The Exceptional X-ray Evolution of SN1996cr in High Resolution

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Abstract: We present X-ray spectra spanning 18 years of evolution for SN1996cr, one of the five nearest (~4 Mpc) SNe detected in the modern era. HETG observations allow us to resolve spectrally the velocity profiles of Ne, Mg, Si, S, and Fe emission lines and monitor their evolution as tracers of the ejecta-circumstellar medium (CSM) interaction. To explain the diversity of X-ray line profiles, we explore several possible geometrical models. Based on the highest S/N 2009 epoch, we find that a polar geometry with two distinct opening angle configurations and internal obscuration can successfully reproduce all of the observed line profiles. We extend this model to seven further epochs with lower S/N ratio and/or lower spectral-resolution between 2000-2018, yielding several interesting evolutionary trends.

General features

We focus on the nearby SN 1996cr, classified as a type IIn ~11 years after the explosion by Bauer et al. 2008 (ApJ, 688, 1210). It was initially discovered in the Circinus Galaxy at ~4 Mpc (Fig. 1, left panel) by Chandra. The X-ray (and radio) luminosity exhibits an initial increase with time, seen previously in the SN 1987A (Fig. 1, right panel) and in SN 2014C.

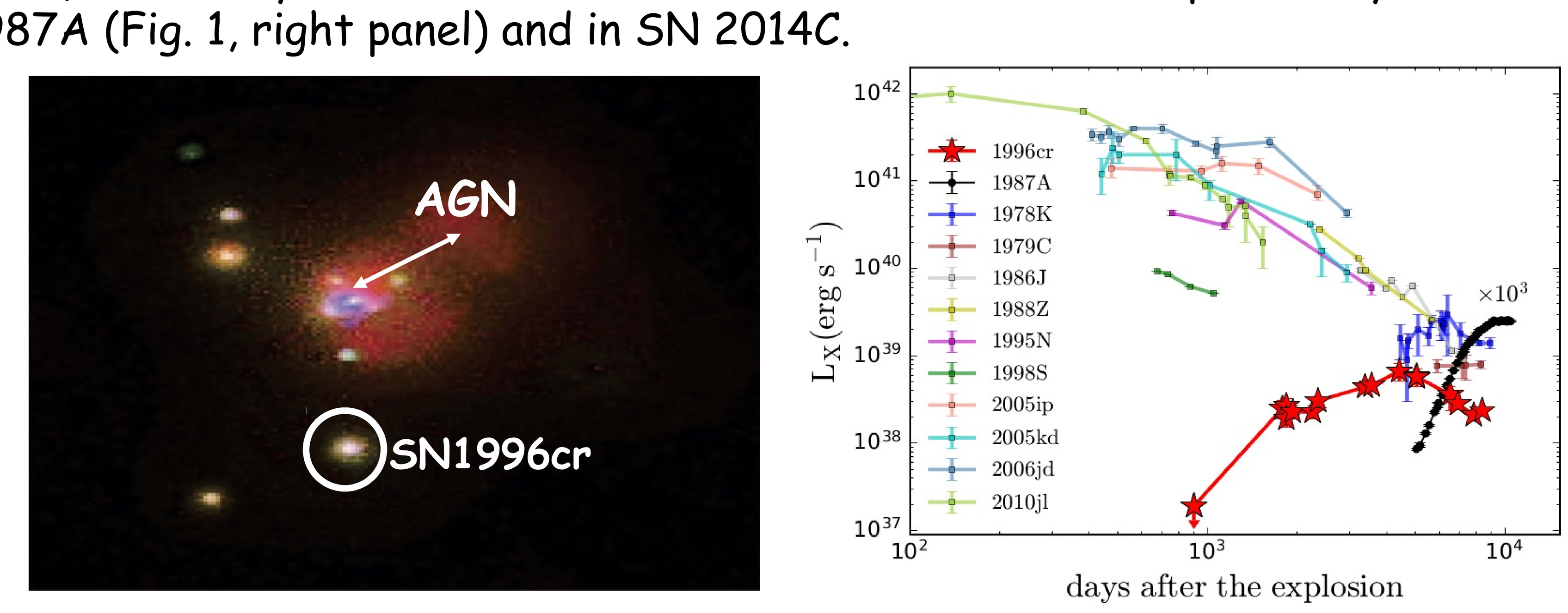

Figure 1: Left: Chandra 0.5-8.0 keV color image of Circinus and SN 1996cr location (white circle). Right: X-ray light curves for a handful of strong CSM-interacting SNe (colour points), SN 1987A (black points) and SN 1996cr (red stars).

