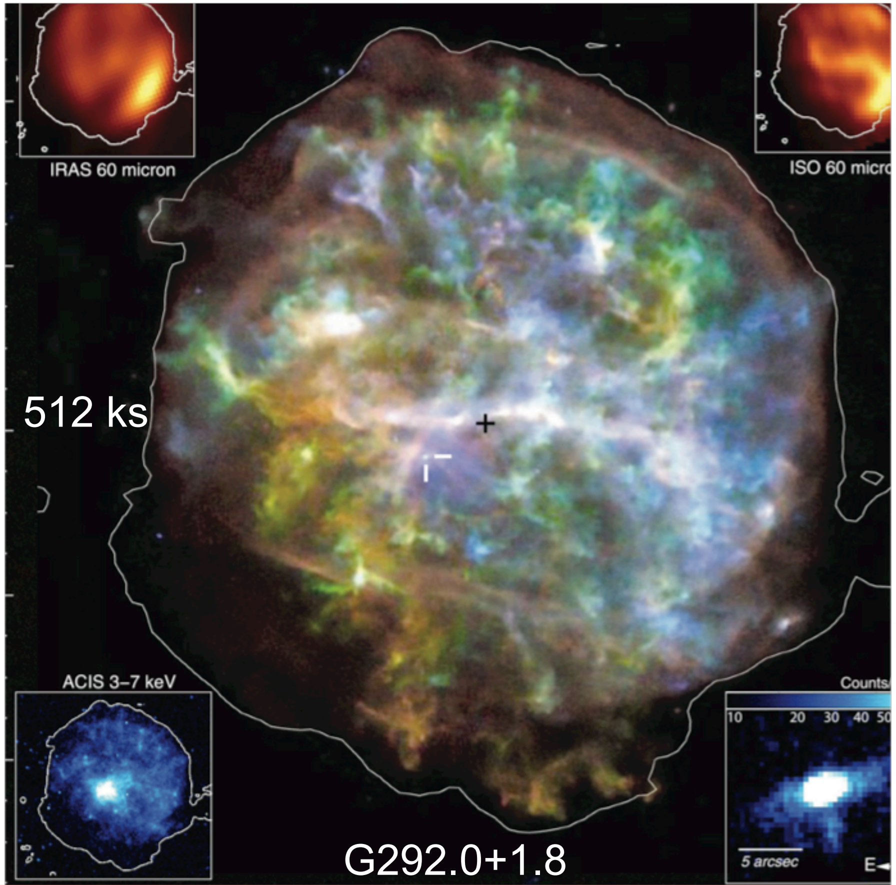
Irfu

Saclay

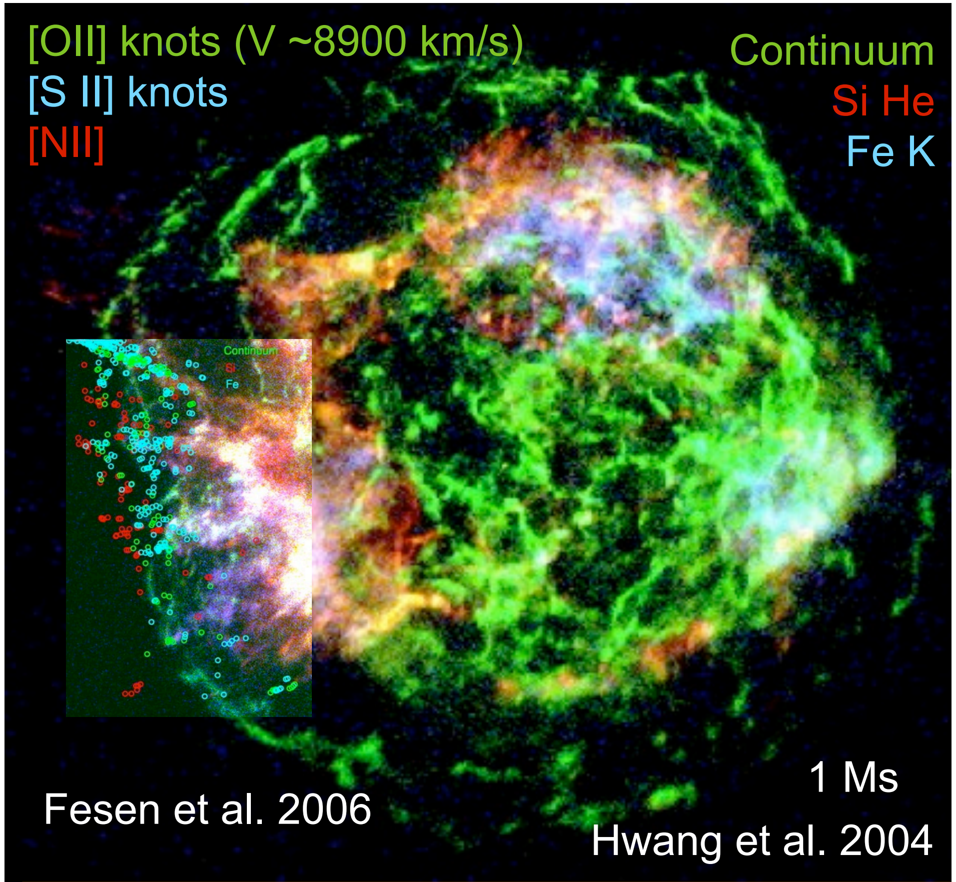
Thermal emission from the shocked ejecta

Access to the repartition and kinematics of the synthesized elements

- understanding of SN explosion (asymmetry, level of mixing of elemental layers)
- level of mixing with the ambient medium (chemical enrichment in galaxies)



