X-raying Supernova Remnants in the Magellanic Clouds

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CEA Saclay - IRFU/SAp

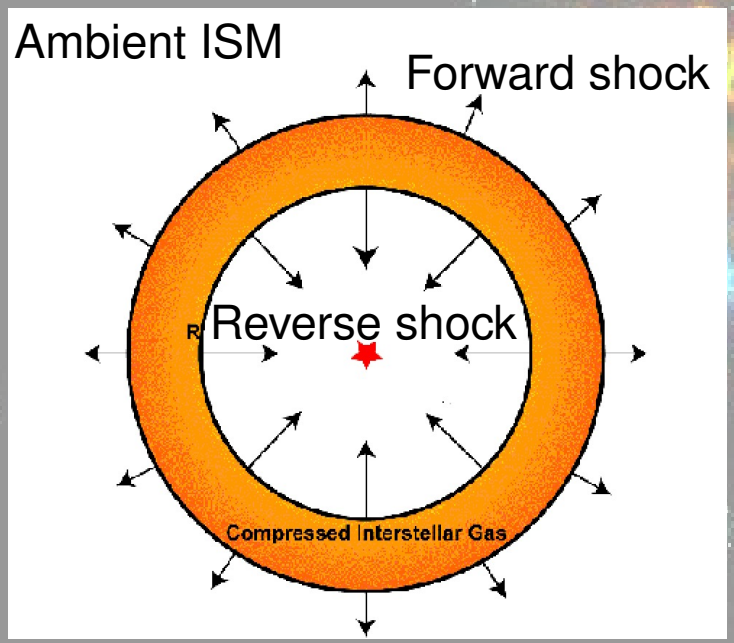
Post-doc seminar, 8 December 2015

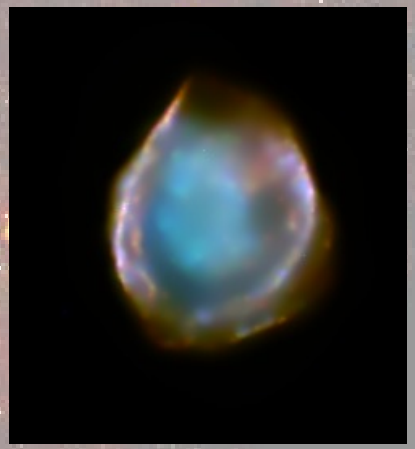
- Undergraduate studies in Strasbourg (Master's degree at the Observatory).
- PhD at the Max Planck Institute for extraterrestrial Physics (MPE), Garching.
- Since April 2015 in SAp @ CEA Saclay with a CNES post-doctoral grant.
  ↪ In LEPCHE, SNR group (Jean Ballet). **Room 22**

1. Introduction
   - Supernova Remnants and Astrophysical Relevance
   - The Magellanic Clouds as Ideal Laboratories
2. The SNR population of the LMC
3. SMC SNRs
4. The most evolved type Ia SNRs
5. Other projects

Two types of supernovae

- Type Ia (or thermonuclear) SNe :
  - Explosion of a white dwarf (accreting or merger)
  - associated with old population, $N_{\rm Ia} \propto$ stellar mass
  - "delay" of several 10^8 yr to 10^{10} yr
  - produce mostly Fe (+ Si, S, . . .)
- Core-collapse (CC) SNe :
  - Explosion of a massive star ($M_{\rm MS} \gtrsim 8\ M_\odot$)
  - associated with recent star formation, $N_{\rm CC} \propto$ SFR
  - short-lived (< 40 Myr)
  - produce mostly O (+ Ne, Mg, Si)



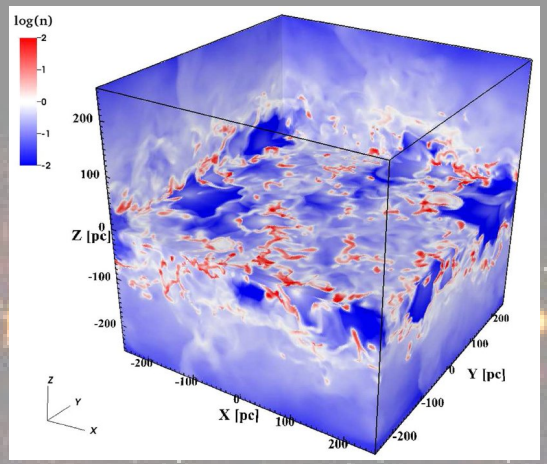


DEM L71, an SNR in the LMC
(Chandra SNR catalog)

Impact on the interstellar medium

↦ Dominant source of energy and turbulence in the ISM (Mac Low & Klessen 2004)

- Creating large structures (up to kpc, Chu 2008)
- Essential part of stellar feedback in galaxy evolution models (e.g. Henriques+2013)
- Drive chemical enrichment in galaxies and intra-cluster gas (Yates+2013, Kapferer+2006)

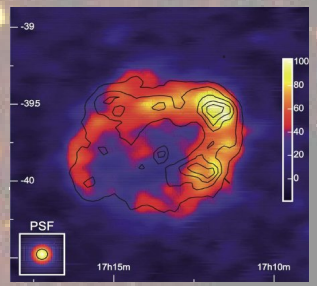


3D simulations of ISM including SN feedback (Kim+2013)

Accelerators of cosmic rays

↦ Compelling evidence that Galactic CRs are accelerated at SNR shock fronts

- 10-20% of SN energy into CRs

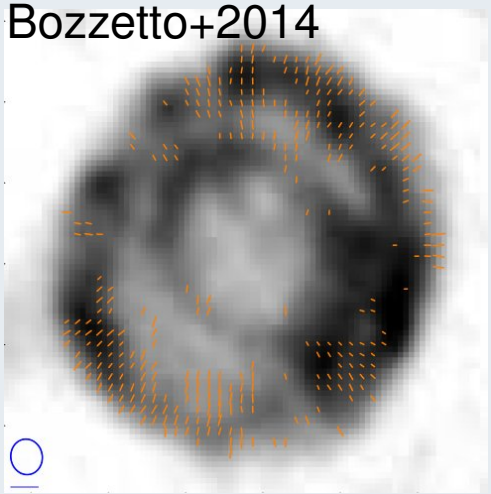


SNR RX J1713.7-3946 in TeV (Aharonian+2007)

⇒ SNRs allows us to probe the SN explosions, the origin of cosmic rays, the ISM (abundance/density) and the star formation cycle

Radio emission

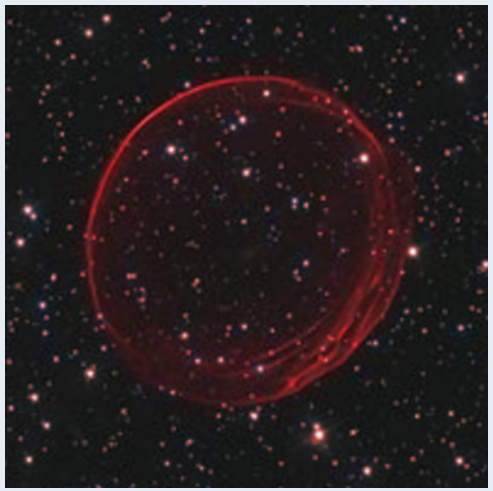
- Synchrotron from relativistic electrons
- non-thermal spectrum
- polarisation



SNR J0509-6731 at 6 cm

Optical

- No continuum, only lines
- shock excitation
- kinematics



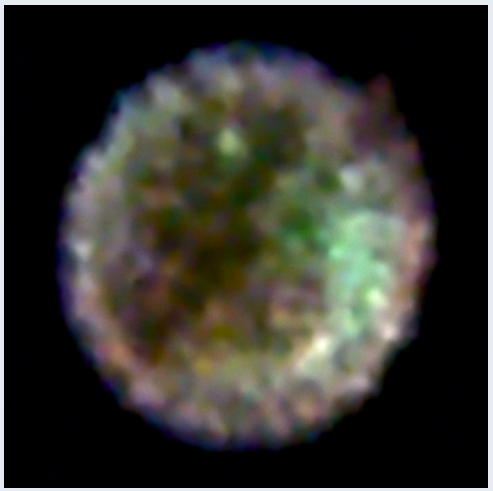
Hα with *Hubble*

X-ray

$kT_s \propto v_s^2 \sim$ keV

- mostly metal lines
- excellent diagnostic:

