X-raying thermal and non-thermal remnants

The case of Magellanic SNRs, superbubbles, and PWNe

Pierre Maggi
Observatoire Astronomique de Strasbourg
MODE Workshop 2019, Orléans

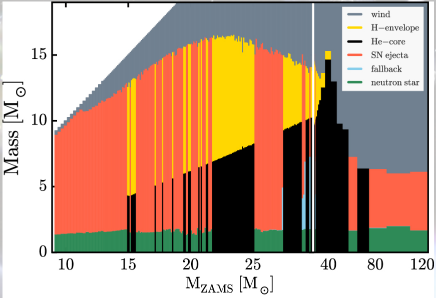
1. Introduction : The Matryoshka dolls of stellar remnants
2. Supernova remnants in the Magellanic Clouds
3. On types and progenitors
4. Non-thermal X-ray stellar remnants

- Type Ia (or thermonuclear) SNe :
  - Explosion of a white dwarf (accreting or merger)
  - associated with old population, “delay” of several 10^8 yr to 10^{10} yr
  - $N_{\mathrm{Ia}} \propto$ stellar mass
  - ⇒ produce mostly Fe

© Mark A. Garlick space-art.co.uk

Accreting or merging WD(s) ?

- Core-collapse (CC) SNe :
  - Explosion of a massive star ($M_{\mathrm{MS}} \gtrsim 8\ M_{\odot}$)
  - associated with recent star formation, short-lived (< 40 Myr)
  - $N_{\mathrm{CC}} \propto$ SFR
  - ⇒ produce mostly O (+ Ne, Mg, Si)



End fate of massive stars (Sukhbold+2016)

$$10^{51}\ \mathrm{erg} \times \text{(a lot of SNe)} = \text{a lot of energy !} \tag{1}$$

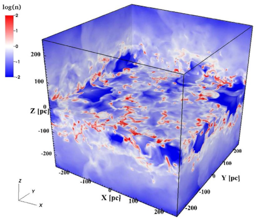
Impact on the interstellar medium

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

▶ Carve large structures (up to kpc, Chu 2008)

▶ Create the hot phase ($T \gtrsim 10^6$K) of the ISM, which dominates by volume

▶ Drive chemical enrichment in galaxies and intra-cluster gas (Kapferer+2006, Yates+2013)

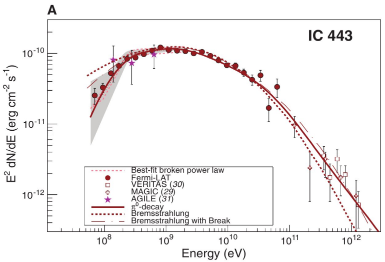


3D simulations of ISM including SN feedback (Kim+2013)

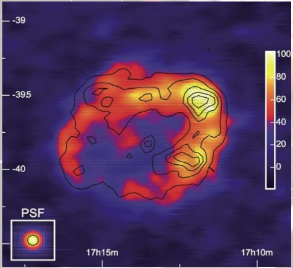
- SN feedback is essential in cosmological models of galaxy evolution (hydrodynamic or semi-analytic, Hopkins+2012, Henriques+2013) to reproduce reasonable galaxy properties.

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

- ▶ 10-20% of SN energy into CRs
- ▶ Diffusive shock acceleration



Spectral signature of π^0-decay (Ackermann+2013)



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

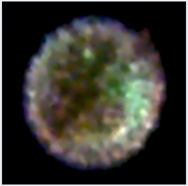
⇒ SNRs allow us to probe the SN explosions, the origin of cosmic rays, the ISM (abundance/density) and the star formation cycle

X-ray

$kT_s \propto v_s^2 \sim \mathrm{keV}$

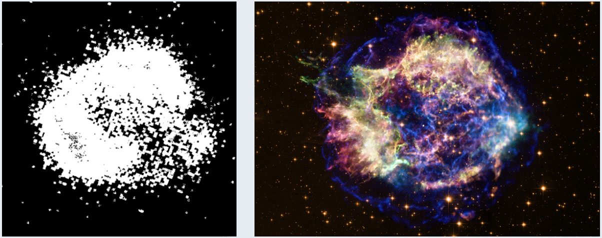
- mostly metal lines
- excellent diagnostic:

$\hookrightarrow$ age, ISM density, Z



X-rays with *Chandra*

The Milky Way is ideal for studies of *invididual* objects



Cas A in X-rays, with Exosat (Peacock 1984) and *Chandra*(NASA/CXC)

The Milky Way is not suited for *population* studies

Large sample (300 SNRs, Green 2014), but:

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

The Magellanic Clouds as Ideal Laboratories

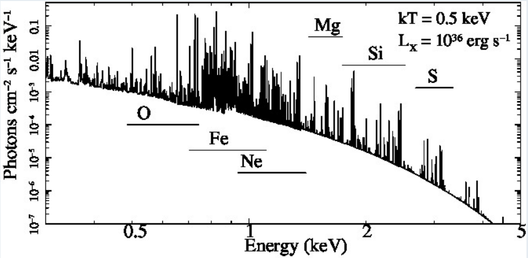
Magellanic Clouds over ALMA

	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



The Magellanic Clouds as Ideal Laboratories

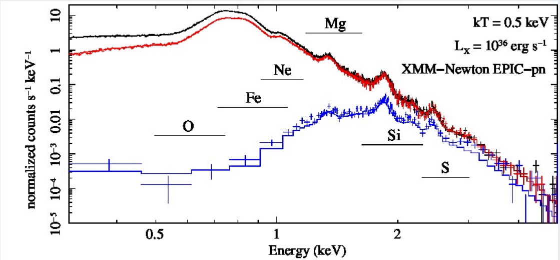

Magellanic Clouds over ALMA

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

LMC and SMC

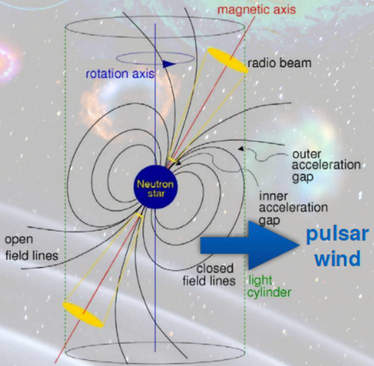
Nearest star-forming galaxies
(50 & 60 kpc)
Out of Galactic plane

