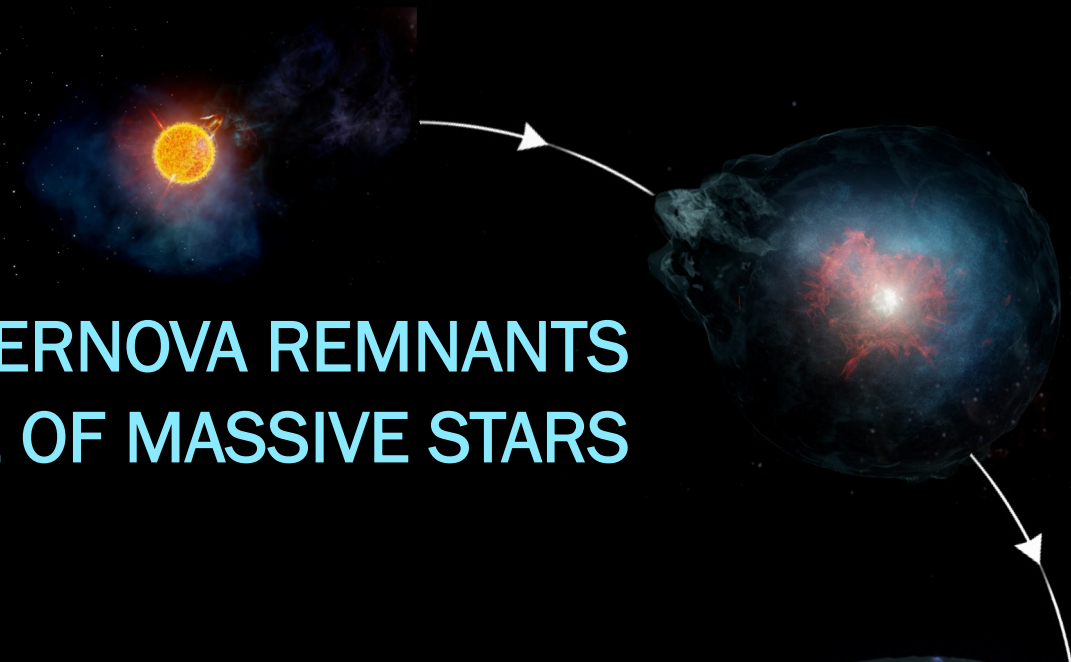

CC SUPERNOVA REMNANTS
LIFE, DEATH AND AFTERLIFE OF MASSIVE STARS

Salvatore Orlando

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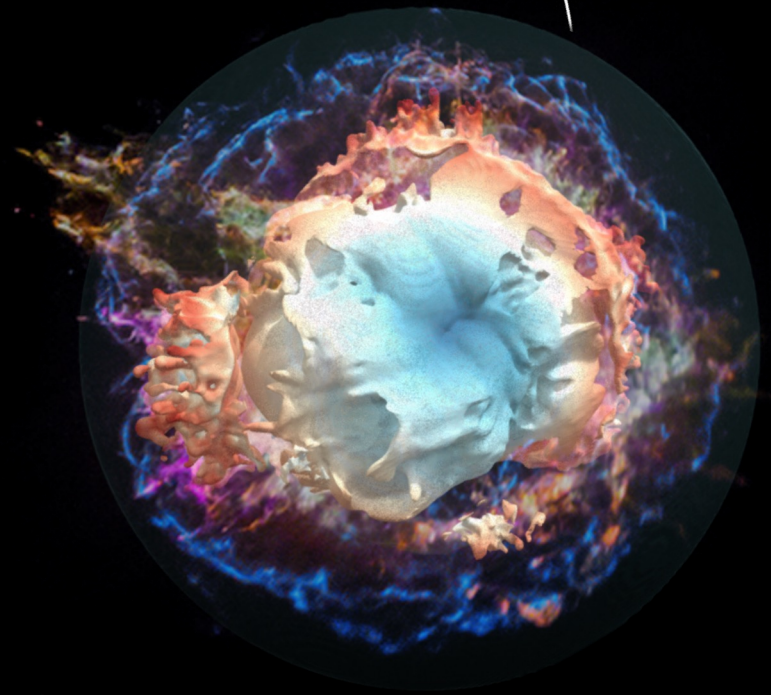
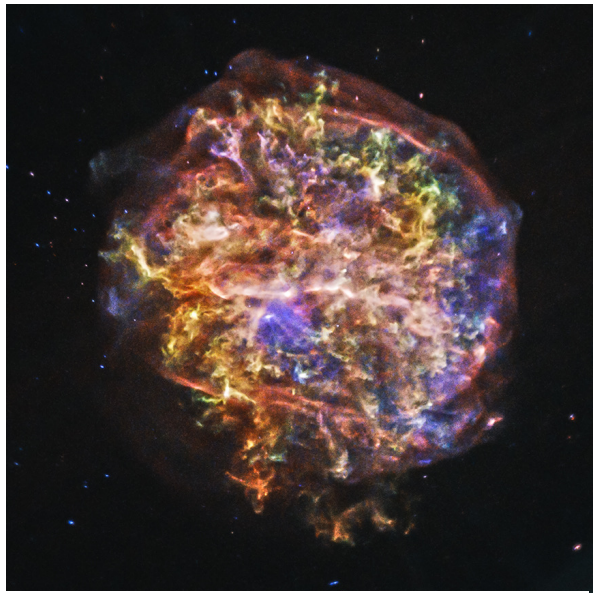
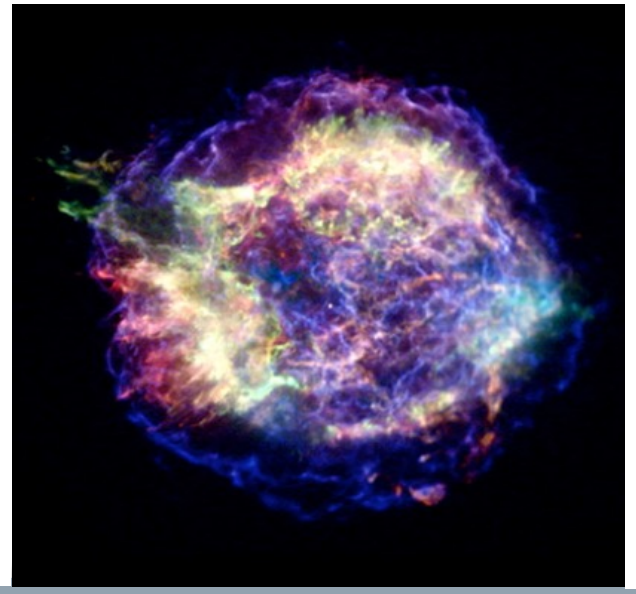
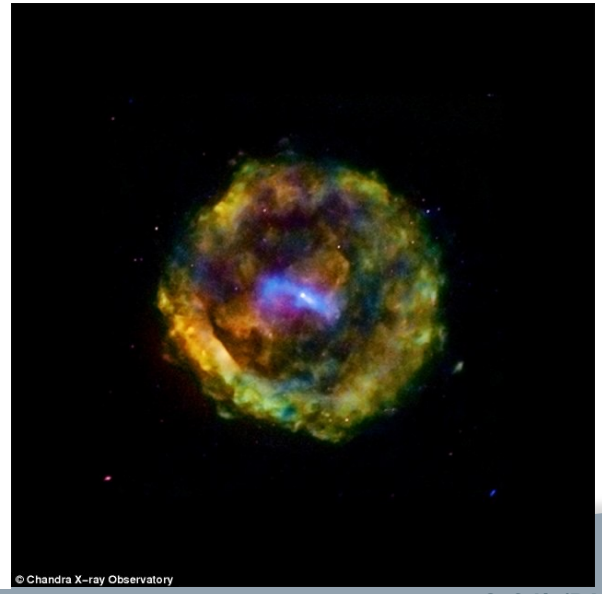
F. Bocchino, B. Olmi, O. Petruk, S. Ustamujic, A. Tutone	(INAF – OAPA, Italy)
M. Miceli, G. Peres, R. Giuffrida, V. Sapienza	(Università di Palermo, Italy)
H.-T. Janka, A. Wongwathanarat	(Max-Planck-Institut für Astrophysik, Germany)
S. Nagataki, M. Ono, A. Dohi, G. Ferrand	(ABBL/RIKEN, Japan)
E. Greco, J. Vink, L. Sun	(University of Amsterdam, NL)
H. Umeda	(Tokyo University, Japan)
H. Lee	(Kyoto University, Japan)
M. A. Aloy, 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)



