Bridging the gap between SNe and their remnants through multi-dimensional hydrodynamic modeling

Salvatore Orlando

INAF - Osservatorio Astronomico di Palermo, Italy

M. Miceli	***Università di Palermo, Italy***
O. Petruk	***INAF – Oss. Astr. di Palermo, Italy***
F. Bocchino	***INAF – Oss. Astr. di Palermo, Italy***
G. Peres	***Università di Palermo, Italy***

La Reunion, France, Feb. 2017

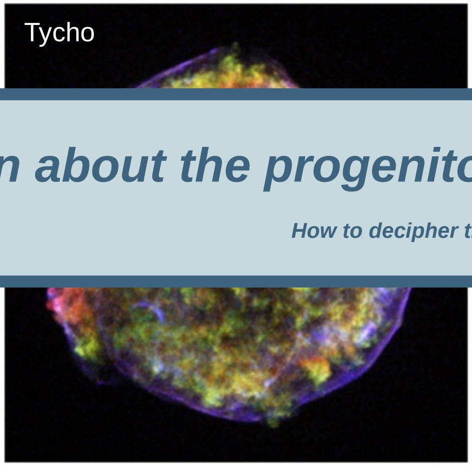
Supernova Remnants

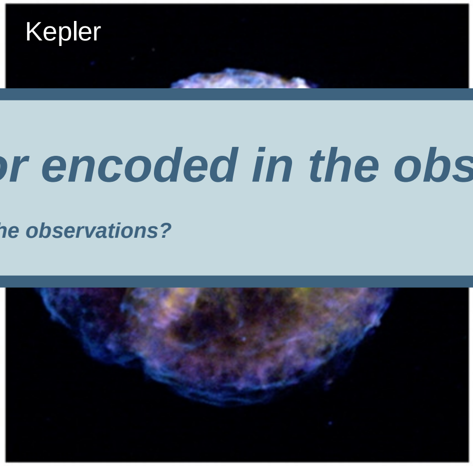
Supernova Remnants

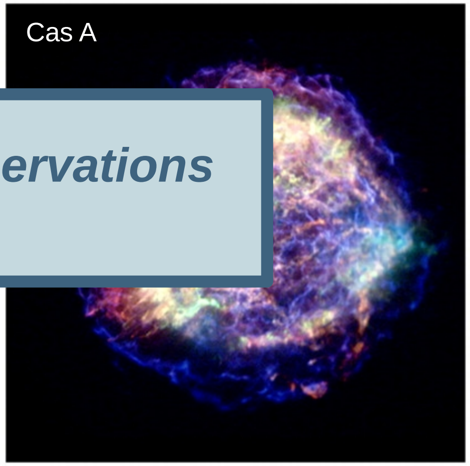
- **Extended sources with a complex morphology**
- **highly non-uniform distribution of ejecta**
- **propagation of ejecta drives shocks back and forth in the ISM and through ejecta themselves**

Multi-wavelength Observations

- **Thermal and non-thermal emission**
- **Low- and high-resolution spectra**
- **Morphology, projected distributions of properties**
- **Evolution, dynamics**







Information about the progenitor encoded in the observations

How to decipher the observations?

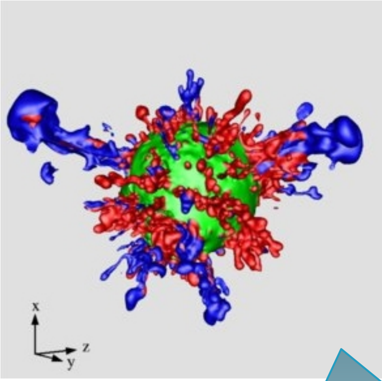
The link between SNe and SNRs

The morphological properties of SNRs may reflect

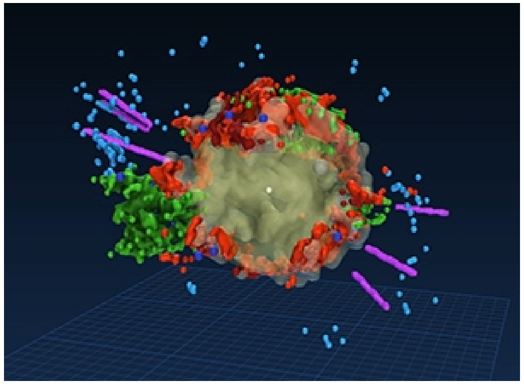
- **pristine structures and features of the progenitor SN explosion**
- **the physical and chemical properties of the progenitor SN**

Investigating the intimate link between the morphological properties of a SNR and the complex phases in the SN explosion

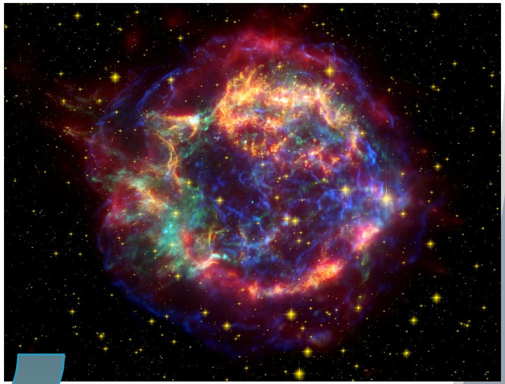
- **trace back the structure and chemical composition of SN ejecta, and the dynamics and energetics of the SN explosion**



SN explosion
(Hammer et al. 2010)



Structure of the SNR
(De Laney et al. 2010)



Morphology of the SNR
(Cassiopeia A - Chandra)

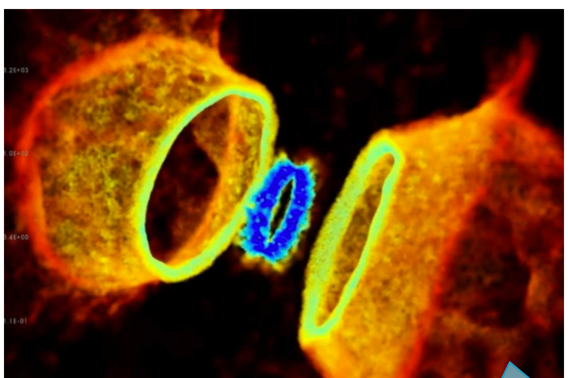
The link between SNRs and SNe

The morphological properties of SNRs may also reflect

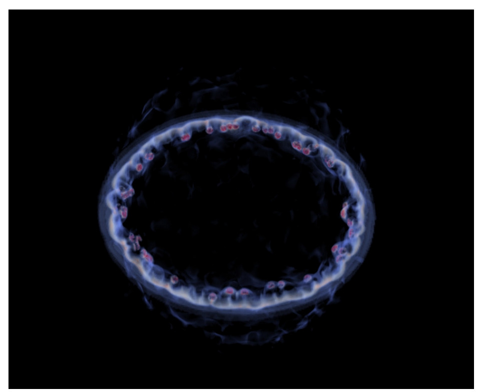
- **Early interaction of the SN blast with the inhomogeneous CSM**
- **CSM: formed during the latest stages of the progenitor's evolution**

Analyzing the morphology of a SNR

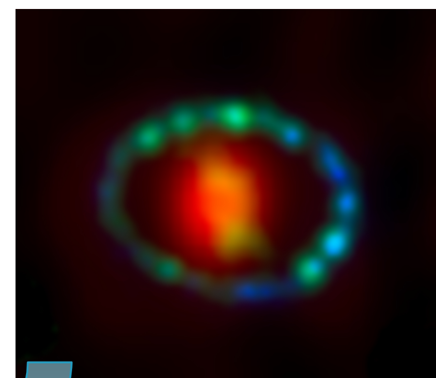
- **probe the structure and geometry of the CSM immediately surrounding the SN, providing important clues on the final stages of stellar evolution**



Structure of the pre-SN CSM
(Morris & Podsiadlowski 2009)



Blast wave-CSM interaction
(Orlando et al. 2015)



Morphology of the SNR
(SN 1987 A)

THE GOAL:
Connect the SNRs morphology and properties to their SNe and star progenitors

an essential step to open new exploring windows on SN and SNR issues

How to link SNe to SNRs ?