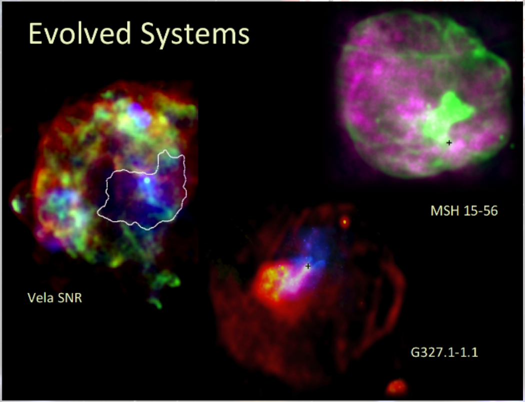
$\mapsto$ Ideal for population studies



PWN : The remnant within a remnant

Bubbles of relativistic particles inflated by pulsar's wind

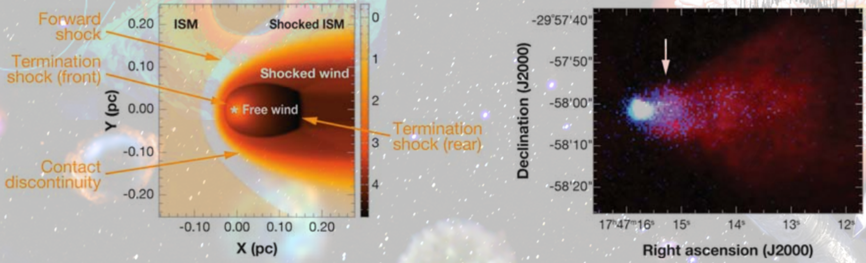




The outer pressure is set by the changing environment.

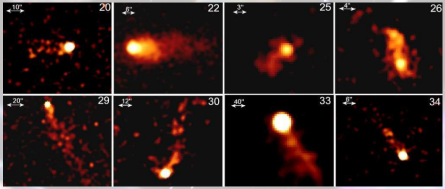
In the Milky Way, about 100 PWN or candidates for ≈ 350 SNRs, 70 with detected pulsars [SNRcat, Ferrand & Safi-Harb 2012].

Pulsars are born with a kick !

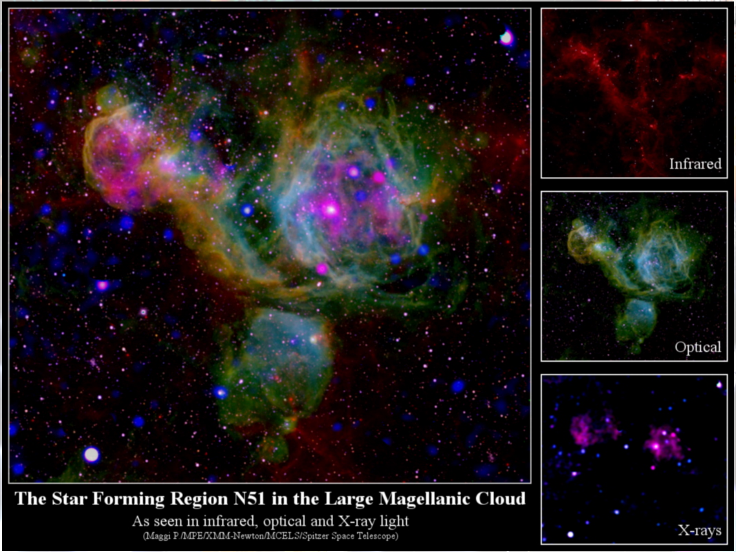


PWN around a supersonic neutron star [Gaensler et al. 2004]

This produces a **bow-shock** structure around the PWN.



X-ray PWN bow-shock [Kargaltsev & Pavlov 2008]

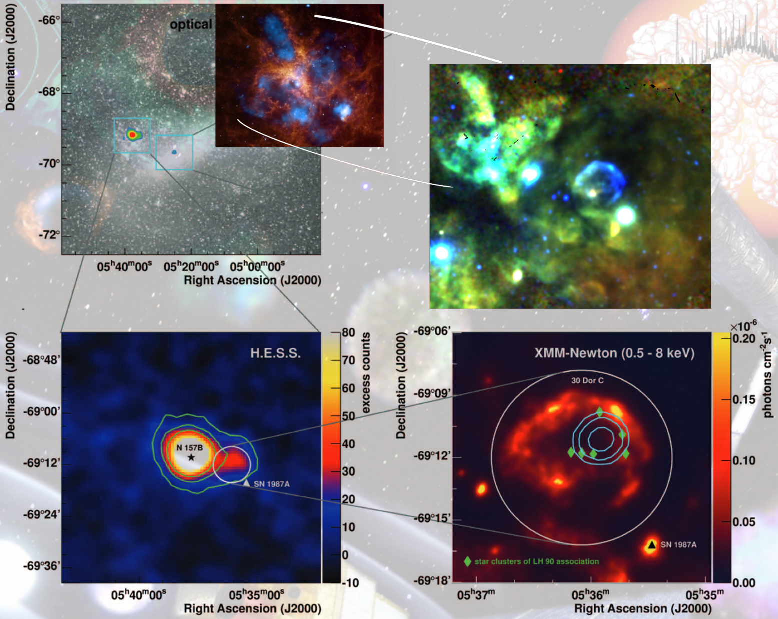


The Star Forming Region N51 in the Large Magellanic Cloud

As seen in infrared, optical and X-ray light

(Maggi P./MPE/XMM-Newton/MCELS/Spitzer Space Telescope)

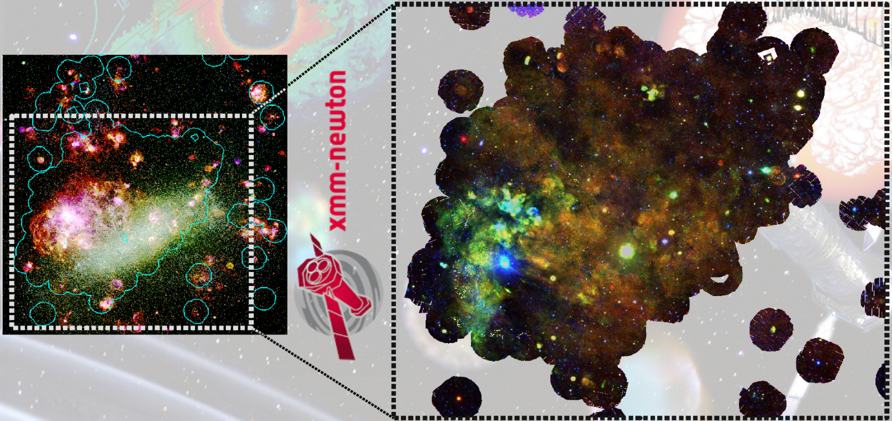
Superbubbles : The remnants of remnants



1. Introduction : The Matryoshka dolls of stellar remnants
2. Supernova remnants in the Magellanic Clouds
3. On types and progenitors
4. Non-thermal X-ray stellar remnants

