Modeling post-explosion anisotropies of ejecta in SNR Cassiopeia A

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Outline

- **Introduction:**
  the 3D structure of Cas A as inferred from observations
- **Rationale of the work and methodological approach**
- **Modeling the SN explosion and subsequent SNR evolution**
- **Modeled distribution of ejecta in Cas A**
- **Summary and Conclusions**

SNR Cassiopeia A

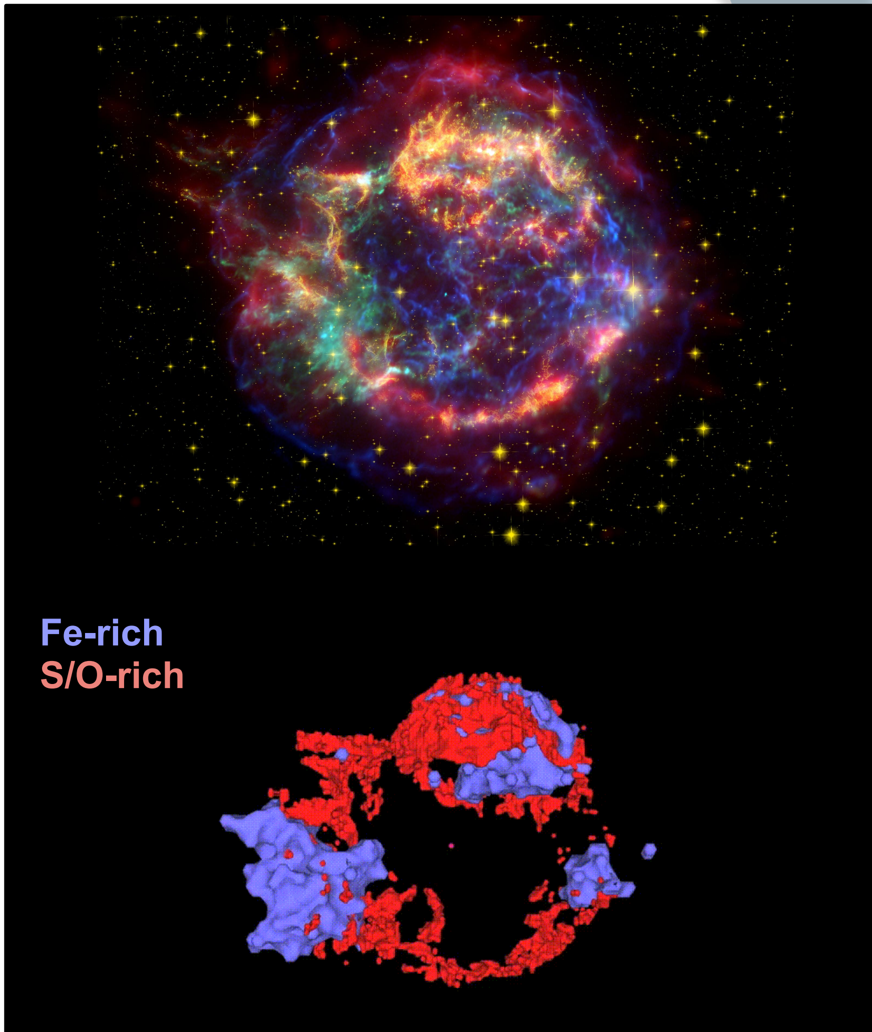
Observations suggest that its morphology and expansion rate are consistent with a remnant expanding through the wind of the progenitor red supergiant (e.g. Lee+ 2014)

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



(Milisavljevic & Fesen 2013)

Aims of this work

Study the ejecta dynamics from the immediate aftermath of the SN explosion to their expansion in the SNR with accurate model resolution and completeness

We use jointly a SN explosion model and a 3D hydrodynamic model of SNR

- To derive the physical parameters characterizing the progenitor SN (mass of ejecta and energy of explosion) and the surrounding medium (wind density)
- To investigate how fine ejecta structures form during the remnant evolution and how the final remnant morphology reflects the characteristics of the SN explosion
- To derive the total mass and kinetic energy of the post-explosion anisotropies responsible for the observed distributions of Fe and Si/S

