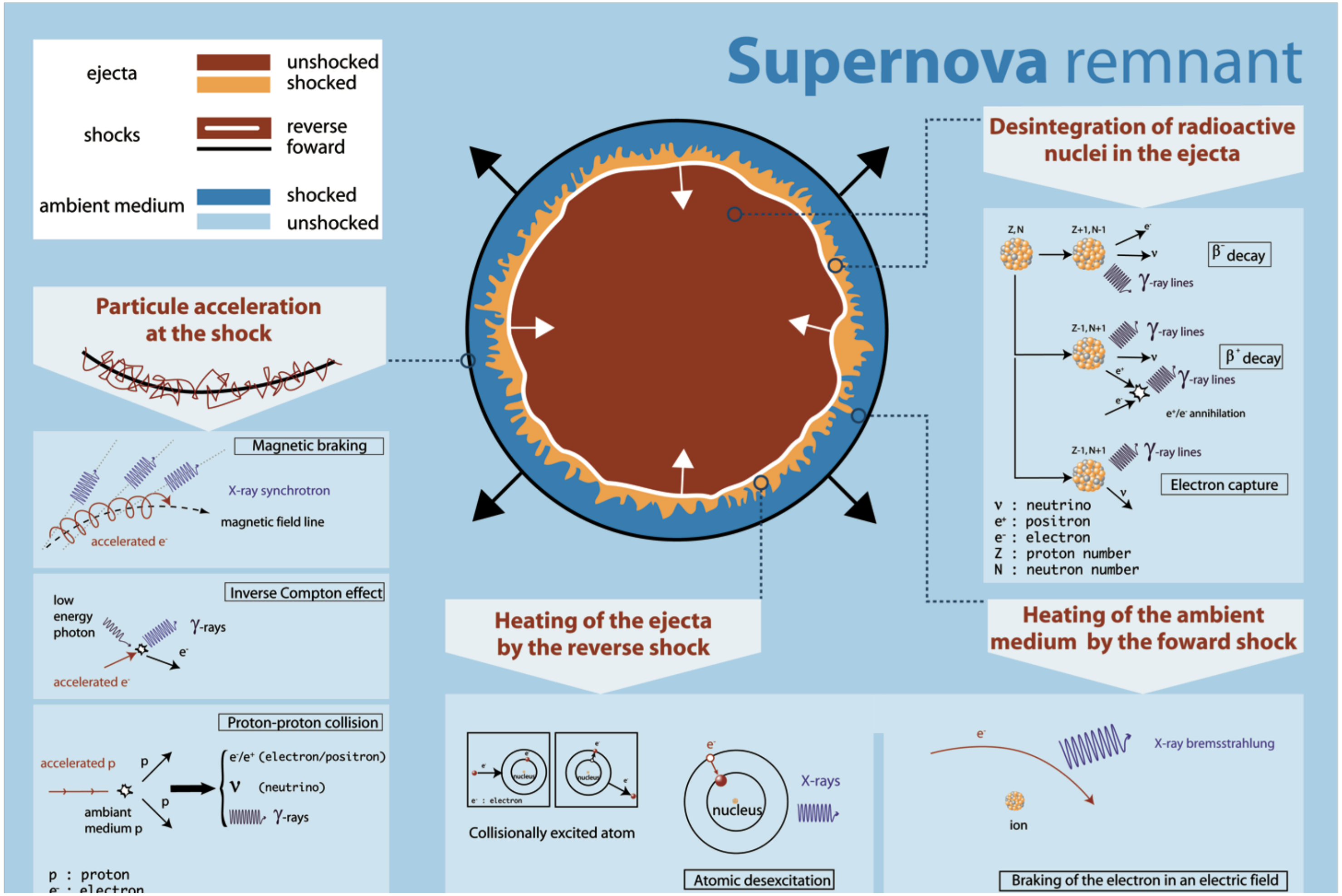
Supernovae remnants

Anne Decourchelle
Department of Astrophysics- UMR AIM
CEA Paris-Saclay

From radio to very high energy gamma rays

Supernovae remnants in X-rays :

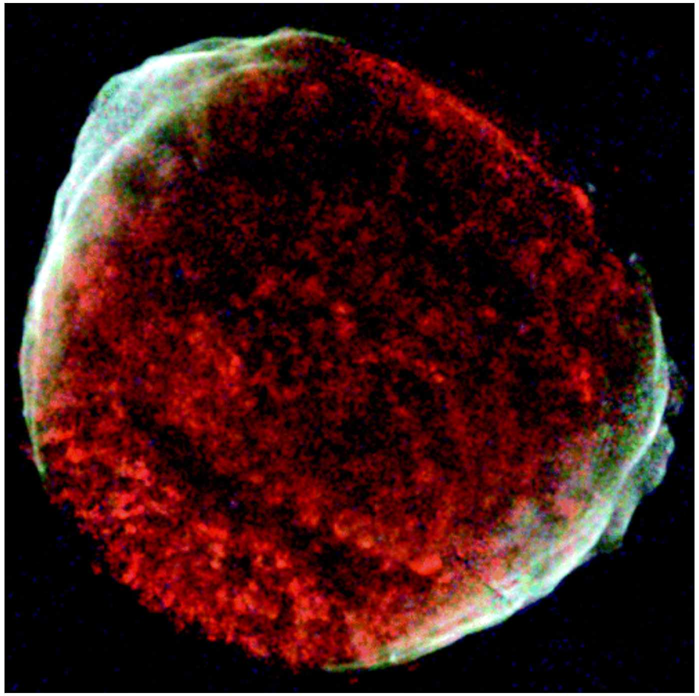
- Shocked ejecta heated to millions degrees emit X-rays
- X-ray synchrotron from electrons accelerated at the shock to TeV energies



INTRODUCTION

Observing in X-rays supernovae remnants tells us about

- Supernovae explosion mechanism
- Nucleosynthesis, driving chemical enrichment
- Progenitor and SN environment (stellar wind, molecular clouds, superbubbles,..)
- Particle acceleration, contributing to the Galactic Cosmic rays
- Shocks physics, magnetic field amplification
- Injection of energy and turbulence in the ISM



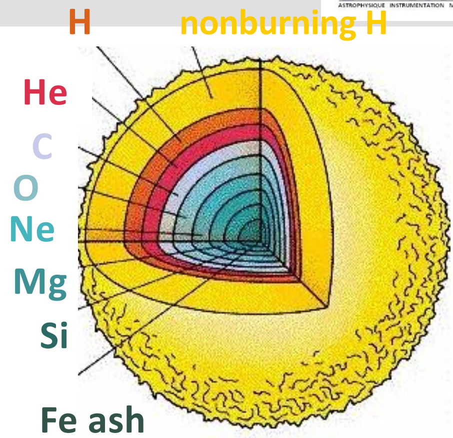
Nucleosynthesis

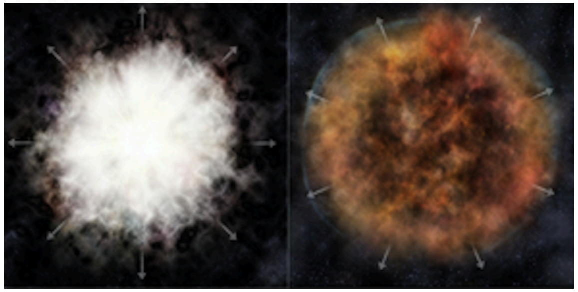
Nucleosynthesis of the elements in the Universe

- In stars during their lifetime: hydrostatic nucleosynthesis => **long timescale, classic onion-skin structure**
- In supernovae: explosive nucleosynthesis => **very short timescale** (s) **and large energy** (kinetic ~ 10^{51} ergs)

⇒ most of heavy elements from Si to Fe peak, and heavier elements

⇒ **SNe are the effective mechanism for producing and dispersing the synthesized element in the ISM**





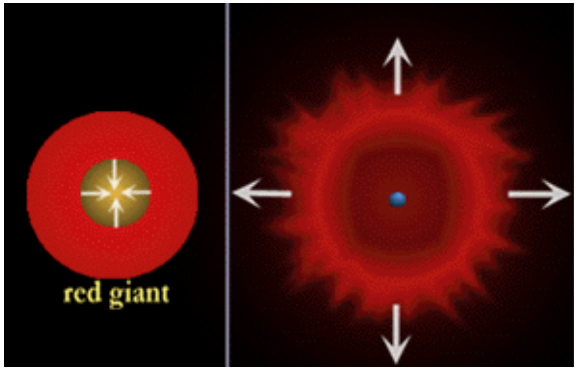
Supernovae:

- Thermonuclear explosion: SN Ia

main provider of Fe (~75 %) and Fe peak nuclei

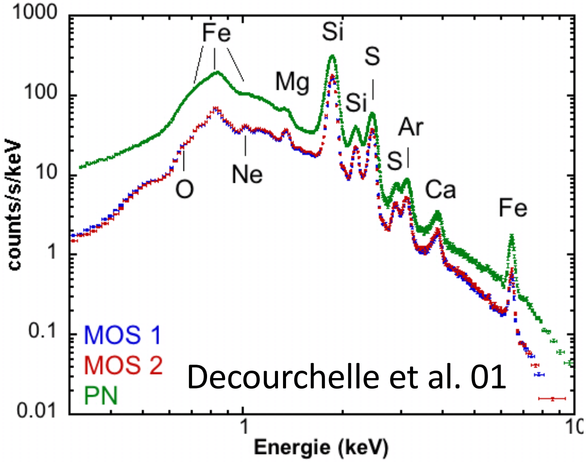
- Gravitational core collapse for stars > 8 Msol

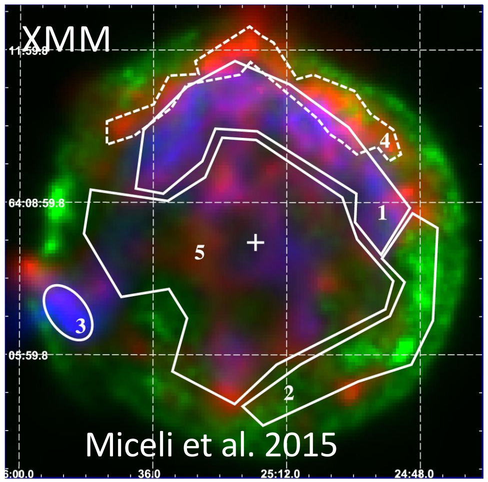
main provider of intermediate elements (Si-Ca): 70 %



Nucleosynthesis in SN Ia: Tycho (SN 1572) supernova remnant

XMM-Newton global spectrum





Equivalent width maps of Ca and Fe K lines

SNIa explosion mechanism : Tycho's X-ray spectrum favours a delayed detonation model (Badenes et al. 06)

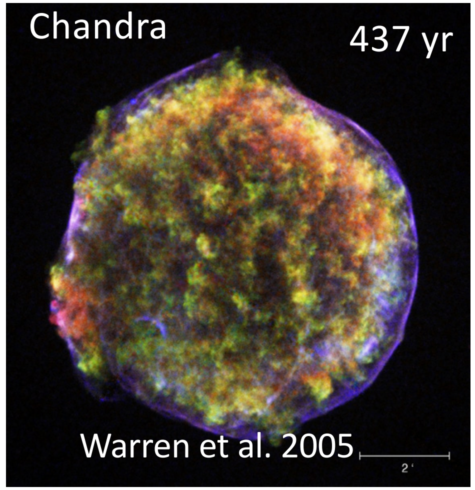
Elemental distribution in the ejecta

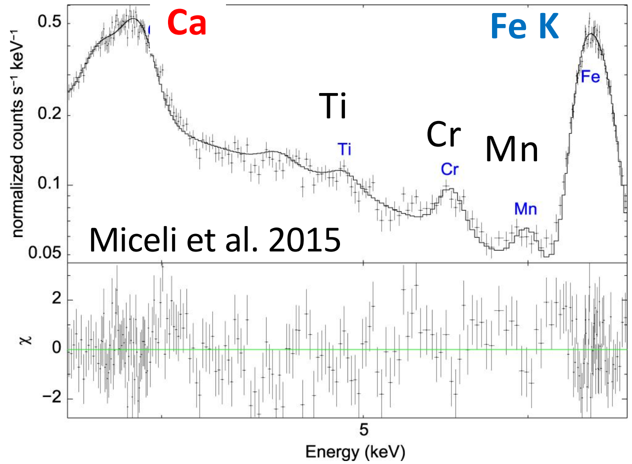
- **radial stratification** of the elements (Fe inside)
- **anisotropies** in the distribution of Fe-rich and Si-K/Ca-rich ejecta

Presence of rare elements: Ti, Cr and Mn

- Well correlated to Fe K
- Indications of Ti line emission (at >2 sigmas)

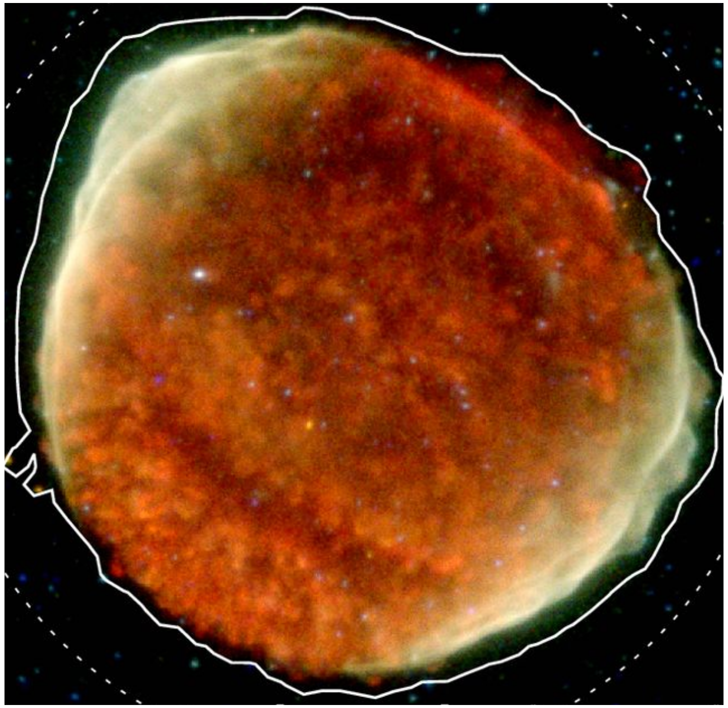
Fe-peak nuclei seem to be spatially co-located in the remnant, in agreement with the predictions of Type Ia SN models.





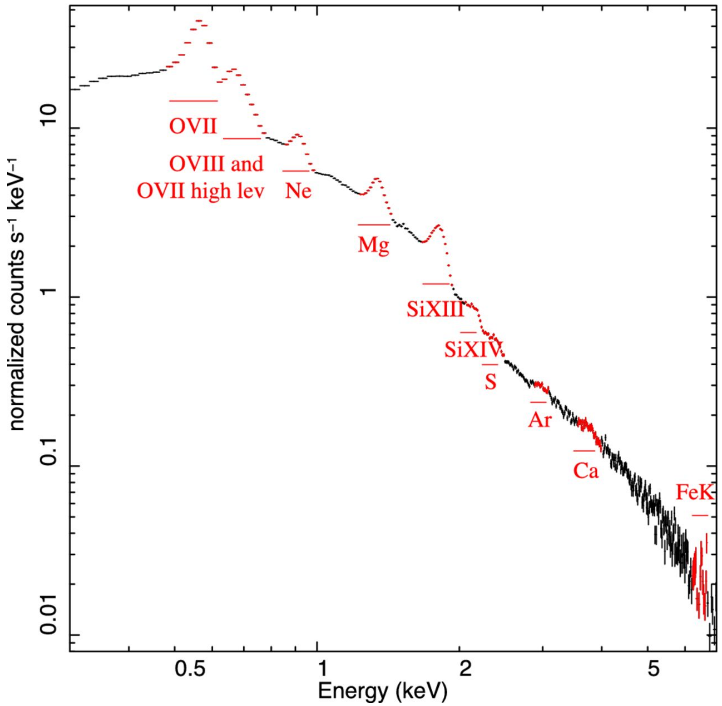
SN 1006: SN Ia
a detailed characterization of the plasma properties

