3D HYDRODYNAMIC MODELING OF SN 1987A FROM THE SUPERNOVA EXPLOSION TILL THE ATHENA+ ERA

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Outline

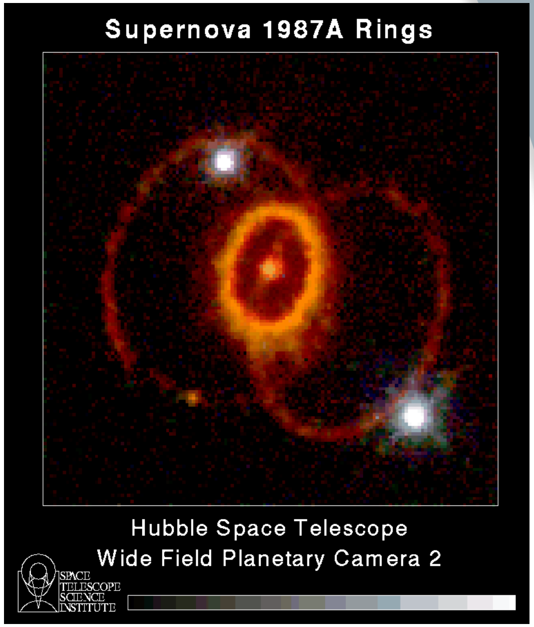
- Observed interaction of the SNR with the inner equatorial ring
- Aims of this project
- Modeling the SN explosion and subsequent SNR evolution
- Comparison with observations: X-ray lightcurves and spectra
- Predictions on the future evolution ⇨ Athena+
- Summary and Conclusions

SN 1987A

The remnant of SN 1987A provides a unique opportunity to investigate the evolution of a CC SNR during the early phase of its evolution:

- Probe the structure of the CSM immediately surrounding the SN
  (clues on the final stages of the star's evolution)

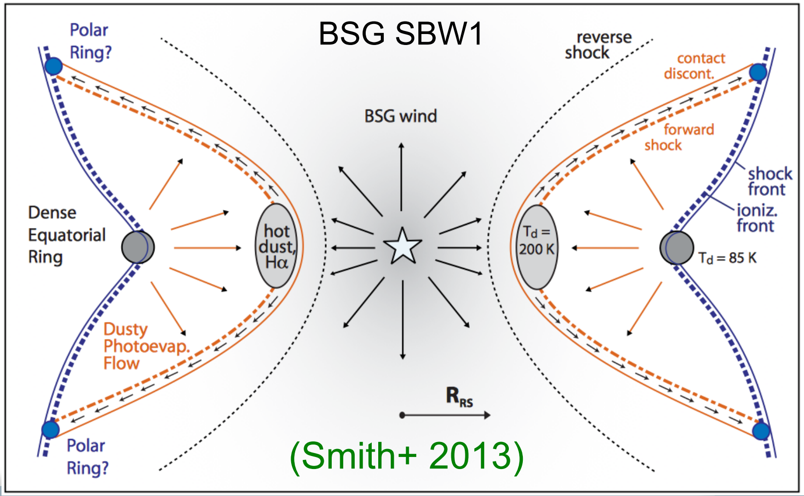
- Probe the structure of the ejecta
  (clues on the dynamics of the SN explosion)



Origin of the CSM

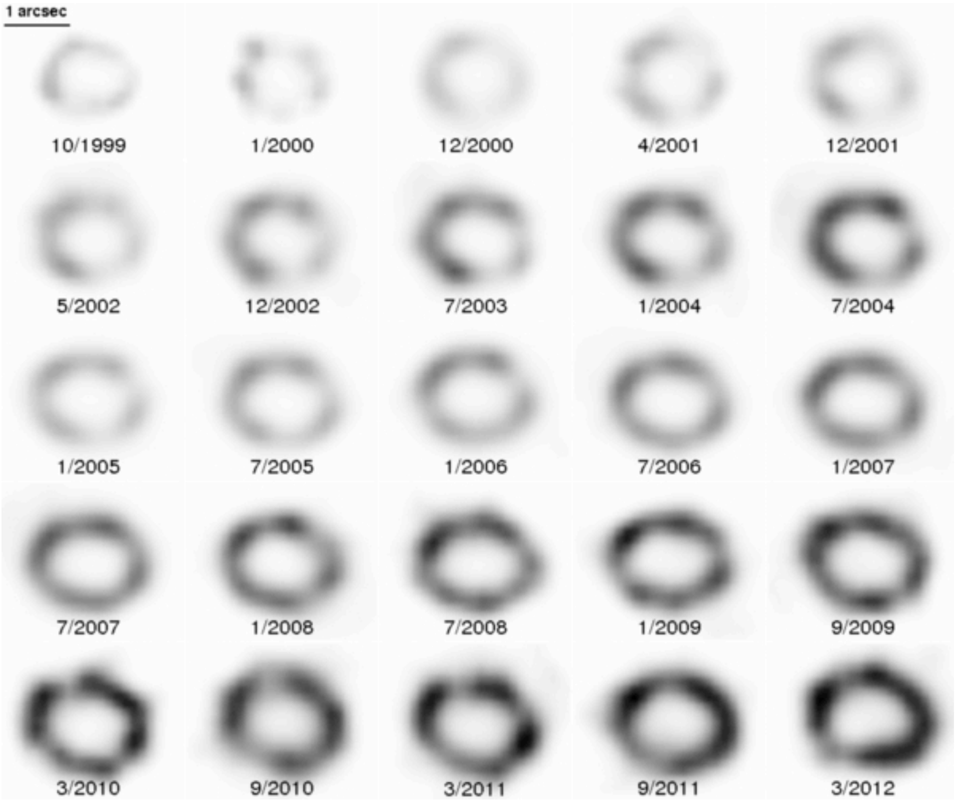
interaction of a slow wind from the red supergiant phase with the faster wind from the blue supergiant phase
(e.g. Luo & McCray 1991;
Morris & Podsiadlowski 2007).

