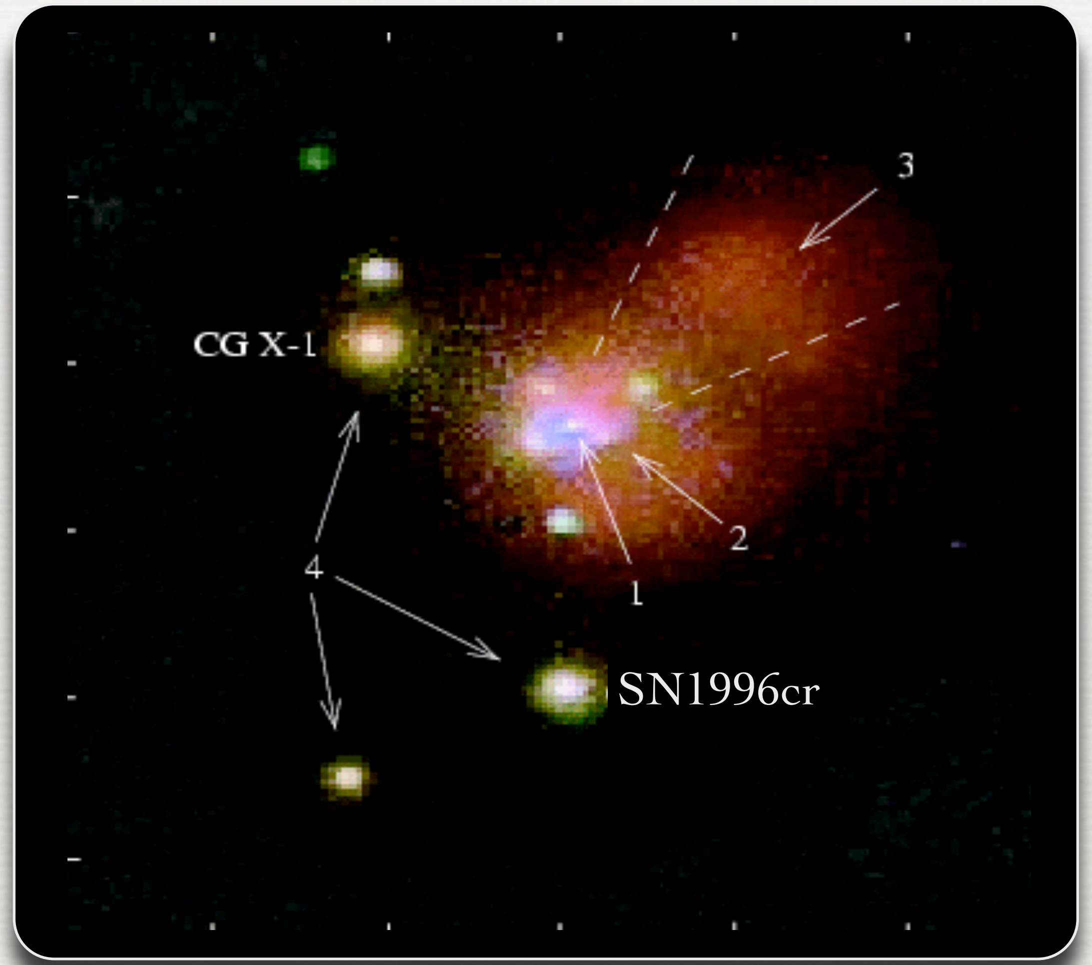
X-ray Constraints on the Nearby SN 1996cr



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•THANK TO ORGANIZERS

•I WILL PRESENT OUR RECENT CONSTRAINTS ON SN1996CR. THIS SN IS ESTIMATED TO HAVE GONE OFF IN 1995-1996 IN THE CIRCINUS GALAXY (~3.7MPC, BUT LOW GALACTIC LATITUDE - THUS FOREGROUND EXTINCTION/ABSORPTION). 96CR WASN'T DISCOVERED UNTIL 2000 DURING THE FIRST CHANDRA OBSERVATIONS AND NOT CONFIRMED AS A SN UNTIL 2006-2007. THUS A GREAT DEAL OF WHAT I WILL PRESENT IS MORE OR LESS AN ARCHIVAL STUDY.