This particular tendency, both in the radio and X-ray bands, is best explained by the interaction of ejecta material with a density enhancement (i.e., a dense shell) in the CSM.

X-ray emission lines

SN 1996cr has remained bright at X-ray, optical, and radio wavelengths for ~18 yr, attributed to ejecta-CSM interaction. The X-ray emission lines are well-resolved and asymmetric (see Fig. 2), providing critical insight on the kinematic of the ejecta-shock interaction(s).

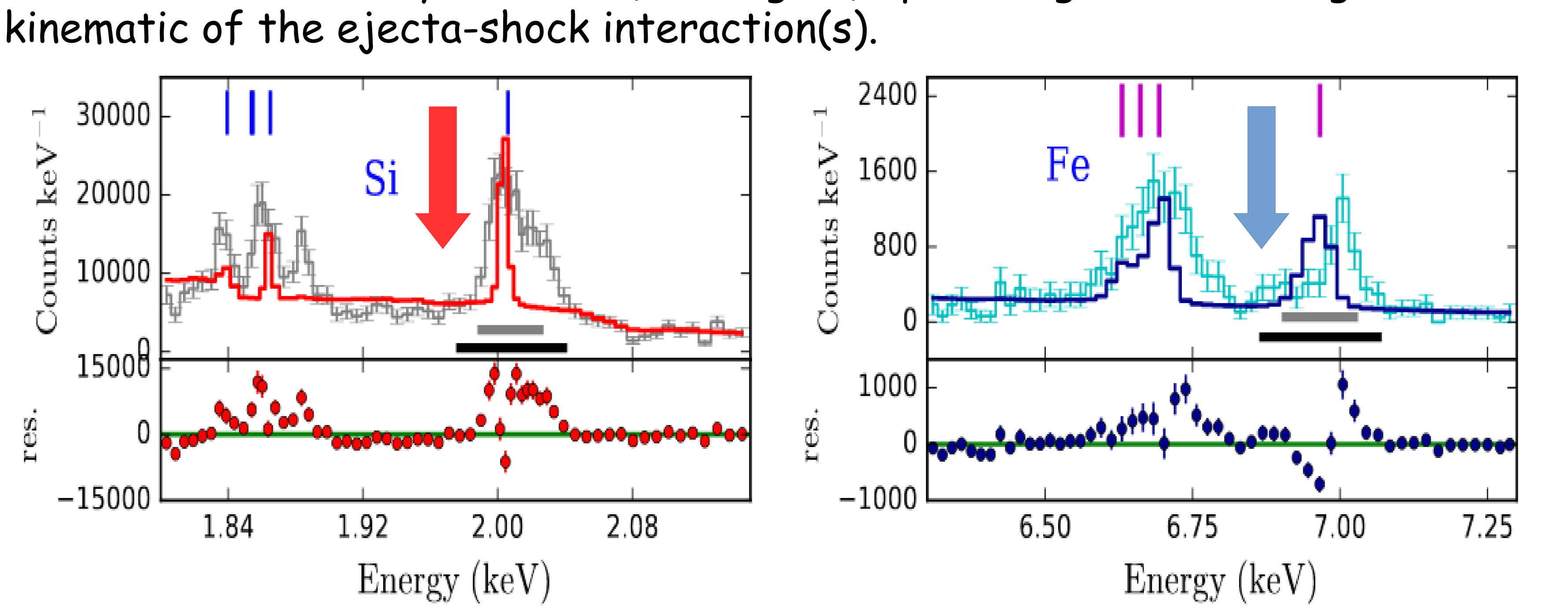

Figure 2: Close-up spectra of the H-like and He-like emission complexes for Si and Fe (grey and cyan spectra). Red and blue solid lines representing a simple NEI model (vpshock) at native HETG resolution. As highlighted by the arrows, the high velocity redshifted side of the profile is partially/completely obscured.

