UNIVERSITÀ DEGLI STUDI DI PALERMO

INAF ISTITUTO NAZIONALE DI ASTROFISICA OSSERVATORIO ASTRONOMICO DI PALERMO

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Investigating the origin of the X-ray emission from SN 1987A

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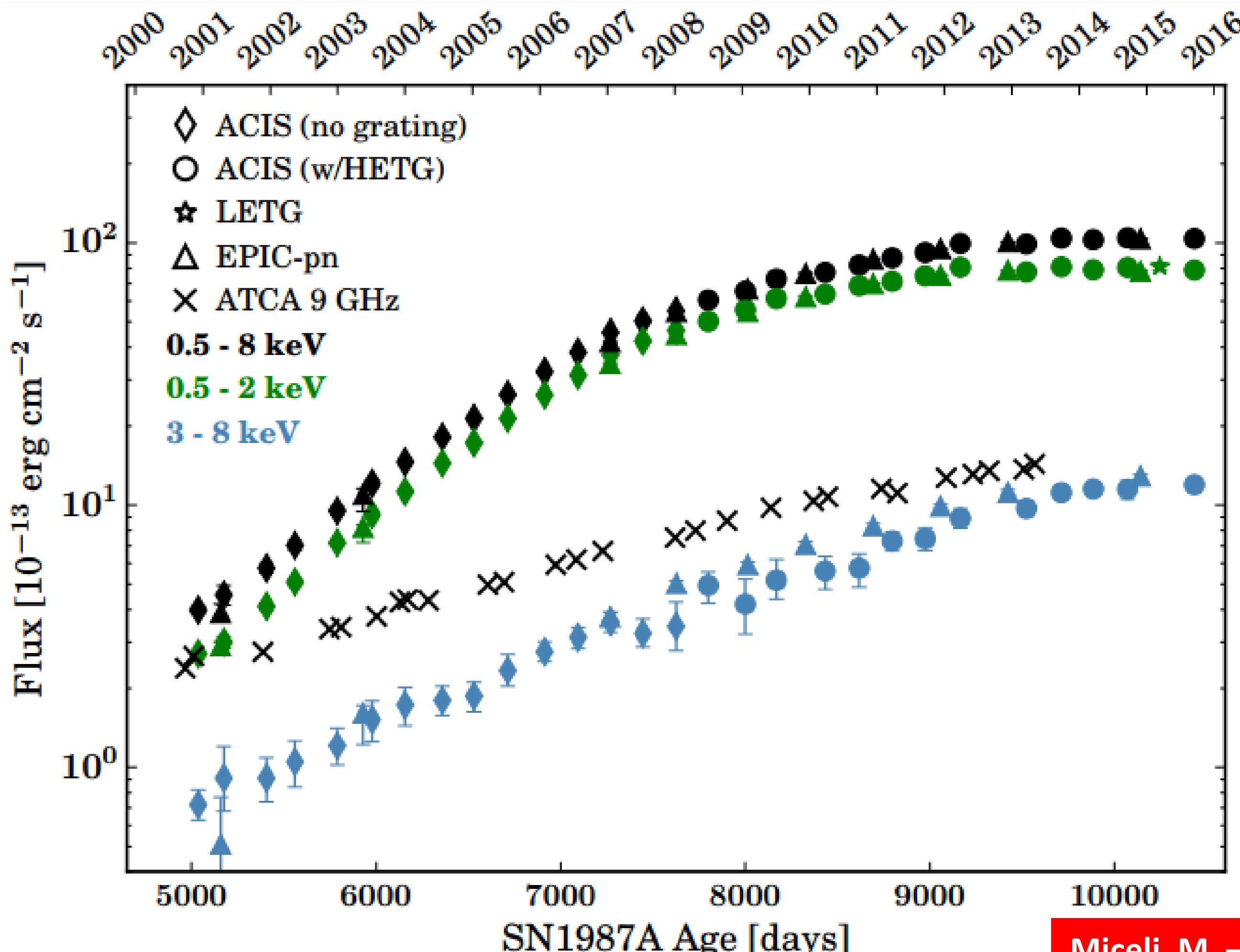
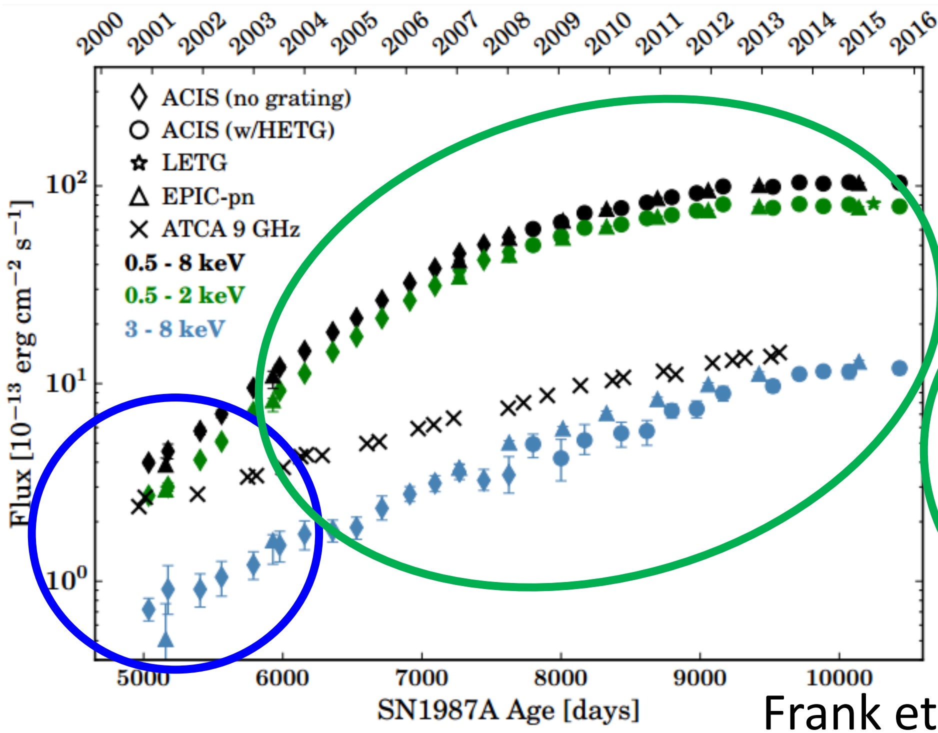
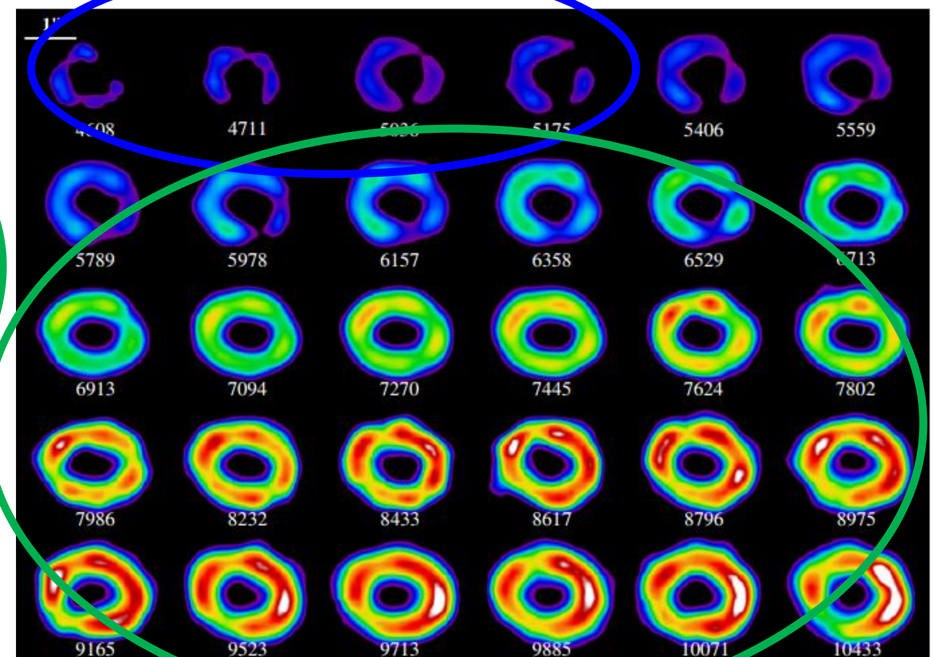
X-ray observations of SN 1987A

Continuous monitoring with X-ray observatories to follow the **transition from a SN to a SNR** thus providing a Rosetta stone for the link between these two phases of evolution



