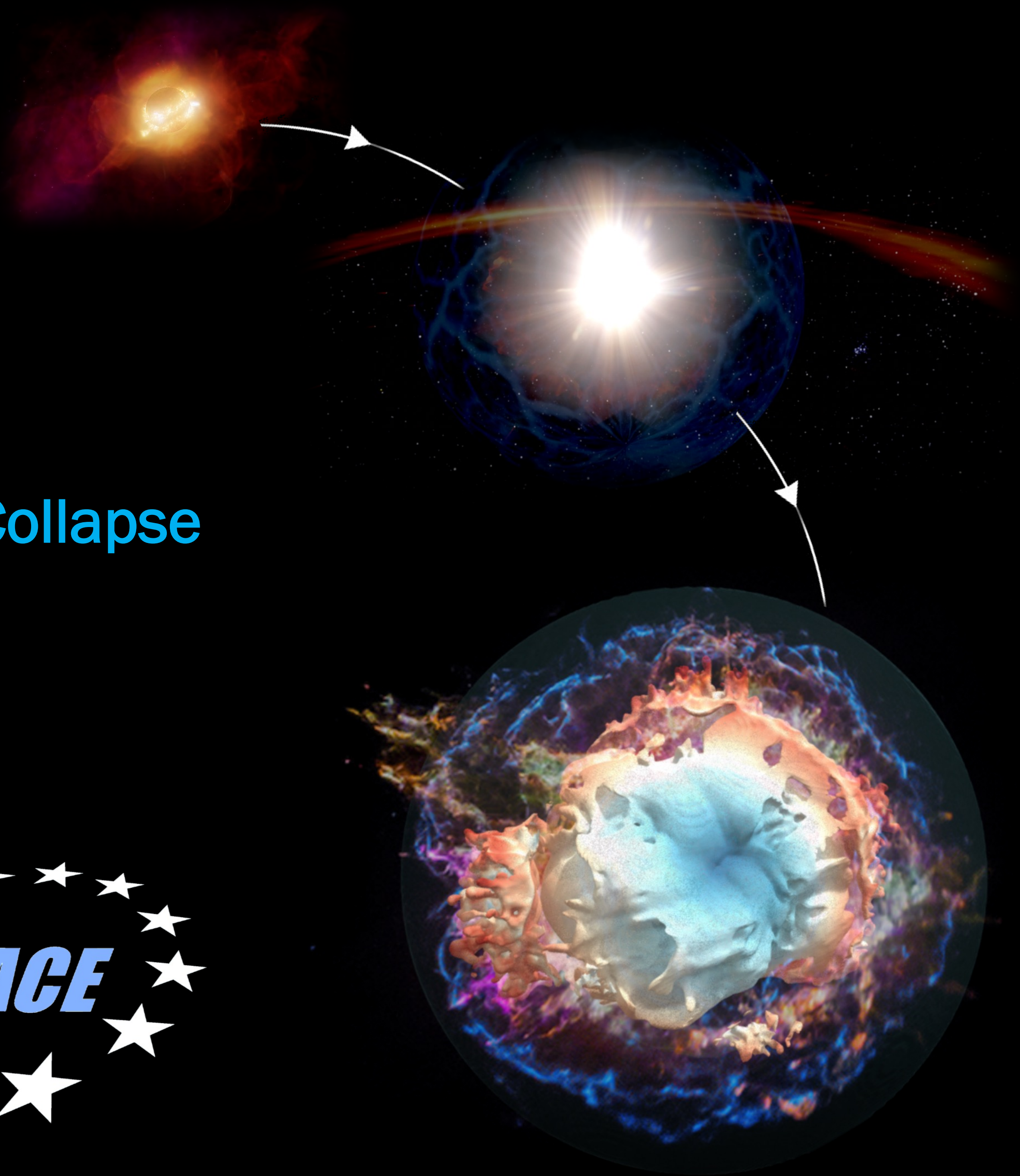
Unveiling the Complexity through HPC: the link between Massive Stars, Core-Collapse Supernovae and their Remnants