Highly non-uniform distribution of thermodynamic conditions
=> asymmetric SN explosion ? (Park et al. 07)



Highly non-uniform distribution of element
=> spatial inversion of a significant portion of the SN core (Hughes et al. 00)

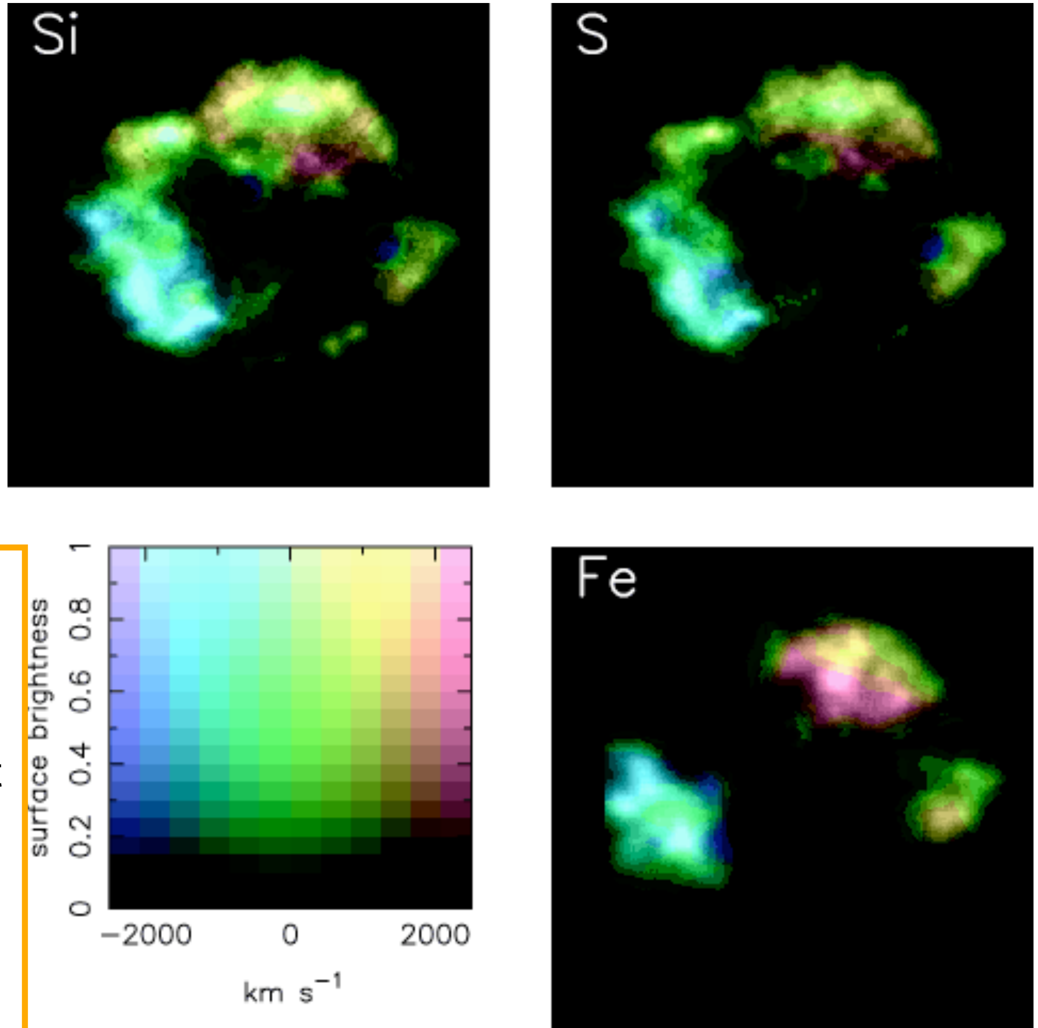
What is the kinematics of the ejecta ?