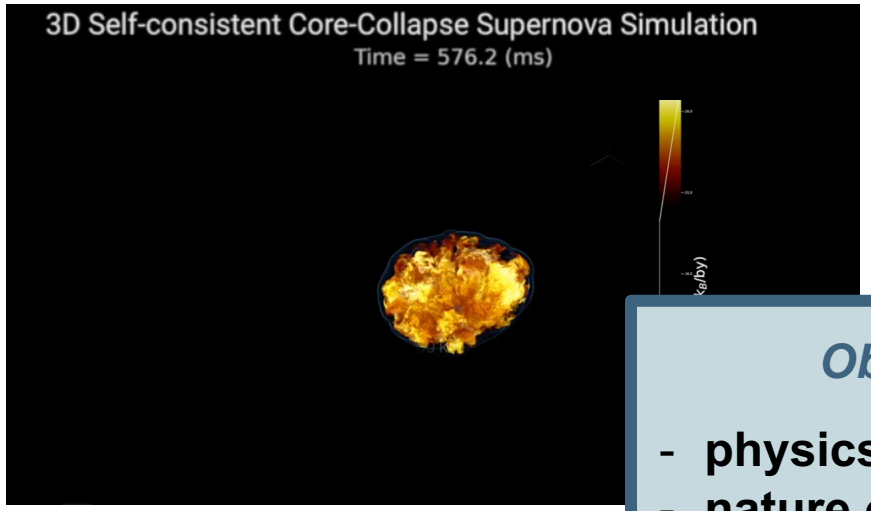
The remnants of core-collapse SNe





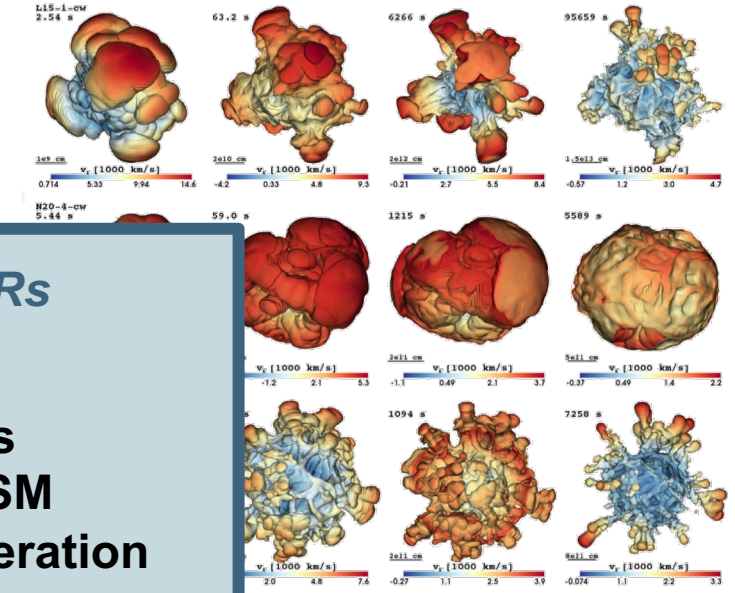


Origin of the complex morphology of CC SNRs



SN explosion (Kuo-Chuan Pan+

progenitor star (Wongwathanarat+ 2015)

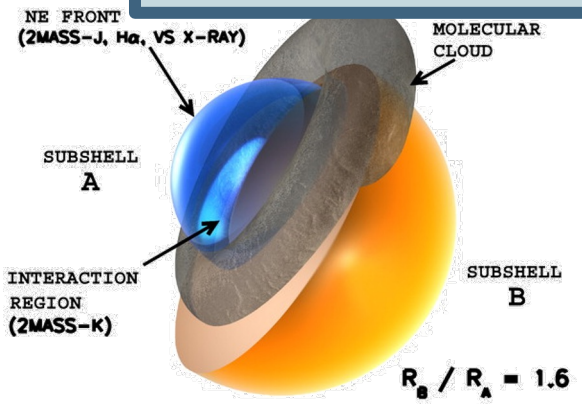


Observations of SNRs

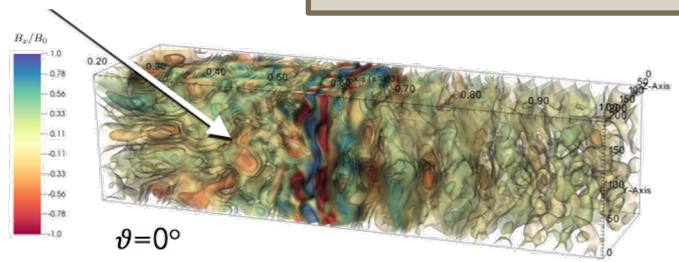
- physics of SN engines
- nature of progenitor stars
- properties of the CSM / ISM
- process of particle acceleration

ambient environment

(T



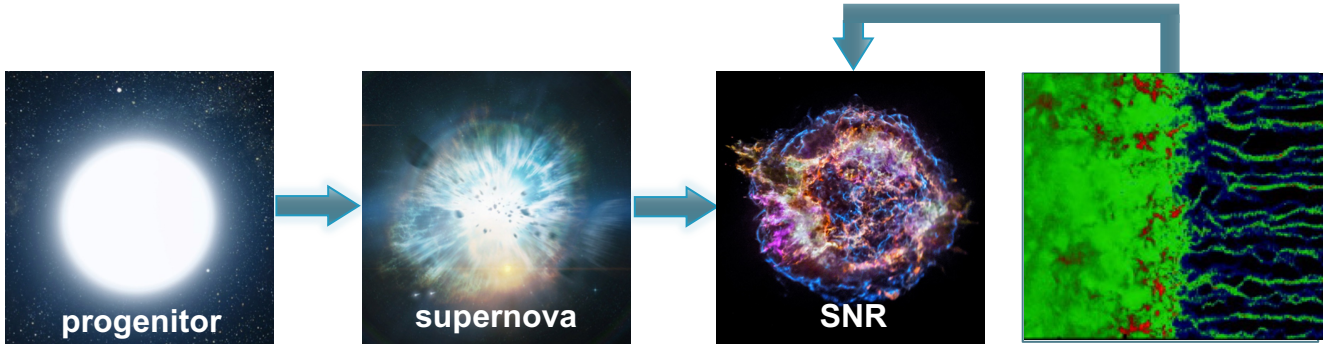
Particle acceleration



(Caprioli 2015)

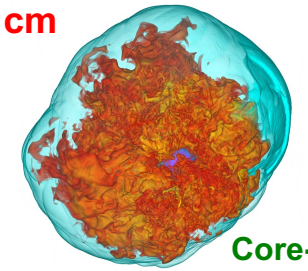
How to link progenitor – SN – SNR ?