X-ray observations of SN 1987A





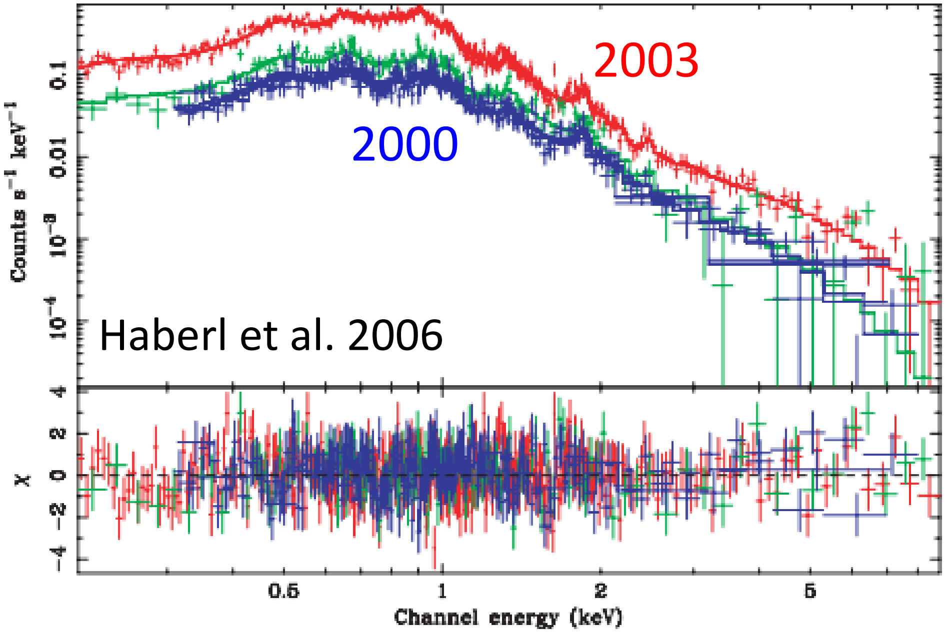
Frank et al. 2016

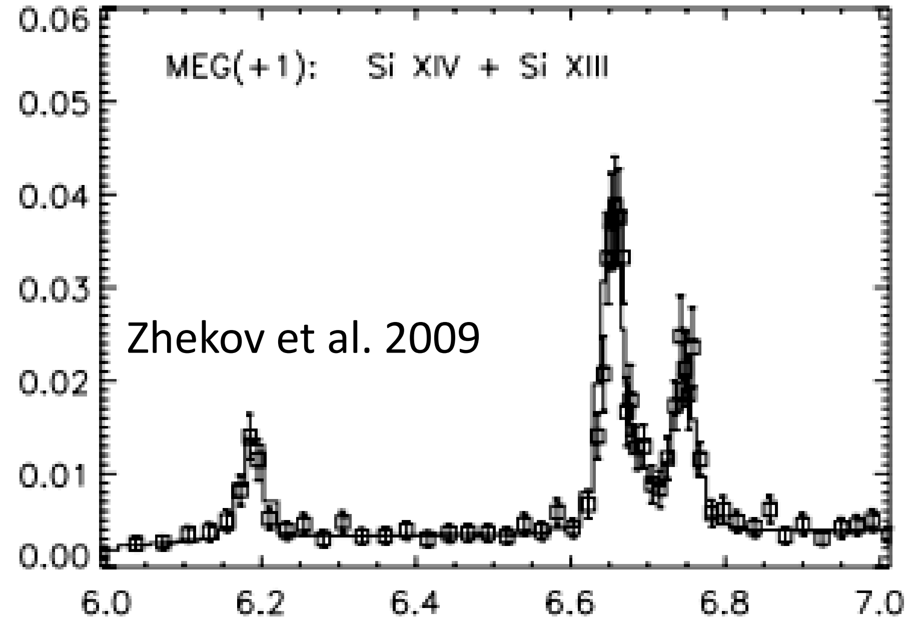
X-ray lightcurves and high-resolution images reflect the complex interaction with the multi-phase circumstellar material characterized by

1. A tenuous (10^2 cm^{-3}) HII region with harder X-ray thermal emission

2. A circumstellar dense (10^3 cm^{-3}) equatorial ring with knots (10^4 cm^{-3}) with softer emission

X-ray spectra of SN 1987A





Evolution from an isothermal model to a model with three components (the coldest one in CIE) associated with

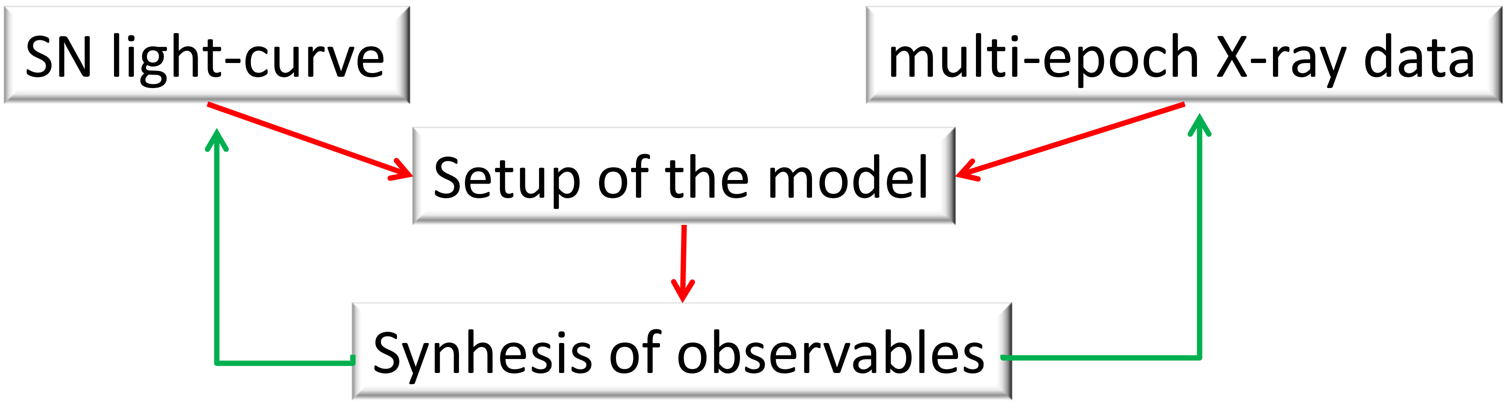
- The slow transmitted shock in the equatorial ring ; T_e ~0.3–0.5 keV
- The fast forward shock in the HII region
- Plasma, reheated by a reflected shock from the ring; T_e ~ 3keV

(e.g., Park et al. 2004, Haberl et al. 2006, Zhekov et al. 2010, Maggi et al. 2012, Helder et al. 2013)

Aims

Current models are *phenomenological* (*ad hoc* isothermal components) and analyze single observations, regardless of the whole succession of data sets (ignoring information embedded in the data)

We perform **3-D hydrodynamic simulations** to model the evolution of SN 1987a with a forward modeling approach



This approach aims at understanding the physical origin of the emission and studying how the "initial conditions" (the SN physics) and the "boundary conditions" (the ambient medium) affect the evolution

Initial conditions and parameter space

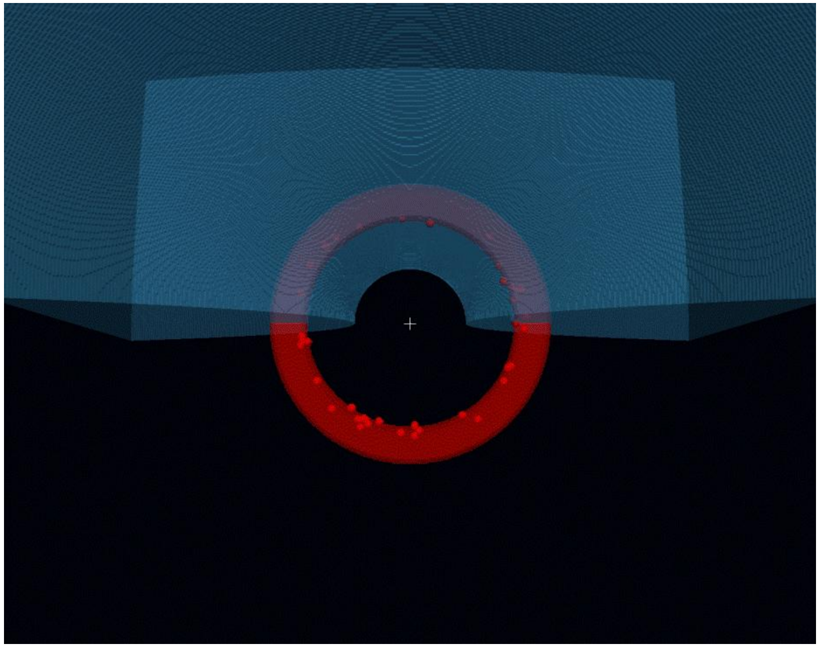
- Clumping of ejecta (Orlando+ 2012)
- Radiative losses from optically thin plasma
- Non-equilibrium of ionization
  - time evolution of each parcel of gas is followed (Dwarkadas+ 2010)
  - deviations from equilibrium of selected elements (O, Ne, Mg, Si) is calculated
- Tracers to follow the evolution of ejecta, HII region, and ring material

Spatial resolution

- Initial remnant radius ~ 20 AU (3e14 cm)
- Full spatial domain ~ 1 pc (3e18 cm)

18 nested levels of adaptive mesh refinement
effective resolution ~ 0.2 AU (3e12 cm)

> 100 cells per remnant radius during the whole evolution



			range of values explored	best-fit values
HII reg.	n_{HII}	(10^2 cm^{-3})	0.8 – 3	0.9
	r_{HII}	(pc)	0.08 – 0.2	0.08
unif. ring	n_{rg}	(10^3 cm^{-3})	1 – 2	1
	r_{rg}	(pc)	0.16	0.16
	w_{rg}	(10^{17} cm)	0.7 – 2	1.7
	h_{rg}	(10^{16} cm)	3.5	3.5
clumps	$< n_{cl} >$	(10^4 cm^{-3})	1 – 3	2.2 – 2.8
	$< r_{cl} >$	(pc)	0.14 – 0.17	0.14 – 0.17
	w_{cl}	(10^{16} cm)	1 – 3	1.7
	N_{cl}		40 – 70	50