Bulk motion of the ejecta through Doppler shift measurements

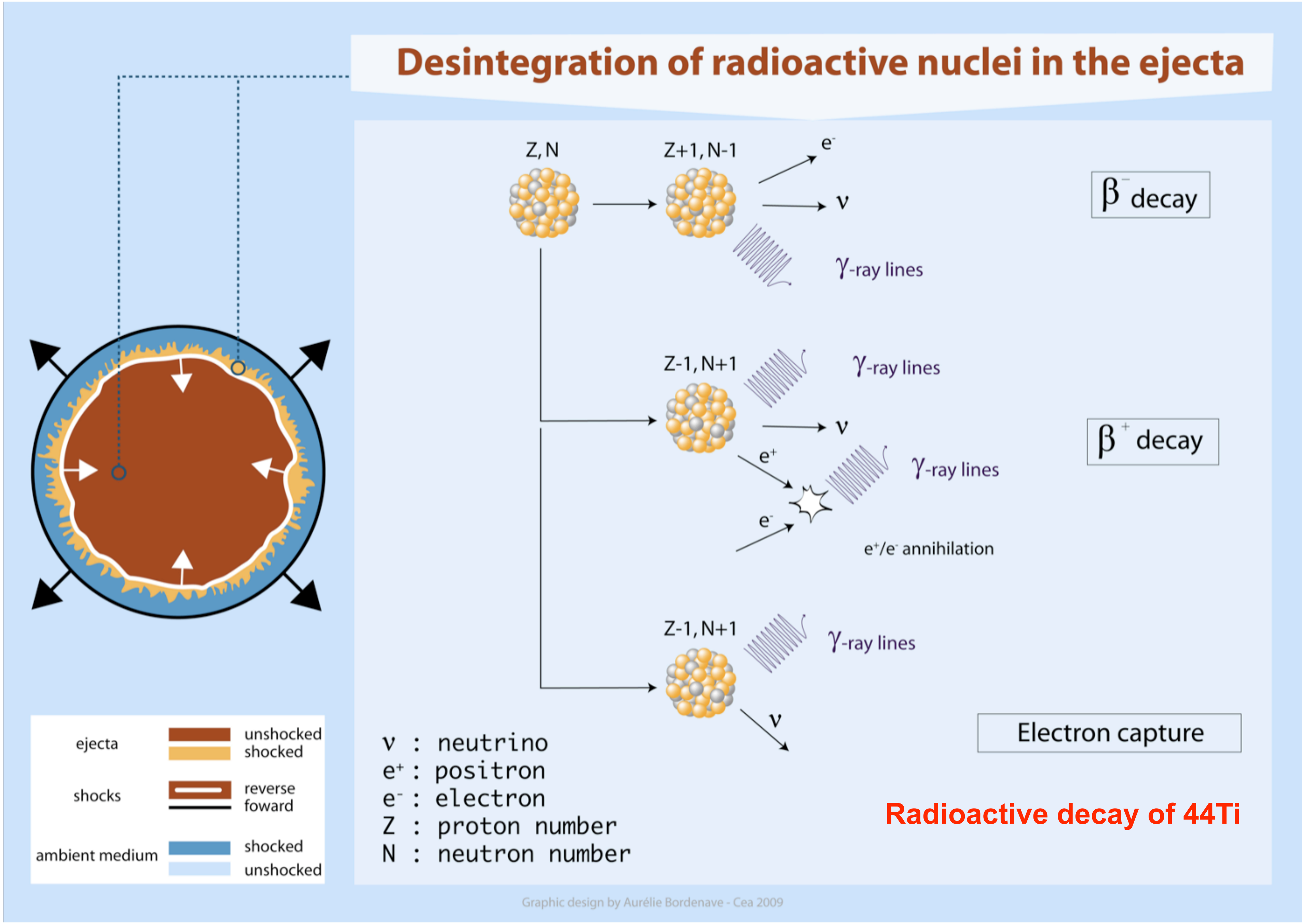
=> deep insight in the expansion of the ejecta and explosion mechanism through asymmetries and inversion of the nucleosynthesis product layers.