In general models describe either the SN evolution or the expansion of the remnant

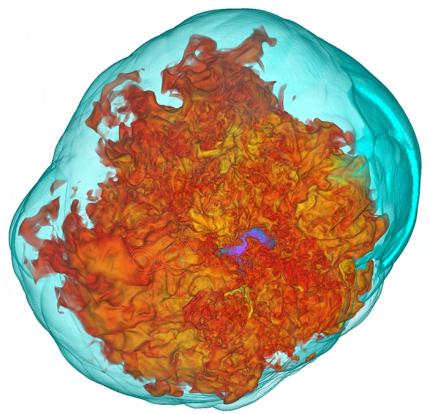
- **the former describe the SN evolution and not follow its subsequent interaction with the CSM**
- **the latter assume an initial parametrized ejecta profile (leaving out an accurate description of the ejecta soon after the SN explosion); describe the interaction with the environment**

Prevent to disentangle the effects of the initial conditions (i.e. the SN event) from those of the boundary conditions (i.e. the interaction with the environment)

Criticality: **Very different time and space scales of SNe and SNRs**

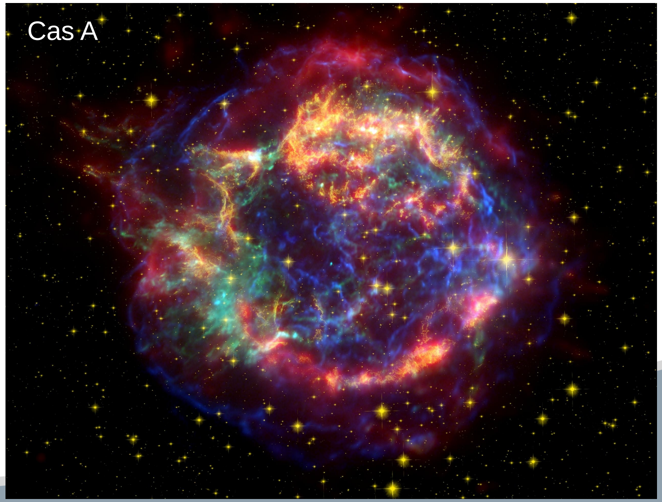
$\Rightarrow$ **difficult to study their connection in detail**

~ 10^9 cm



CC SN
t < 1 sec

~ 5 pc (~ 10^{19} cm)



SNR
t ~ 300 yr

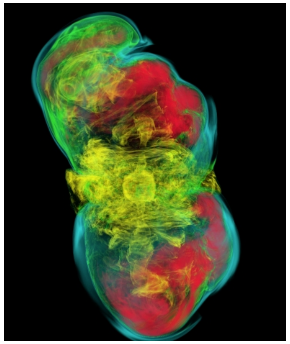
How to link SNe to SNRs ?

SN-SNR connection studied through 1D hydro models

The problem is inherently 3D

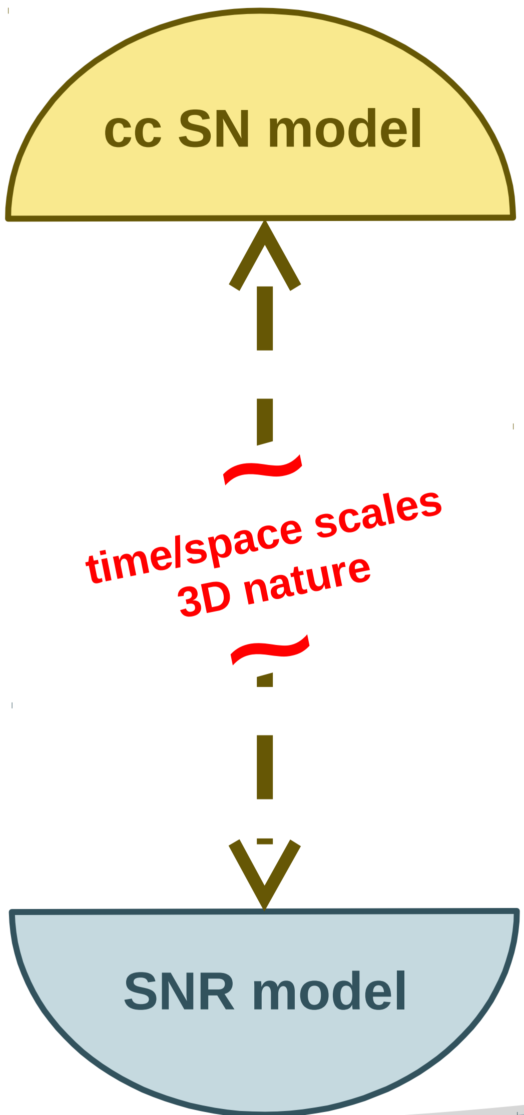
→ **huge amount of numerical resources**

- **SN explosion**
  - **Asymmetries (jets, knots, clumps, shrapnels)**
  - **Hydrodynamic instabilities (dense fingers)**
  - **Turbulence**
  - **Mixing of ejecta**



- **Ambient medium**
  - **Inhomogeneous CSM/ISM (nebula, rings, clouds, gradients of density)**
  - **Non-uniform ambient magnetic field (different obliquity angles)**
  - **Hydrodynamic instabilities**

How to link SNe to SNRs ?



Tools:

- **Numerical codes**
- **Adaptive mesh techniques**

Numerical resources:

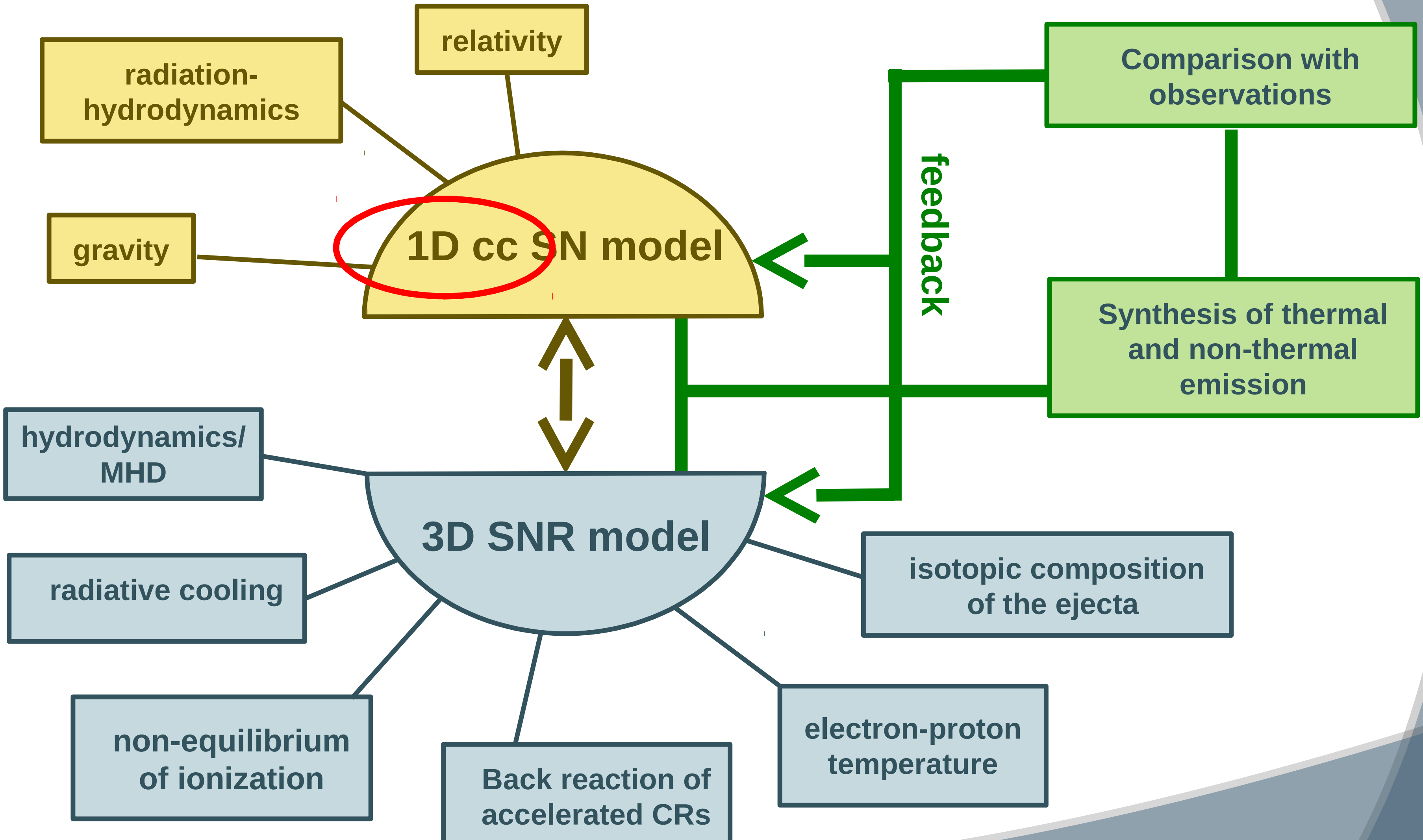
- **Large number of CPUs**
- **Memory (RAM, storage)**

(see M. Gabler's talk)

Requirements

- **Improve the communication between the SNe and SNRs communities** ***(IAUS 331)***
- **Improve our understanding of the final stages of stellar evolution**

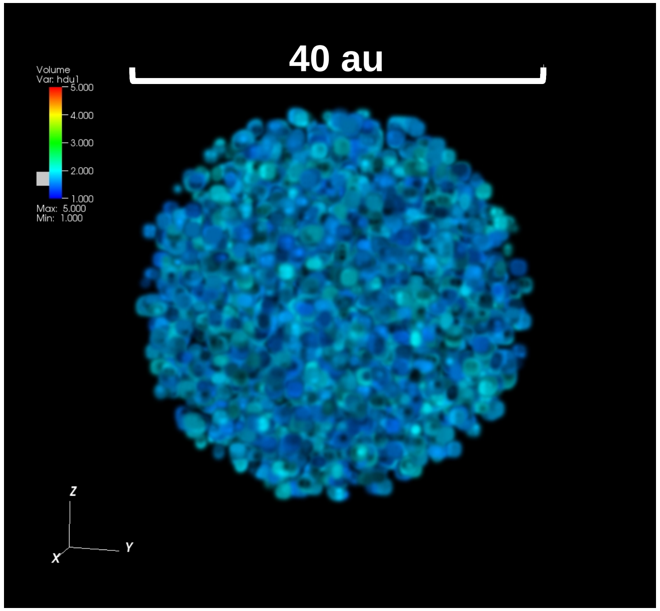
Link SNe to SNRs: The strategy



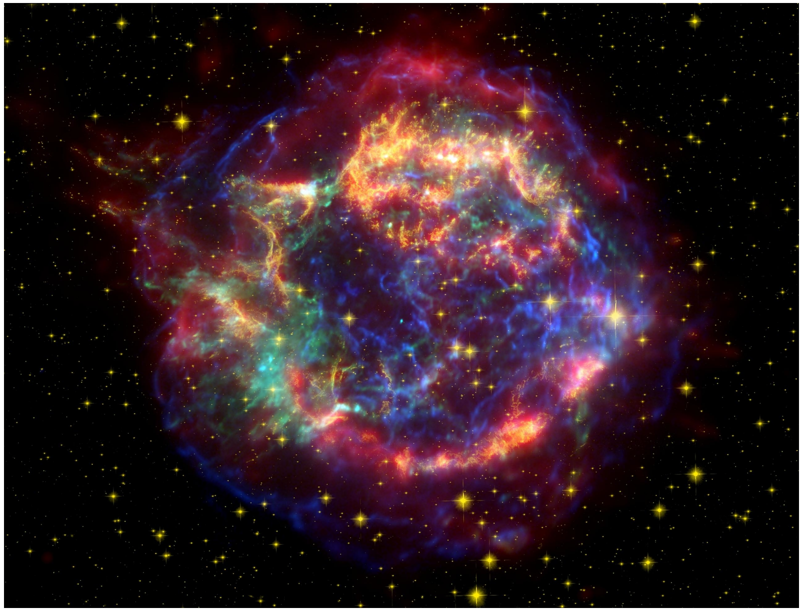
Modeling the SN-SNR evolution

A major challange is capturing the enormous range in spatial scales

Initial condition ~ 1 day after the SN event
Initial size ~ tens of AU



Final time ~ hundeds of yr (current age)
Final size several pc



18/20 nested levels of adaptive mesh refinement
→ **effective resolution ~ 0.2 AU (3e12 cm)**

> 100 cells per remnant radius during the whole evolution

Two study cases
- **Cas A**
- **SN 1987A**

Effects of SN anisotropies

The case of SNR Cassiopeia A

SNR Cassiopeia A

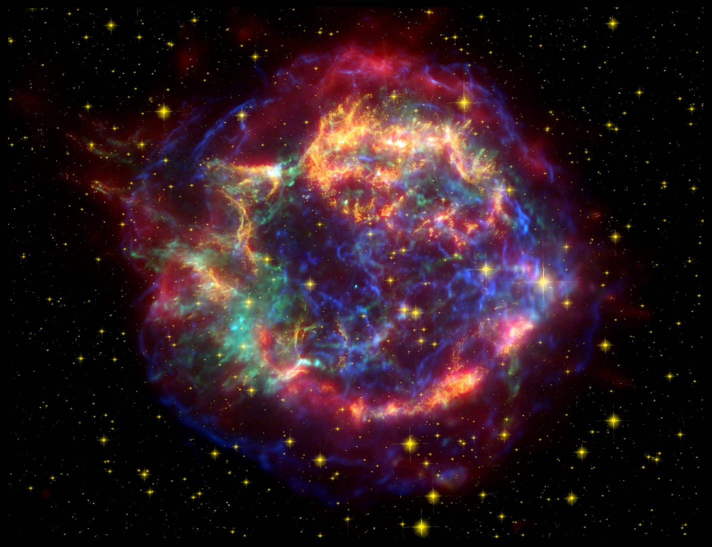
Observations suggest that its morphology and expansion rate are consistent with a remnant expanding through the wind of the progenitor red supergiant (e.g. Lee+ 2014)

