INVESTIGATING ASYMMETRIES OF SUPERNOVA REMNANTS THROUGH LONG-TERM 3D SN-SNR SIMULATIONS

Salvatore Orlando

INAF - Osservatorio Astronomico di Palermo, Italy

F. Bocchino, S. Ustamujic (INAF – OAPA, Italy)

M. Miceli, G. Peres, E. Greco, A. Tutone (Palermo University, Italy)

S. Nagataki, M. Ono, G. Ferrand (ABBL/RIKEN, Japan)

H. Umeda (Tokyo University, Japan)

S.-H. Lee (Kyoto University, Japan)

M.A. Aloy, P. Mimica (Valencia University, Spain)

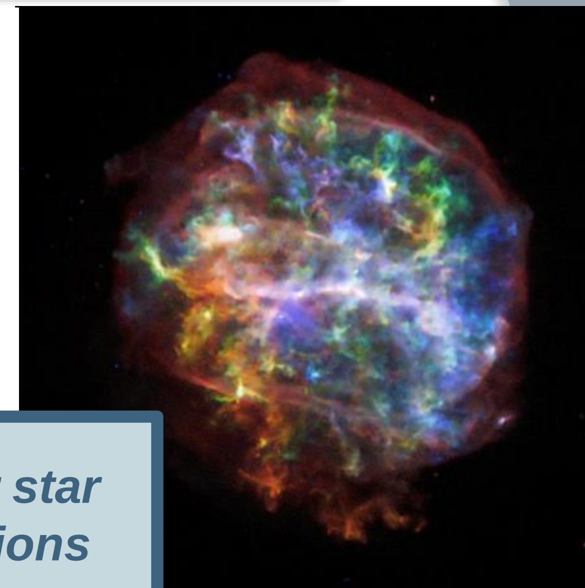
O. Petruk (IAPMM, Ukraine)

D. Burrows (Penn State University, USA)

S. Park, A. Pazhayath Ravi (Stanford University, USA)

Supernova Remnants

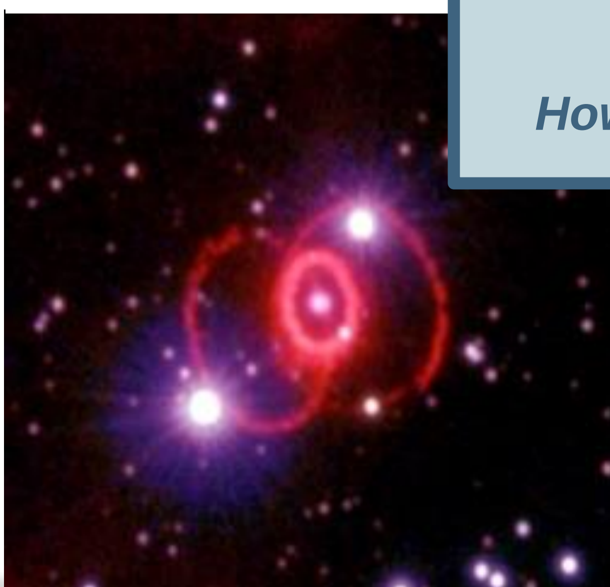
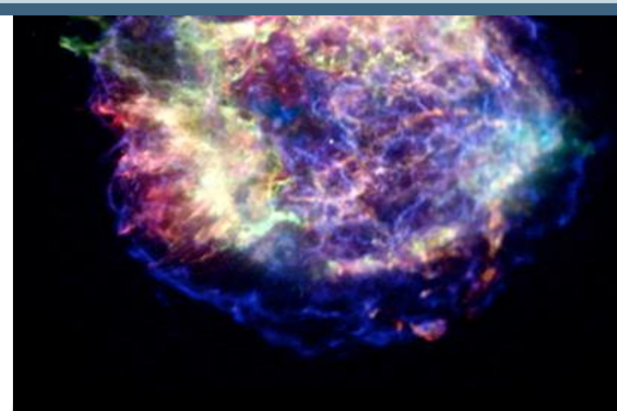
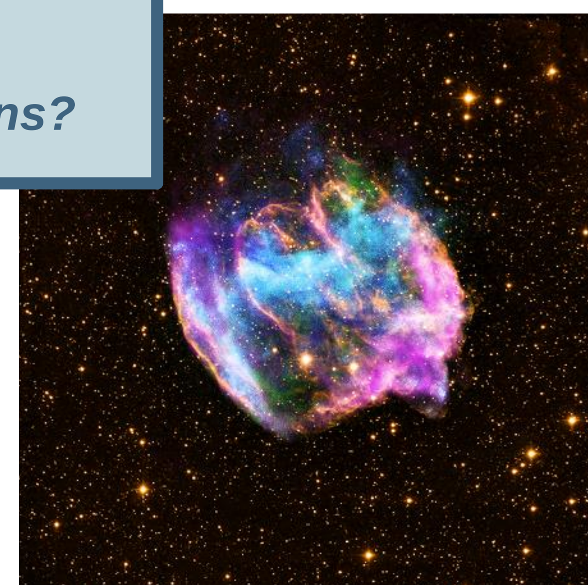




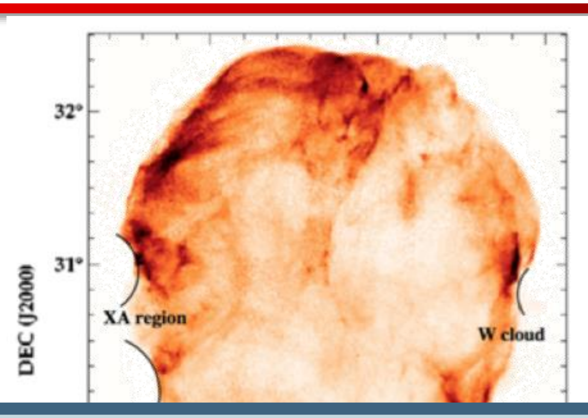
Information about the progenitor star and SN encoded in the observations

Which information?

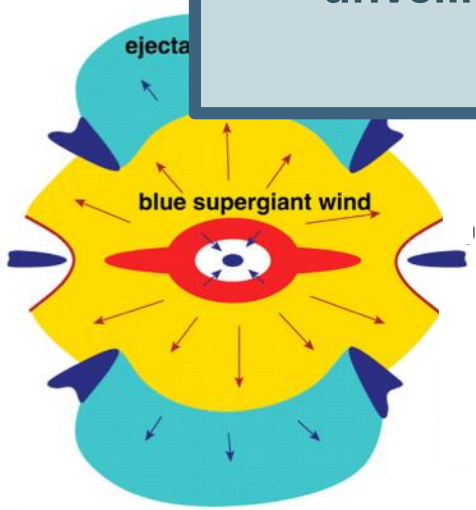
How to decipher the observations?

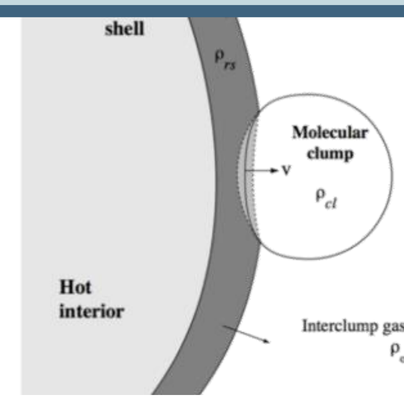
Interaction with the ambient medium



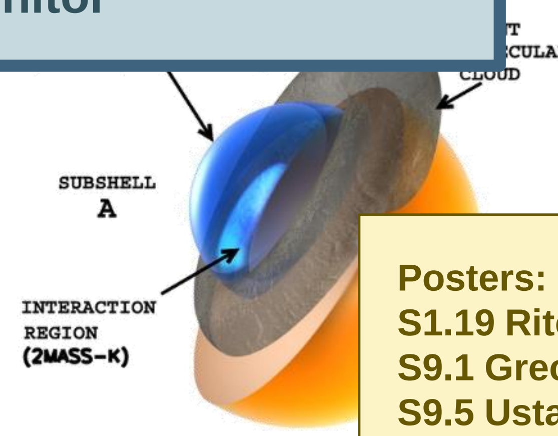
Asymmetries in SNRs offer the possibility to investigate the final stages of stellar evolution by unveiling the structure of the medium immediately surrounding the progenitor



(Morris & Podsiadlowski 2007)



(Slane+2015)



(Troja+ 2006)

Posters:
S1.19 Ritchey
S9.1 Greco
S9.5 Ustamujic

Anisotropies in the SN

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)

