Connecting Supernova Remnants to their progenitor SN explosions: the Cassiopeia A and SN 1987A laboratories

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Collaborators

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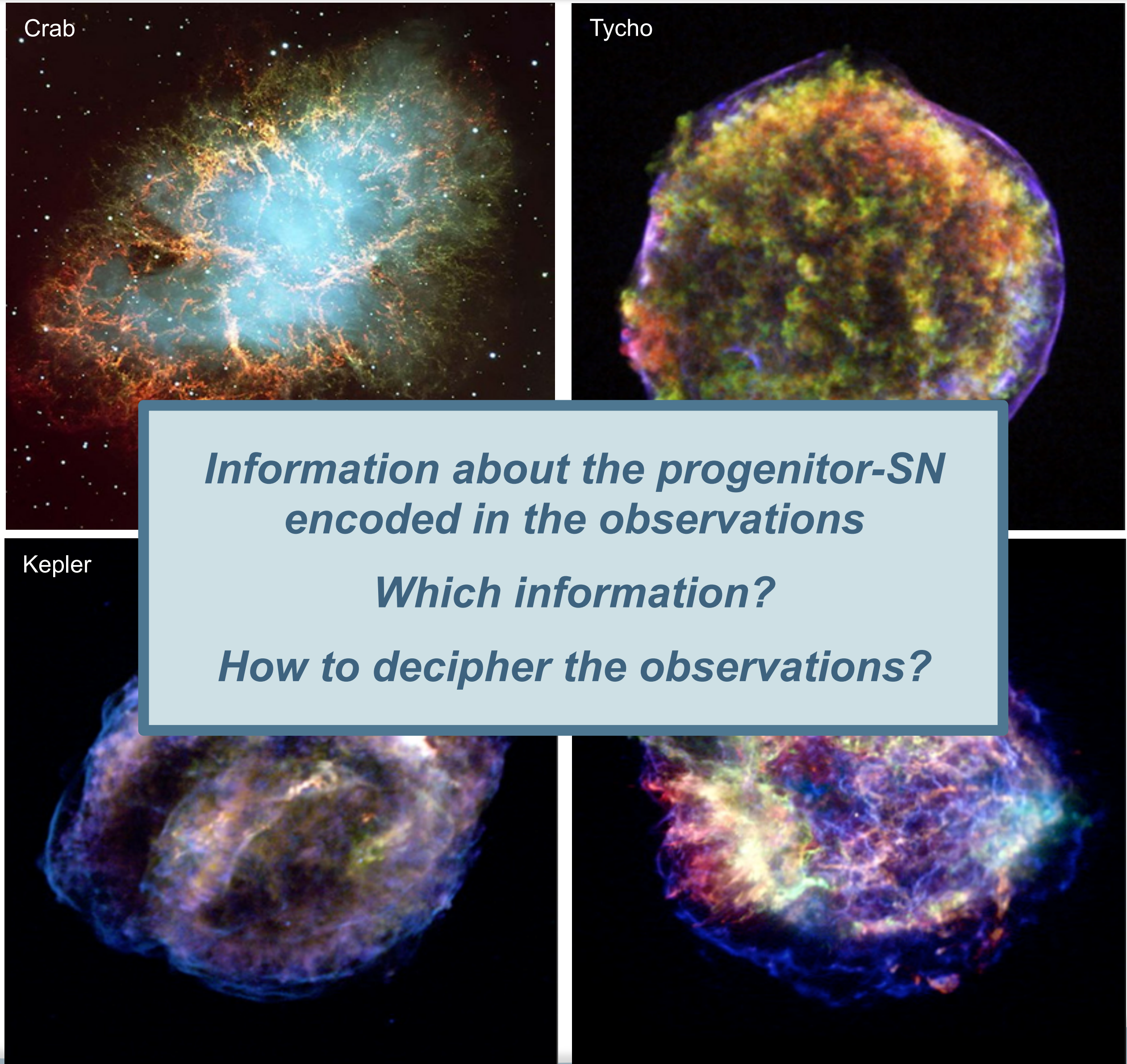
Supernova Remnants

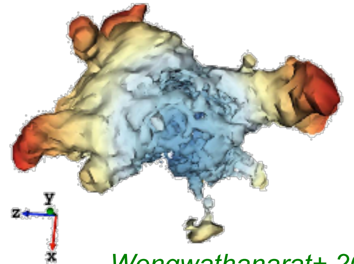


Information about the progenitor-SN encoded in the observations

Which information?

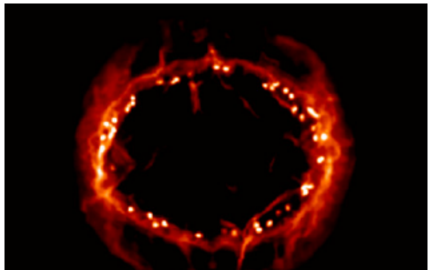
How to decipher the observations?

- pristine structures and features of progenitor SN



Wongwathanarat+ 2017

- interaction of SN blast with the CSM



Orlando+ 2015

Supernova Remnants

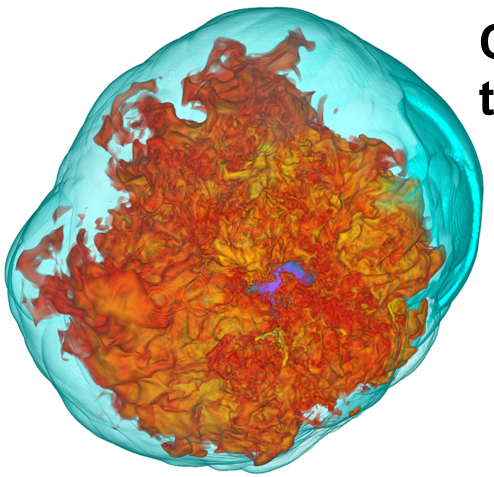
SNRs offer the quite unique possibility

- to probe the physics of SN engines by providing insight into the asymmetries that occur during the SN explosion
- to investigate the final stages of stellar evolution by unveiling the structure of the progenitor star and of the medium immediately surrounding the progenitor