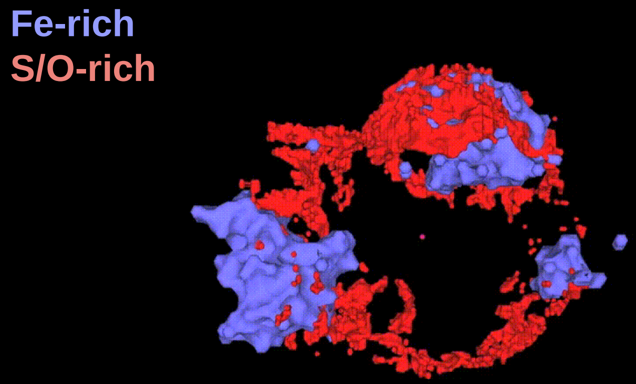
Cassiopeia A is an attractive laboratory to bridge the gap between SNe and their remnants

This remnant is one of the best studied and its 3D structure has been characterized in good detail

(e.g. DeLaney+ 2010, Milisavljevic & Fesen 2013, 2015)

- 3 Fe-rich regions
- 2 Si-rich jets
- Rings circling Fe-rich regions





(Milisavljevic & Fesen 2013)

Initial conditions and parameter space

Radial profiles of ejecta from the 1D cc SN model (Pumo & Zampieri 2011)

The 3D post-explosion structure of the ejecta is described by small-scale clumping of material and larger-scale anisotropies

(e.g. Kifonidis+ 2006; Wang & Wheeler 2008; Gawryszczak+ 2010)

- Small-scale clumping as in Orlando+ (2012)
- Large-scale anisotropies as overdense spherical knots

Parameters of large scale anisotropies

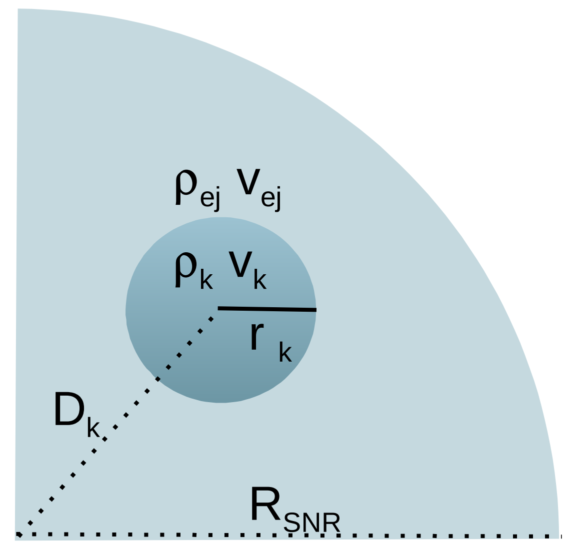
(Kifonidis+ 2003, Ellinger+ 2012)

D_k = [0.15 – 0.35] R_{SNR}

r_k = [3% - 10%] R_{SNR}

ρ_k = [10 – 100] ρ_{ej}

v_k = [1 – 10] v_{ej}



(Orlando+ 2016)

Spatial Distribution of the Cas A ejecta

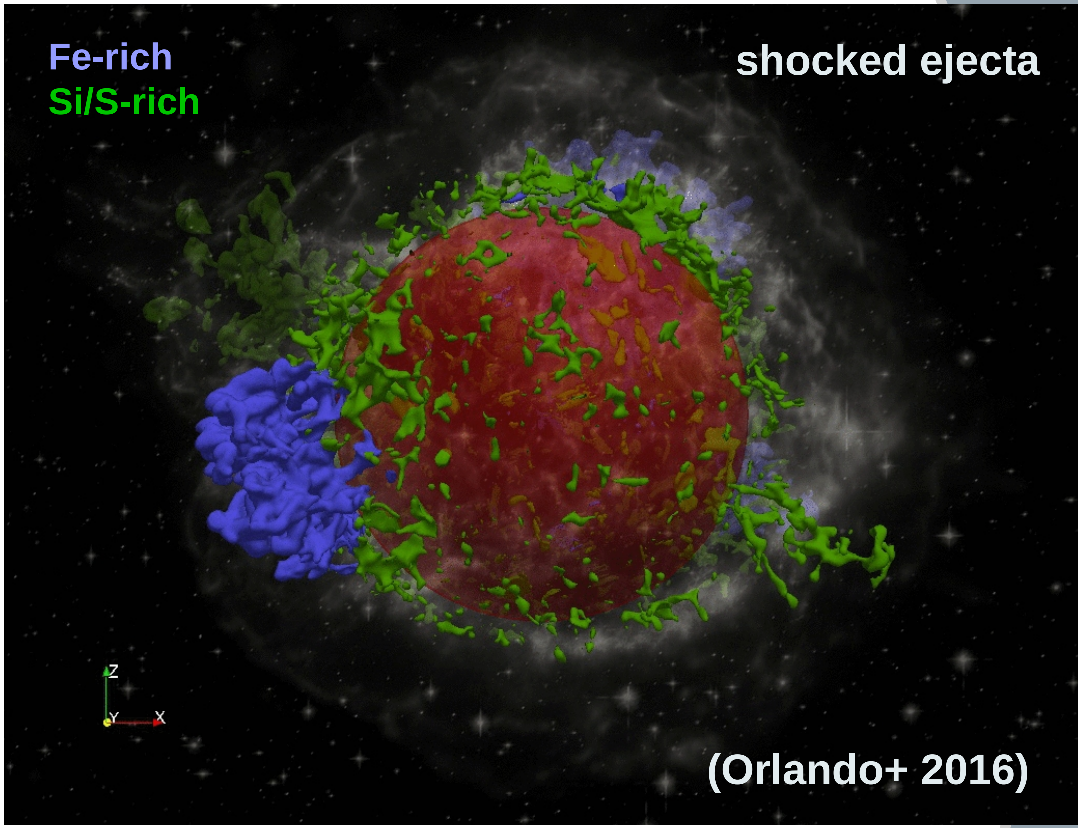
Shocked ejecta

Post-explosion anisotropies (pistons) reproduce the observed distributions and masses of Fe and Si/S if

- mass of $\approx 0.25\ M_{sun}$ (5% of the tot.)
- kinetic energy of $\approx 1.5 \times 10^{50}$ erg (7% of the total)

The pistons produce a spatial inversion of ejecta layers at the epoch of Cas A, leading to the Si/S-rich ejecta physically interior to the Fe-rich ejecta

The pistons are also responsible for the development of rings of Si/S-rich material which form at the intersection between the reverse shock and the material accumulated around the pistons during their propagation