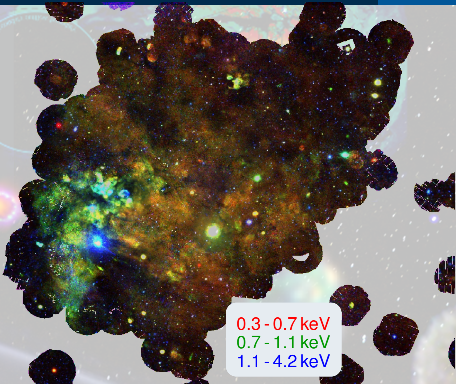
The XMM-Newton survey of the LMC

PI: F. Haberl



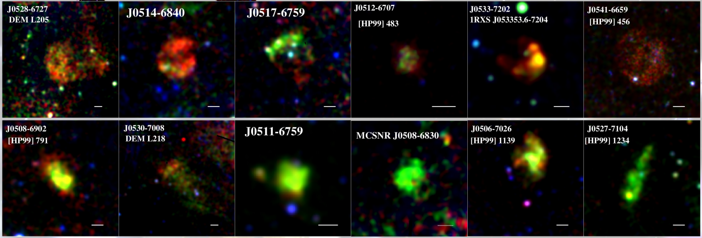
Footprint of XMM survey on the LMC and final X-ray mosaic, combining 200+ pointings, almost 3 Ms (35 days) of exposure time

The XMM-Newton survey of the LMC



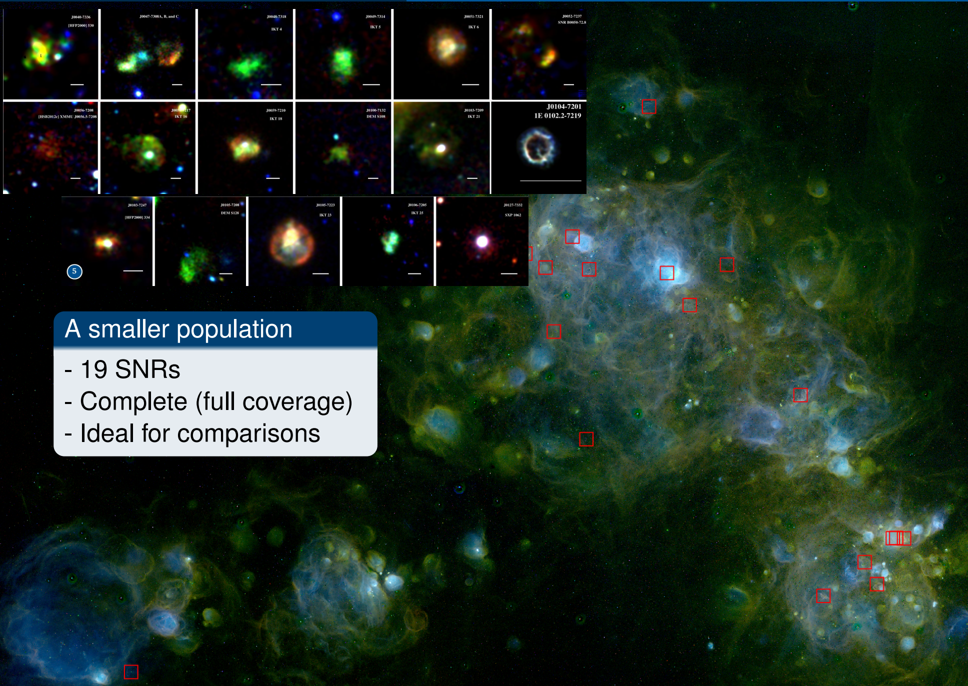
59 confirmed SNRs

- 51 with XMM, many for the 1st time
- 12 new with our XMM programmes
- 6 serendipitously in the survey



Grondin+2012, Horta+2012, **PM+2012, 2014, 2016**, Bozzetto+2014, Kavanagh+2013, 2015

The Small Magellanic Cloud SNRs



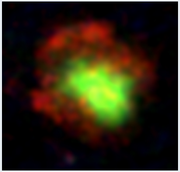
A smaller population

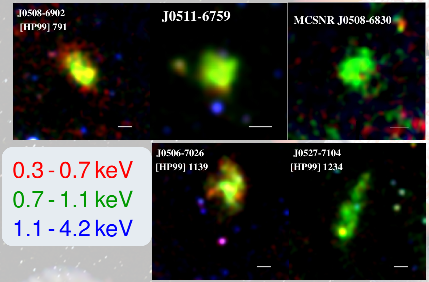
- 19 SNRs
- Complete (full coverage)
- Ideal for comparisons

The most evolved type Ia SNRs

Prototype: DEM L238 (Borkowski+2006)

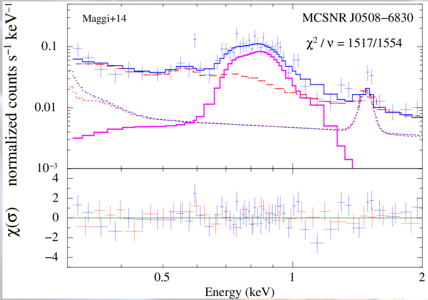
- Shell: shocked ISM
- **Iron-rich** core, X-ray bright





0.3 - 0.7 keV
0.7 - 1.1 keV
1.1 - 4.2 keV

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

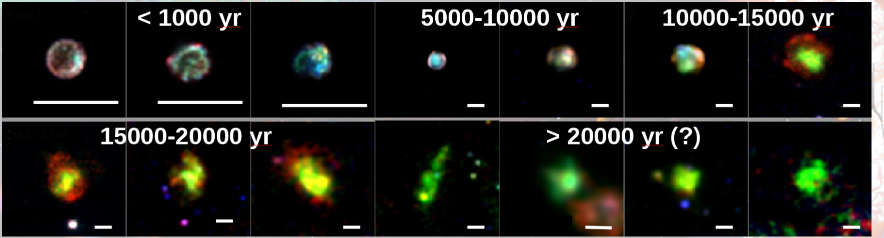


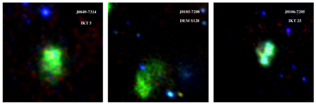
Iron-rich gas in the interior

- 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

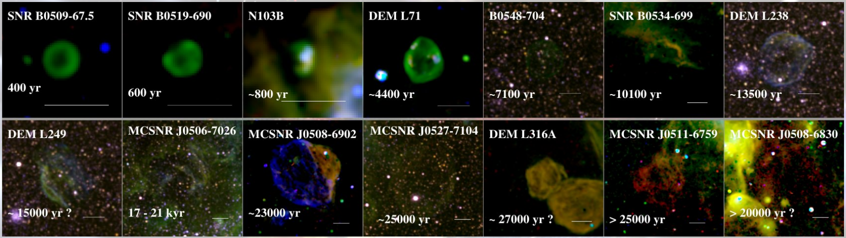
The most evolved type Ia SNRs



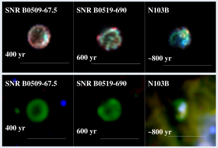


+ Three Fe-rich SNRs in the SMC

Optical images : [S II] Hα [O III]

