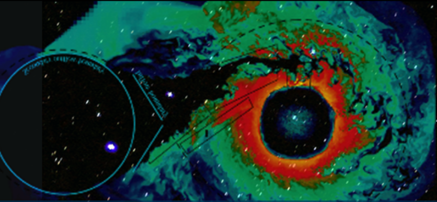
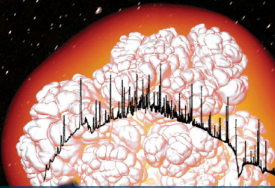




Clues to the progenitors of type Ia supernovae from Athena observations of their remnants

Detecting the elusive neutron-rich elements

Pierre Maggi

CEA Saclay / Observatoire de Strasbourg

Exploring the Hot and Energetic Universe

24-27 September 2018, Palermo, Italy

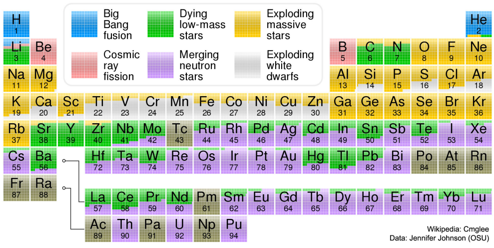
SN Ia : A violent and luminous explosion of a CO white dwarf (WD)

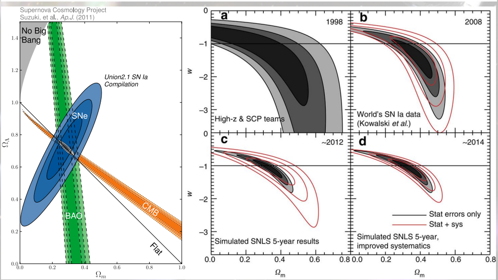
Nucleosynthesis :

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

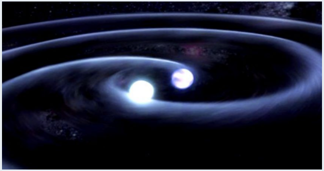
Standard(-isable) candles :

A probe of the accelerating universe

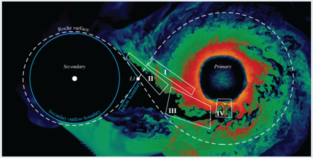




Double-Degenerate (DD)

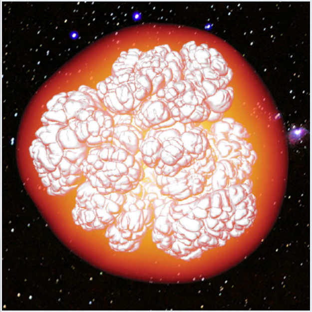


Violent merger



(Dynamically-driven) double-detonation DD (D^6)

Single-Degenerate (SD)



\+ ?

Accretion from a **companion**

⇒ Merger scenario

Sub-M_{Ch} WD

⇒ Accretor scenario

Near-M_{Ch} WD

Both channels can reproduce observed SN Ia properties (light curves, spectra).
Other signatures are needed to identify the dominant progenitor channel :

- Search for surviving companion.
- WD binaries population.
- Ionising radiation of accreting WDs.
- Properties of host galaxies / local stellar populations.
- Nucleosynthesis yields

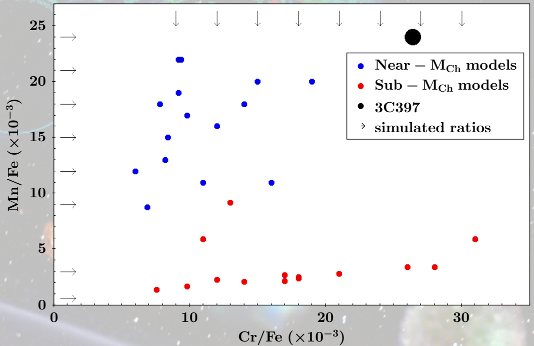
Both channels can reproduce observed SN Ia properties (light curves, spectra). Other signatures are needed to identify the dominant progenitor channel :

- Search for surviving companion.
- WD binaries population.
- Ionising radiation of accreting WDs.
- Properties of host galaxies / local stellar populations.
- **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-$M_{\rm Ch}$ WDs ("accretor") → higher Cr, Mn, Ni to Fe.
Sub-$M_{\rm Ch}$ WDs ("merger") → lower Cr, Mn, Ni to Fe.