the bulk of asymmetries observed in Cas A are intrinsic to the explosion

Effects of inhomogeneous CSM

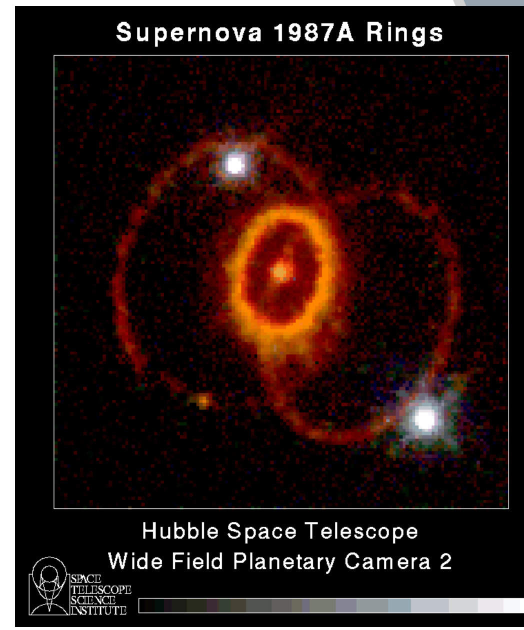
The case of SN 1987A

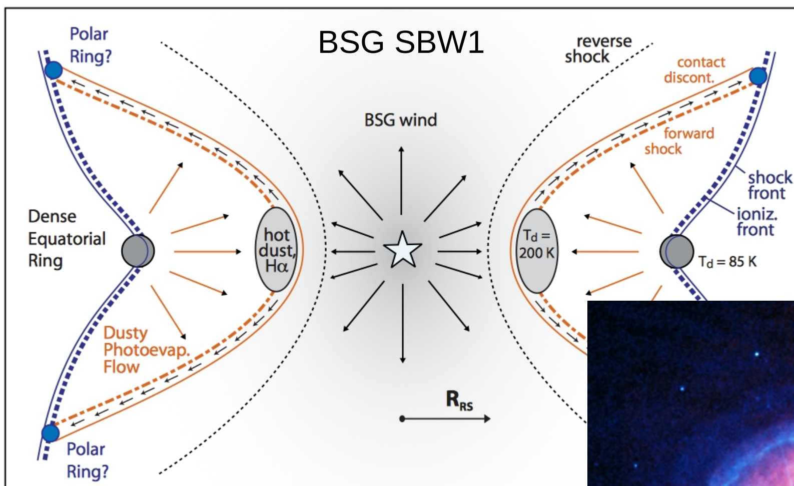
Effects of inhomogeneous CSM: SN 1987A

Origin of the CSM

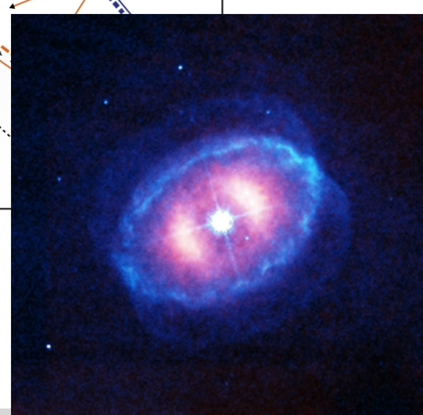
interaction of a slow wind from the red supergiant phase with the faster wind from the blue supergiant phase
(e.g. Luo & McCray 1991; Morris & Podsiadlowski 2007)

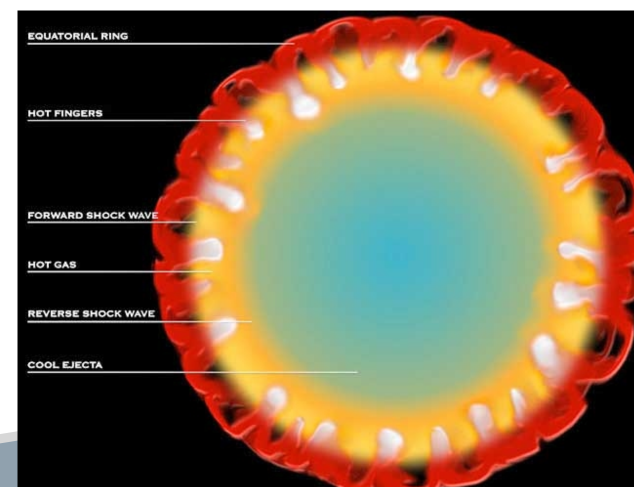
Currently, the explosion is sweeping up the inner equatorial ring that was formed by the late stages of the star’s evolution.



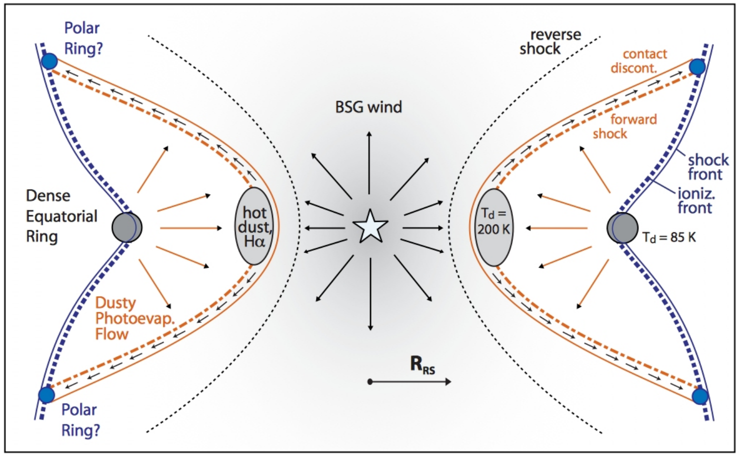


(Smith+ 2013)





Initial conditions and evolution

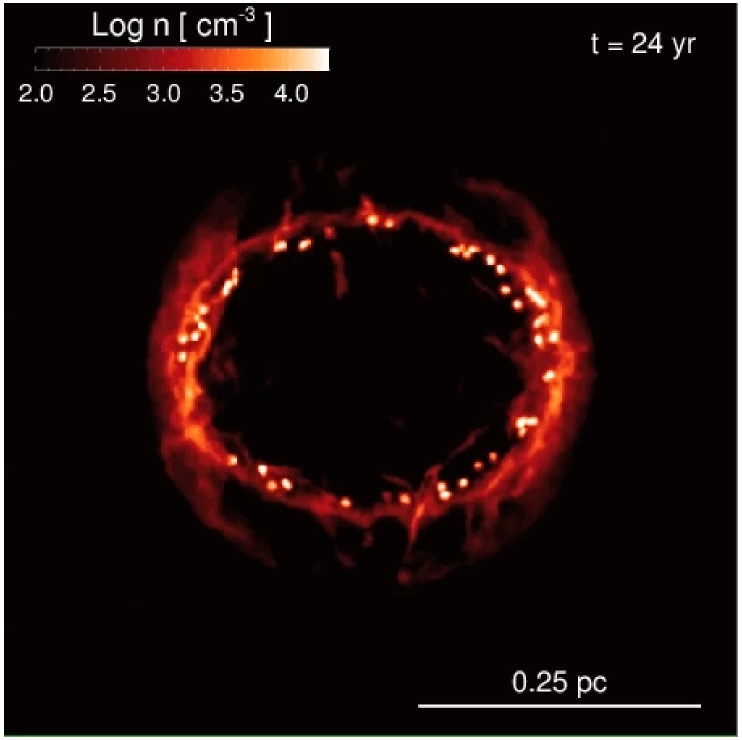


The model

M_{rg} ~ 0.062 M_{sun}

~ 0.040 M_{sun} @ n = 10^3 cm^{-3}

~ 0.022 M_{sun} @ n ~ 2.5 x 10^4 cm^{-3}



(Orlando+ 2015)

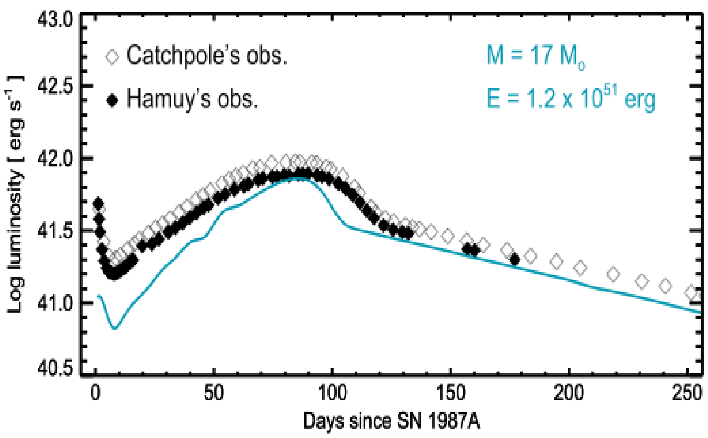
Density structure of ionized gas of the ring from optical spectroscopic data (Mattila+ 2010)