Criticality: Very different time and space scales of SNe and SNRs

→ difficult to study their connection in detail

~ 10^9 cm



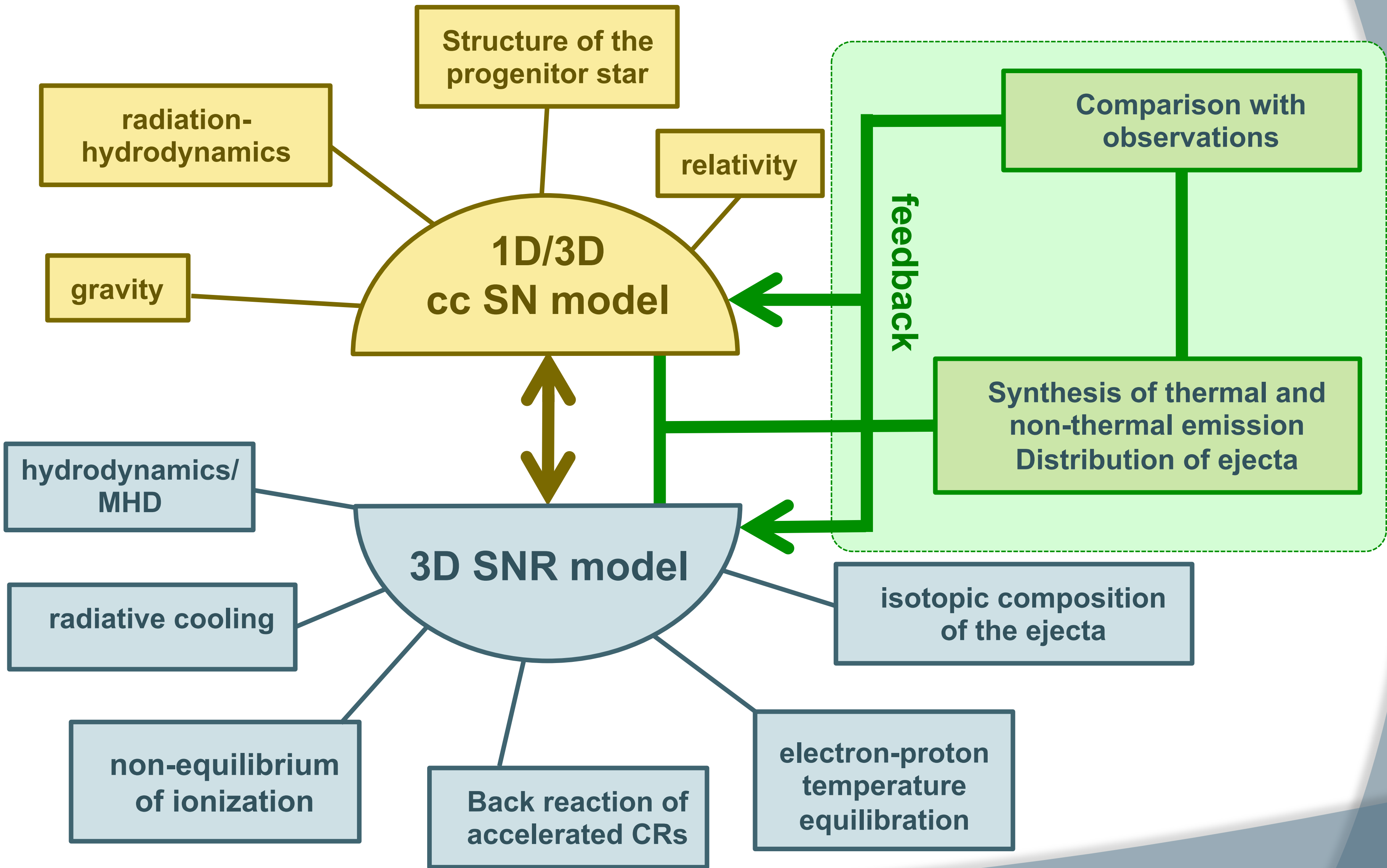
CC SN
t < 1 sec

~ 5 pc

SNR
t ~ 350 yr

The problem is inherently 3D

How to link SNe to SNRs ? The strategy

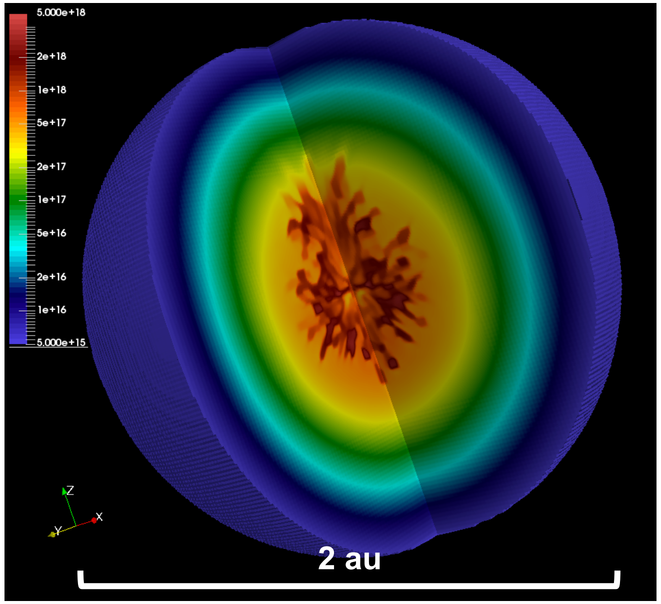


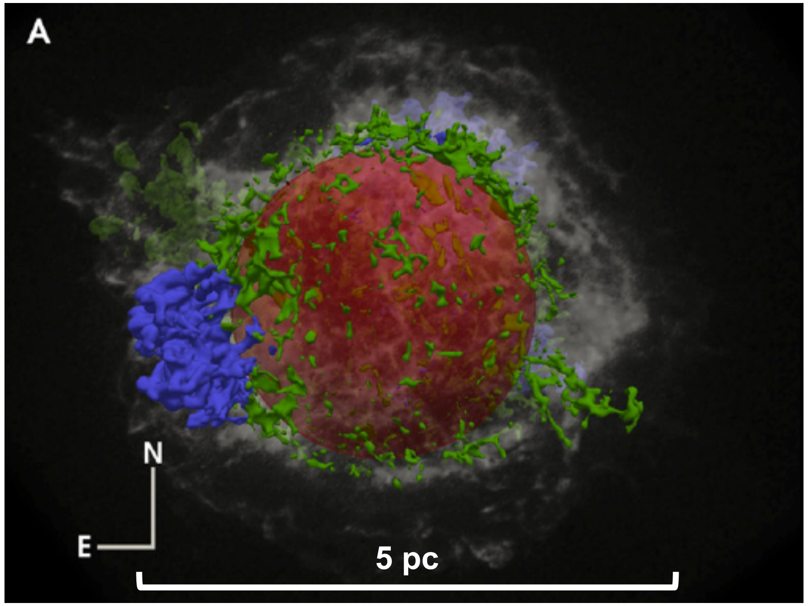
Modeling the SN-SNR evolution

A major challenge is capturing the enormous range in space and time scales

SNR Initial condition ~ 1 day after the SN
SNR Initial size ~ tens of AU

Final time ~ hundeds of yr (current age)
Final size several pc





> 20 nested levels of adaptive mesh refinement
→ effective resolution ~ 0.2 AU (3e12 cm)

> 300 cells per blast wave radius during the whole evolution

Two study cases
- Cassiopeia A
- SN 1987A

Effects of SN anisotropies: SNR Cassiopeia A

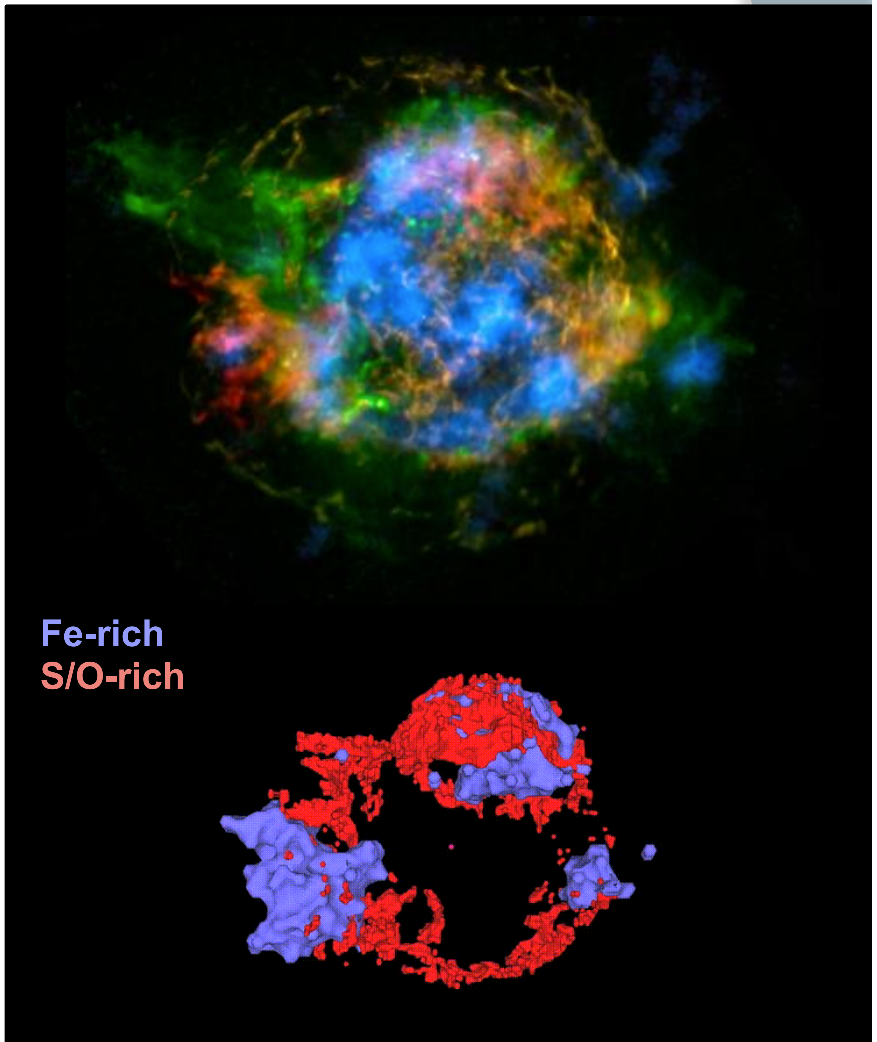
Observations suggest that its morphology and expansion rate are consistent with a remnant expanding through the wind of the progenitor red supergiant **(e.g. Lee+ 2014)**

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

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)**

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

Can post-explosion anisotropies explain the ejecta distribution?