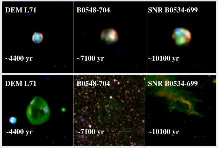


The most evolved type Ia SNRs



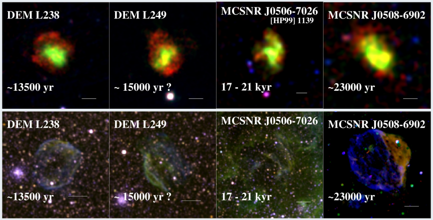
Phase I:

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



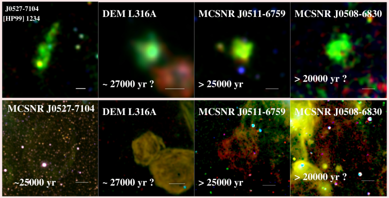
Phase II:

- 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 (?)

- Using sub-samples unaffected by SN ejecta ↦ ISM abundance

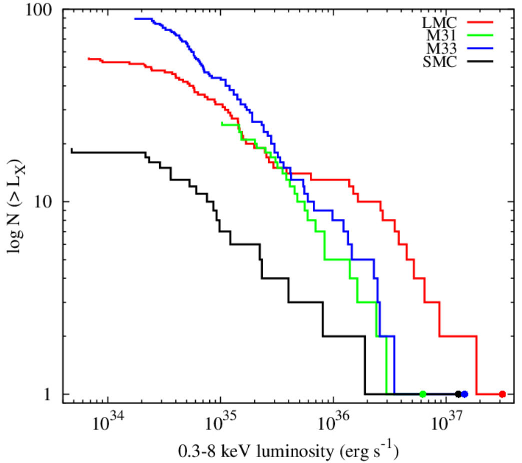
	12+log(X/H)				
	O	Ne	Mg	Si	Fe
MW	8.69	7.94	7.40	7.27	7.43
LMC	$8.01^{+0.14}_{-0.21}$	$7.39^{+0.11}_{-0.15}$	$6.92^{+0.20}_{-0.37}$	$7.11^{+0.20}_{-0.41}$	$6.97^{+0.13}_{-0.18}$
SMC	$7.63^{+0.57}_{-0.15}$	$7.08^{+0.47}_{-0.13}$	$6.75^{+0.42}_{-0.13}$	—	$6.37^{+0.55}_{-0.24}$

► Metallicity between 0.1–0.2 (SMC) and 0.2–0.5 solar (LMC)

► Lower [O/Fe] (0.15 dex) compared to *ASCA* SNRs (LMC, Hughes et al. 1998)
↦ SN ejecta contamination (confirmed with *Chandra*, Schenck et al. 2016)

► Higher [O/Fe] (0.25 dex) in SMC than in LMC
↪ different ancient star formation history, dust depletion, or only measuring abundances in star forming regions ?

Comparison of SNRs in external galaxies



XLF (Maggi+2016)

Main differences:

- **Numbers:**

M33 dominates

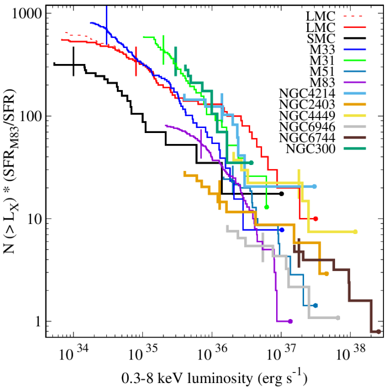
- **Shape:**

M31 ~ M33, SMC flatter

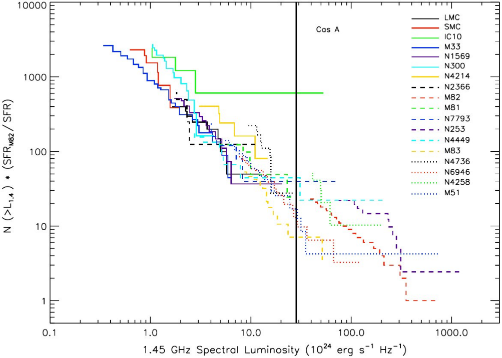
LMC shape is more complex:

Bright tail
Flat faint end (incomplete)

Comparison of SNRs in external galaxies



XLF scaled by SFR (Maggi+, in prep.)



radio LF, Chomiuk & Wilcots 2009

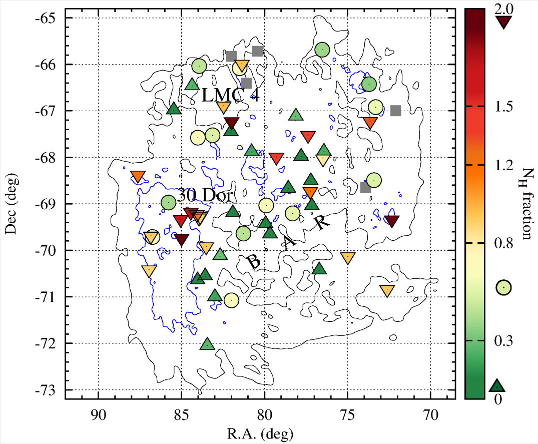
Shape differences subsist, larger spread.
X-ray luminosity function is not universal, unlike **radio** LF
↦ effects of metallicity and ISM density