M_{rg} ~ 0.058 M_{sun}

~ 0.046 M_{sun} @ n ~ 10^3 cm^{-3} and n ~ 3 x 10^3 cm^{-3}

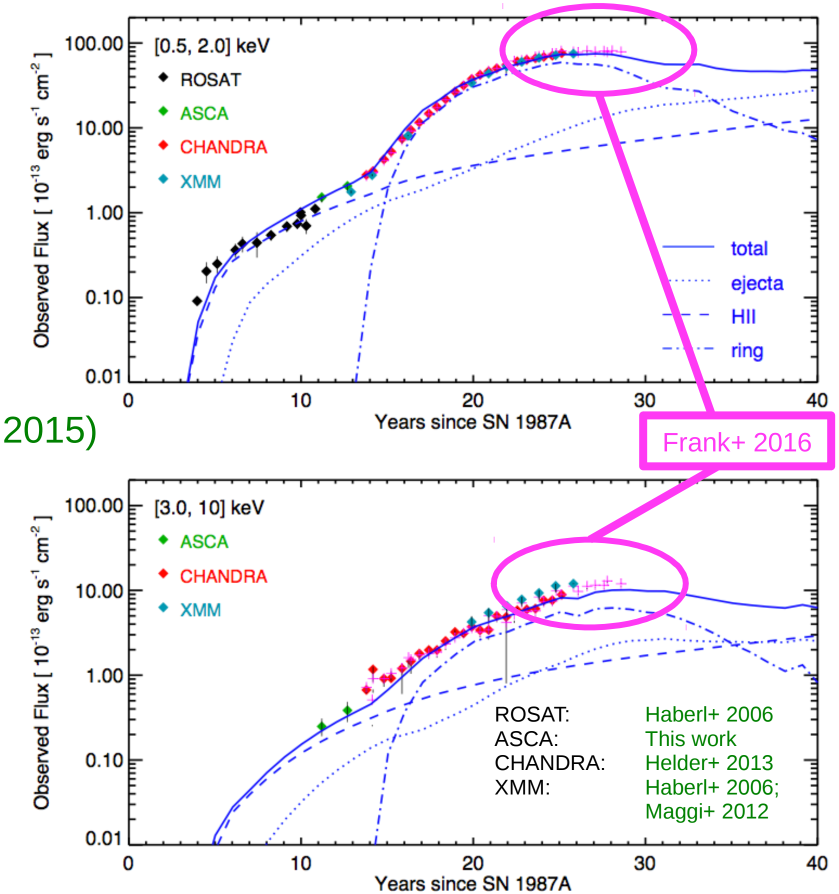
~ 0.012 M_{sun} @ n ~ 3 x 10^4 cm^{-3}

Lightcurves



(Orlando+ 2015)

Bolometric lightcurve of the SN model compared to that observed



Frank+ 2016

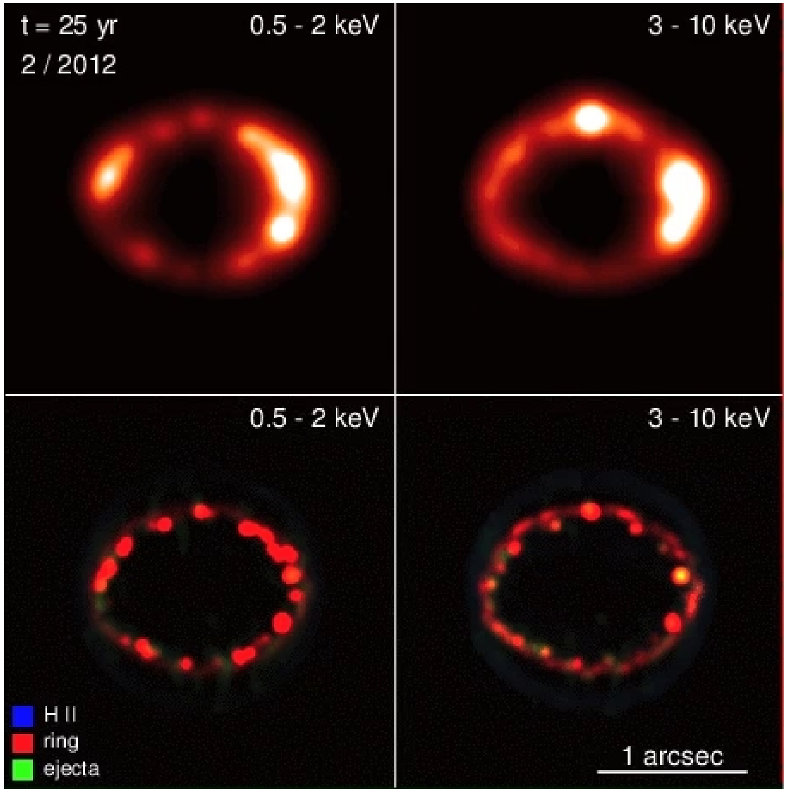
the physical model reproducing the observables of the supernova (the cause) is able to reproduce also the observables of the subsequent expanding remnant (the effect)

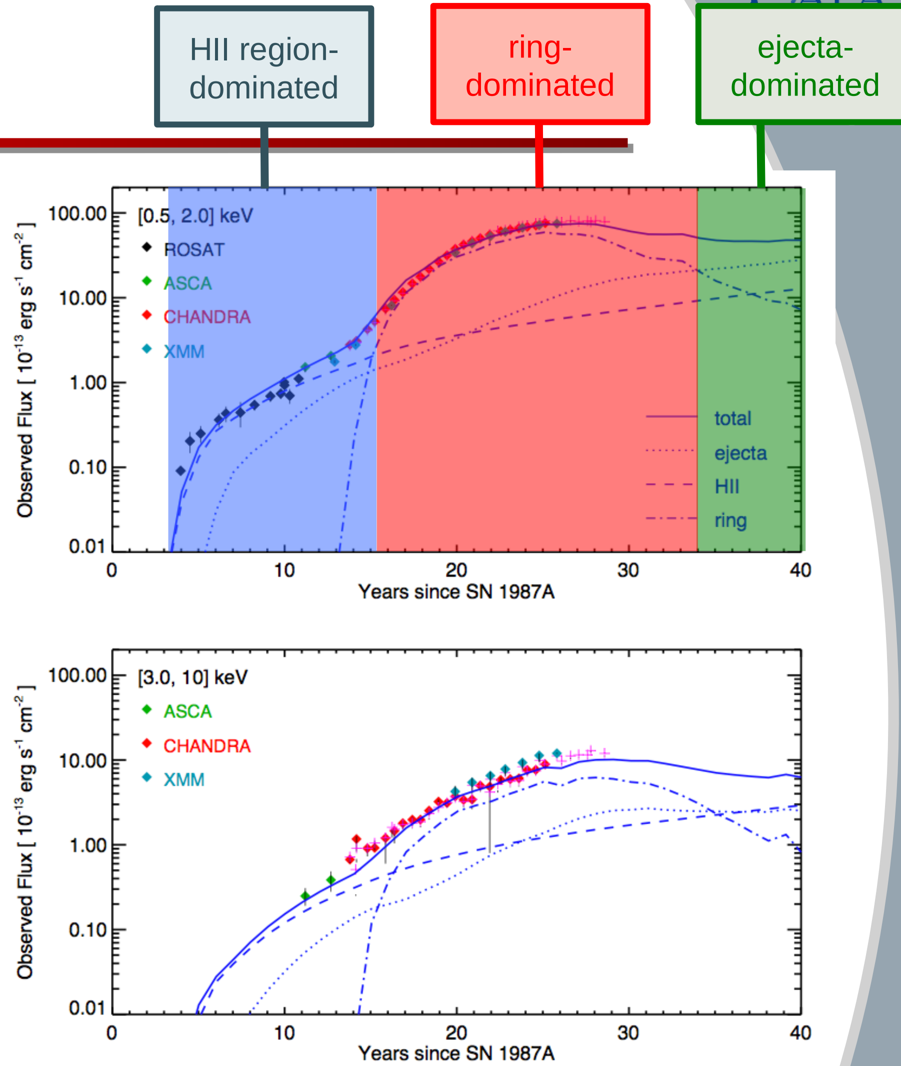
Abundances from Zhekov+ (2009)