$\hookrightarrow$ age, ISM density, Z



X-rays with *Chandra*

+ Infrared (lines, **dust**), UV (cooling lines)

300 Galactic SNRs (Green 2014)

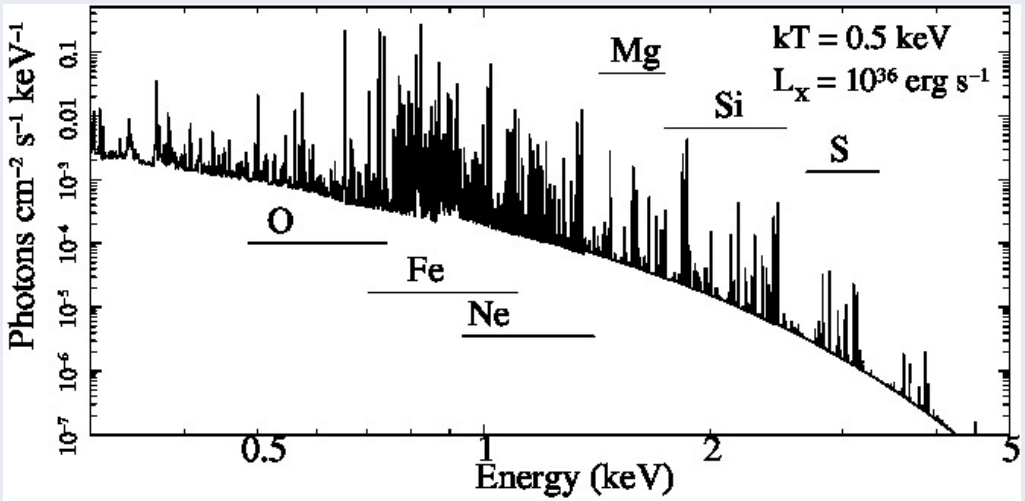
- Distance uncertainties
- Line-of-sight confusion/crowding
- Absorption/reddening

	MW	MCs
Distance	☒	✓
Multi-λ coverage	✓	✓
Absorption N_H	$\gtrsim 10^{22}$ cm^{-2}	$\lesssim$ few 10^{21} cm^{-2}

LMC and SMC

Nearest star-forming galaxies
(50 & 60 kpc)
Out of Galactic plane

↦ Ideal for population studies



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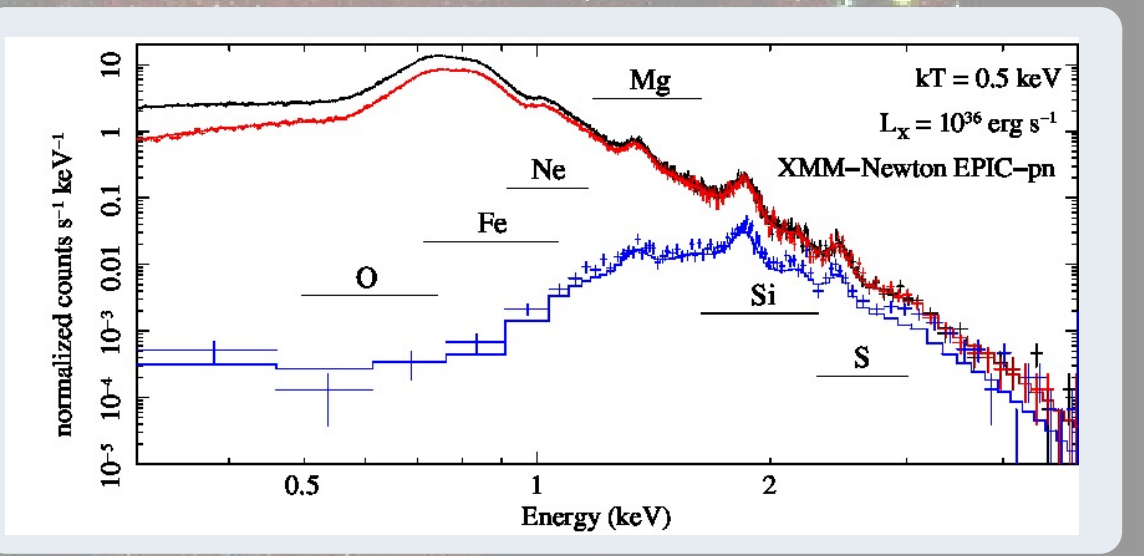
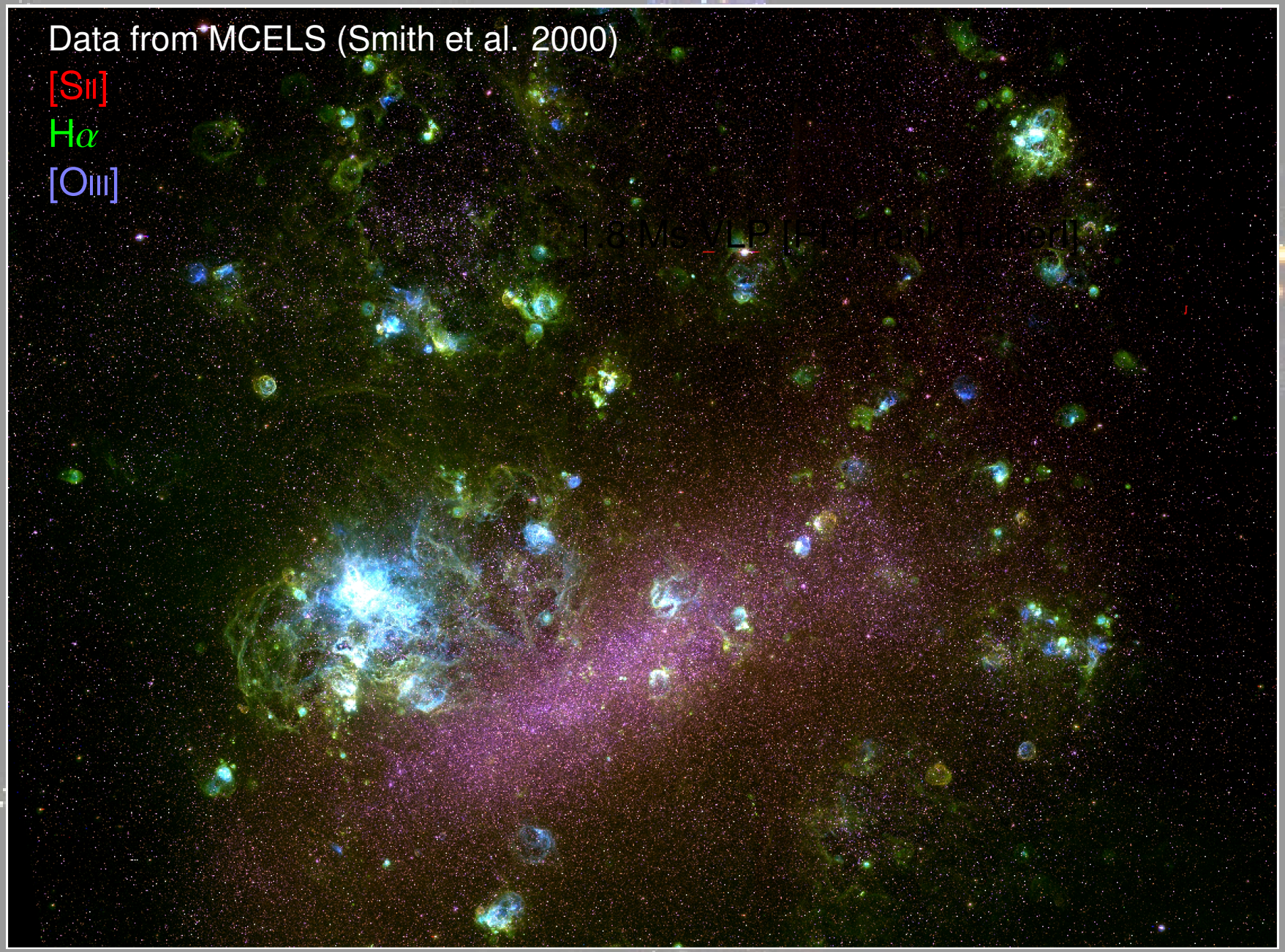