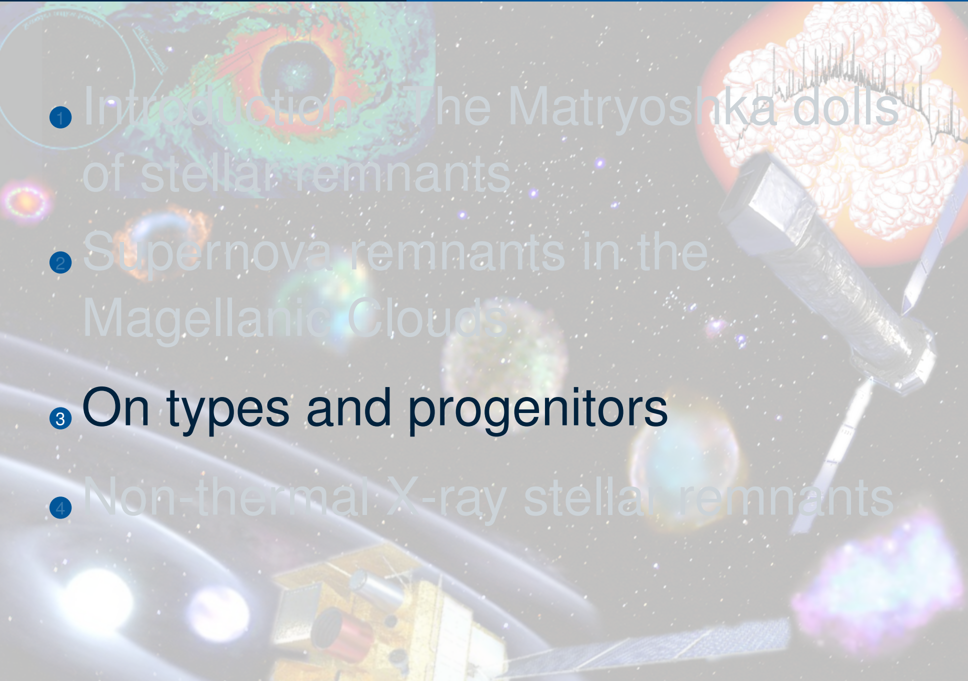
The “3D” Distribution of LMC SNRs

“N_H **fraction**” $= N_H^X / N_H^{21\,\mathrm{cm}}$ gives the line-of-sight position relative to the main gas disc

- **SNRs in the Bar** are (almost) all in front of the disc :
  ▶ Supports the (challenged) findings that the Bar is indeed “floating” in front of the disc
- **SNRs in 30 Dor** → behind:
  ▶ Confirms that 30 Dor is on the far side of the LMC
- N_H **fraction** $\gg$ **1.2 ?**
  ▶ molecular phase!

Adding a sense of depth with X-ray spectra



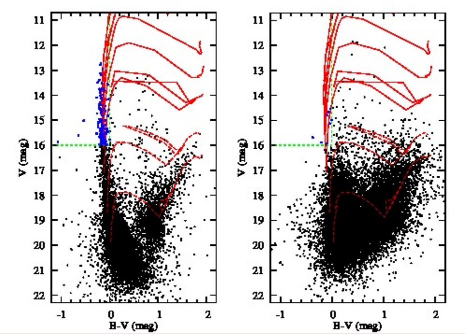


1. Introduction : The Matryoshka dolls of stellar remnants
2. Supernova remnants in the Magellanic Clouds
3. On types and progenitors
4. Non-thermal X-ray stellar remnants

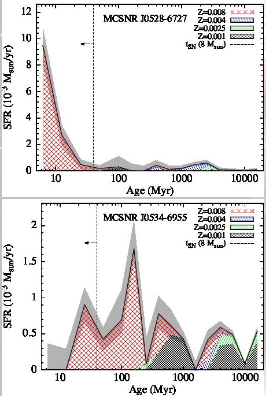
Typing the whole MC sample from the **local stellar environment**

Photometric survey of Zaritsky+(04)

Colour-magnitude diagrams (CMD) ↦ $N_{\rm OB}$



- Star formation history (SFH) map



Harris & Zaritsky (2008)

Measuring the ratio of CC to type Ia SNe

$N_{\mathrm{CC}}/N_{\mathrm{Ia}}$ **in the LMC** 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	$N_{\mathrm{CC}}/N_{\mathrm{Ia}}$	Ref.
LMC SNRs	1.1–1.5	Maggi+2016
Local SNe	3	Li+2011
Abundances in galaxy clusters	3.5 (2–4) 1.7–3.5 1.5–3	Sato+2007 de Plaa+2007 Lovisari+2011

More type Ia SNe in the LMC ?

- Unlikely biased either way

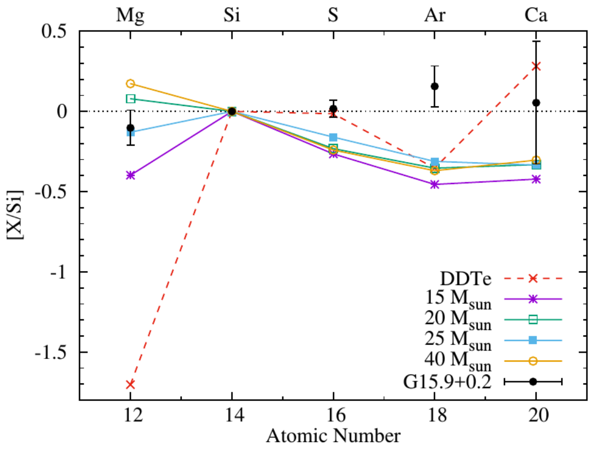
↦ Specific SFH of the LMC (bursts 100 Myr, 500 Myr, and 2 Gyr ago)

\+ Timescale of type Ia SNe (the majority explodes within 2 Gyr)

$N_{\mathrm{CC}}/N_{\mathrm{Ia}}$ **in the SMC** is 2.2 (1.4–2.8) with the same method

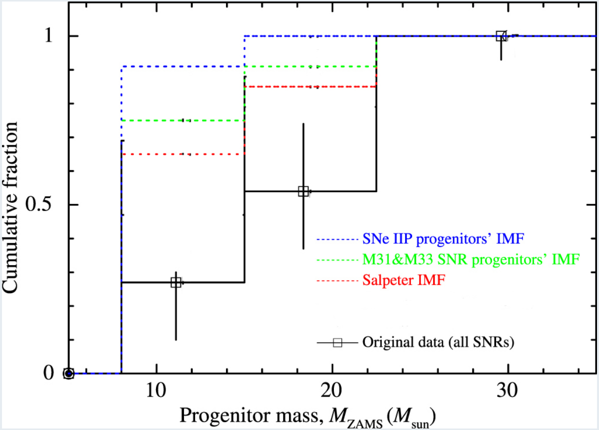
The CC-SN progenitor mass distribution

observed ejecta abundance ratios vs. explosion *models* ↦ progenitor mass



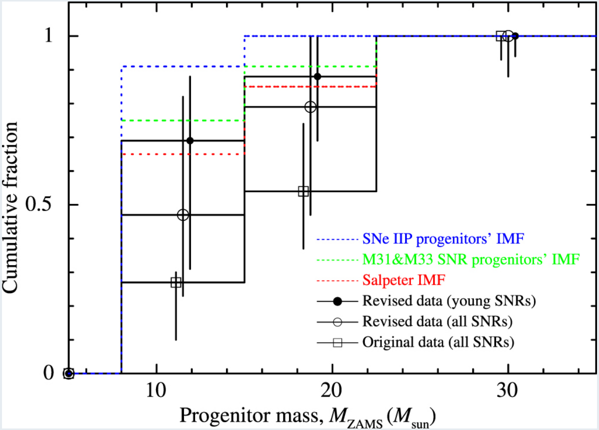
Maggi & Acero (2017)

