Molecular clouds as probes of cosmic-ray acceleration in supernova remnants
Palavas-les-Flots, France
7-9 september 2009

X-ray emission from SNRs interacting with interstellar clouds

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Summary

- **Introduction**

- **Physical origin of the X-ray emission**
  - Hydrodynamic (HD) effects
  - Effects of diffusive shock acceleration (DSA)

- **X-ray observations of HD effects**
  - Cygnus Loop
  - Kes 27
  - W49 B
  - IC 443
  - Mixed-Morphology (MM)

- **X-ray observations of DSA effects**
  - RX J1713.7-3946
  - IC 443
  - Kes 69 (?)

Introduction

We expect to find several SNRs interacting with dense clouds because:

1. Core-collapse supernovae are expected to explode in the same environment where their progenitors were born (massive stars cannot drift far away from the star-forming region because of their very short life-times).

2. Massive stars modify the circumstellar medium with strong stellar winds in their post-MS stages (RSG, LBV, Wolf-Rayet), creating wind-blown bubbles enclosed by dense cavity wall (e.g. Ring Nebula G79.29+0.46, Rizzo et al. 2008). Therefore, SNRs can interact with wind residuals and impact on the cavity wall (see Dwarkadas 2005 and 2007).

Since around 80% of SNe are core collapse, these interactions drive the exchange of energy and mass in the interstellar medium and contribute to the chemical enrichment for future generations of stellar populations.

Introduction

Over a total of 274 SNRs in the Green catalogue **54 SNRs (~20%) interacting with MC** (they were **44 in 2003** and **25 in 1998**)

Table 1: SNRs and MCs. Seta et al 1998, Roberts et al 2001, Torres et al. 2003

Name	Other name	H_2	CO	X-ray	Other	Ref. & Notes
G0.0-0.0	SgrA East				OH,3EG	Fatuzzo 2003ApJ...596.1035F
G1.4-0.1					IR	Hewitt et al 09
G5.4-1.2					OH	Hewitt & Yusef-Zadeh 09
G5.7-0.0					OH	Hewitt & Yusef-Zadeh 09
G6.4-0.1	W28 (MM)		+	A	OH,3EG	1,2, Lazendic 218, Rho et al 02
G9.7-0.0					OH	Hewitt & Yusef-Zadeh 09
G16.7+0.1			+	N	OH	Helfand et al 03 plerion
G21.8-0.6	Kes 69			**R**	OH	Yusef et al 03
G22.7-02					IR	Reach et al. 06
G31.9+0.0	3C391 (MM)		+	A	OH	Reach et al. 98,99, Chen et al 01
G32.8-0.1	Kes78				OH	Yusef et al 03
G33.6+0.1	Kes79		+	A,C	OH	3, Tsunemi et al 02, Sun et al 02
G34.6-0.5	W44 (MM)	+	+	R,C	OH,3EG	2,4-8, Petre et al 02 plerion
G39.2-0.3	3C396				IR	Hewitt et al. 09
G42.8+0.6					OH	Chomiuk 2002AAS, Green et al 97
G43.3-0.2	W49 B			+	IR	Miceli et al. 06, Keohane et al 07
G49.2-0.7	W51 (MM)		+	**A**	OH	10, Koo et al 02 HXS, Green et al 97
G54.5-0.3			+			11
G69.0+2.7	CTB80		+	R		12, Safi-Harb et al 95
G74.0-8.5	CygLoop	+	+	A,C		13, 14, Tenorio-Tagle et al 85, Miyata et
G74.9+1.2	CTB87		+		3EG?	15, 16
G78.2+2.1	γ Cyg		+	**A**	OH, 3EG	Yamamoto 1999sf99.proc..110Y, Uchiyam
G84.2-0.8			+			15
G89.0+4.7	HB21 (MM)		+	R,A		15, 17, 18, Yanamoto 99, Leahy et al 96,
G93.7-0.3	CTB104A		+			15
G94.0+1.0	3C434		+			15
G109.2-1.0	CTB109		+	B,**N**		15, 19, 20, Rho et al 97, Plucinsky et al (
G111.7-2.1	CasA		+	C		15, 21
G120.1+1.4	Tycho		+	N		Lee et al 03, Decourchelle et al 01
G132.7+1.3	HB3		+		OH	15
G160.4+2.8	HB9		+	R		15, Lehay et al 95
G166.1+4.4	VRO42.05.01		+	R,A		15, Burrows et al 94, Guo et al 97
G166.3+2.5			+			15
G189.1+3.0	IC443	+	+	**N**	3EG,OH	14,15,23–36, Bocchino et al 2000,2003
G192.8-1.1			+			15
G205.5+0.5	Monoceros		+		3EG	15, 37, 38, Jaffe et al 98
G260.4-3.4	Puppis A			+		Hwang et al. 08
G263.9-3.4	Vela		+	N		39, Moriguchi et al 01
G266.2-1.2	VelaJr			**A,C**		Slane et al 01, Pannuti et al 03
G284.3-1.8	MSH10-53		+		3EG	40
G304.6+0.1	Kes 17				IR	Hewitt et al. 09
G327.4+0.4	Kes 27			+		Chen et al. 08
G329.7+0.2					OH	Lazendic 218
G332.4-0.4	RCW103	+	+	**A**		41, Gotthelf et al 99
G337.0-0.1	CTB33				OH	Lazendic 218
G337.8-0.1	Kes 41				OH,3EG	Yusef et al 03, Torres et al 03
G347.3-0.5	RX J1713		+	**A,C**	3EG	Uchiyama et al 02b, Butt et al 01 hadror
G346.6-0.2					OH	Yusef et al 03
G348.5+0.1	CTB37A		+		OH	Yusef et al 03
G348.5-0.0					IR	Reach et al 06
G349.7+0.2			+	**C**	OH	Lazendic 2003HEAD...35.1015L
G357.7-0.1	Tornado			**C**	OH	Lazendic 218, Gaensler et al 2003, Broga
G357.7+0.3	Square				OH	

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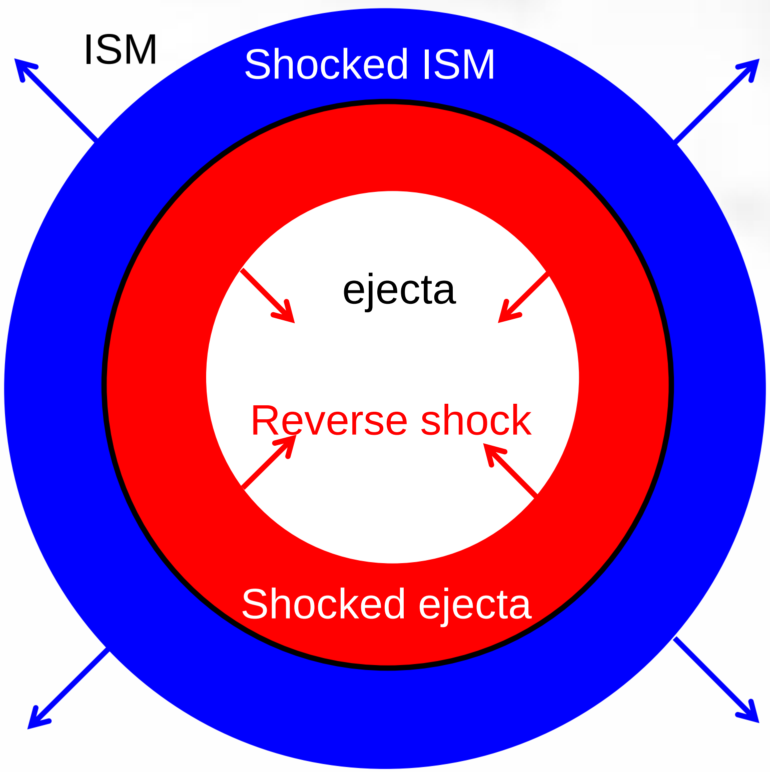
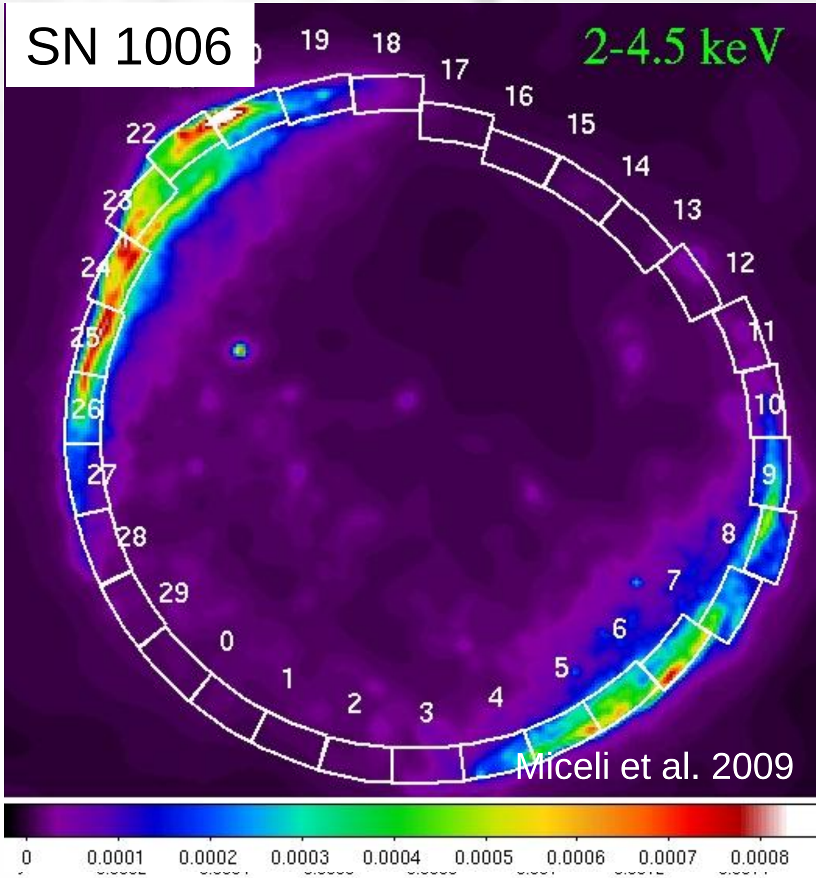
Physical origin of X-rays

