MODELING THE PATH FROM MASSIVE STARS TO SNE AND SNRS: RECENT ADVANCES AND FUTURE PROSPECTS

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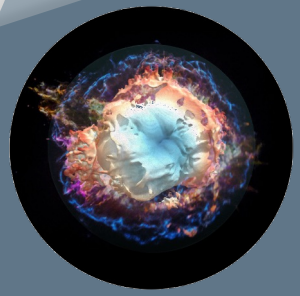
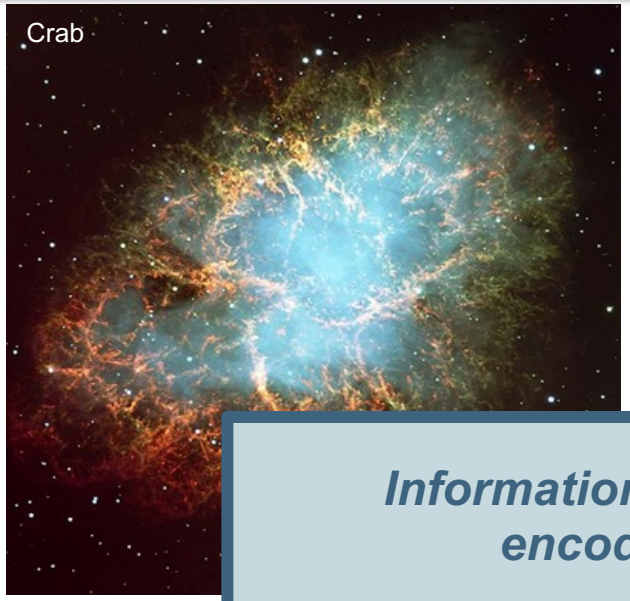
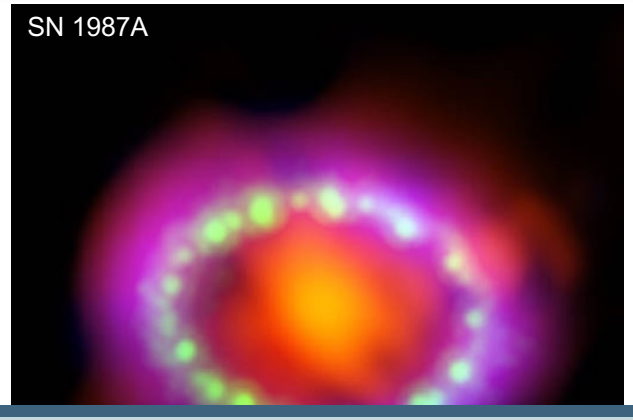
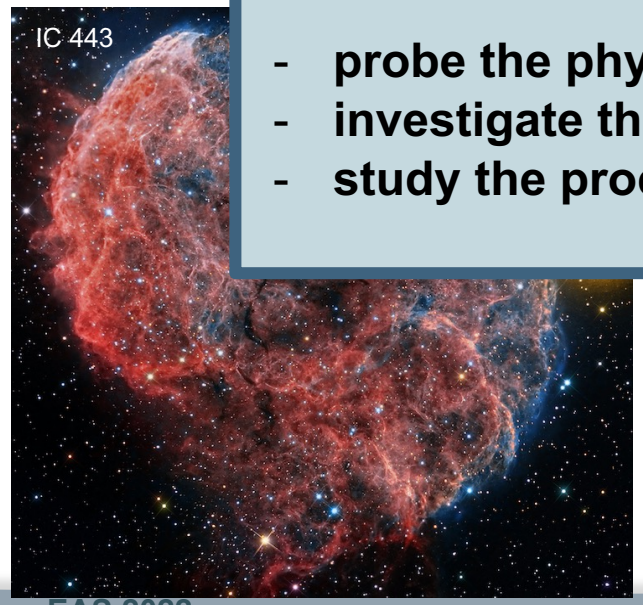
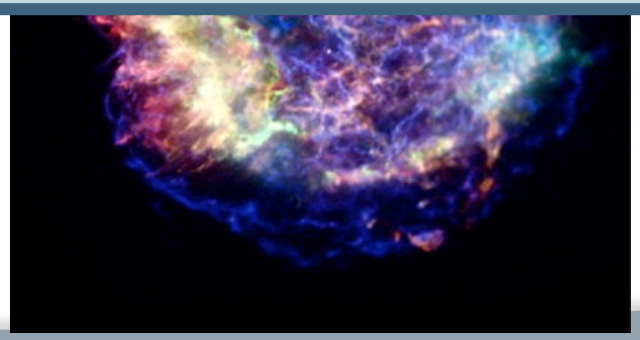


Supernova Remnants





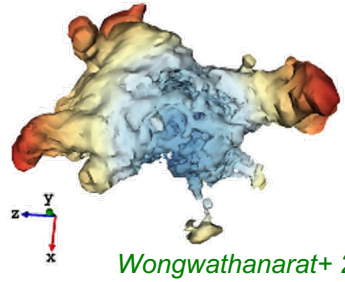




Information about progenitor - SN - CR encoded in the observations

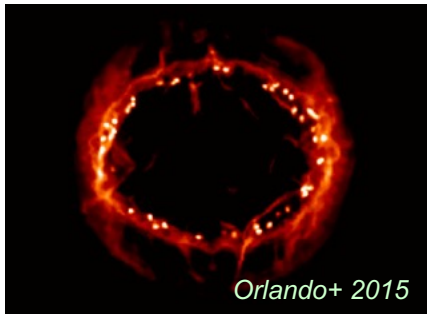
- **probe the physics of SN engines**
- **investigate the final stages of stellar evolution**
- **study the process of particle acceleration**