(Milisavljevic & Fesen 2013)

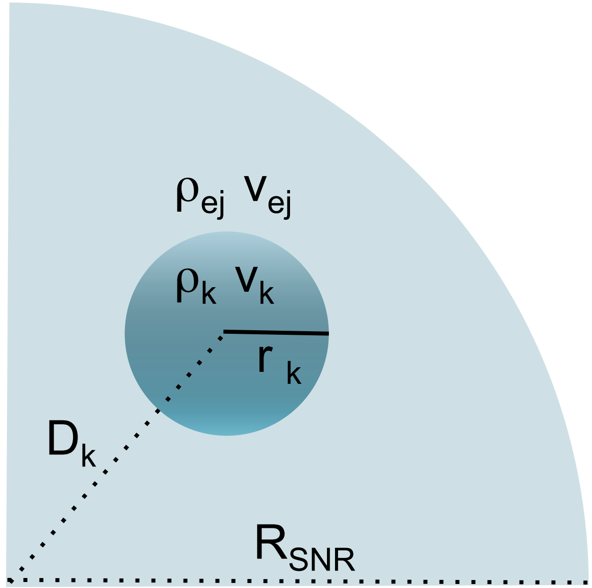
Initial conditions and parameter space

The post-explosion structure of the ejecta is described by small-scale clumping of material and larger-scale anisotropies
(e.g. Kifonidis+ 2006; Wang & Wheeler 2008; Gawryszczak+ 2010)

- **Small-scale clumping as in Orlando+ (2012)**
- **Large-scale anisotropies as overdense spherical knots**

Parameters of large-scale anisotropies
(Kifonidis+ 2003; Ellinger+ 2012)

$D_k = [0.15 – 0.35]\ R_{SNR}$
$r_k = [3\% - 10\%]\ R_{SNR}$
$\rho_k = [10 – 100]\ \rho_{ej}$
$v_k = [1 – 10]\ v_{ej}$



Numerical Code: FLASH

Effect of a post-explosion anisotropy of ejecta

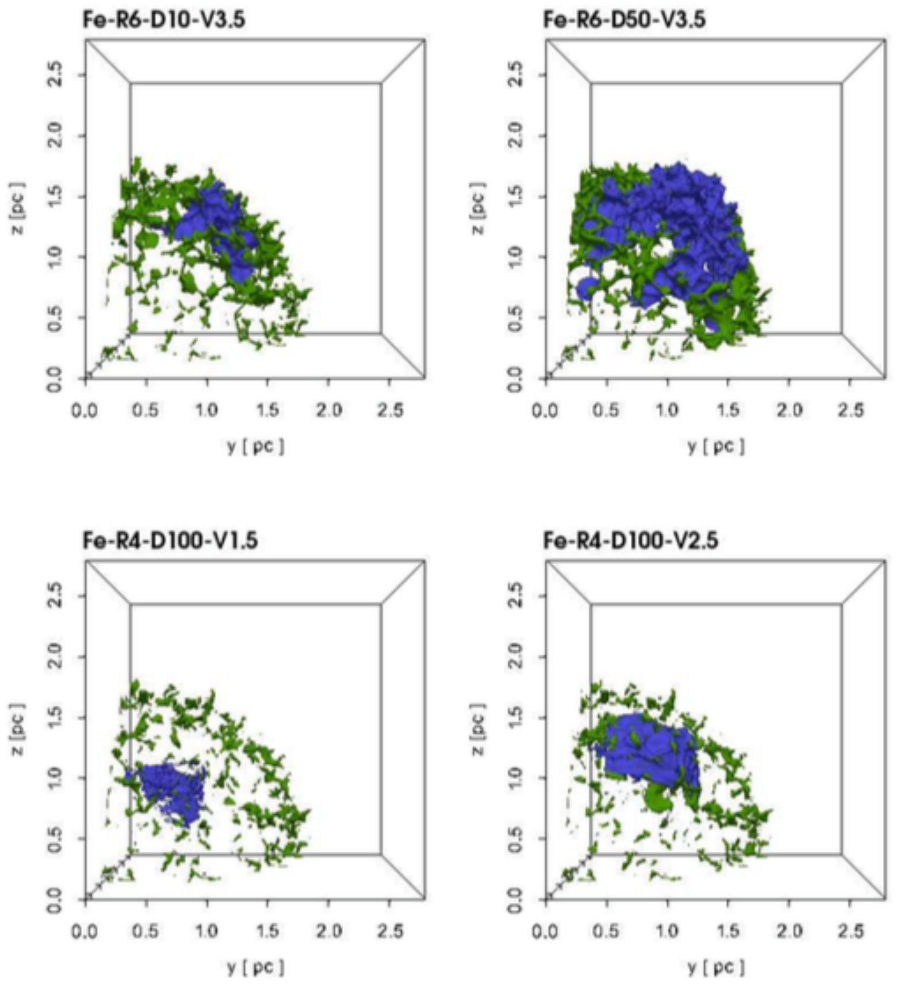
We searched for the knot parameters best reproducing

- **The masses of shocked Fe and Si/S**
- **The extension of Fe-rich regions**
- **The extension of Si-rich jets**

Parameters of large-scale anisotropies

Piston/Jet	D_{knot}	r_{knot}	χ_n	χ_v	M_{knot}	E_{knot}
	(R_{SNR})	(R_{SNR})			($M_\odot$)	(10^{49} erg)
Fe-rich SE	0.15	0.05	100	4.2	0.10	5.0
Fe-rich SW	0.15	0.02	50	4.2	0.0015	0.076
Fe-rich NW	0.15	0.06	50	4.2	0.10	4.8
Si-rich NE	0.35	0.1	5.0	3.0	0.040	4.2
Si-rich SW	0.35	0.1	1.2	3.0	0.0091	1.0

(Orlando+ 2016)