1. Introduction
2. The SNR population of the LMC
   - The XMM-Newton survey of the LMC
   - Global Spectral Analysis
   - Measuring the ratio of CC to type Ia SNe in the LMC
   - "3D Distribution"
3. SMC SNRs
4. The most evolved type Ia SNRs
5. Other projects


Data from MCELS (Smith et al. 2000)
[SII]
Hα
[OIII]

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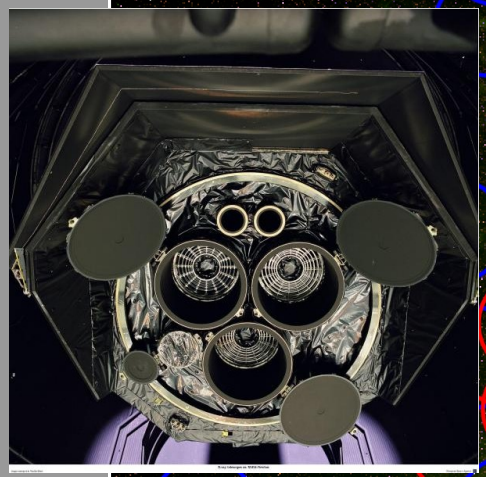
[SII]

Hα

[OIII]

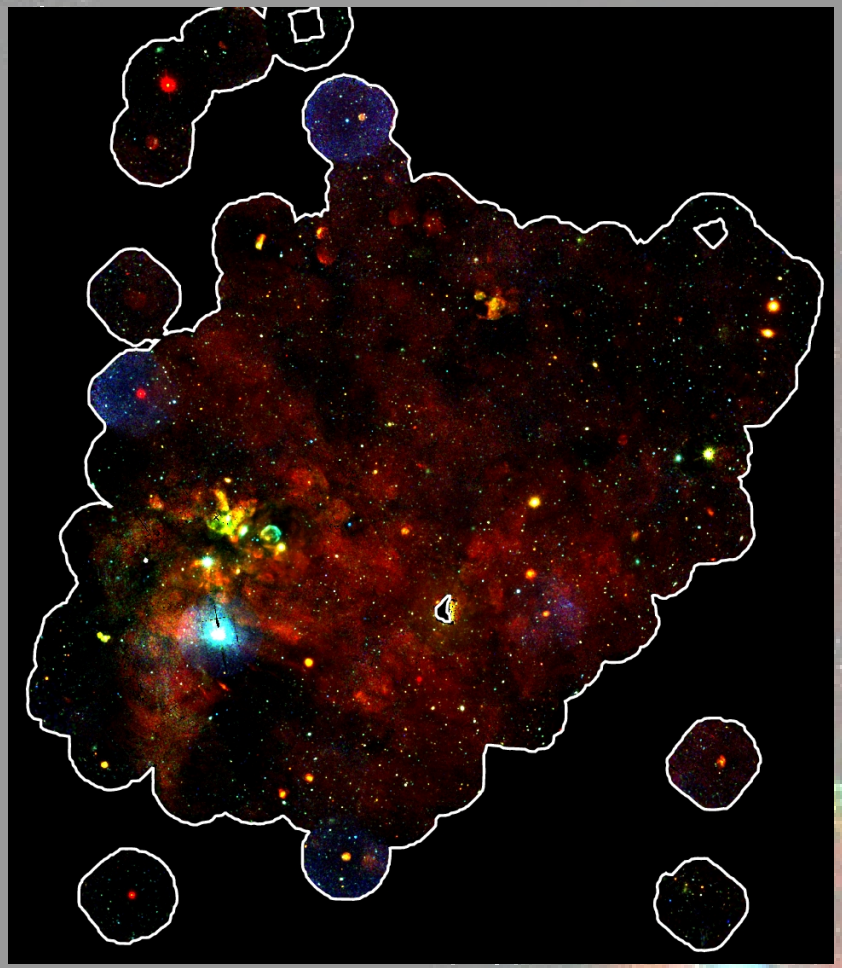


1.8 Ms VLP [PI: Frank Haberl]

N

30'

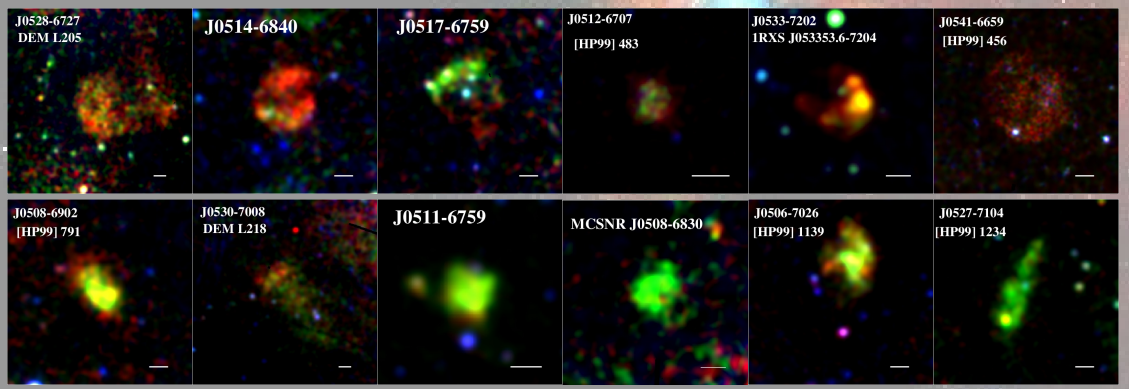
E



0.2 – 1 keV
1 – 2 keV
2 – 4.5 keV

59 CONFIRMED SNRs

- 12 new with our XMM programmes
- 6 serendipitously in the survey
- 51 covered by XMM

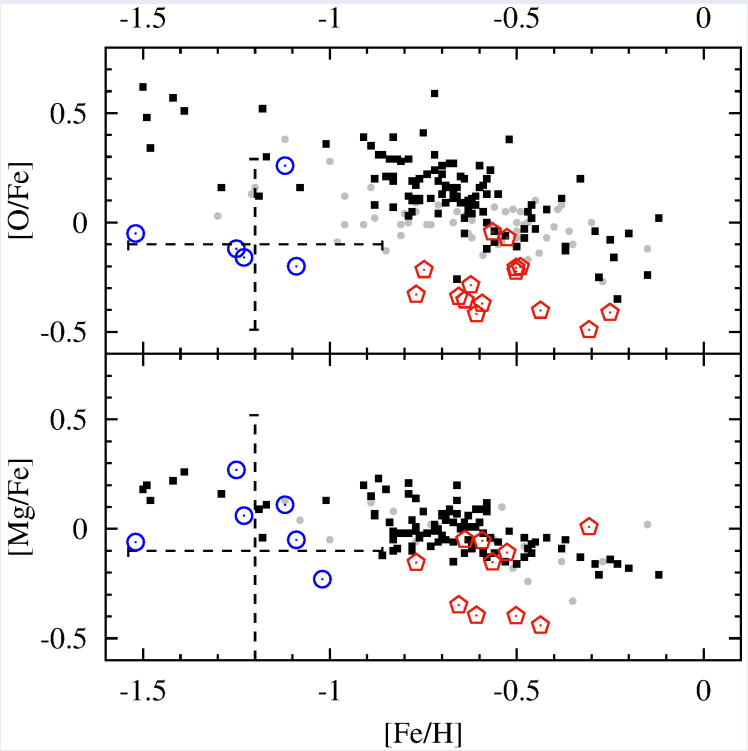


Grondin+2012
de Horta+2012
Maggi+2012, 2014
Bozzetto+2014
Kavanagh+2013, 2015

First homogeneous global analysis of the X-ray spectral properties of LMC SNRs

51/59 LMC SNRs observed with XMM-Newton ↦ all spectra are analysed

- Catalogue of spectral parameters (± associated uncertainties)
- Complete census of SNRs with : ▸ Fe K emission ▸ SN ejecta emission



Dots: Red giants; Globular clusters
SNRs (Maggi+2015)

LMC abundances measured with SNRs

- ▸ Metallicity between 0.2 and 0.5 solar
- ▸ Lower [O/Fe] (by 0.15 dex) compared to *ASCA* SNRs (Hughes et al. 1998)

↪ SN ejecta contamination ?