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



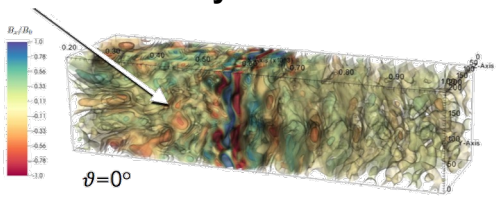
Wongwathanarat+ 2017

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

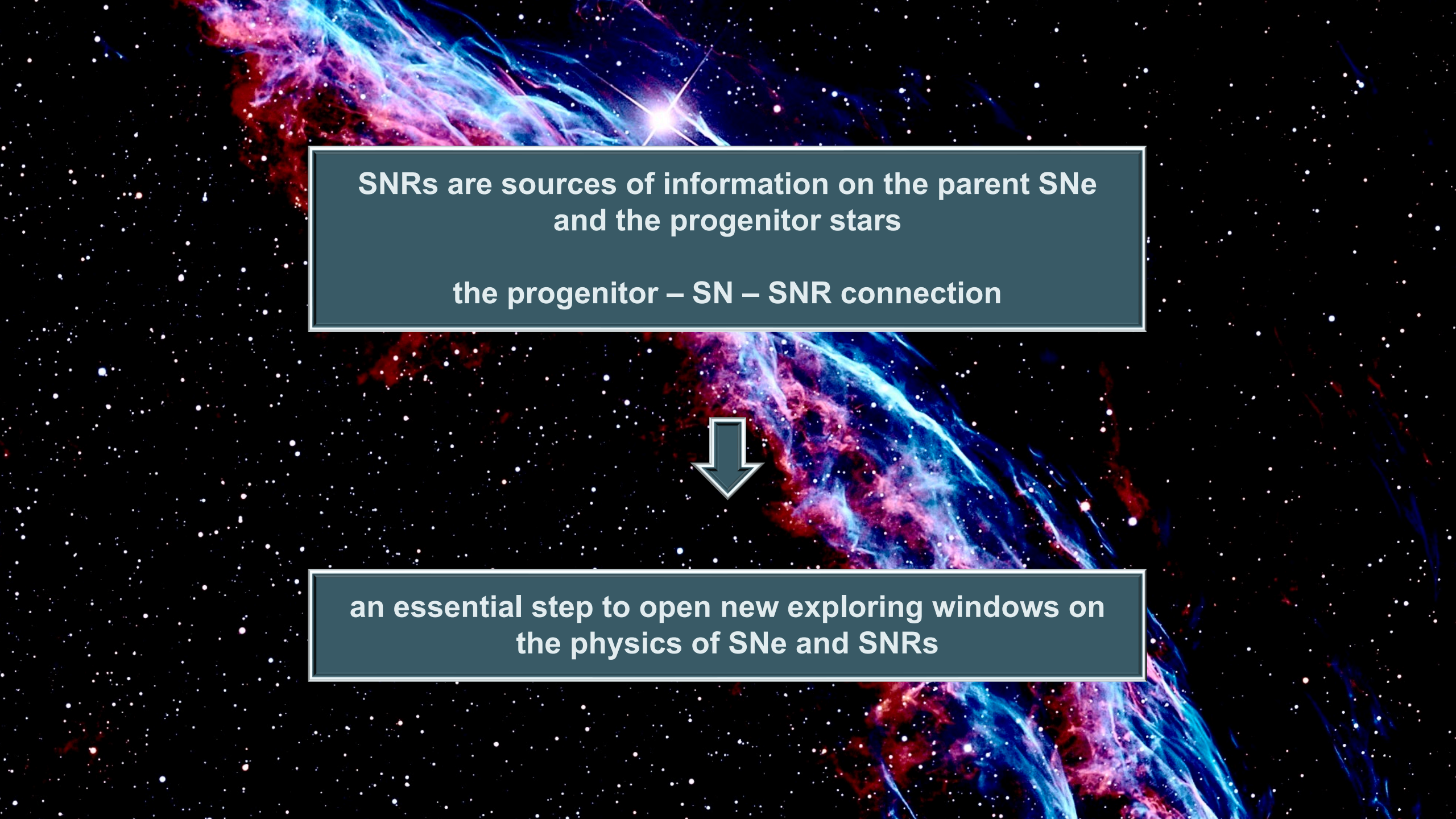


Orlando+ 2015

- **cosmic rays acceleration**

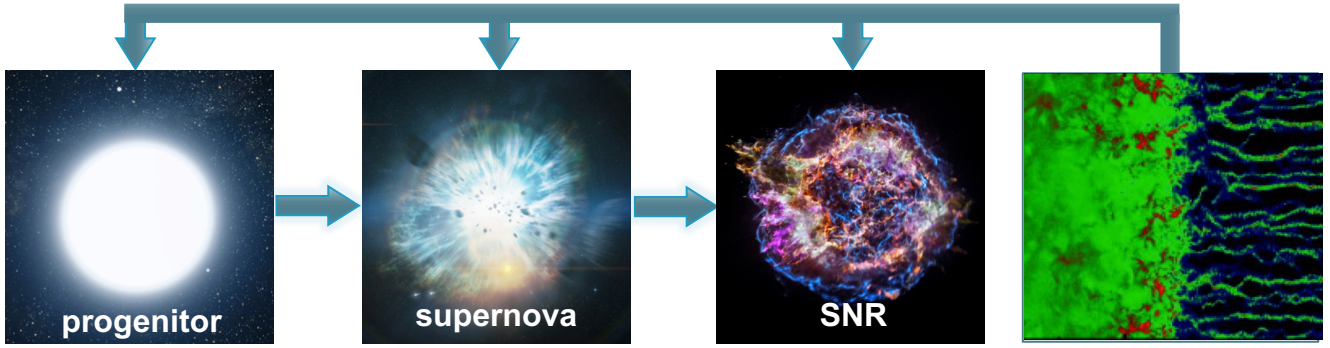


Caprioli 2015


SNRs are sources of information on the parent SNe and the progenitor stars
the progenitor – SN – SNR connection
an essential step to open new exploring windows on the physics of SNe and SNRs

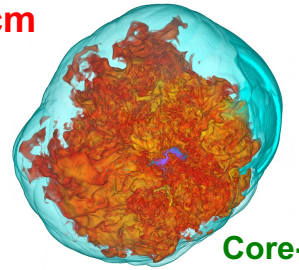
How to link progenitor – SN – SNR ?

- **Multi-physics**



- **Multi-scale**

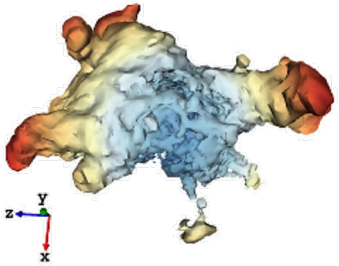
l: 10^9 cm
t: 1 s

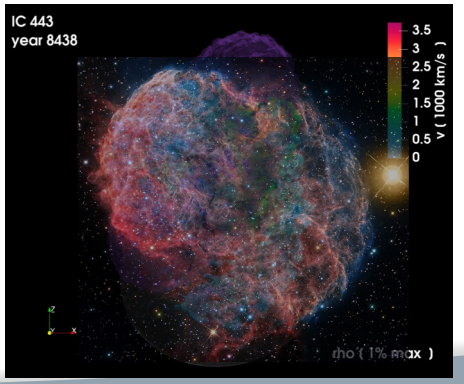


Core-collapse

l: a few pc
t: 100-10000 yrs

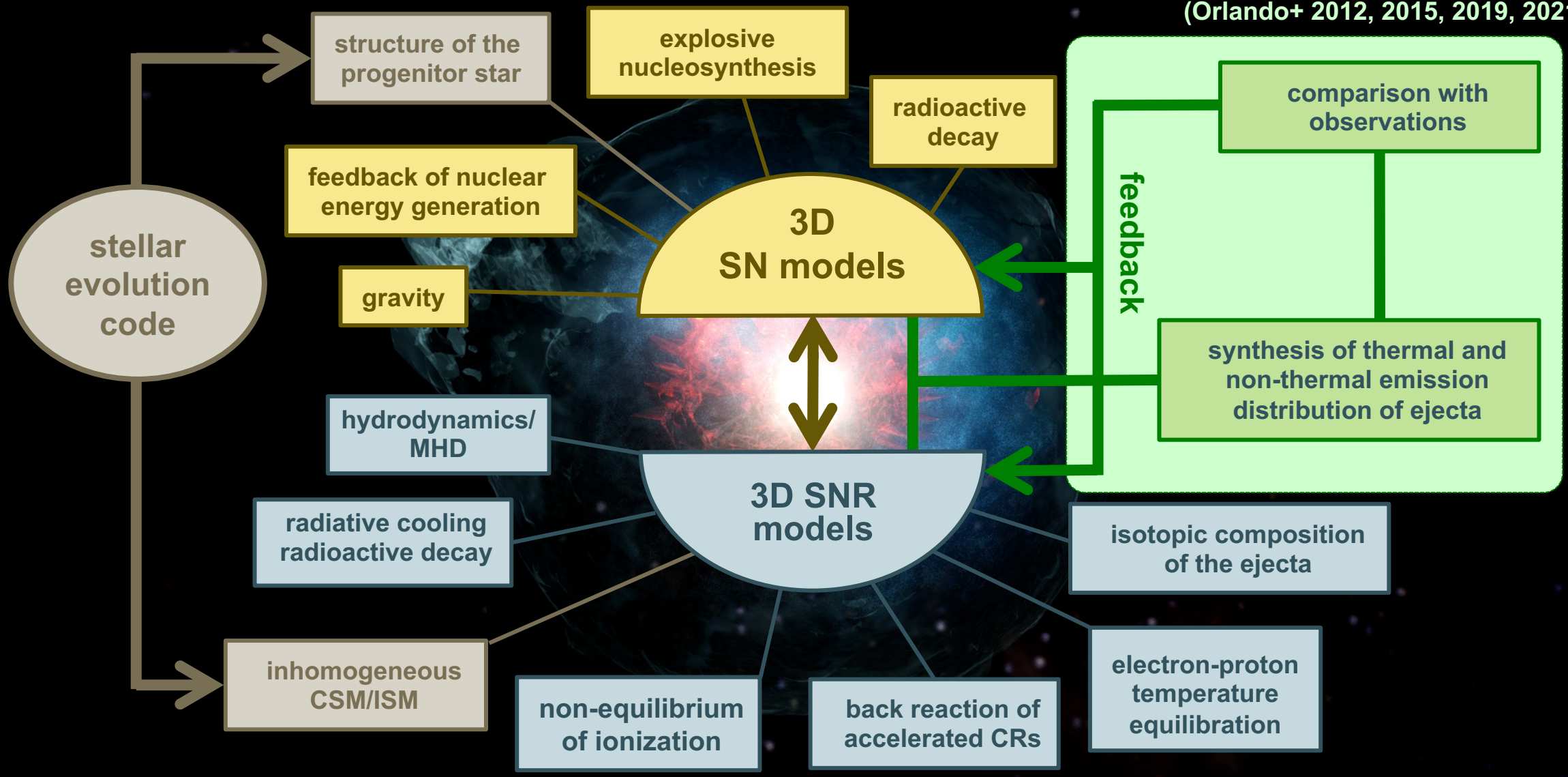
- **Multi-dimensions**





How to link progenitor – SN – SNR ? The strategy

(Orlando+ 2012, 2015, 2019, 2021)