Spatially resolved spectroscopy analysis

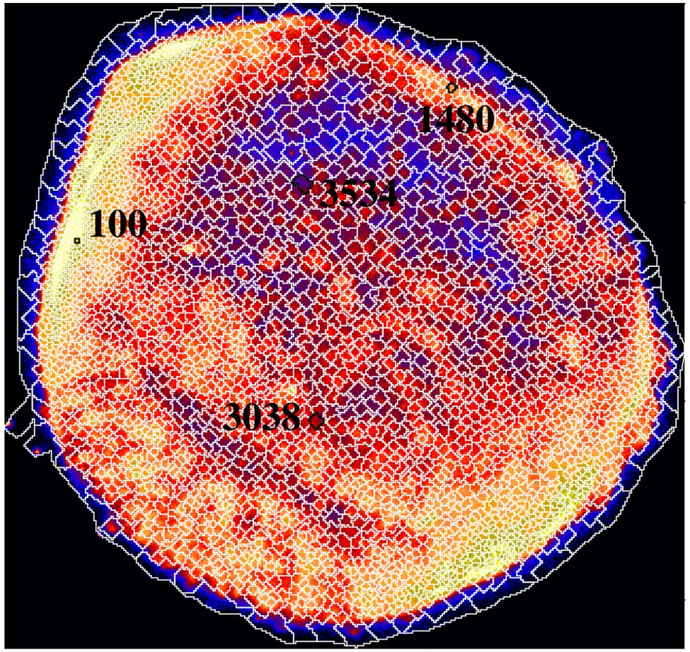


XMM-Newton 3 color images
(Red: 0.3–1 keV; Green: 1–2 keV; Blue: 2–8 keV)

30 arcmin diameter



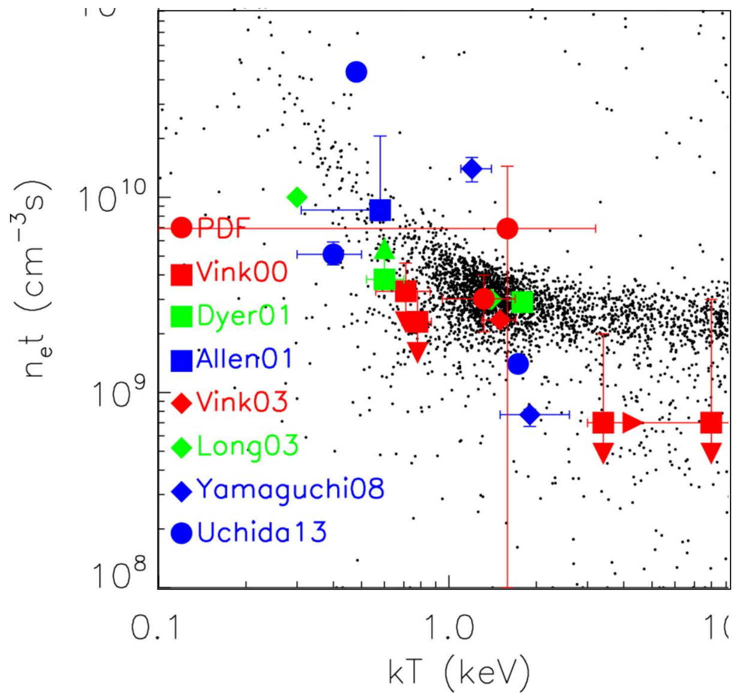
XMM-Newton global spectrum of SN1006



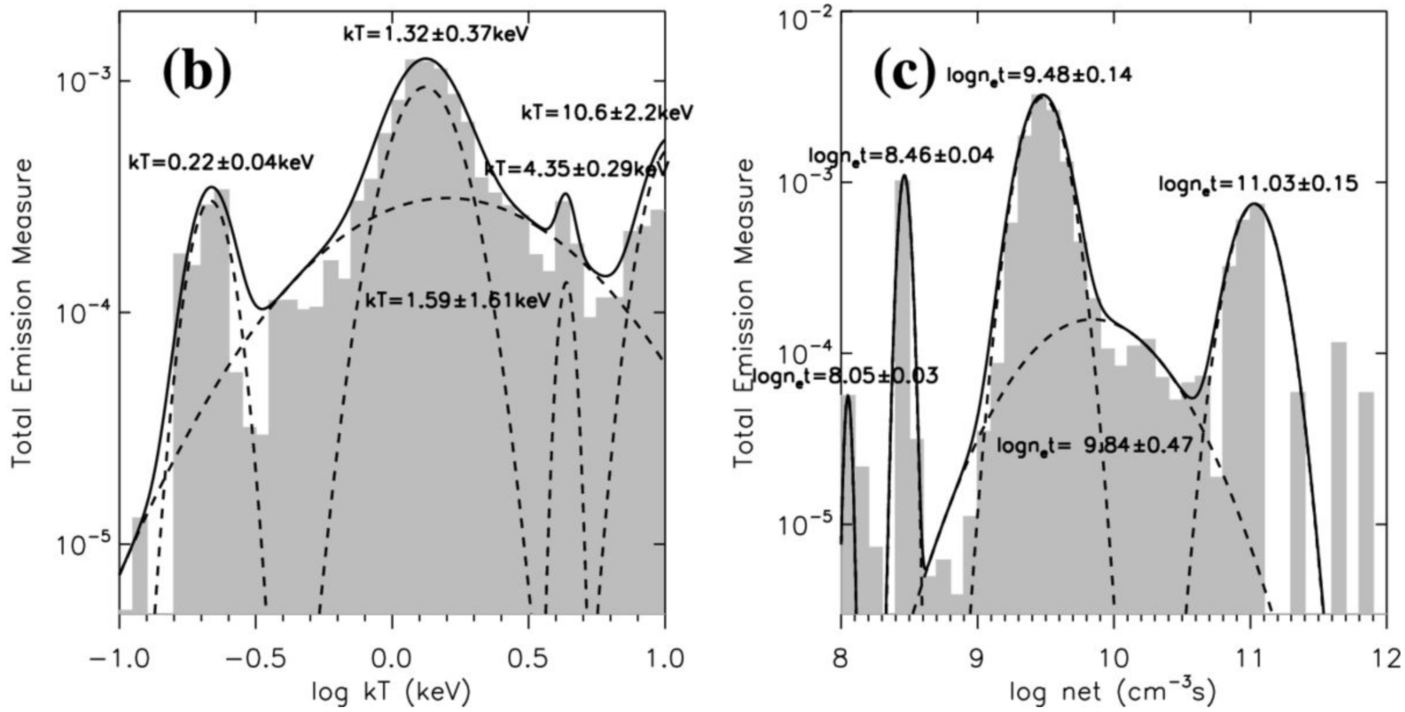
Tessellated meshes overlaid on the 0.3–8 keV: 3596 regions, each containing $\gtrsim 10^4$ counts from the combination of MOS-1, MOS-2, and PN