- **Multi-physics**



- **Multi-scale**

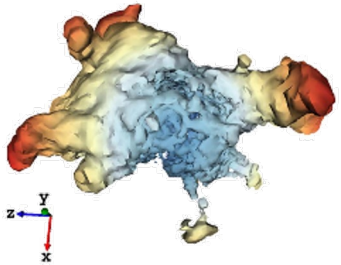
L: 10^9 cm
t: 1 s

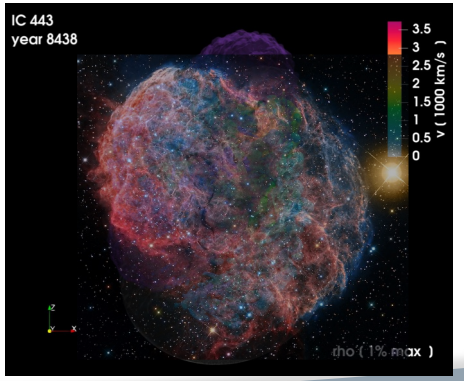


Core-collapse

L: a few pc
t: ~ 10000 yrs

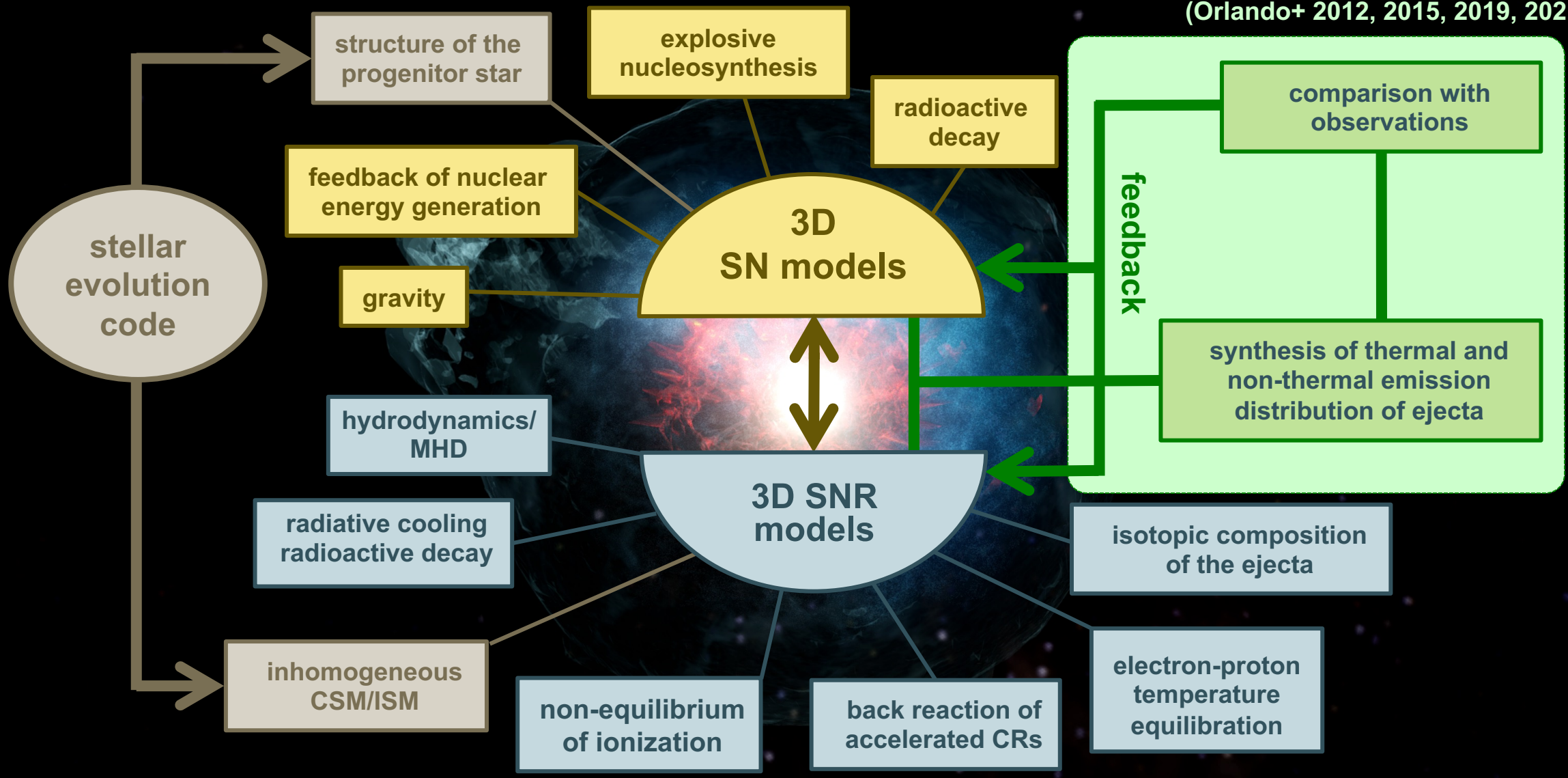
- **Multi-dimensions**

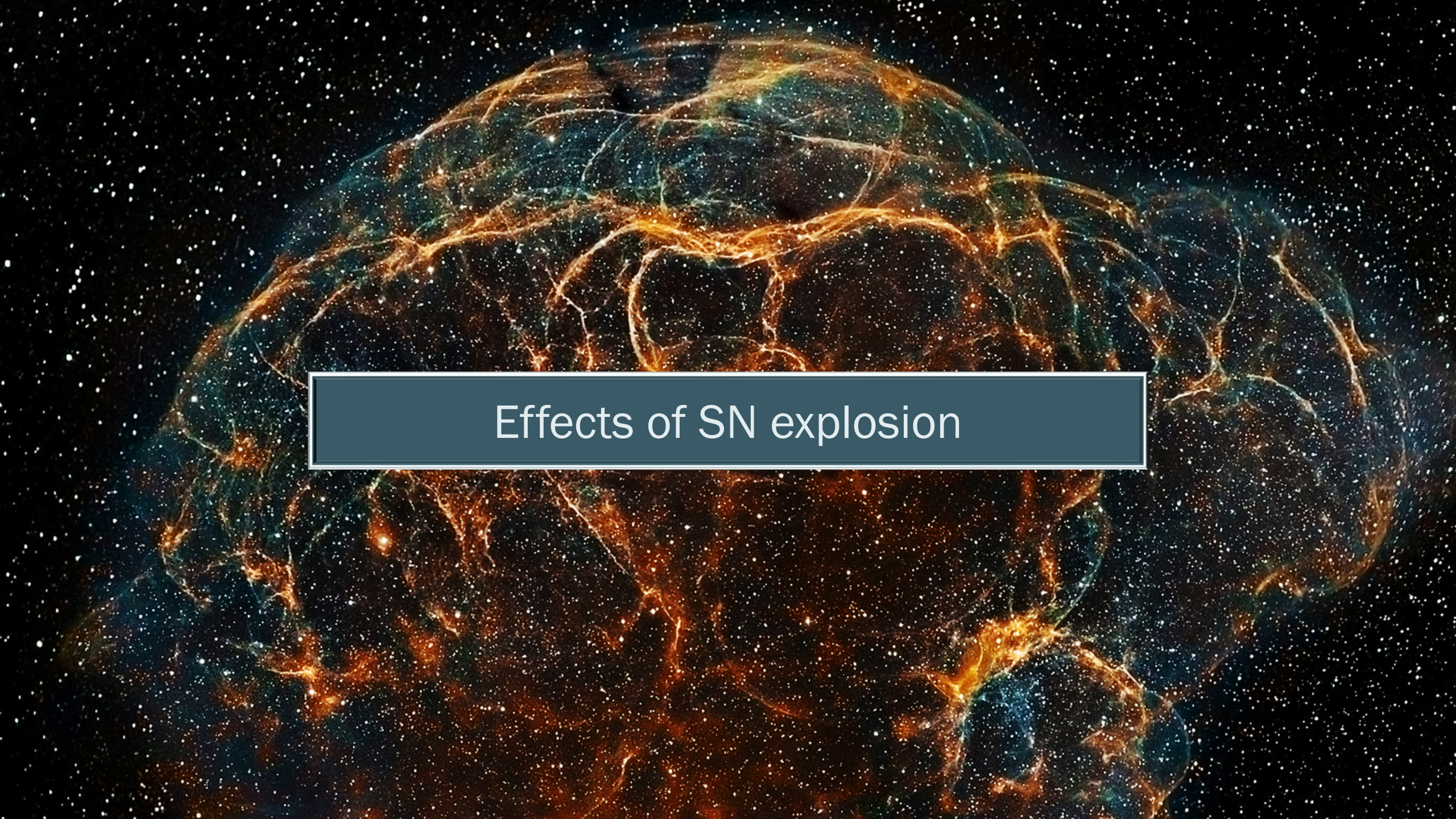




How to link progenitor – SN – SNR ? The strategy

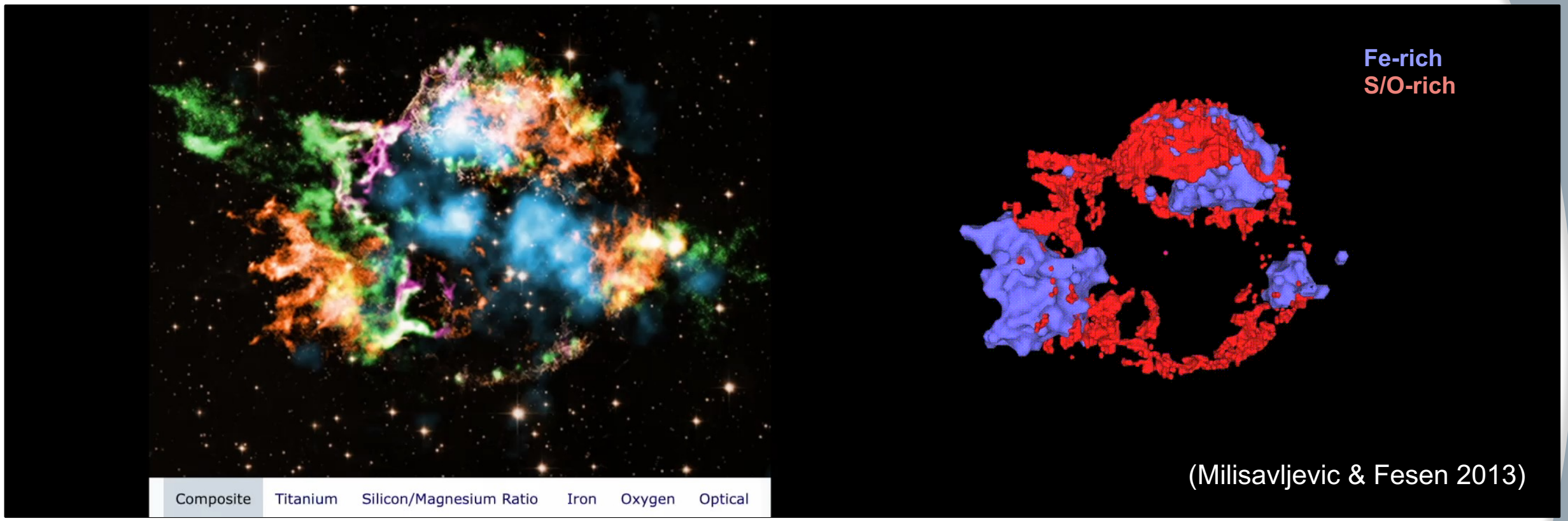
(Orlando+ 2012, 2015, 2019, 2021)