The bulk o
is intrinsic

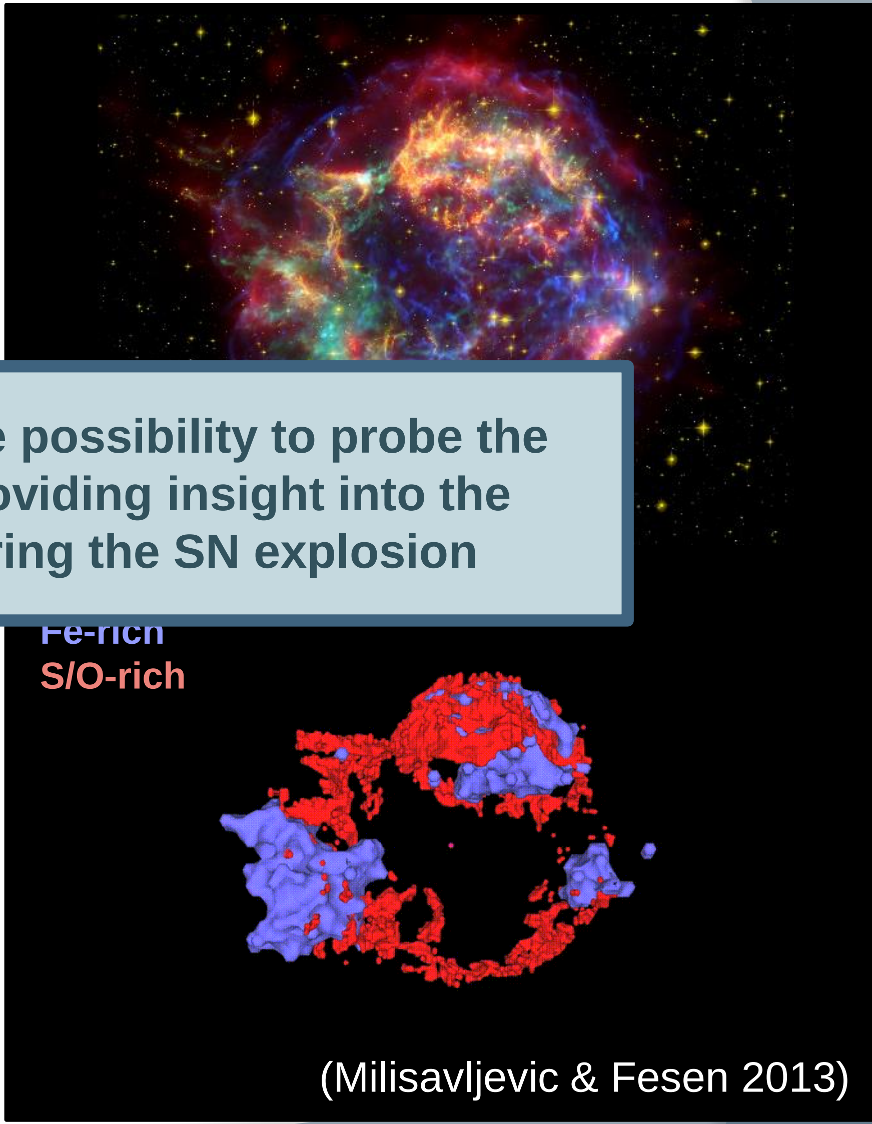
Asymmetries in SNRs offer the possibility to probe the physics of SN engines by providing insight into the asymmetries that occur during the SN explosion

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,

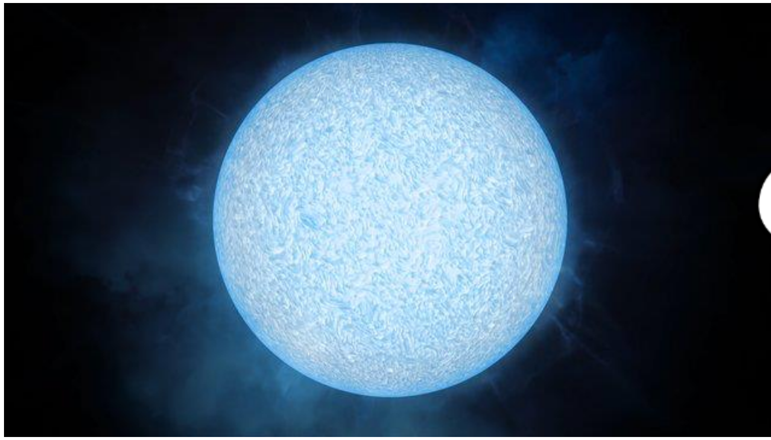
talks: Fesen, Holland-Ashford, Picquenot)

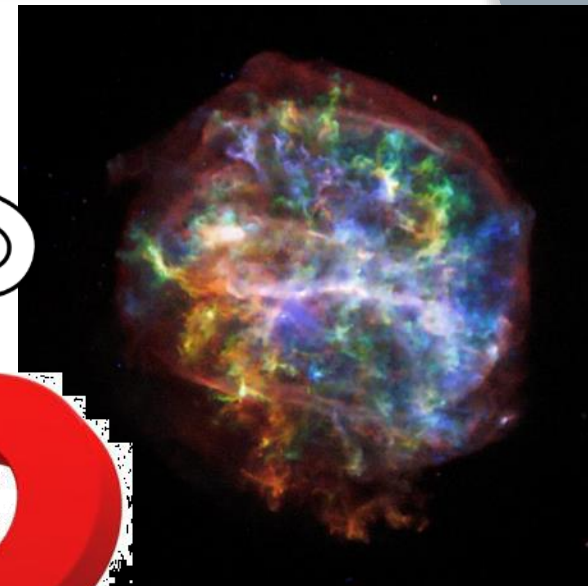
- **3 Fe-rich regions**
- **2 Si-rich jets**
- **Rings circling Fe-rich regions**



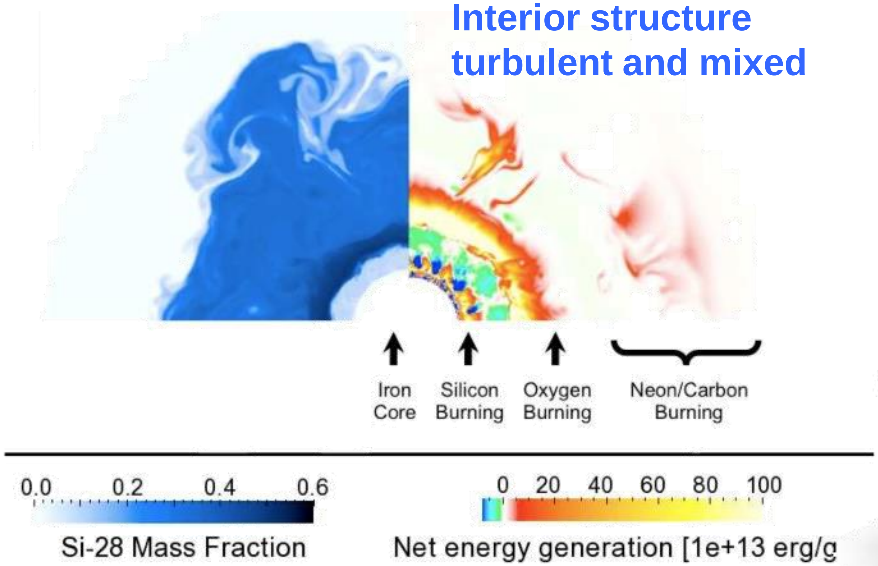
(Milisavljevic & Fesen 2013)

Structure of the progenitor stars





Interior structure turbulent and mixed



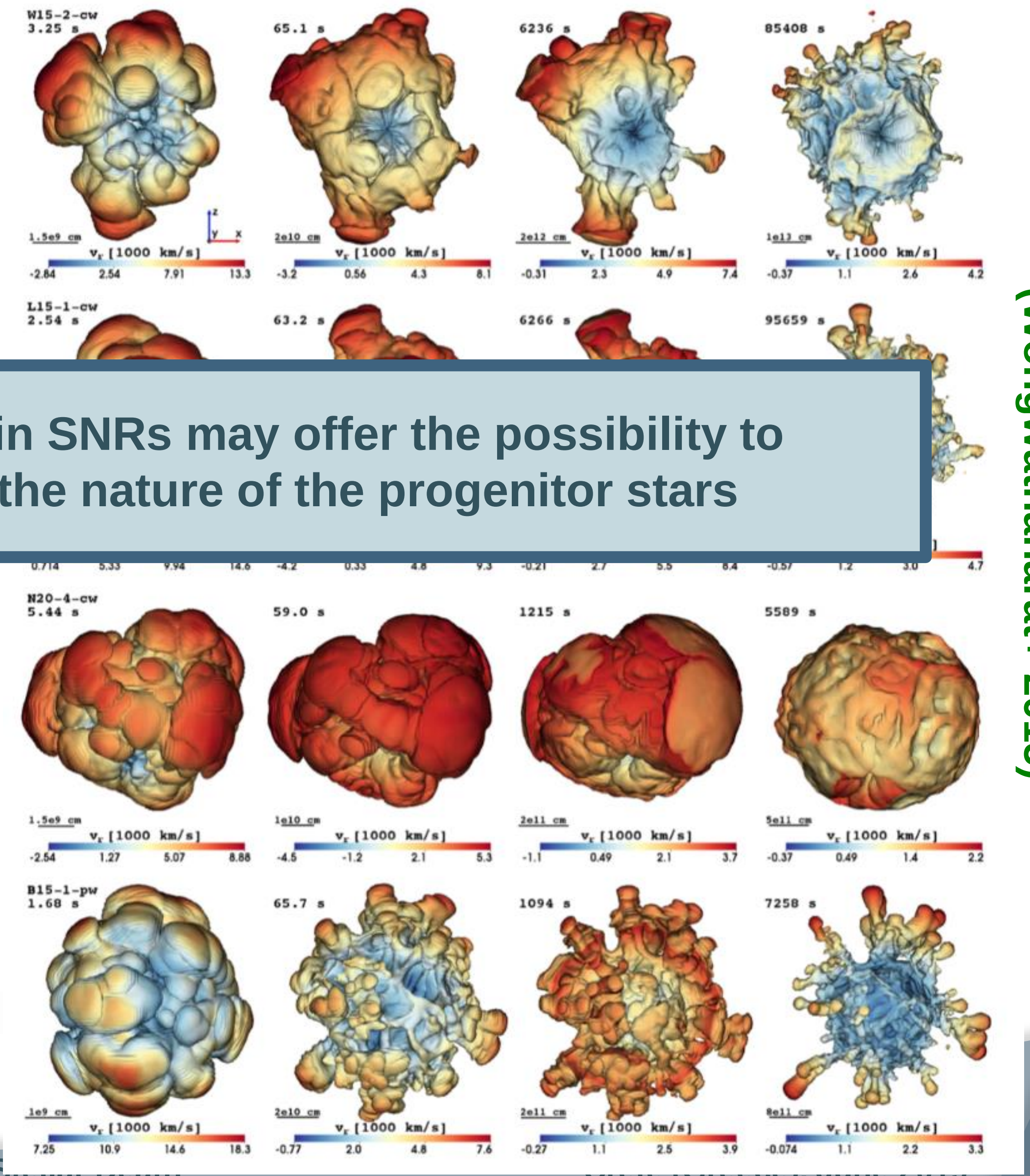
(Arnett & Meakin 2011)

Structure of the progenitor stars

egg

apple

tomato



(Wongwathanarat+ 2015)

Anisotropies in SNRs may offer the possibility to investigate the nature of the progenitor stars

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 SNe to SNRs ?