Modeling the post-explosion evolution of the SN

Initial distribution of ejecta for the 3D SNR model

⇨ derived from a 1D relativistic, radiation-hydrodynamics Lagrangian code, specifically tailored to simulate the evolution of the main observables in core-collapse SNe (Pumo & Zampieri 2011)

- Fully general relativistic treatment
- Radiative transfer coupled to relativistic hydrodynamics at all regimes
- Gravitational effects of the central compact remnant on the evolution of the ejecta (fallback of material onto the compact remnant; amount of ejected ^{56}Ni)

We follow the SN evolution from the breakout of the shock wave at the stellar surface up to the so-called nebular stage

Grid of models

M_{ej} = 4 M_{sun} (Young+ 2006; van Veelen+ 2009)
M_{ni} = 0.1 M_{sun} (Eriksen+ 2009)
E_{SN} = [1 – 3] x 10^{51} erg
R_0 = [100 – 1000] R_{sun} (Lavesque+ 2005)

Modeling the SNR evolution

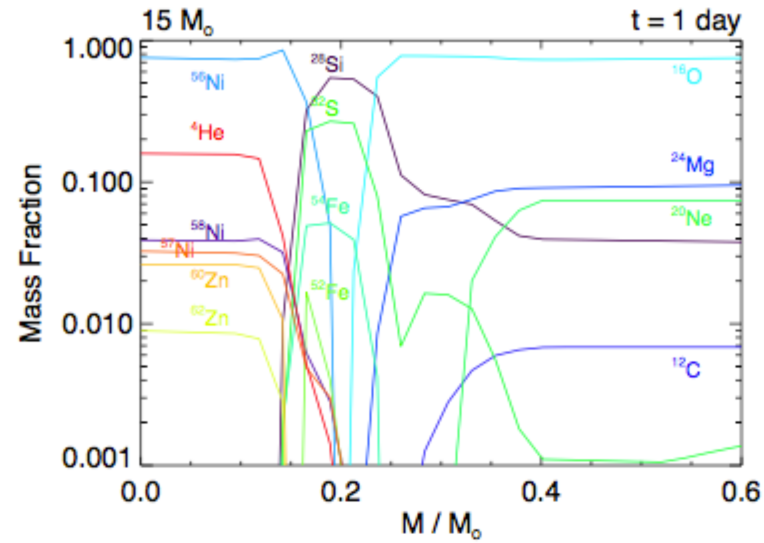
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \ ,$$

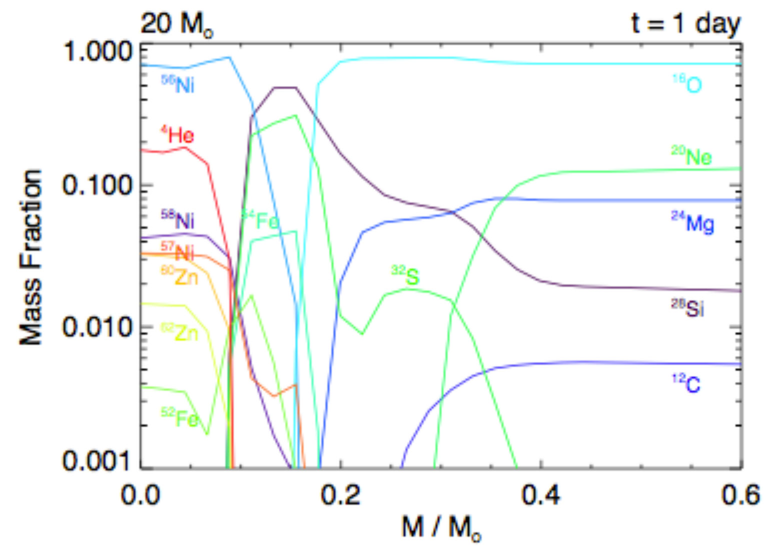
$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} + \nabla P = 0 \ ,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{u} = -n_{\rm e} n_{\rm H} \Lambda(T) \ ,$$

$$\text{where} \qquad E = \epsilon + \frac{1}{2}|\mathbf{u}|^2 \ ,$$

- Radiative losses from optically thin plasma
- Back reaction of accelerated CRs (Ferrand+ 2010)
- Non-equilibrium of ionization (Dwarkadas+ 2010)
- hydro multi-species simulations with post-explosion isotopic composition of the ejecta (Thielemann+ 1996)