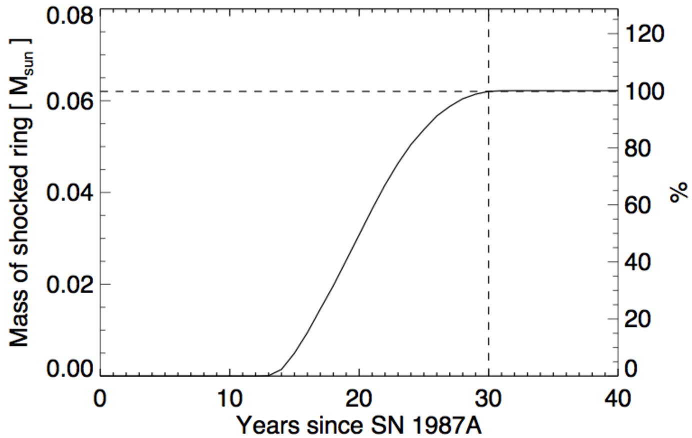
The evolution of SN 1987A

Our model

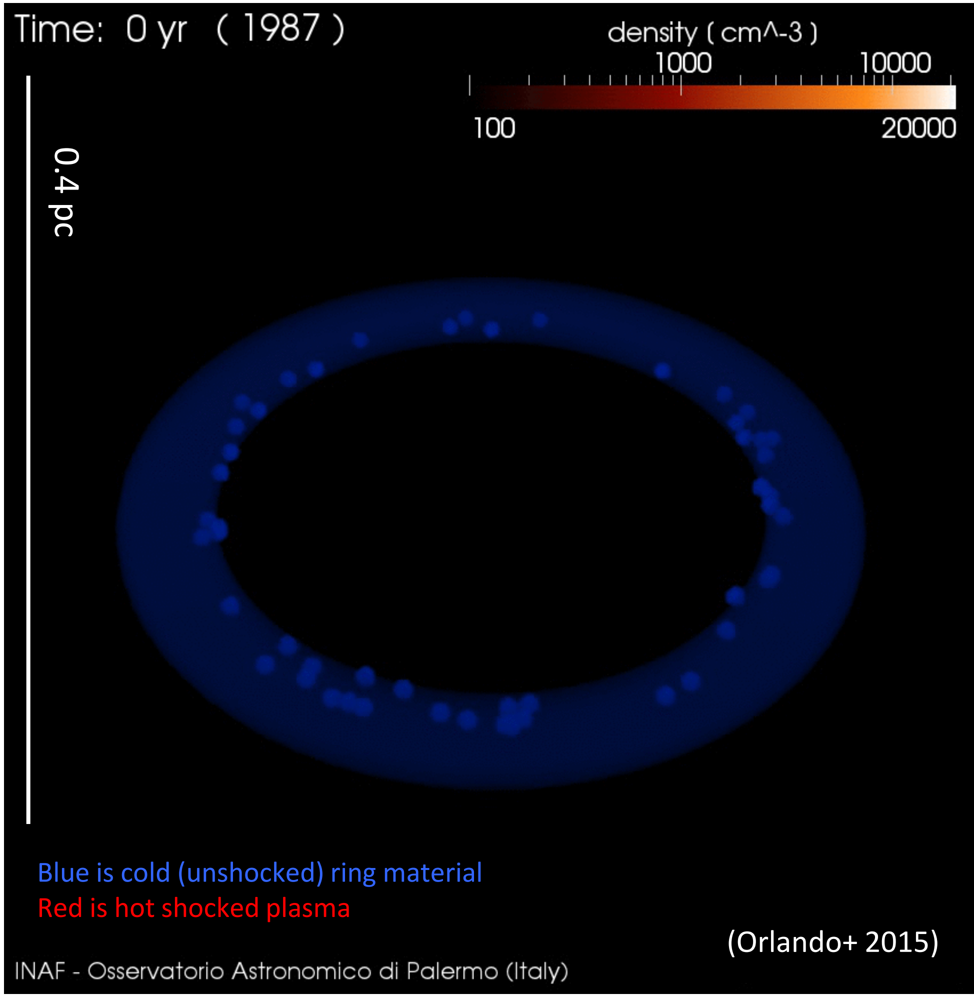
$M_{rg} \sim 0.062\ M_{sun}$
$\sim 0.040\ M_{sun}$ @ $n = 10^3\ cm^{-3}$
$\sim 0.022\ M_{sun}$ @ $n \sim 2.5 \times 10^4\ cm^{-3}$

Density structure of ionized gas of the ring from optical spectroscopic data (Mattila+ 2010)

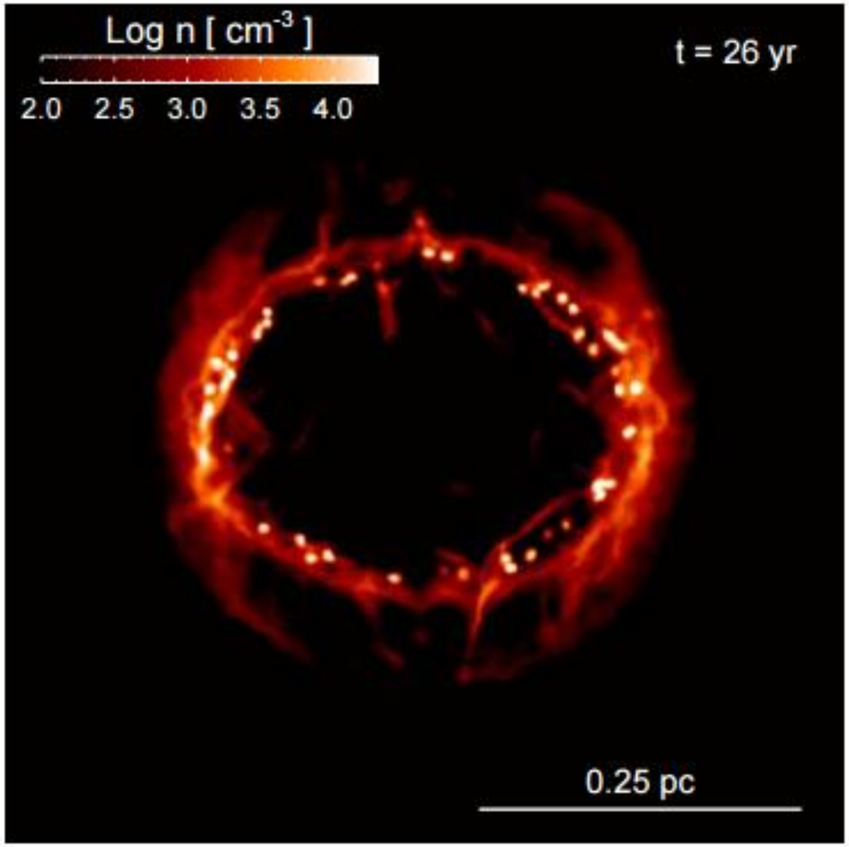
$M_{rg} \sim 0.058\ M_{sun}$
$\sim 0.046\ M_{sun}$ @ $n \sim 10^3\ cm^{-3}$ and $n \sim 3 \times 10^3\ cm^{-3}$
$\sim 0.012\ M_{sun}$ @ $n \sim 3 \times 10^4\ cm^{-3}$



~ 100 % of the ring material has been shocked at the current time (2017)