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

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

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)

Multi-physics approach required

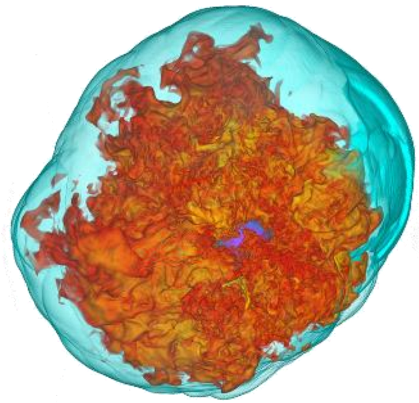
Requirements:

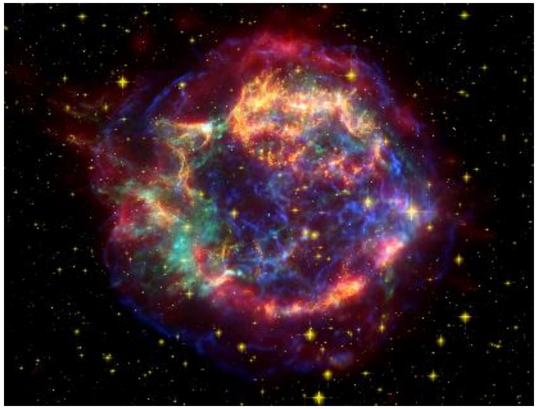
- **Hydrodynamics/magnetohydrodynamics**
- **Properties of the progenitor stars**
- **Supernova physics (explosive nucleosynthesis, radioactive decays, gravity, etc.)**
- **Ambient environment (constraints from observations)**
- **Microphysics (radiative cooling, NEI, temperature equilibration, CR acceleration)**
- **Synthesis of observables (thermal and non-thermal emission, ejecta distribution)**

How to link SNe to SNRs ?

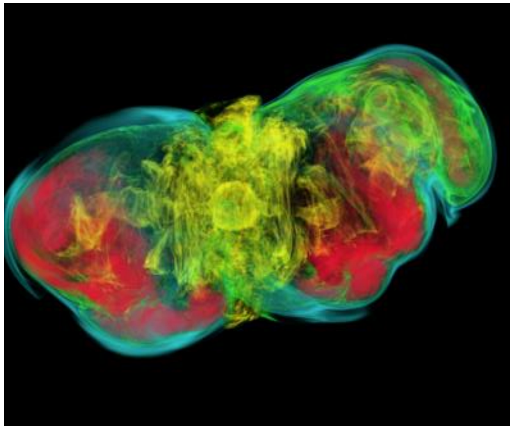
Criticalities:

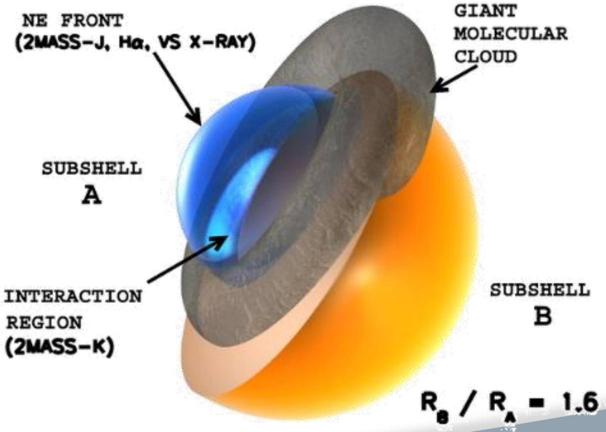
- **Very different time and space scales of SNe and SNRs**



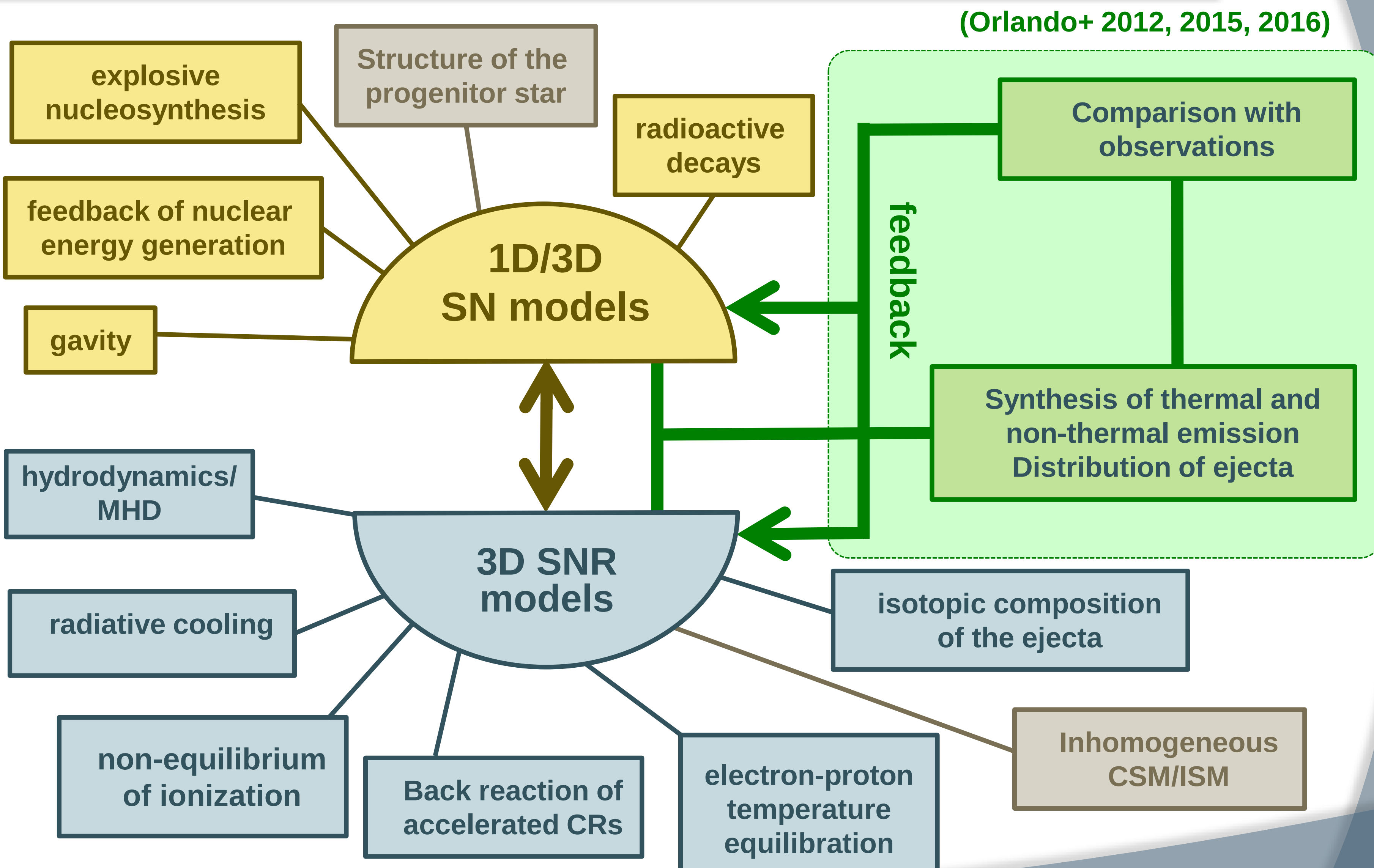


- **The phenomenon is inherently 3D**

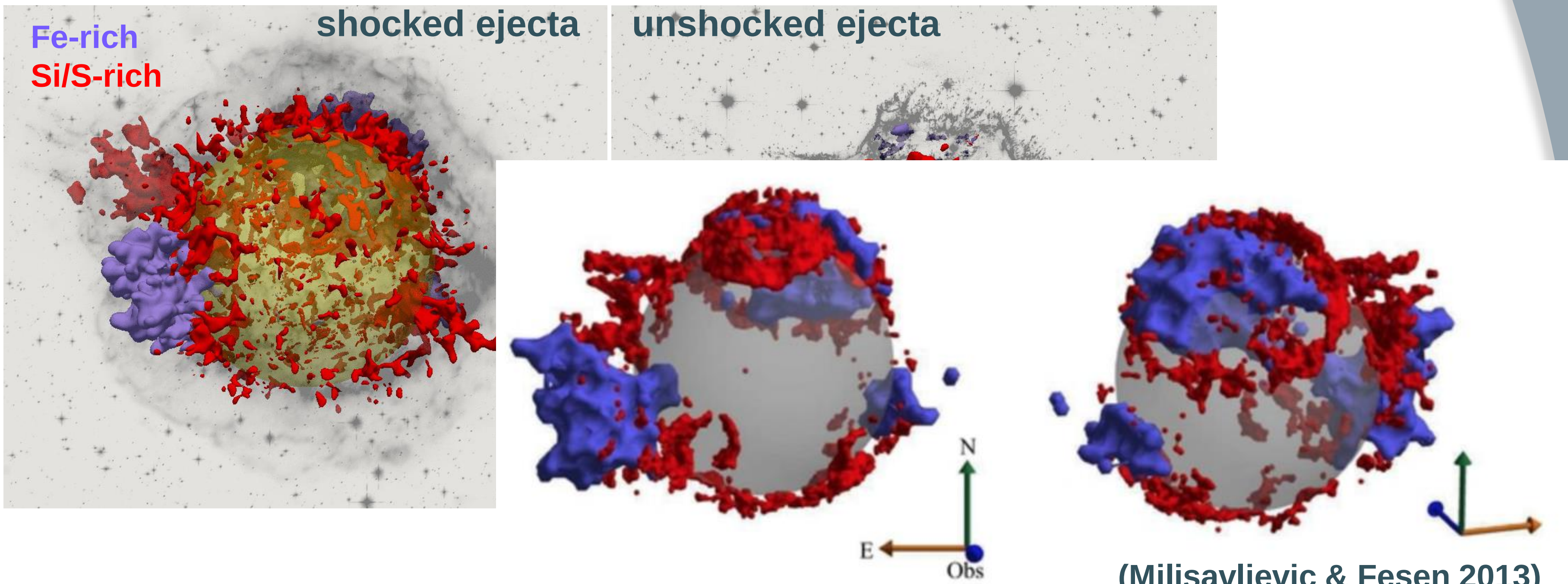




How to link cc SNe to SNRs ? The strategy



Spatial Distribution of the Cas A ejecta



(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

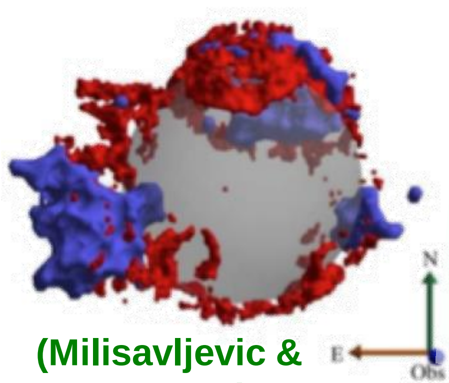
average physical characteristics of post-explosion anisotropies that are able to reproduce the observed Fe-rich regions and Si-rich jets