SNRs are, by themselves, sources of thermal and non-thermal X-rays



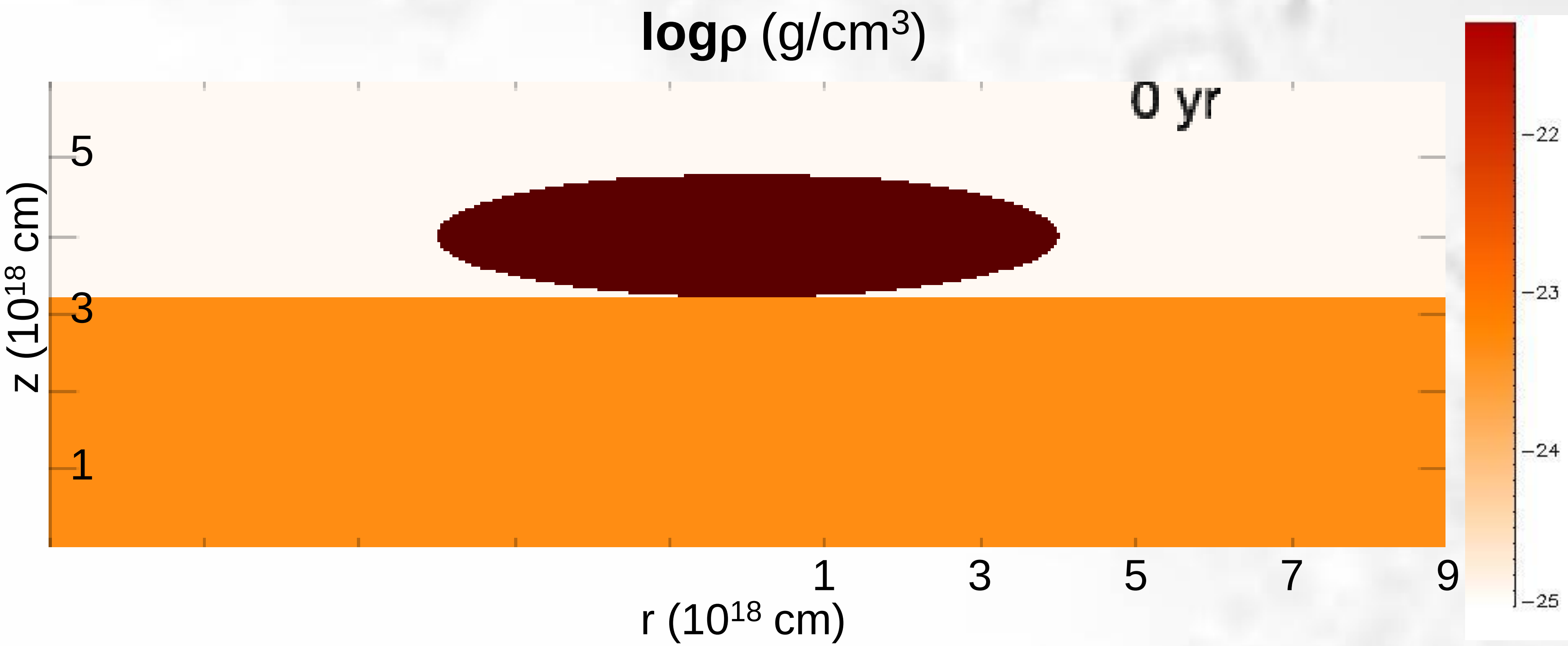


- Thermal emission from shocked ISM
- Thermal emission from shocked ejecta
- Non-thermal emission from e⁻ accelerated at the shock front

When a SNR interacts with a dense cloud additional effects are present…

Hydrodynamic effects

Interaction of the shock front with a density inhomogeneity: **density evolution**

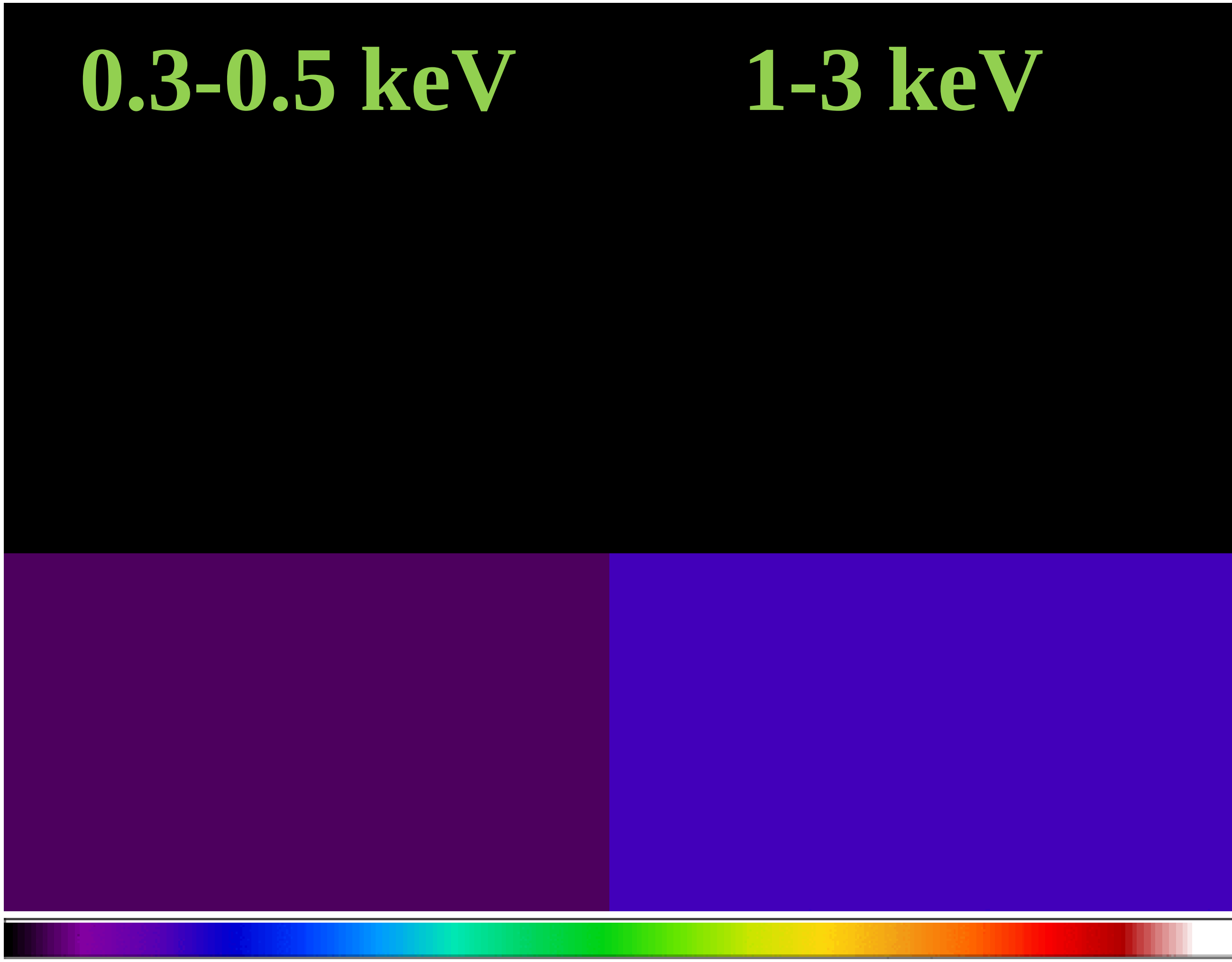


- Density contrast = 100
- Intercloud density = 0.1 cm^{-3}
- Cloud mass ~ 0.1 $M_\odot$
- Shock speed = 650 km/s
- Shock temperature = 6×10^6 K

Hydrodynamic simulation performed with the FLASH code (Fryxell et al. 2000), including thermal conduction and radiative cooling

Hydrodynamic effects

Interaction of the shock front with a density inhomogeneity: **X-ray emission**



- Hard X-rays behind the reflected shock
- Soft emission (and strong emission at larger λ) from the cloud shock

EPIC MOS synthesized count-rate maps (obtained with $N_H = 1 \times 10^{20}$ cm^{-5}).
(see also Orlando et al. 2005, 2006, 2008 and Miceli et al. 2006)

Effects of DSA I.

Bykov et al. 2000 modelled the non-themal X-ray emission from SNR shocks interacting with a molecular cloud.

The transmitted (radiative) cloud-shock is mildly super-Alfvenic and is site of particle acceleration due to MHD turbulences (low $\mathcal{M}_A$ are sufficient, see Bykov & Uvarov 1999)

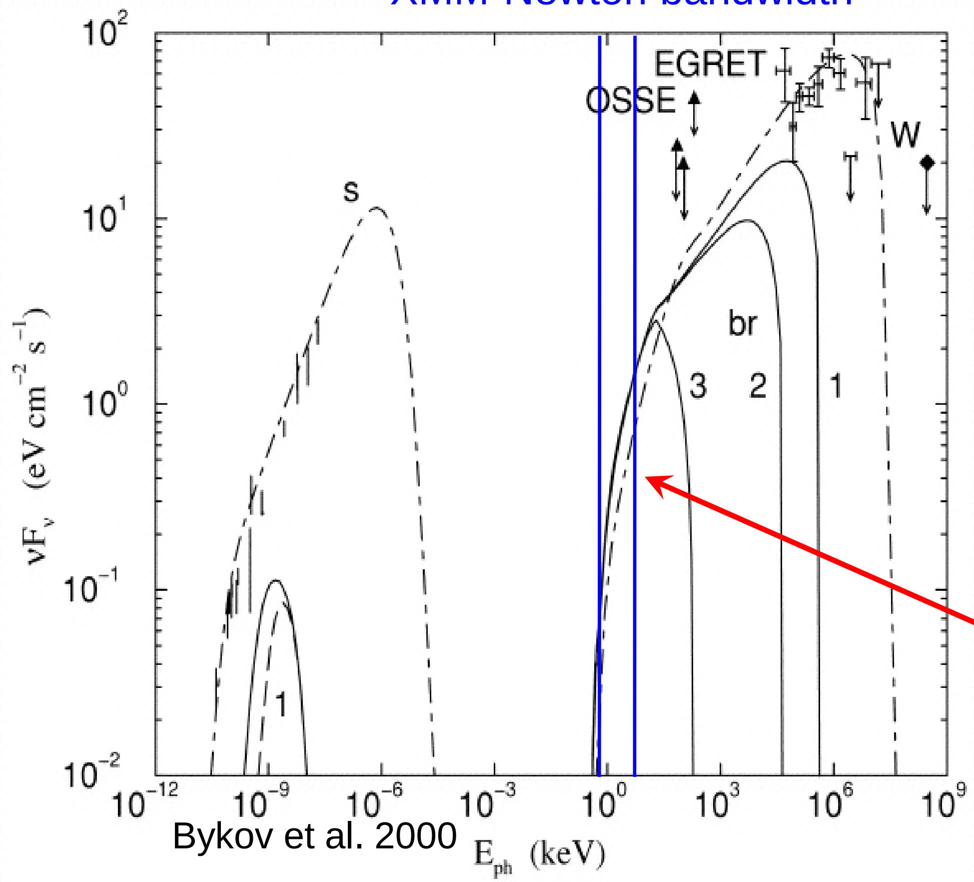
The spectrum of accelerated particles in the cloud-shock is modeled taking account of DSA in turbulent plasma (accurately parametrized), Coulomb losses, bremsstrahlung, synchrotron, and IC, for different values of density

Example

For a cloud density $10^4 cm^{-3}$, with B=0.1 mG, v_{cl}=25 km/s, we have $\mathcal{M}_A$>1, the shock is collisionless and we can accelerate e^- up to ~1 GeV

Effects of DSA I.

XMM-Newton bandwidth



Electrons from the cloud thermal pool in the ionized shock precursor are accelerated by the radiative shock.