Salvatore Orlando
INAF - Osservatorio Astronomico di Palermo, Italy



INAF USCVIII – Calcolo Critico

Catania (IT) June 2023

The Team

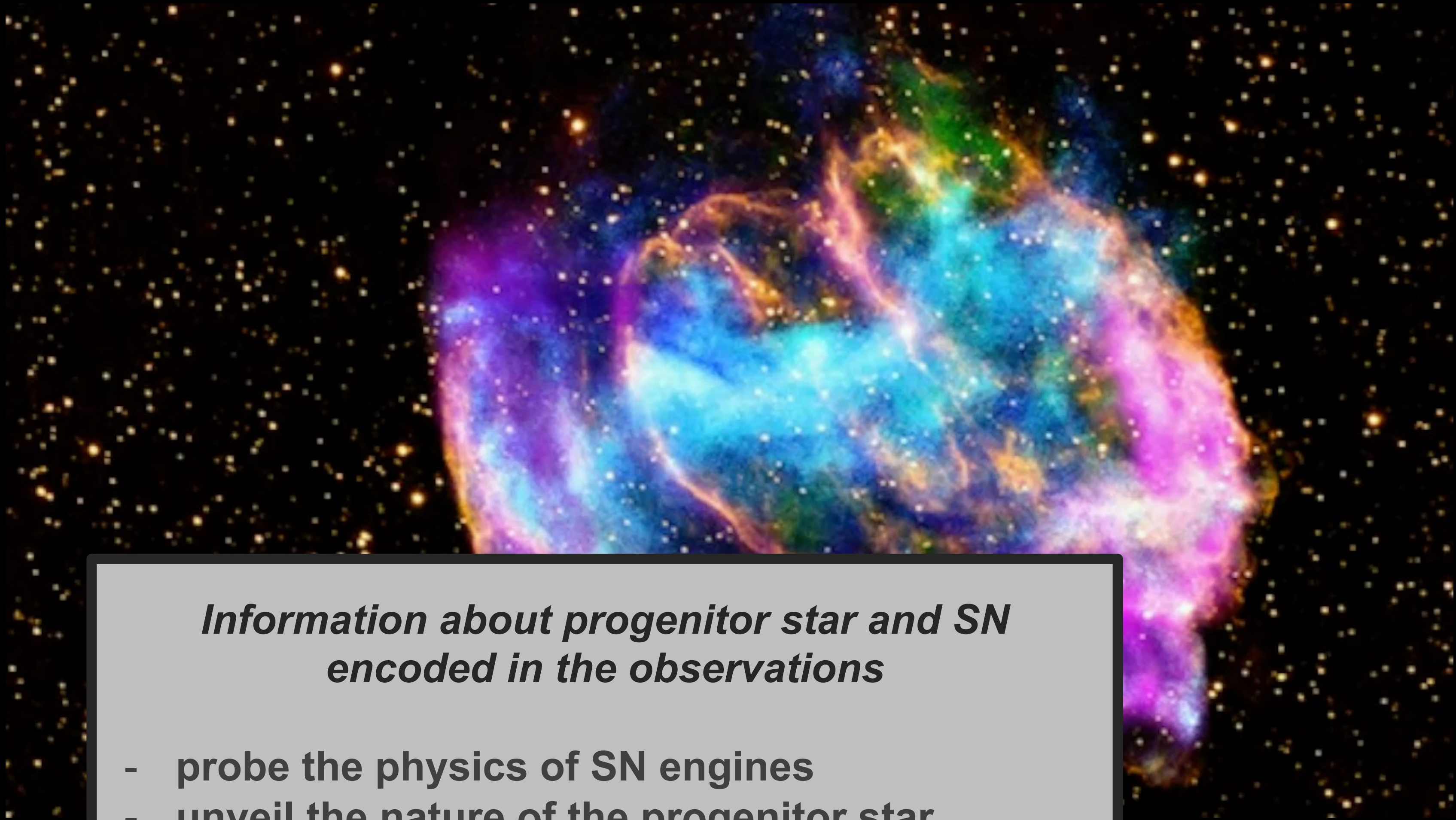
F. Bocchino, B. Olmi, O. Petruk, S. Ustamujic, M.L. Pumo, A. Tutone	*(INAF, Italy)*
M. Miceli, G. Peres, R. Giuffrida, V. Sapienza	*(Università di Palermo, Italy)*
H.-T. Janka, A. Wongwathanarat	*(Max-Planck-Institut für Astrophysik, Germany)*
S. Nagataki, M. Ono, A. Dohi, G. Ferrand	*(ABBL/RIKEN, Japan)*
E. Greco, J. Vink, L. Sun	*(University of Amsterdam, NL)*
H. Umeda	*(Tokyo University, Japan)*
H. Lee	*(Kyoto University, Japan)*
M. A. Aloy, M. Obergaulinger, M. Gabler, P. Mimica	*(Valencia University, Spain)*
D. Milisavljevic	*(Purdue University, USA)*
D. Patnaude	*(Smithsonian Astrophysical Observatory, USA)*
D. Burrows	*(Penn State University, USA)*
S. Park, A. Pazhayath Ravi	*(Stanford University, USA)*