Synthesis of the X-ray emission



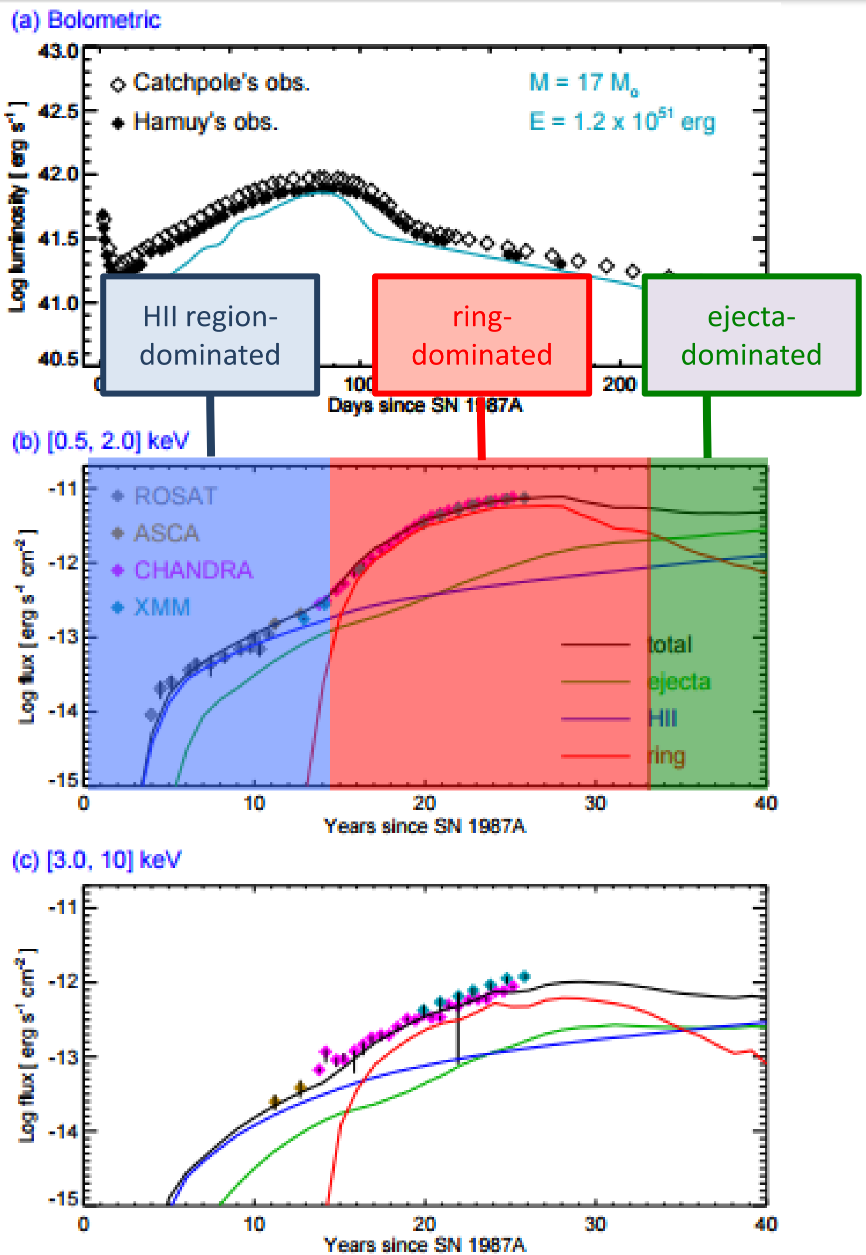
By adopting **ATOMDB V3.0,** we derive the synthetic X-ray emission in each computational cell from

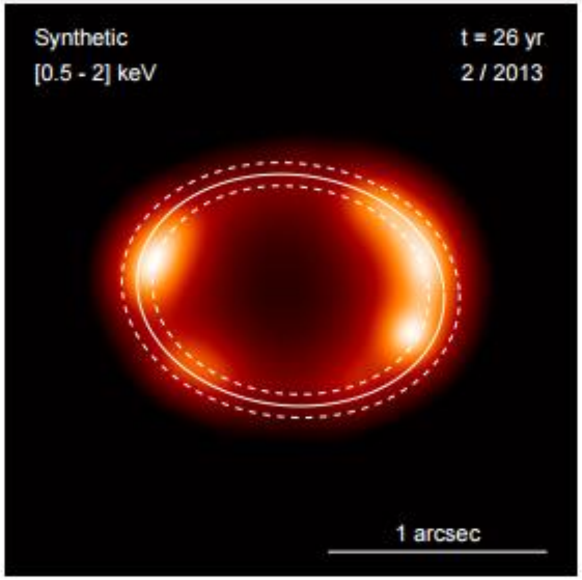
- Electron temperature (by including p^+-e^- Coulomb collisions)
- Plasma density
- Time elapsed after the shock heating

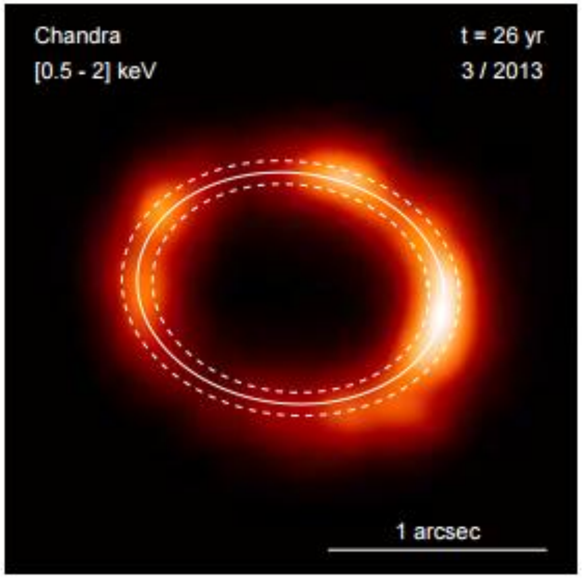
Abundances	Zhekov+ (2009)
ISM Absorption:	2.35e21 cm^{-2} (Park+ 2006)
Distance:	51.4 kpc (Panagia 1999)

The synthetic emission is then **folded through the instrumental *XMM-Newton* and *Chandra* responses**