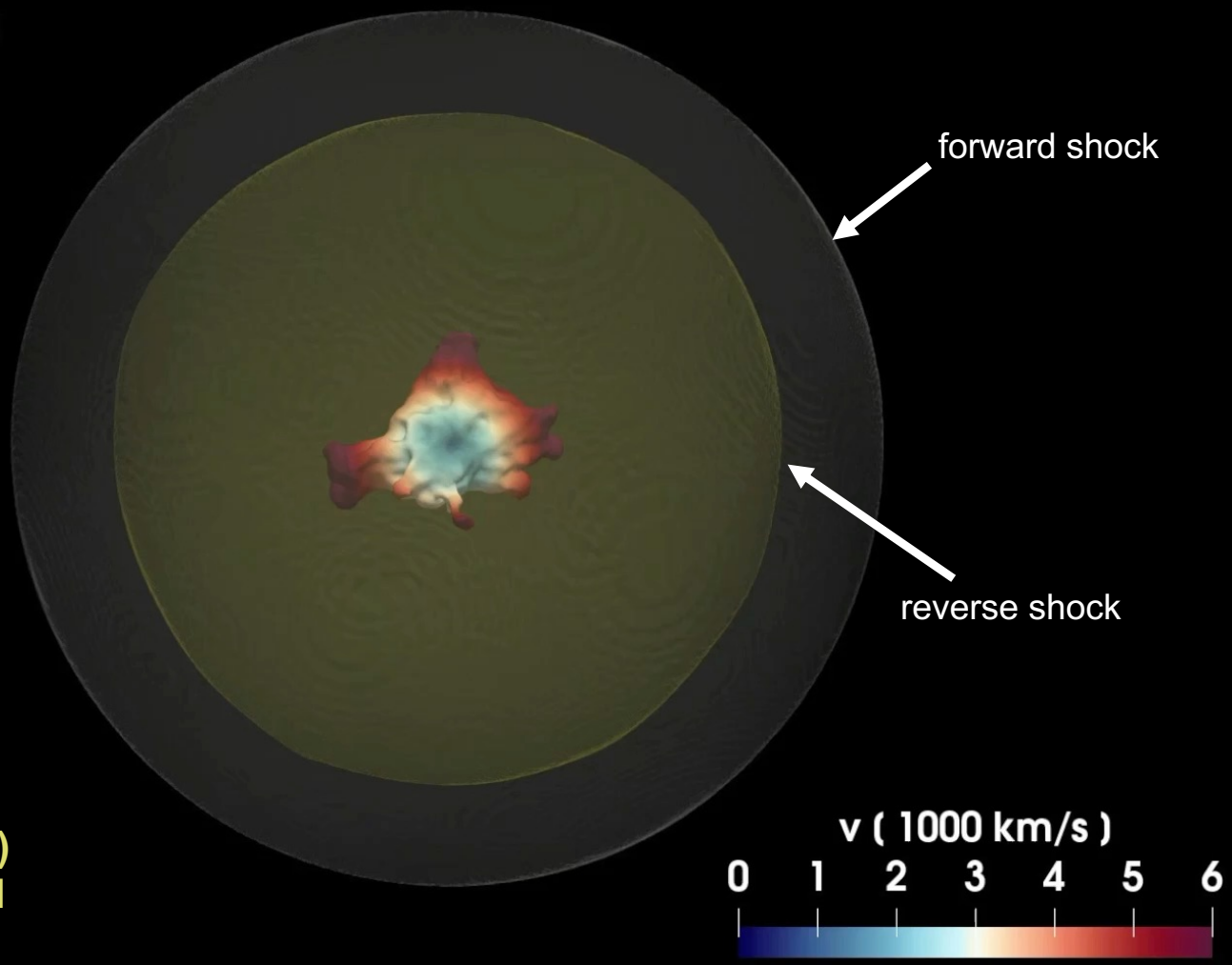
Effects of SN explosion

Unique laboratory to study the SN-SNR connection



The bulk of asymmetries observed in Cas A is intrinsic to the explosion

The remnant of a neutrino-driven CC SN



Major asymmetries observed in Cas A explained by a neutrino-driven SN explosion

Ejecta structure originates from stochastic processes (e.g., convective overturn and SASI) that develop during the first seconds of the SN blast