Li et al. MNRAS 2015

SN1006: SNIa
deep insight into the properties of the thermal plasma



Li et al. MNRAS 2015

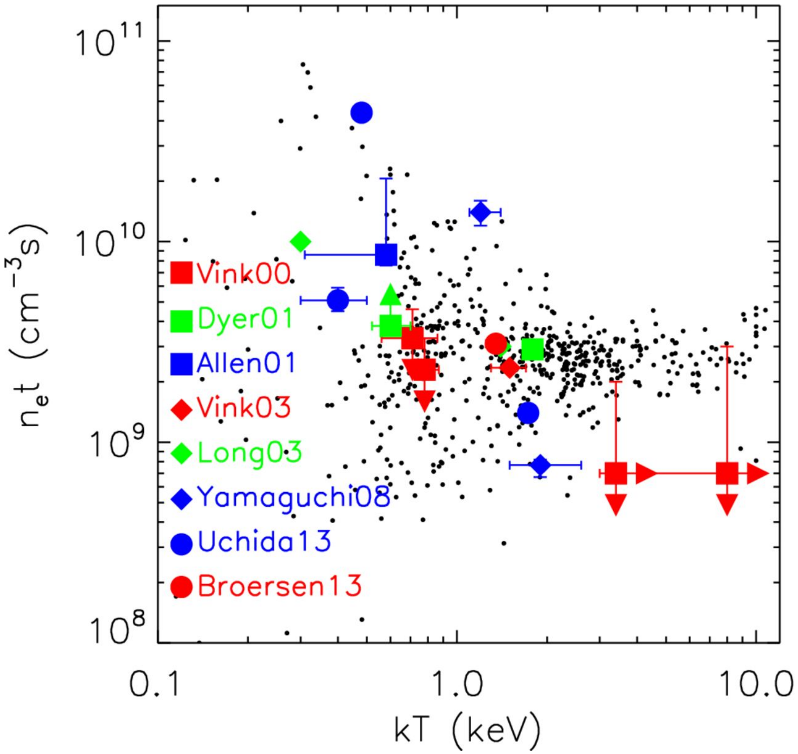


Probability distribution functions

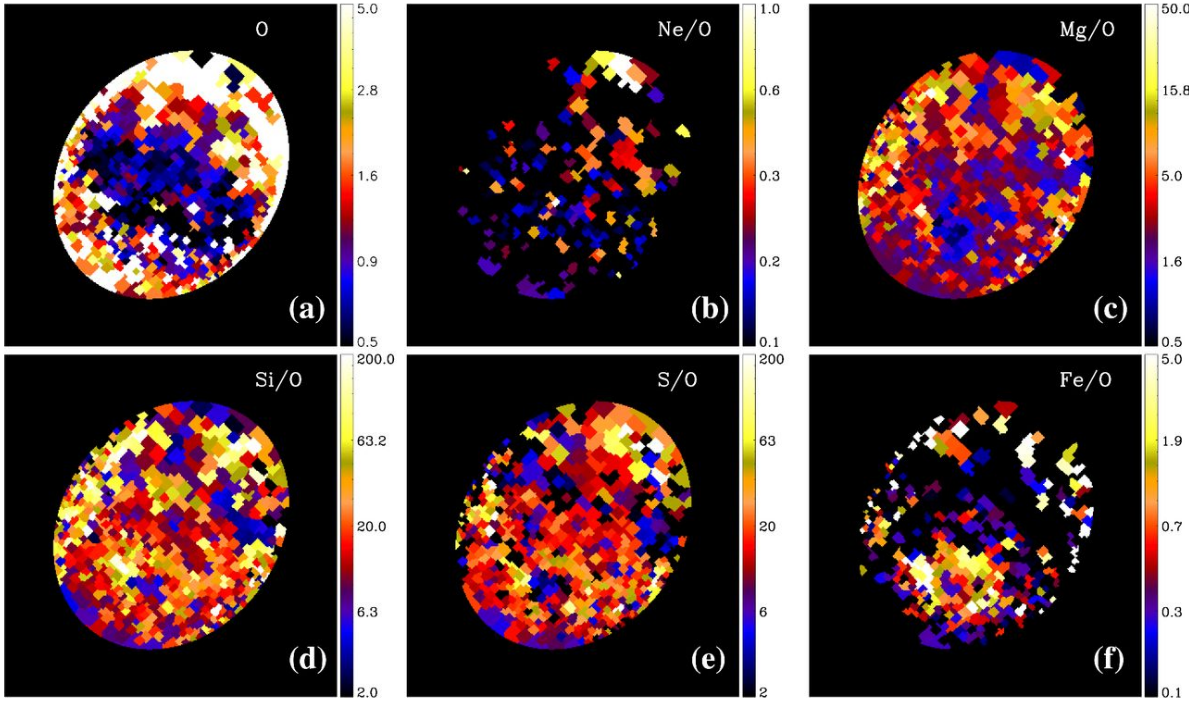
Properties of the thermal non equilibrium plasma :

- characterize the average thermal and ionization states of such an extended source
- the gas spans a large range of hydrodynamical evolutionary stages.

SN1006: elemental distribution



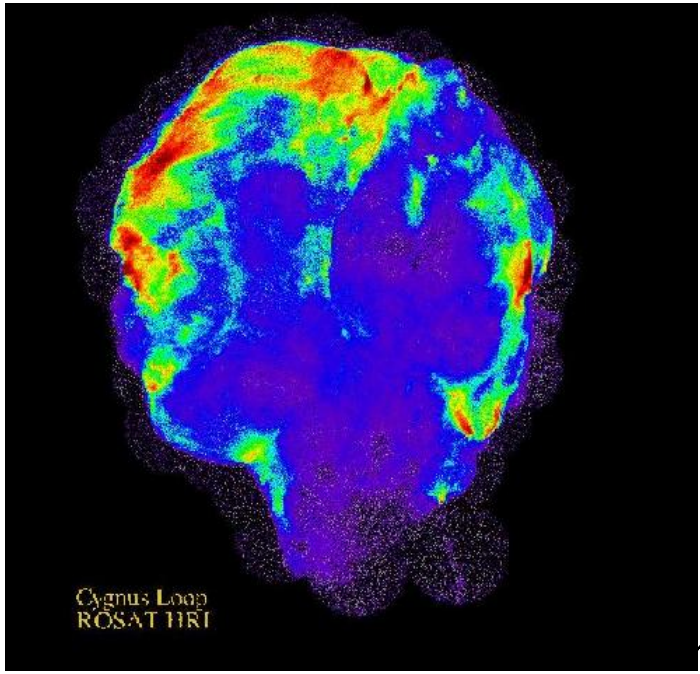
583 tessellated regions dominated by thermal emission



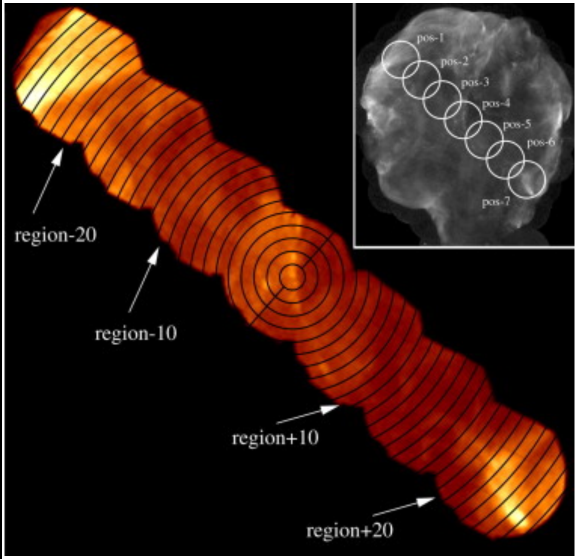
Li et al. 2016, MNRAS, 462, 158

- Abundance pattern in the ejecta consistent with typical Type Ia SN products.
- Spatial distribution of heavy elements (Fe) supports an asymmetric explosion
- Asymmetric environment

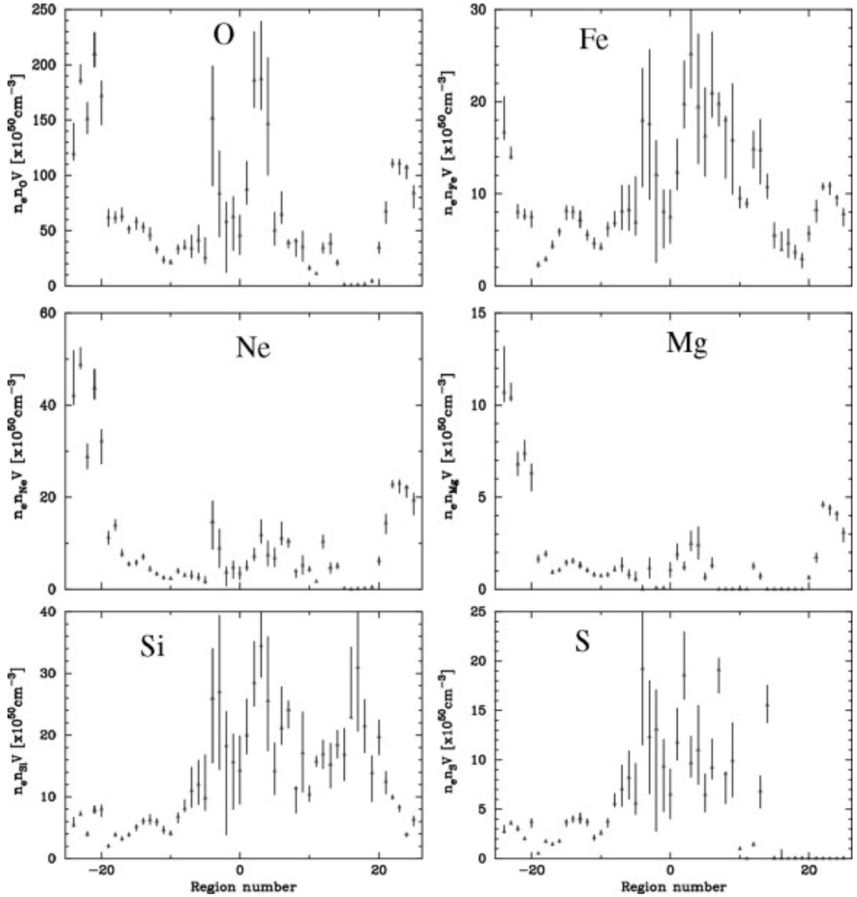
Mature remnants: Cygnus Loop ~15000 years
EPIC observations