Spatial Distribution of the Cas A ejecta

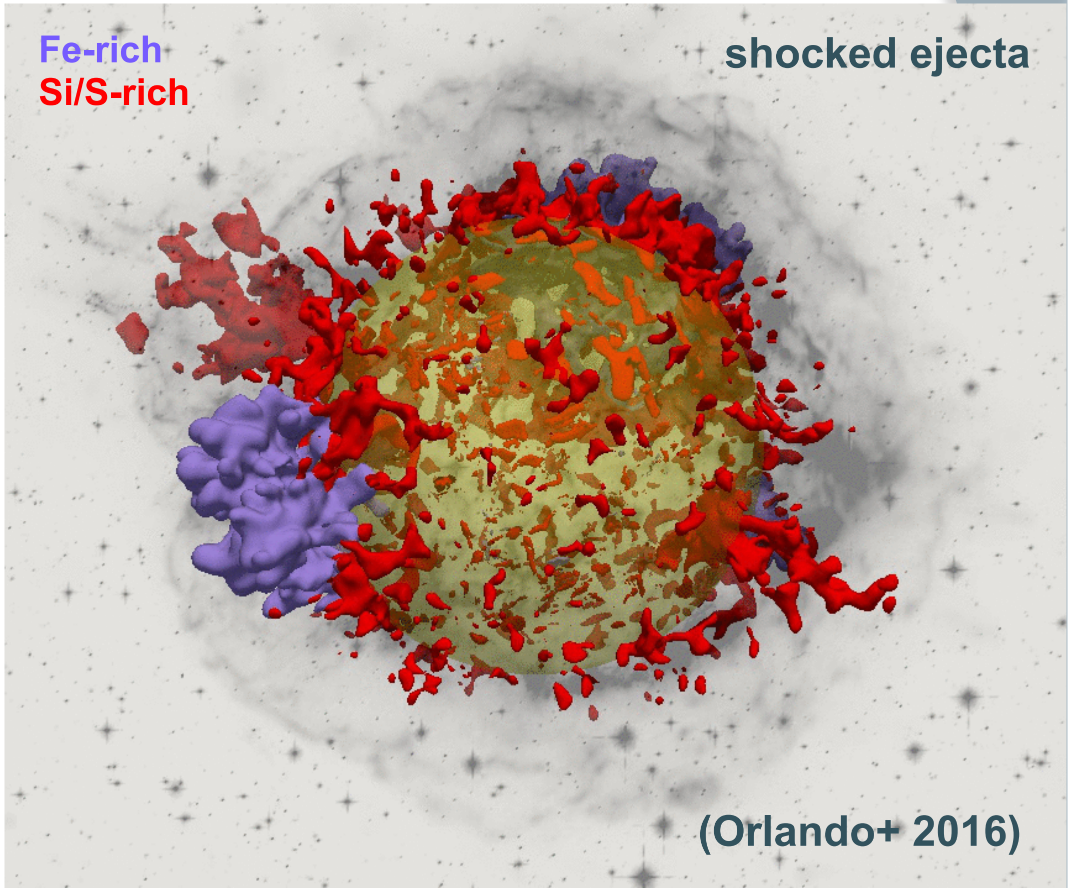
Shocked ejecta

Post-explosion anisotropies (pistons) reproduce the observed distributions and masses of Fe and Si/S if

- **mass of $\approx 0.25\ M_{\odot}$ (5% of the tot.)**
- **kinetic energy of $\approx 1.5 \times 10^{50}$ erg (7% of the total)**

The pistons produce a spatial inversion of ejecta layers at the epoch of Cas A, leading to the Si/S-rich ejecta physically interior to the Fe-rich ejecta

The pistons are also responsible for the development of rings of Si/S-rich material which form at the intersection between the reverse shock and the material accumulated around the pistons during their propagation



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

Shocked ejecta

The simulation predicts kT_e and τ values in the observed ranges with highly peaked distributions

(Hwang & Laming 2012)

This results from the multiple secondary shocks following reverse shock interaction with ejecta inhomogeneities

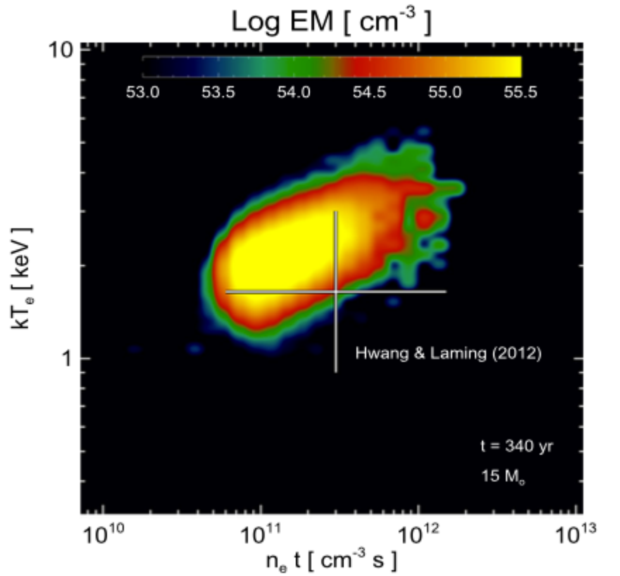
X-ray emitting plasma largely out of equil. of ionization

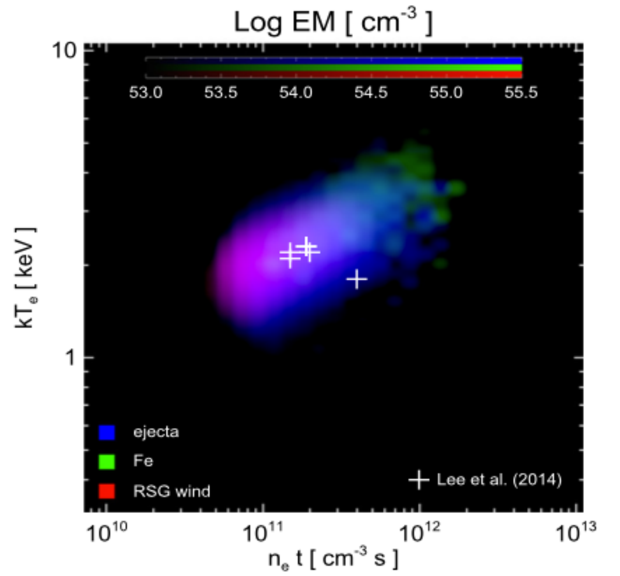
EM(T, τ) peaks at $kT_e \approx 2$ keV and $\tau \approx 10^{11}$ cm^{-3} s in a region dominated by shocked wind

Agreement with the best-fit parameters derived by Lee+ (2014)

Shocked Fe is at an advanced ionization age relative to the other elements ($\tau \approx 10^{12}$ cm^{-3} s)

Agreement with observations (e.g., Hwang & Laming 2003, 2012)