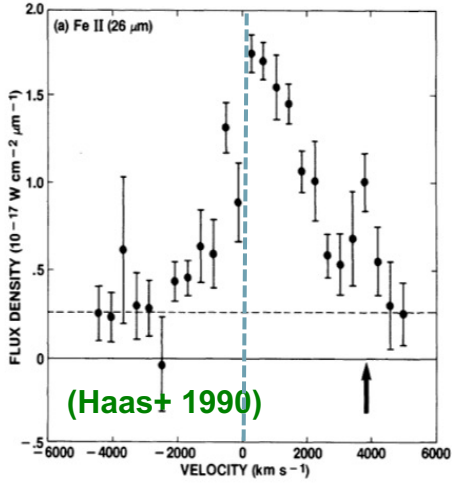
(Orlando et al. 2016, 2021; Wongwathanarat 2017)

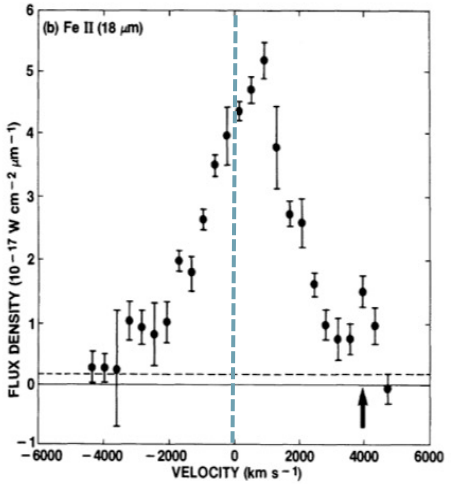
Effects of the progenitor star

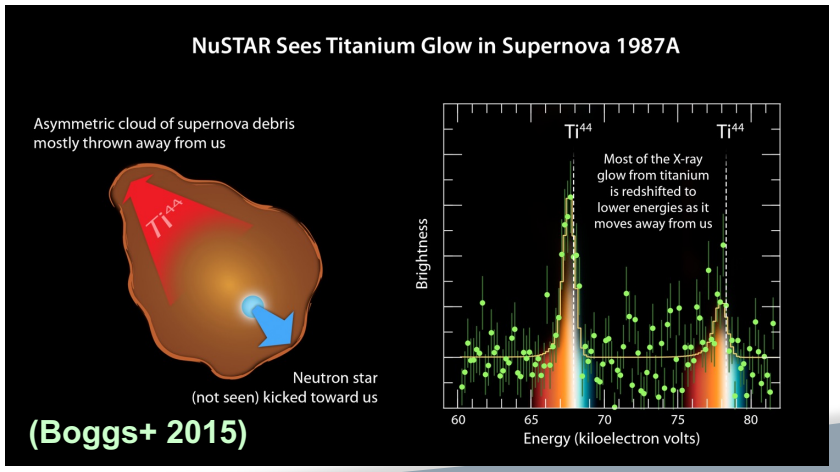
Anisotropies in SN 1987A

- Soon after the SN event: Fe lines redshifted centroid ~ 280 ±140 km/s; wings > 3000 km/s (Haas+ 1990)
- At later times (> 20 yrs): lines from decay of ^{44}Ti redshifted with a Doppler velocity of ~700 km/s (Boggs+ 2015)
- 3D distributions of CO and SiO emission have a torus-like distribution (Abellan+ 2017)

Direct evidence of large-scale asymmetry in the explosion







Linking SNR 1987A to the SN and progenitor star

1D stellar progenitor models

(Ono+2020)

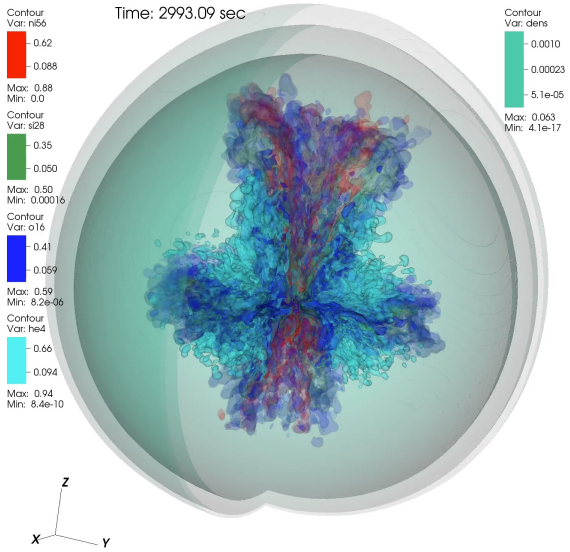
3D cc SN model

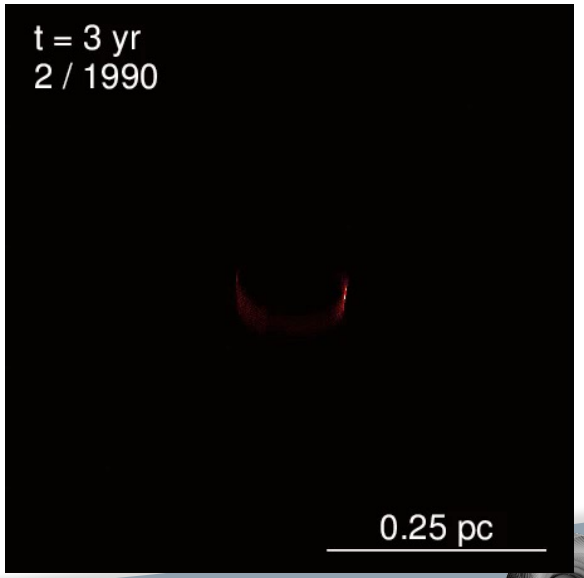
(Orlando+2020)

3D SNR model

Progenitor star

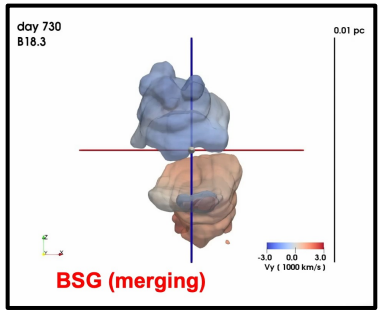
- **16.3$M_\odot$ BSG (Nomoto+1988)**
- **18.29 $M_\odot$ BSG resulting from the merging of 14 and 9 $M_\odot$ stars (Urushibata+2018)**
- **19.8$M_\odot$ RSG (Woosley+2002)**

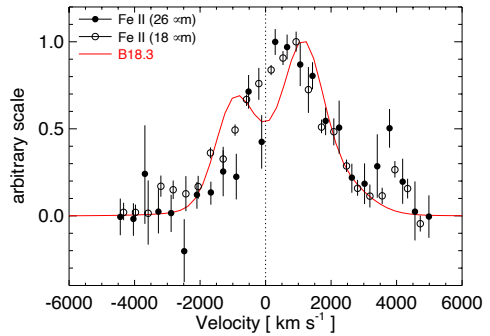




Linking SNR 1987A to the SN and progenitor star

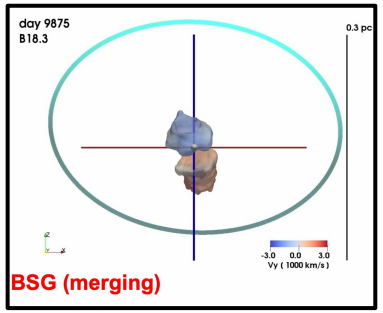
Age
2 years

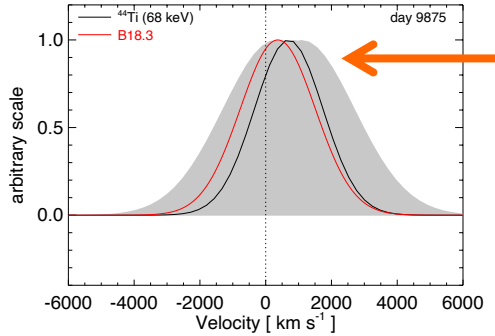




(Orlando+ 2020)