Emission mechanisms:

- Synchrotron

- Inverse Compton

- Non-thermal bremsstrahlung

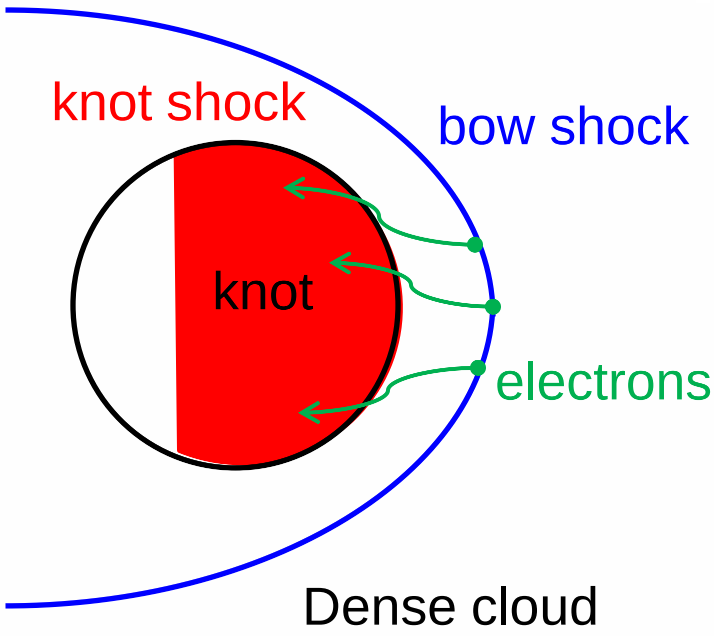
In X-rays MC clumps (solid line) are expected to be brighter than shell emission (dot-dashed)

- 1) V_{cl}=100 km/s, $n_{cl}=10^3$ cm^{-3}, $B_{cl}=10^{-4}$G, E_{max}= 0.5 GeV
- 2) same as 1 with E_{max}=0.05 GeV
- 3) V_{cl}=30 km/s, $n_{cl}=10^4$ cm^{-3}, E_{max}= 10 keV
- Dot-dashed) V_{sh}=150 km/s, n_{sh}=25, $B_{sh}=1.1\times10^{-5}$G
- Points) observed fluxes in SCR 10,11,12 of IC443

Effects of DSA II. Fast-moving knots

Supersonic knots are a common feature of both young and middle-aged SNRs like **Cas A** (Fesen et al 2001), **Puppis A** (Katsuda et al. 2008), **G292.0+1.8** (Park et al. 2001), and **Vela** (Aschenbach et al. 1995, Miceli et al. 2008).

Bykov (2002) showed that these knots can be sources of X-ray line-emission that is most prominent when they interact with a dense cloud



Fast non-thermal particles accelerated at the bow shock diffuse through the knot suffering Coulomb losses and ionizing the metal rich knot

Emerging X-ray emission

1) **Thermal component:** soft X-rays behind the knot shock)
2) **Non-thermal component:** hard continuum (bremsstrahlung with Γ~1.5) + K-shell lines

Effects of DSA II. Fast-moving knots

The Bykov 2002 model calculates the spectra of non-thermal e$^-$ accounting for injection, diffusive transport, advection, Fermi acceleration, synchrotron and Coulomb losses

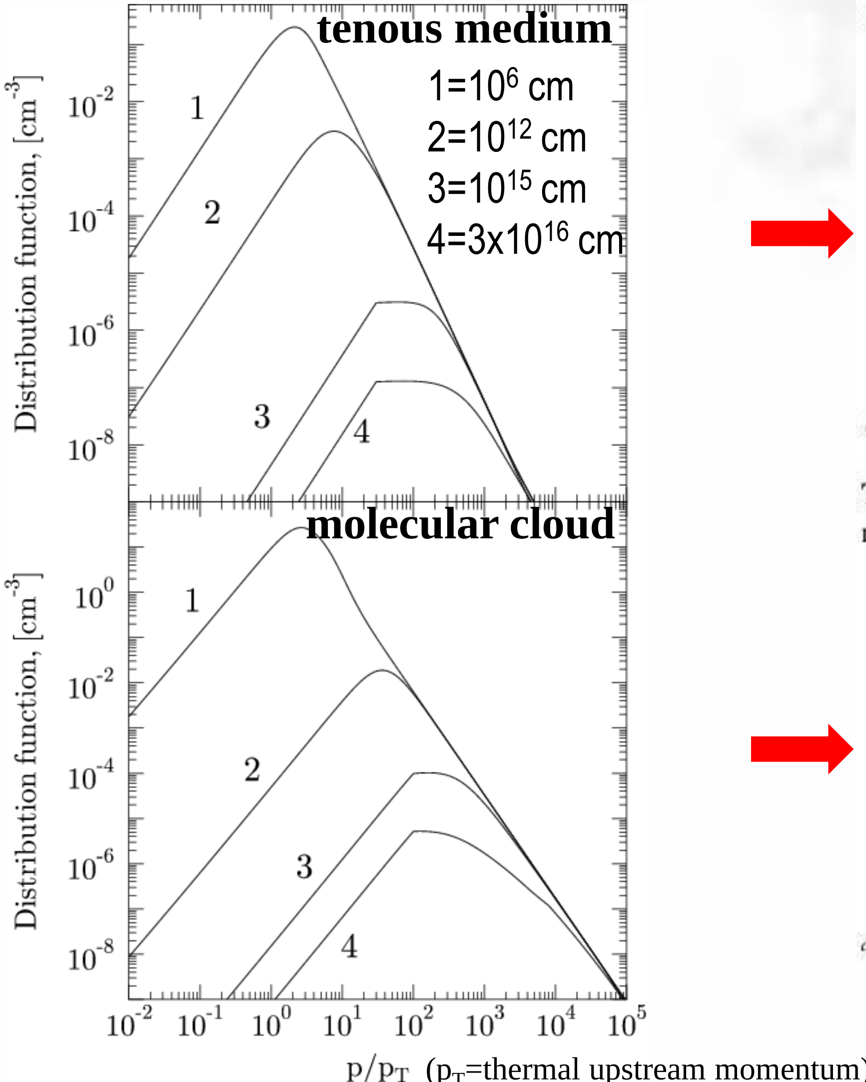


Table 2. K-shell line from the fragment interacting with low-density gas.

Line[a]	v_k (km s^{-1}) 1600	3200	6400	τ_{max}
O (0.5–0.6 keV)	38.0	66.5	99.8	33 880
Si (1.7–1.8 keV)	2.6	4.5	6.7	592[b]
Ar (2.9–3.1 keV)	1.9	3.4	5.0	272[b]
Fe (6.4–6.9 keV)	0.8	1.4	2.1	78[b]
$T^{(2)}$ [10^7 K]	1.2	2.8	6.6	

[a] The luminosities are in 10^{36} ph s^{-1}

Table 1. K-shell line luminosities of the fragment interacting with a molecular cloud.

Line[a]	v_k (kms^{-1}) 1080	1620	2700	τ_{max}
O (0.54 keV)	40.4	104	1638	33 880
Si (1.7 keV)	1.3	10	48	592[b]
Ar (2.9 keV)	0.5	4	20	272[b]
Fe (6.4 keV)	0.4	3	15	78 [b]
$T^{(2)}$ [10^7 K]	0.3	0.5	1.0	

[a] The luminosities are in 10^{38} ph s^{-1}.

Physical origin of X-rays

Hydrodynamic effects

Stratified emission (and temperature) at different distances from the cloud:

- IR, optical, and soft X-rays from the cloud shock
- Hard X-rays behind the reflected shock

Effects of particle acceleration at the shock front

- Shock in molecular clumps: enhanced non-thermal X-rays
- Fast moving knots: non-thermal continuum+line

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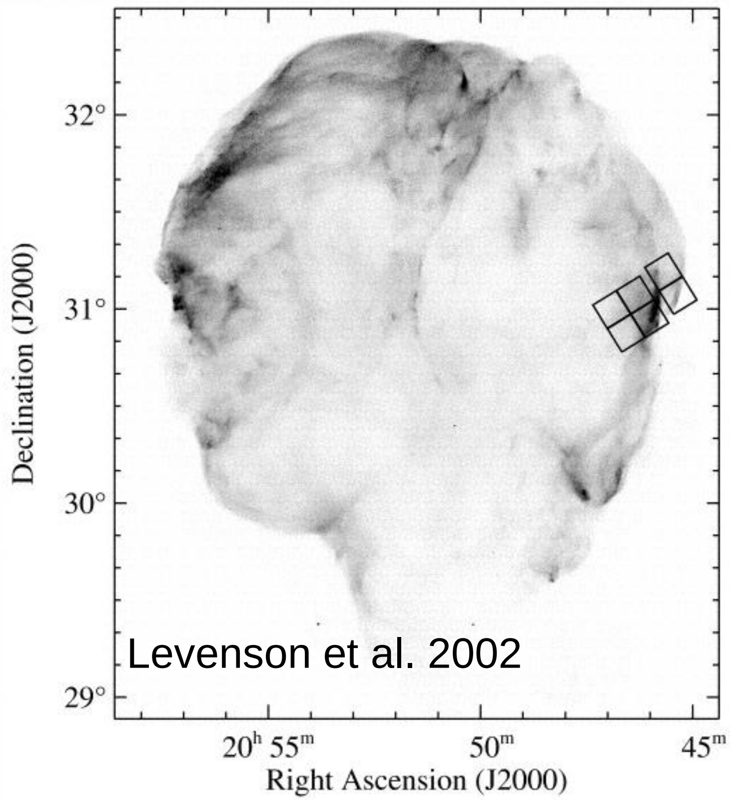
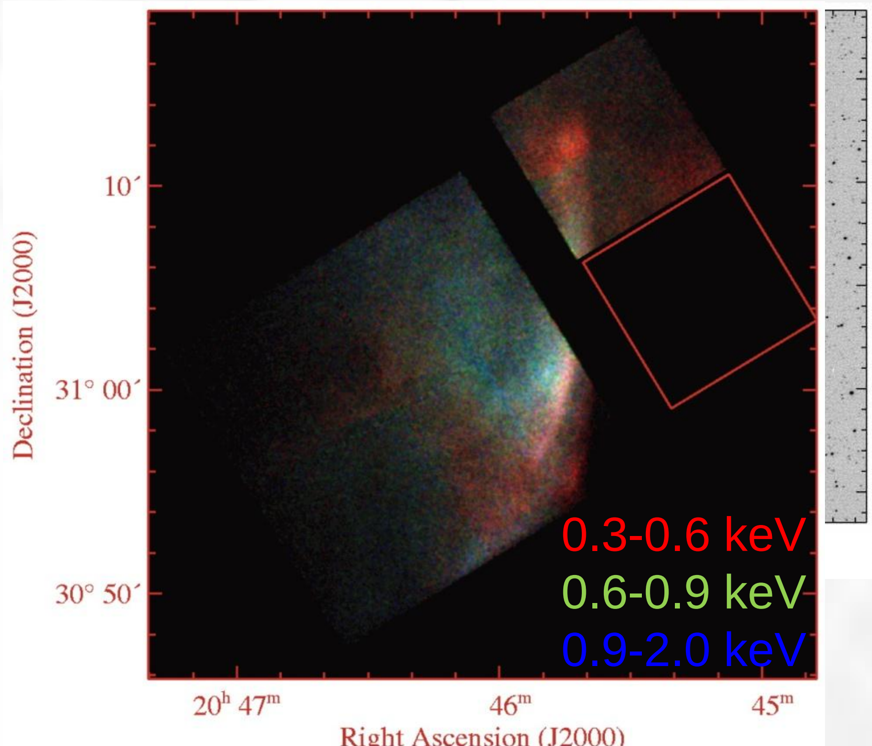
The Cygnus Loop (effects at small scales)

Middle-aged SNR (~8000 yr, Levenson et al 98; @500 pc, Blair et al. 99) interacting with a cavity wall.