Levenson et al. 97

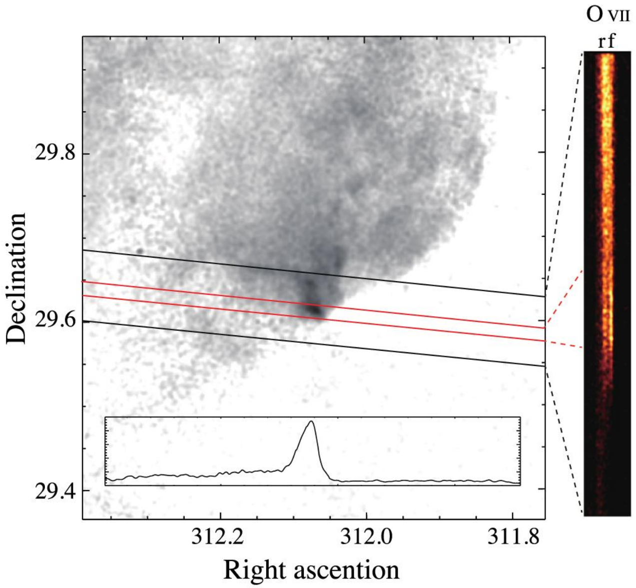


Tsunemi et al. 2007

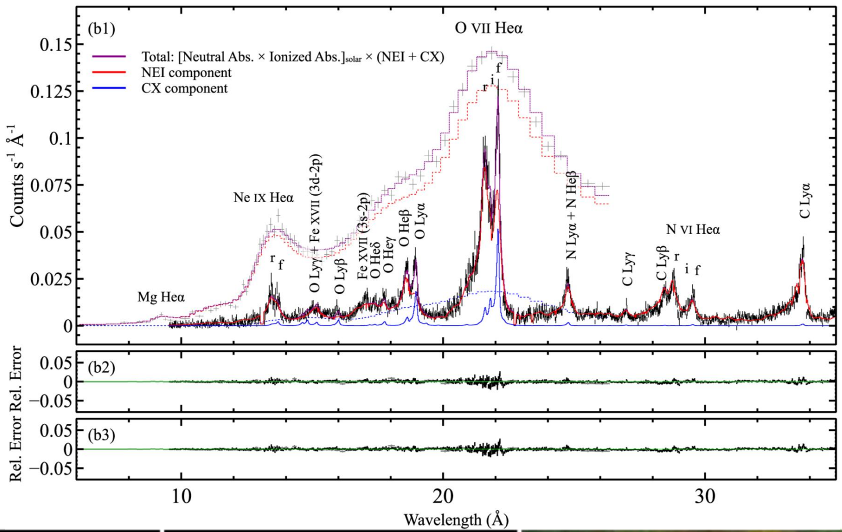


- asymmetric explosion of the progenitor star.
- Non uniformity of the metal distribution
- abundances pattern indicate a progenitor mass of about 15 Msolar.

Mature remnants: Cygnus Loop
RGS observations of the southwestern knot



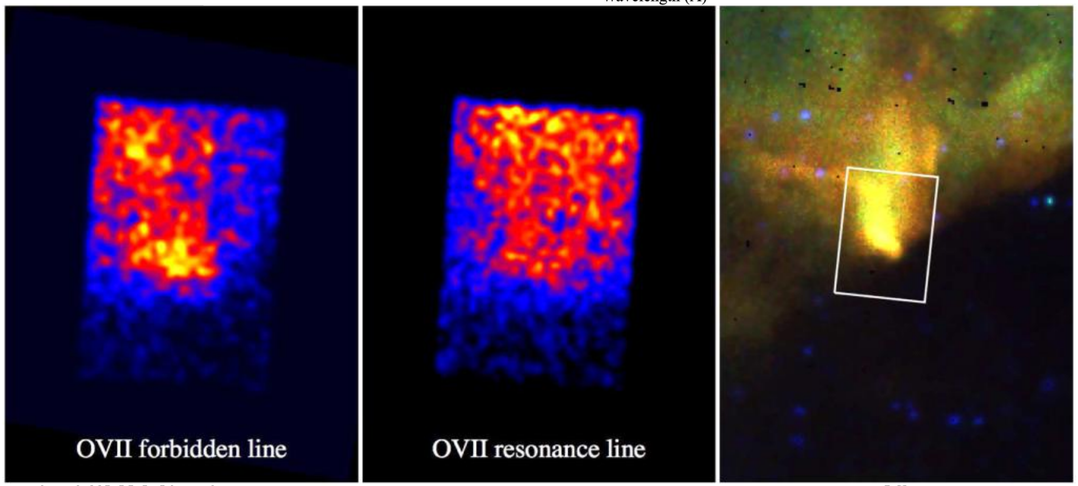
Uchida et al. 2019, ApJ



High Forbidden-to-resonance Line Ratio of O VII discovered inthe Cygnus Loop

- Charge exchange contribution enhanced around dense shock-cloud interaction (post-shock ions/neutral gas)

- Confirmation of low abundances (0.2-0.4 solar)



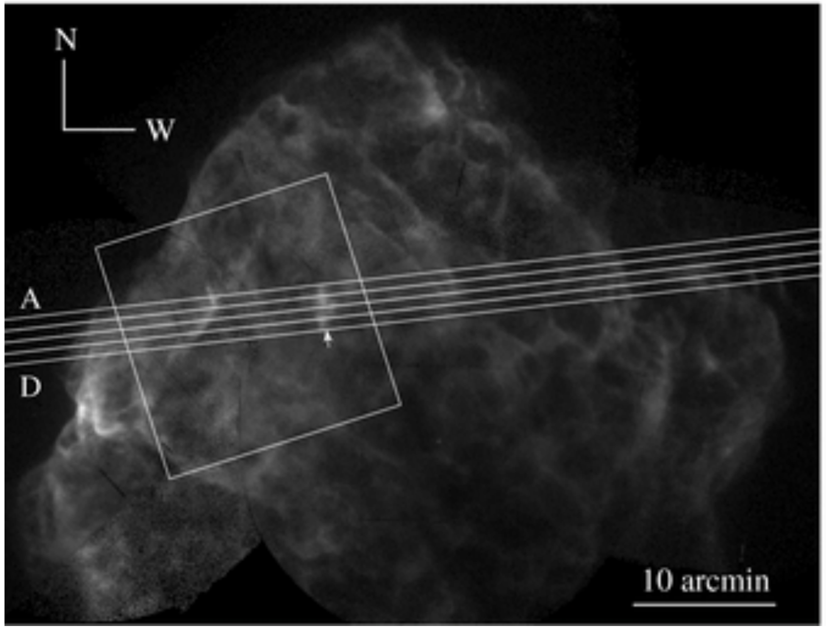
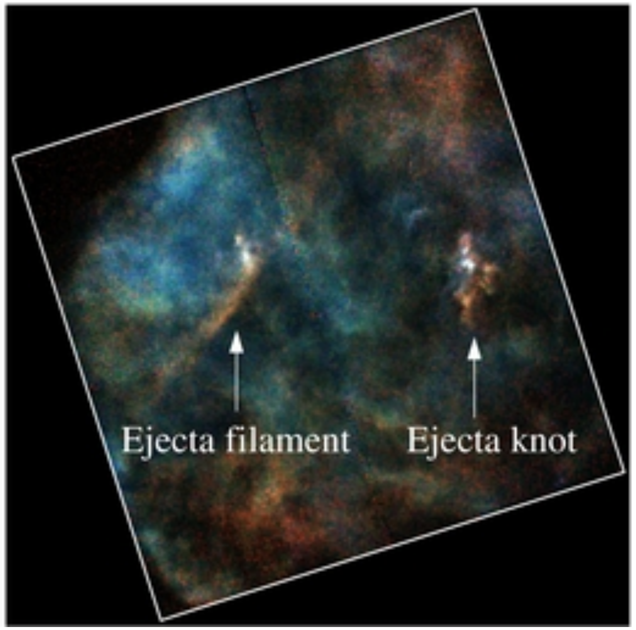


Image in the energy band 0.5–5 keV



3 color image:
0.5–0.7 keV (red), 0.7–1.2 keV (green), and 1.2–5.0 keV (blue)

- Dynamics of the X-ray emitting ejecta oxygen knot
- Thermodynamic properties (kT_e, kT_O)
- Shock physics