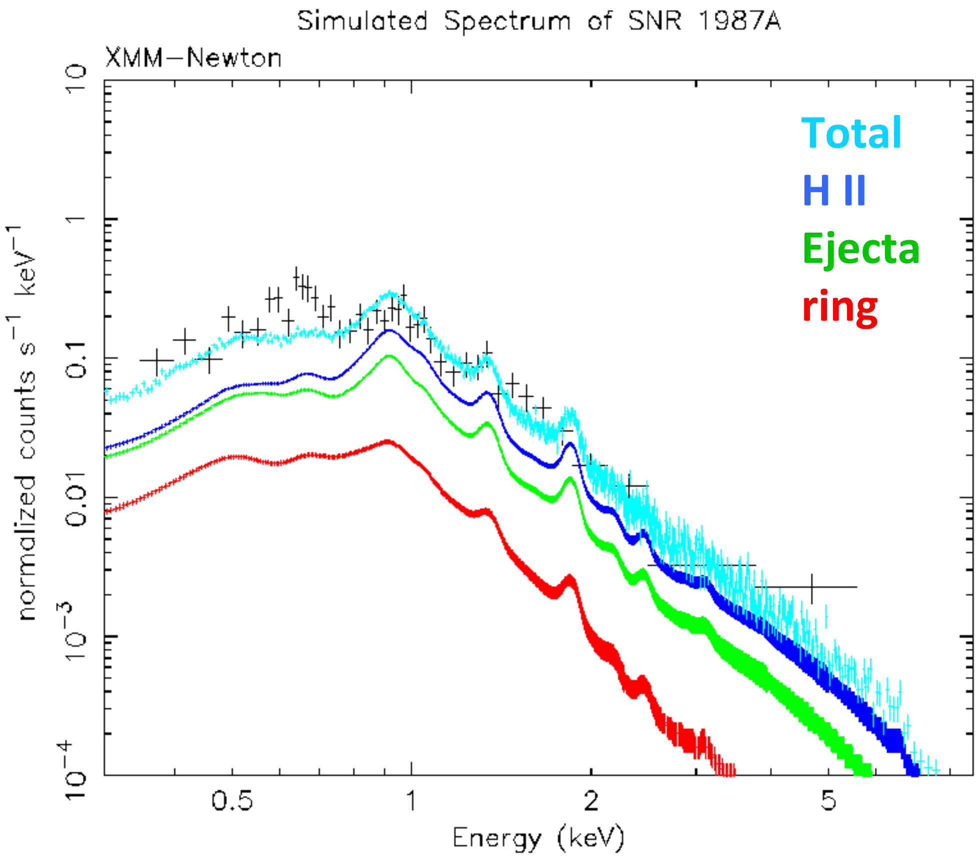
Synthetic fluxes and images





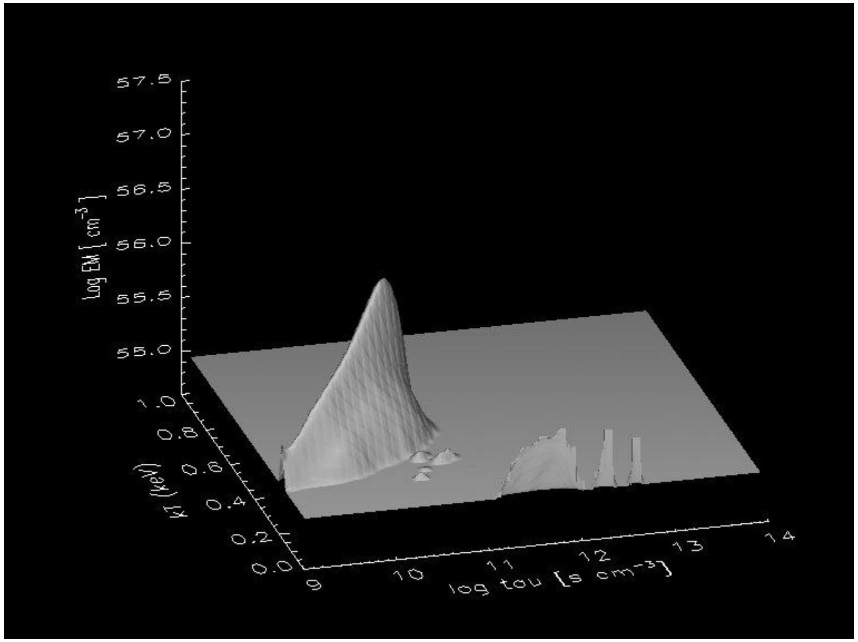


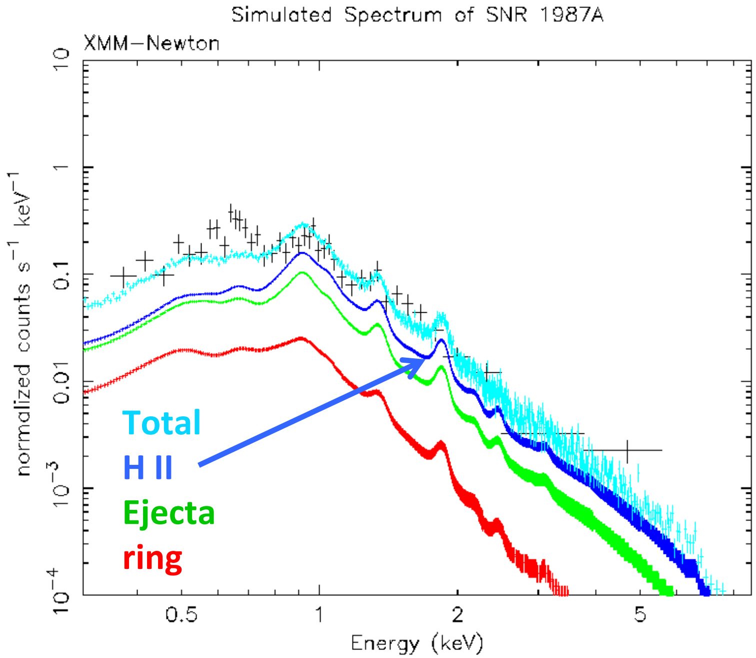
XMM spectra in 2001 (HII region dominated)



Both 2001 XMM EPIC data and the corresponding synthetic spectra can be fitted by an isothermal optically thin plasma in NEI with kT = 1.7±0.4 keV and τ = 2±1×10^{10} s cm^{-3}

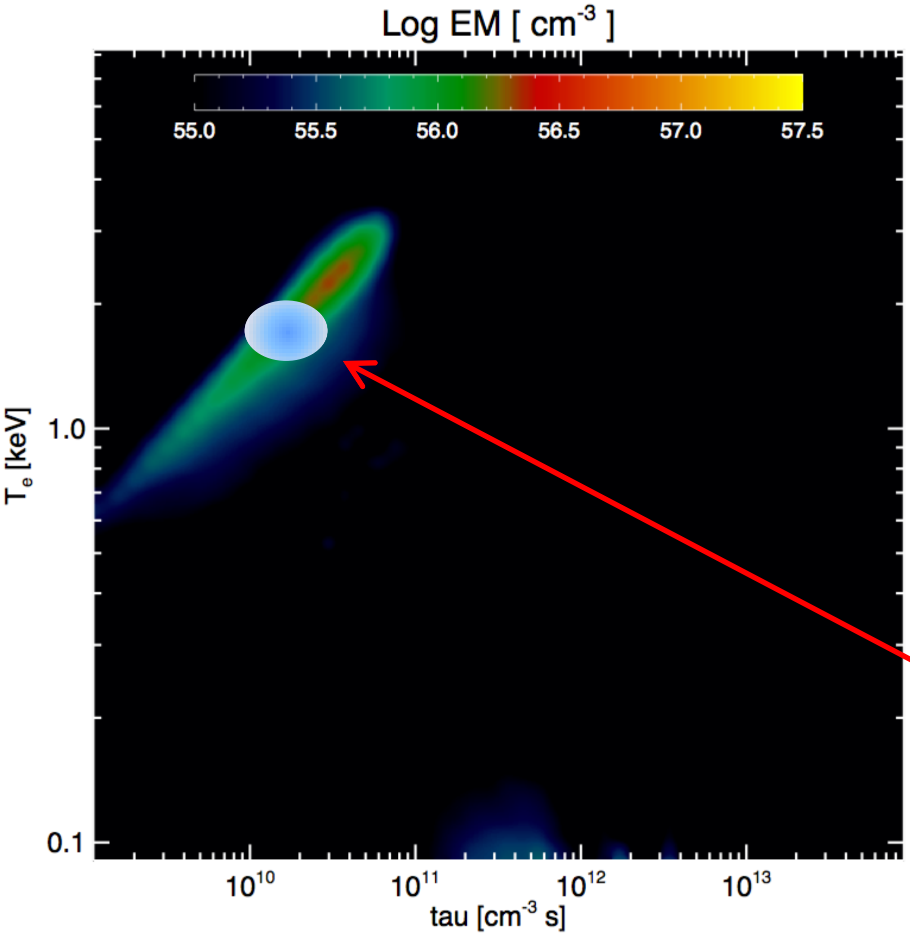
XMM spectra in 2001 (HII region dominated)

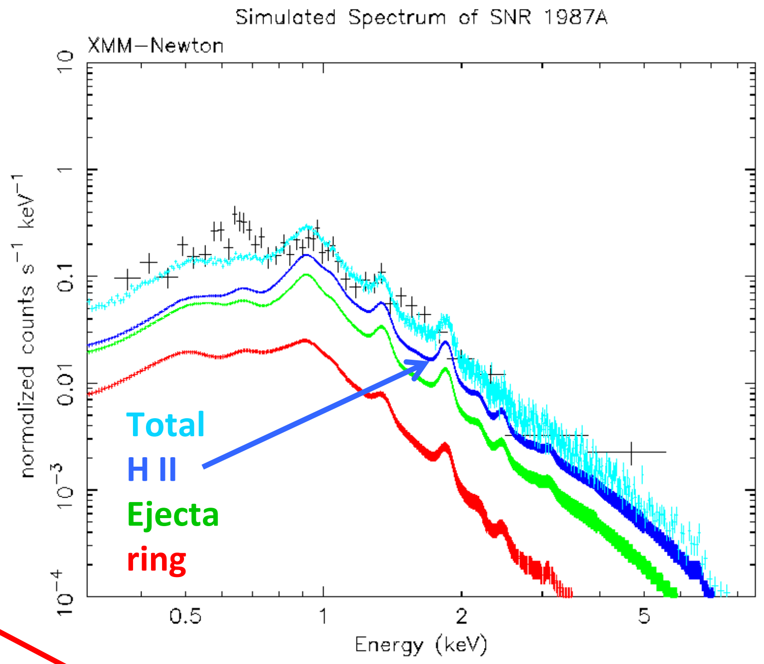




Though XMM EPIC spectra can be modelled by a **single thermal component**, the actual distribution of EM (T,τ) is quite complex

XMM spectra in 2001 (HII region dominated)

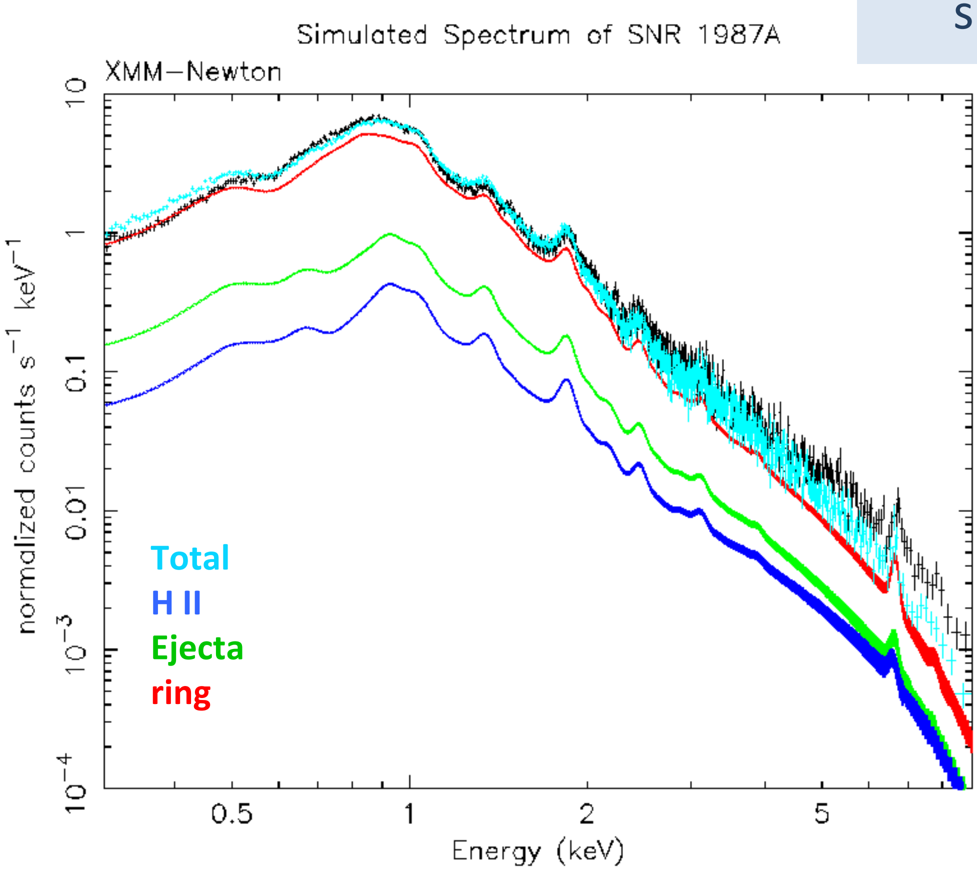




Though XMM EPIC spectra can be modelled by a **single thermal component**, the actual distribution of EM (T,τ) is quite complex