(Orlando+ 2016)

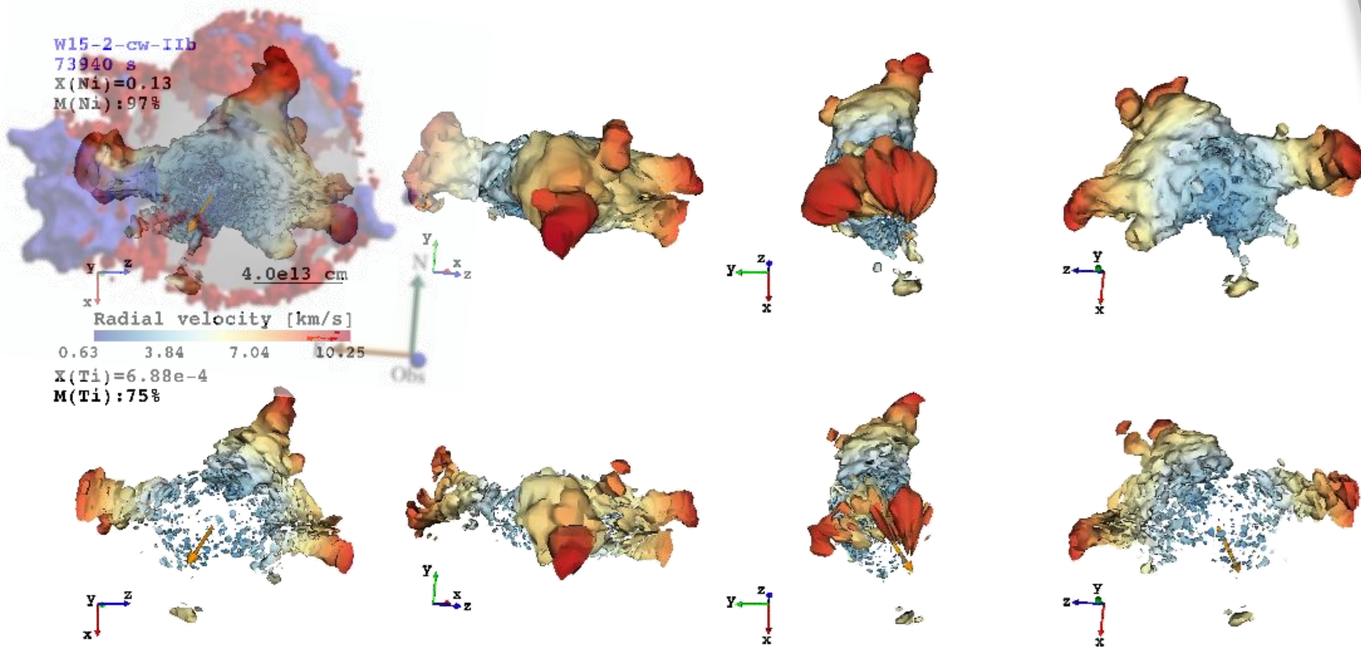
Constrain energy and masses of post-explosion asymmetries

Cas A: effects of anisotropies in the SN

3D simulations of a neutrino-driven SN explosion reproducing basic properties of Cas A **(Wongwathanarat+ 2017; see talk at this meting)**



(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 exlosion

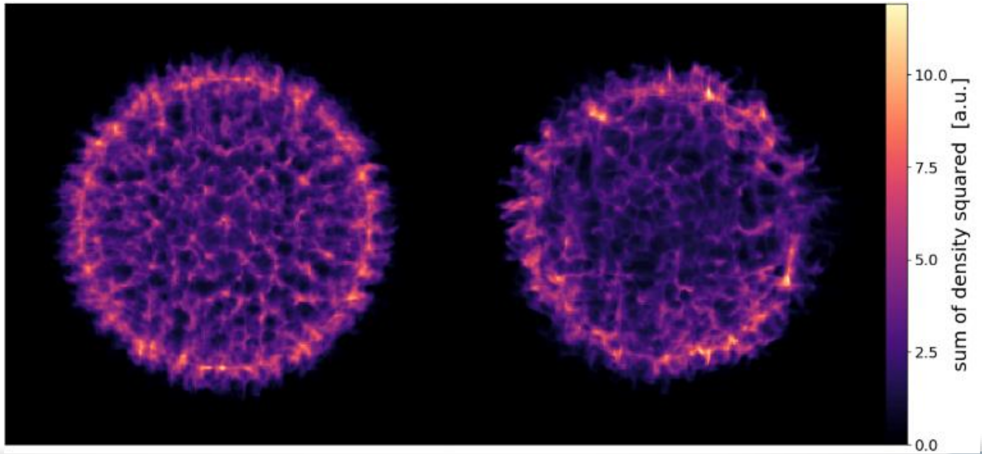
Type Ia SNe: post-explosion asymmetries

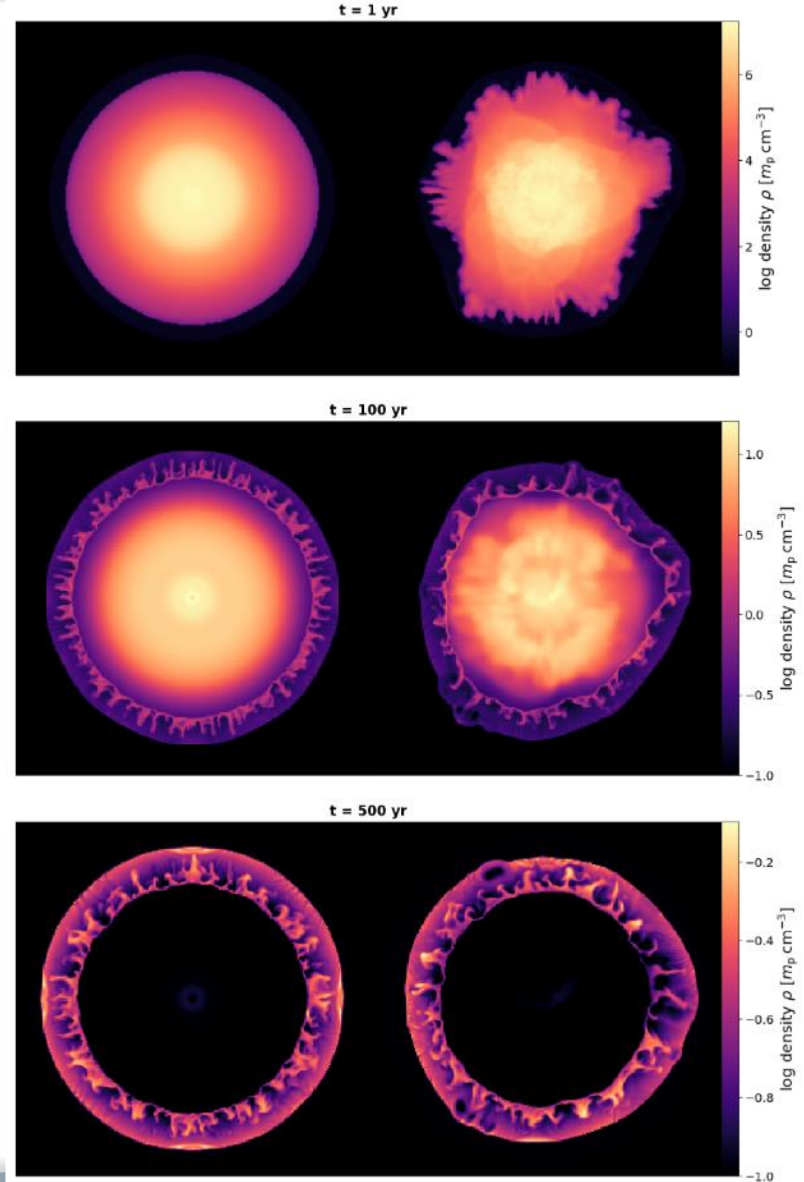
3D model for thermonuclear explosion of a carbon-oxygen white dwarf star (type Ia SN)
(Seitenzahl+ 2013)

SNR model shows that the impact of the SN on the SNR may still be visible after hundreds of years

Simulations suggest that type Ia SNRs keep memory of the initial asymmetries from the SN
(Ferrand+ 2019)