- **Tycho :** 2800-3250 km/s for the shell of iron-emitting ejecta (Suzaku, Furuzawa et al. 09)
- **Puppis A :** fast-moving oxygen knots at -3400 and -1700 km/s (Katsuda et al. 08)
- **Cas A :** from -2500 to + 4000 km/s (Chandra/HETG, Lazendic et al. 06, XMM -Newton, Willingale et al. 01; Chandra, Hwang et al. 01)

86 ks XMM-Newton observation of Cas A



Si-K, S-K and Fe-K Doppler maps
20" x 20 " images, Willingale et al. 02


Desintegration of radioactive nuclei in the ejecta
Z, N
Z+1, N-1
e⁻
ν
γ-ray lines
β⁻ decay
Z-1, N+1
γ-ray lines
ν
e⁺
γ-ray lines
β⁺ decay
e⁻
e⁺/e⁻ annihilation
Z-1, N+1
γ-ray lines
ν
Electron capture
ν : neutrino
e⁺ : positron
e⁻ : electron
Z : proton number
N : neutron number
Radioactive decay of 44Ti
ejecta
unshocked
shocked
shocks
reverse
foward
ambient medium
shocked
unshocked
Graphic design by Aurélie Bordenave - Cea 2009

Irfu

Saclay

Radioactive decay in supernova remnants : ^{44}Ti

Access to the total mass of ^{44}Ti synthesized by the supernovae

=> keys to the very depths of SNe and to the physical conditions of the explosion

Decay-chain by electronic capture :

^{44}Ti (85 yr)→ ^{44}Sc (5.6 h) → ^{44}Ca

=> 3 γ-ray lines (detected in Cas A)

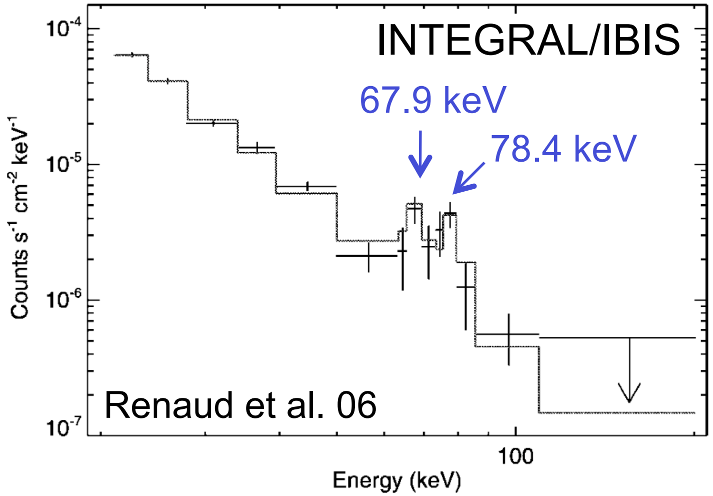
- 67.9 and 78.4 keV (BeppoSAX, Vink et al. 01, INTEGRAL, Renaud et al. 06)