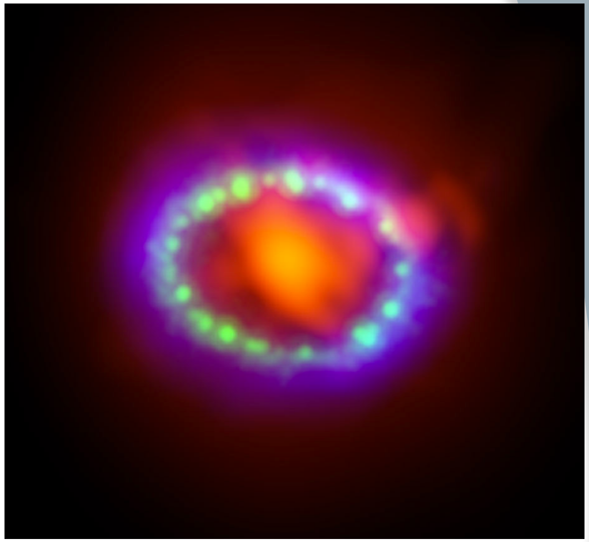
Ring

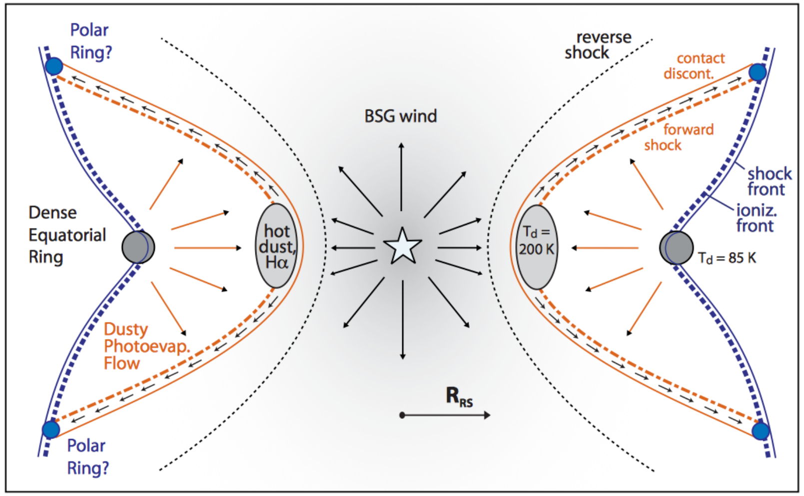
Effects of inhomogeneous CSM: SN 1987A

Origin of the CSM

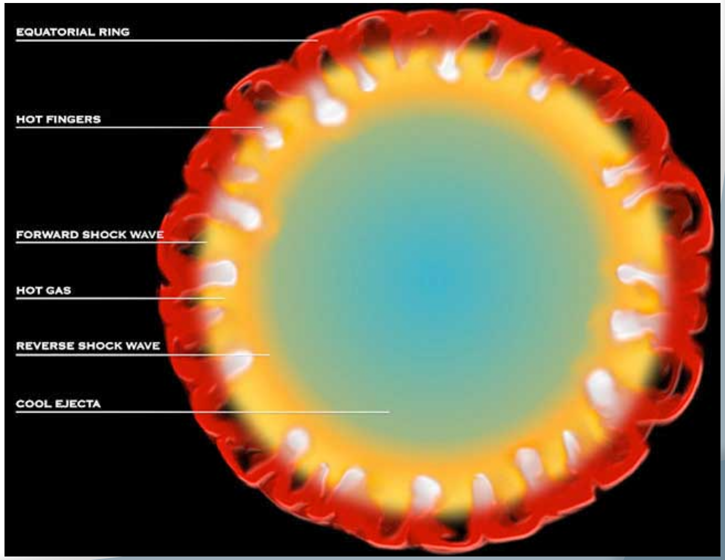
interaction of a slow wind from the red supergiant phase with the faster wind from the blue supergiant phase
(e.g. Morris & Podsiadlowski 2007)

Currently, the explosion is leaving the inner equatorial ring that was formed by the late stages of the star's evolution.

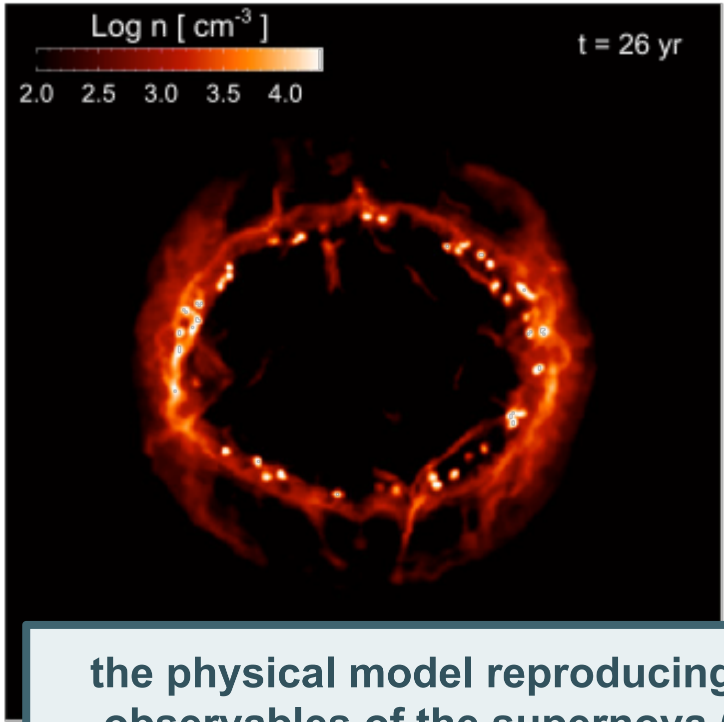




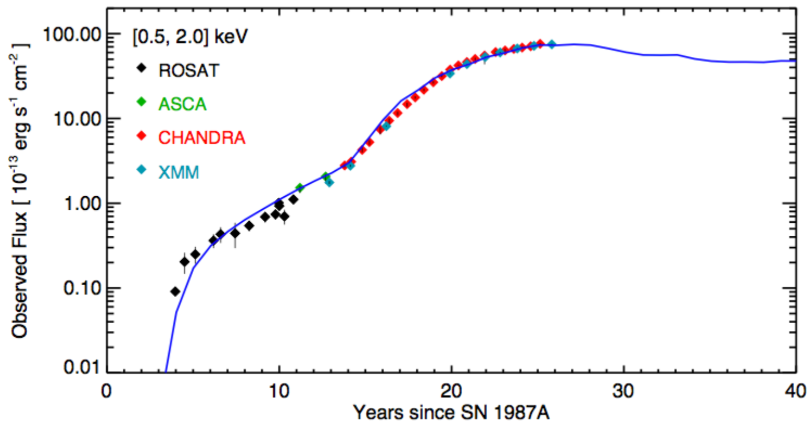
(Smith+ 2013)

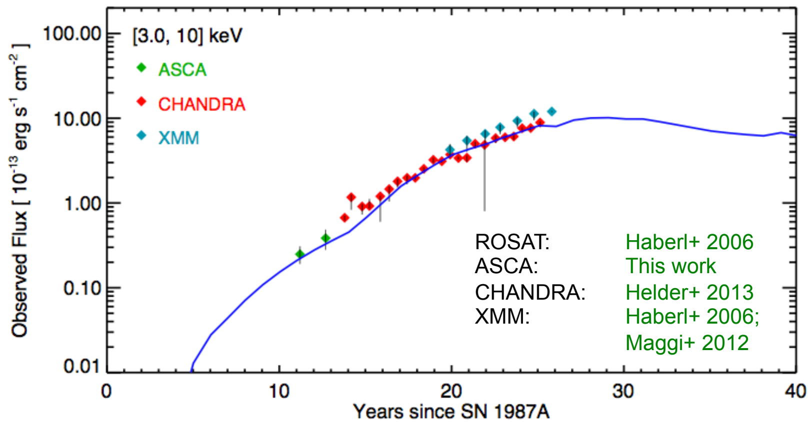


Previous results (Orlando+ 2015)



the physical model reproducing the observables of the supernova (the cause) is able to reproduce also the observables of the subsequent expanding remnant (the effect)