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Initial conditions

~ few days after the SN explosion

Spatial resolution

A major challange was capturing the enormous range in spatial scales

- Initial remnant radius ~ 20 AU (~ 3e14 cm)
- Full spatial domain ~ 6 pc (~ 1.8e19 cm)

20 nested levels of adaptive mesh refinement

→ effective resolution ~ 0.3 AU (~ 4e12 cm)

> 100 cells per remnant radius during the whole evolution

Equivalent uniform grid ~ 5e6 X 5e6 X 5e6

FLASH code (Univ. of Chicago)

PRACE Award N.2012060993

Initial conditions and parameter space

The post-explosion structure of the ejecta is described by small-scale clumping of material and larger-scale anisotropies

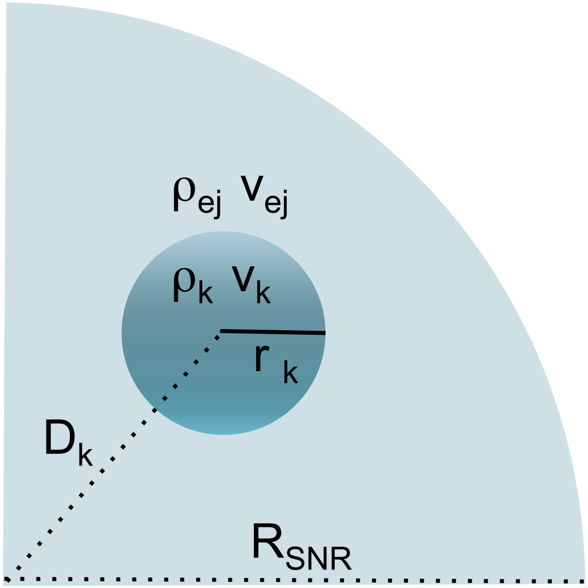
(e.g. Kifonidis+ 2006; Wang & Wheeler 2008; Gawryszczak+ 2010)

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

Parameters of large-scale anisotropies

(Kifonidis+ 2003; Ellinger+ 2012)

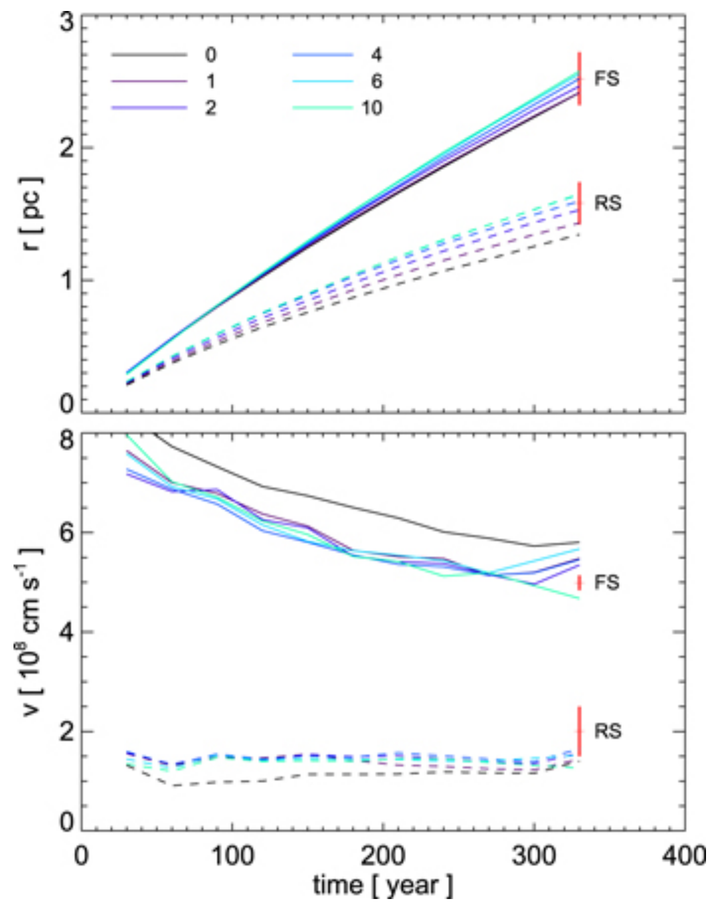
D_k = [0.15 – 0.35] R_{SNR}
r_k = [3% - 10%] R_{SNR}
ρ_k = [10 – 100] ρ_{ej}
v_k = [1 – 10] v_{ej}