Method : EPIC + RGS observations

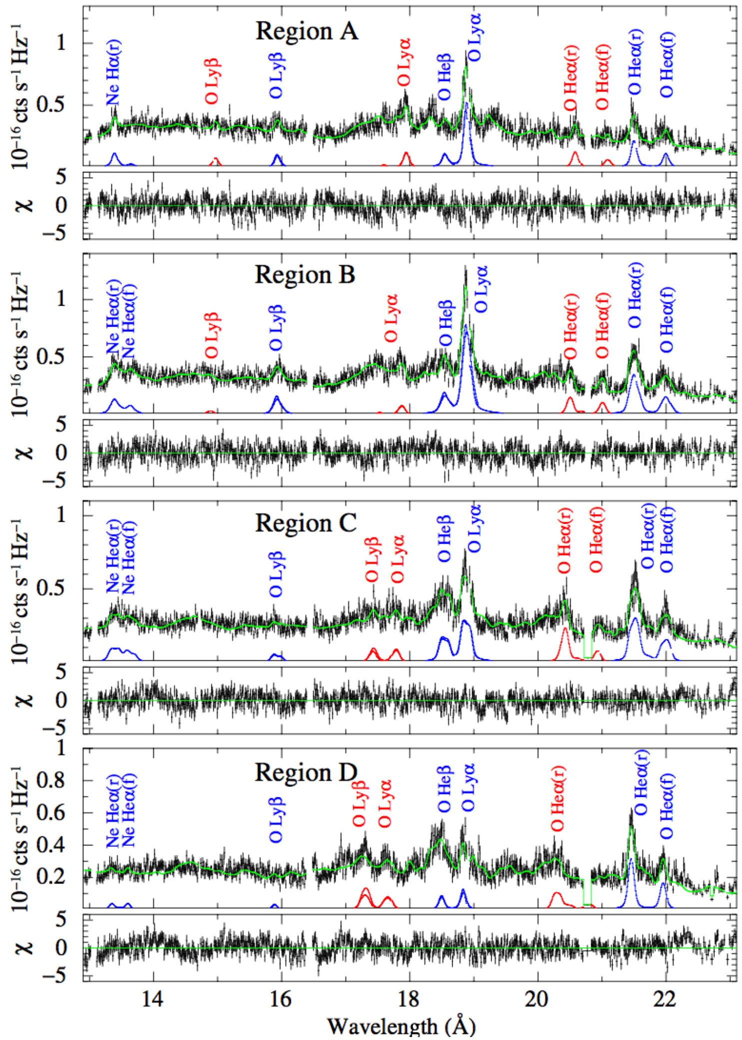
Katsuda et al. 2013

Dynamics of X-ray-emitting ejecta in the oxygen-rich CC SNR Puppis A

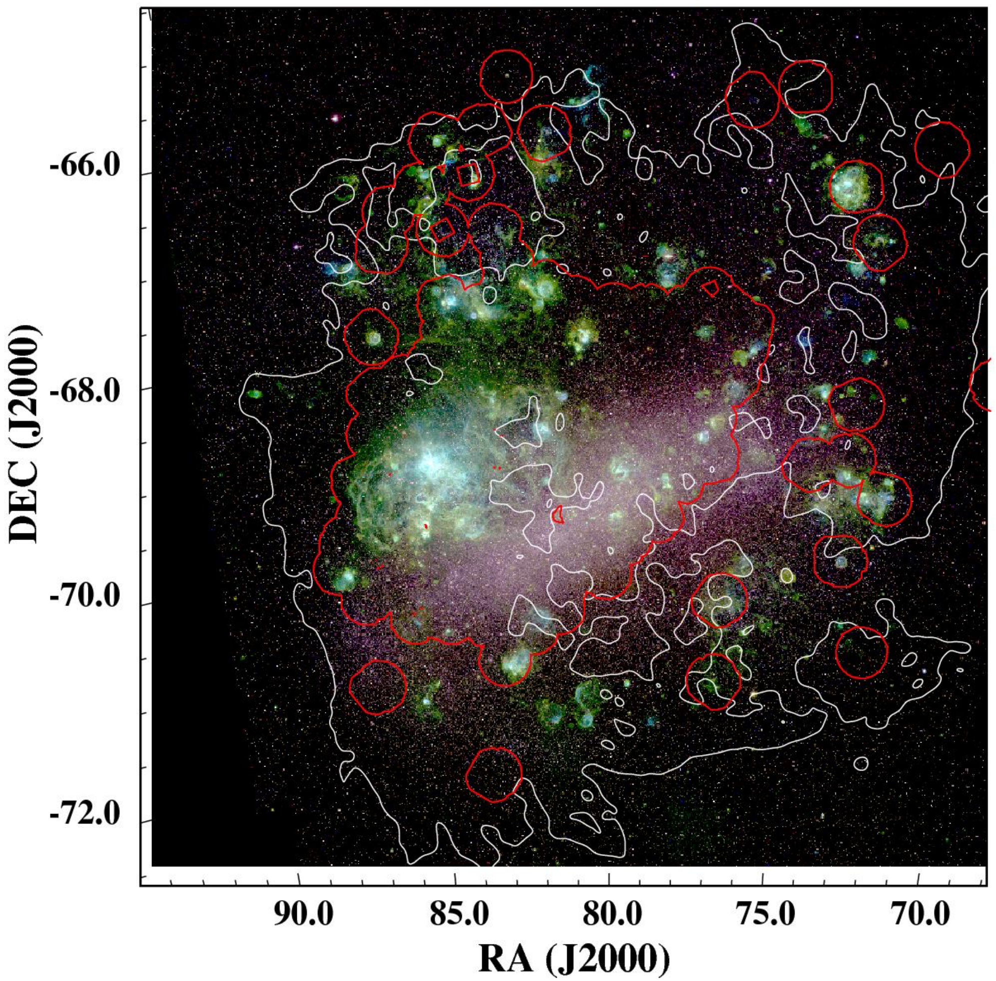
Katsuda et al. 2013

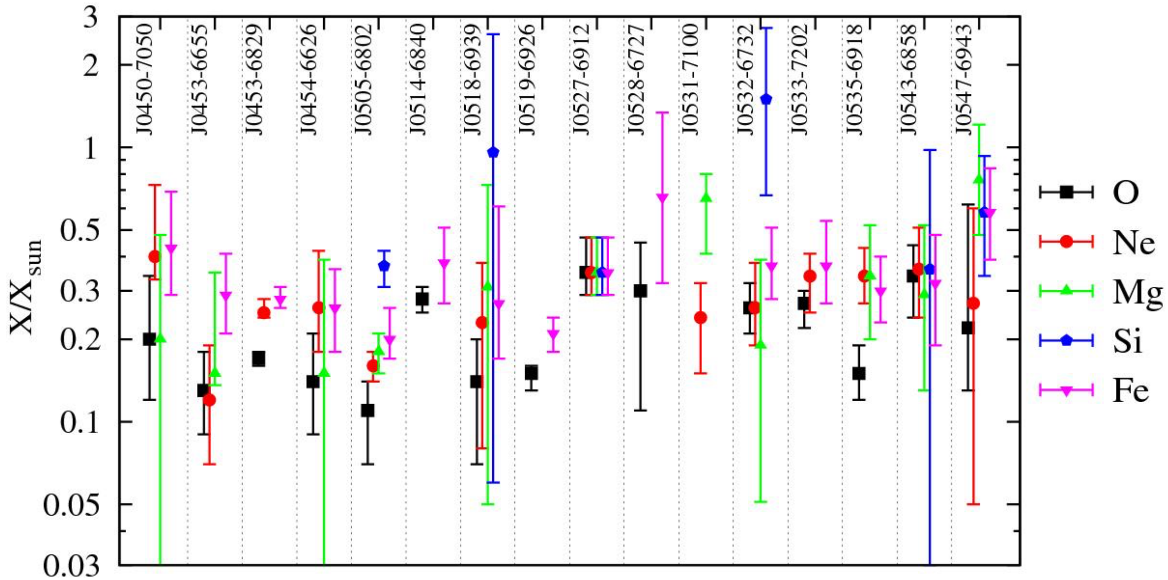
- **Prominent K-shell lines**, including O VII Heα forbidden and resonance, O VIII Lyα, O VIII Lyβ, and Ne IX Heα resonance,
- **Line centroids blueshifted** by~ 1480 km s^{-1} fully consistent with that of the optical Ω filament.
- Line broadening of O VIII Lyα < 0.9 eV, indicating an oxygen temperature of **30 keV**, 10 times lower than the O knot in SN1006 (Broersen et al. 1013)
- EPIC: kTe ∼0.8 keV and ionization timescale of ∼2 × 10^{10} cm^{-3} s