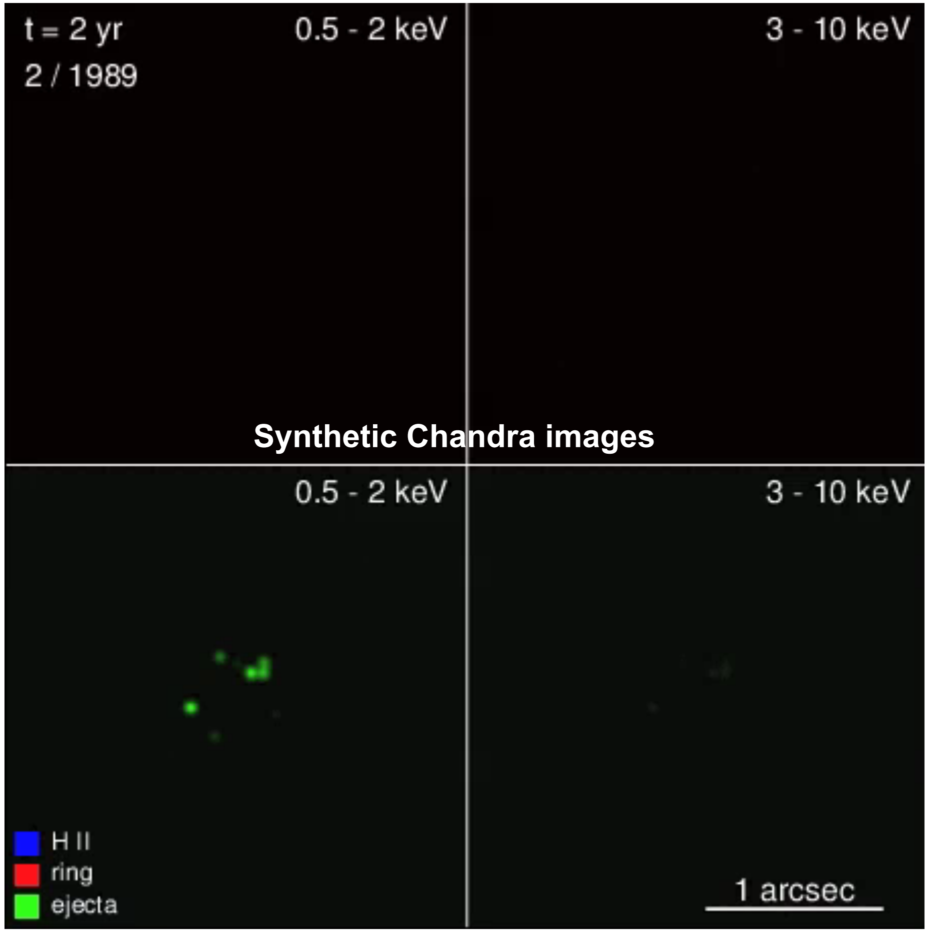


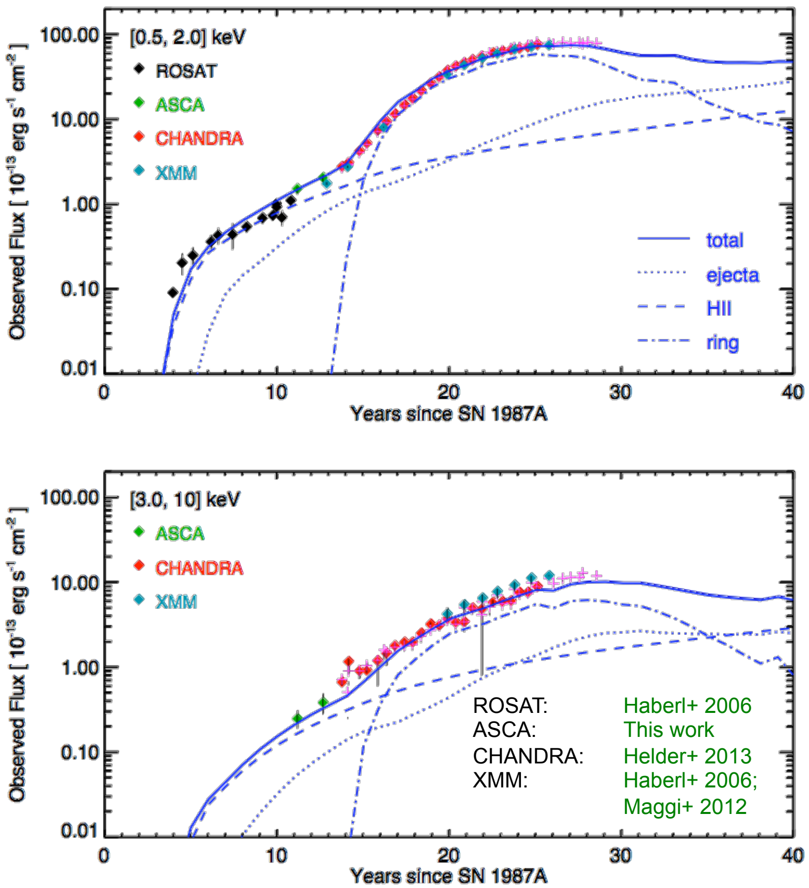
We use jointly a 1D SN explosion model (24 hours) and a 3D hydrodynamic model of SNR (40 years)

Numerical Code: FLASH

Abundances from Zhekov+ (2009)
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)
Distance: 51.4 kpc (Panagia 1999)

Previous results (Orlando+ 2015)





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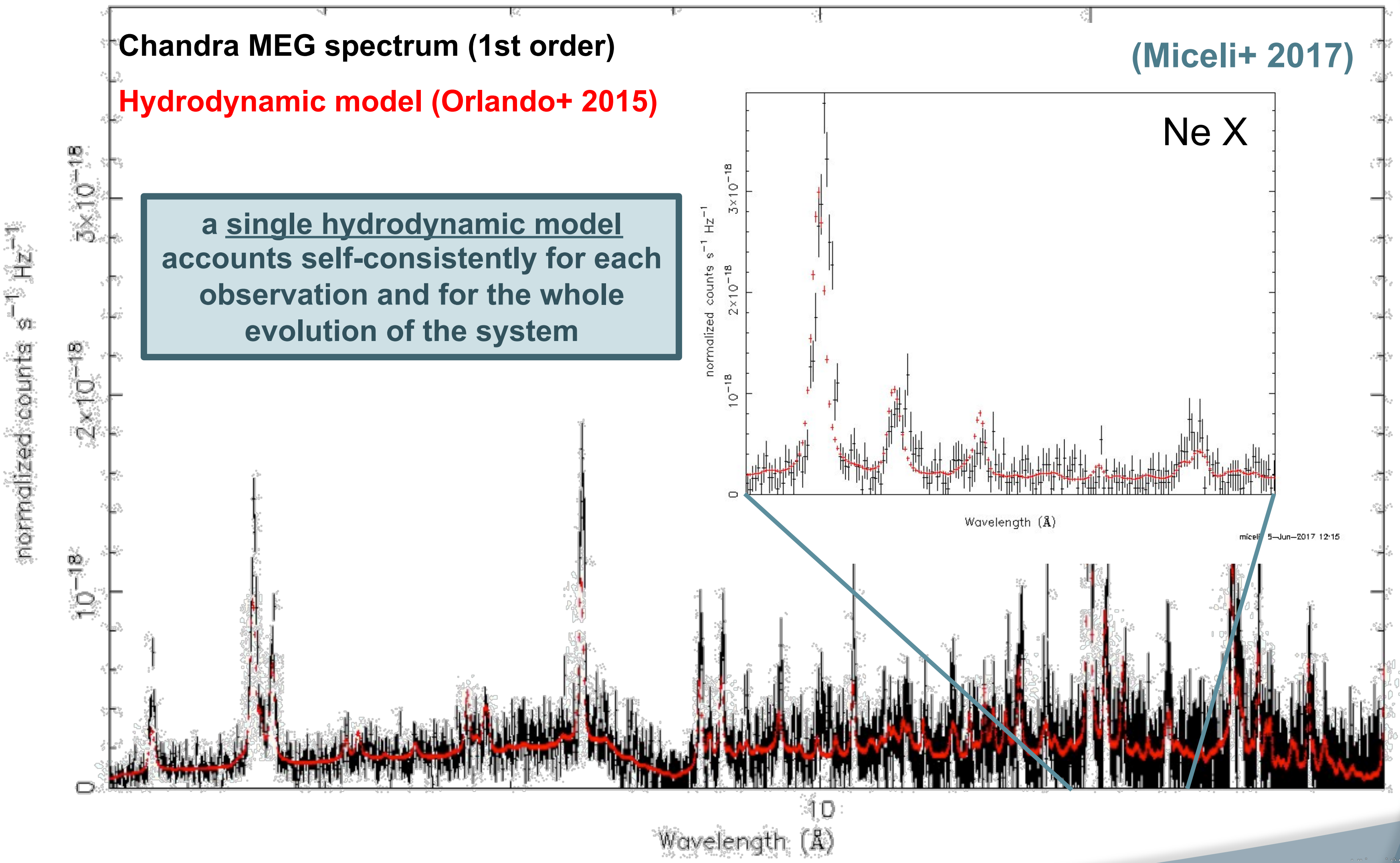
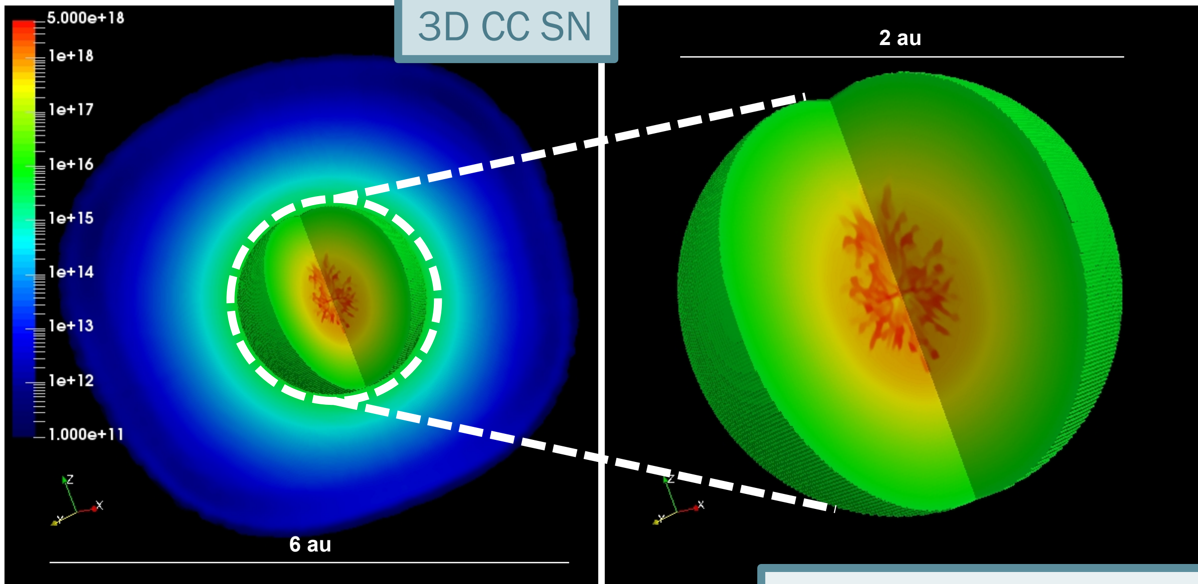
High-resolution spectra (2011)