The asymmetric profiles are interpreted as a consequence of an expanding shock-interaction region whereby the redshifted (back) side is obscured by internal dense ejecta. We developed a geometrical convolution model (called shellblur; see above QR code) to explain the line-shape, parameterized by: a half-opening angle (θ; defined by two angles θ_{max} and θ_{min}), line-of-sight inclination (i), velocity expansion (v_{max}) and internal absorption by ejecta (N_{ejecta}). We applied several models (M1-M5), with M5 as the best. The match to the emission lines in the 2009 spectra by model M5 strongly suggests a polar-interaction scenario (see Fig. 3).

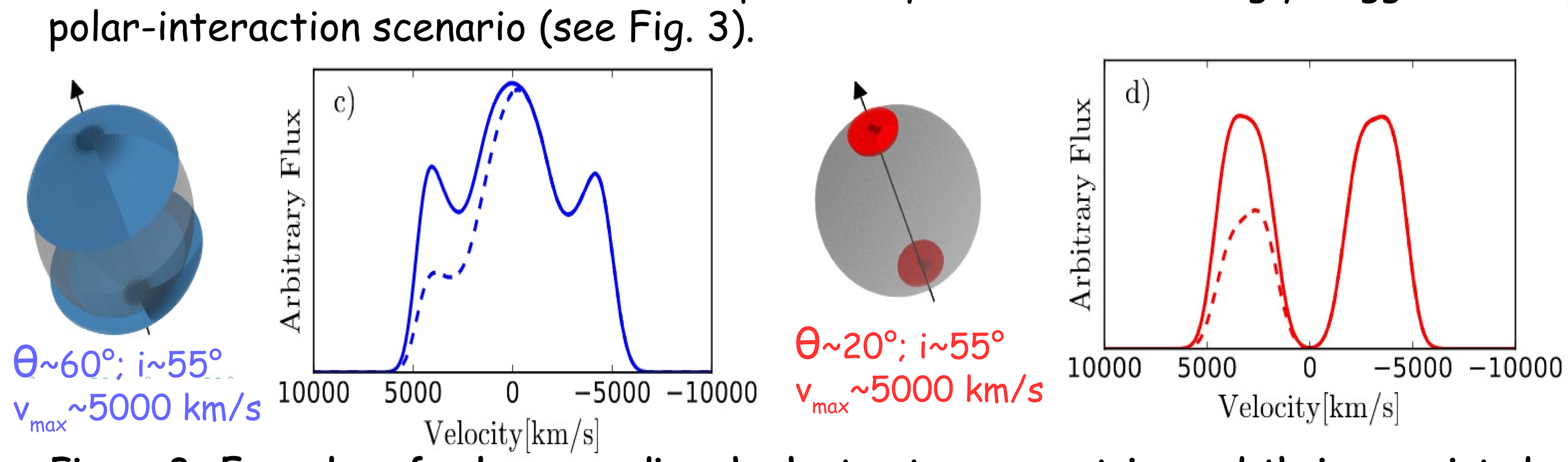

Figure 3: Examples of polar expanding shock structure geometries and their associated profiles (using shellblur model) which explain well the X-ray emission line profiles of SN 1996cr. Dashed lines indicate internal uniform density obscuration by N_{ejecta}=1e23 cm^{-2}.

Best fit model (M5 model; Quirola-Vasquez+19, MNRAS submitted)

The best fit model consists of two TBabs(shellblur*vpshock) components: C_R (high kT, high N_H and narrow polar interaction for lines >4 keV), and C_F (low kT, low N_H and wide polar interaction for lines <4 keV).