=> ejecta knot was heated by a collisionless shock of ∼600–1200 km s^{-1} and subsequently equilibrated due to Coulomb interactions



Population studies: SNRs in the LMC





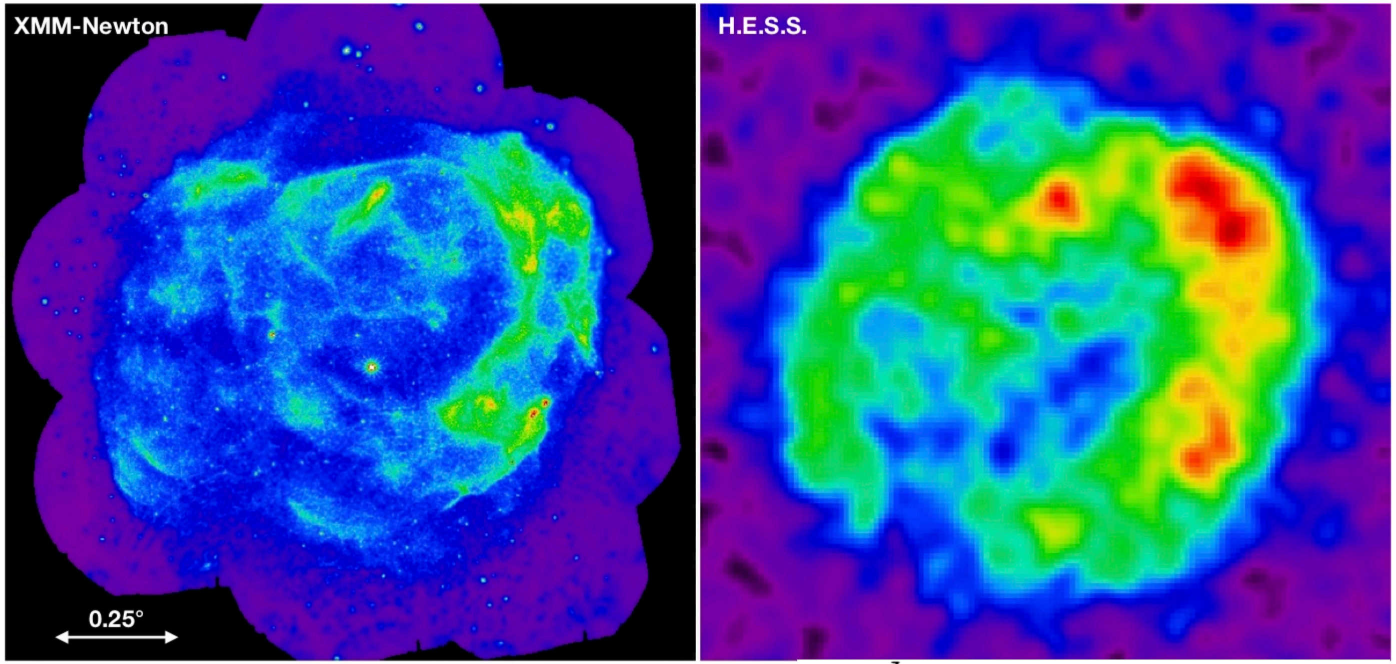
First homogeneous catalogue of the X-ray spectral properties of SNRs (51) in the LMC (Maggi et al. 2016)

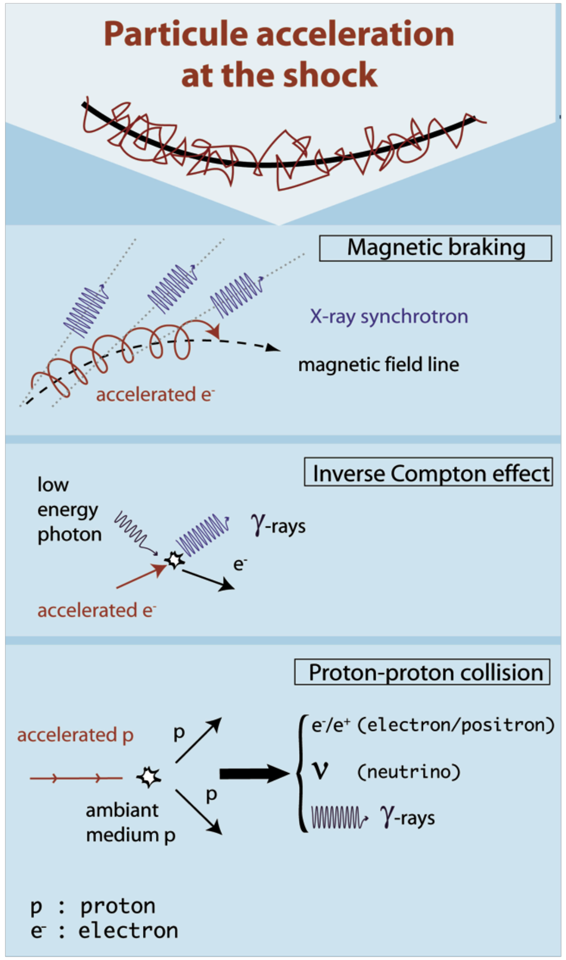
=> Clues to progenitor types (13% exhibits Fe K lines, 39% supernova ejecta)

⇒ ISM abundances (O, Ne, Mg, Si, Fe) ~ 0.2-0.5 solar

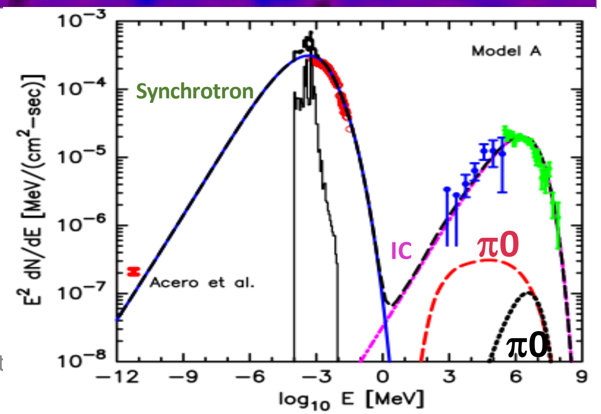
⇒ Ratio of SN CC/SN Ia ~ 1.35 over last few 10^4 years

Non-thermal dominated SNRs: RXJ1713-3946





- Hydrodynamical and broadband modelling to constrain the SNR origin and nature of particle acceleration



Ellison et al. 2012

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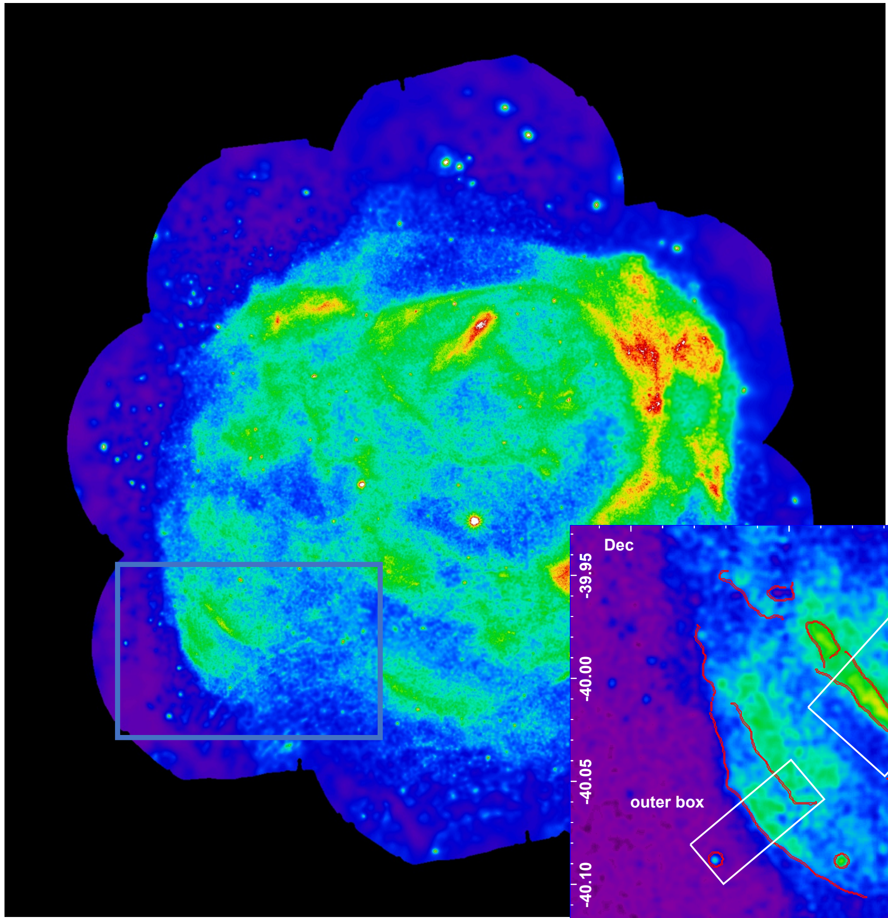
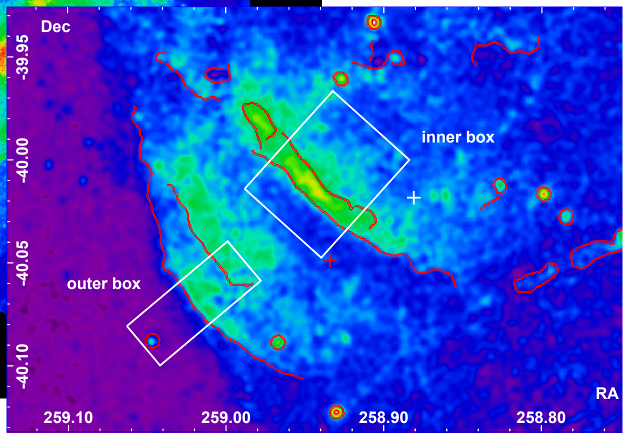
Non-thermal dominated SNRs: RXJ1713-3946