Currently, the explosion is sweeping up the inner equatorial ring that was formed by the late stages of the star's evolution.

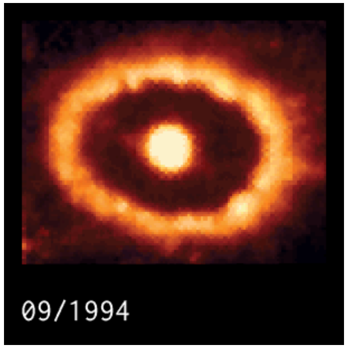


(Smith+ 2013)

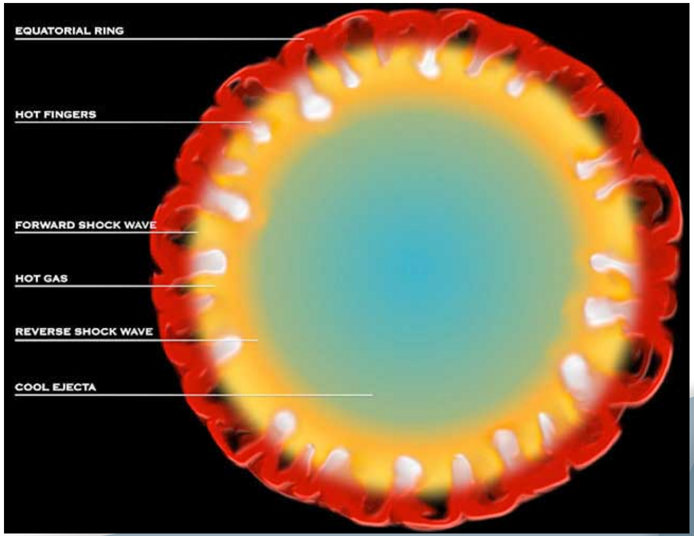
Interaction with the inner equatorial ring



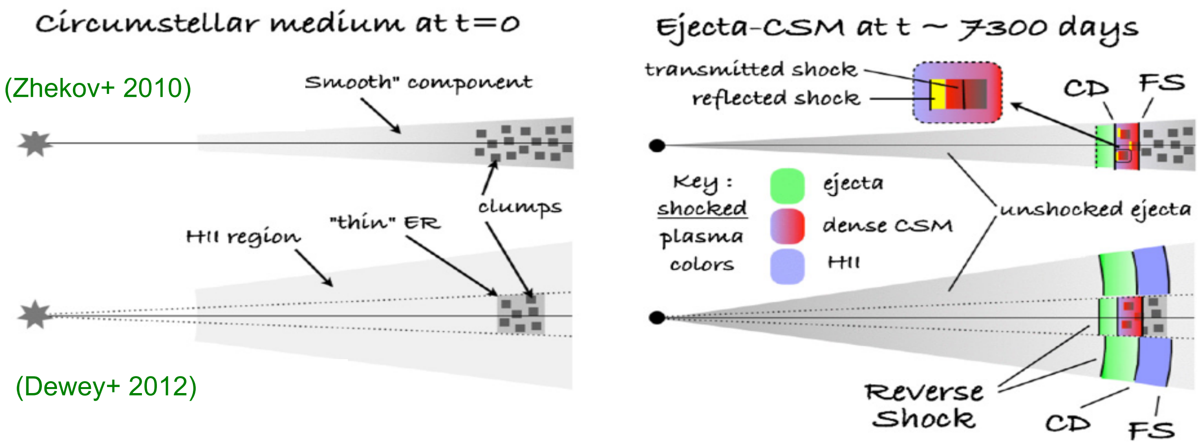
Estimated intrinsic morphology (corrected for the *Chandra* PSF) of SN 1987A (Helder+ 2013)



A time sequence of Hubble Space Telescope (Larsson+ 2011)



Modeling the emission of SN 1987A



Origin of X-ray emission: interpretation of the observations

Proposed model consisting of 3 emitting components (Zhekov+ 2010; Dewey+ 2012):

1) material in the dense ring heated by a slow shock (500 km s^{-1}); T_e ~0.3–0.5 keV

2) shock-heated CSM (HII region) located above and below the equatorial ring

3) shocked plasma, reheated by a reflected shock caused by the interaction with the equatorial ring (Zhekov+ 2010) or, alternatively, fast shock traveling through a uniform equatorial ring material (Dewey+ 2012); T_e ~ 3keV

Aims of this project

We describe the three-dimensional evolution of SN 1987A from the immediate aftermath of the SN explosion (~ 20 hrs) to its expansion in the SNR with high model resolution and taking into account all relevant physical processes

We compare model results with observations to derive:

- the physical parameters characterizing the progenitor star (mass of ejecta and energy of explosion)
- the density structure of the CSM immediately around the SN
- the contribution of the different shocked plasma components to the observed X-ray emission and spectra

We use the model to derive preditions on the future evolution of the remnant until the Athena+ era

Modeling the supernova explosion

Initial distribution of ejecta for the 3D SNR model

derived from a 1D relativistic, radiation-hydrodynamics Lagrangian code, specifically tailored to simulate the evolution of the main observables in core-collapse SNe

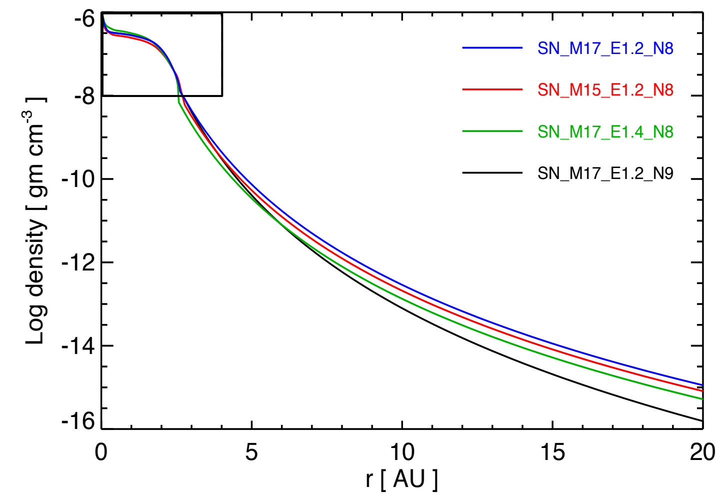
(Pumo & Zampieri 2011)

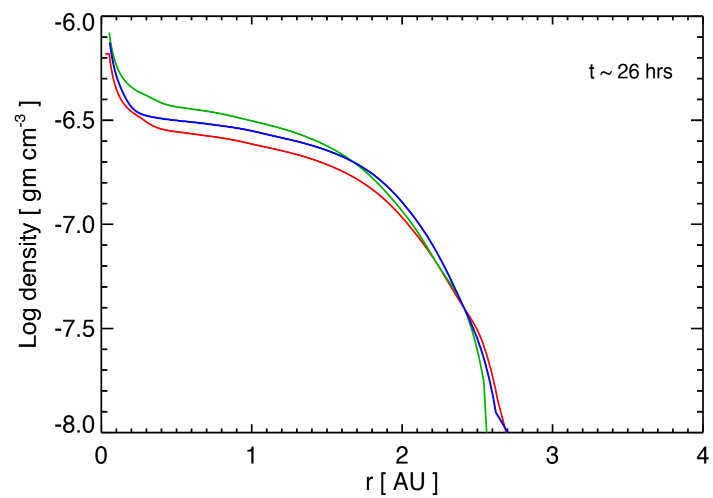
- Fully general relativistic treatment
- Radiative transfer coupled to relativistic hydrodynamics at all regimes
- Gravitational effects of the central compact remnant on the evolution of the ejecta (fallback of material onto the compact remnant; amount of ejected ^{56}Ni)

We follow the SN evolution from the breakout of the shock wave at the stellar surface up to the so-called nebular stage

Grid of models (see also Pumo & Zampieri 2011)

		range of values explored	best-fit values
envelope mass	$(M_{\odot})$	$8-18$	$15-17$
Energy	$(10^{51}$ erg$)$	$1-2$	$1.2-1.4$





Modeling the SNR evolution

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \ ,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} + \nabla P = 0 \ ,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{u} = -n_{\rm e} n_{\rm H} \Lambda(T) \ ,$$

$$\text{where} \qquad E = \epsilon + \frac{1}{2}|\mathbf{u}|^2 \ ,$$

- 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

Initial conditions

20 hours after the SN explosion

Spatial resolution

A major challange was capturing the enormous range in spatial scales

- 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)

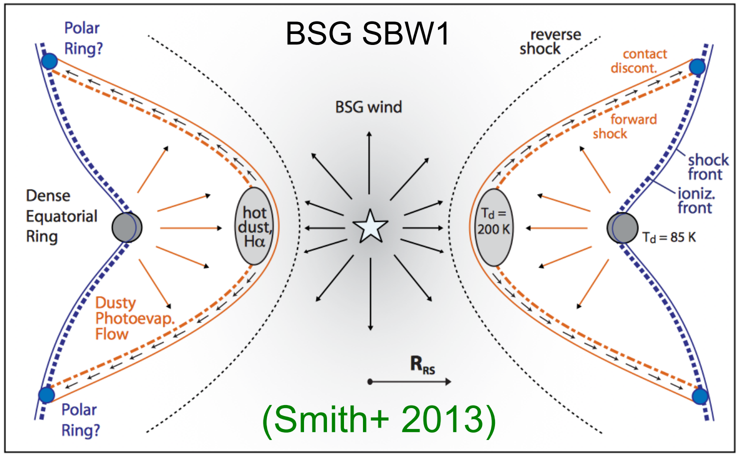
> 100 cells per remnant radius during the whole evolution