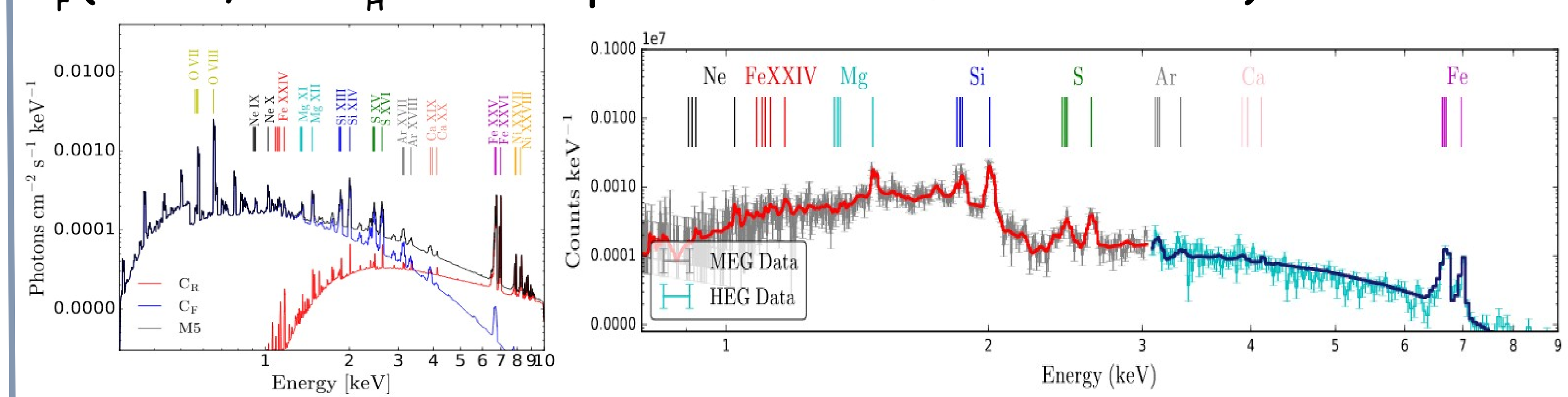

Figure 4: Left: Best-fit model M5 (black curve), with components C_R (red curve) and C_F (blue curve). Right: the best-fit model M5 compared to the 2009 epoch HETG spectra.

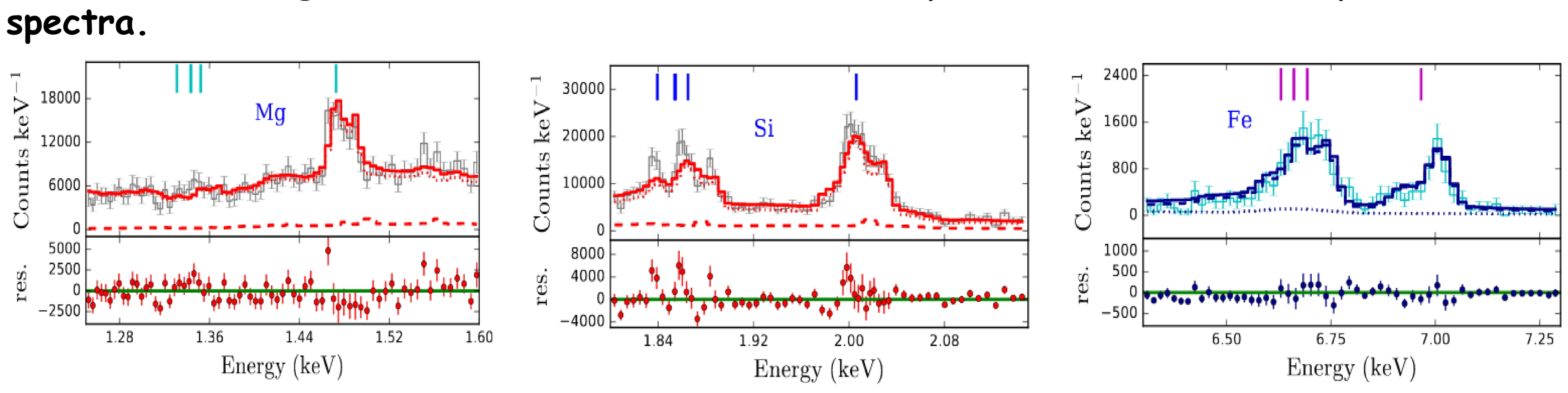

Figure 5: Close-up spectra of several detected H-like and He-like emission complexes and their residuals for 2009 epoch: Magnesium (left), Silicon (center) and Iron (right).