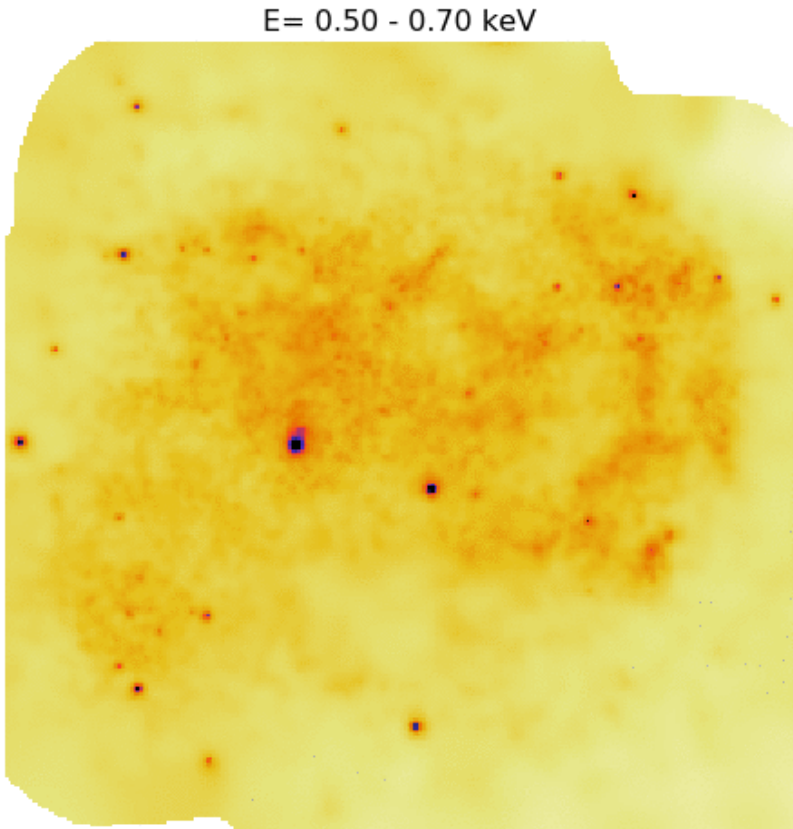




Acero et al. 2017

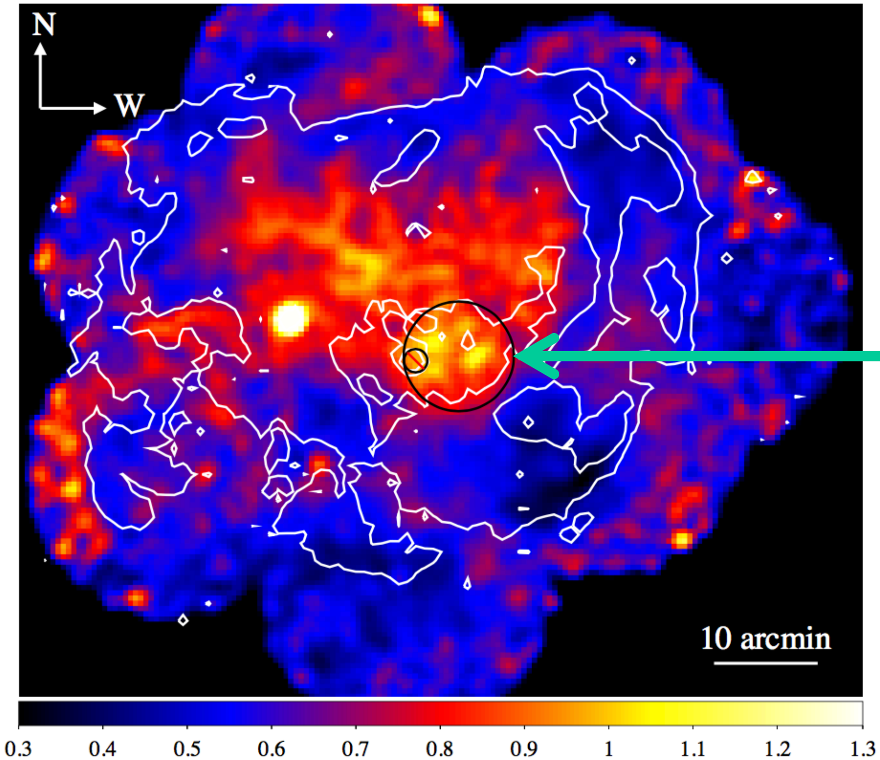
Proper motion between 13 yr => Velocity measurement ~ 3500 km/s

Age ~1500-2500 yrs

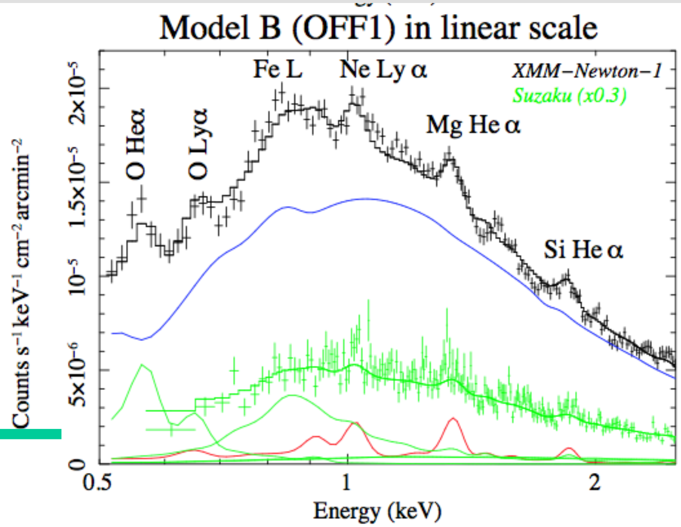


Acero, in prep

Katsuda et al. 2015, ApJ



Softness map (0.5–1.5keV/1.5–8keV) plus contours as X-ray surface brightness.



Relative abundances of Ne, Mg, Si and Fe
=> progenitor mass of about 20 Msun

=> result of SN Ib/c from a close binary system in which binary interactions removed a massive hydrogen envelope.

Conclusions

A large tribute of XMM-Newton to the study of supernova remnants

- **key contribution for the spatially resolved spectroscopy of SNRs: acceleration properties, thermal plasma, kinematics**
- **key contribution for source population studies in the LMC**

-**nucleosynthesis, particle acceleration, shock physics, shock interaction with the ISM-**

- **very rich scientific exploitation**
- **in synergy with other observatories in X-rays with Chandra, Suzaku, in gamma-rays, optical, infrared, ..**
- **with modelling and theory**

Large programs are key to perform ambitious studies

Prepare the path to Athena Observatory