Measuring neutron-rich elements in X-rays



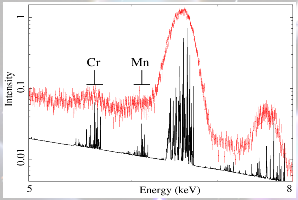
Cr- and Mn-to-Fe ratio for type Ia SN models

Nickel mass as another discriminant :

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

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

Ion	Energy (keV)
Cr XXIII (He-like)	**5.62 – 5.69**
Cr XXIV (H-like)	5.92 ; 5.93
Mn XXIII	5.96 – 6.03
Mn XXIV (He-like)	**6.13 – 6.18**



Previous works using nucleosynthesis

Stellar abundances

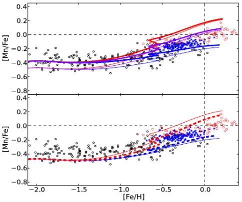
Comparing chemical evolution models to observed [Mn/Fe] [Seitenzahl+13]

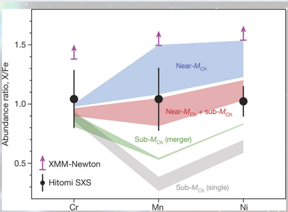
Intra-cluster medium

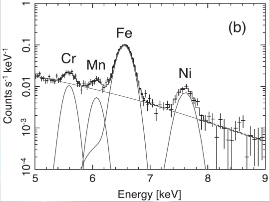
Abundance of neutron-rich species in hot (X-ray) ICM [Hitomi+17]

Supernova remnants

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



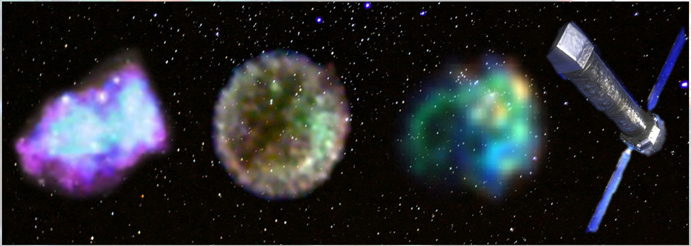




⇒ Mixture of near-M_{Ch} and sub-M_{Ch} WDs
similar contributions from DD and SD channels

⇒ Only massive WDs
only SD progenitors so far

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

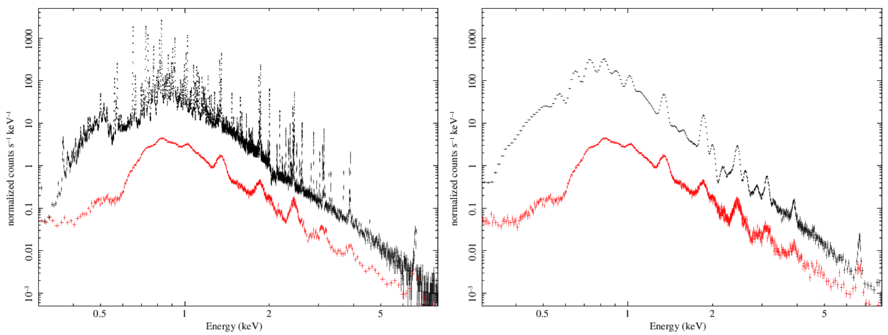


X-ray images of 3C397, SNR 0509-675, and N103B.

SNR	Distance (kpc)	Age (yr)	F_X $[5-8\ \mathrm{keV}]$	$M_{\mathrm{Cr}}/M_{\mathrm{Fe}}$	$M_{\mathrm{Mn}}/M_{\mathrm{Fe}}$	***kT* (keV)**	**t_{exp} (ks)**
3C397	8–9	1500-5000	3.5×10^{-12}	0.027	0.025	**2.2–5**	**25/80/150**
N103B	50 (LMC)	860	3.6×10^{-14}	?	?	**1.5–4**	**50/100/150**
0509-675	50 (LMC)	400	1.2×10^{-14}	?	?	**2–10**	**50/100/150**

- X-IFU response : Baseline-config, 2018 August, THIN filter
- WFI response : 2017 August, **15 rows**, with filter, 5 arcmin average
- Simulated $M_{\mathrm{Cr}}/M_{\mathrm{Fe}}$: 0.009 to 0.030, and $M_{\mathrm{Mn}}/M_{\mathrm{Fe}}$: 0.006 to 0.024

Forward spectral analysis of simulated spectra :
↦ How well do we recover the input mass-ratios ?