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

Distance: 51.4 kpc (Panagia 1999)

Lightcurves





(see M. Miceli's talk)

Abundances from Zhekov+ (2009)

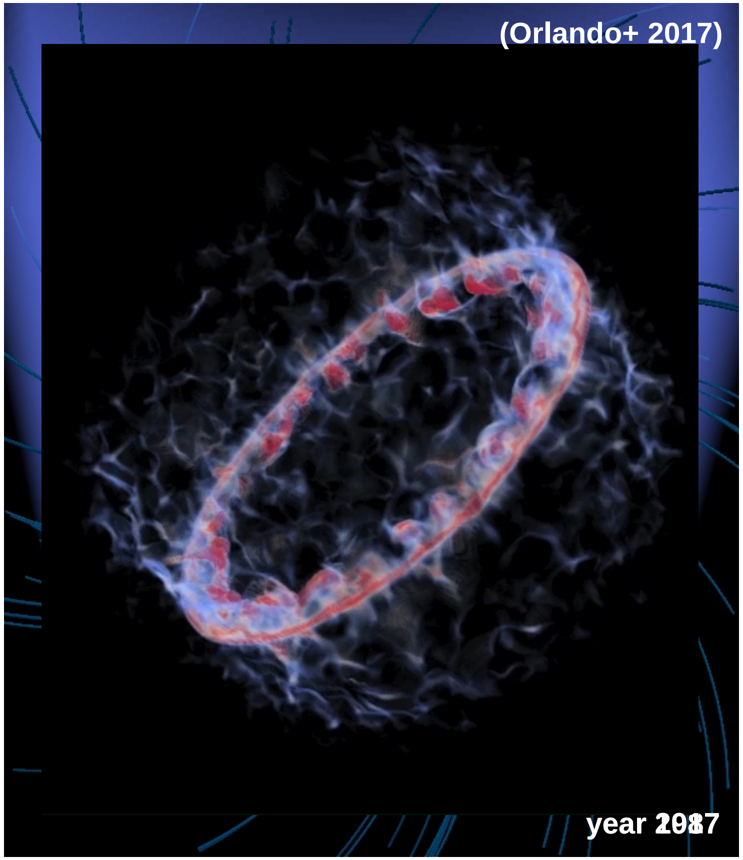
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

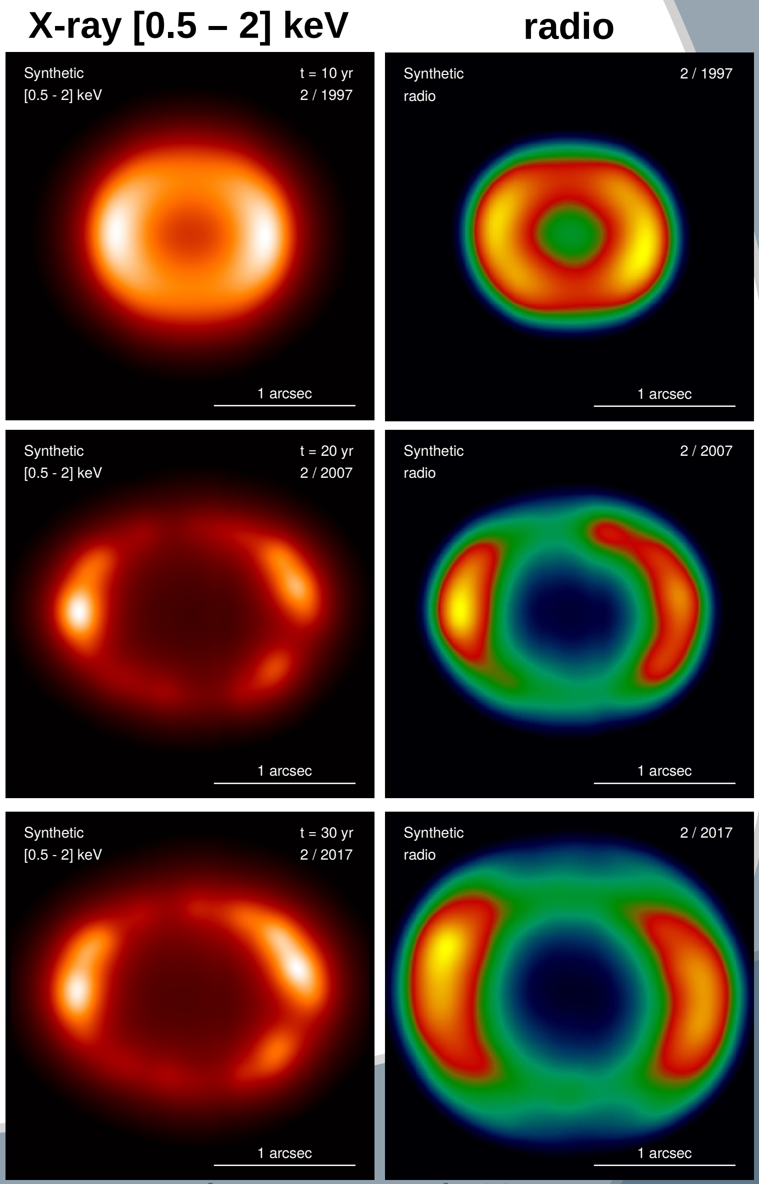
Distance: 51.4 kpc (Panagia 1999)

Future Prospects

- Hydrodynamics → MHD
- Joint 3D cc SN – 3D SNR
- Connect progenitor - SN - SNR

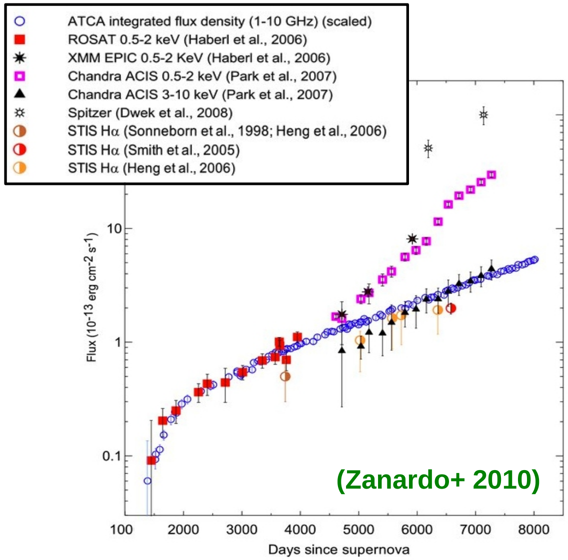
SN 1987A: MHD evolution and radio emission

