INAF

The path from massive stars to supernovae and supernova remnants

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PRACE PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

The Team

OAPA	OAA	OAR + IAPS	OACt	OAPd + OATs	OAC
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- The Astrophysical Big Bang Laboratory, RIKEN (Japan)
- Tokyo University (Japan)
- Max Planck Institute for Astrophysics (Germany)
- Lviv Astronomical Observatory (Ukraine)
- Penn State University (USA)
- The University of Texas at Arlington (USA)
- The University of Chicago (USA)
- Purdue University (USA)
- Ecole Polytechnique, Paris (France)
- The University of Amsterdam (The Netherlands)
- The University of Valencia (Spain)

Synergies with other projects

SNR	M. Miceli	RSN4
CRACHEN	E. Amato	RSN4
FIFA	M. Limongi	RSN2
BIDSTAR	A. Chieffi	RSN2
PanHRS4IBiT	E. Mason	RSN2
PDSNET	A. Pastorello	RSN2
SCAN	S. Orlando	RSN5

Leadership INAF and Funding

Timeline of the project

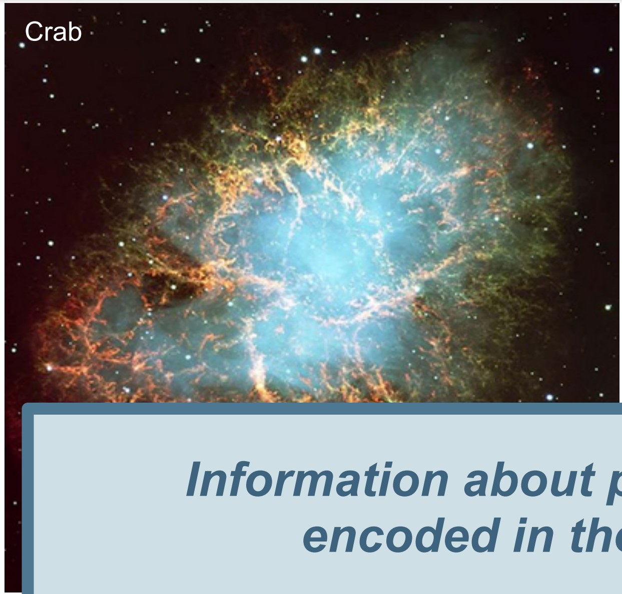
	2015-16	2017	2018	2019	2020	2021	2022-23
Funding	PRIN INAF 2014 (PI Orlando)						
			ASI-INAF (PI Orlando)				
			PRIN SKA-CTA (PI Tavecchio)				
				Mainstream (PI Amato)			
						PRIN INAF 2019 (PI Orlando)	
							PRIN MIUR (PI Orlando) ?
Numerical Resourc.	**PRACE** 2014 (PI Orlando)	ISCRA-C (PI Orlando)	**PRACE** 2017 (PI Orlando)	INAF-CINECA (PI Orlando)	ISCRA-B (PI Orlando)	PRACE (PI Usta **SCAN @ OAPa**	
Observ. proposal			Chandra C19 XMM AO-18	Chandra C20	Chandra C21	Chandra C22 JWST	
INAF	OAPa		OAA		OAR, IAPS, OACt	OAPd, OAC, OATs	
Partners	UNIPa	RIKEN Tokyo U. Penn State U. Lviv Astr. Obs.	U. of Texas U. of Valencia	MPA U. of Amsterd.	E.Polyt. Paris Purdue U. U. of Chicago CEA/Saclay		