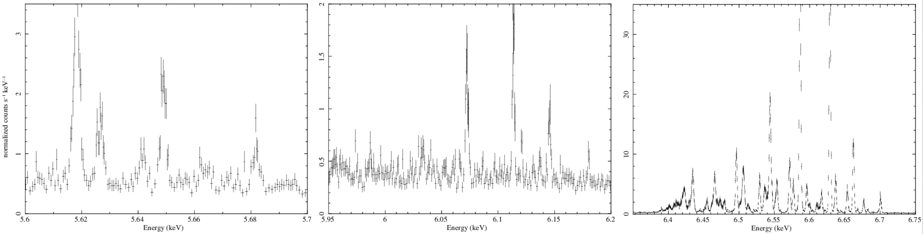


X-IFU and WFI spectra (black) of N103B compared to *Suzaku*/XIS (red).

- X-IFU response : Baseline-config, 2018 August, THIN filter
- WFI response : 2017 August, **15 rows**, with filter, 5 arcmin average
- Simulated $M_{\mathrm{Cr}}/M_{\mathrm{Fe}}$: 0.009 to 0.030, and $M_{\mathrm{Mn}}/M_{\mathrm{Fe}}$: 0.006 to 0.024

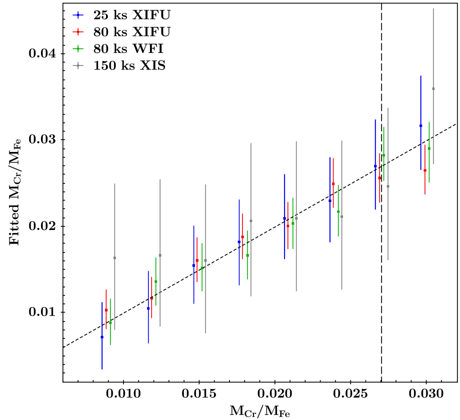
Forward spectral analysis of simulated spectra :
↦ How well do we recover the input mass-ratios ?

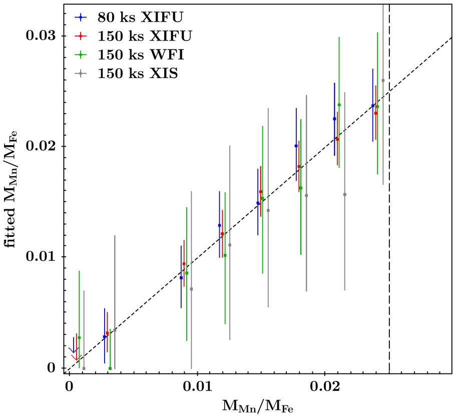
5.6 – 5.7 keV. **5.95 – 6.2 keV.** **6.35 – 6.75 keV.**



Close-ups on Cr XXIII, Mn XXIV, and Fe line regions (X-IFU).

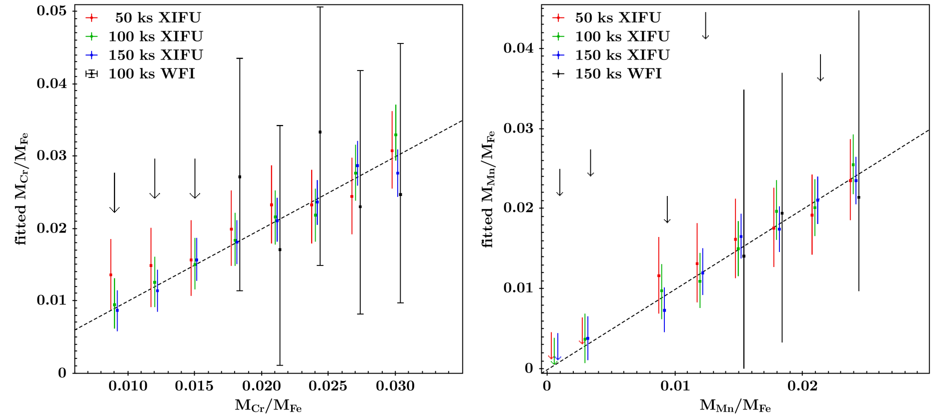
(All error bars at 3σ.)