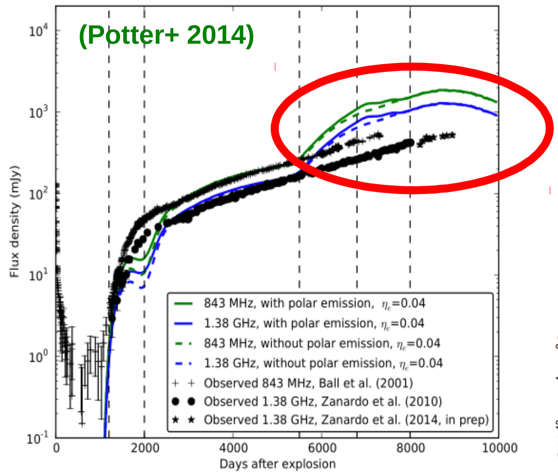


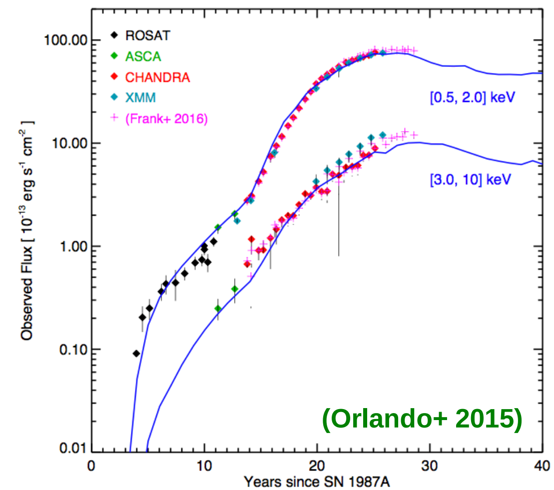


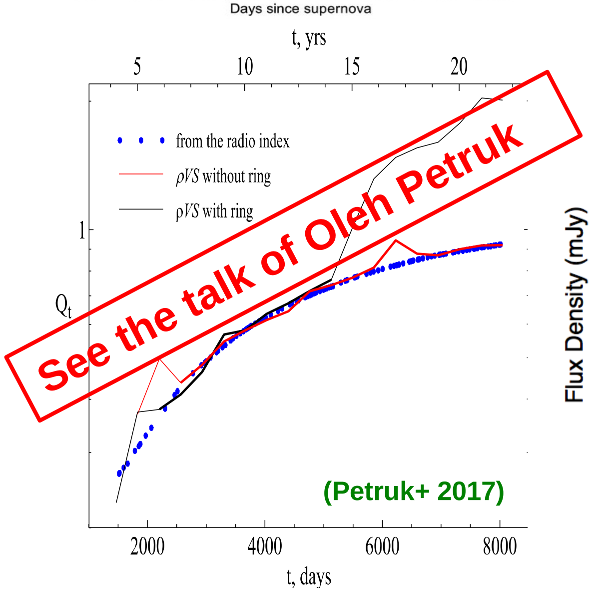
- **3D MHD simulations performed with *PLUTO* (Mignone+ 2007, 2012)**
- **Synthesis or radio emission performed with *REMLIGHT* (Orlando+ 2007, 2011)**

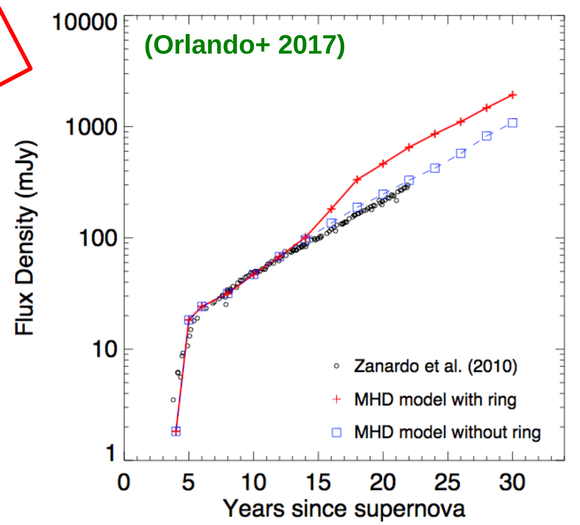
SN 1987A: The Radio Flux







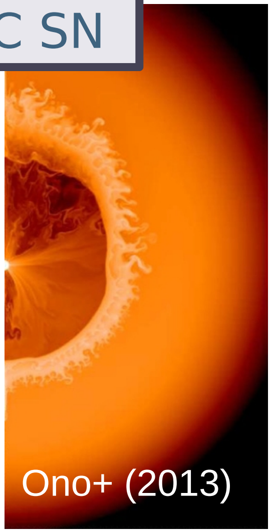




The radio emission from the dense ring is negligible

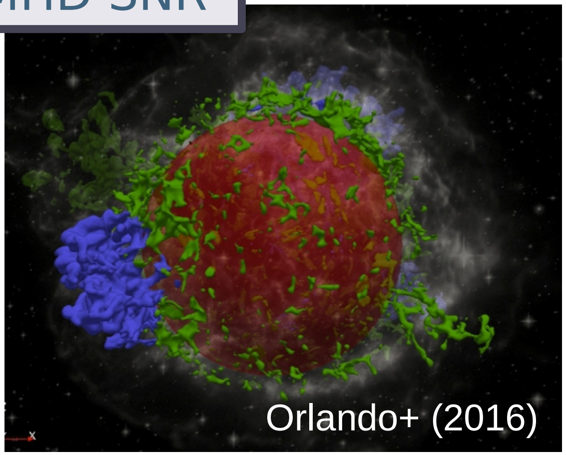
Evolving 3D SN explosions to 3D SNRs

3D CC SN



Ono+ (2013)

3D MHD SNR



Orlando+ (2016)

PRACE proposal submitted

Salvatore Orlando	(INAF – Osservatorio Astronomico di Palermo, Italy)
Marco Miceli	(Universita` di Palermo, Italy)
Oleh Petruk	(INAF – Osservatorio Astronomico di Palermo, Italy)
Giovanni Peres	(Universita` di Palermo, Italy)
Shigehiro Nagataki	(The Astrophysical Big Bang Laboratory, RIKEN, Japan)
Masaomi Ono	(The Astrophysical Big Bang Laboratory, RIKEN, Japan)
Shiu-Hang Lee	(Kyoto University, Japan)
Annop Wongwathanarat	(The Astrophysical Big Bang Laboratory, RIKEN, Japan)
Gilles Ferrand	(The Astrophysical Big Bang Laboratory, RIKEN, Japan)
Tomoya Takiwaki	(National Astronomical Observatory, Japan)
Ko Nakamura	(Fukuoka University, Japan)

Conclusions

FACTS

- **SNRs morphology and properties reflect the physical and chemical properties of the progenitor SNe and the environment in which blast waves travel**
- **Multi-wavelenght/multi-messenger observations of SNRs encode information about the physical and chemical properties of both stellar debris and surrounding CSM**
    - **anisotropies, dynamics and energetics of the SN explosions**
    - **clues on the final stages of stellar evolution**

Linking SNe to SNRs has breakthrough potential to open new exploring windows on SN and SNR issues

TASKS

Deciphering observations might depend critically on models

- **Models should connect stellar progenitor → SN → SNR**
- **Observational facts as a guidance for models (account for dynamics, energetics, and spectral properties of SNe and SNRs)**
- **Strongly improve the synergy and comunication among communities (progenitors, SNe, SNRs)** ***(IAUS 331, this meeting!)***