The case of a spherically symmetric explosion

We searched for the SN parameters best reproducing altogheter

- the density of the shocked RSG wind (Lee+ 2014)
- the radii and velocities of the FS and RS (van Veelen+ 2009)



Best-fit parameters

- Ejecta mass: $4\ M_{sun}$
- explosion energy: 2.3×10^{51} erg

Fraction of explosion energy converted to CRs

Comparison with observations (Abdo+ 2010; Yuan+ 2013)

- injection rate of particles η: $< 10^{-4}$

Effect of a post-explosion anisotropy of ejecta

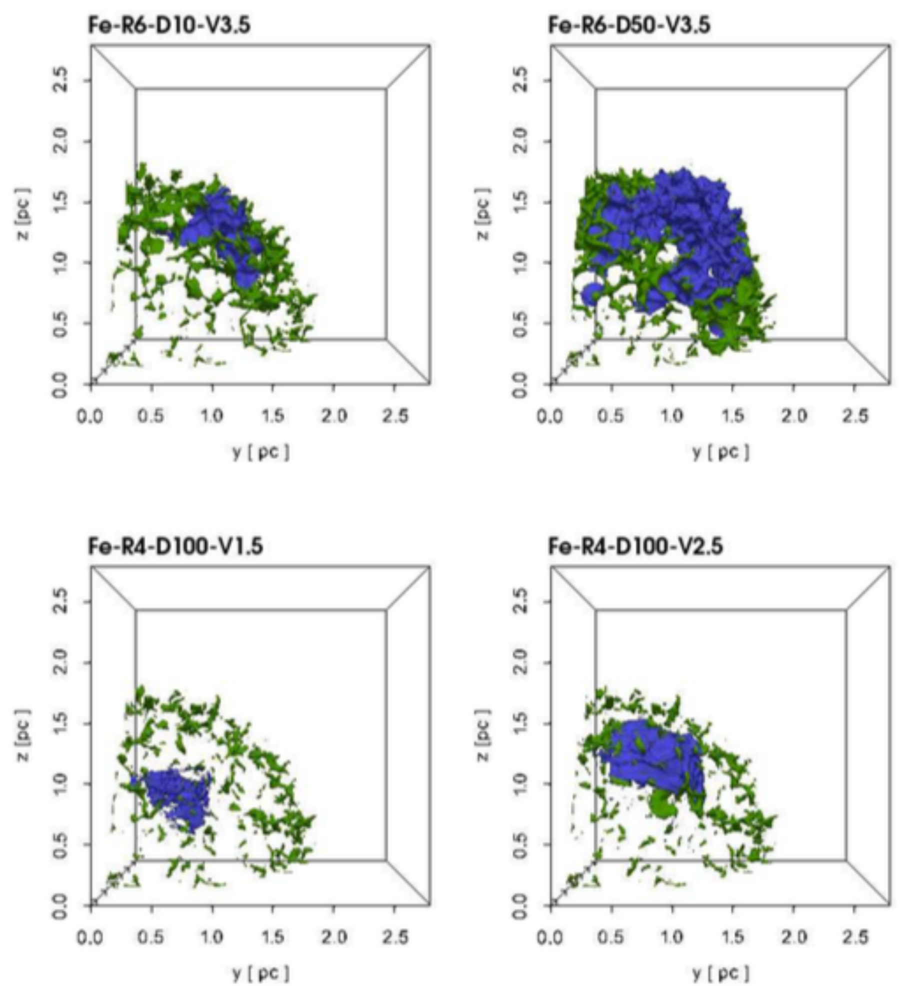
We searched for the knot parameters best reproducing

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

Parameters of large-scale anisotropies

Piston/Jet	$D_{\rm knot}$	$r_{\rm knot}$	$\chi_{\rm n}$	$\chi_{\rm v}$	$M_{\rm knot}$	$E_{\rm knot}$
	($R_{\rm SNR}$)	($R_{\rm SNR}$)			($M_\odot$)	(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