A unique laboratory to study the star-SN-SNR connection

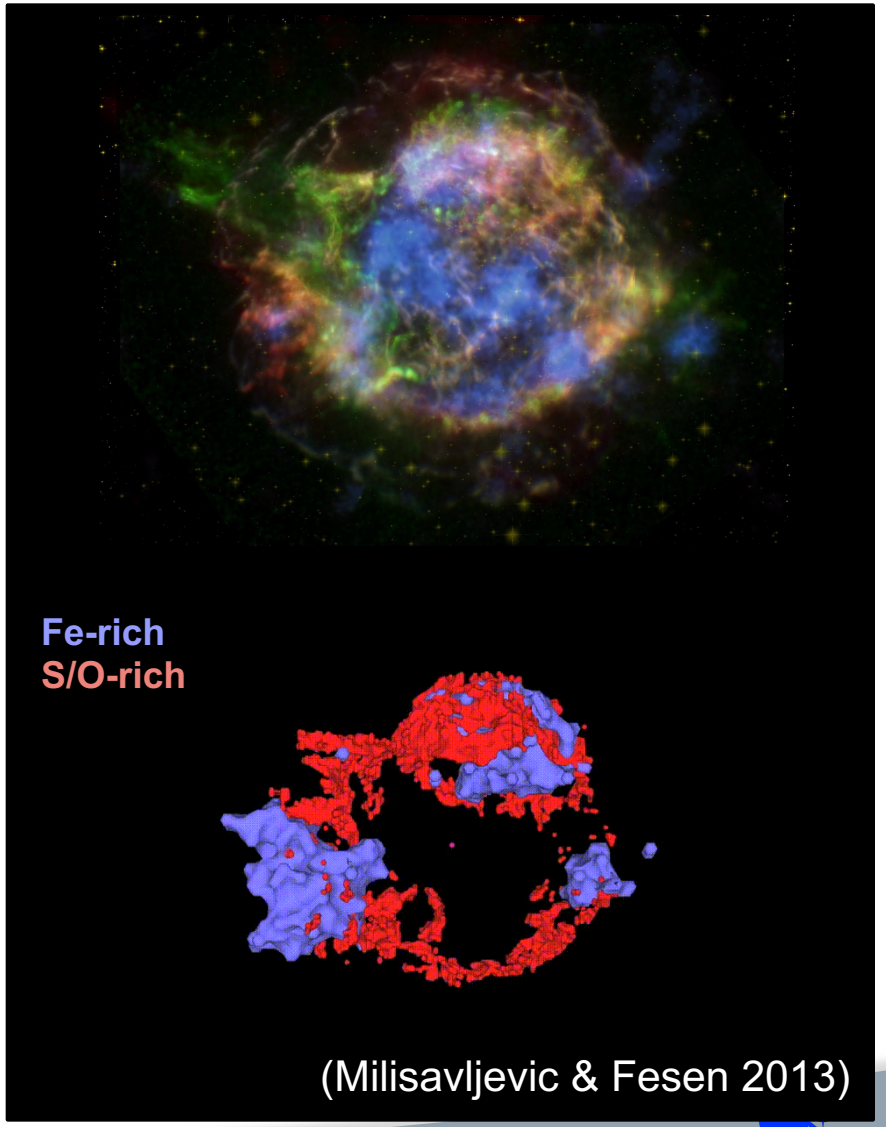
Cassiopeia A

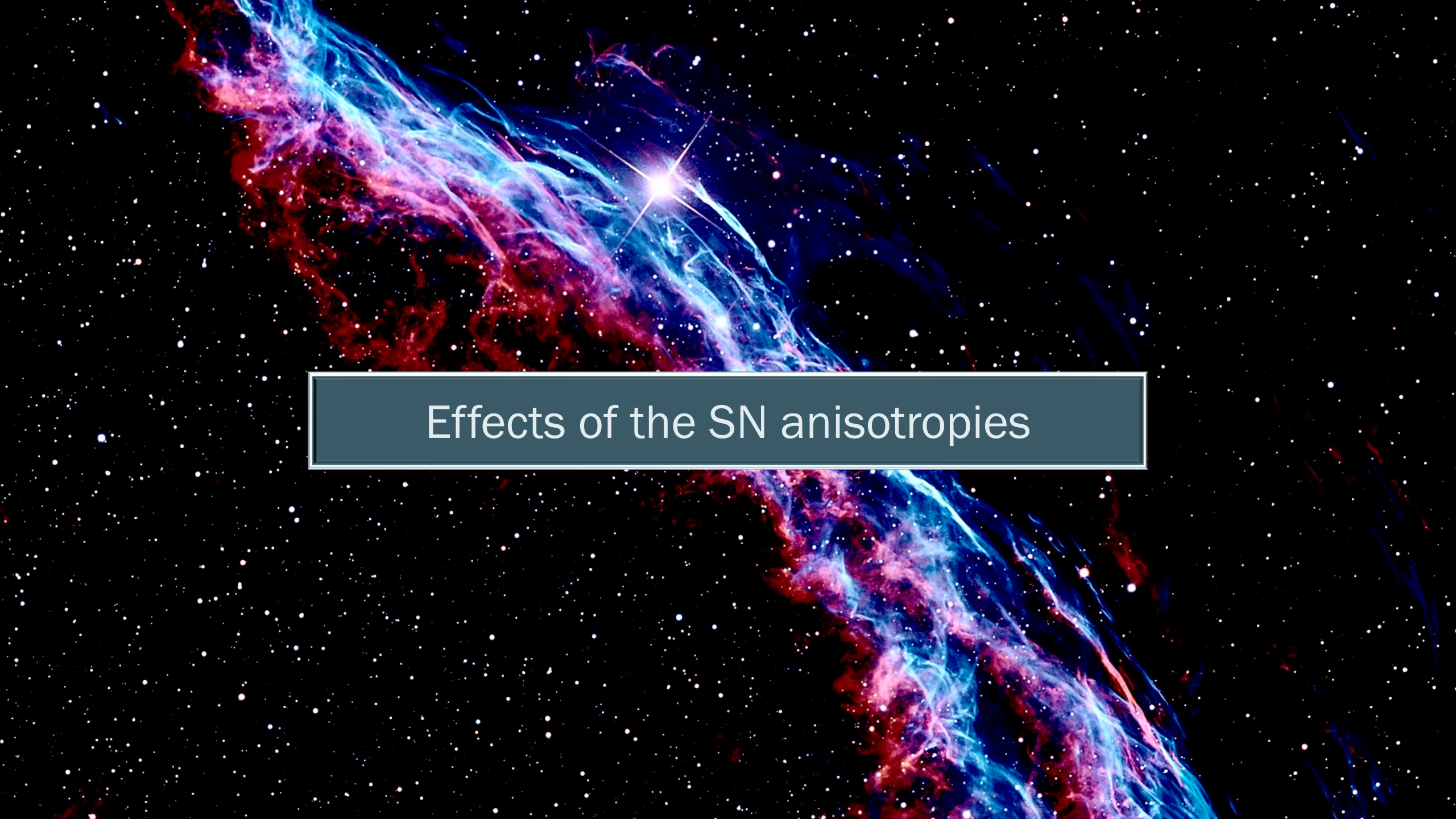
Observations suggest that its morphology and expansion rate are consistent with a remnant expanding through the wind of the progenitor star
(e.g. Lee+ 2014)

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

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, Holland-Ashford+ 2019,

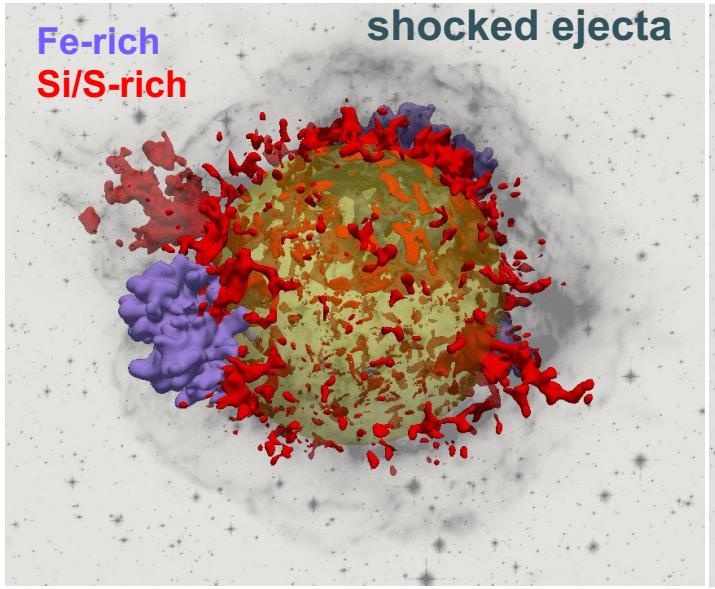
- 3 Fe-rich regions
- 2 Si-rich jets
- Rings circling Fe-rich regions