Equivalent uniform grid ~ 1e6 X 1e6 X 1e6

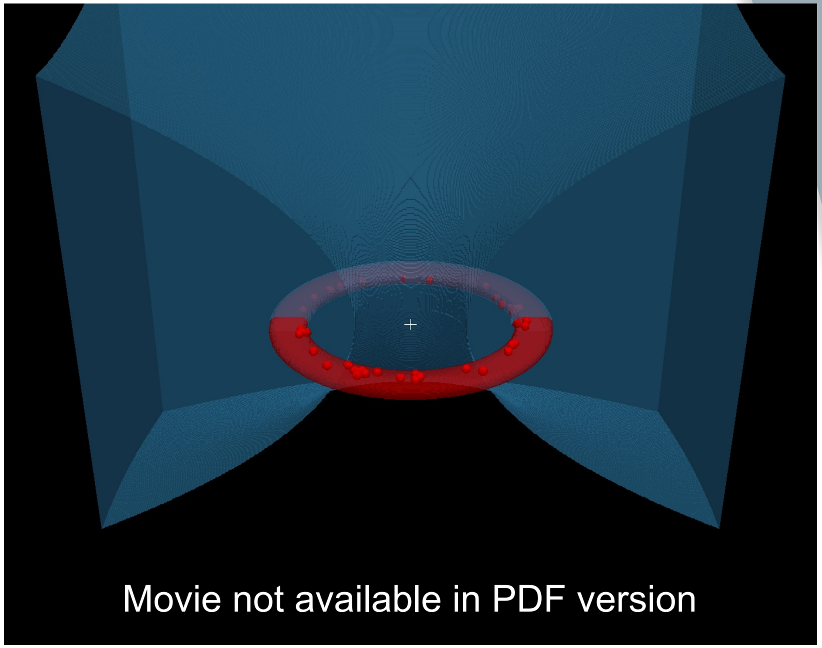
FLASH code (Univ. of Chicago)

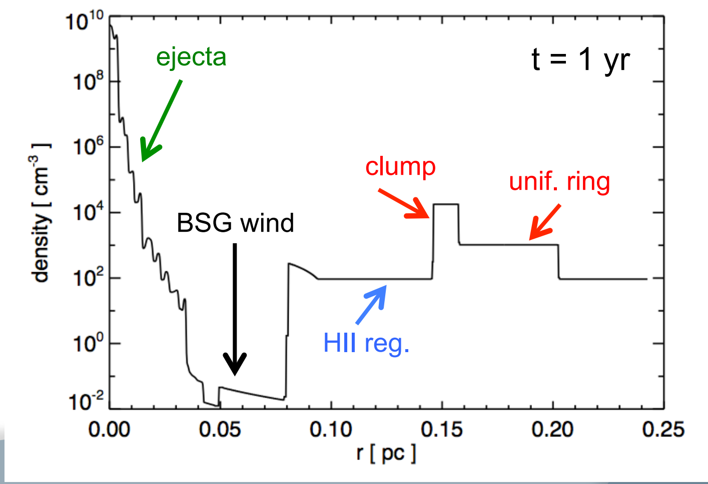
PRACE Award N.2012060993

Initial conditions and parameter space



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





The evolution of SN 1987A

Our model

$M_{rg} \sim 0.062\ M_{sun}$

$\sim 0.040\ M_{sun}$ @ $n = 10^3\ cm^{-3}$

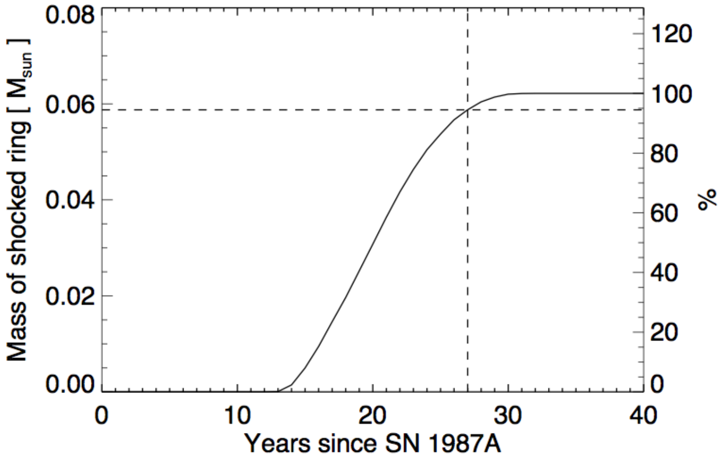
$\sim 0.022\ M_{sun}$ @ $n \sim 2.5 \times 10^4\ cm^{-3}$