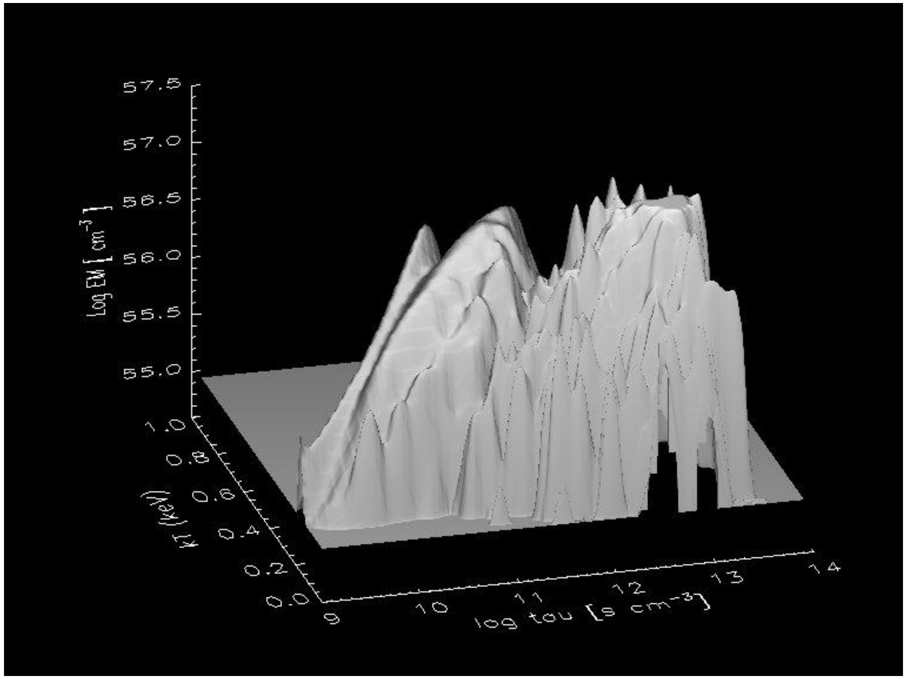
XMM spectra in 2013 (ring dominated)

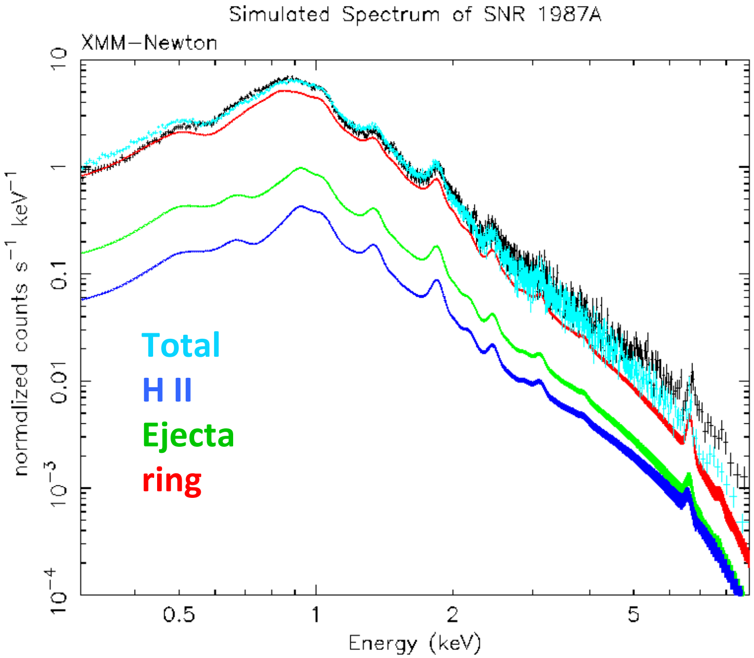
Same HD model fits the spectra at all epochs



Both 2013 XMM EPIC data and the corresponding synthetic spectra can be fitted by **3 thermal components**

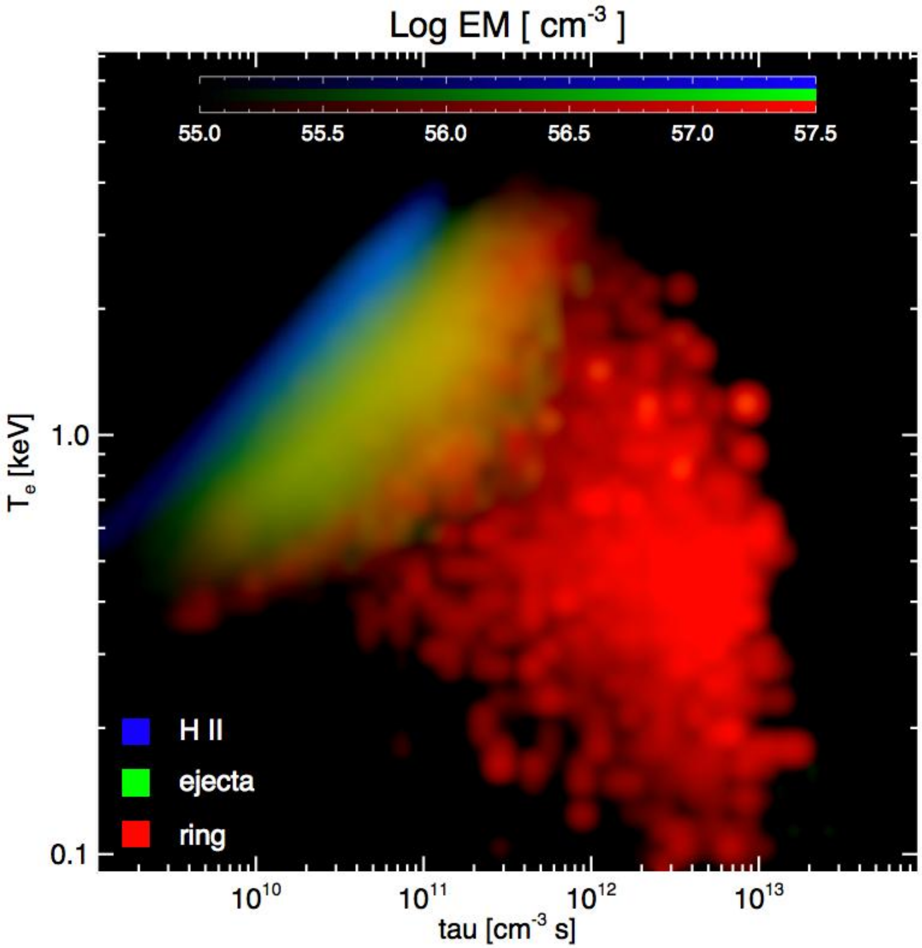
XMM spectra in 2013 (ring dominated)

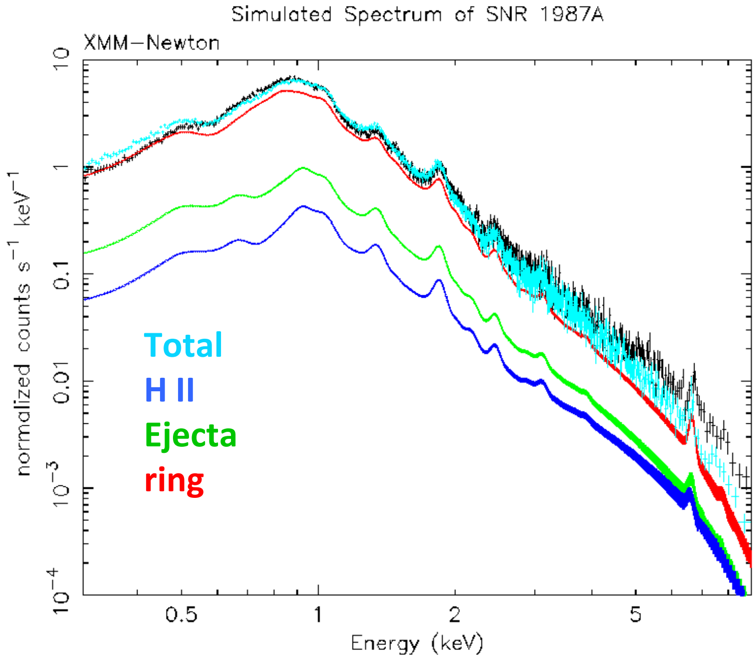




The 2013 spectrum is the result of an extremely complex distribution of temperatures and ionization parameters with different contributions from HII region, ring and ejecta

XMM spectra in 2013 (ring dominated)