SN evolution and final comments

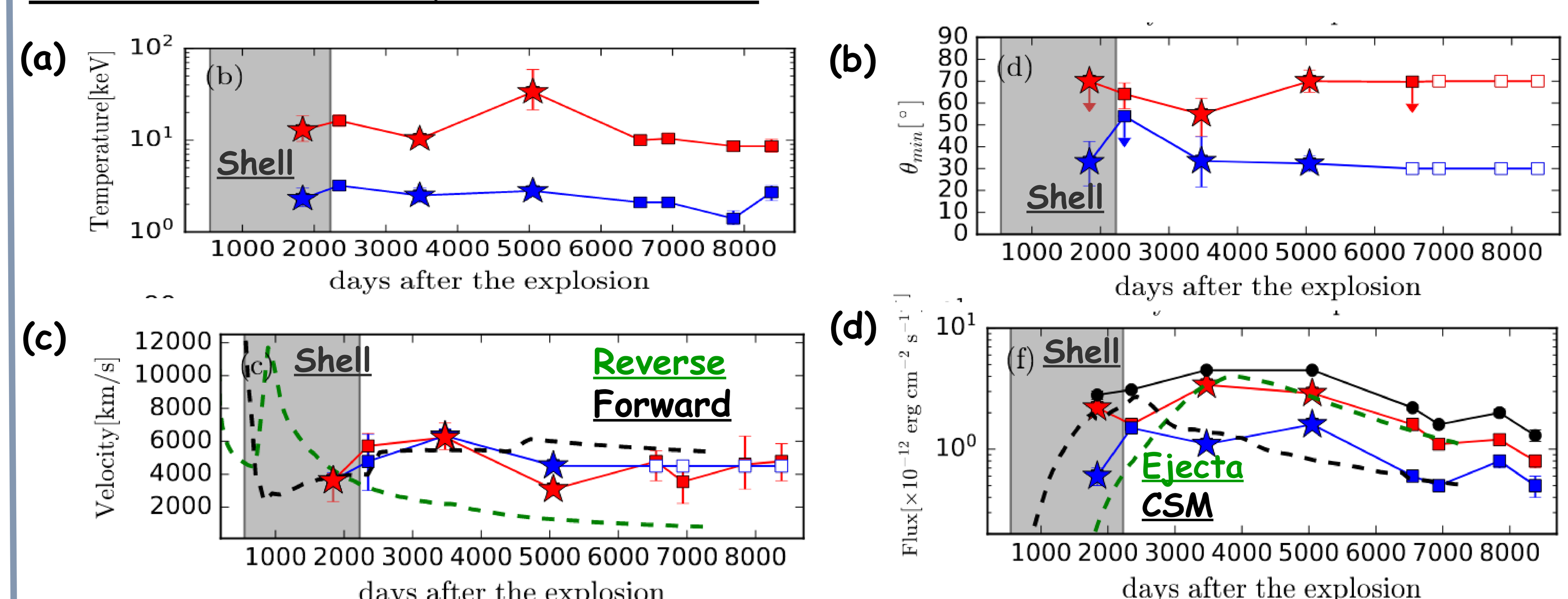

Figure 6: Evolution of temperature (a), θ_{min} (b), expansion velocity (c) and flux (d) for components C_R (red) and C_F (blue). Dashed black and green lines denote 1-D model predictions by Dwarkadas et al. 2010 (hereafter D10; MNRAS,407,812); in (c) they denote the forward and reverse shock velocities, respectively; in (d) they are the fluxes from the CSM and ejecta, respectively.