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

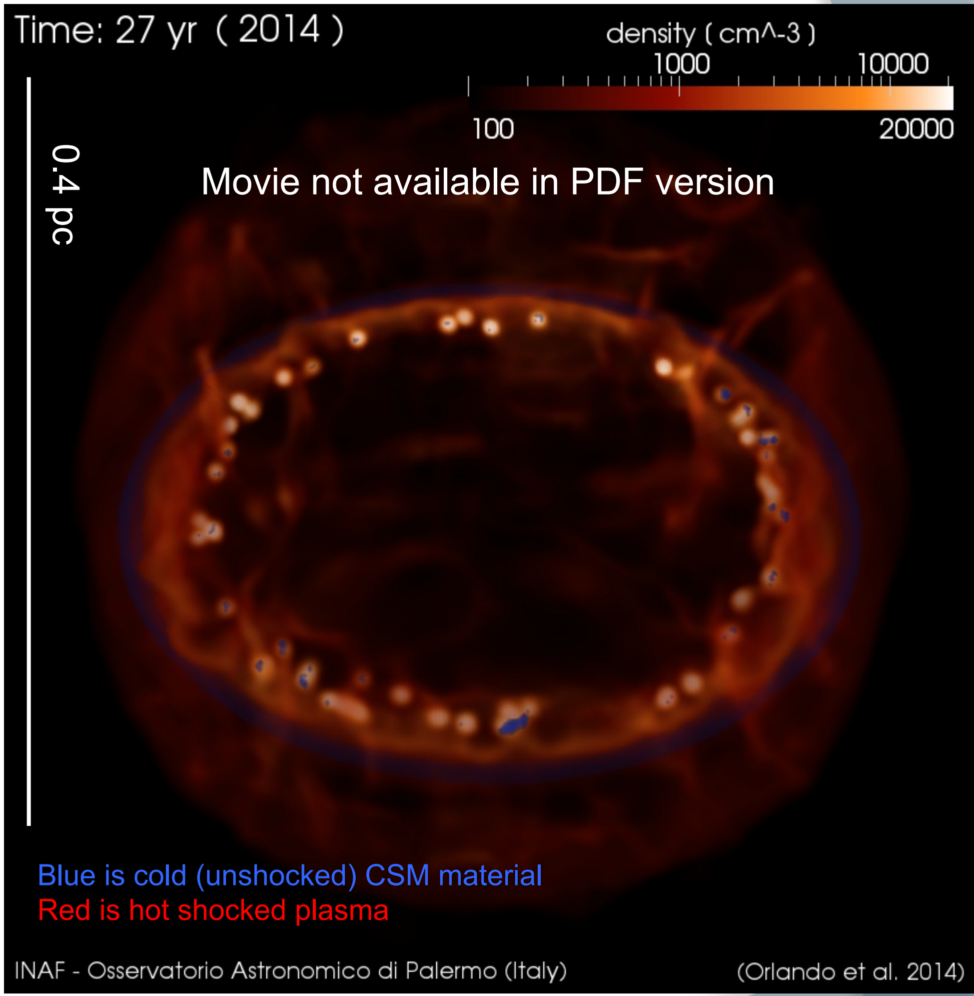
$M_{rg} \sim 0.058\ M_{sun}$

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

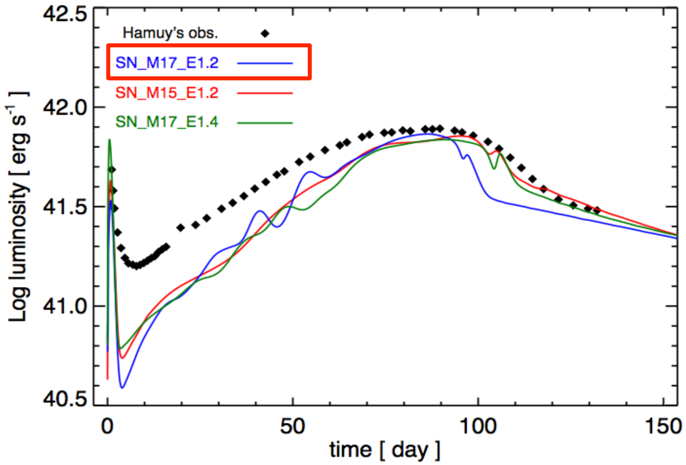
$\sim 0.012\ M_{sun}$ @ $n \sim 3 \times 10^4\ cm^{-3}$



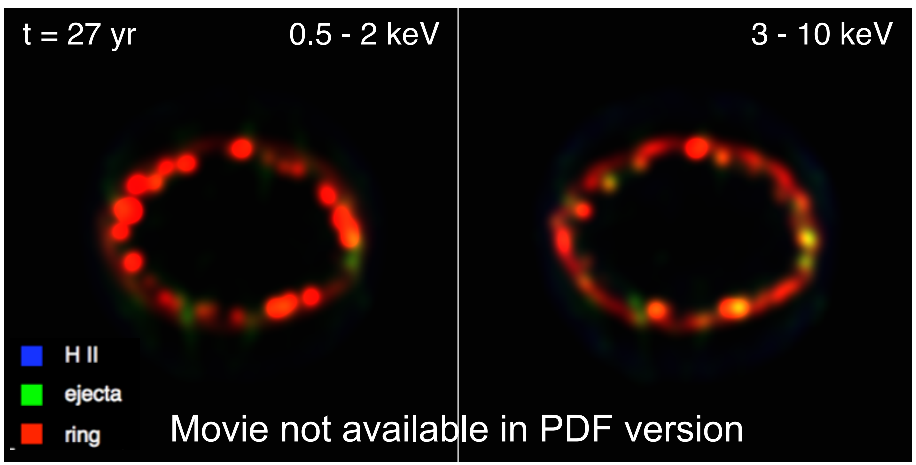
~ 95% of the ring material has been shocked at the current time (2014)