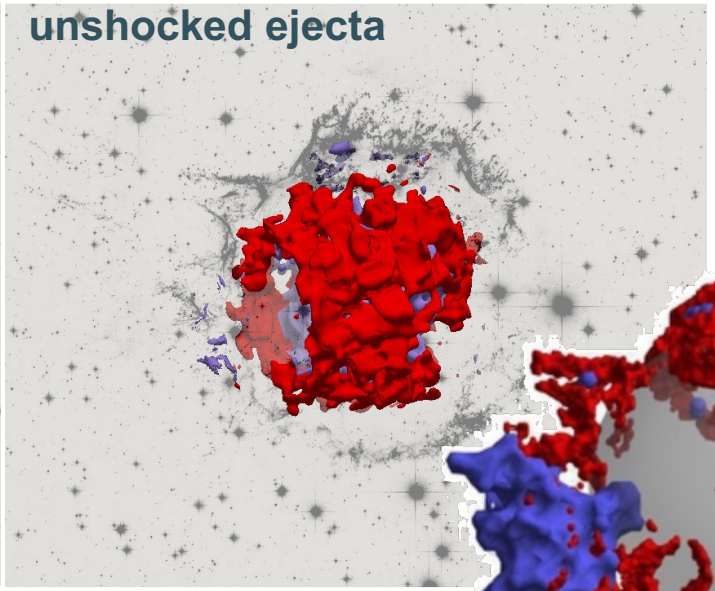




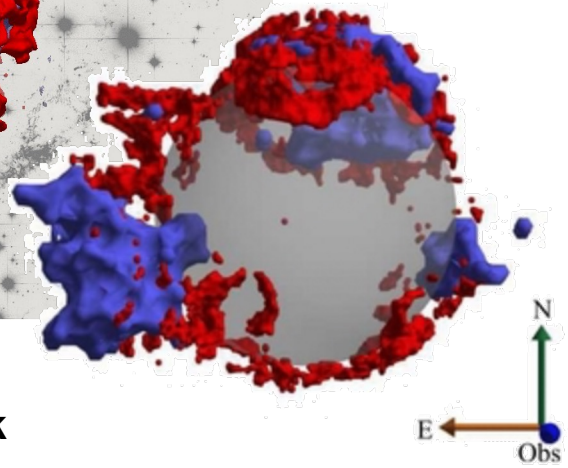
Effects of the SN anisotropies

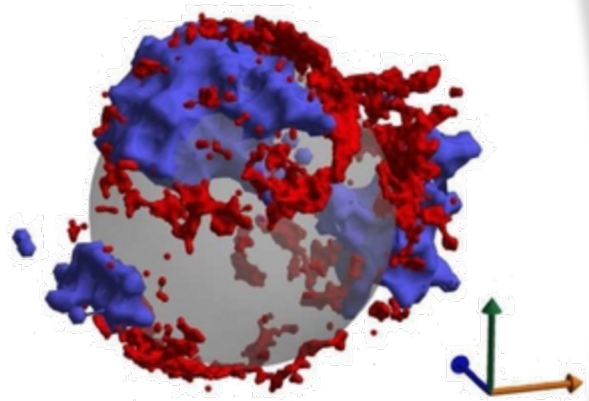
Cas A: Spatial Distribution of the ejecta





(Orlando+ 2016)





(Milisavljevic & Fesen 2013)

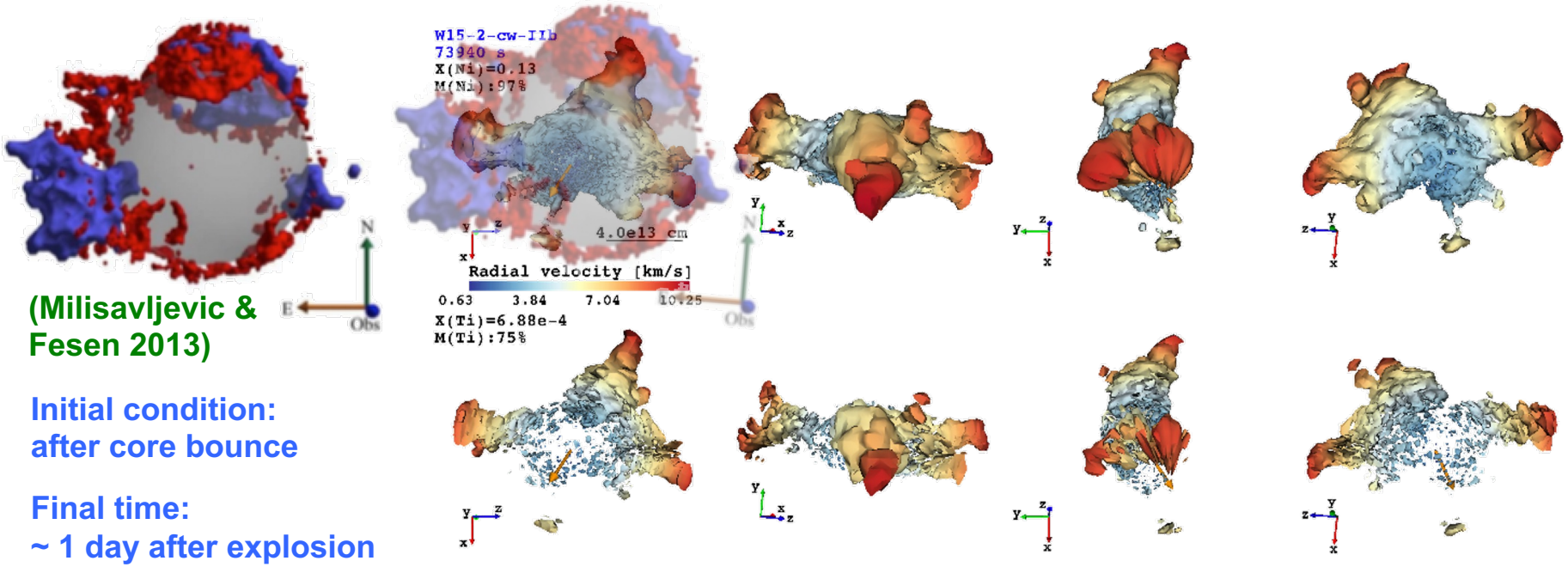
link the main asymmetries and geometry of Cas A's bulk ejecta to the physical characteristics of anisotropies developed soon after the SN explosion

average physical characteristics of post-explosion anisotropies that are able to reproduce the observed Fe-rich regions and Si-rich jets

Constrain energy and masses of post-explosion asymmetries

Cas A: effects of anisotropies in the SN

3D simulations of a neutrino-driven SN explosion reproducing basic properties of Cas A **(Wongwathanarat+ 2017)**



(Milisavljevic & Fesen 2013)

Initial condition: after core bounce

Final time: ~ 1 day after explosion

Three pronounced iron-rich fingers that may correspond to the extended iron-rich regions observed in Cas A

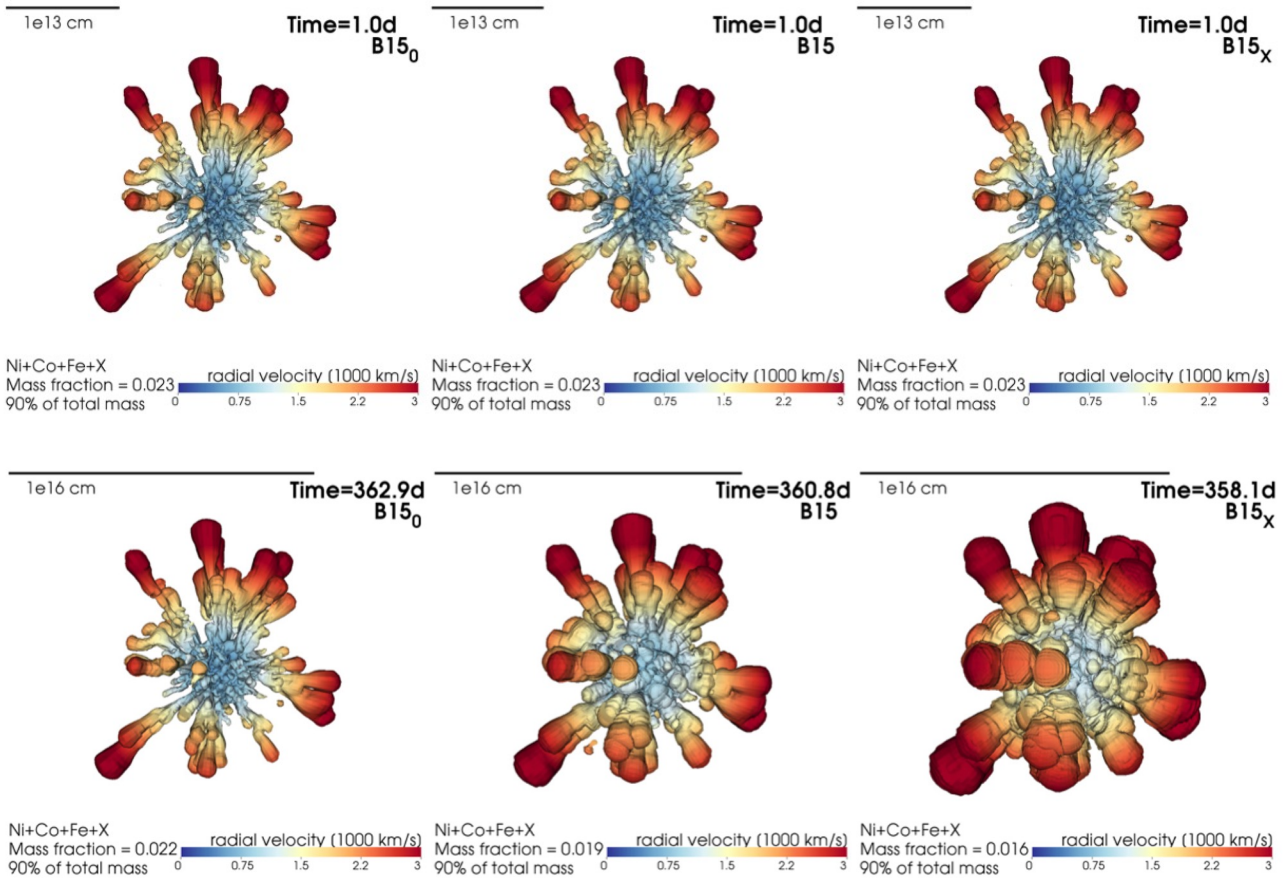
Major asymmetries observed in Cas A explained by a neutrino-driven explosion
No need to invoke rapid rotation or jet-driven explosion