Chemical enrichment history

- ▸ Higher metallicity, lower [α/Fe] than older populations

How to type all the sample ?

- Typing methods are limited to relatively young, bright remnants
  - ↦ More than half unknown

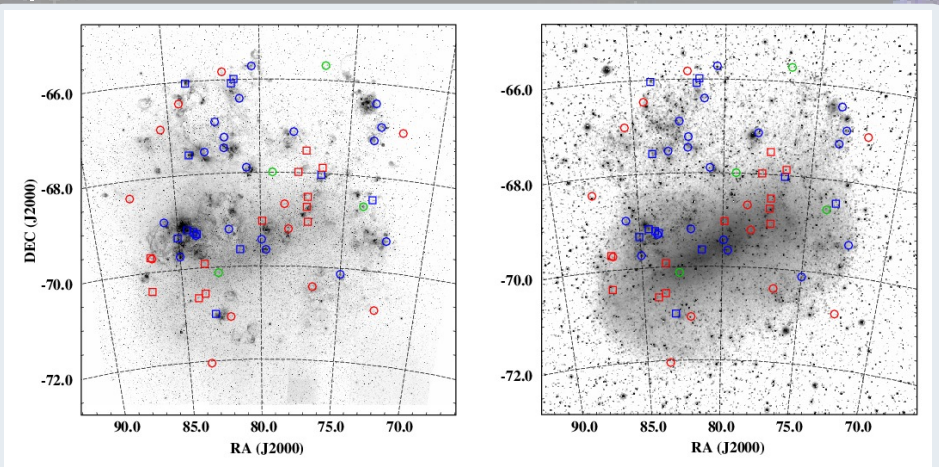
⇒ Tentative typing of the whole sample based on the **local stellar environment**

N_{CC}/N_{Ia} is 1.47 (1.2–1.8) based on star formation, or 1.35 (1.1–1.5) including spectral results (SN ejecta/pulsars)

Method	N_{CC}/N_{Ia}	Ref.
LMC SNRs	1.1–1.5	this work
Local SNe	3	Li+2011
Abundances	3.5 (2–4)	Sato+2007
in galaxy	1.7–3.5	de Plaa+2007
clusters	1.5–3	Lovisari+2011

More type Ia SNe in the LMC ?

- Unlikely biased either way
  - ↦ Specific SFH of the LMC (bursts 0.5 and 2 Gyr ago)
  - \+ Timescale of type Ia SNe (the majority explodes within 2 Gyr)

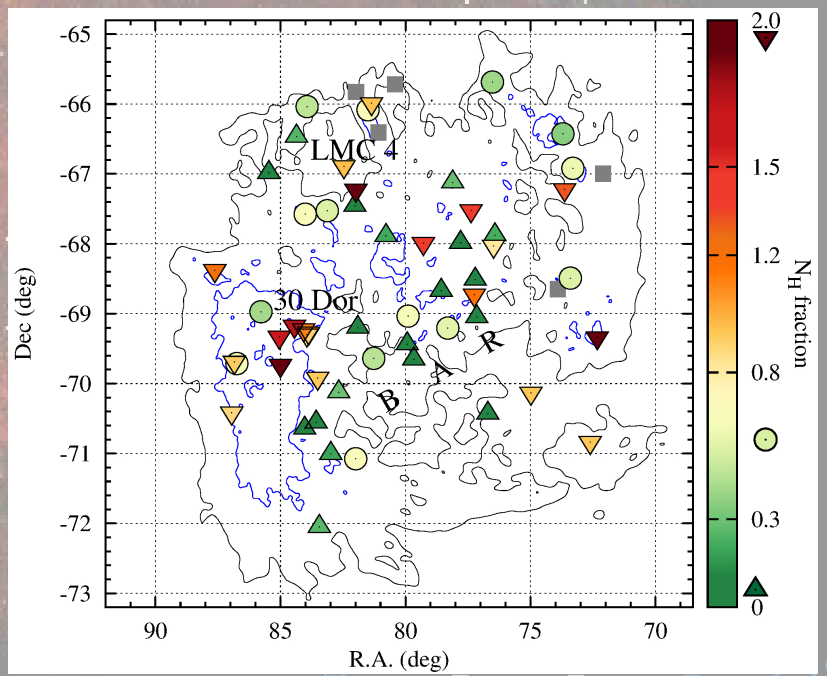


Type Ia and CC SNRs compared to Hα (left), and red continuum (right); from Maggi+2015

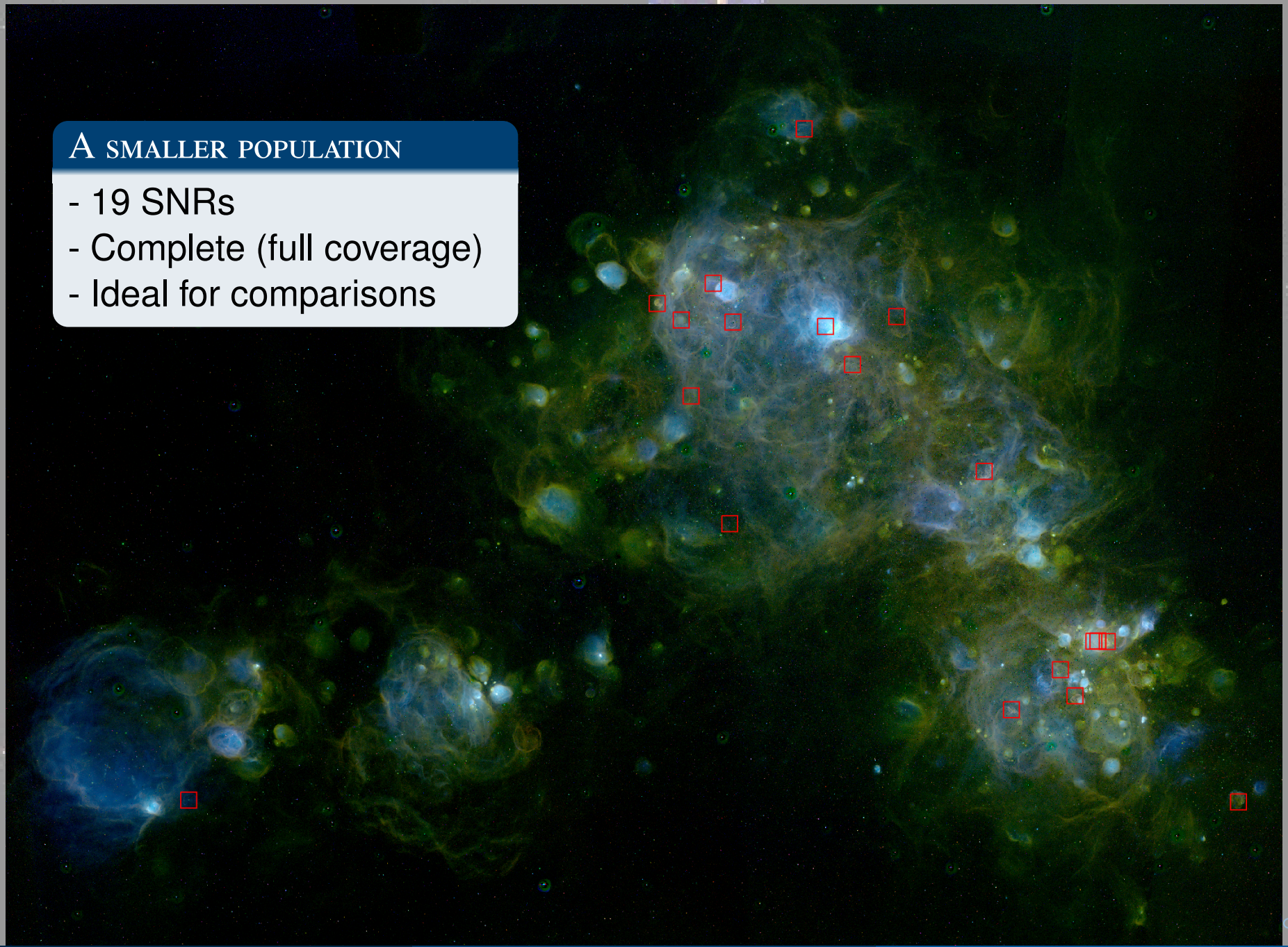
Spatial correlation with:

- Sites of star formations (giant H II regions), edges of supergiant shells (e.g. LMC4)
  $\mapsto$ CC SNRs
- High stellar densities, or "empty" regions
  $\mapsto$ type Ia SNRs

$N_H^X / N_H^{21\,\mathrm{cm}}$ (right) gives the line-of-sight position relative to the main gas disc



- **SNRs in the Bar** are (almost) all in front of the disc : $\mapsto$ Supports the (challenged) findings that the Bar is indeed "floating" in front of the disc
- **SNRs in 30 Dor** are behind: $\mapsto$ Confirms that 30 Dor is on the far side of the LMC
- **Highly absorbed:** molecular material



A smaller population

- 19 SNRs
- Complete (full coverage)
- Ideal for comparisons

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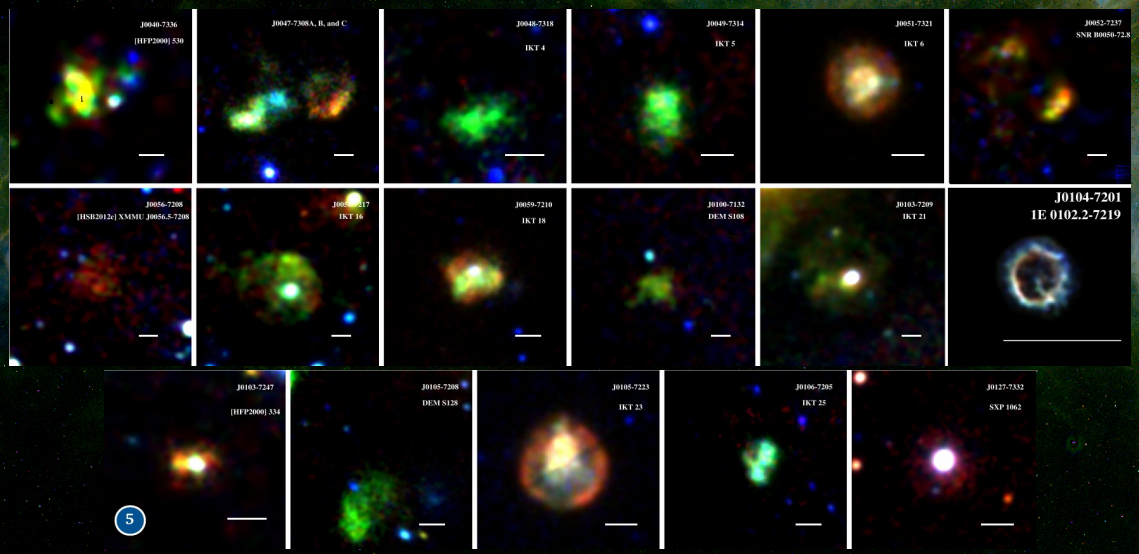
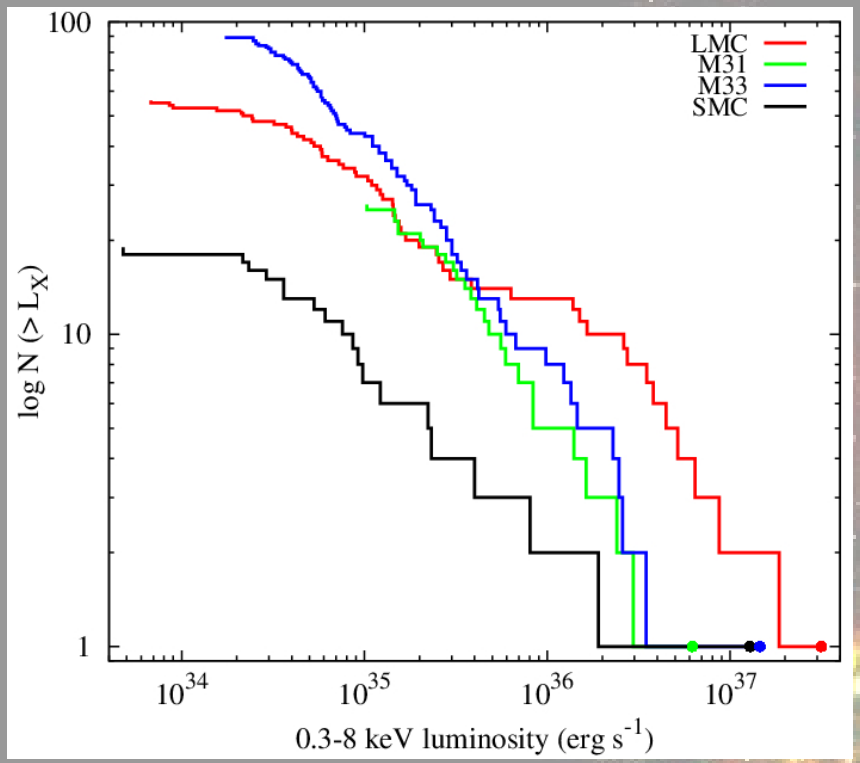




XLF (Maggi+2015)

Main differences:

- **Numbers:**

M33 dominates (better coverage ?)