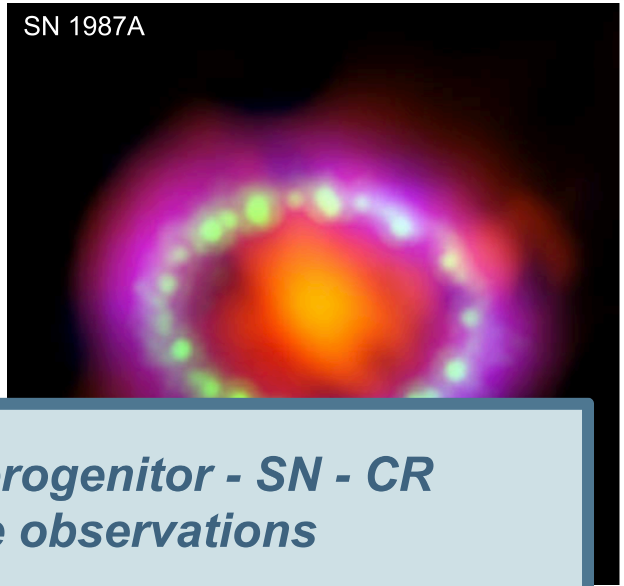
Funding

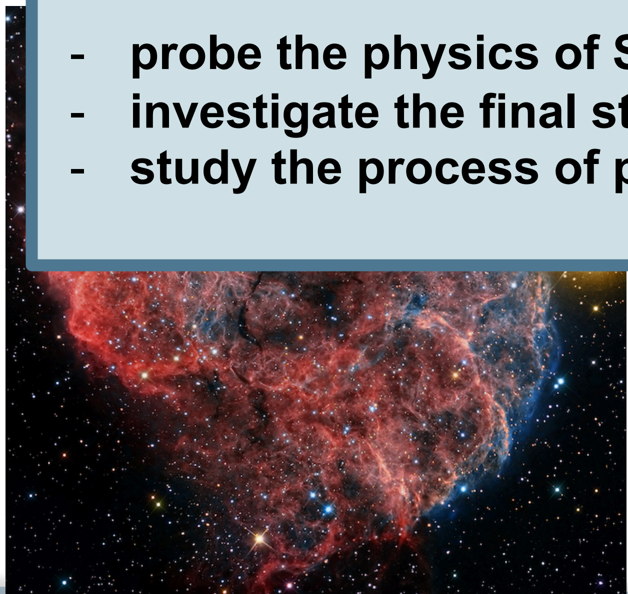
- 2015-17: "Filling the gap between supernova explosions and their remnants through MHD modelling and high performance computing" (PI Orlando) PRIN-INAF 2014; 56 k€
- 2018: "Connecting supernova remnants to their progenitor supernovae by combining 3D MHD simulations and analysis of high energy observations" (PI Orlando) ASI-INAF n. 2017-14-H.0; 10 k€
- 2018-19: "Probing particle acceleration and gamma ray propagation with CTA and its precursors" (PI Tavecchio) INAF-SKA-CTA; 8 k€
- 2019-20: "Particle Acceleration in Galactic Sources in the CTA era" (PI Amato) INAF Mainstream; 14 k€
- 2021-22: "From massive stars to supernovae and supernova remnants: driving mass, energy and cosmic rays in our Galaxy" (PI Orlando) PRIN-INAF 2019; 85 k€

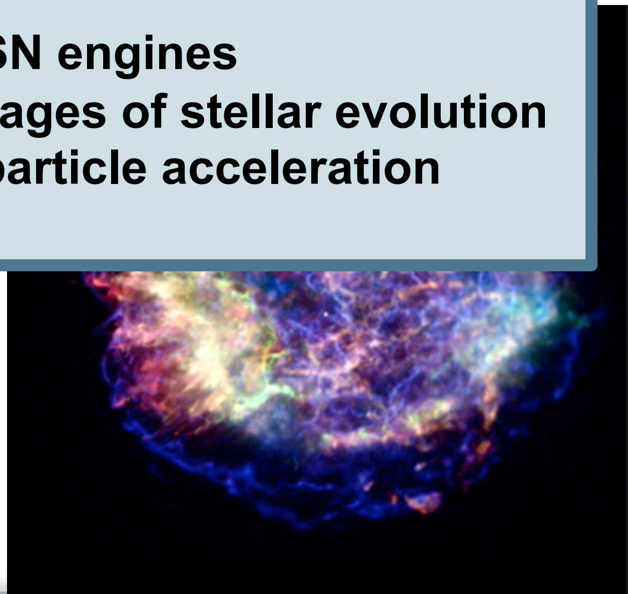
- 2022-24: "Life, death and after-death of massive stars: reconstructing the path from the pre-supernova evolution to the supernova remnant" (PI Orlando) PRIN MUR 2020; requested funding ~ 890 k€