Leadership INAF and Funding

Timeline of the project

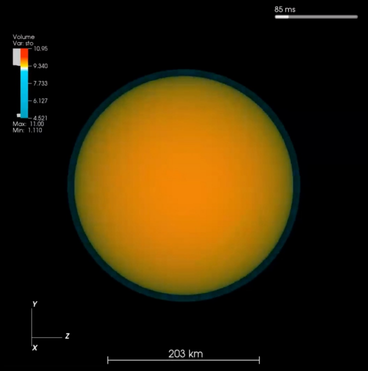
	2015-16	2017	2018	2019	2020	2021	2022	2023	2024
Funding	PRIN INAF 2014 (PI Orlando)								
			ASI-INAF (PI Orlando)						
			PRIN SKA-CTA (PI Tavecchio)						
				Mainstream (PI Amato)					
						PRIN INAF 2019 (PI Orlando)			
								PRIN MUR 2022 (PI Orlando)	
Numerical Resourc.	**PRACE** 2014 (PI Orlando)	ISCRA-C (PI Orlando)	**PRACE** 2017 (PI Orlando)	INAF-CINECA (PI Orlando)	ISCRA-B (PI Orlando)	**PRACE-ICEI** (PI Ustamujic)	SCAN@OAPA	SCAN@OAPA ISCRA-B (PI Orlando)	
Observ. proposal			Chandra C19 XMM AO-18	Chandra C20	Chandra C21	Chandra C22 JWST	Chandra C23	Chandra C24	Chandra C25

The Remnants of Core-Collapse Supernovae

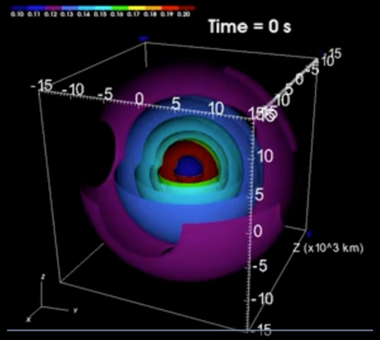


Information about progenitor star and SN encoded in the observations

- probe the physics of SN engines
- unveil the nature of the progenitor star
- investigate the final stages of stellar evolution



pristine structures and features of progenitor SN (MPA, Garching, Germany)

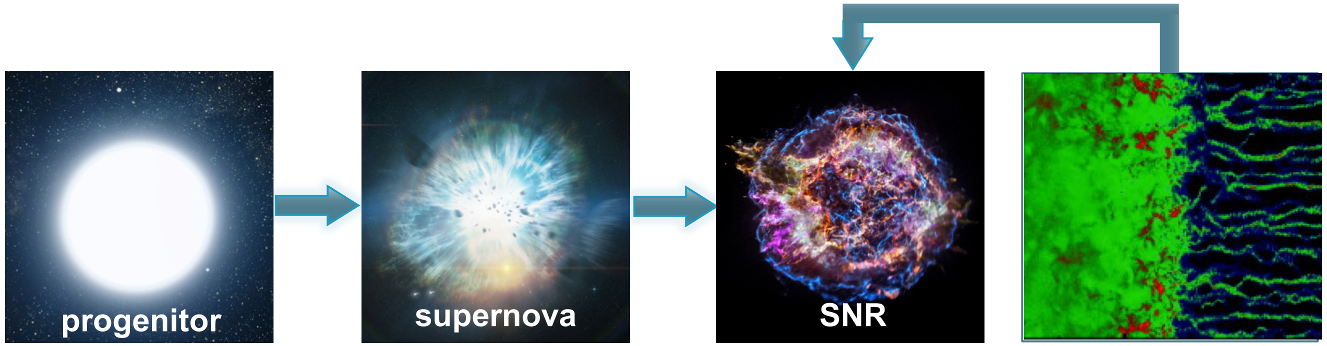


Internal structure of the progenitor star (Yoshida+ 2021)

Interaction with the inhomogeneous CSM (Orlando+ 2015)

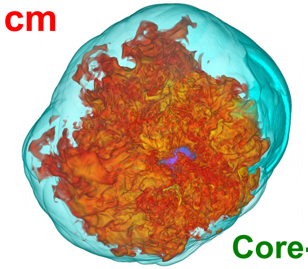
How to link progenitor – SN – SNR ?