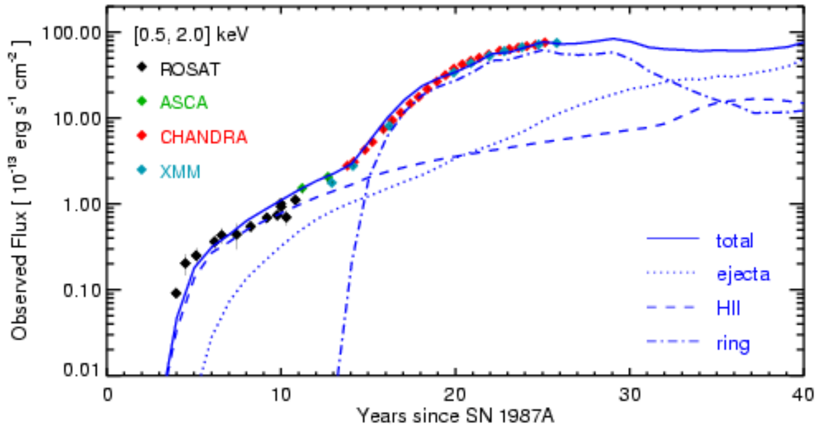
Lightcurves

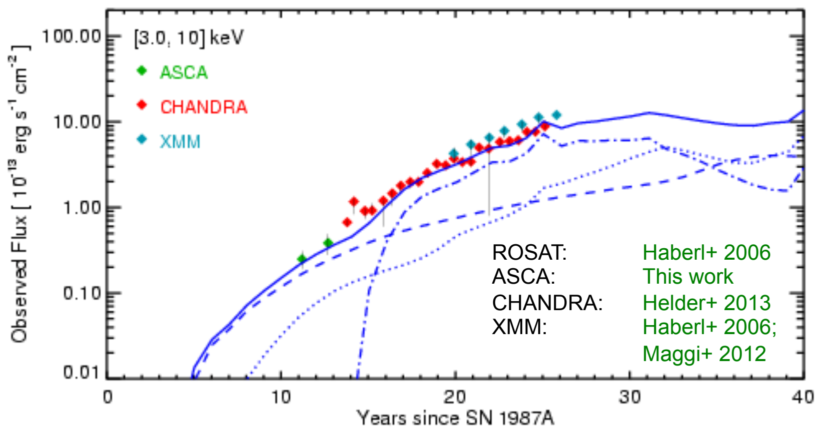


Bolometric lightcurves of the SN models compared to that observed (Hamuy+ 1988)



Each image is normalized to its maximum



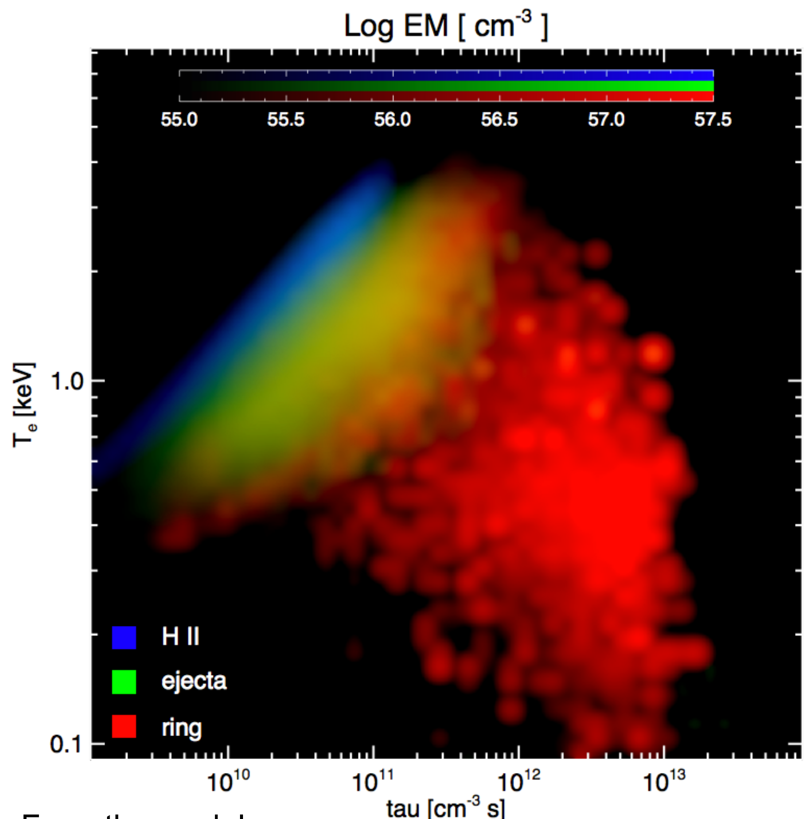


Abundances from Zhekov+ (2009)