Supernova Remnants





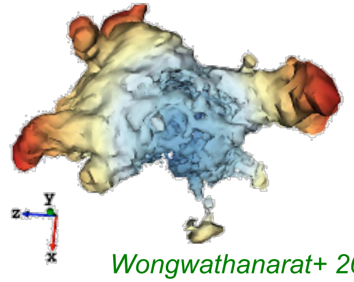




Information about progenitor - SN - CR encoded in the observations

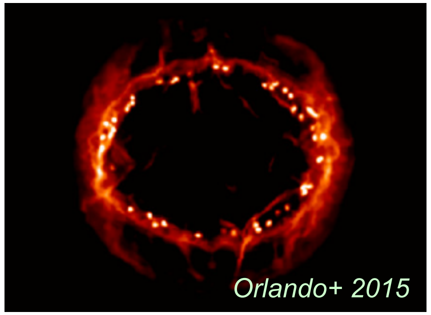
- **probe the physics of SN engines**
- **investigate the final stages of stellar evolution**
- **study the process of particle acceleration**

- **pristine structures and features of progenitor SN**



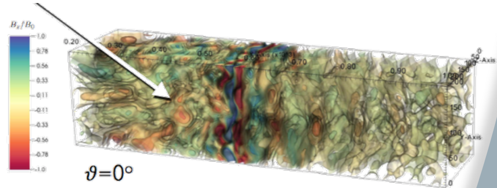
Wongwathanarat+ 2017

- **interaction of SN blast with the CSM**



Orlando+ 2015

- **cosmic rays acceleration**



Caprioli 2015

Motivation

- Establish links among the physical and chemical properties of CC SNRs, the processes associated with the parent SNe, and the nature of their progenitor stars;
- Shed light on the contribution of massive stars, SNe, and SNRs to the origin of CRs in our Galaxy.

Aims

1. How SN and SNR properties and structure reflect the nature of the progenitor star;
2. How SNR morphology reflects the post-explosion initial anisotropies;
3. How particles accelerated at the termination shock of MSWs contribute to galactic CRs;
4. How CR acceleration influence the dynamics of young CC SNRs.

Multi-disciplinary Approach

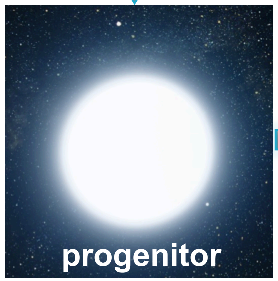
- state-of-the-art stellar evolution models and 3D SN and SNR models (including CR acceleration)
  OAPa, OAA, OAR

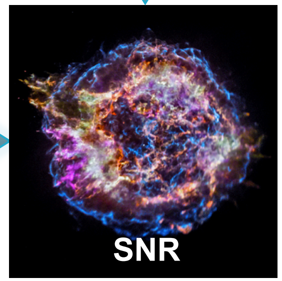
- multi-band data of progenitors, SNe, and SNRs to describe the path from massive stars to SNe and SNRs
  OAPa, OAPd, OAC, OACt, OATs, UNIPa

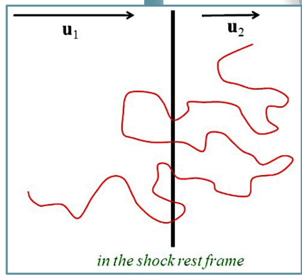
Synergic collaboration among groups studying different aspects of stellar - SN - SNR evolution and CR acceleration

How to link progenitor – SN – SNR – CR ?