- **Multi-physics**



- **Multi-scale**

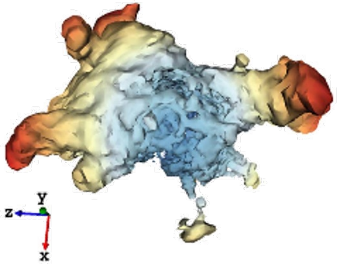
L: 10^9 cm
t: 1 s

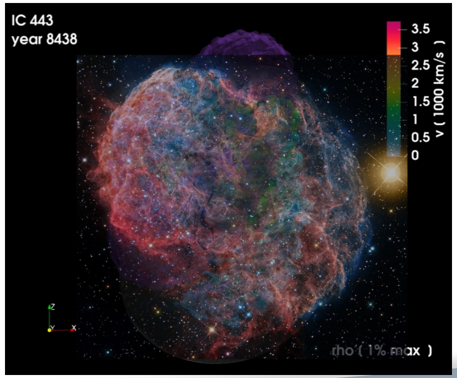


Core-collapse

L: a few pc
t: ~ 10000 yrs

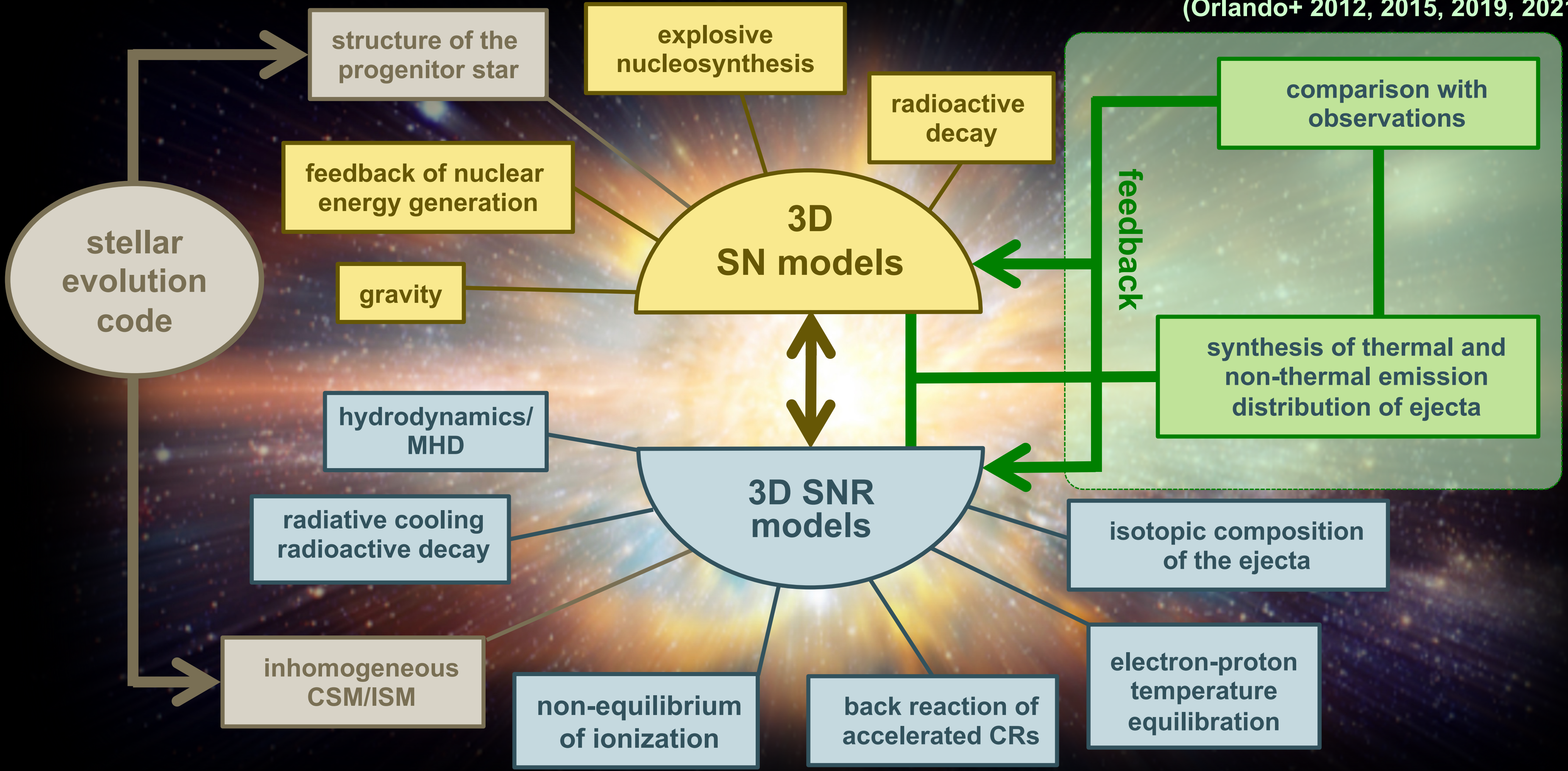
- **Multi-dimensions**





How to link progenitor – SN – SNR ?   The strategy

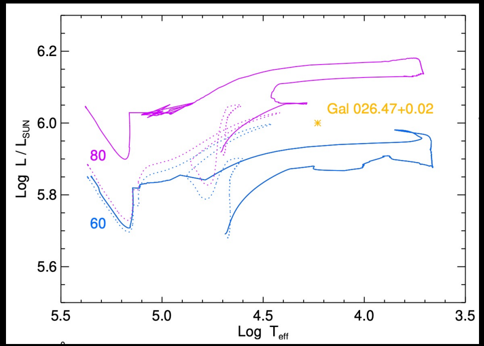
(Orlando+ 2012, 2015, 2019, 2021)



Numerical Codes

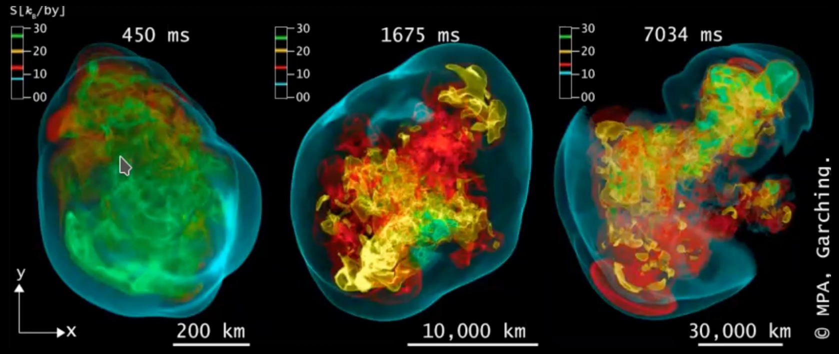
Progenitor Star

- Stellar Evolution Code (1D)