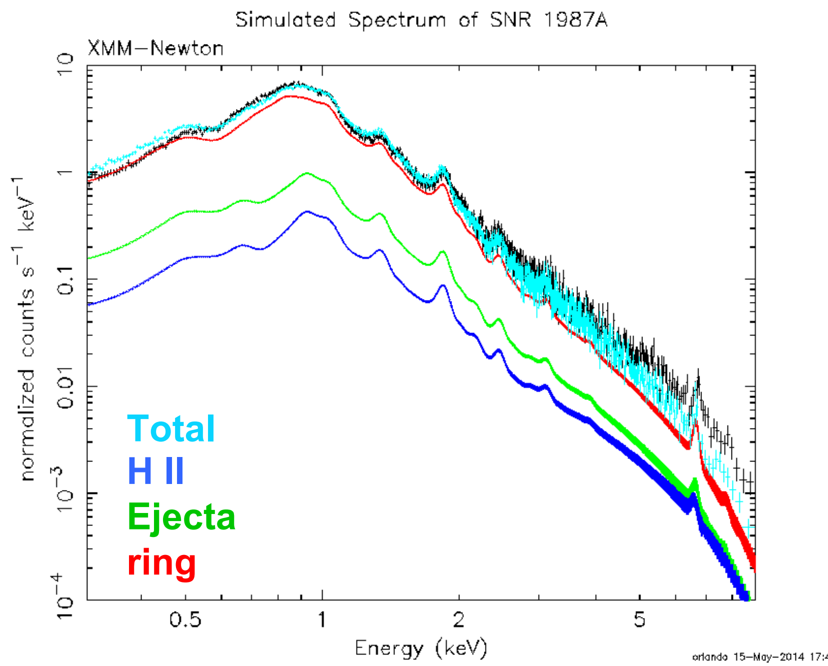
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

Distance: 51.4 kpc (Panagia 1999)

X-ray spectra in 2013 (XMM-Newton)



From the model

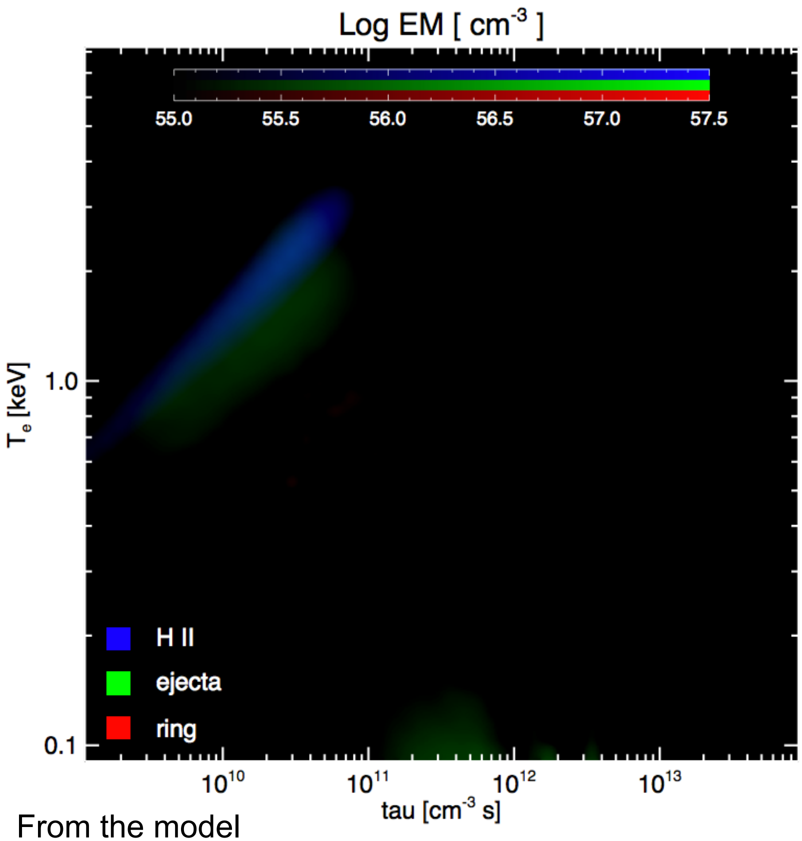


Abundances from Zhekov+ (2009)

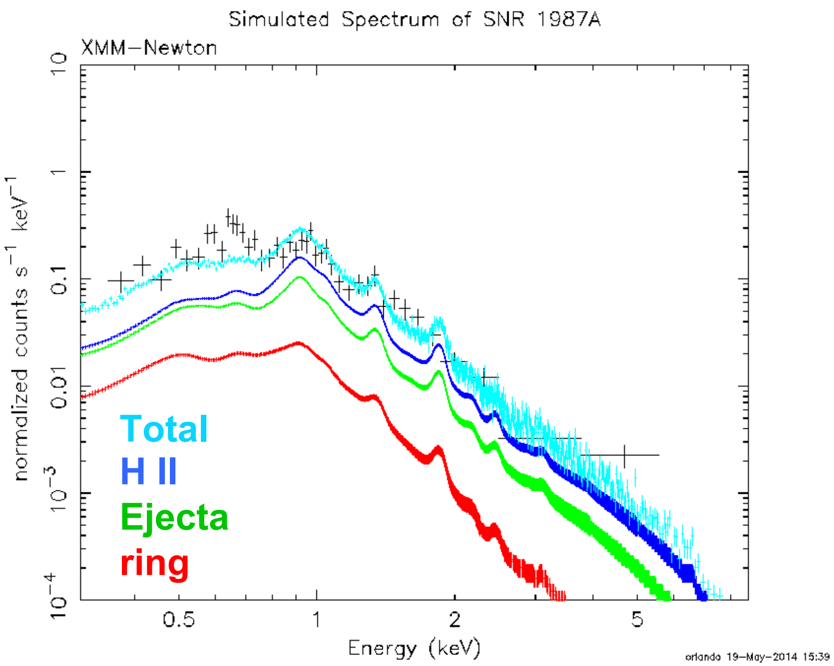
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