Chandra obs. of the W region (Levenson et al. 02)





Levenson et al. 2002

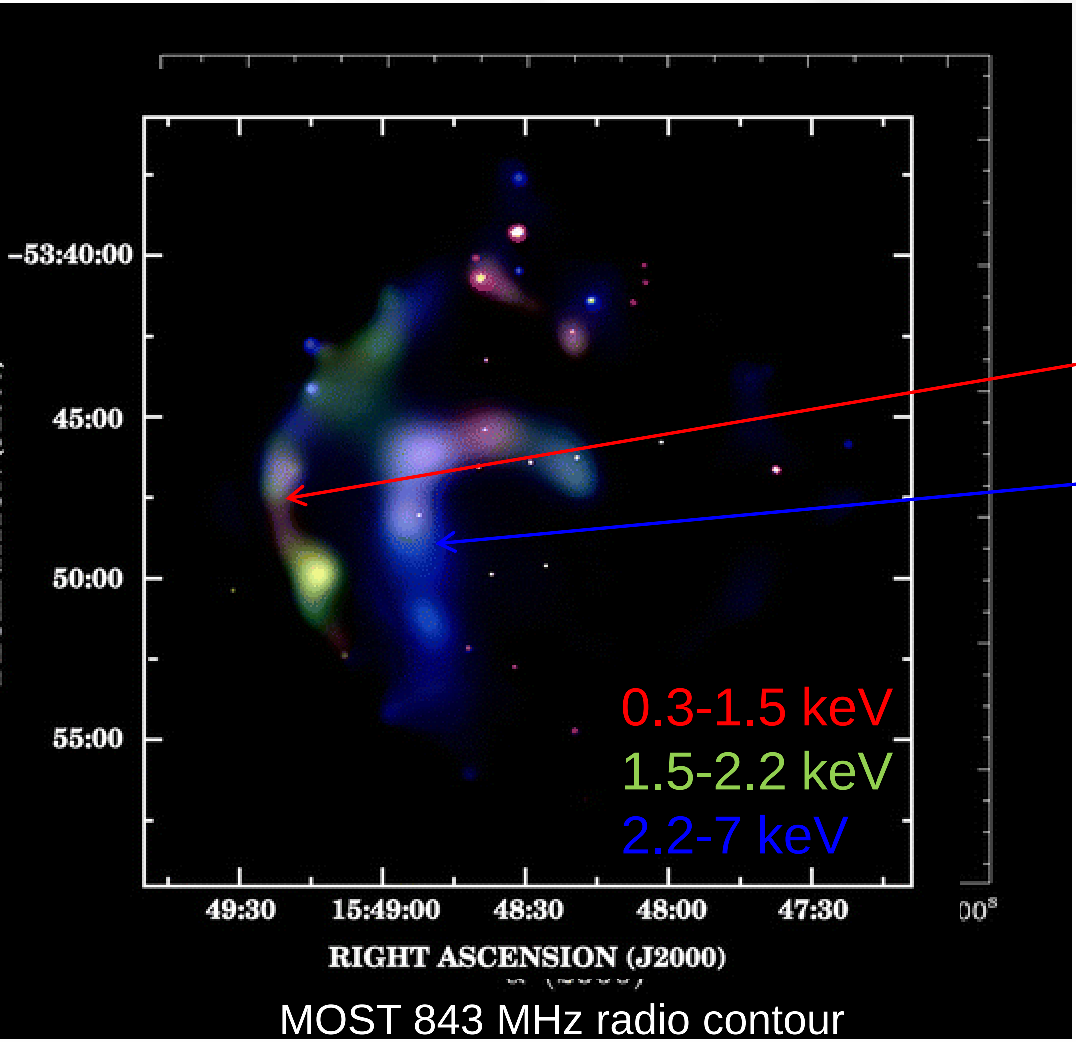
Stratified emission (and temperature) at different distances from the cloud:

- IR, optical, and soft X-rays (kT=0.03 keV) from the cloud shock
- Hard X-rays behind the reflected shock (kT=0.2 keV)

Kesteven 27 (effects at large scales)

Thermal composite SNR (cool rim, hot interior) at ~4 pc, embedded in a H I cloud and interacting with it (McClure-Griffiths et al. 01).

Analysis of Chandra data by Chen et al. 2008:

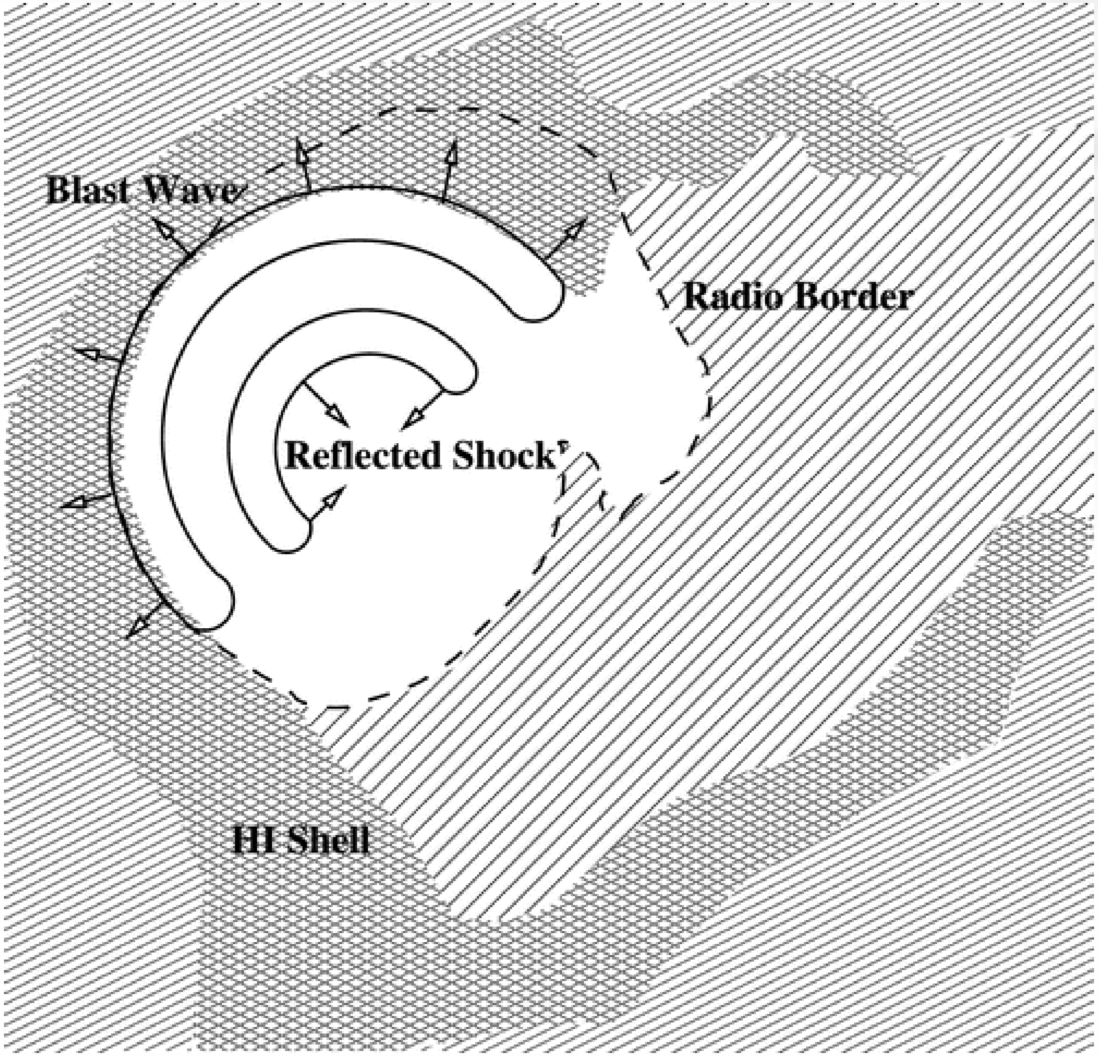


Spatially resolved spectral analysis on a set of 10 regions

kT ~0.5 keV, n~2 cm^{-3}

kT ~1.2 keV, n~0.4 cm^{-3}

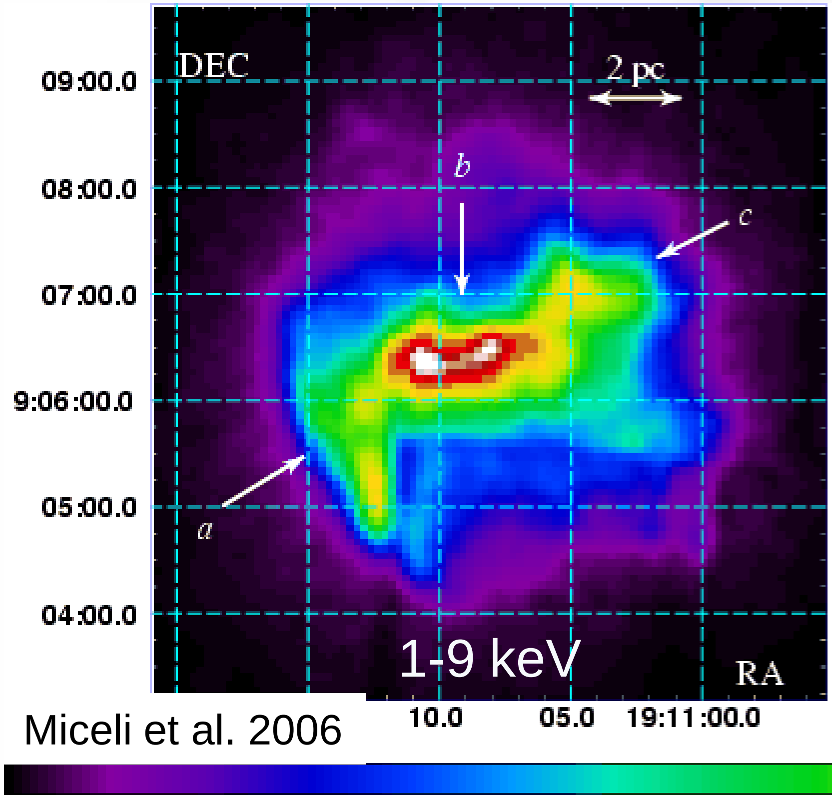
Kesteven 27 (effects at large scales)