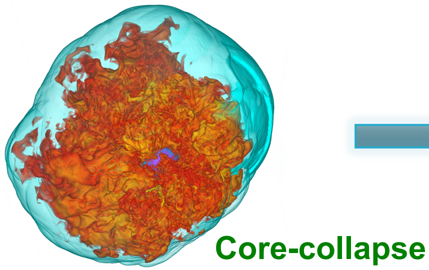
- **Multi-physics**



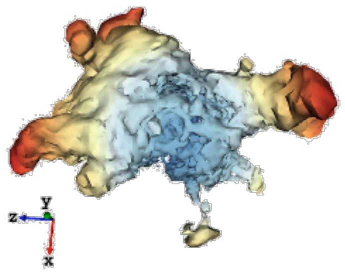


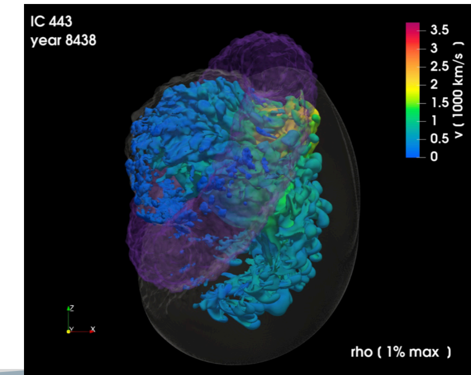


- **Multi-scale**

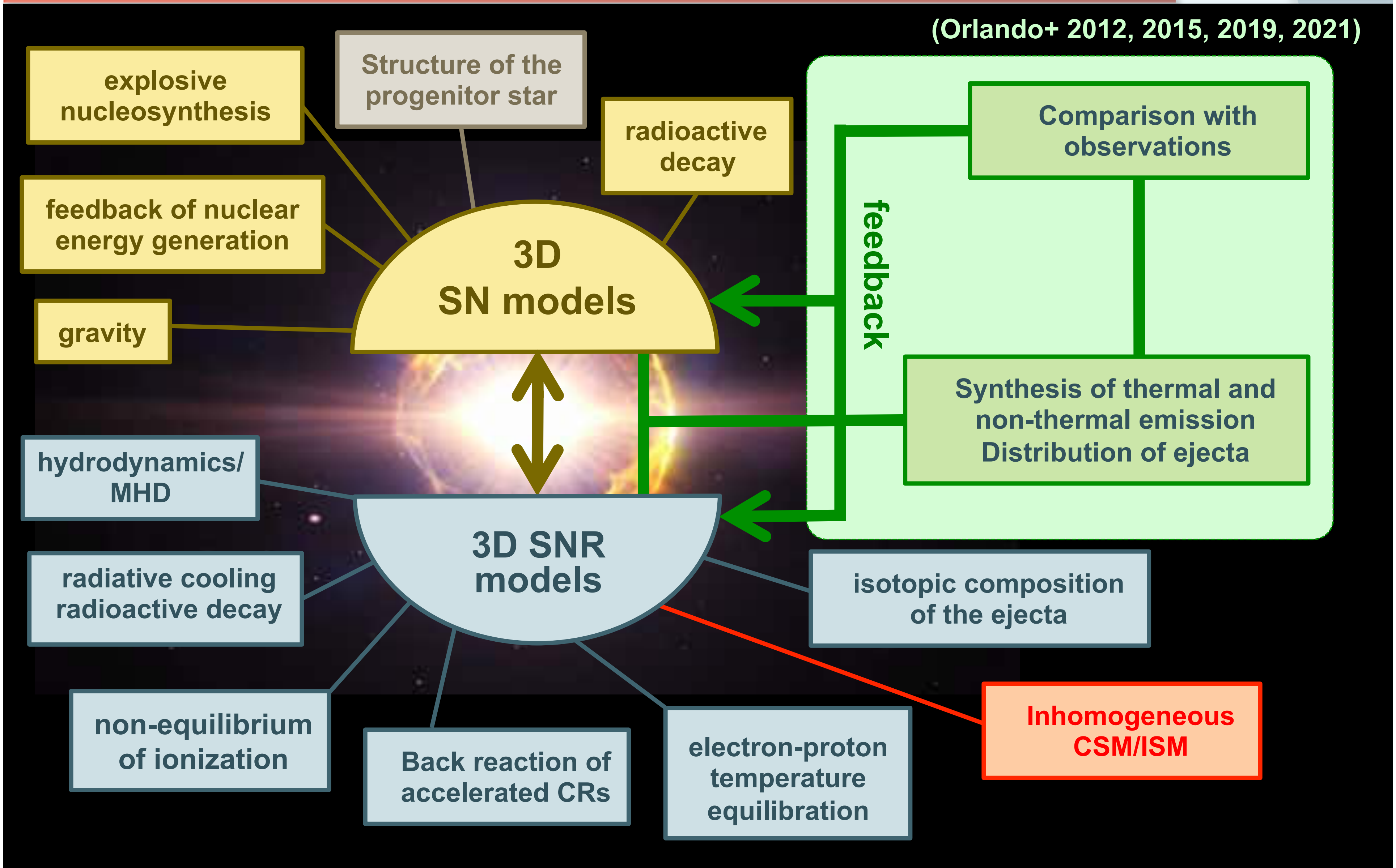


- **Multi-dimensions**





How to link cc SNe to SNRs ? The strategy



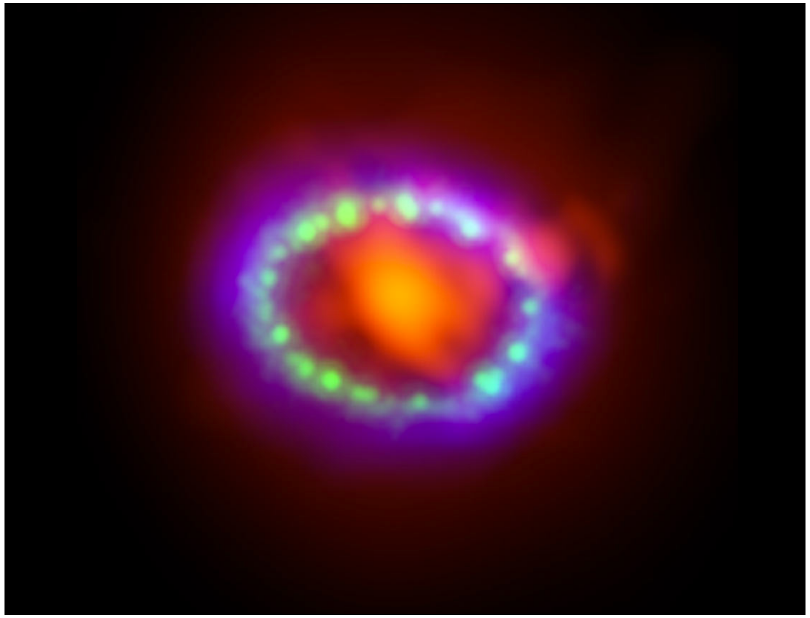