=> $M(^{44}Ti) = 1.6\ 10^{-4}\ M_{sun}$ in Cas A

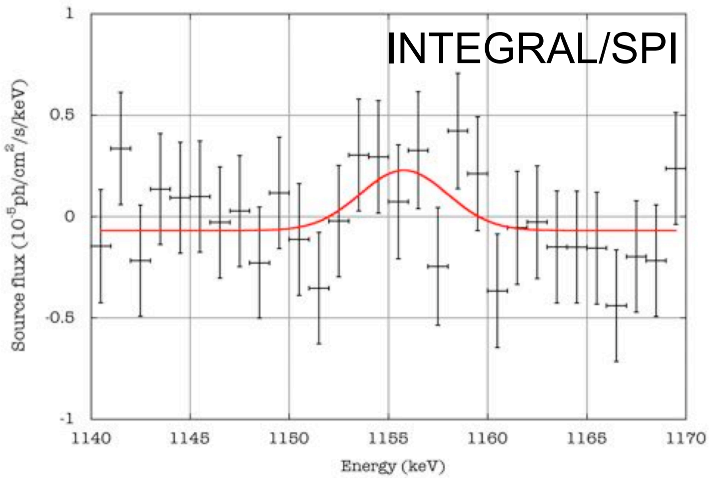
- 1157 keV (Comptel, Iyudin et al. 94) + search with INTEGRAL/SPI (Martin et al. 09)

=> X-ray Kα lines of ^{44}Sc at 4.1 keV due to K-shell vacancies (Leising et al. 01)