The Ni-bubble effect in the transition SN - SNR

3D simulations of a neutrino-driven SN explosion

Asymmetrically expanding ejecta from shock breakout to homologous expansion phase (roughly one year)

(Gabler et al. 2021)



Ni-bubble effect

inflation of the ejecta caused by the heating due to the radioactive decay chain ^{56}Ni – ^{56}Co – ^{56}Fe

→ acceleration of bulk of Ni

→ inflation of initially overdense Ni-rich clumps

→ underdense, extended fingers, enveloped by overdense skins of compressed surrounding matter

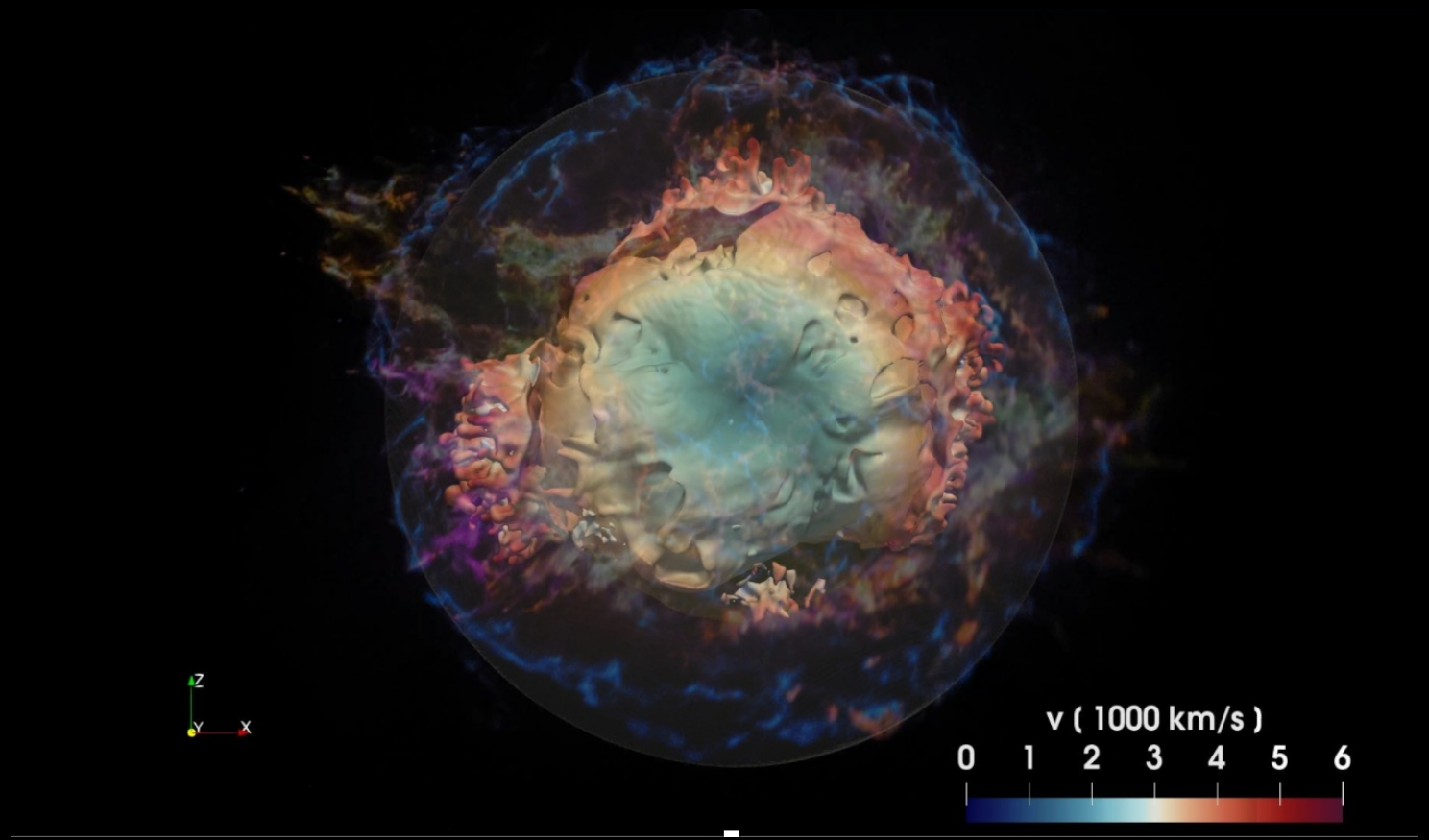
The remnant of a neutrino-driven CC SN

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

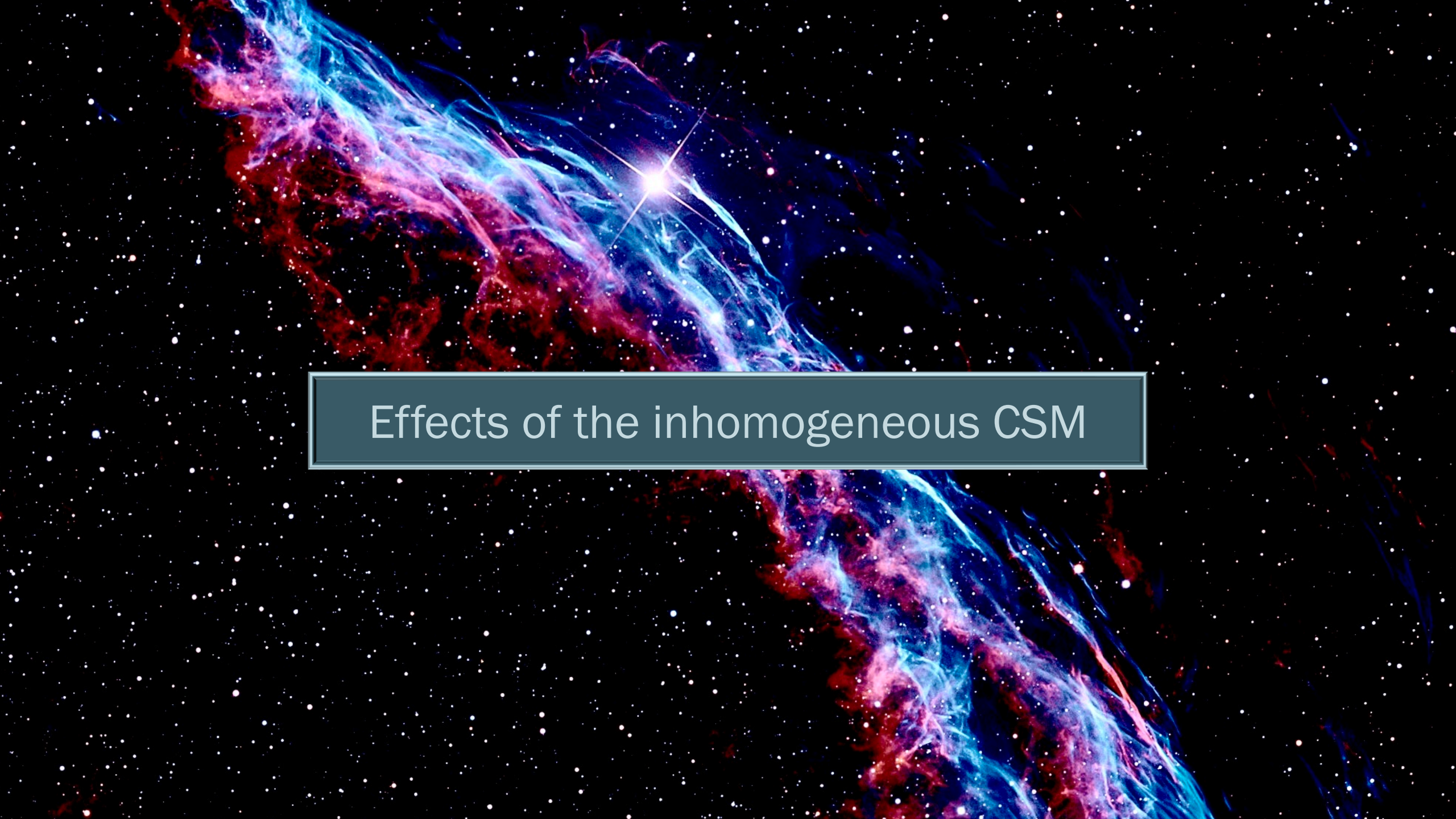
identify the geometric and physical properties of the post-explosion anisotropies responsible for the morphology of Cas A