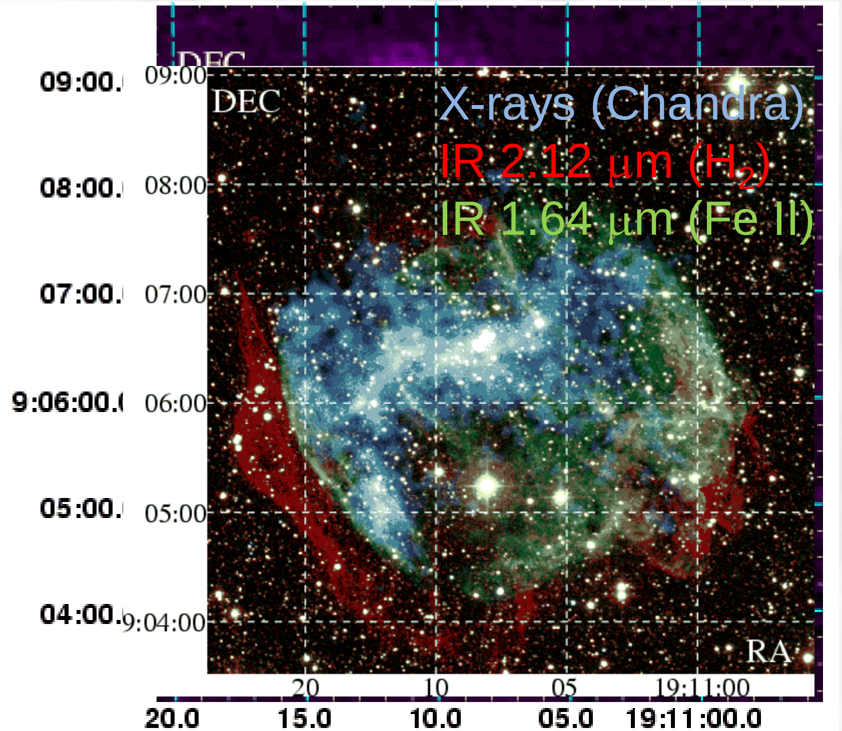
W49 B (effects on the ejecta)

One of the brightest ejecta-dominated SNR in X-rays (age~1000yr, D~8 kpc)

XMM-Newton observation analized by Miceli et al. (2006, 2008) and Spitzer IR data (Keohane et al. 2007)



Miceli et al. 2006



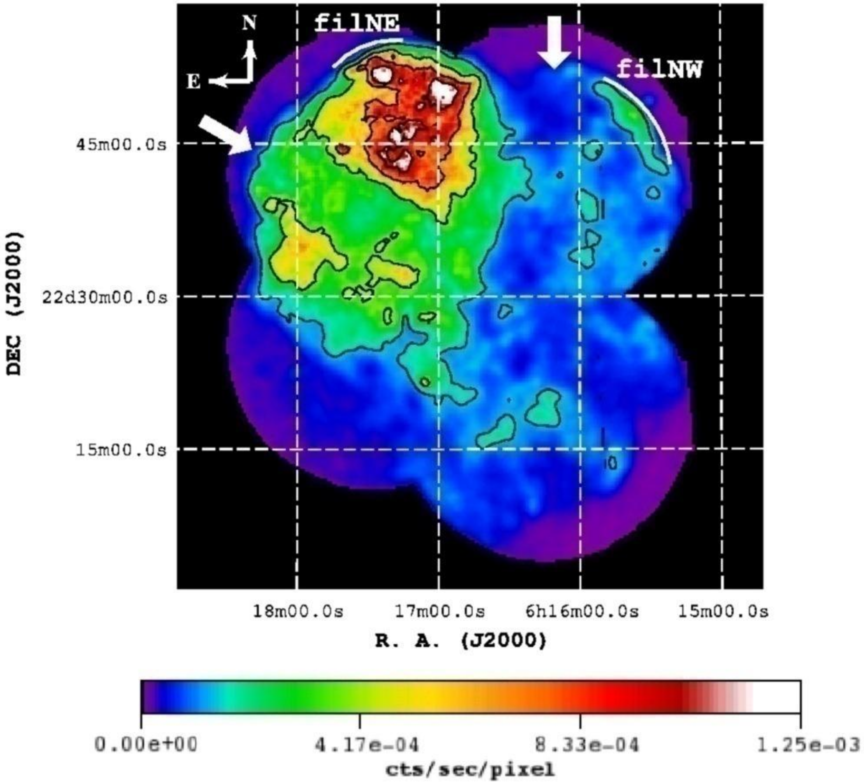
The hot (kT~2 keV) and tenuous (n~2.5 cm^{-3}) ejecta (see Miceli et al. 06) form a jet (Miceli et al. 08) distorted by the interaction with a dense cavity wall (n_{H_2}~3000 cm^{-3},see Keohane 07)

IC 443 (atomic and molecular clouds)

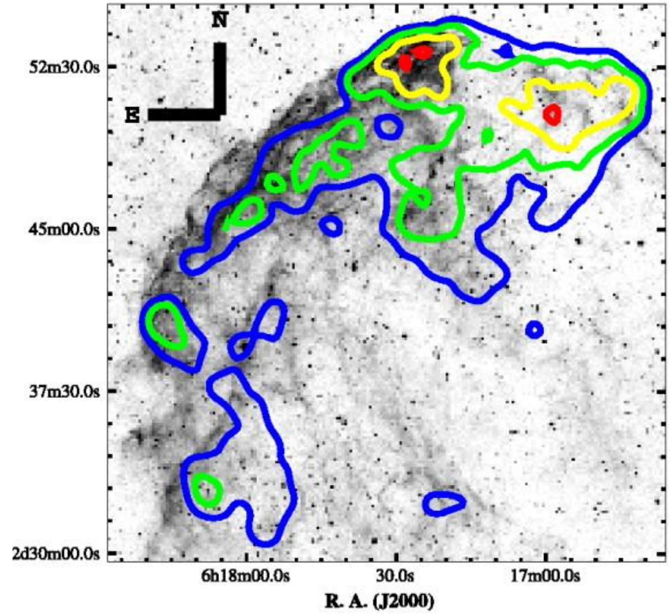
Mixed-Morphology SNR (D~1.5 kpc) evolving in a complex environment: dense cloud (n~10^2, see Rho et al 01) at NE, molecular cloud from NW to SE.

X-ray observation analyzed by Troja et al. (2006)

0.3-1.4 keV



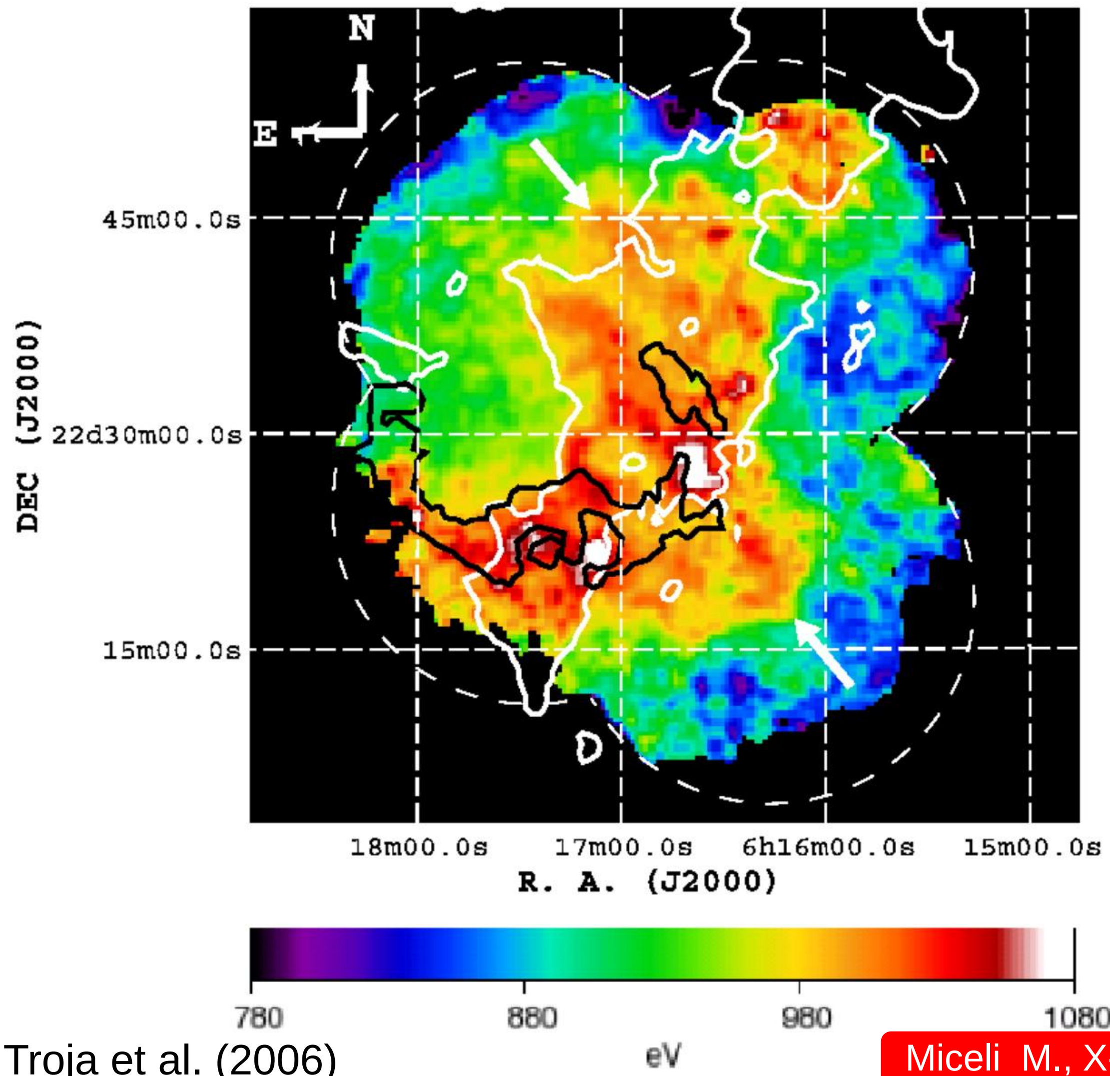
Hα + 0.3-0.5 keV contours



Troja et al. (2006)

IC 443 (atomic and molecular clouds)