Poster: S3.4, S. Nagataki





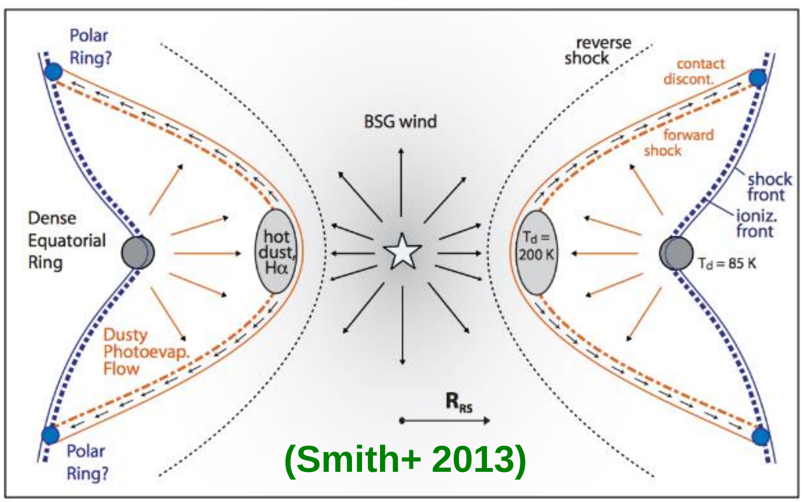
A case study: SN 1987A

When: **23 February 1987**
Where: **Large Magellanic Cloud**

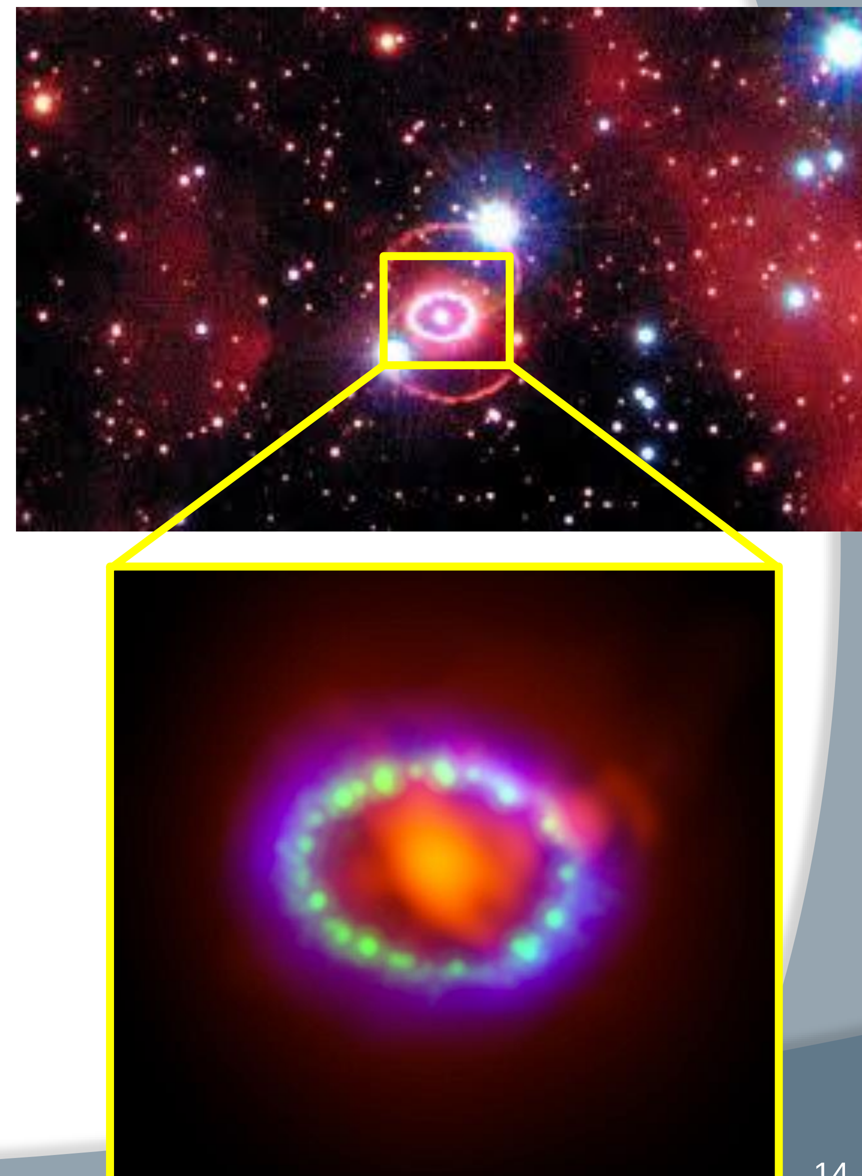
Stellar progenitor: Sk -69^{o}202

Nearest supernova explosion observed in hundreds of years

Unique opportunity to watch a SN change into a SNR



(Smith+ 2013)

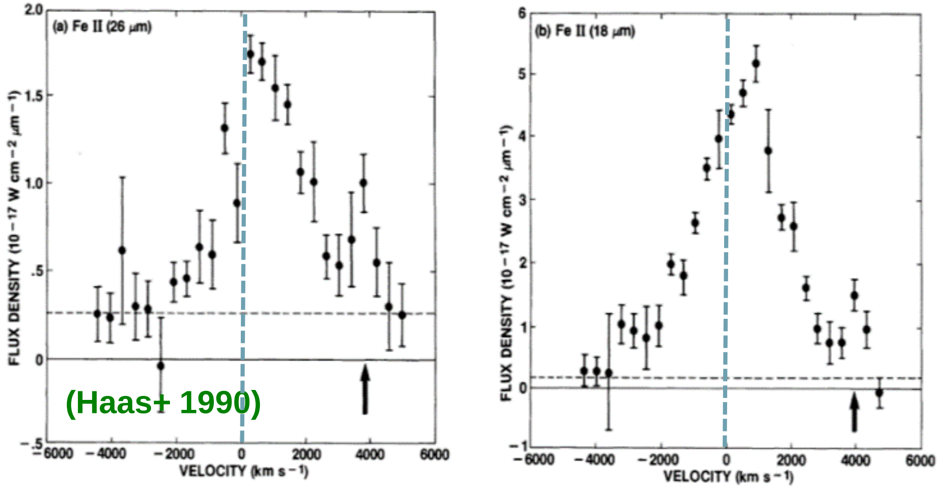


Anisotropies in SN 1987A

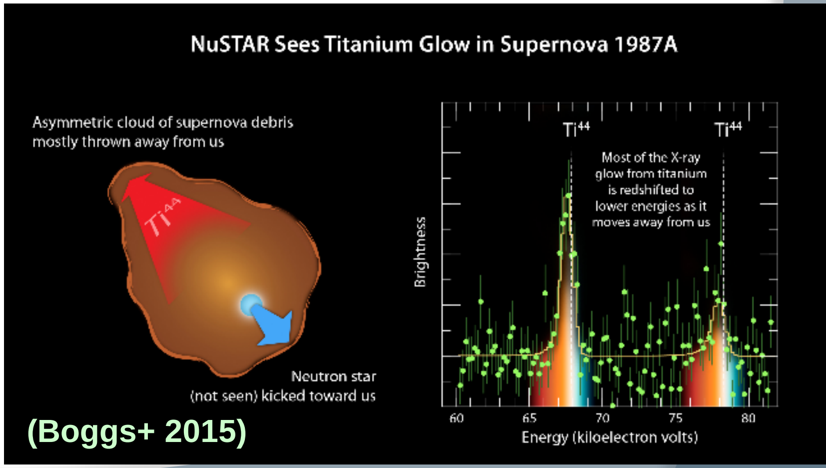
- **Soon after the SN event: Fe lines redshifted centroid ~ 280 ±140 km/s; wings > 3000 km/s** **(Haas+ 1990)**
- **At later times (> 20 yrs): lines from decay of ^{44}Ti narrow and redshifted with a Doppler velocity of ~700 km/s** **(Boggs+ 2015)**
- **3D distributions of CO and SiO emission have a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

(Abellan+ 2017)

Direct evidence of large-scale asymmetry in the explosion



(Haas+ 1990)



(Boggs+ 2015)

Linking SNR 1987A to the SN and progenitor star

1D stellar progenitor model

3D cc SN model

(Ono+2019 in preparation)

3D SNR model

(Orlando+2019 in preparation)

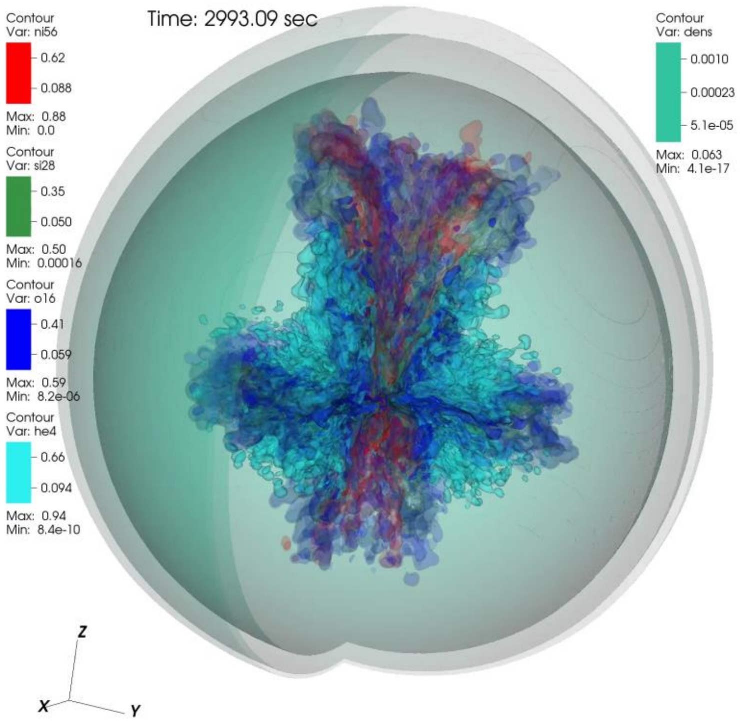
Progenitor star

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

The 18.29 $M_\odot$ BSG model reproduces the main observables of Sk −69° 202

- red-to-blue evolution
- lifetime
- total mass and position in the HR diagram at collapse

The SN explosion



Simulations start:

- **soon after the core-collapse**
- **SN explosion initiated by injecting kinetic and thermal energies artificially around the central compact object**

Explored range of injected energy

(1.8 – 3.0) FOE

Explored range of initial anisotropy:

$v_{pol}/v_{eq} = \beta =$ **[2.0 – 16]**

$v_{up}/v_{dw} = \alpha =$ **[1.1 – 1.5]**

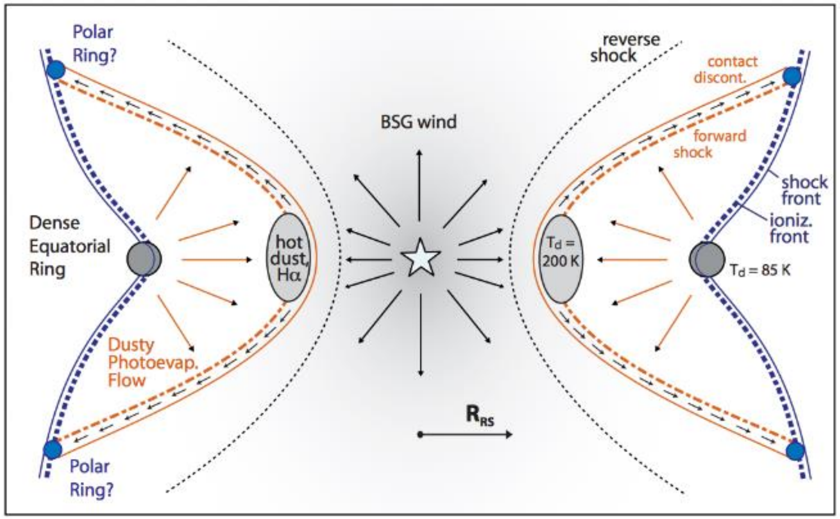
(Ono+2019)

Adapted from the model of Ono+ (2013) to 3D

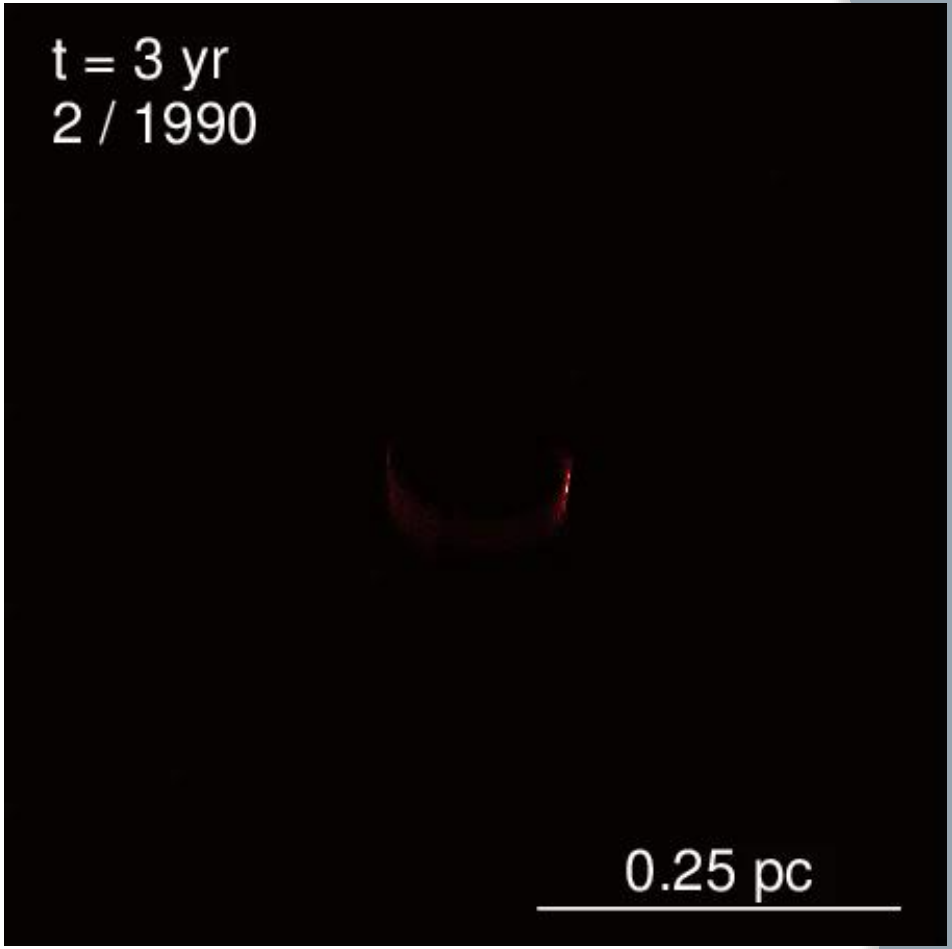
- **explosive nucleosynthesis through a nuclear reaction network (19 isotopes);**
- **energy deposition due to radioactive decays of isotopes synthesized in the SN;**
- **gravitational effects of the central compact object;**
- **fallback of material on the compact object.**

Numerical code: FLASH
(Fryxell+ 2000)

The SNR evolution



Density structure of the nebula constrained by optical spectroscopic data **(e.g. Mattila+ 2010)**



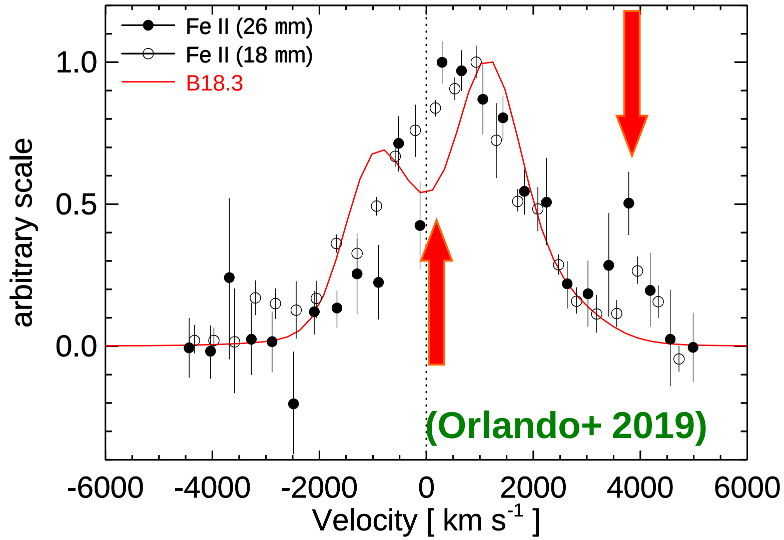
(Orlando+ 2019)

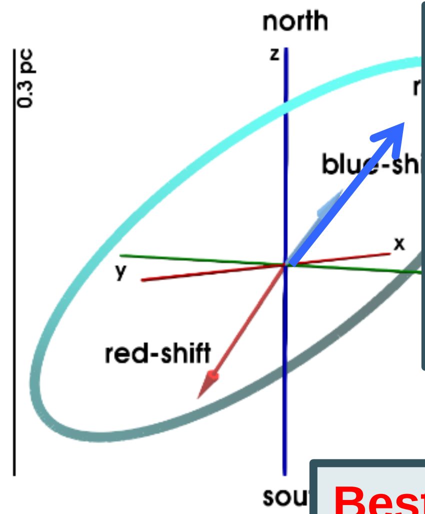
Numerical code: PLUTO **(Mignone+ 2007)**

(see Fabrizio Bocchino's poster + VR experience)

Effects of initial large-scale asymmetry in SN 1987A

Post-explosion anisotropies: [Fe II] line profiles

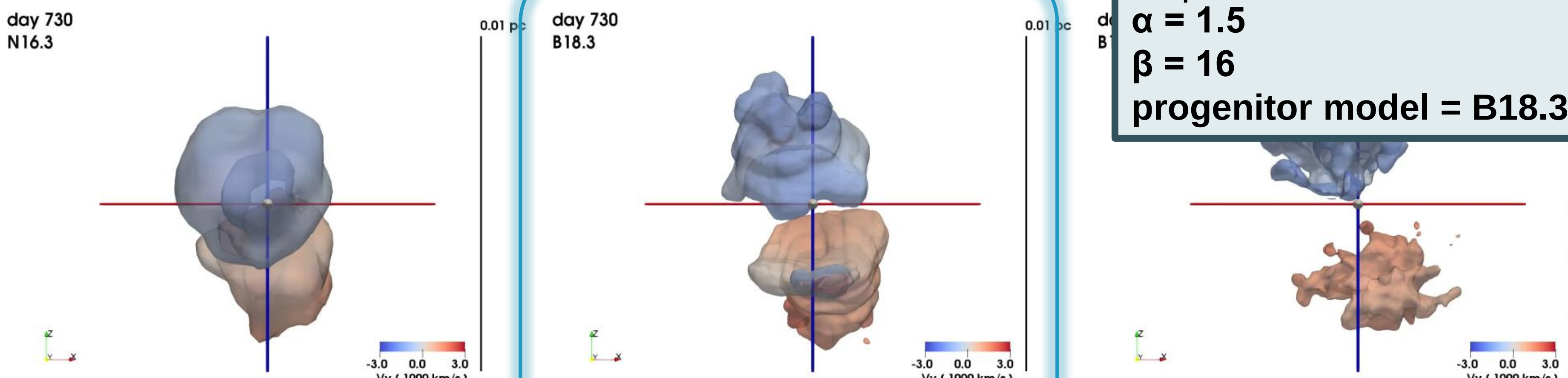




NS kick
~ 300 km/s
toward us to the north
(Nagataki 2000; Wongwathanarat 2013; Janka 2017)

Best-fit parameters

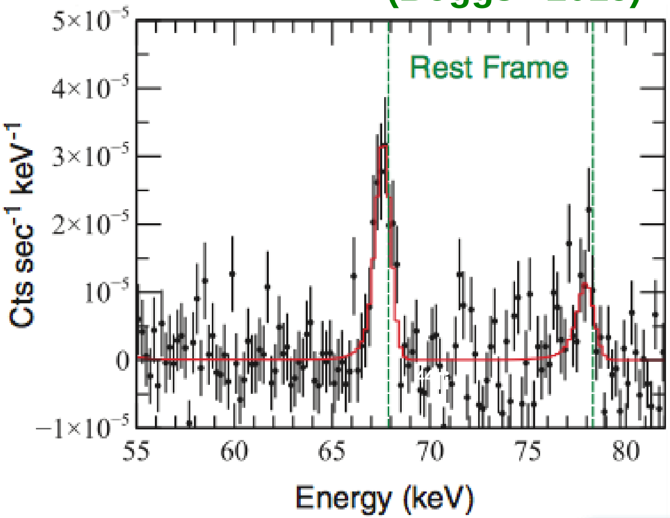
E_{exp} ~ 2 x 10^{51} erg
α = 1.5
β = 16
progenitor model = B18.3