  (Takahashi et al. 2014; Urushibata et al. 2018)
- FRANEC (1D)
  (Chieffi & Limongi 2013; Limongi & Chieffi 2018)
- MESA (1D)
  (Paxton et al. 2014)



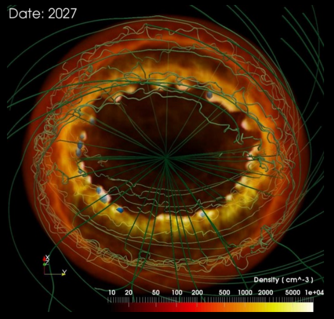
Supernova

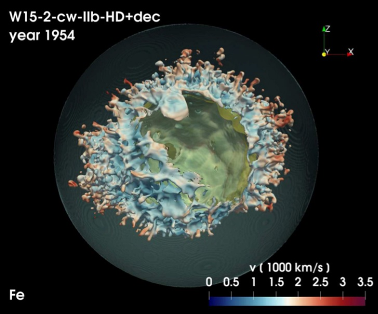
- General-relativistic, radiation-HD, Lagrangian code (1D)
  (Pumo, Zampieri & Turatto 2010; Pumo & Zampieri 2011)
- HYPERION (1D)
  (Limongi & Chieffi 2020)
- FLASH (3D)
  (Fryxell et al. 2000)
- PROMETHEUS (3D)
  (Fryxell et al. 1991; Mueller et al. 1991; Wongwathanarat et al. 2013)