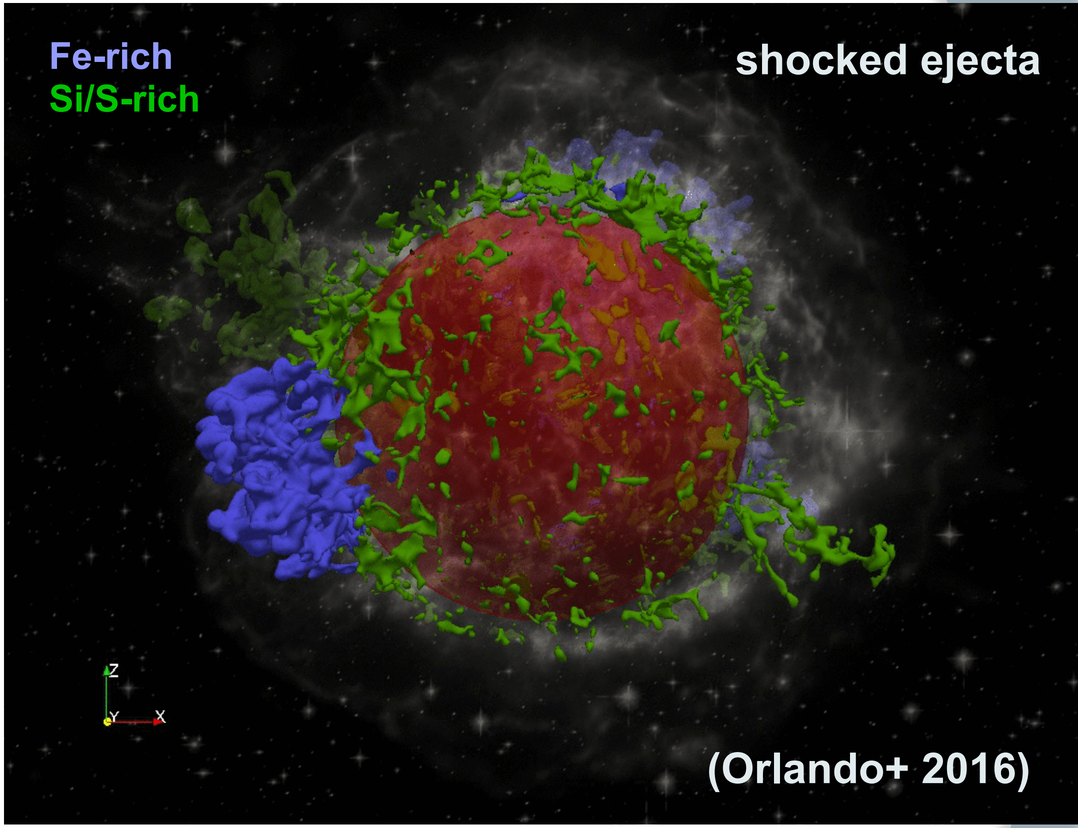
Shocked ejecta

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

- mass of $\approx 0.25\ M_{sun}$ (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 are intrinsic to the explosion

Shocked ejecta

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)