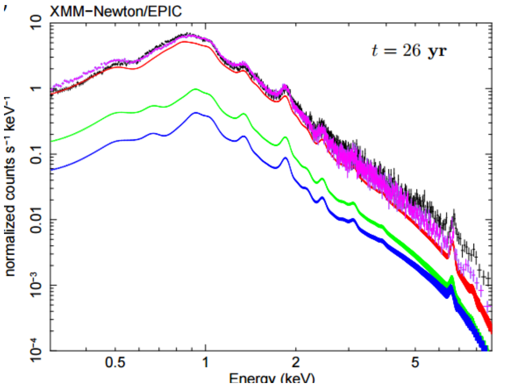


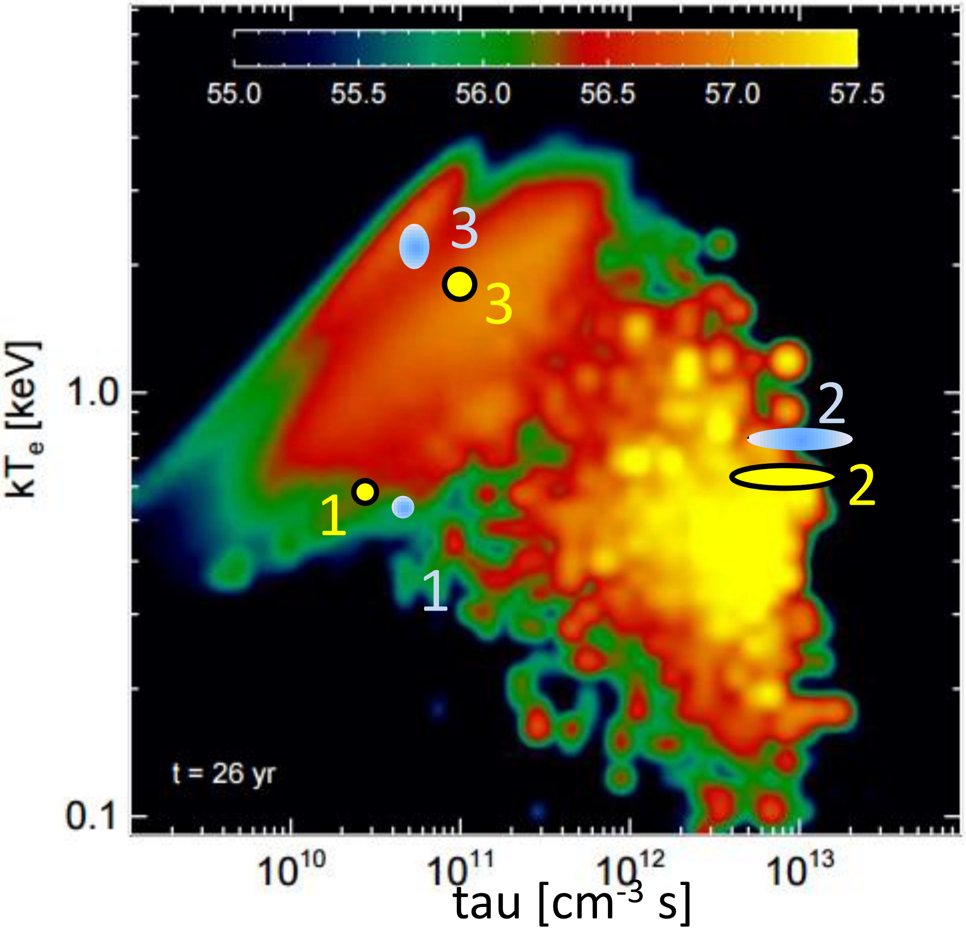
The 2013 spectrum is the result of an extremely complex distribution of temperatures and ionization parameters with different contributions from HII region, ring and ejecta

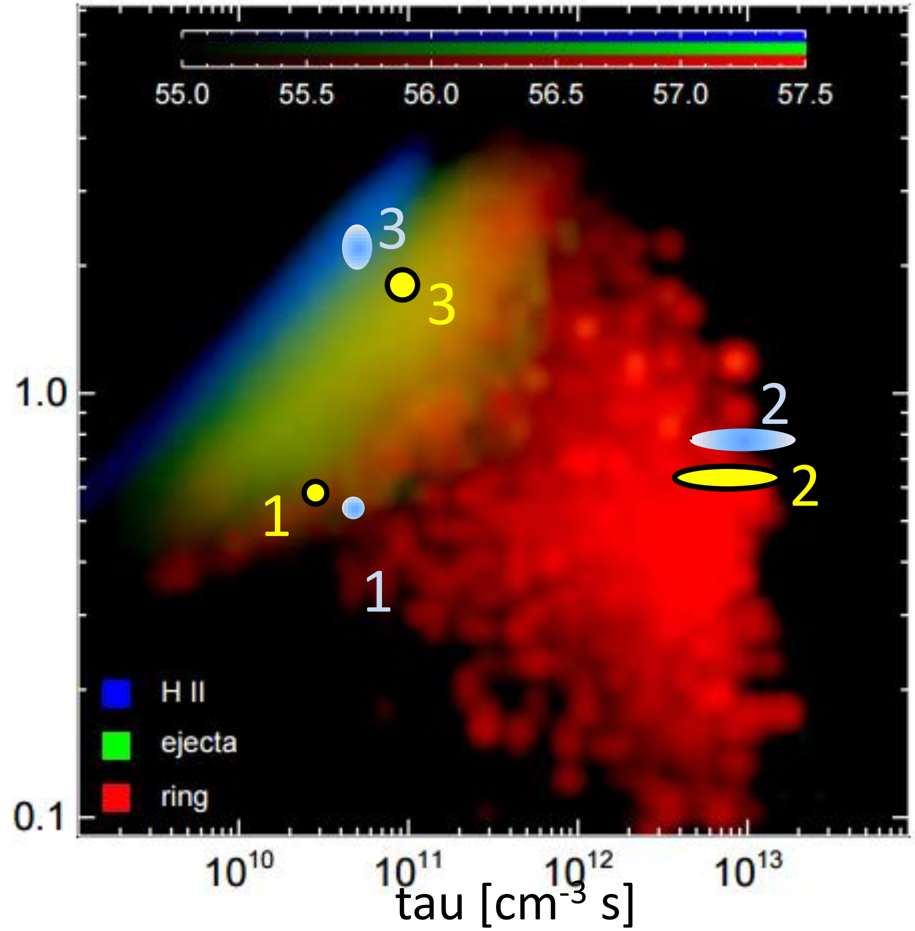
Synthetic X-ray spectra (2013)

Data: EM_1=1.8±0.1, EM_2=2.0±0.1, EM_3=0.75±0.05 (10^{59} cm^{-3})

Model: EM_1=0.95, EM_2=2.4, EM_3=1.1 (10^{59} cm^{-3})