↦ Much improved measurement for Cr and Mn with even short X-IFU exposures.
↦ High-resolution becomes needed for Mn.

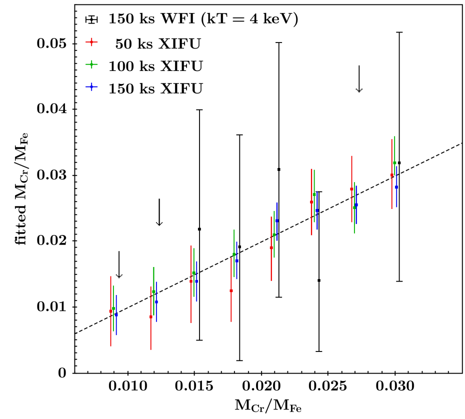
(All error bars at 3σ.)

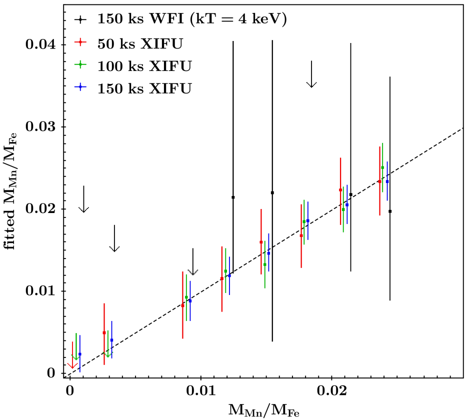


↦ Meaningful measurements only with high-resolution.

↦ Reasonably short X-IFU exposures to study extragalactic type Ia SNRs.

(All error bars at 3σ.)





↦ Meaningful measurements only with high-resolution.
↦ Reasonably short X-IFU exposures to study extragalactic type Ia SNRs.

Systematics-dominated

1. Temperature and non-equilibrium ionisation uncertainties
2. Atomic physics uncertainties
3. **Expansion** : Ejecta launched at $\gtrsim 1000\ \mathrm{km\,s^{-1}}$

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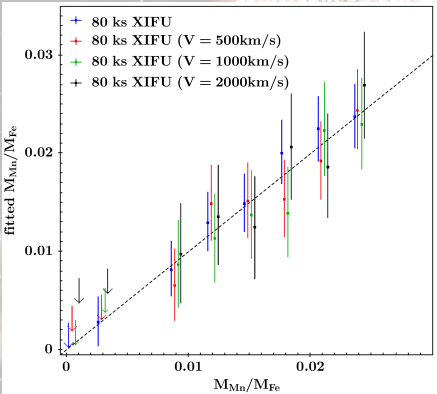
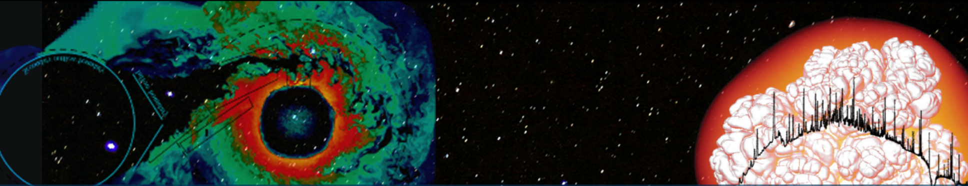
1. Iron-group elements co-spatial ?
2. Path cleared by XRISM ?
3. *Spatially-resolved* spectroscopy



Mn/Fe measurement vs. expansion FWHM velocity (3C397).

⇒ Full spectro-spatial simulations (SIXTE) as next step.

Novel analysis methods to spectro-imaging instruments : See F. Acero's poster.



- Neutron-rich elements are a probe of the mass of an exploding WD

  ↪ X-ray spectroscopy can identify type Ia progenitors

- Athena capabilities are well-suited to increase the sample of individual Ia SNRs with indication of WD mass

  ↪ Complementarity to hot ICM (integrated) studies

⇒ **Another example of bright future ahead**