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

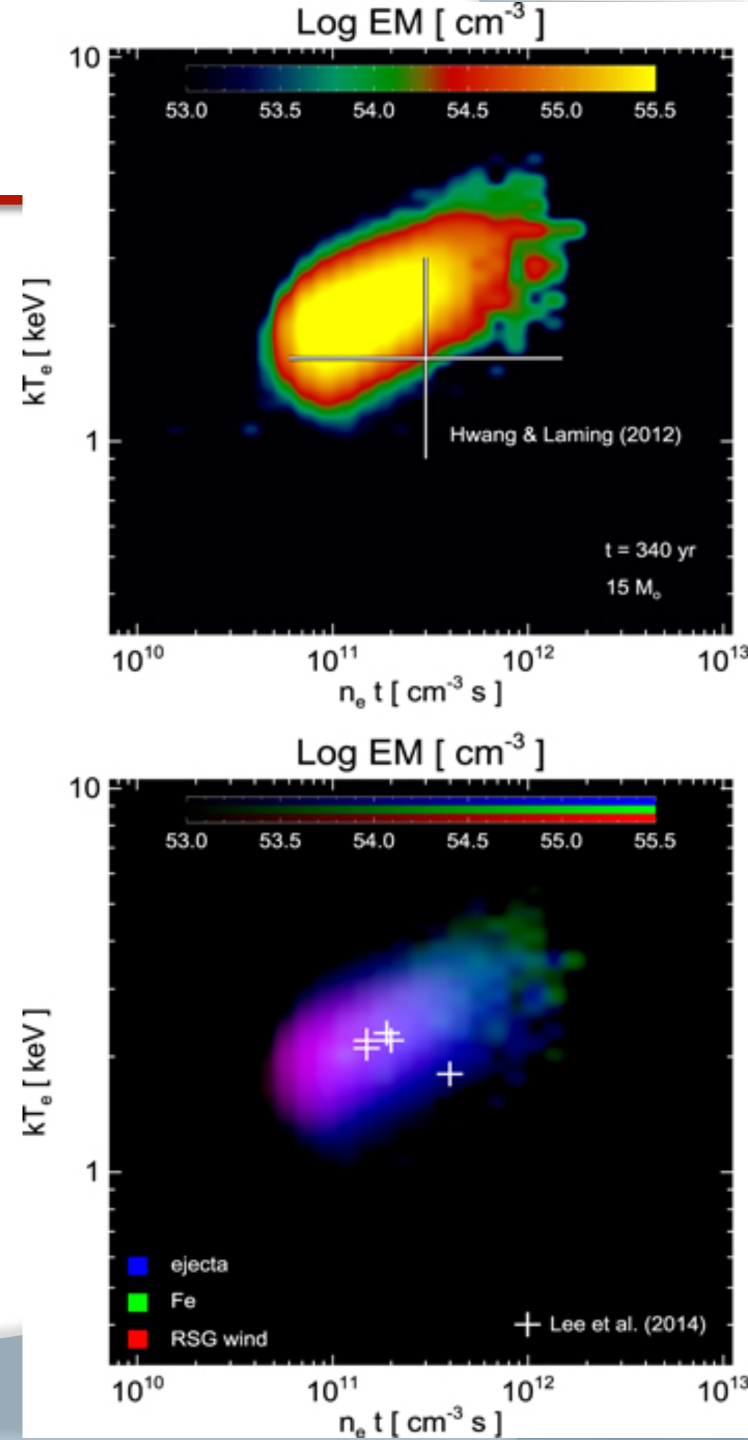
(Hwang & Laming 2012)

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

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)