The CC-SN progenitor mass distribution



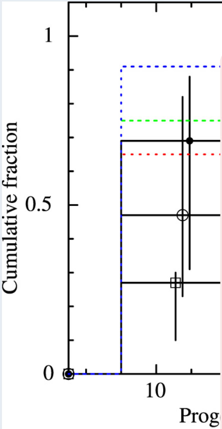
Katsuda et al. (2018)

The CC-SN progenitor mass distribution

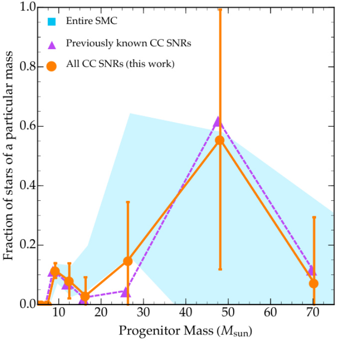


Katsuda et al. (2018)

The CC-SN progenitor mass distribution



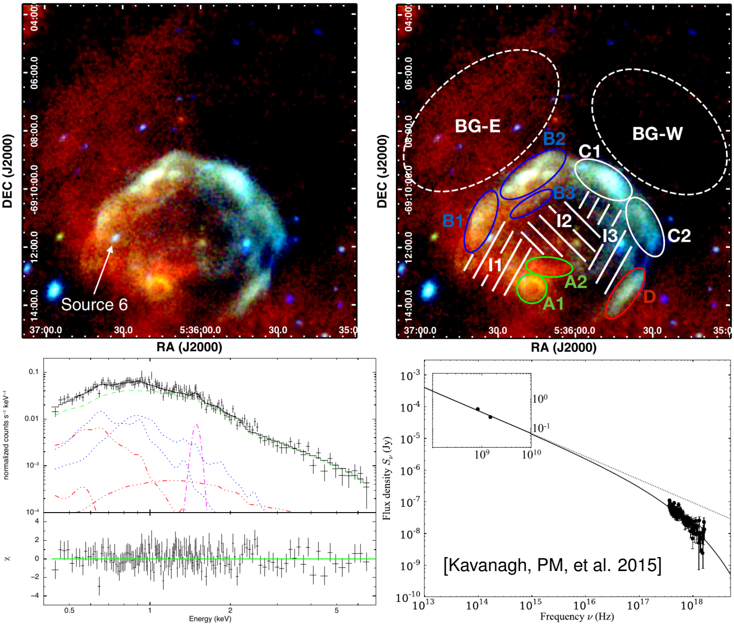
Ka



SMC CC SN progenitor mass distribution (Auchettl+2019)

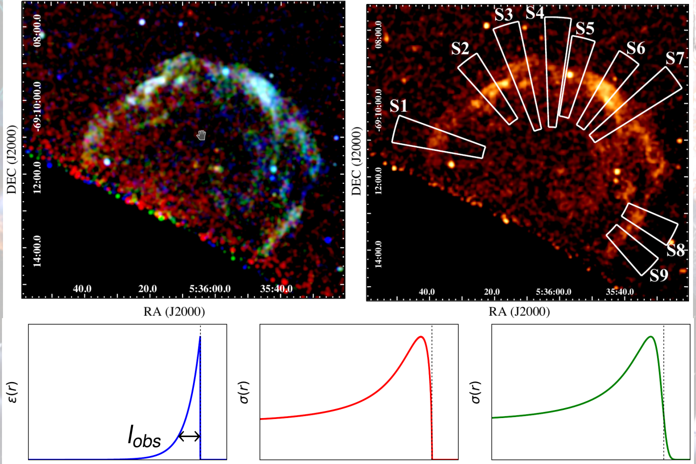
1. Introduction : The Matryoshka dolls of stellar remnants
2. Supernova remnants in the Magellanic Clouds
3. On types and progenitors
4. Non-thermal X-ray stellar remnants

The synchrotron superbubble 30 Dor C



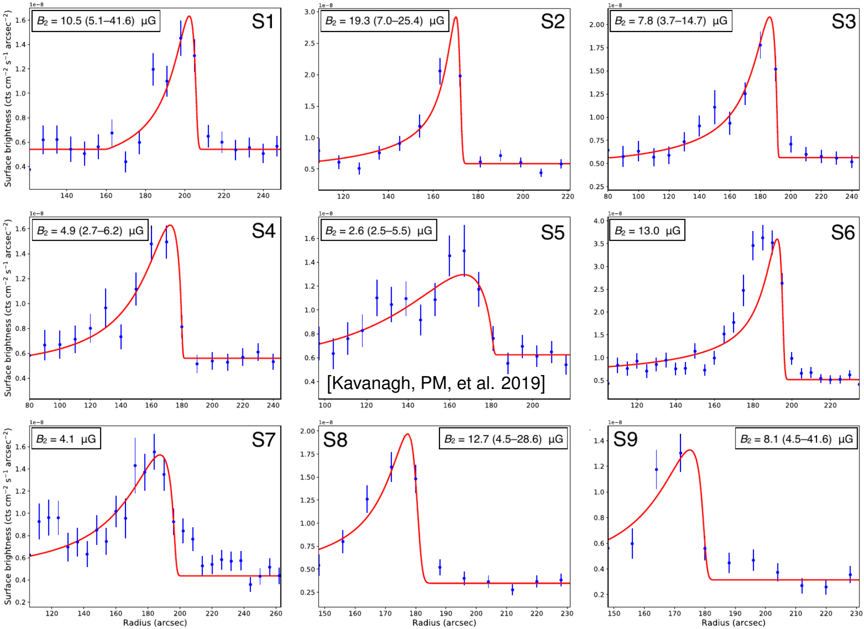
[Kavanagh, PM, et al. 2015]