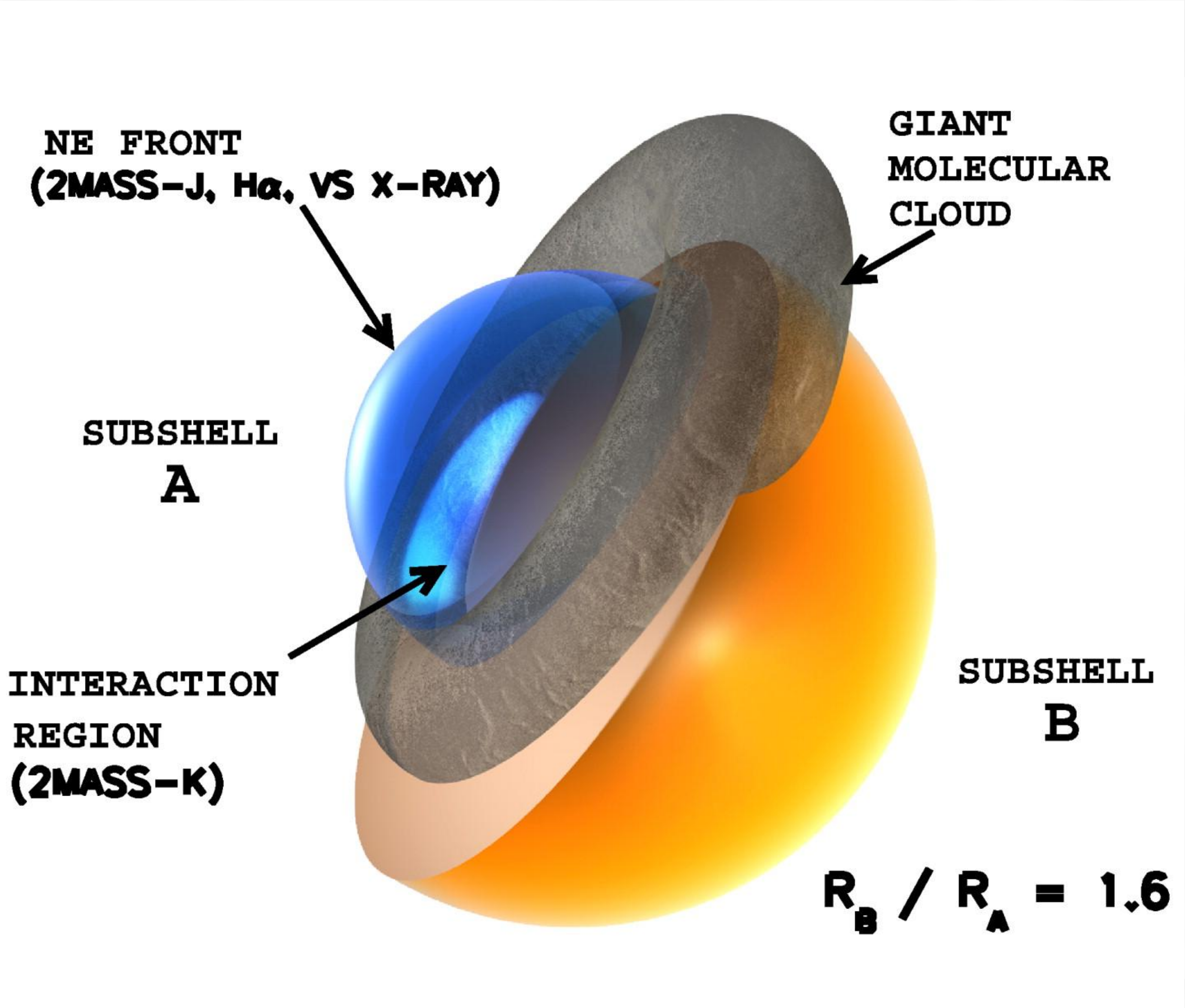
Median energy (0.3-1.4 keV) = tracer of absorption
Quiscent CO (white) Interacting H_2 (black)



- Image analysis
  The cloud is in front of IC443
- Spectral analysis
  The density increases at NE

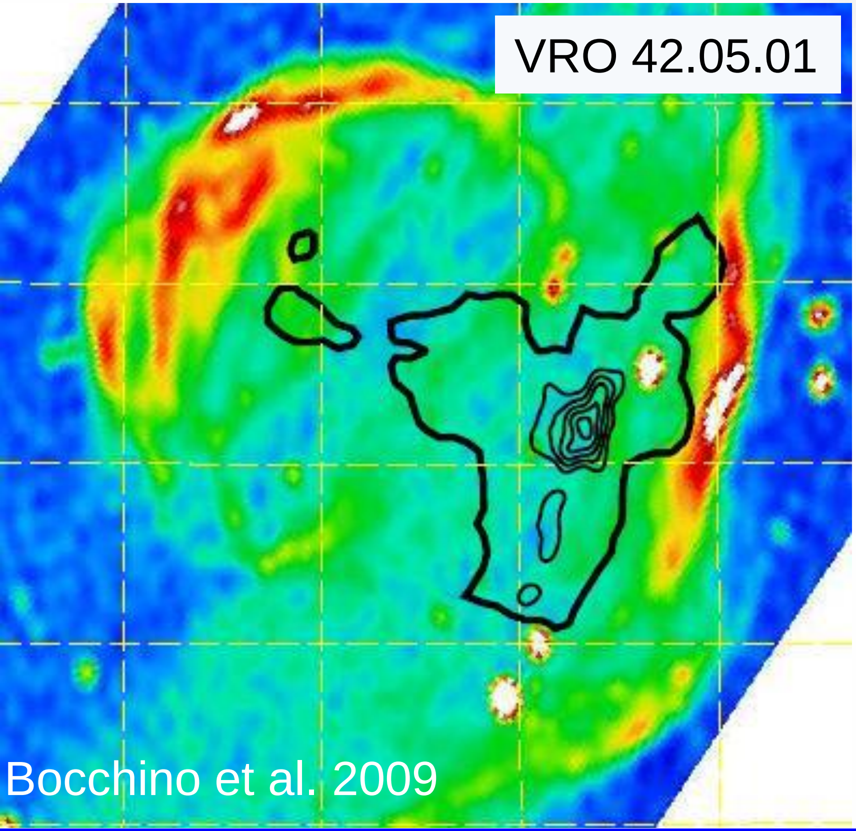
Troja et al. (2006)

IC 443 (atomic and molecular clouds)



Mixed-morphology SNRs

MM SNR (Rho & Petre 98): **radio shell**, **centrally-peaked thermal X-rays** with flat T profile. All MM SNR interact with dense clouds. All the models proposed associate the whole X-ray emission with the **ISM**



1420 MHz radio image with X-ray contour (0.3-5 keV)

Lazendic and Slane 2006 report a list of 26 MMSNRS, **10 of which show enhanced metal abundances**. X-ray emitting ejecta have also been observed in the MMSNRs IC 443 (Troja et al. 2008) and **VRO 42.05.01** (Bocchino et al. 2009).

Current models are not valid for this metal-rich subclass, since they do not account for the ejecta. **Contribution of the reflected shock on the ejecta?**

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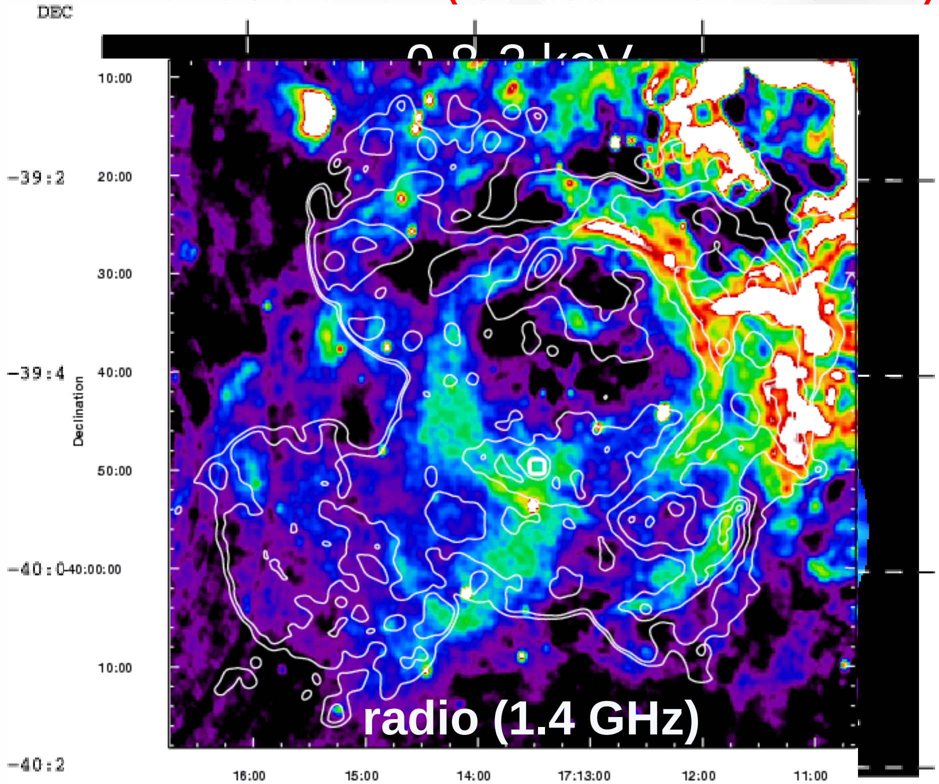
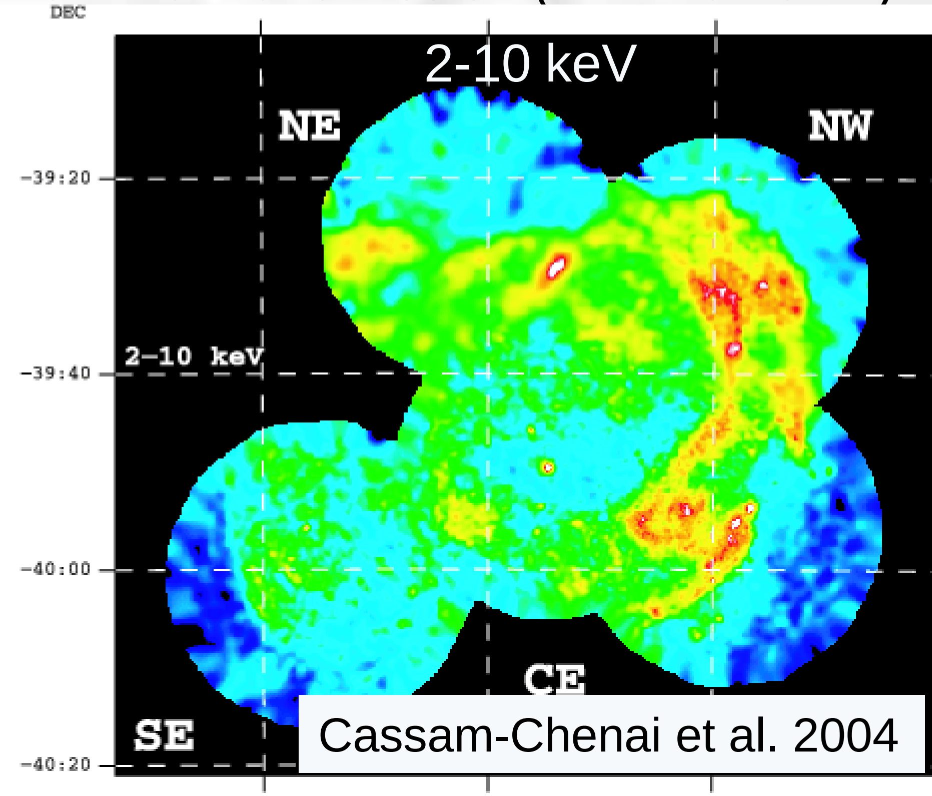
RX J1713.7-3946