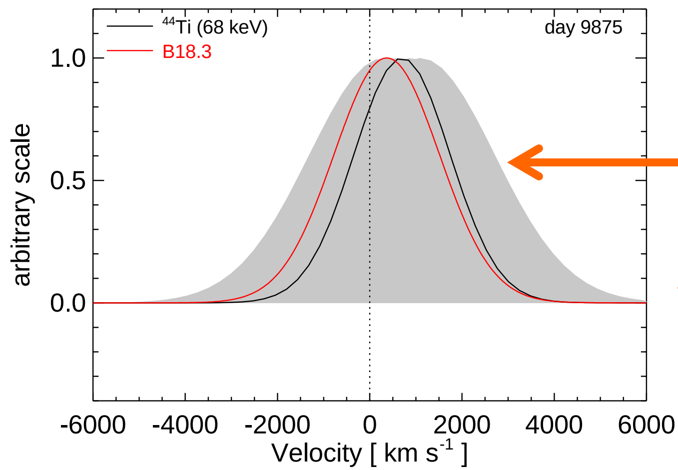
BSG **BSG (merging)** **RSG**

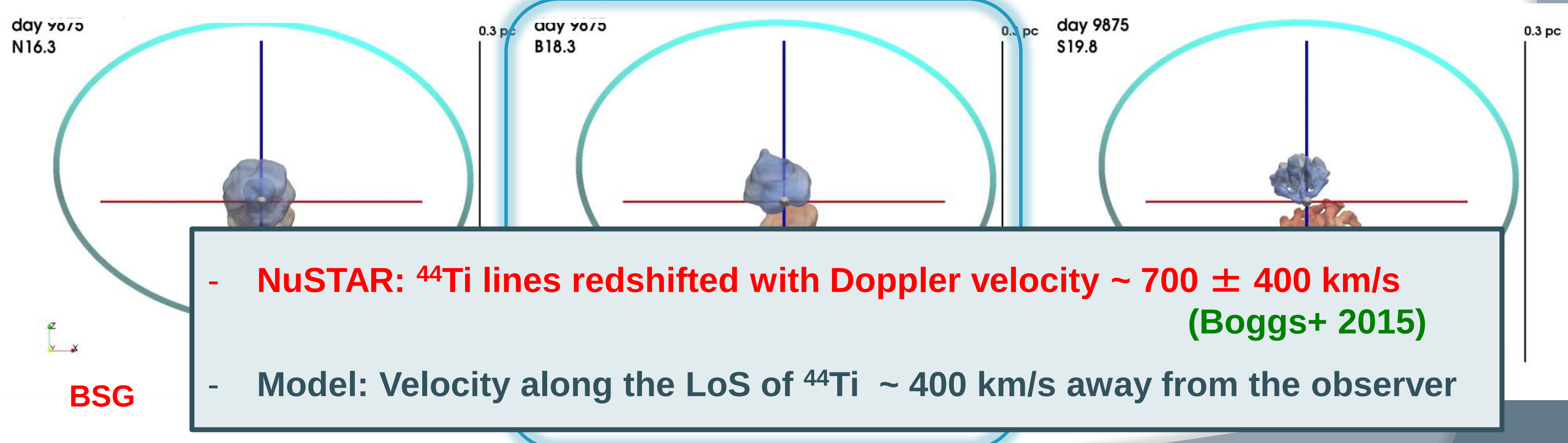
Distribution of ^{44}Ti in the evolved SNR

(Boggs+ 2015)



(Orlando+ 2019)

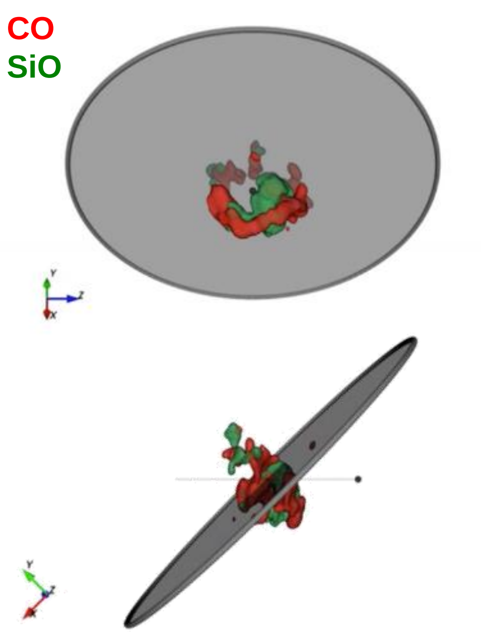


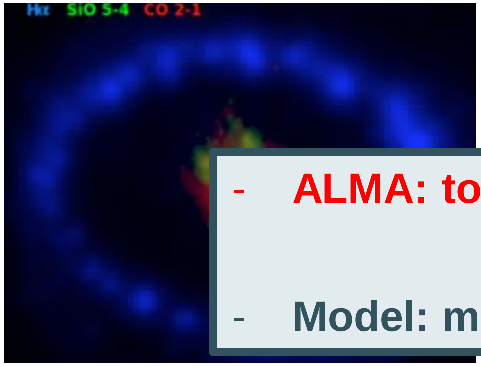


- **NuSTAR: ^{44}Ti lines redshifted with Doppler velocity ~ 700 ± 400 km/s (Boggs+ 2015)**
- **Model: Velocity along the LoS of ^{44}Ti ~ 400 km/s away from the observer**

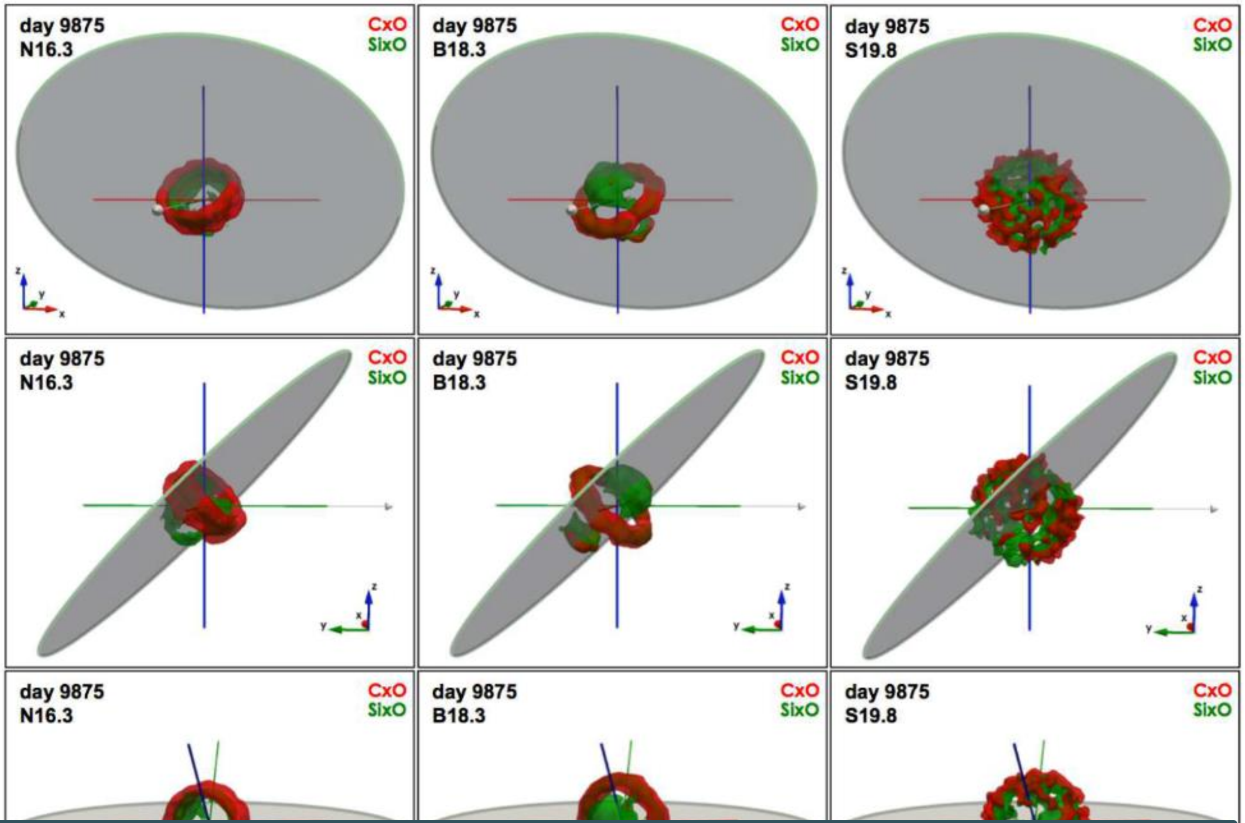
Molecular structure in the evolved SNR

(Abellan+ 2017)