Scientific production

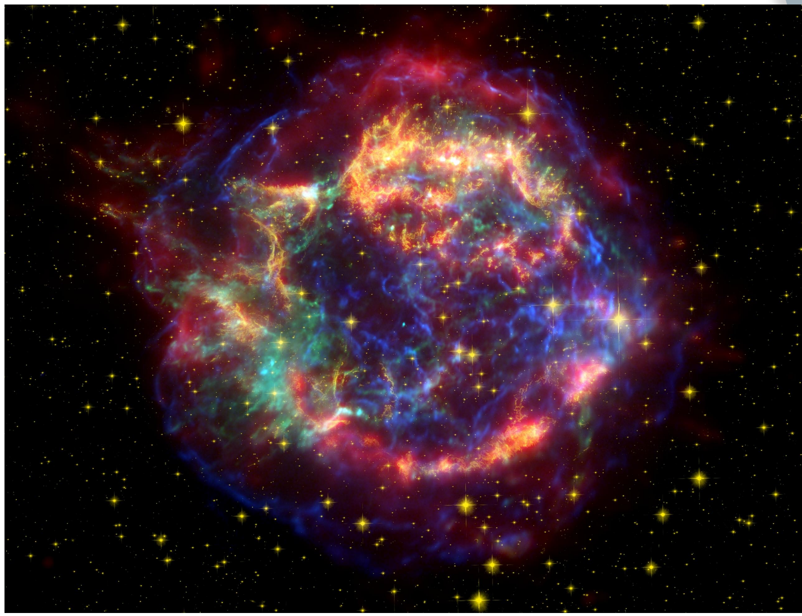
- 34 refereed papers;
- more than 40 invited and contributed talk/poster presentations at international meetings;
- Accepted proposals for numerical resources and observations;
- Web page, public outreach products (3D interactive graphics, movies, figures).