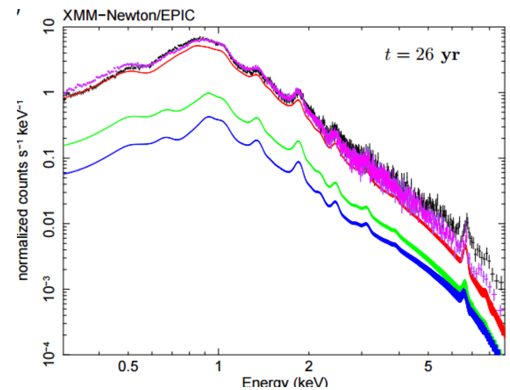


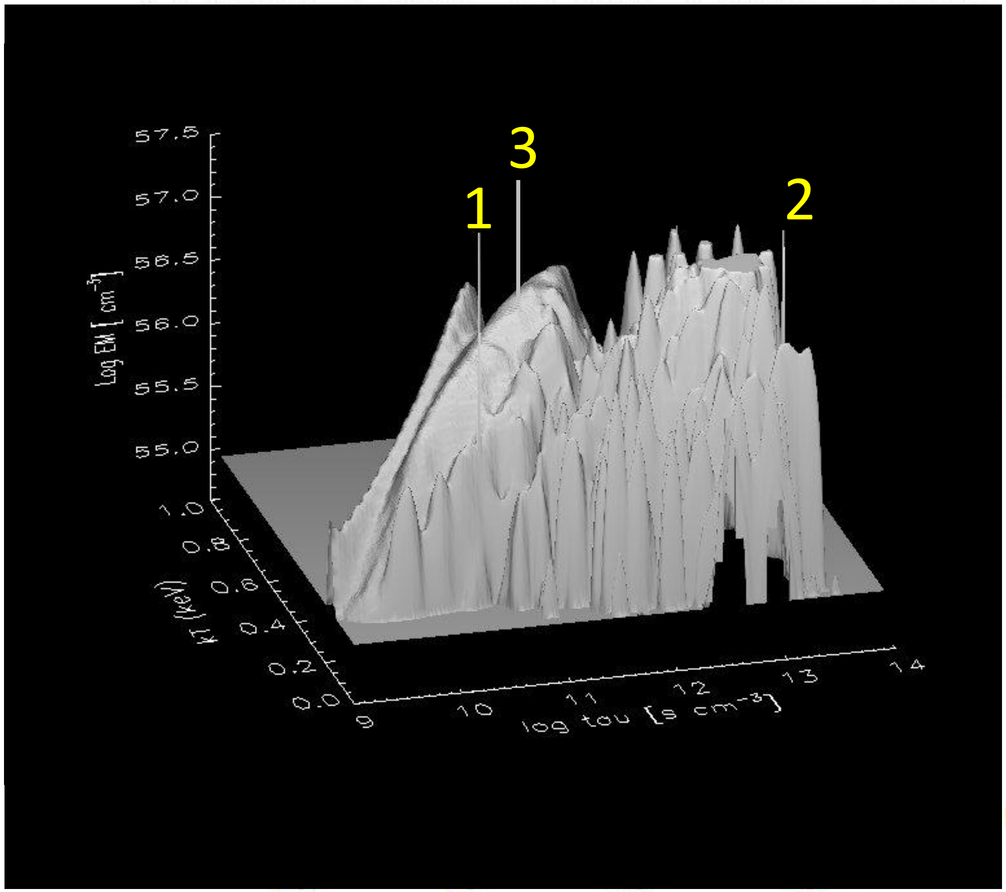


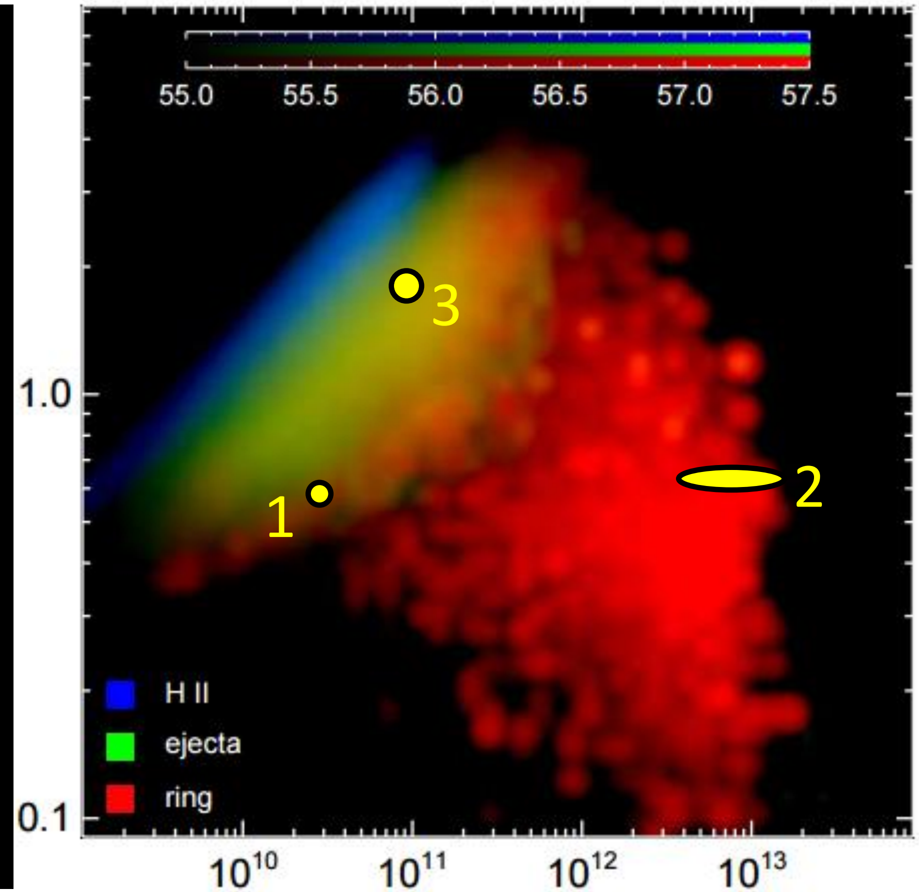
Complex physical origin of the components

Synthetic X-ray spectra (2013)

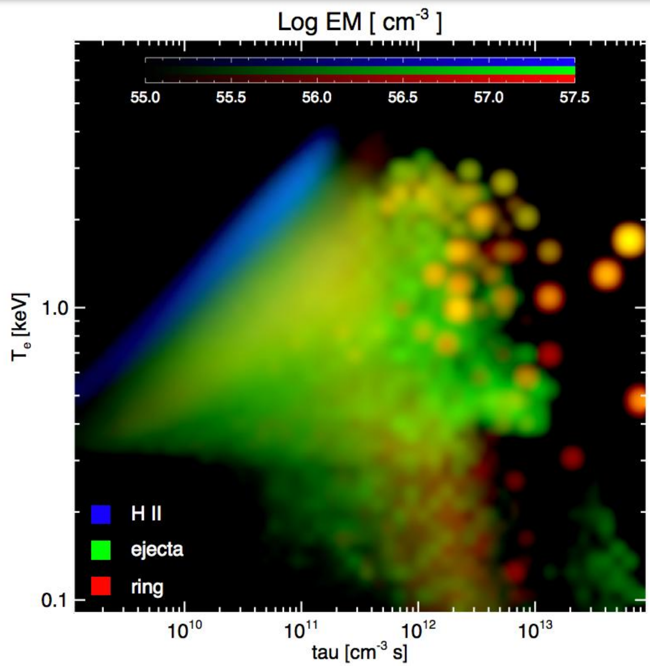
The isothermal components do *not* obviously reflect the actual physical conditions of the plasma

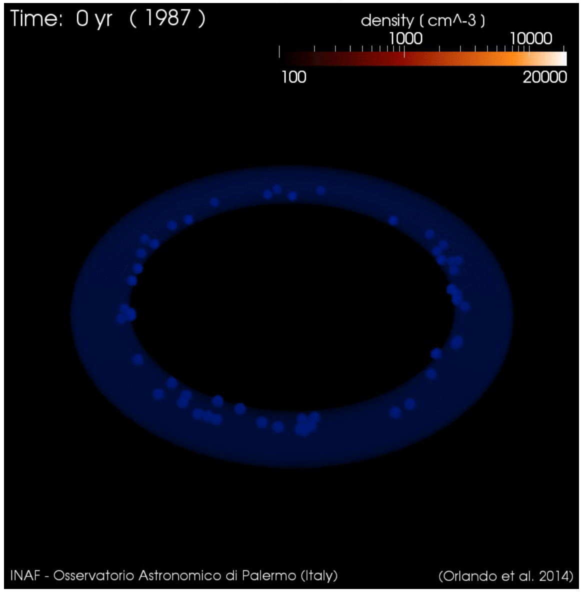


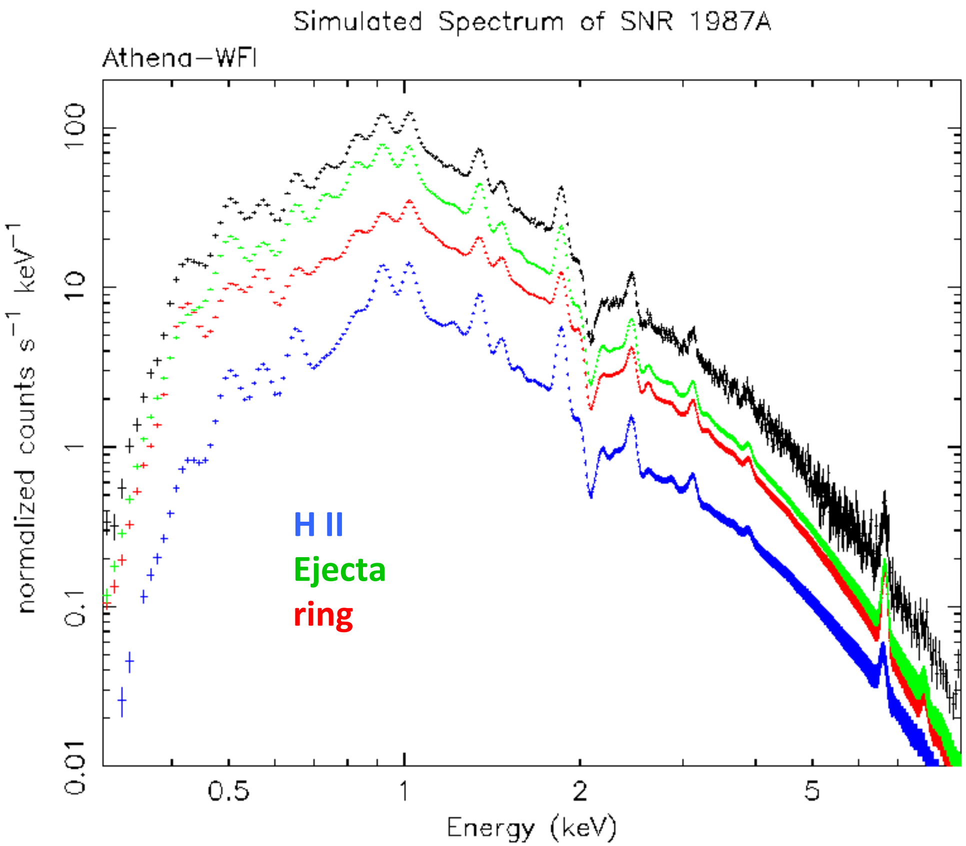




Athena X-ray spectra in 2028 (ejecta dominated)







The contribution of the ejecta will be dominant in a few years

Conclusions

The wealth of X-ray observations of SN 1987A requires a thorough data analysis: **phenomenological models only analize single observations,** regardless of the whole succession of data sets, **and the best-fit parameters do not necessarily describe the actual physical conditions**

We investigate all the available (and future) data sets with a **<u>unique hydrodynamic model</u>** that **accounts self-consistently for the single observations and for the evolution of the system**

The synthesis of observables from the HD simulations allows us to

- Test the model
- Make quantitative predictions
- Get a deep physical insight on the origin of the observed emission
- Constrain the physical and chemical parameters of the X-ray emitting plasma (CSM and ejecta) with the high-res. spectroscopy

Acknowledgements

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