The synchrotron superbubble 30 Dor C



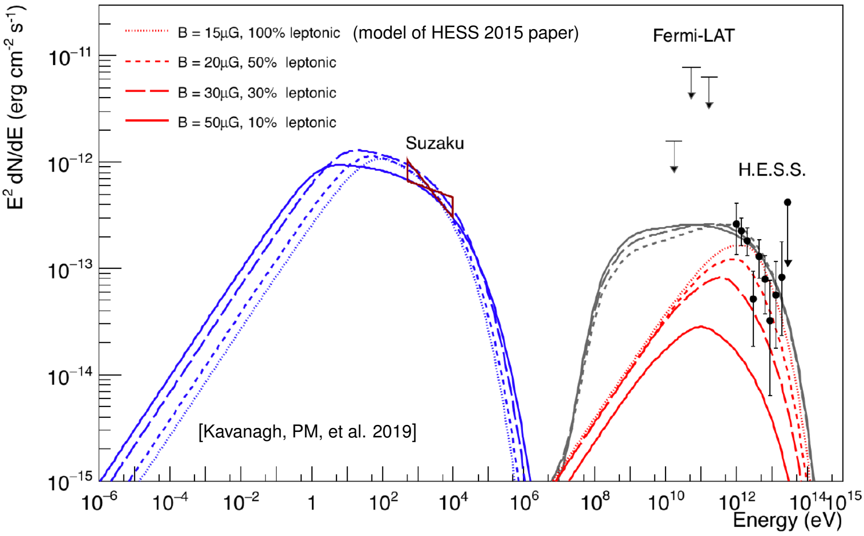
$$B_2 \approx 26 \left(\frac{l_{adv}}{10^{18}\ \mathrm{cm}\ (= 1.3'')} \right)^{-2/3} \eta_g^{1/3} \left(r_4 - 1/4 \right)^{-1/3}\ \mu\mathrm{G} \quad ; \quad l_{obs} \approx \sqrt{2} l_{adv} \qquad (1)$$

The synchrotron superbubble 30 Dor C

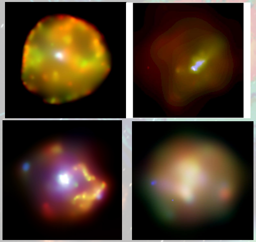


[Kavanagh, PM, et al. 2019]

The synchrotron superbubble 30 Dor C



Extragalactic PWN

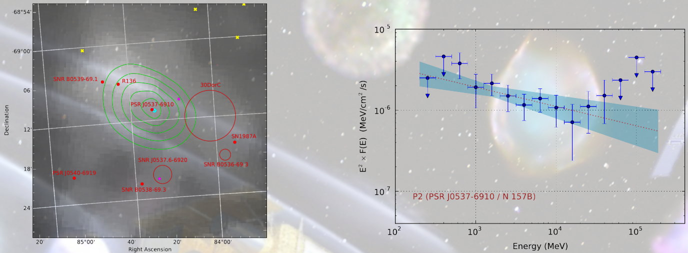


PWN or candidates in the LMC

[CXO/NASA]

PWN allow us to :

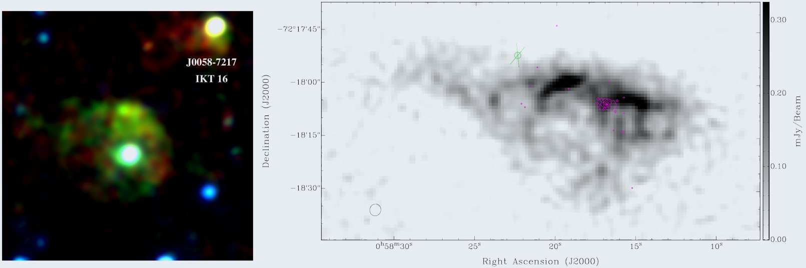
- Find and study young pulsars
- Measure pulsar kick velocity
- Probe the origin of (some) relativistic particles and high-energy sources



The Fermi sources of the LMC: N157B [Ackermann et al. 2015]

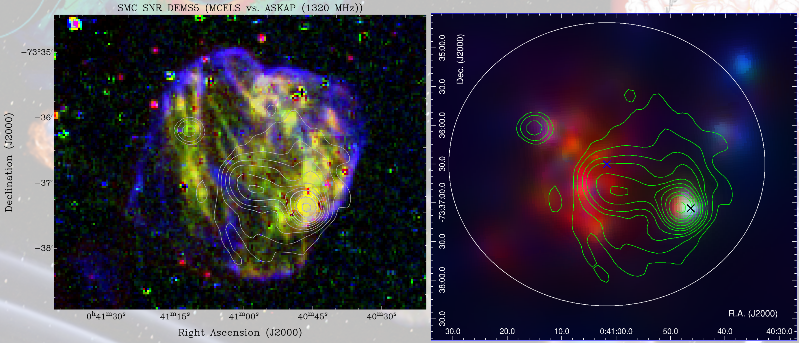
The first PWN of the SMC

First suggested by XMM-Newton and radio data [Owen et al. 2011], confirmed with Chandra [Maitra et a. 2015].



The SNR IKT16 with its central PWN

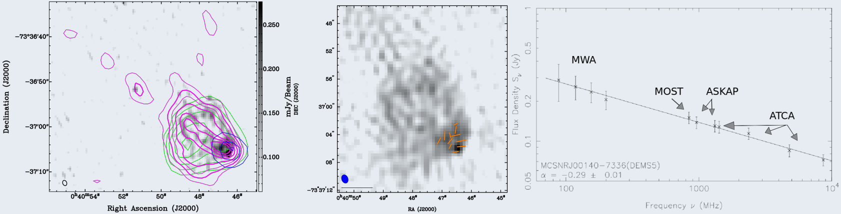
A new SMC PWN



GHz emission of the SNR shell overlaid on optical (left) and soft X-rays (right).

⇒ Detection of extended + compact source radio emission.

A new SMC PWN

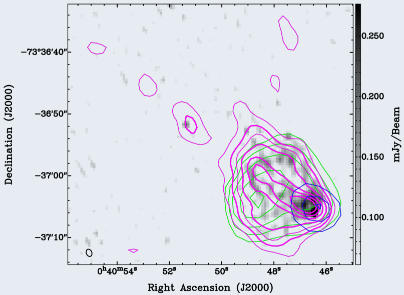


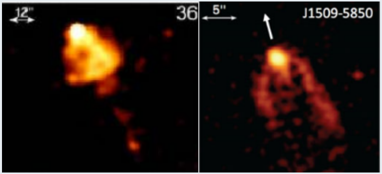
Left: 5.5 GHz emission with 2.1 GHz radio contours (magenta), and soft and hard X-ray emission (green and blue). Middle: Polarisation vectors. Right: Radio SED

Peak fractional polarisation $P = 32 \pm 7\%$ and average polarisation $\sim 23\%$.

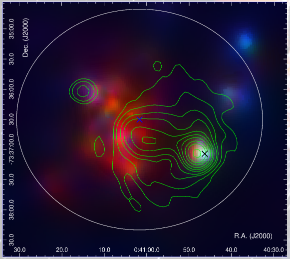
The "pulsar" emission measured above 2 GHz has $\alpha \approx -1.8$.

The first extragalactic supersonic pulsar ?