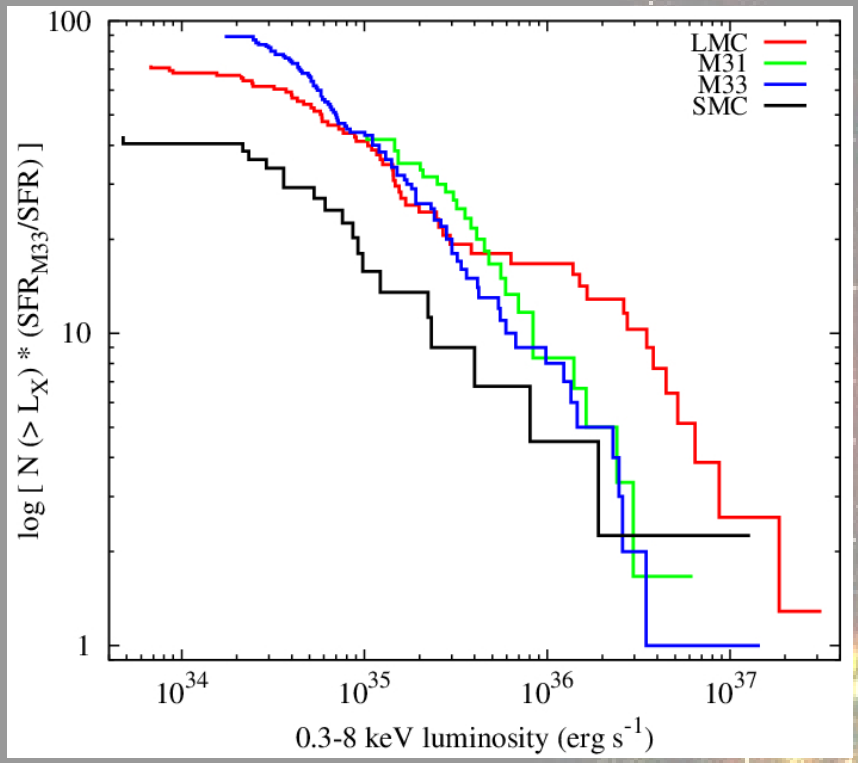
- **Shape:**

M31 ~ M33, SMC flatter

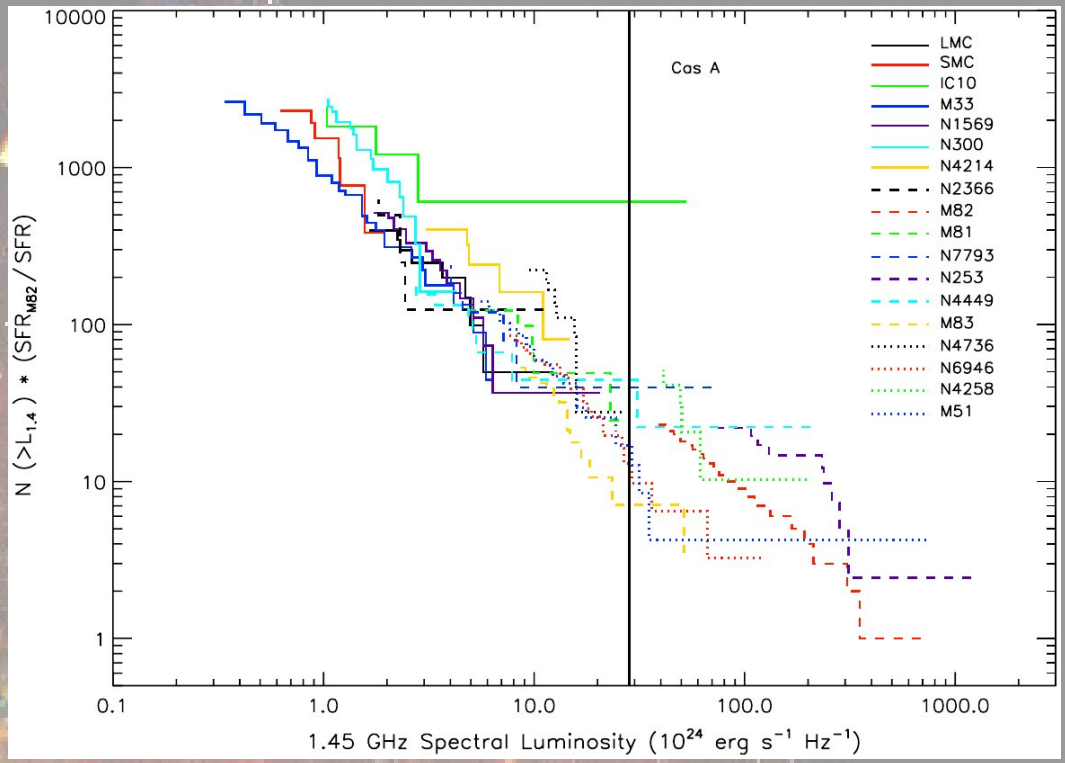
LMC shape is more complex:

Bright tail

Flat faint end (incomplete)



XLF scaled by SFR



radio LF, Chomiuk & Wilcots 2009

Shape differences subsist (particularly in SMC, completeness issue in LMC).
X-ray luminosity function is not universal, unlike **radio** LF
$\mapsto$ effects of metallicity and ISM density

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2 The SNR population of the LMC
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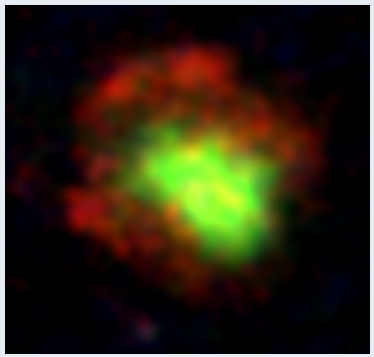
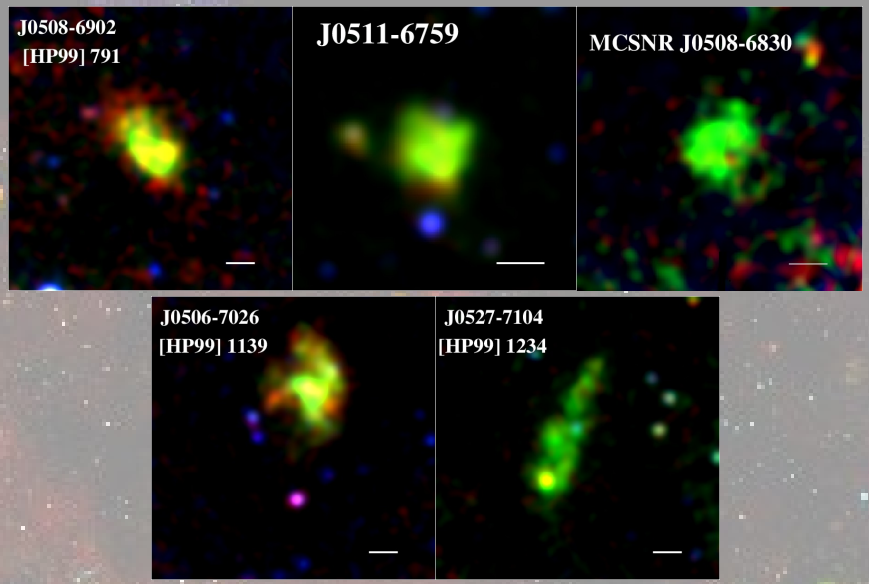
Hot Iron in the Sky
A New Evolutionary Phase
Open Questions and Potential for next instruments
5 Other projects

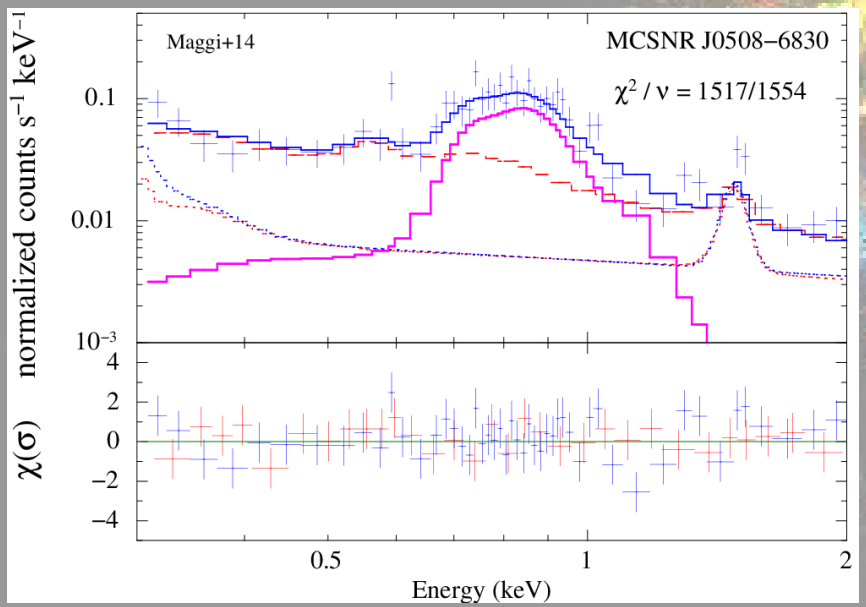
PROTOTYPE: DEM L238 (BORKOWSKI+2006)