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

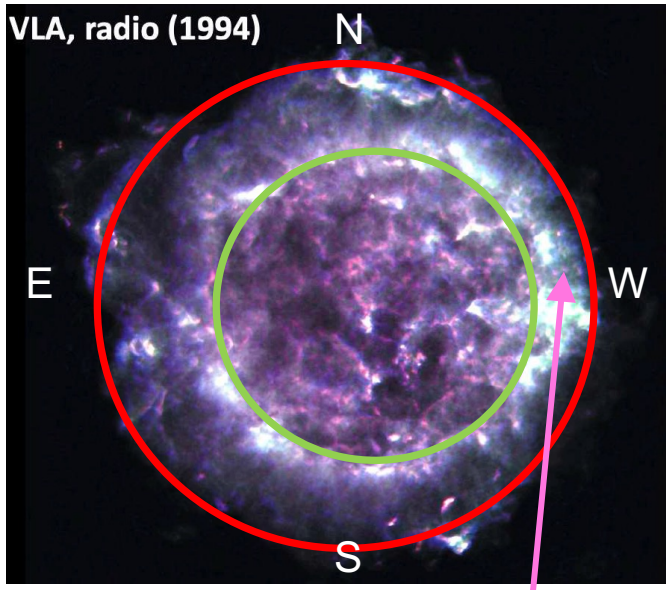
stochastic processes (e.g., convective overturn and the standing accretion shock instability; SASI) that originate during the first seconds of the SN blast

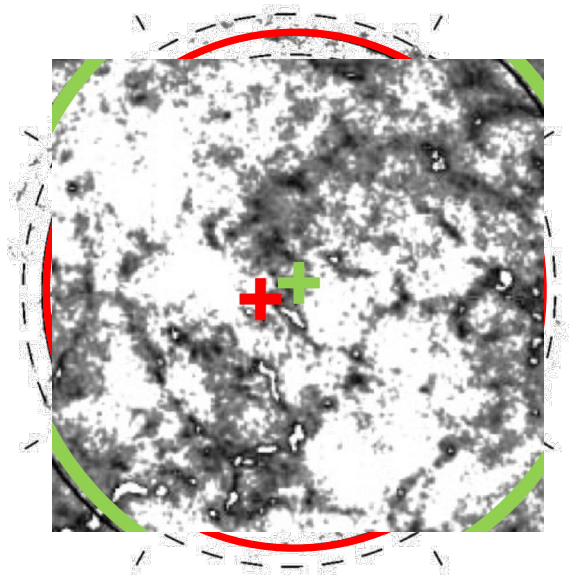


(Orlando et al. 2021)

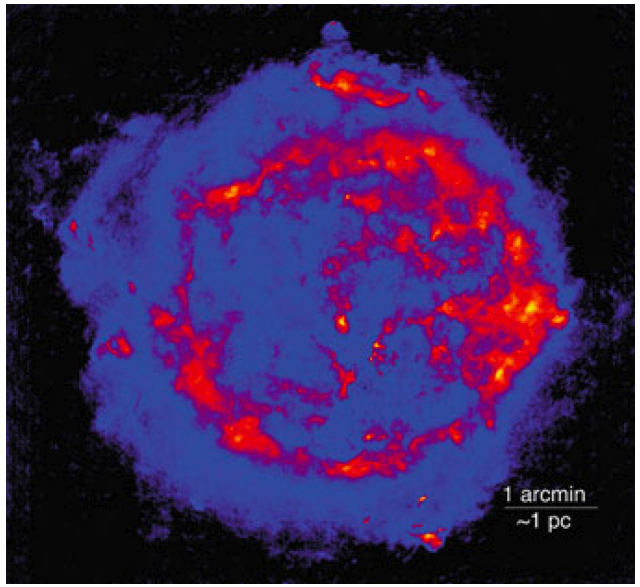

Effects of the inhomogeneous CSM

The forward and reverse shock dynamics of Cas A

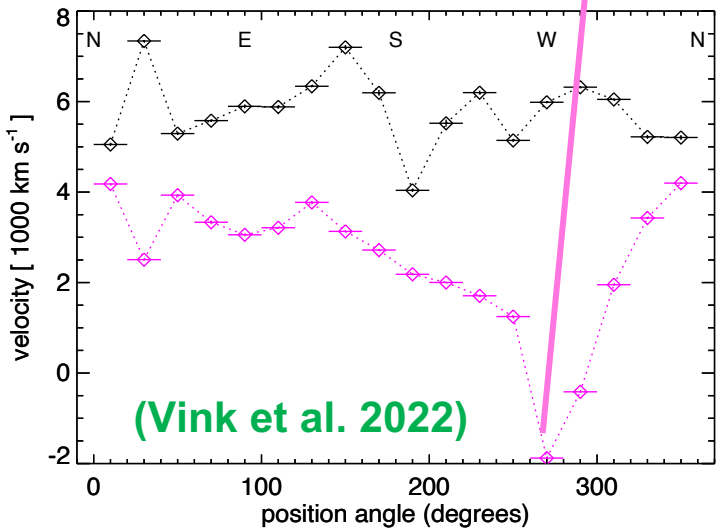




(Gotthelf et al. 2001)



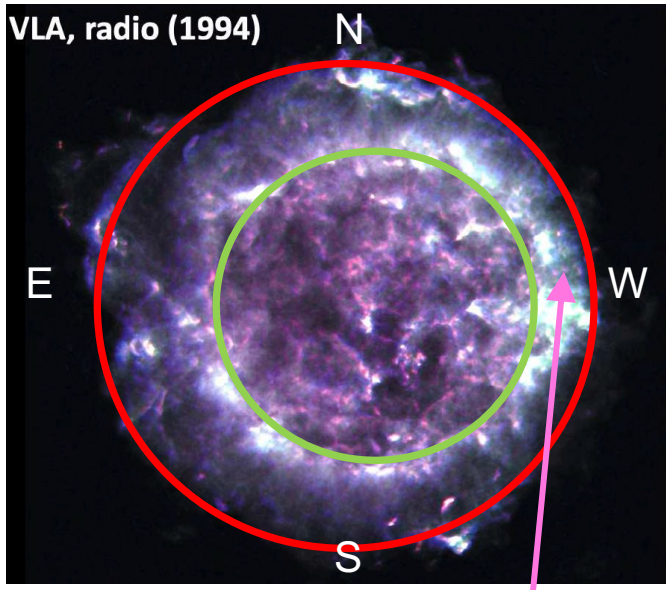
(Delaney 2004)