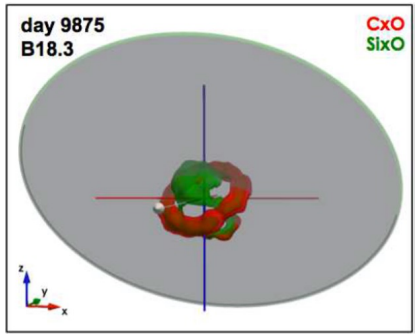
Age
27 years



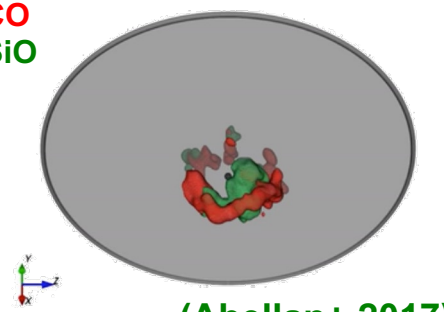


90% confidence area for the position of the peak and for the width of the Gaussian

Age
27 years



CO
SiO



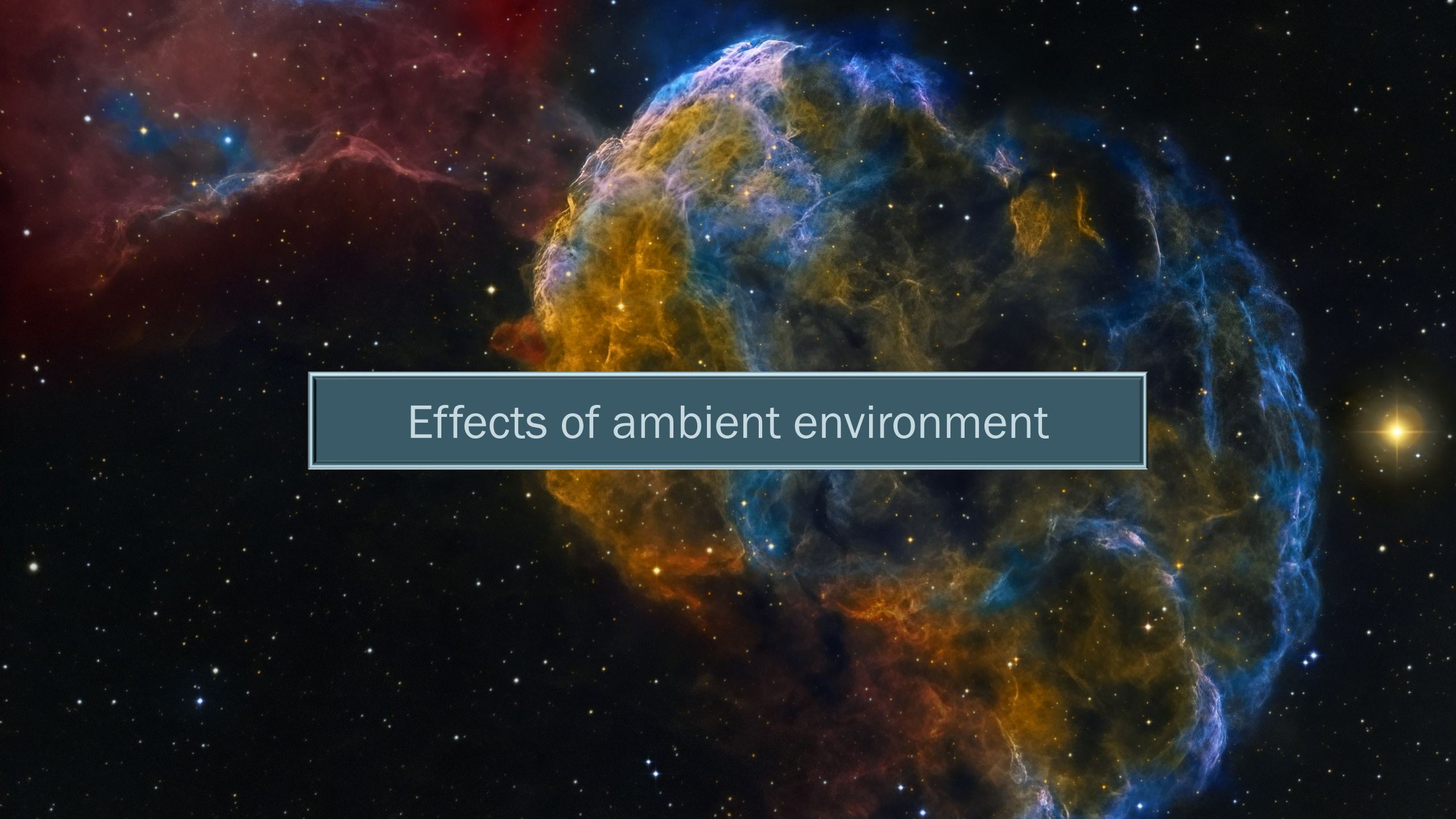
(Abellan+ 2017)

Best-fit parameters

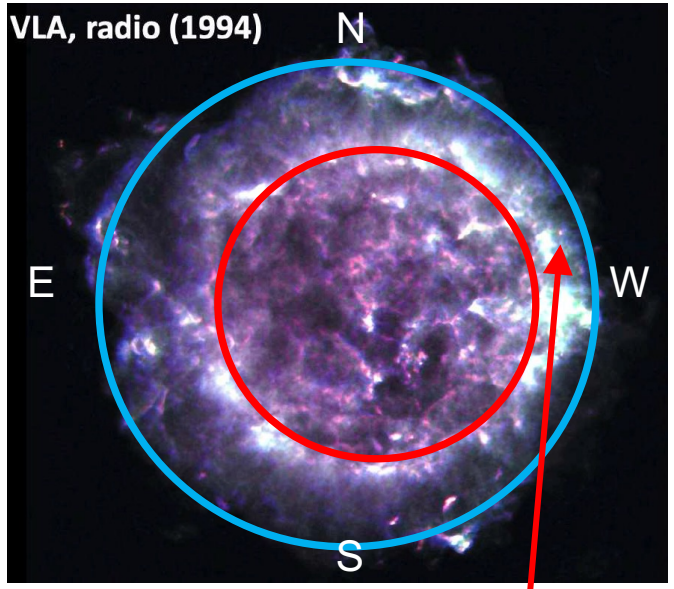
E_{exp} ~ 2 x 10^{51} erg

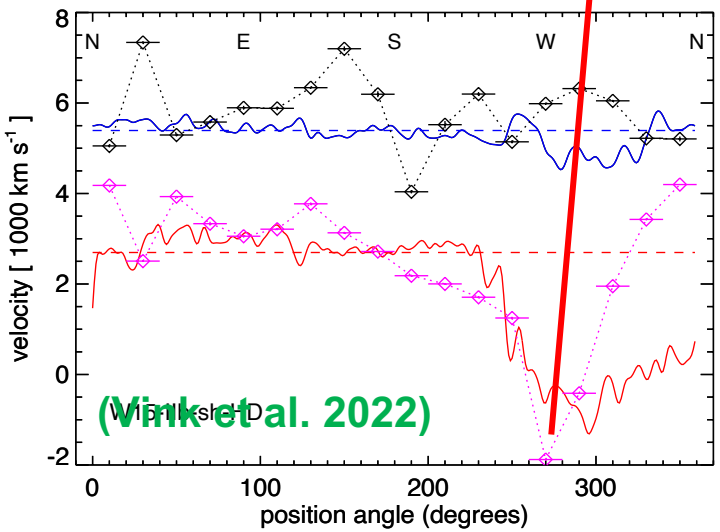
Asymmetry: physical + geometric prop.