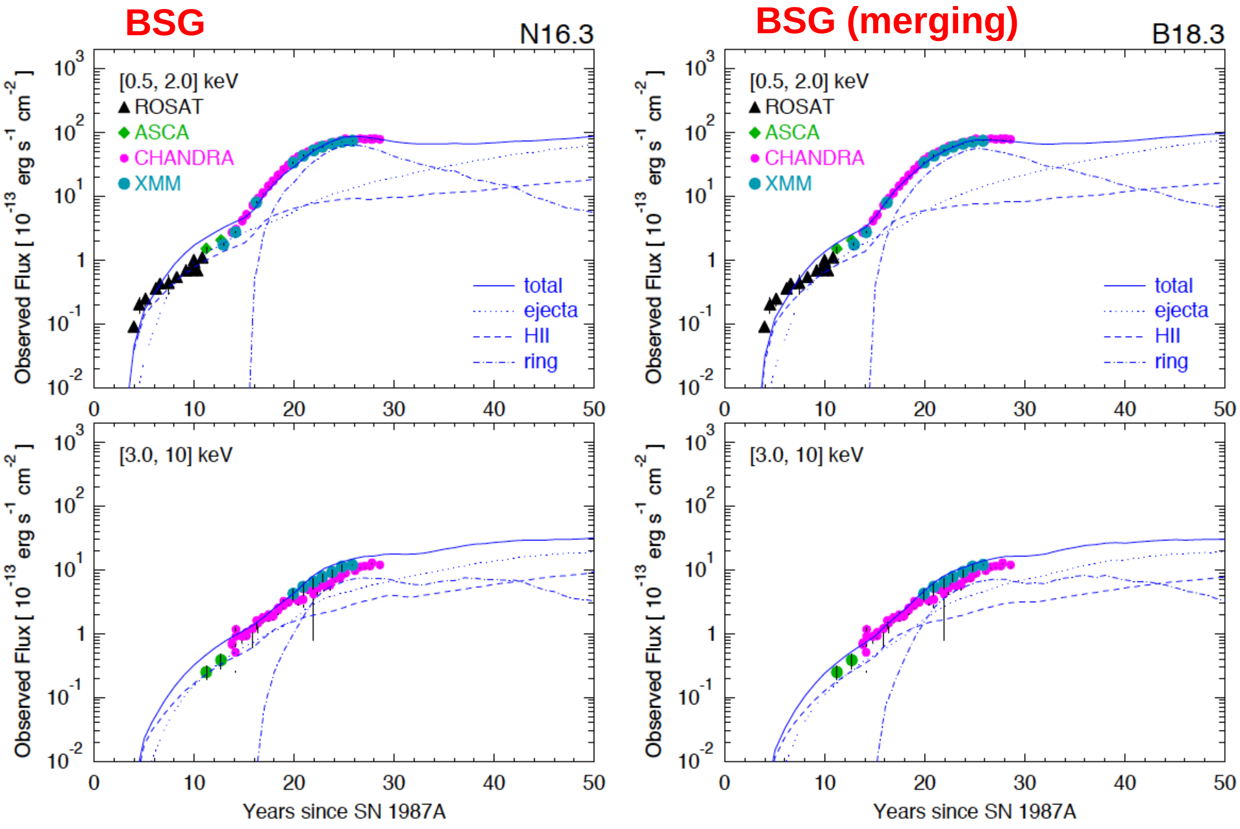
BSG | BSG (merging) | RSG



- **ALMA: torus-like structure evident in SiO and CO** (Abellan+ 2017)
- **Model: modeled torus-like feature with similar orientation and size** (Orlando+ 2019)

Effects of inhomogeneous CSM in SN 1987A

X-ray Lightcurves

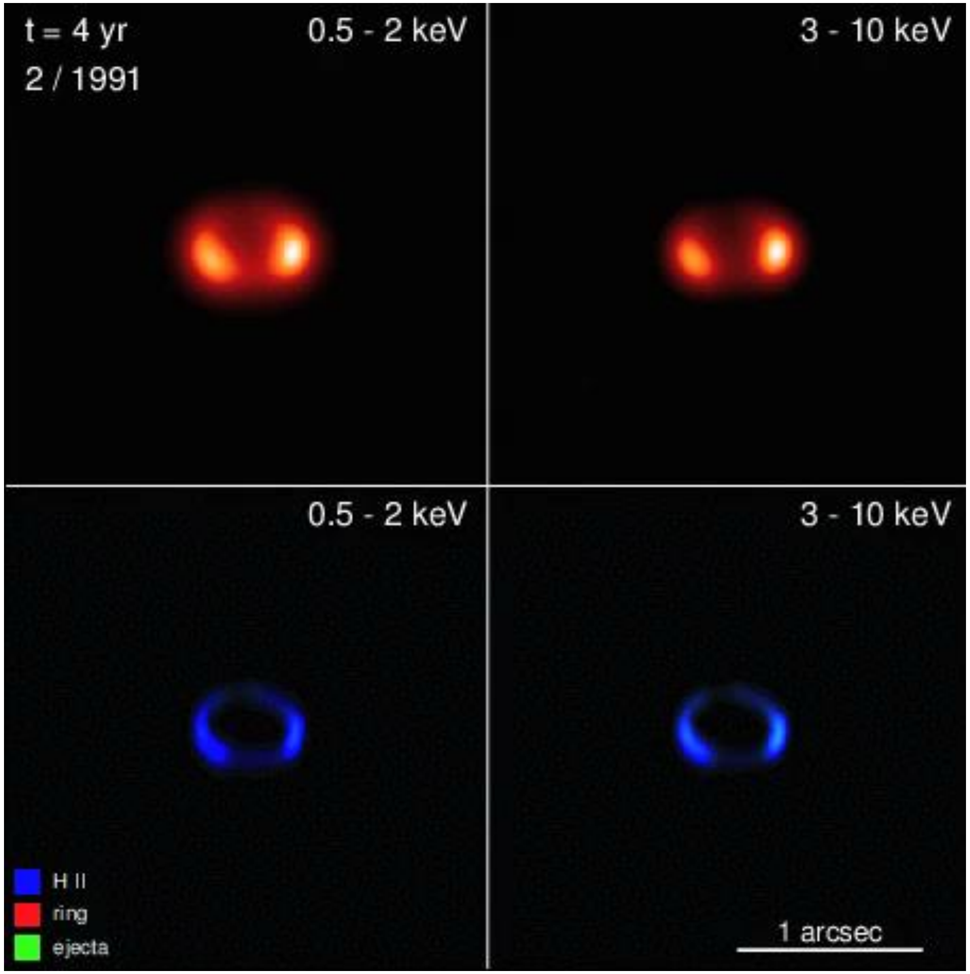


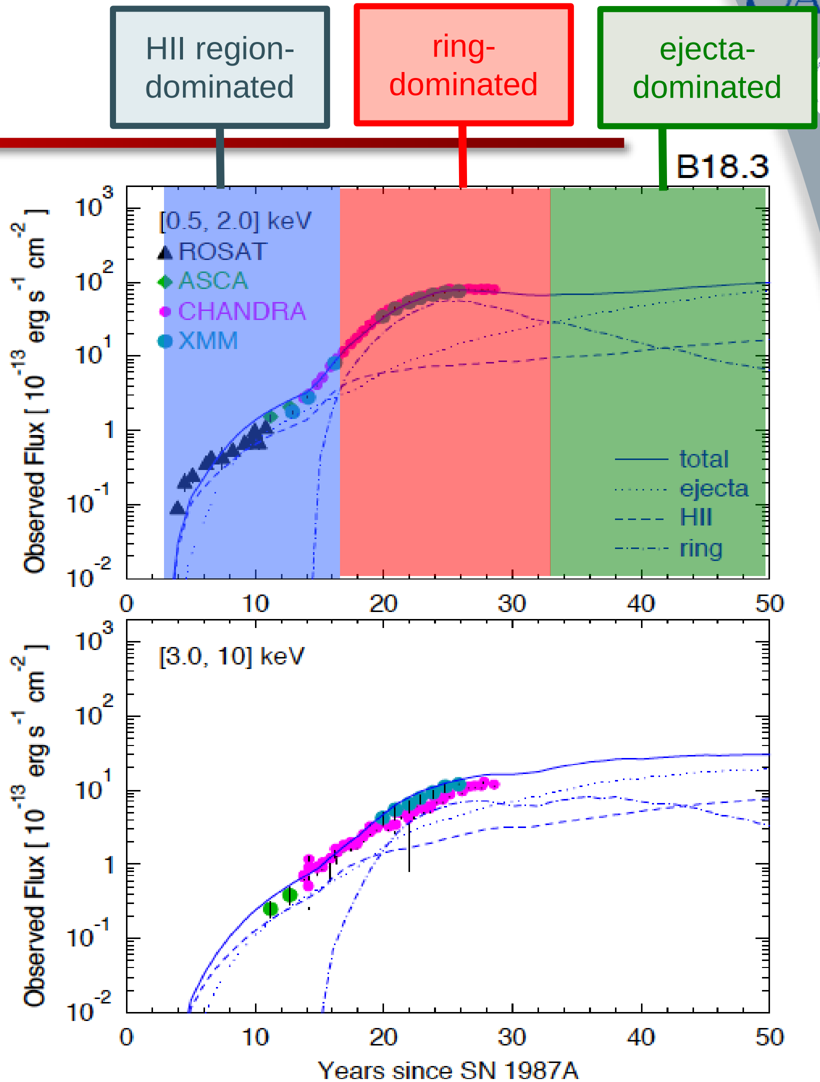
Abundances from Zhekov+ (2009)

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

Distance: 51.4 kpc (Panagia 1999)

X-ray Lightcurves





Abundances from Zhekov+ (2009)

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

Distance: 51.4 kpc (Panagia 1999)

SN 1987A

progenitor star

$18.3\ M_\odot$ BSG resulting from the merging of 14 and 9 $M_\odot$ stars

explosion energy

$E_{exp} \sim 2 \times 10^{51}$ erg

Initial large-scale asymmetry

$\alpha = 1.5$
$\beta = 16$

NS kick

~ 300 km/s toward us to the north

Conclusions

TAKE AWAY POINTS

- **SNRs morphology and properties reflect the physical and chemical properties of the parent SNe, the stellar progenitor, 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**

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

THE CHALLANGE

Deciphering observations might depend critically on models

- **Models should connect stellar progenitor → SN → SNR**
    - **multi-physics, multi-scale, multi-dimension (progenitor, SN, SNR)**
- **Observational facts as a guidance for models (account for dynamics, energetics, and spectral properties of SNe and SNRs)**
- **Promote the synergy and comunication among communities (progenitors, SNe, SNRs)**

→ **THE DREAM**
Coupling together state-of-the-art models in each field
- self-consistent picture -