Recently accepted / submitted papers

- Yao et al. 2021, "Laboratory evidence for proton energization by collisionless shock surfing", *Nature Physics* in press
- Petruk et al. 2021, "Magneto-hydrodynamic simulations of young supernova remnants and their energy-conversion phase", *MNRAS* in press
- Giuffrida et al. 2021, "The supernova remnant SN 1006 as a Galactic particle accelerator", submitted to *Nature Communication*
- Ustamujic et al. 2021, "Modeling the Remnants of Core-collapse Supernovae from Luminous Blue Variable stars", to be submitted to *A&A* at the end of May
- Pazhayathravi et al. 2021, "Spectral Evolution of the X-Ray Remnant of SN 1987A : A High Resolution Chandra HETG Study", to be submitted to *ApJ* at the end of May

Cases study: SN 1987A and Cassiopeia A





When: 23 February 1987
Where: Large Magellanic Cloud

Stellar progenitor: Sk -69°202

Nearest supernova explosion observed in hundreds of years

Unique opportunity to watch a SN change into a SNR

Remnant expanding through the wind of the progenitor red supergiant

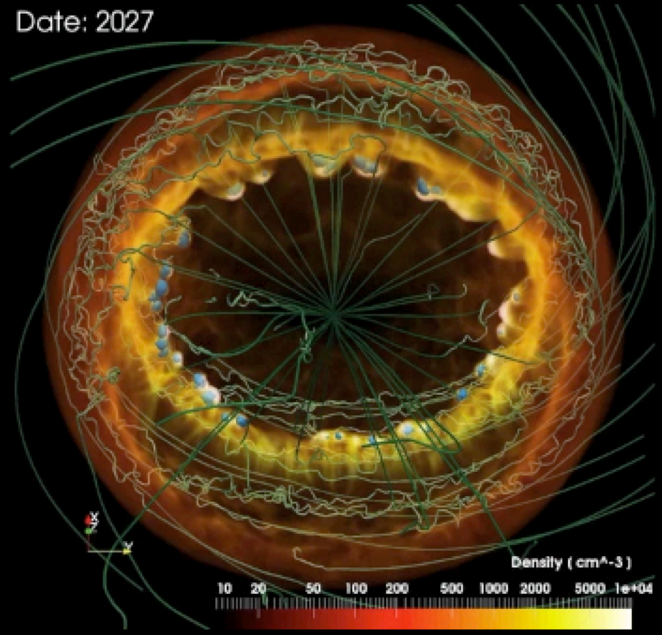
Cassiopeia A is an attractive laboratory to bridge the gap between SNe and their remnants