progenitor model: merger scenario

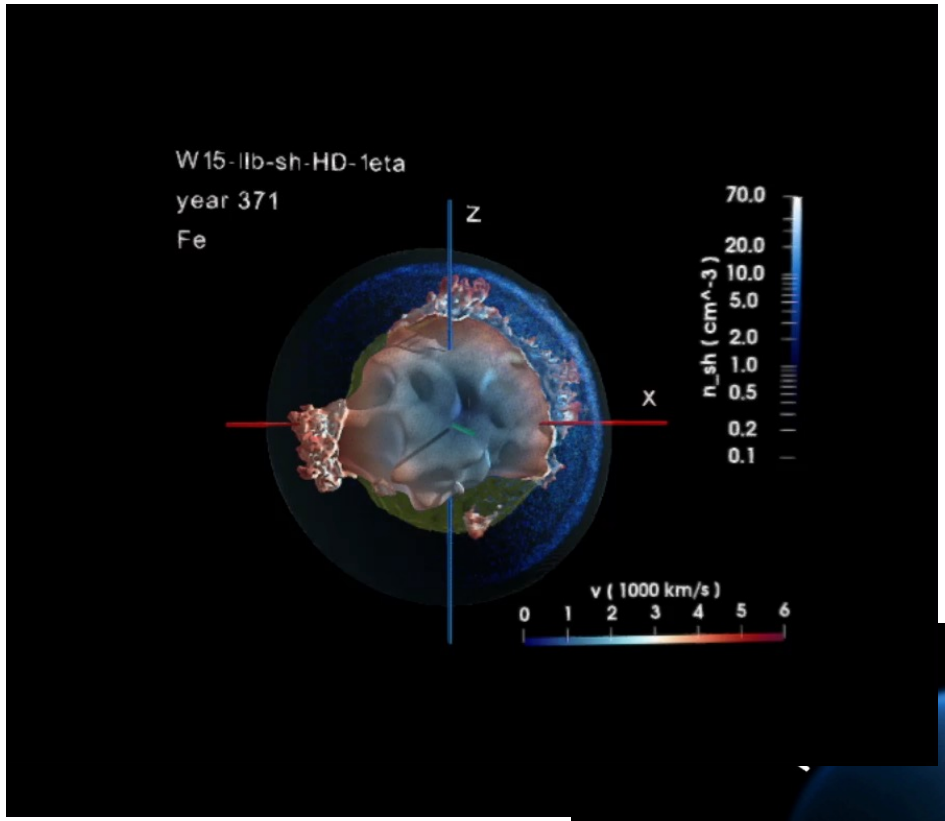

Effects of ambient environment

Cas A reveals past interaction with CSM shell



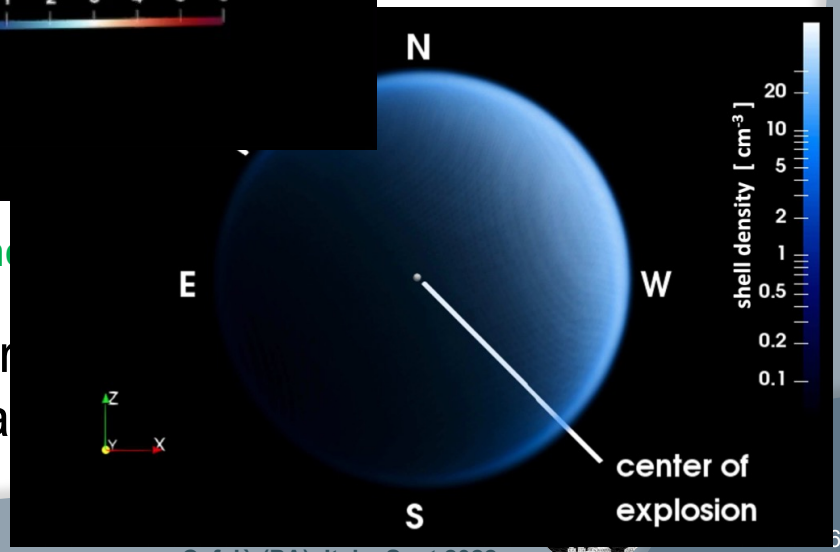


(Vink et al. 2022)



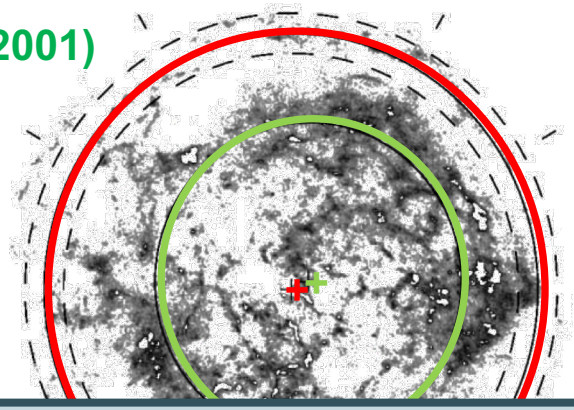
(Orlan

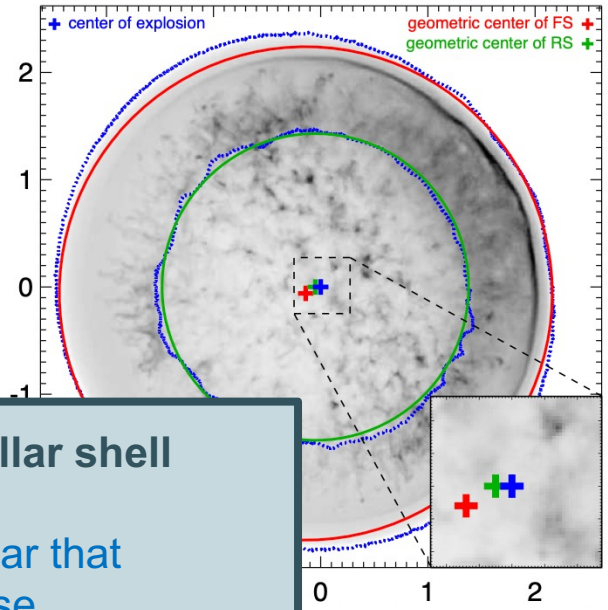
Hints on the mass-loss histor
the progenitor star and its na



Cas A reveals past interaction with CSM shell

(Gotthelf et al. 2001)



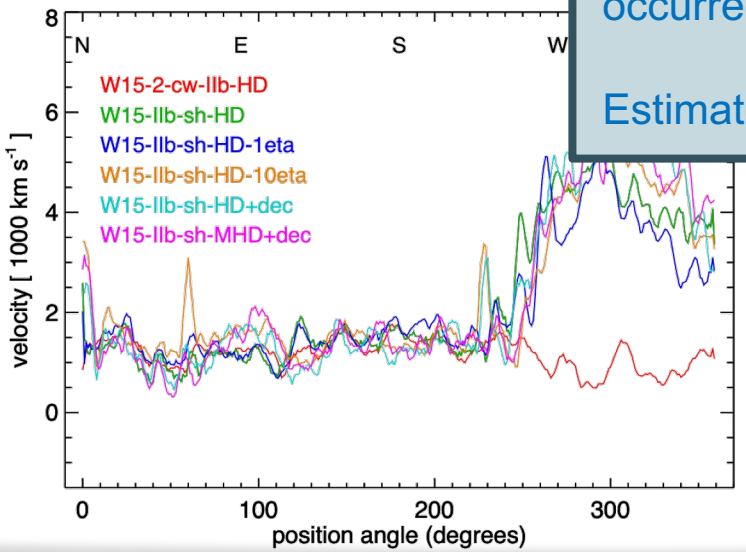


(Orlando et al. 2022)