Spatial Distribution of the Cas A ejecta

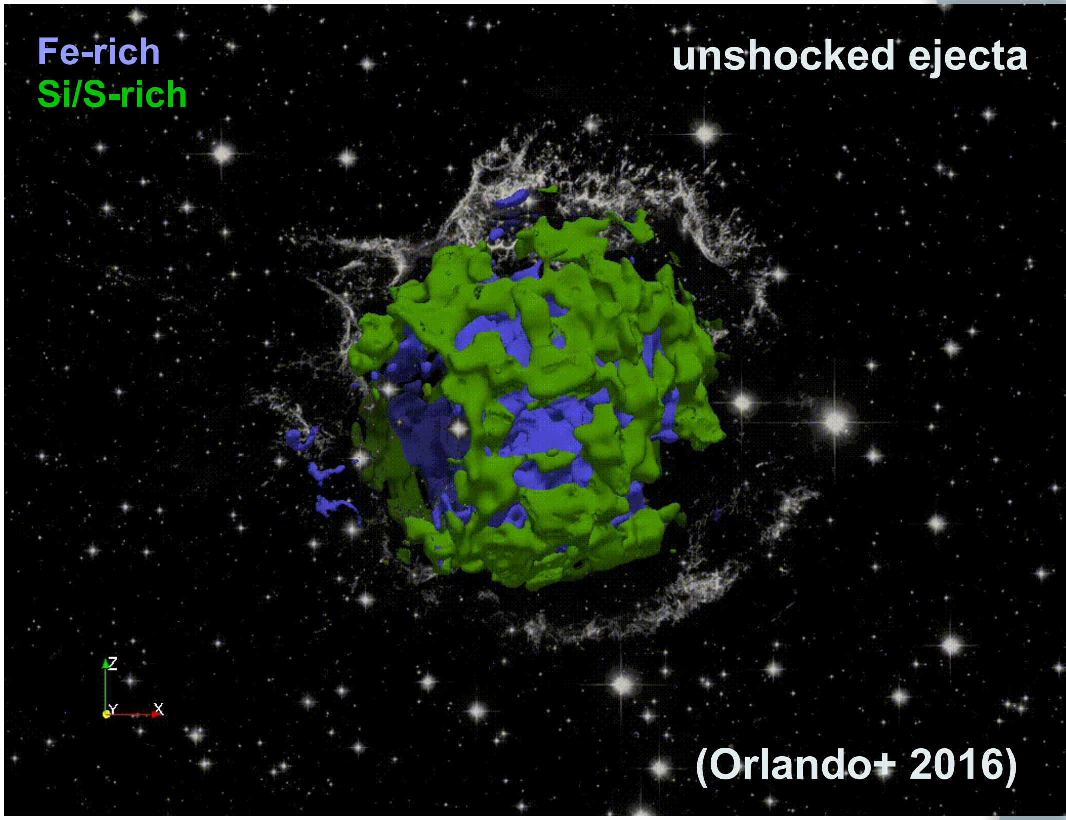
Unshocked ejecta

The distribution of unshocked Si/S is characterized by large cavities corresponding to the directions of propagation of the pistons/jets

This may explain why the cavities observed in near-IR observations are physically connected to the bright rings in the main-shell
(e.g., Milisavljevic & Fesen 2015)

Our model predicts that the structure of Si/S is filled by low-density unshocked Fe

We estimated a total mass of unshocked Fe of $\approx 0.1\ M_{sun}$



Summary and conclusions

3D hydrodynamic model describing the evolution of SNR Cas A from the immediate aftermath of the SN explosion (~ 1 day) to its expansion in the SNR

⇨ high spatial resolution and accounting of all relevant physical processes

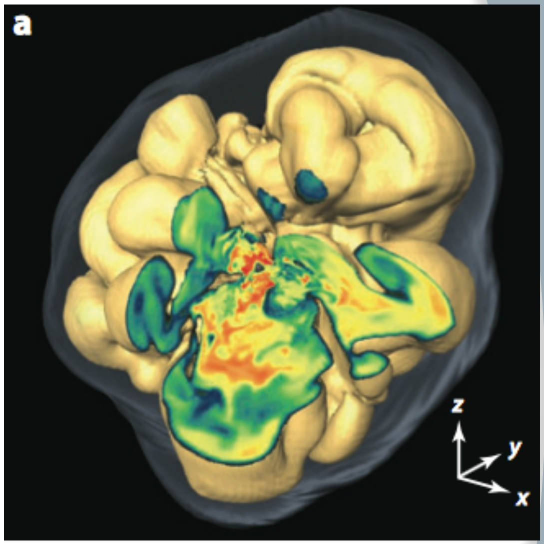
- Observed average expansion rate and shock velocities well reproduced by models with ejecta mass $M_{ej} \approx 4M_{sun}$ and explosion energy $E_{SN} \approx 2.3 \times 10^{51}$ erg
- Post-explosion anisotropies reproduce observed distributions of Fe and Si/S if they had a total mass of $\approx 0.25\ M_{sun}$ and kinetic energy of $\approx 1.5 \times 10^{50}$ erg
- 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 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

Future prospects

- We adopted a 1D model describing the SN evolution from the breakout of the shock wave at the stellar surface up to the so-called nebular stage

    Highly desirable to couple our 3D SNR model with a 3D model describing the evolution of core-collapse SN

    Trace how features and anisotropies developed during the SN evolution influence the final morphology of SNRs



(Wongwathanarat, Gabler, Kifonidis, Janka, Mueller, etc.)

- Our model is hydrodynamic

    We plan to include the effects of a magnetic field (MHD)

    If the ejecta are magnetized, the clumps/pistons can be preserved and longer-living (B limits the development of hydro instabilities)