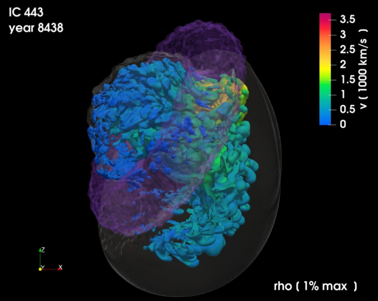


Supernova Remnant

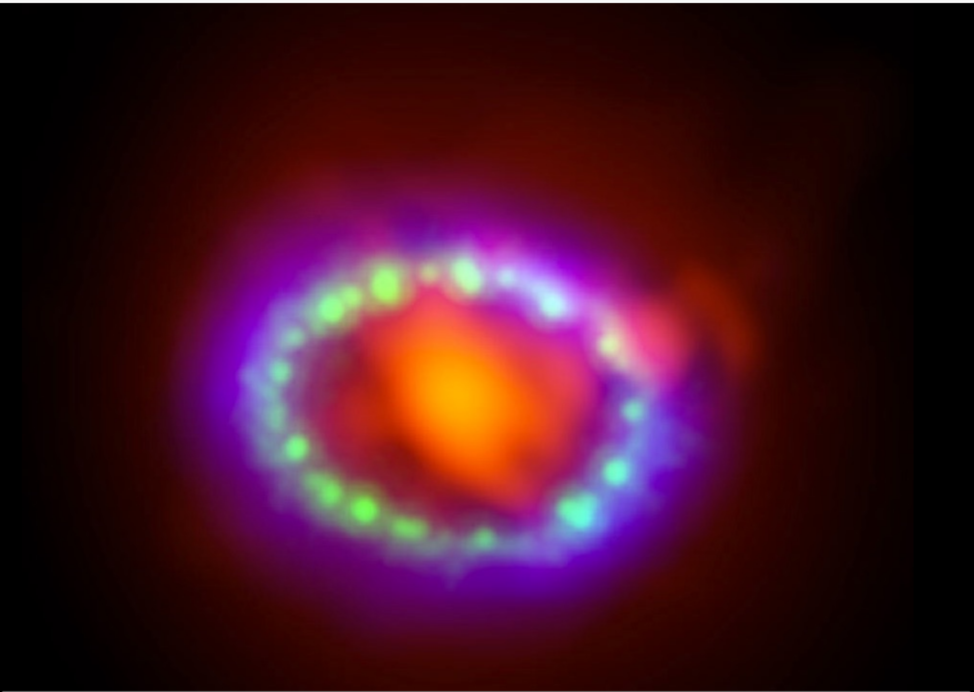
- FLASH (3D)
  (Fryxell et al. 2000)
- PLUTO (3D)
  (Mignone et al. 2012, 2012)