Interaction with a dense asymmetric circumstellar shell

Most likely massive eruption from the progenitor star that occurred about 10^4 - 10^5 years prior to core-collapse

Estimated mass of the shell $M_{sh} \sim 2\ M_{\odot}$

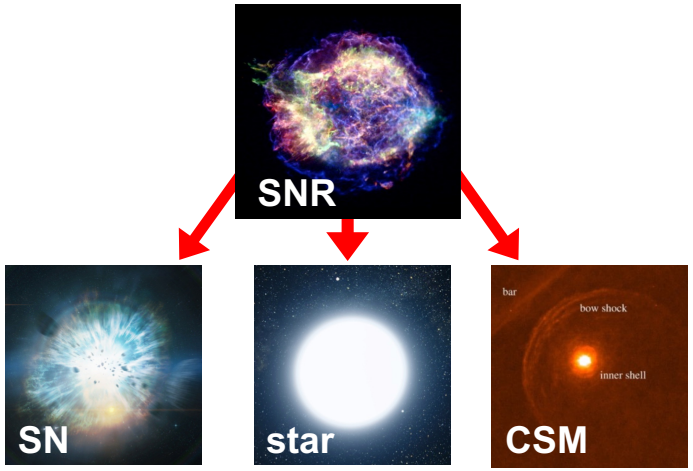


Reverse shock velocity in the ejecta reference frame

explain why most of the X-ray synchrotron emission originates from the western part of the reverse shock

Conclusions

- **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

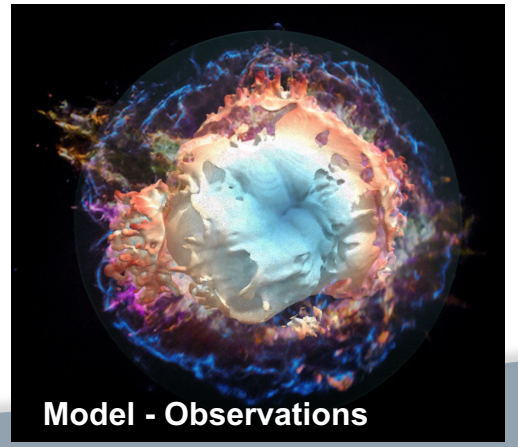
3D HD / MHD models can help in linking
SNRs to their parent SNe and progenitor stars

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

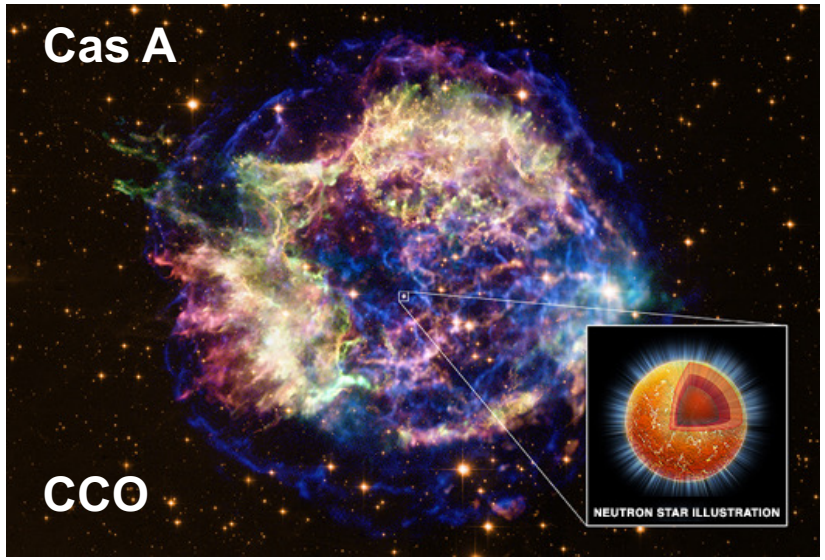
- They should connect *self-consistently* progenitors → SN → SNR
  - multi-physics, multi-scale, multi-dimension (progenitor, SN, SNR)
- They should be based on *solid observational facts*
  - account for dynamics, energetics, and spectral properties of SNe and SNRs

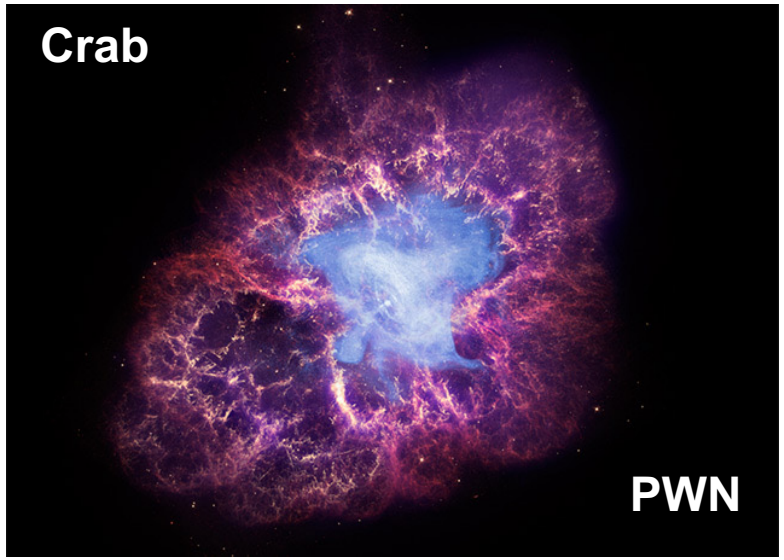


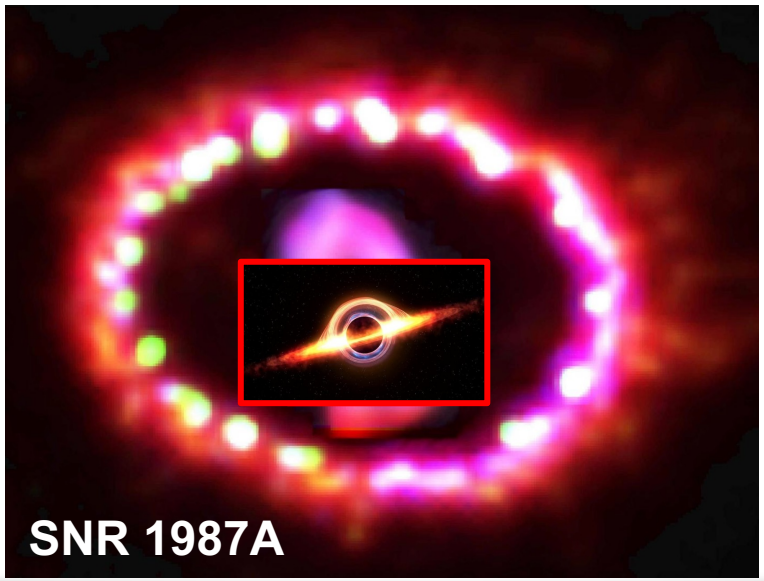
Supernova Remnants:
storytellers of the life and death of massive stars ...

... and what about after life ?

Compact remnants







See talk by
Emanuele Greco