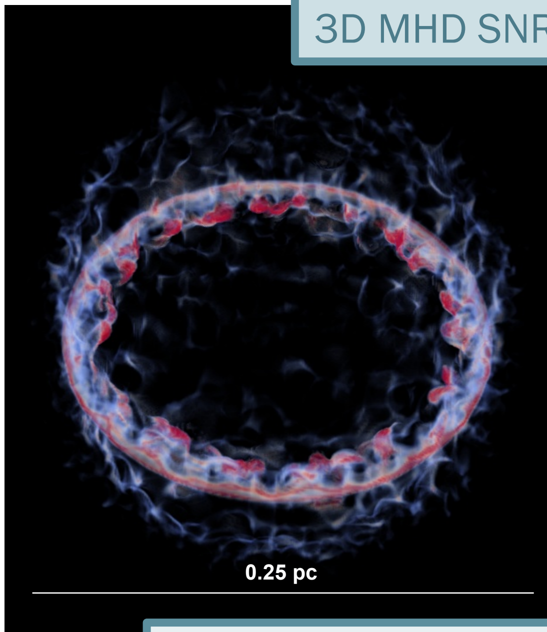
SN 1987A: from the SN to the SNR

3D CC SN



~ 12 hours since the SN event

3D MHD SNR



30 years since the SN event

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Gilles Ferrand	(RIKEN, Japan)
Annop Wongwathanarat	(RIKEN, Japan)
Shiu-Hang Lee	(Kyoto University, Japan)
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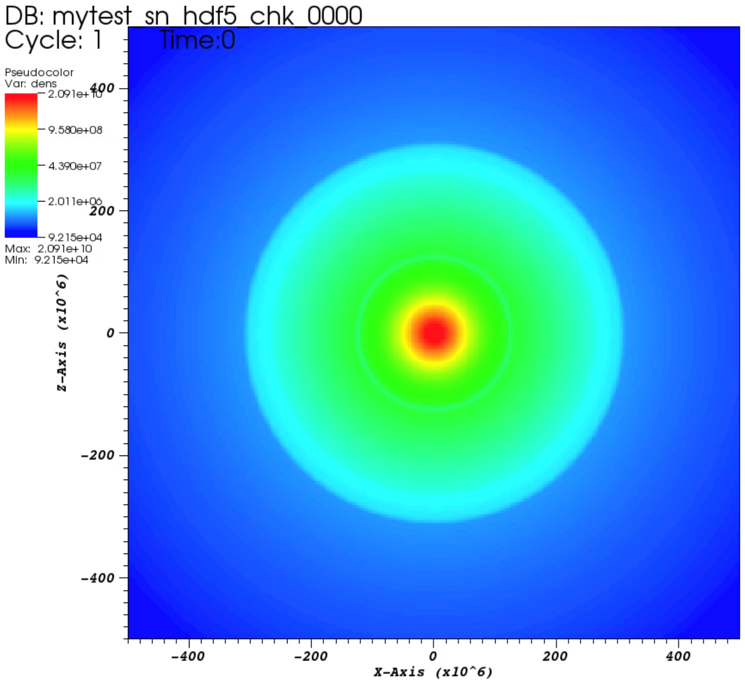
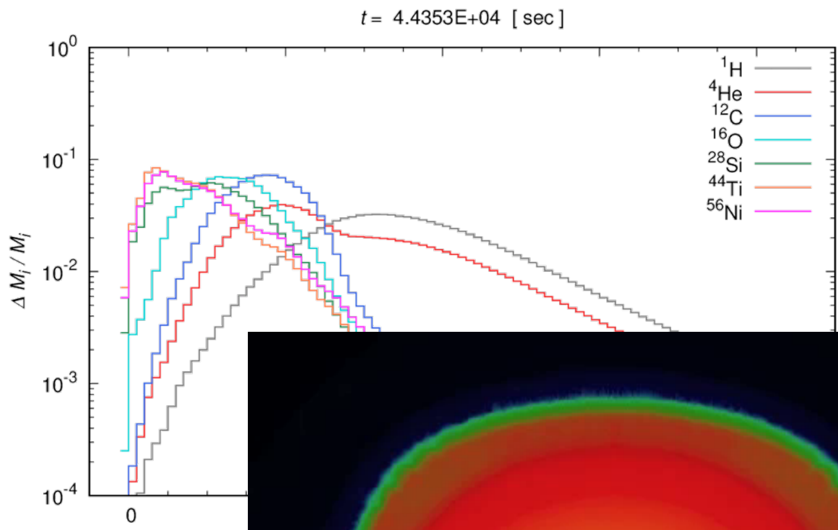
Tomoya Takiwaki	(National Astronomical Observatory, Japan)