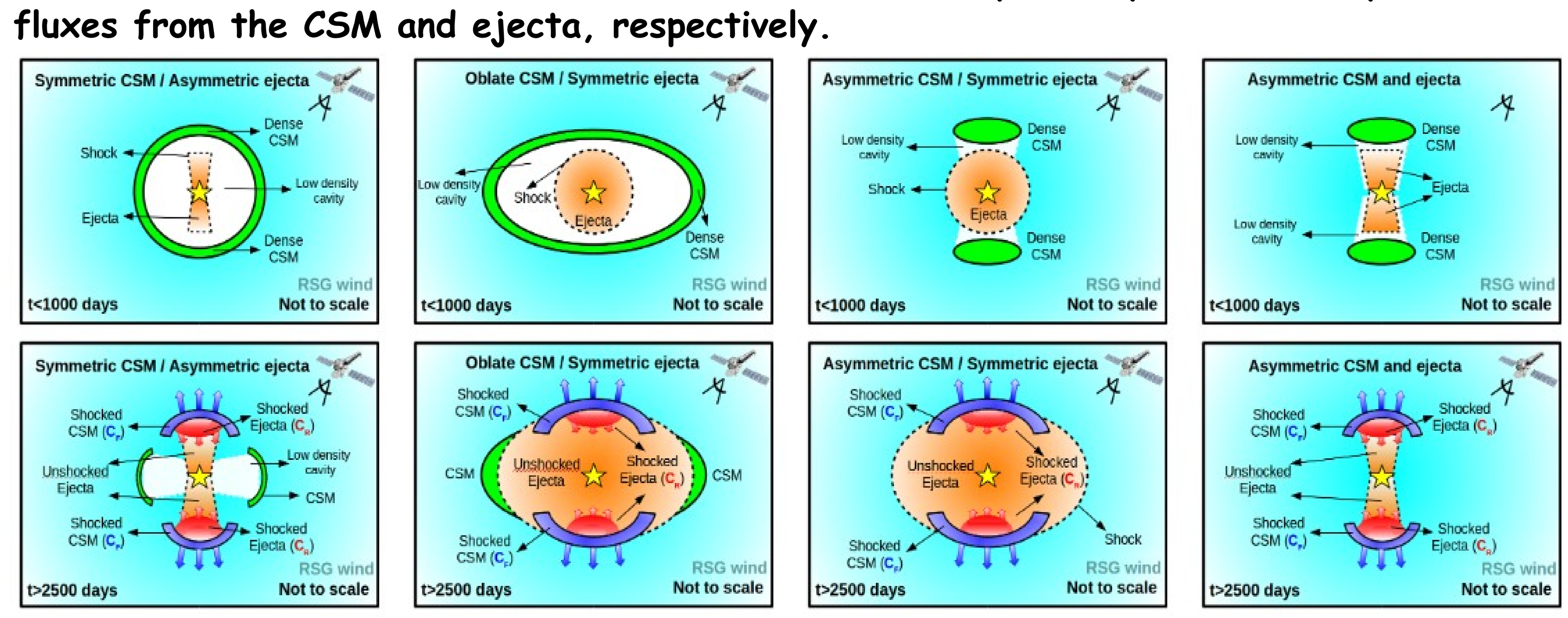

Figure 7: Cartoon depicting four possible geometrical scenarios to generate the X-ray emission of SN 1996cr. Top and bottom panels show the SN explosion before and after the interaction with the dense CSM, respectively.

The X-ray spectra of SN 1996cr are well explained by a bi-polar CSM-ejecta interaction model whereby the farside is obscured by dense ejecta (see Fig. 5). Comparing to D10 and SN 1987A, our best explanation for the two components is that they are associated with the forward shock (C_F) and a reverse or reflected shock (C_R; arising from the SN impacting the dense shell), Our results are crudely consistent with the 1-D hydro model of D10, which is shown in Fig. 6 for comparison. The cause of the asymmetry of the interaction remains unclear, and could arise from the ejecta, the CSM, or both.