Distance: 51.4 kpc (Panagia 1999)

X-ray spectra in 2001 (XMM-Newton)



From the model

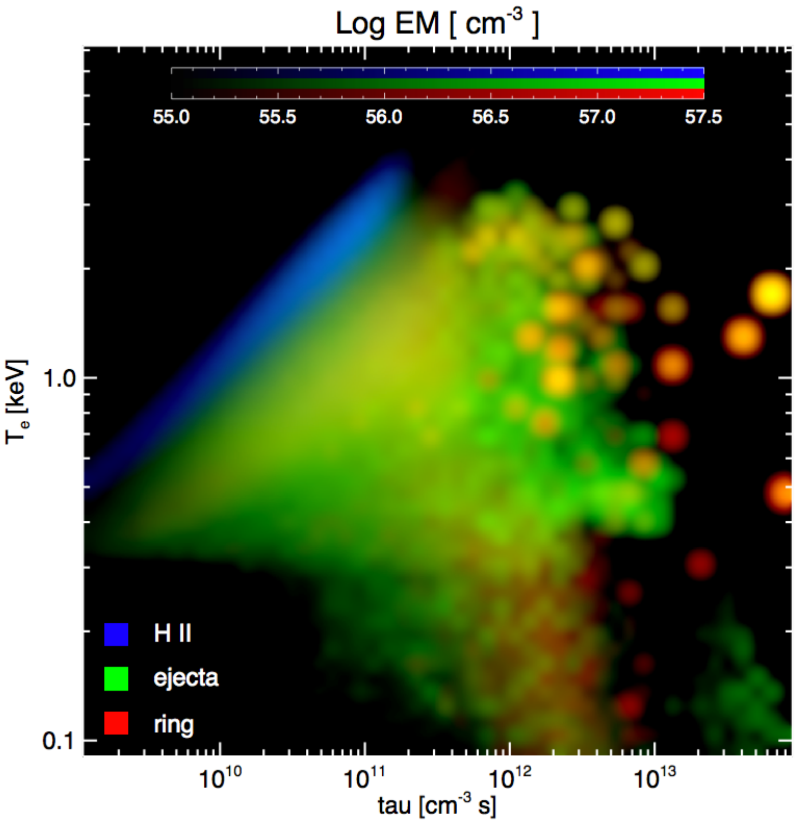


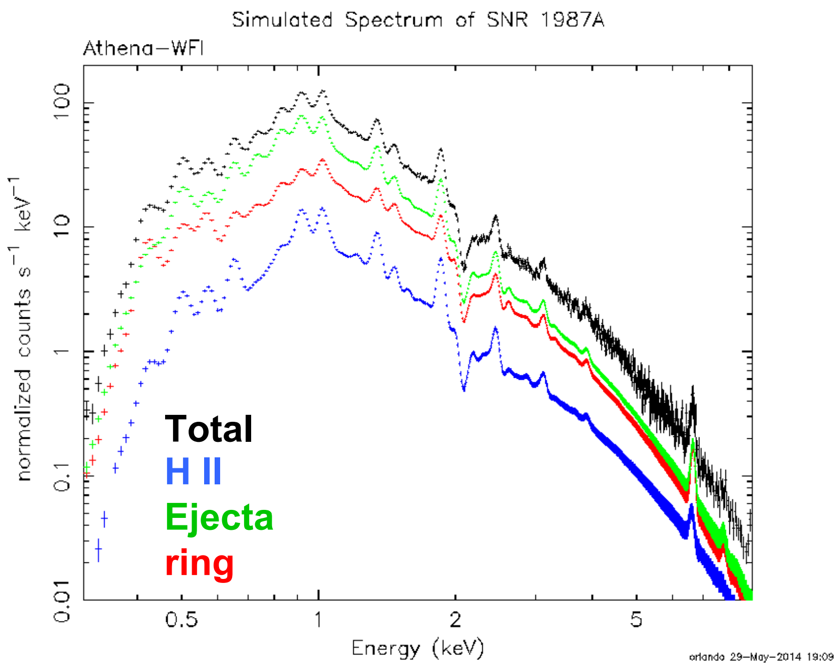
Abundances from Zhekov+ (2009)

ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

Distance: 51.4 kpc (Panagia 1999)

X-ray spectra in 2028 (Athena+)





Abundances from Zhekov+ (2009)

ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

Distance: 51.4 kpc (Panagia 1999)

Summary and conclusions

3D hydrodynamic model describing the evolution of SN 1987A from the immediate aftermath of the SN explosion (~ 20 hrs) to its expansion in the SNR

⇒ high spatial resolution and accounting of all relevant physical processes

- Model validation: comparison with observations
  - observed bolometric lightcurve of the SN explosion (first 150 days);
  - X-ray lightcurves during the interaction of the SNR with the surrounding CSM;
  - low-resolution spectra (XMM-Newton/EPIC) at different epochs;

  ⇒ physical parameters characterizing the SN explosion and the CSM

- Data interpretation

  The model allows to determine the contribution of the different plasma components to the observed emission and offers a unique opportunity for accurate data interpretation; (high-resolution grating spectra)

- Predictions on the future evolution of SNR 1987A

  Shocked ejecta will dominate the contribution in the X-ray band very soon

  ⇒ 87A will allow to probe the structure of the ejecta (clues on the dynamics of the SN explosion)