SN 1987A

Stellar model

→ 3D SN explosion

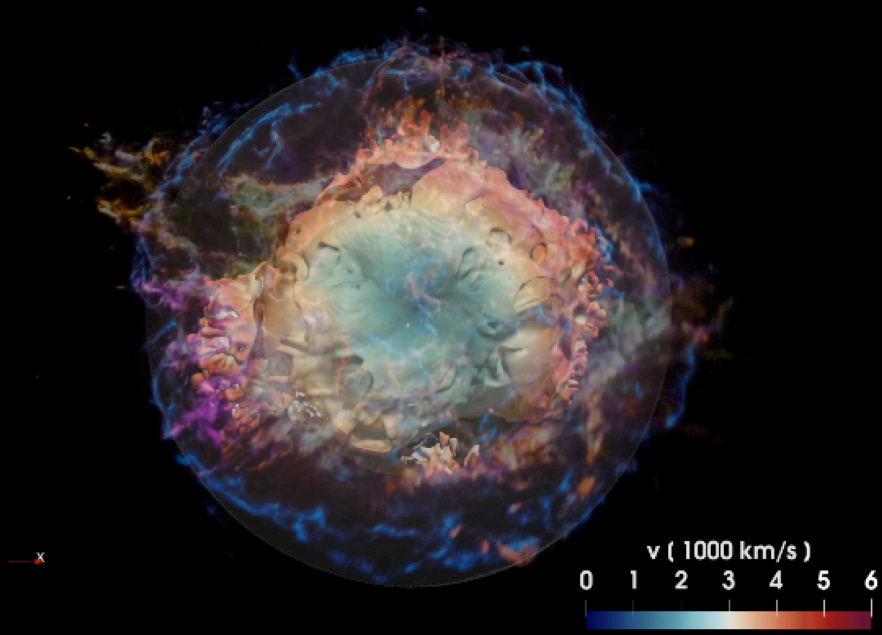
→ 3D SNR expansion



- Origin of non-thermal radio and multi-thermal X-ray emission from SN 1987A (Orlando et al. 2015, 2019)
- Collisionless shock heating of heavy ions in SN 1987A (Miceli et al. 2019)
- identify the physical and geometrical properties of the asymmetric explosion (Ono et al. 2020, Orlando et al. 2020)
- identify the progenitor star of SN 1987A resulted from the merging of two massive stars (Orlando et al. 2020)
- identify the emission from a pulsar wind nebula in SN 1987A (Greco et al. 2021)

SNR Cassiopeia A

Self-consistent description of the whole 3D evolution of a neutrino-driven SN explosion, from the CC to the SNR at the age of 2000 years (Orlando et al. 2016, 2021)



identify the geometric and physical properties of the post-explosion anisotropies responsible for the morphology of Cas A

main asymmetries and features explained by the interaction of the reverse shock with the initial large-scale asymmetries

stochastic processes (e.g., convective overturn and the standing accretion shock instability; SASI) that originate during the first seconds of the SN blast

Planning / organization

			2021		2022		2023	
	months	t0	1 6	7 12	13 18	19 24	25 30	31 36
Work Packages		→	Activities					
WP1	Management		Regular project meetings					
WP2	Imprint of star progenitor on SN-SNR				A2.1 Analysis of CSM in progenitor systems			
			A2.2 Progenitor stars modeling					
				A2.3 SN-SNR modeling (fingerprints of progenitors)				
WP3	SN anisotropies and origin of jet-like features				A3.1 Analysis of SN observations			
			A3.2 Analysis of SNR observations					
				A3.3 SN-SNR modeling (ejecta distrib., anisotropies, jets)				
					A3.4 data mining and machine learning			
WP4	Cosmic-rays acceleration		A4.1 CR acceleration at the termination shock of MSWs					
					A4.2 CR acceleration in SNRs			
WP5	Dissemination		A5.1 Papers, talks/posters at conferences, production of outreach material					
				A5.2 Inclusive outreach (audio recording, 3D print of the models)				

Plan for 2021-2023

- **WP2. Imprint of progenitors on the physical / chemical properties of SNRs**
  - analysis of observations of progenitor systems to infer the geometry and density distribution of pre-SN CSM; **OACt, OAPd, OATs, OAC**
  - modeling the evolution from the MS, to the SN, and to the SNR, considering the CSM determined self-consistently from the progenitor; **OAR, IAPS, OAPa, UNIPa**
- **WP3. Investigate the paradigm of the neutrino-driven SN explosion mechanism to explain the chemical and morphological asymmetries observed in young SNRs**
  - analysis of observations of nearby (< 20 Mpc) CC SNe; **OAPd, OATs, OAC**
  - analysis of radio / FIR / X-ray observations of SNRs; **OAPa, UNIPa, OACt, OAC**
  - evolution of 3D models of neutrino-driven SN explosions and subsequent SNRs; **OAPa, UNIPa**
- **WP4. Assess the potential of MSWs and young CC SNRs as PeVatrons**
  - adapting non-linear shock acceleration codes developed for SNRs to describe CR acceleration at the termination shock of MSWs; **OAA**
  - modeling particle acceleration and MFA on top of the MHD simulations of young CC SNRs; **OAA, OAPa, UNIPa**

Criticalities

- feasibility of studying the progenitor-SN-SNR-CR connection through models, observations and comparison of model results with observations
- establishment of fruitful collaborations among communities that have so far conducted independent research on stellar evolution, SNe, SNRs and CRs

To date: support of non-permanent researchers (PhD students and post-docs)

We urge to recruit personnel with expertise

- in the theory/modeling of SNe, SNRs and CRs
- in the analysis of multi-band observations of massive stars, SNe and SNRs

Highly strategical

- to consolidate the synergy and communication among national expertise in the physics of massive stars, SNe, SNRs and CR acceleration;
- to consolidate the leadership role of INAF in the field;
- in the light of the present day blossoming of multi-messenger (e.g., CR, neutrino, gravitational waves) astrophysics