Shell-type, young SNR (remnant of AD393? D~1kpc) interacting with a MC in the NW and SE (Fukui et al. 03, Cassam-Chenai et al. 04, Moriguchi et al.05)
XMM observation (Cassam-Chenai 04): non-thermal emission ($n<2\times10^{-2}$ cm^{-3})





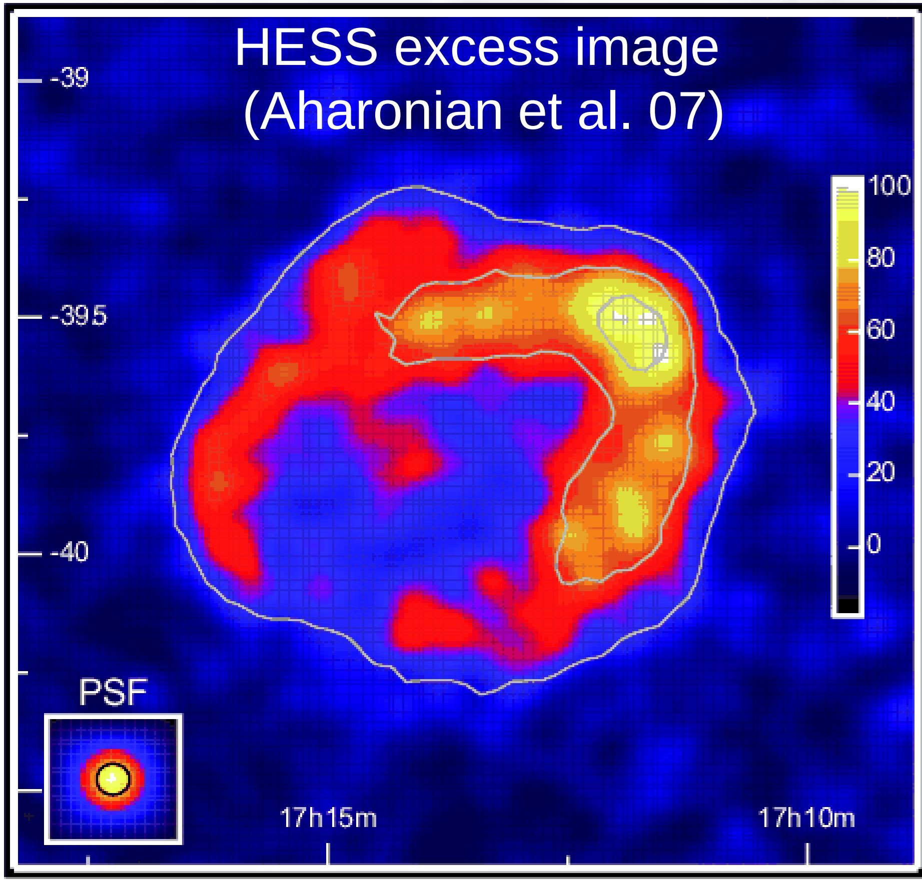
Cassam-Chenai et al. 2004

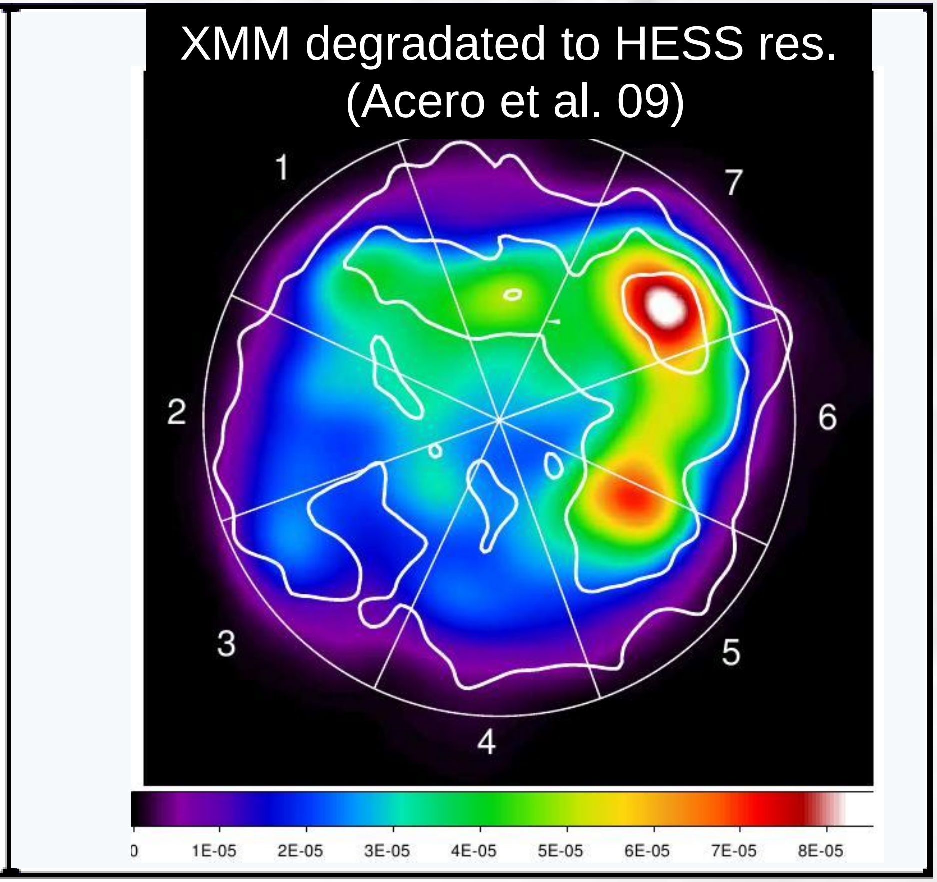
The X-ray non-thermal emission is brighter in the interaction region

Where the shock propagates through the cloud the spectrum is steeper (Γ~2.3-2.7) than where it propagates in a low-density medium (Γ~1.9-2.2)

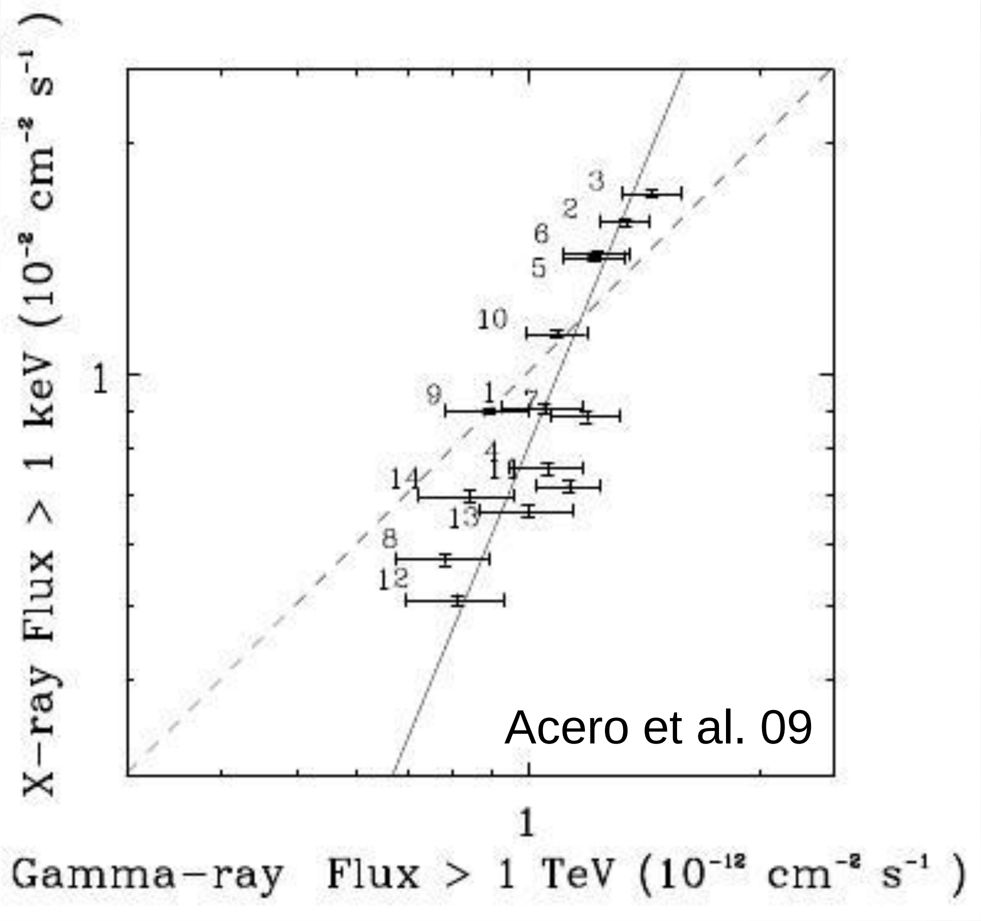
RX J1713.7-3946

Comparison between X-rays and. Γ-rays (Acero et al. 09, Aharonian et al. 07)