Cases study: SN 1987A and Cassiopeia A

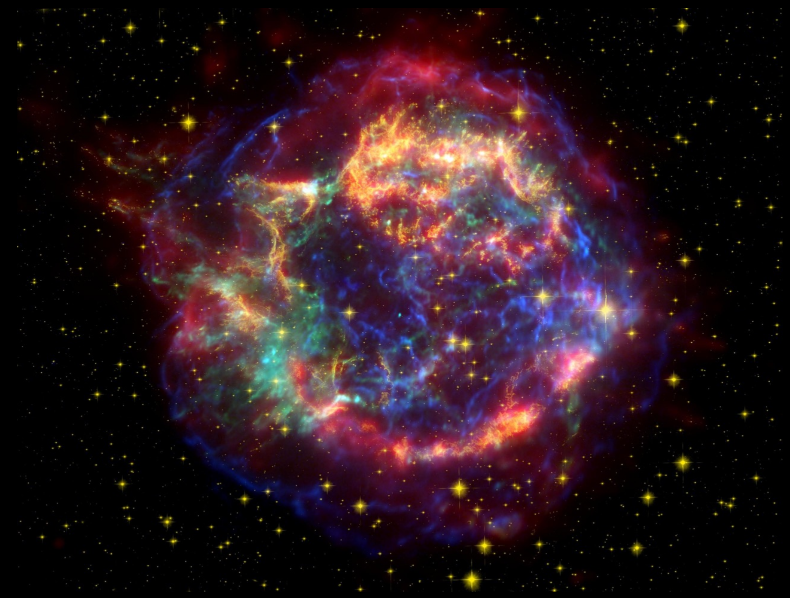


When: 23 February 1987
Where: Large Magellanic Cloud

Stellar progenitor: **Sk -69°202**

Nearest supernova explosion observed in hundreds of years

Unique opportunity to watch a SN change into a SNR



When: ~ 1650 a.d.
Where: 3.4 kpc

Stellar progenitor: **yellow supergiant (?)**

Remnant of a stripped envelope SN expanding through the wind of the progenitor star

Attractive laboratory to bridge the gap between SNe and their remnants

The remnant of SN 1987A

Stellar model (blue SG, red SG, merger scenario)

→ 3D SN explosion (asymmetric explosion)

→ 3D SNR expansion (inhomogeneous CSM)

- Origin of non-thermal radio and multi-thermal X-ray emission (Orlando et al. 2015, 2019; Petruk et al. 2023)

- Analyse the collisionless shock heating of heavy ions (Miceli et al. 2019)

- Constrain 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)

- Unveil the emission from a pulsar wind nebula (PWN) in SN 1987A (Greco et al. 2021, 2022)

- Perform the first self-consistent simulation of the PWN evolving at the center of SN 1987A (Olmi et al. work in progress)

The remnant of a neutrino-driven CC SN: Cassiopeia A

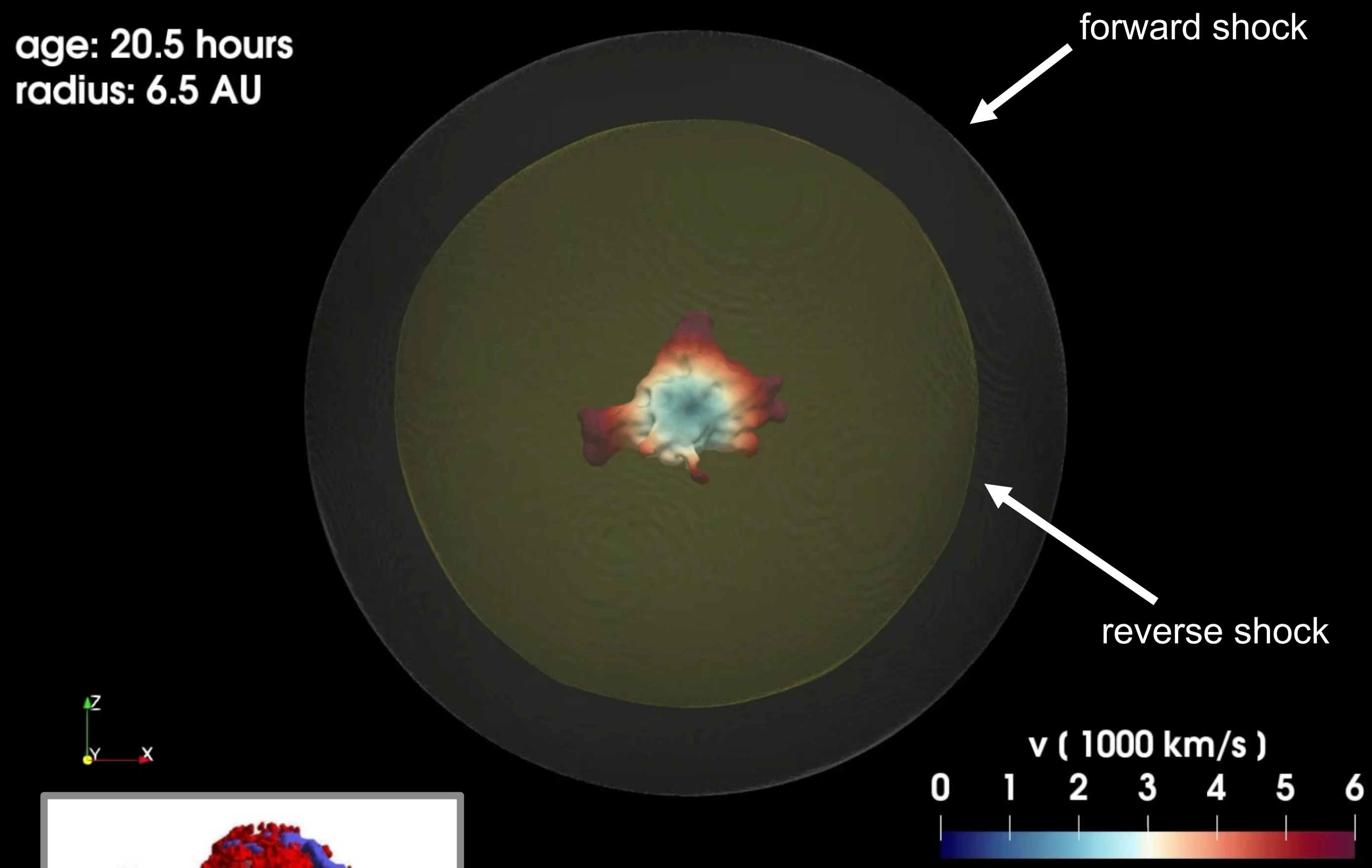
- Self-consistent description of the whole 3D evolution of a neutrino-driven SN explosion, from the CC to the SNR at the age of 2000 years (Orlando et al. 2016, 2021)