- Shell: shocked ISM
- **Iron-rich** core, X-ray bright





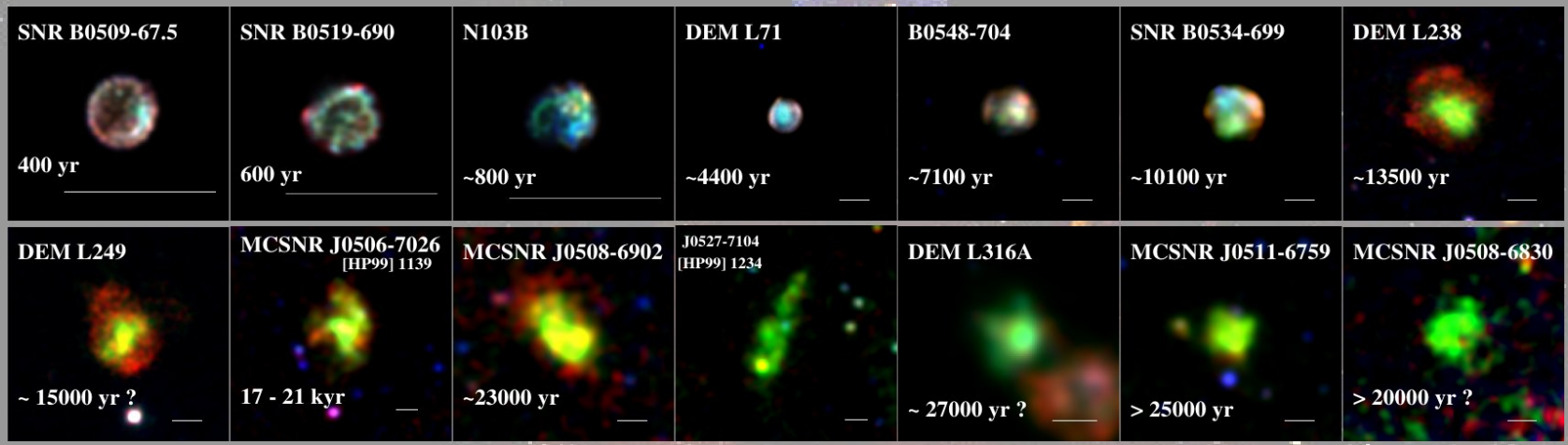
Iron-rich SNRs discovered in Maggi+2014, Bozzetto+2014, Kavanagh+2015

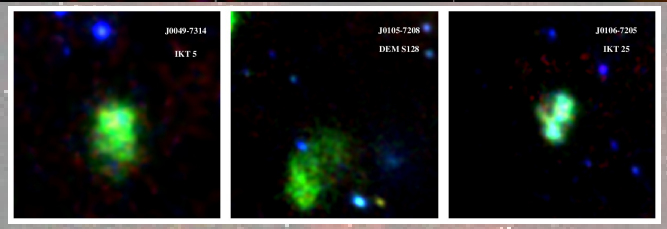


IRON-RICH GAS IN THE INTERIOR

- kT_{Fe} is 0.6 keV – 1 keV
- Inferred M_{Fe} 0.5 to 1.5 $M_\odot$

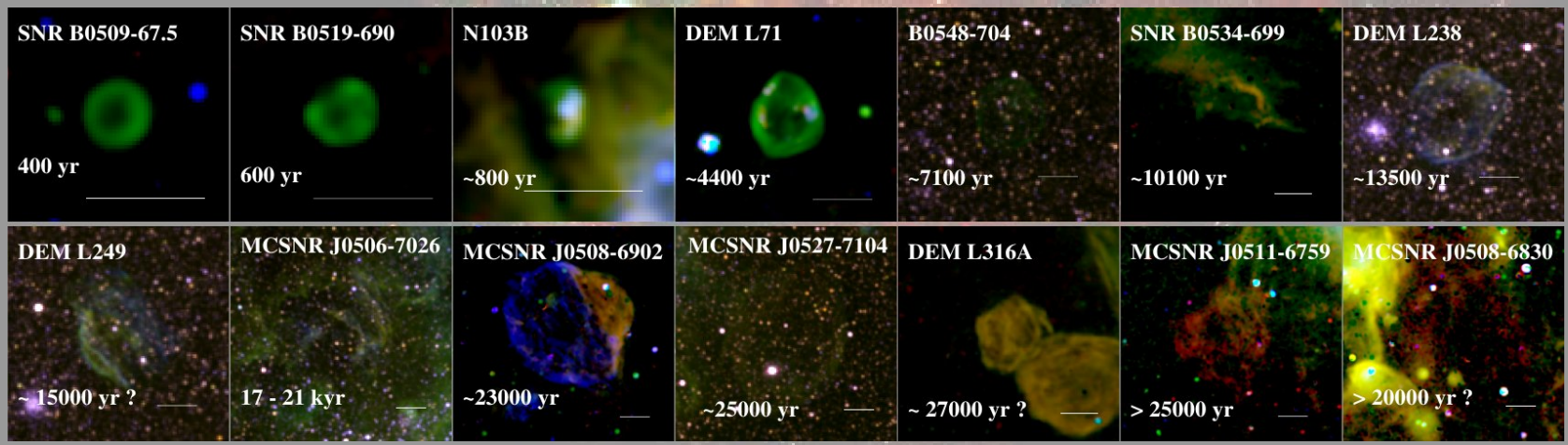
Could NOT be observed in the Galaxy

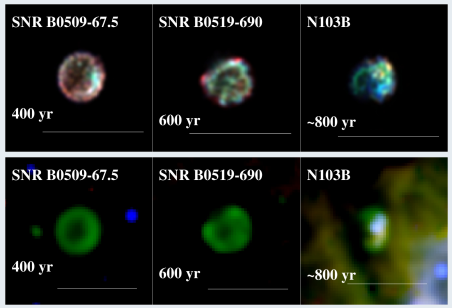




+ Three Fe-rich SNRs in the SMC

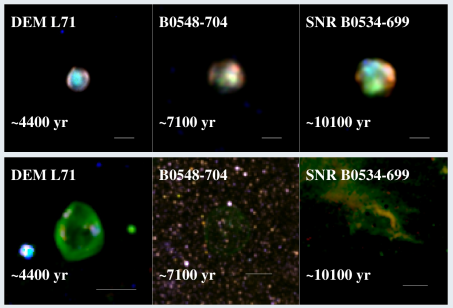
Optical images (MCELS data): [S II] Hα [O III]





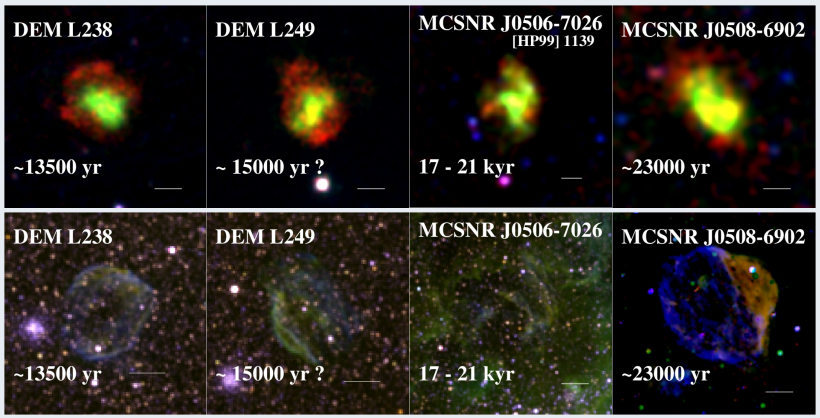
Phase I:

- Ejecta-dominated (X)
- Balmer-dominated (O)
- Lyman-dominated (UV)



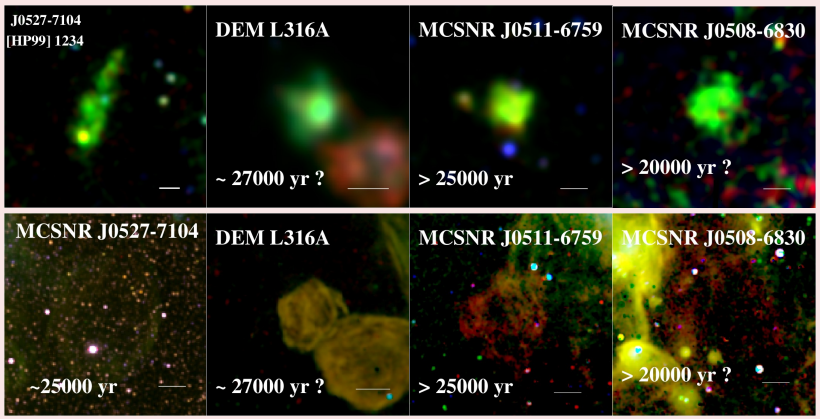
Phase II:

- Early Sedov phase; ejecta + ISM shell (X)
- fading in optical
- little/no UV



Phase III:

- Fading-shell, central iron emission (X)
- Radiative cooling of shell traced by [O III] lines (O) and C III and O VI (UV)

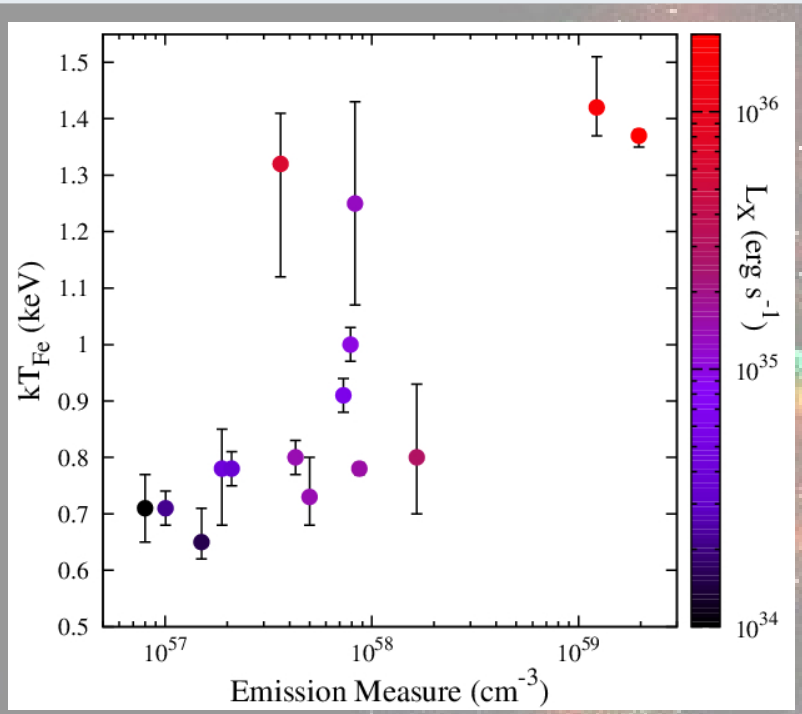


Phase IV:

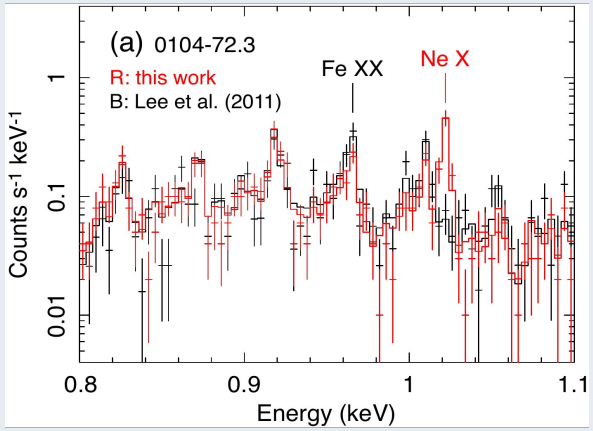
- No shell (too cool), Hot iron cores (X)
- (very) faint "fossil" [S II] lines (O)
- No UV (?)

- Origin of the (asymmetric) morphology of the iron cores ?
- Evolution/fate of the iron cores ?

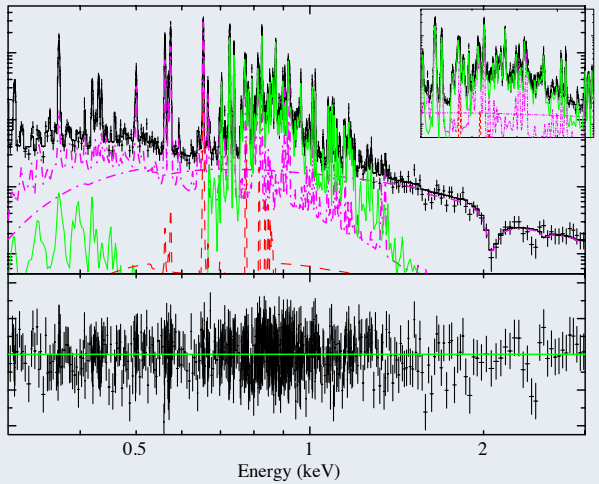
↪ Clues in deeper observations, finding new or missing objects, statistical analysis



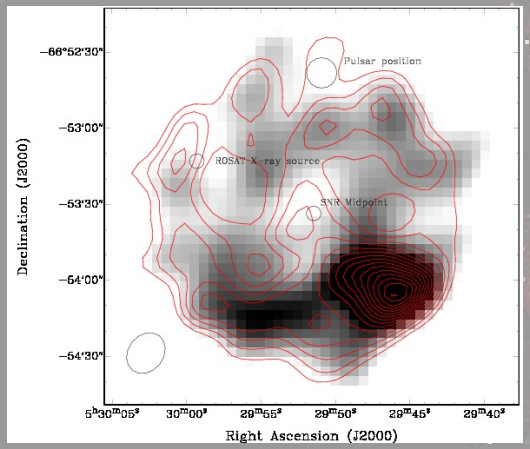
Temperature of the hot iron cores as function of their emission measure $\left(\int n_e n_H dV\right)$.



25 ks simulated **ASTRO-H** observation of a potential Fe-rich SNRs in the SMC (Takeuchi+2015)



20 ks **ATHENA**/X-IFU (MCSNR J0527-7104, Kavanagh+2015)

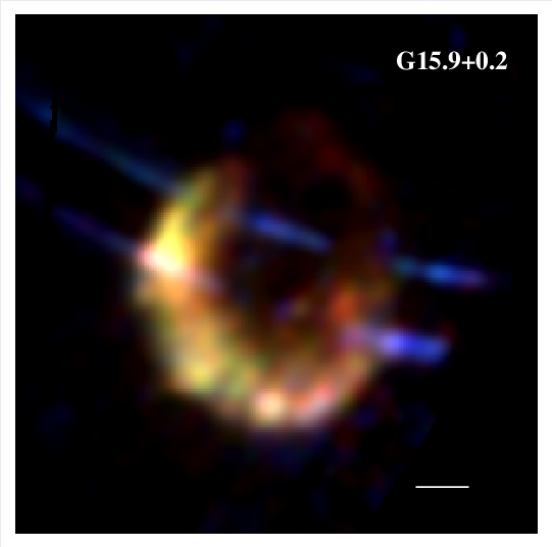


Chandra observations of MCSNR J0529-6653

associated (?) to radio pulsar PSR B0529-66

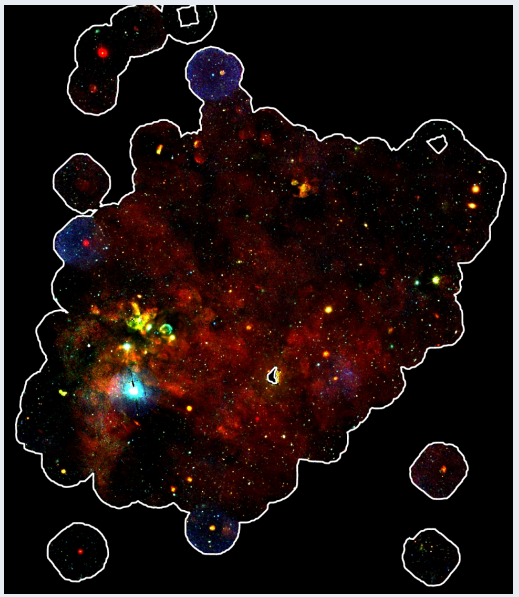
70 ks (GTO) observation in ~~2015~~ 2016

SNR G15.9+0.2



A young, bright Galactic SNRs

Hot Gas in the LMC



Thank you for your attention !

A view of the night sky over La Silla Observatory, Chile