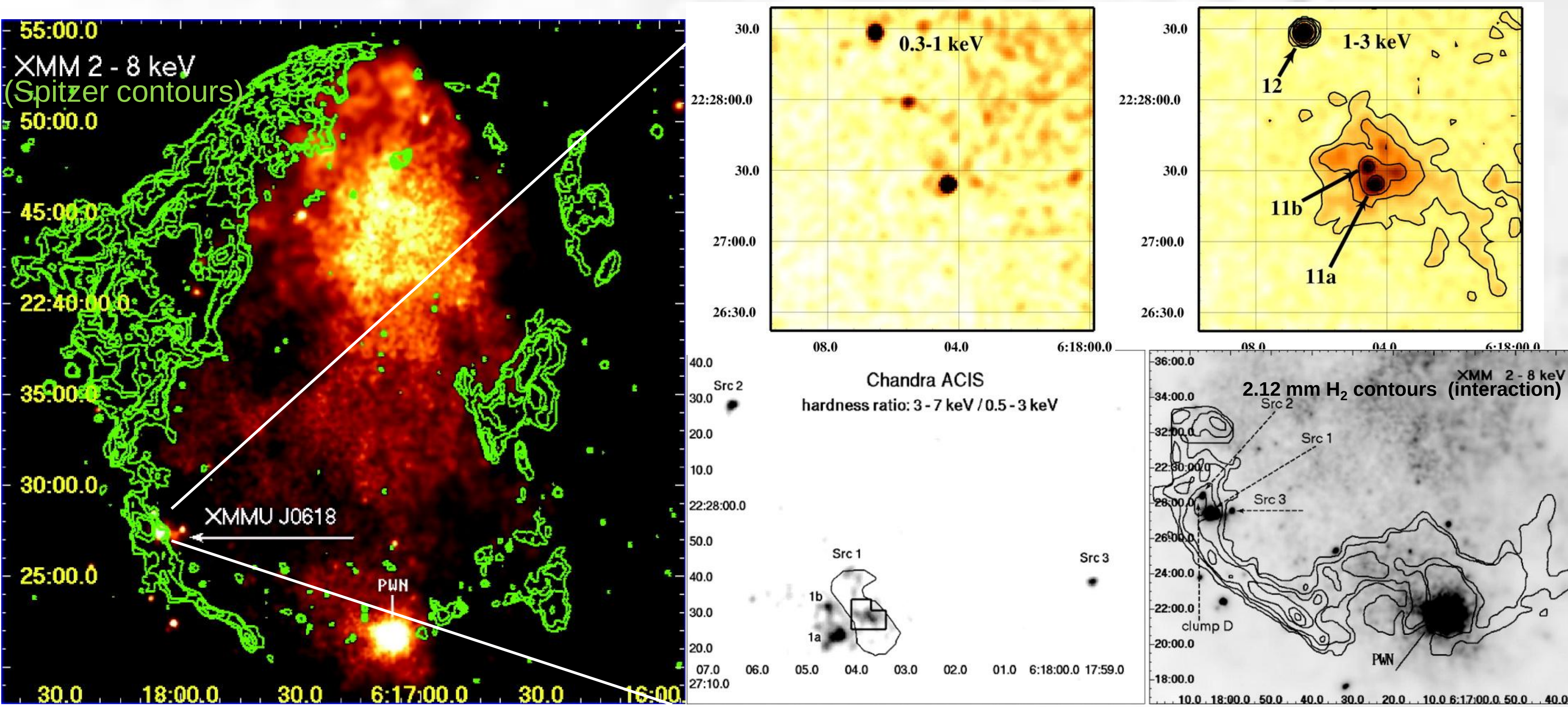
RX J1713.7-3946



Non-linear correlation between X-ray and Γ-ray fluxes

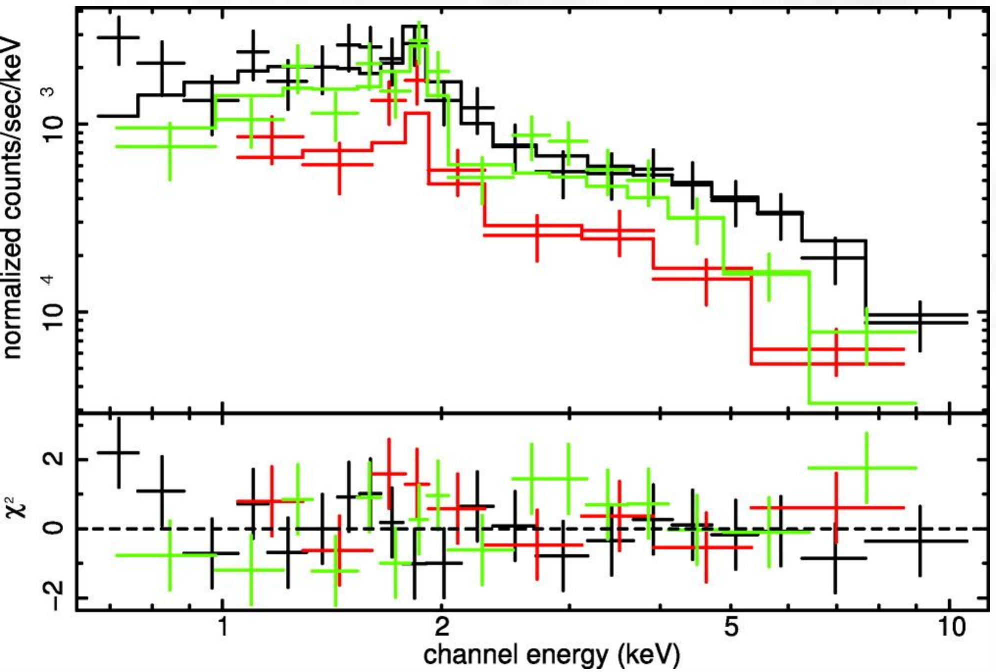
IC 443 (fast moving knots)

Bykov et al. (2005, 2008) identified X-ray emission from fast-moving knots

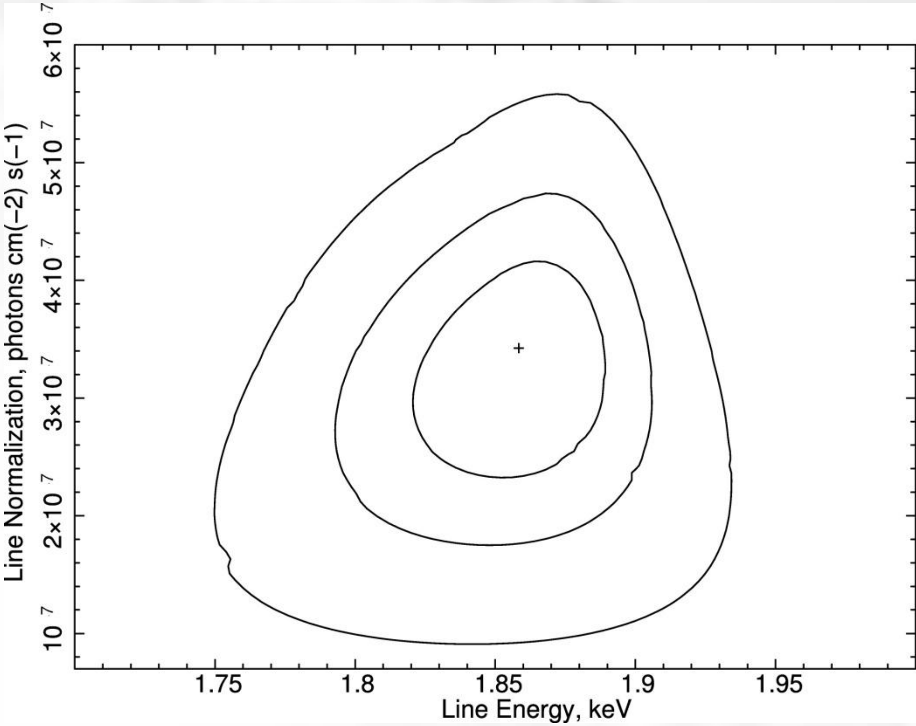


Near IR emission is observed in the knot region (as expected from radiative shocks propagating in a dense environment (Bykov et al. 2008)

IC 443 (fast moving knots)



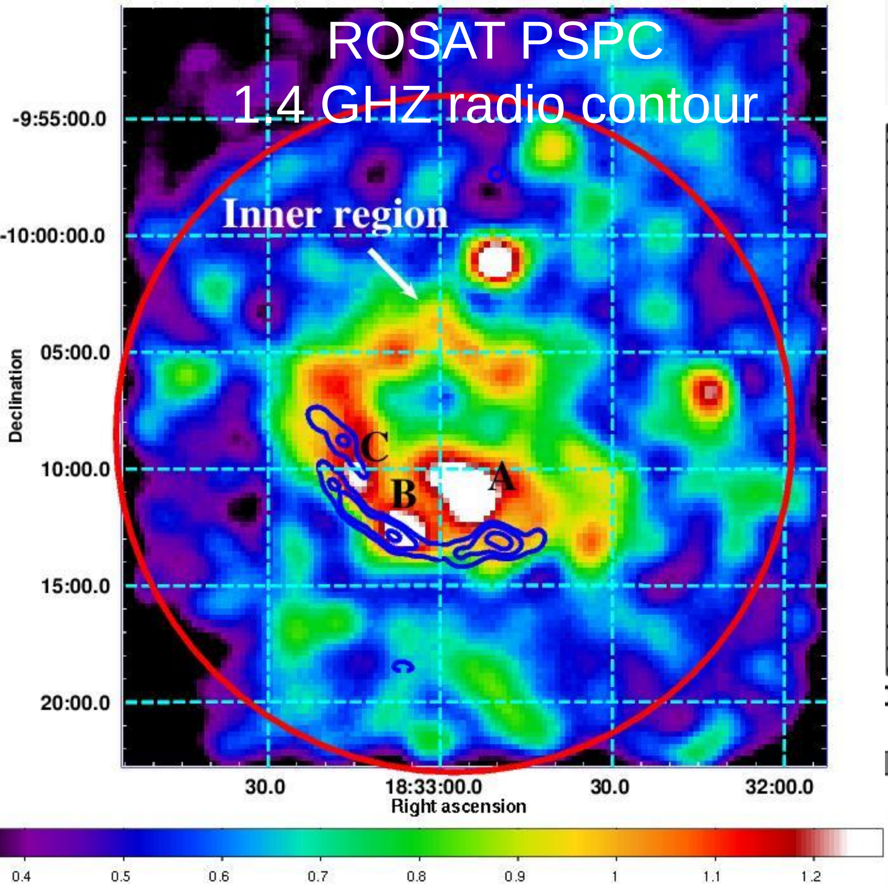
Bykov et al. 2008



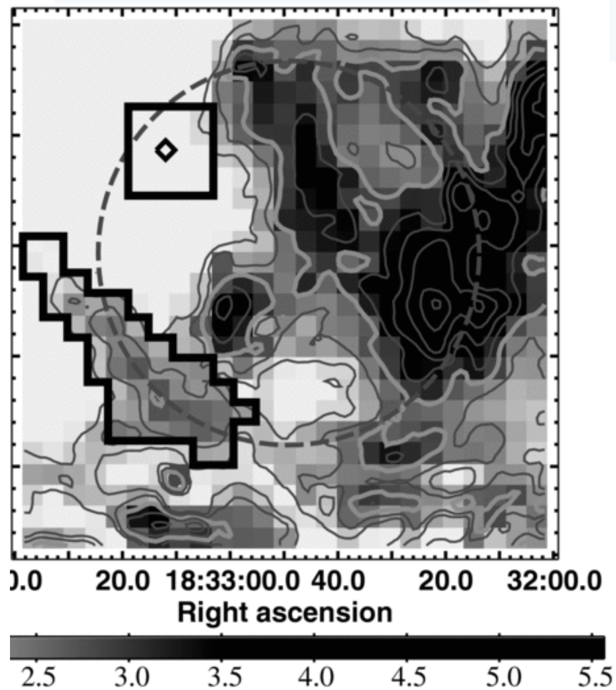
The spectrum is composed by hard non-thermal emission (Γ~1.1) + Si line (at 99% confidence level). X-ray flux and spectral properties in agreement with predictions for a knot of 0.2 pc size, M=0.01 $M_{\odot}$, travelling at 500 km/s through a medium with density ~100 cm^{-3}

Kes 69 (fast moving knots?)

MM-SNR interacting with a MC (Zhou et al. 09)



CO (80-81 km/s)



Zhou et al. 09

Spitzer IRAC

Reach et al. 08

New XMM-Newton data are arriving…stay tuned!

Conclusions

Thermal X-ray emission

- Soft X-rays: (transmitted shock): **physical condition in the MC** (cloud-shock velocity, post-shock temperature, density)

- Hard X-rays: (reflected shock): physical conditions in the **ISM** (temperature, density) and in the **ejecta** (T, n, synthesized abundances)

Non-thermal X-ray emission

- Shock in dense clouds: trace the **interaction region**, study effects of **DSA**

- Fast-moving knots: spatial distribution of **ejecta**, abundances, observation of the high-velocity tail of the ejected knots (important for dynamics of the SN explosion)