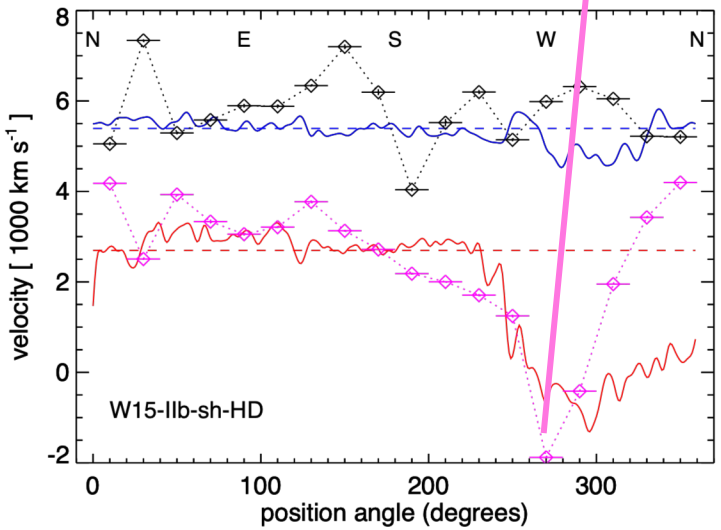


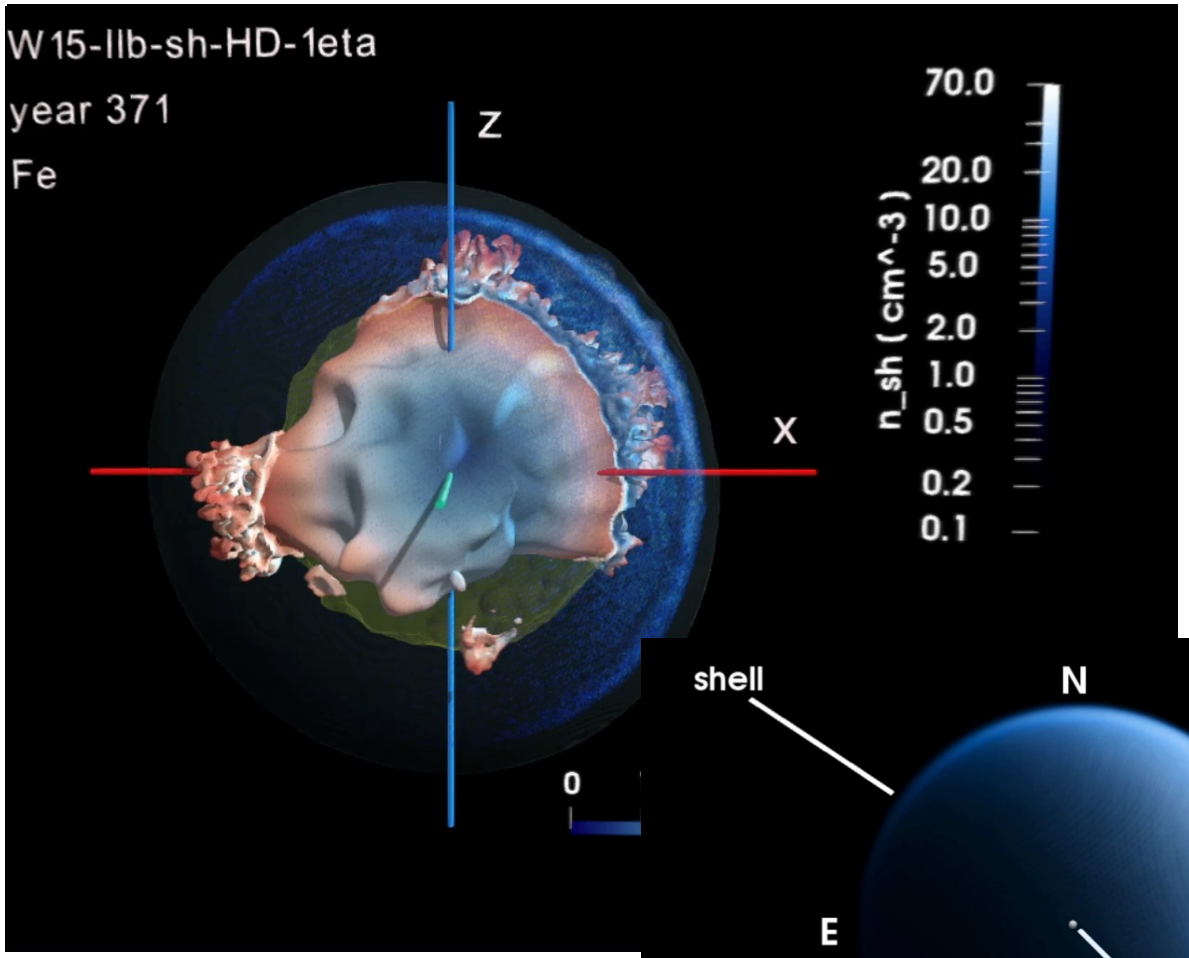
(Vink et al. 2022)

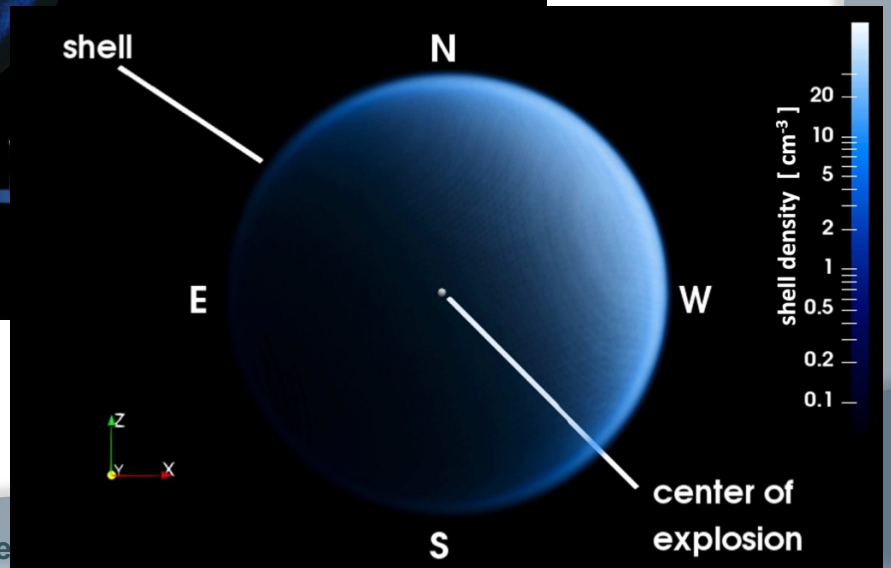
most of the X-ray synchrotron emission originates from the western part of the reverse shock **(Vink 2020)**

Cas A reveals past interaction with circumstellar shell



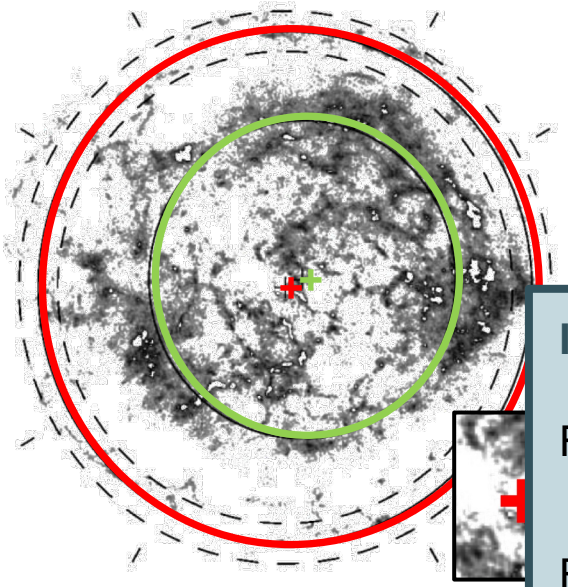




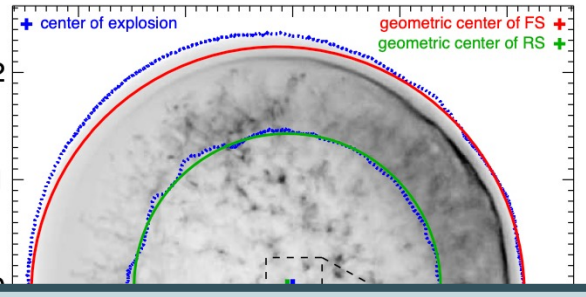


Hints on the mass-loss history of the progenitor star and its nature

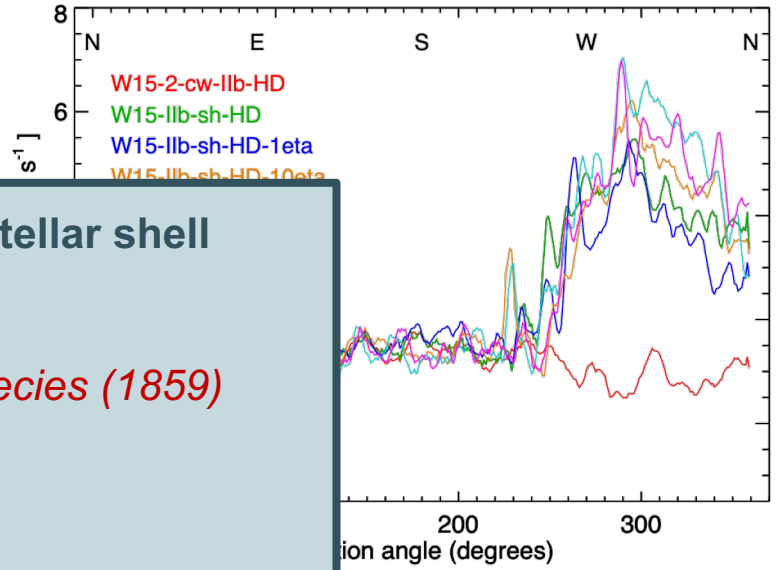
Cas A reveals past interaction with circumstellar shell