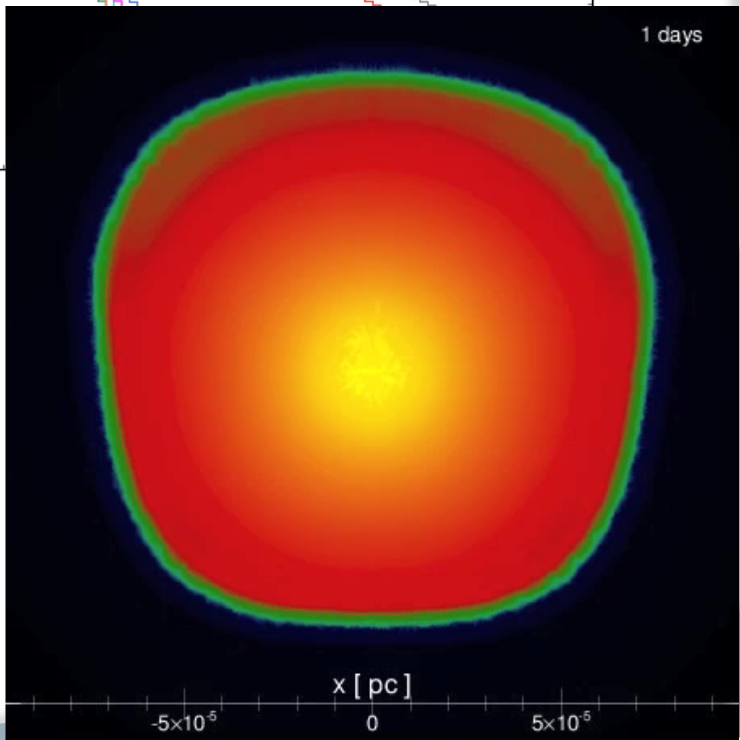
PRACE

64 millions CPU hours

SN 1987A: from the SN to the SNR

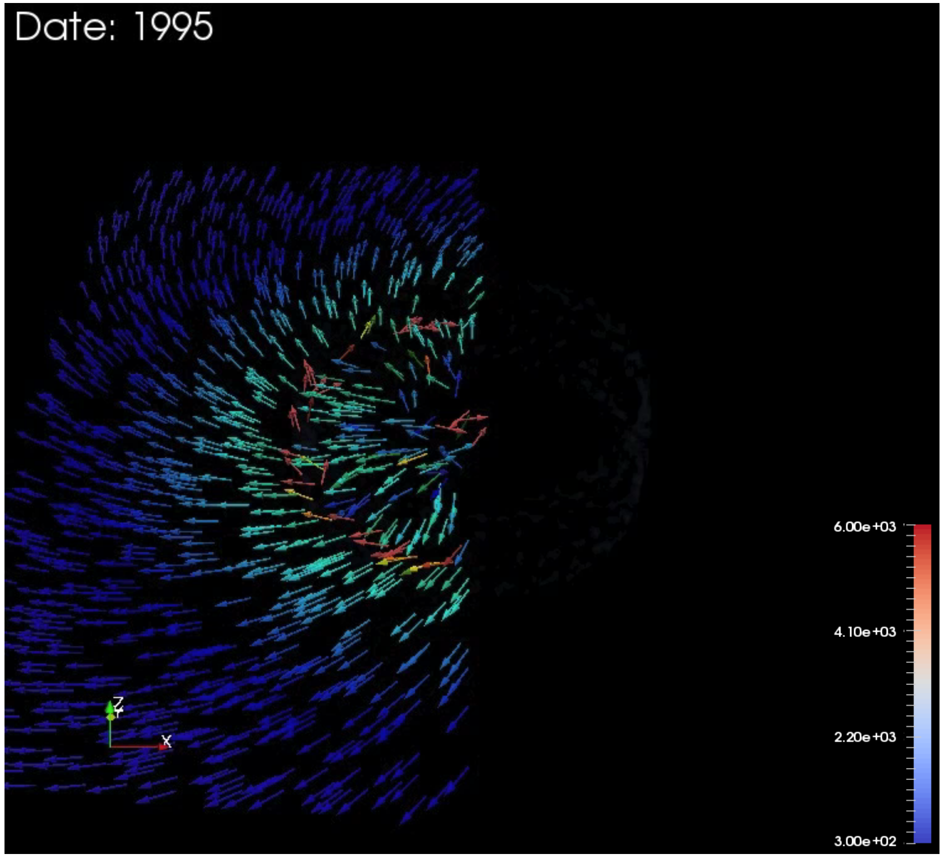


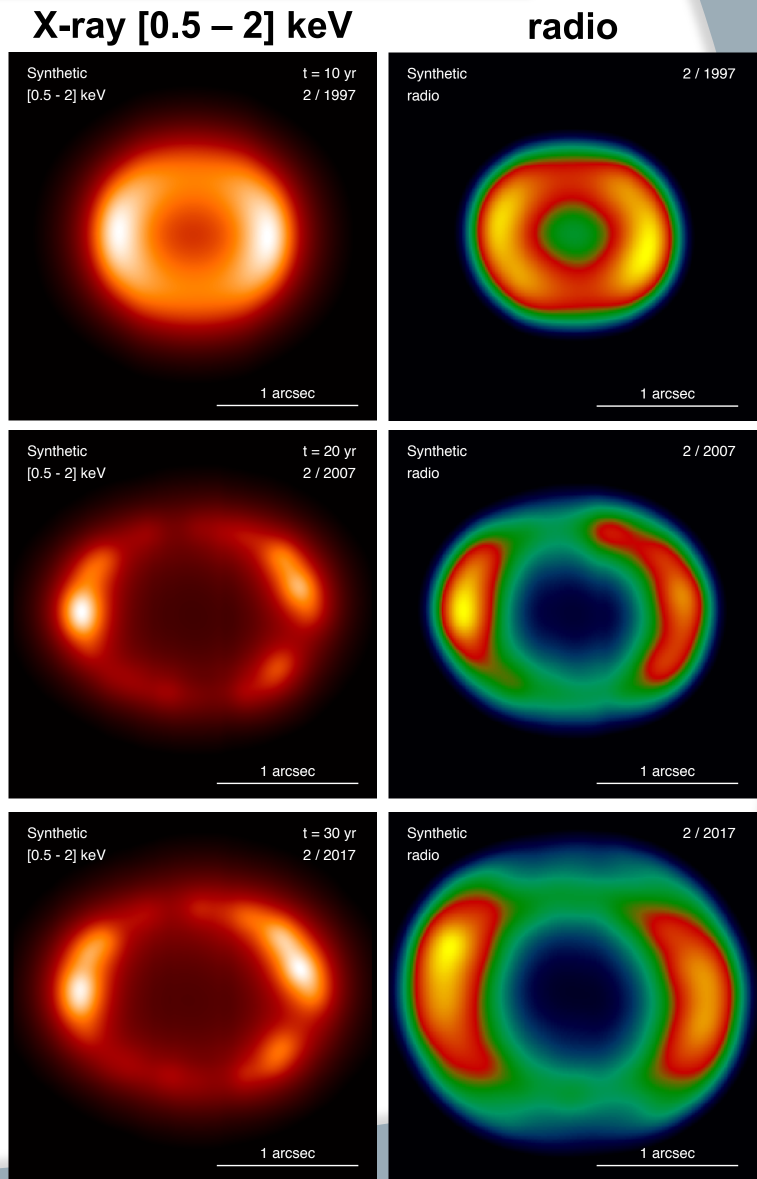




- **Adapted from the model of Ono+ (2013) to 3D**
- **Progenitor: 16.3$M_\odot$ star with a 6$M_\odot$ helium core and a 10.3 $M_\odot$ compact hydrogen envelope**
  (Nomoto & Hashimoto 1988)
- **Explosion energy: 1.8 x 10^{51} erg**
- **3D SN simulations performed with *FLASH***
  (Fryxell+ 2000)

SN 1987A: SNR evolution and observables





- **3D MHD SNR simulations performed with *PLUTO* (Mignone+ 2007, 2012)**
- **Synthesis of radio emission performed with *REMLIGHT* (Orlando+ 2007, 2011)**

Summary

Devised a strategy to study the SN-SNR connection

- Based on coupling 1D/3D CC SN models with 3D SNR models
- Link observations of SNRs to CC SN models

SNR Cassiopeia A

- Post-explosion anisotropies: total mass ≈ 0.25 $M_{\odot}$ kinetic energy ≈ 1.5 × 10^{50} erg
- Origin of spatial inversion of ejecta layers: Si/S-rich ejecta interior to Fe-rich ejecta
- Origin of bright rings of Si/S-rich material encircling Fe-rich regions
- Bulk of asymmetries observed in Cas A is intrinsic to the explosion

SN 1987 A

- The same physical model reproduces the main observables of SN and SNR
- Derive the geometry and density distribution of the nebula
- Multi-temperature nature of X-ray emission: different plasma components
- SNR X-ray emission reflects the structure of outermost ejecta

Work in progress

- High resolution spectra of 87A revisited: physical properties of emitting plasma
- MHD modeling of 87A in 3D from the on-set of SN to the SNR

Conclusions

TAKE AWAY POINTS

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

Linking SNe to SNRs has breakthrough potential to open new exploring windows on SN and SNR issues

FUTURE TASKS

Deciphering observations might depend critically on models

- **Models should connect stellar progenitor $\rightarrow$ SN $\rightarrow$ 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) as done at this meeting !**