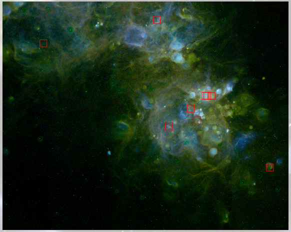




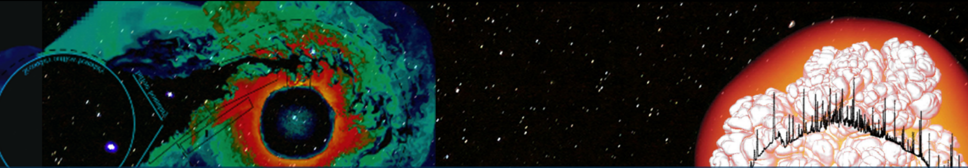
Reminiscent of other supersonically moving pulsars.



$v_{\mathrm{kick}} = 700 - 2000\ \mathrm{km\,s^{-1}}$. ,

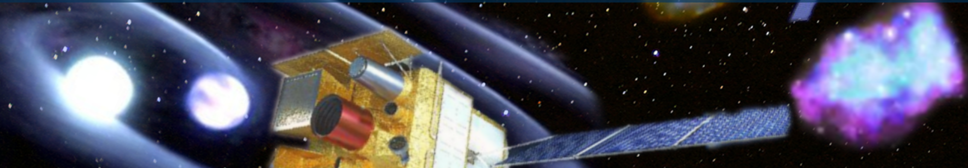


Potential runaway ? Linear distance $\sim 1000\,(t/10\ \mathrm{Myr})\,(v/100\ \mathrm{km\,s^{-1}})$ pc.



- All stages of an SNR life can be followed in nearby galaxies
- Population studies give us insights on the host galaxies
- We do not yet fully understand how/which core-collapse supernovae explode : SNRs can help, but it’s tricky
- The TeV emission in superbubble 30 Dor C is leptonic in origin
- We are slowly unraveling the population of extragalactic PWNe

↪ Observations with next-generation high-energy instruments have a lot of potential



The Progenitors of type Ia SNe

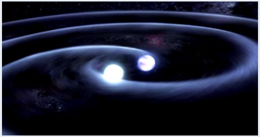
Nucleosynthesis :

Main contributors to the **iron-group elements**

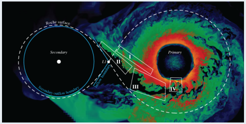
Standard(-isable) candles :

A probe of the accelerating universe

Double-Degenerate (DD)

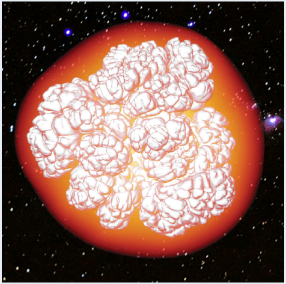


Violent merger



Double-detonation DD

Single-Degenerate (SD)



+ ?

Accretion from a **companion**

⇒ Merger scenario
Sub-M_{Ch} WD

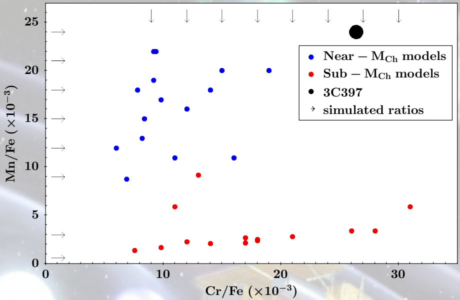
⇒ Accretor scenario
Near-M_{Ch} WD

Constraining progenitors from yields

Nucleosynthesis yields ⇒ focus on the "Iron-peak elements" (Cr, Mn, Ni).

More massive WDs have denser cores. If at the onset of the explosion $\rho_c \gtrsim 10^8$ g cm^{-3}), electron capture reactions ($p + e^- \rightarrow n + \nu_e$) can occur, enhancing the yield of neutron-rich species.

Near-M_{Ch} WDs ("accretor") → higher Cr, Mn, Ni to Fe.
Sub-M_{Ch} WDs ("merger") → lower Cr, Mn, Ni to Fe.



Cr- and Mn-to-Fe ratio for type Ia SN models

Nickel mass as another discriminant :

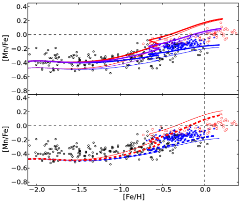
Sub-M_{Ch}WD :
$M_{\mathrm{Ni}} = 0.008 – 0.04\ M_{\odot}$

Near-M_{Ch}WD :
$M_{\mathrm{Ni}} = 0.06 – 0.12\ M_{\odot}$

Previous works using nucleosynthesis

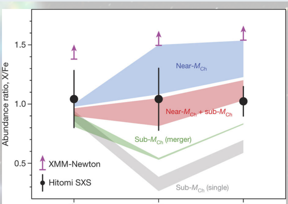
Stellar abundances

Comparing chemical evolution models to observed [Mn/Fe] [Seitenzahl+13]



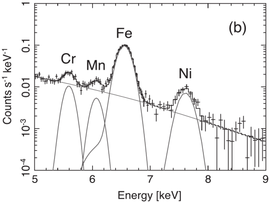
Intra-cluster medium

Abundance of neutron-rich species in hot (X-ray) ICM [Hitomi+17]



Supernova remnants

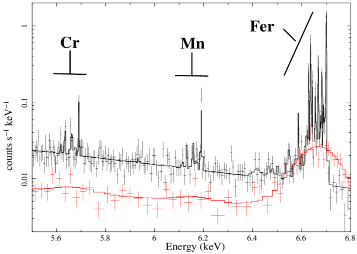
n-rich species in young SNRs : Tycho, Kepler, 3C397 [Badenes+08, Park+13, Yamaguchi+15]

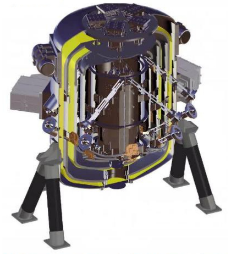


⇒ Mixture of near-M_{Ch} and sub-M_{Ch} WDs
similar contributions from DD and SD channels

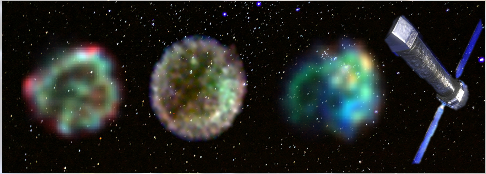
⇒ Only massive WDs
only SD progenitors so far

How to increase the sample of type Ia SNRs in which to measure neutron-rich species abundance ?





Simulated **X-IFU (black)** vs. **CCD (red)** spectra of an LMC type Ia SNR (N103B).



LMC type Ia SNR 0519-6902, SNR 0509-675, and N103B.