(Gotthelf et al. 2001)



Reverse shock velocity in the ejecta reference frame



Interaction with a dense asymmetric circumstellar shell

FS interaction: 185 yr (a.d. 1850-1860)

Charles Darwin publishes *The Origin of Species (1859)*

RS interaction: 296 yr (a.d. 1940-1946)

World War II (1940-45)

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

Total mass of the shell M_{sh} estimated between 2 and 3 $M_\odot$

geometric center of the

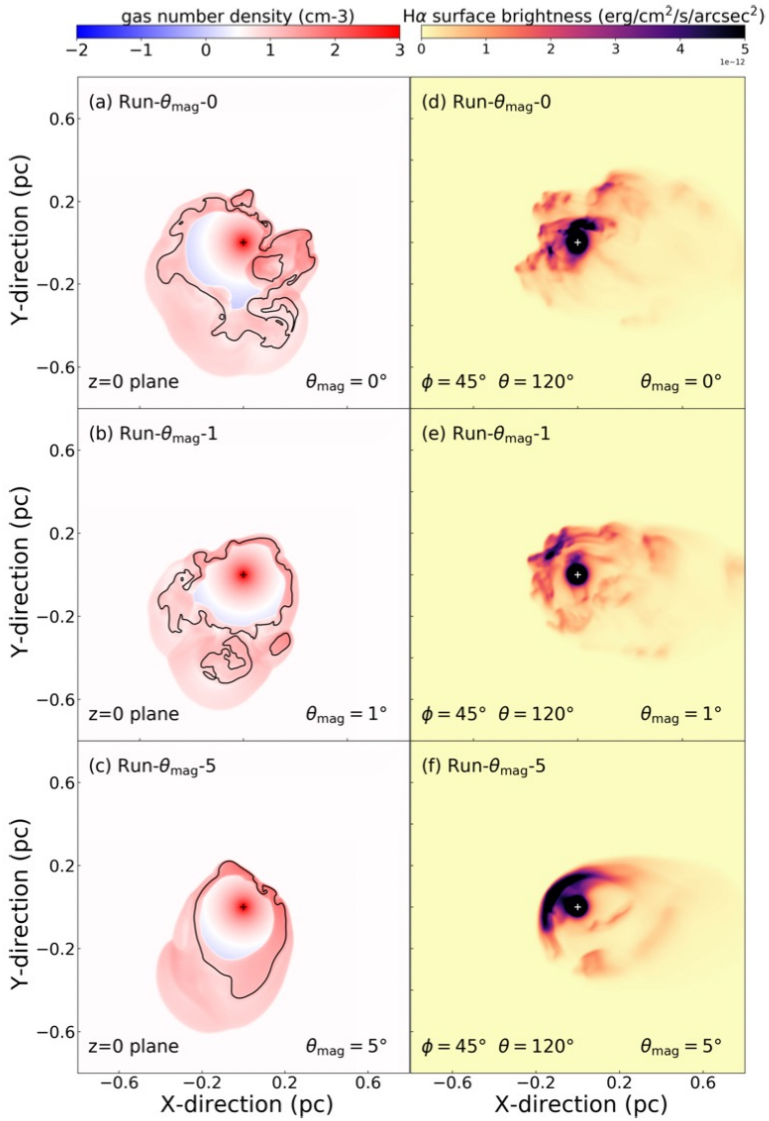
from the geometric cent

of the X-ray synchrotron

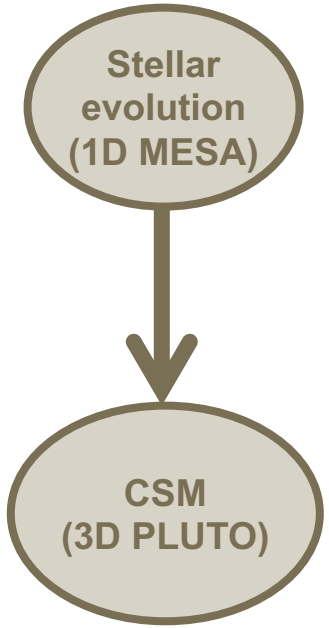
es from the western part

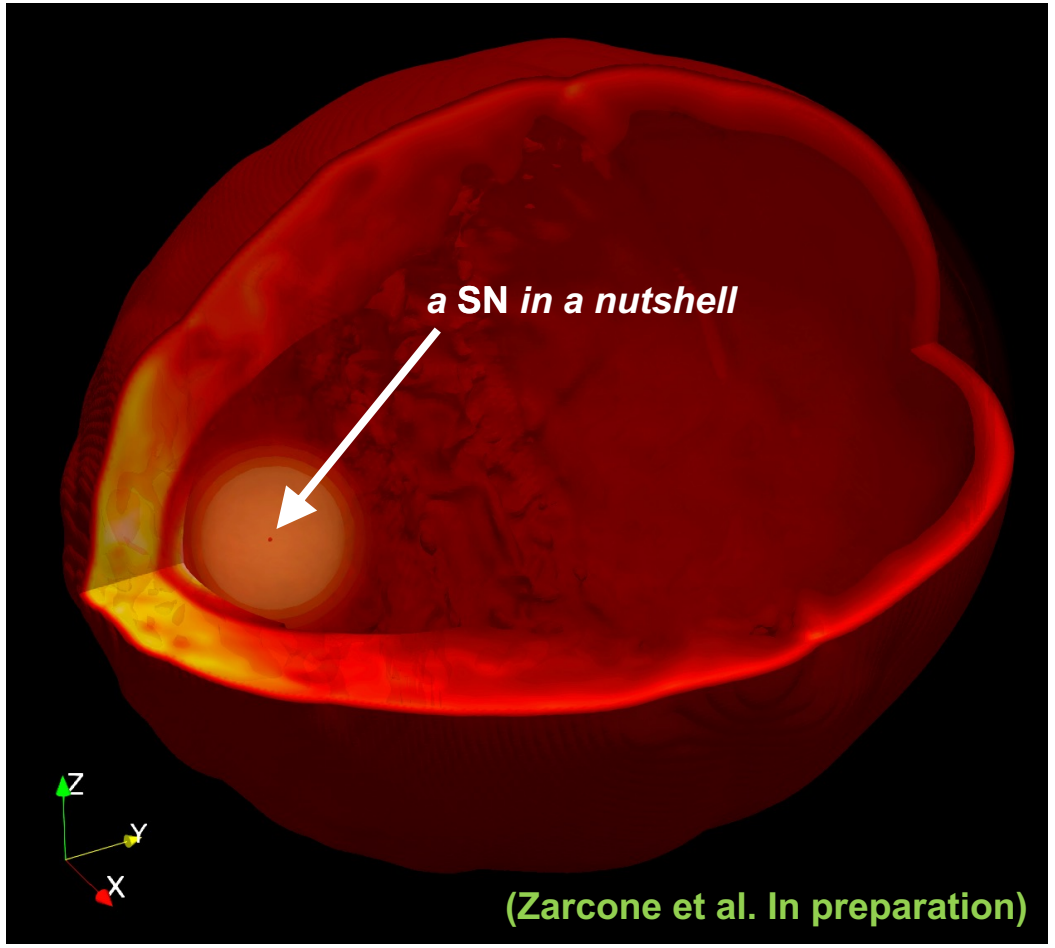
ock

SN explosions in the CSM of massive stars



(Meyer et al. 2021)

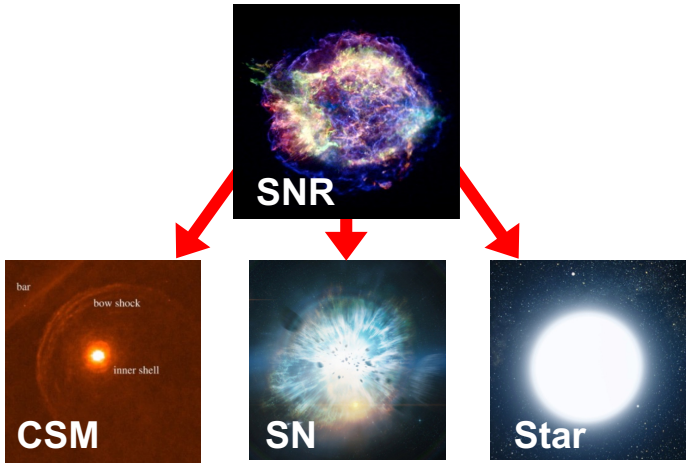




- **Runaway RSG**
- **Episodic mass eruption**
- **Wolf-Rayet star**

Take away points

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



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* stellar progenitor → 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