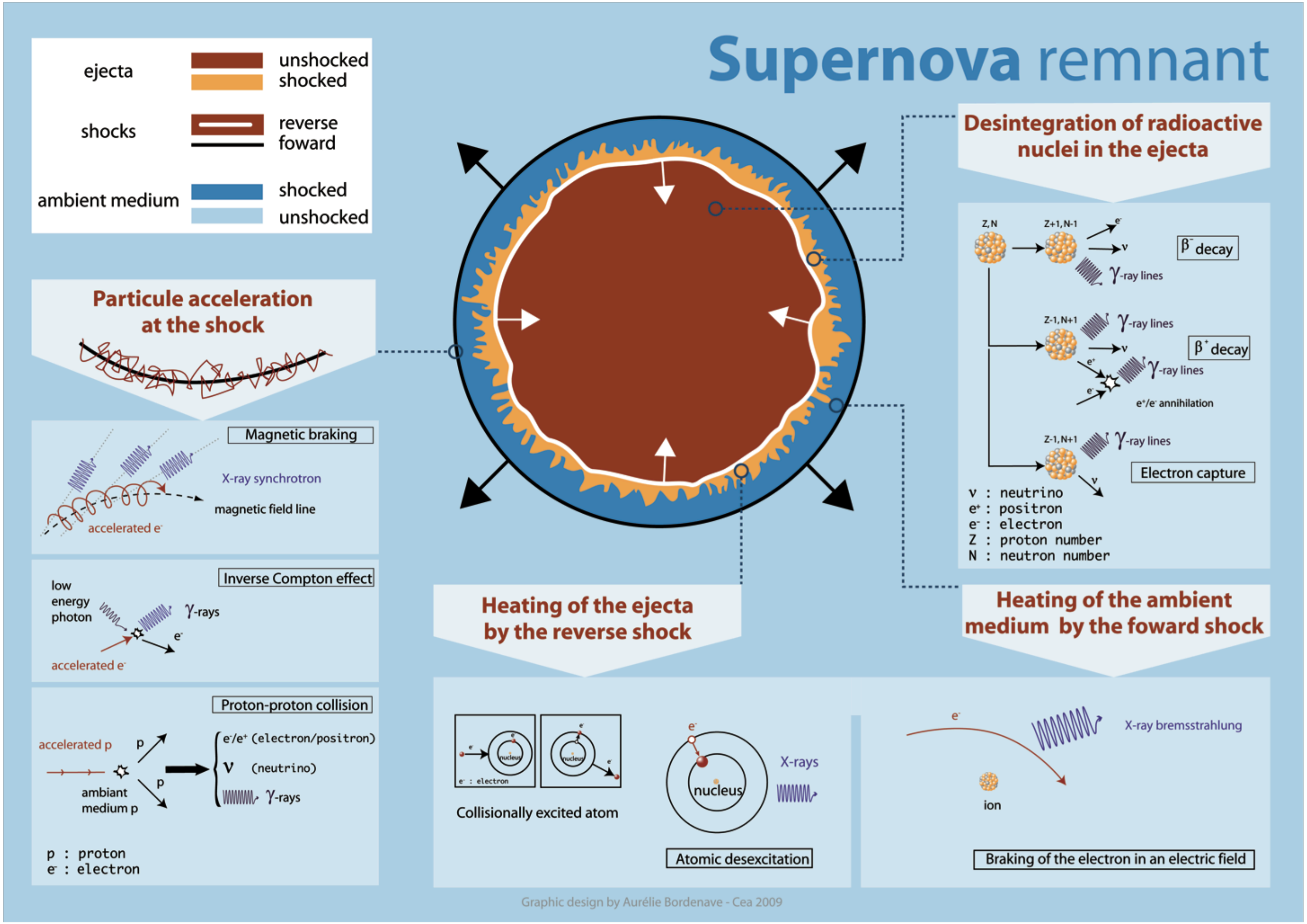
- Claim of a possible detection in RX J0852.0-4622 (ASCA, XMM-Newton, Chandra) but infirmed by Suzaku (Hiraga et al. 09)



Cas A



Difficult task with current hard X-ray instruments
=> NuSTAR (Simbol-X currently cancelled)



Supernova remnant
ejecta
unshocked
shocked
shocks
reverse
foward
ambient medium
shocked
unshocked
Particule acceleration at the shock
Magnetic braking
X-ray synchrotron
magnetic field line
accelerated e-
Inverse Compton effect
low energy photon
γ-rays
e-
accelerated e-
Proton-proton collision
accelerated p
p
p
ambiant medium p
e-/e+ (electron/positron)
ν (neutrino)
γ-rays
p : proton
e- : electron
Desintegration of radioactive nuclei in the ejecta
Z,N
Z+1,N-1
β- decay
γ-ray lines
Z-1,N+1
β+ decay
e+/e- annihilation
Electron capture
ν : neutrino
e+ : positron
e- : electron
Z : proton number
N : neutron number
Heating of the ejecta by the reverse shock
Heating of the ambient medium by the foward shock
Collisionally excited atom
nucleus
X-rays
Atomic desexcitation
X-ray bremsstrahlung
ion
Braking of the electron in an electric field
Graphic design by Aurélie Bordenave - Cea 2009

Summary

X-rays are providing a wealth of in-depth results on supernova remnants which are providing relevant answers to prime astrophysical issues:

- Particles acceleration, magnetic field and the origin of Galactic cosmic rays
- Heating and chemical enrichment of galaxies
- Supernova explosion physics and standard candles for cosmology
- …

Strength of current X-ray observatories :

- Spatially resolved spectroscopy at small spatial scale
- High resolution spectroscopy

⇒ **Needs for large programs** to get sufficient statistics at the spatial, spectral and temporal scales relevant to the processes at work in SNRs.

⇒ **Needs for mission extension of the current X-ray observatories** as long as they give satisfaction, pending and preparing the future international X-ray observatory IXO.