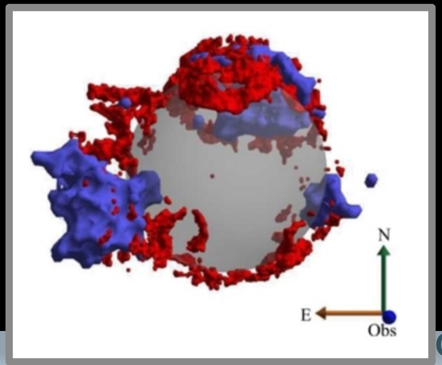
- identify the geometric and physical properties of the post-explosion anisotropies responsible for the morphology of Cas A

- 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

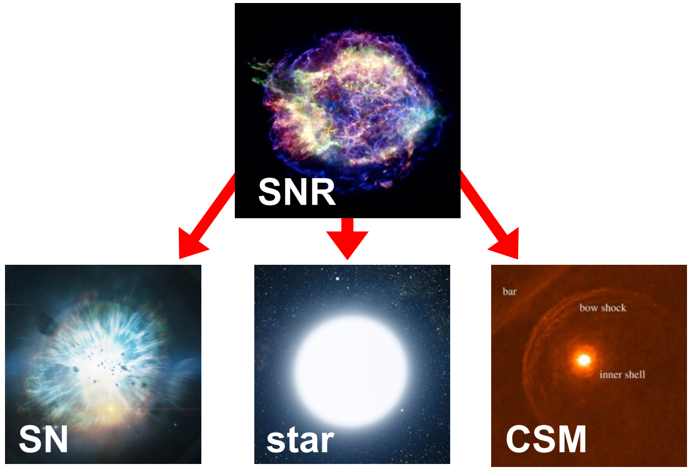
- A fraction of the asymmetries in Cas A reflects the past interaction of the remnant with a dense circumstellar shell (Orlando et al. 2022)





TAKE AWAY POINTS

- **SNRs morphology and properties reflect**
  - Asymmetries inherited from the parent SNe
  - Structure of the progenitor star at collapse
  - Interaction with the inhomogeneous ambient environment
- **Deciphering multi-λ observations of SNRs crucial to extract information about**
  - complex phases after the core-collapse; SN engine
  - nature of the progenitor stellar system
  - CSM; mass loss history of the progenitor star



HOW

3D HD / MHD models can help in linking
SNRs to their parent SNe and progenitor stars

the progenitor – SN – SNR connection
has breakthrough potential to open new exploring
windows on the physics of massive stars, SNe and SNRs

THE CHALLENGE

Deciphering observations might critically depend on the models

- They should connect *self-consistently* progenitors → SN → SNR
  - multi-physics, multi-scale, multi-dimension (progenitor, SN, SNR)
- They should be based on *solid observational facts*
  - account for dynamics, energetics, and spectral properties of SNe and SNRs