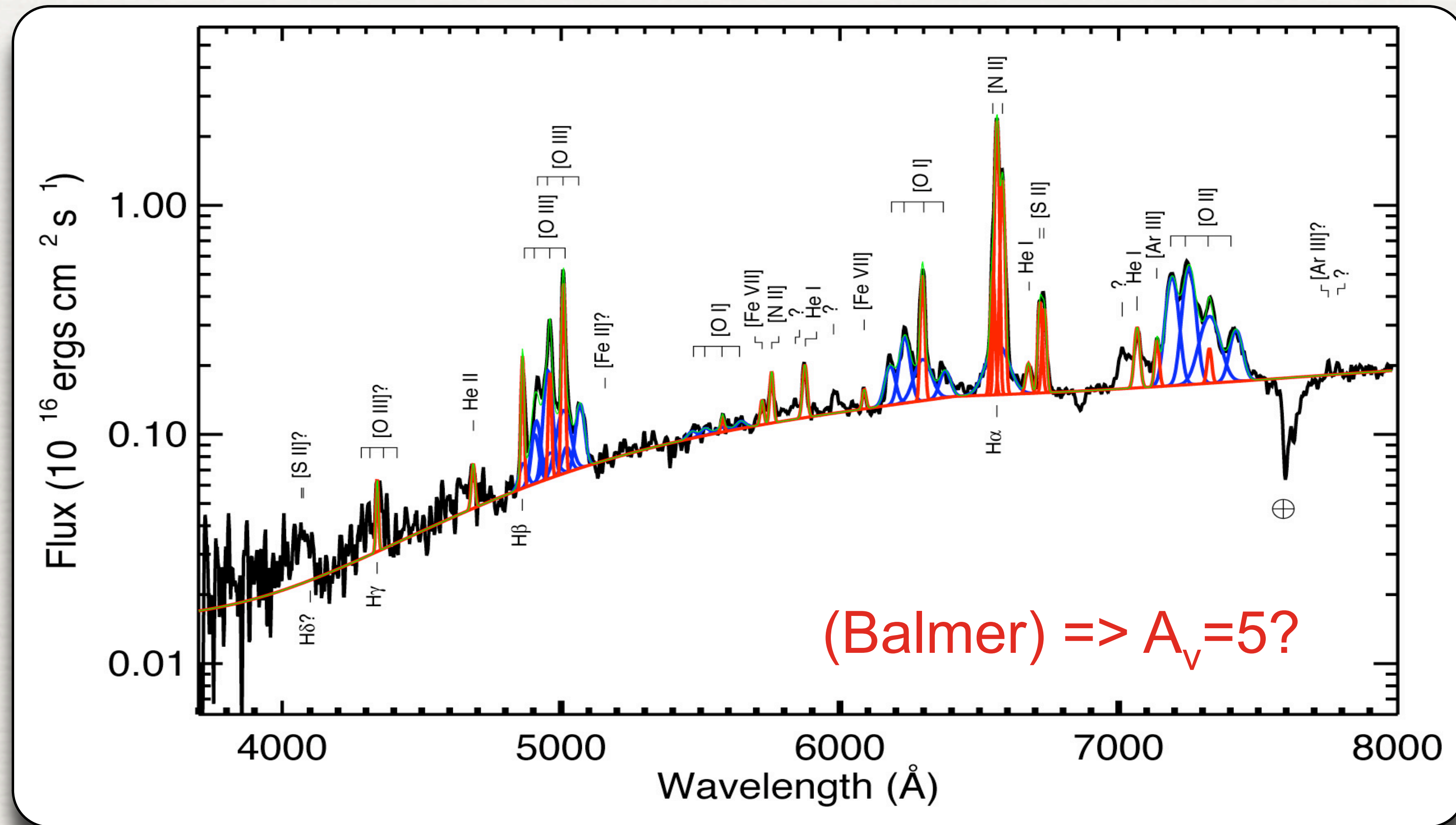
•GROWING LIST OF COLLABORATORS

Spectroscopic Confirmation

VLT FORS1 observations:

2005 March 6-17 (only partial, low S/N)

2006 Jan 26 to March 12 (high quality spectrum, below)

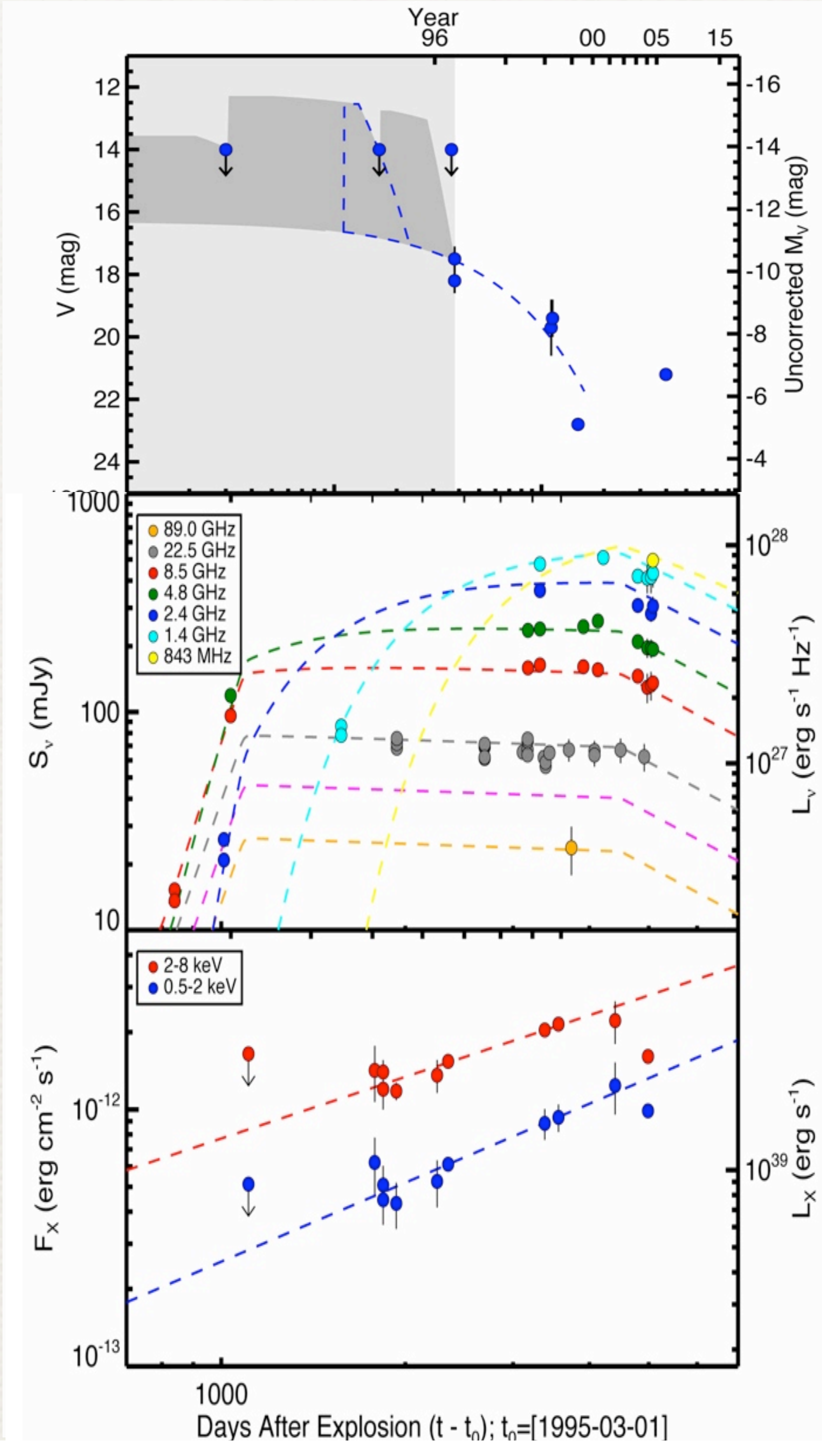


SN1996cr is type IIn (massive progenitor)

CG~X-2 was visited several times in service mode with the VLT FORS~I spectragraph in two campaigns. The first was over the course of 2005 March 6-17, which resulted in a modest signal-to-noise spectrum. The second was over the span of 2006 Jan 26 to 2006 March 12, which yielded a high quality spectrum (below) confirming many of the tentative features seen in the first spectrum.

The spectrum is dominated by strong, complex emission lines, many consisting of very narrow component (FWHM ~ 500 km/s) superposed on broad, asymmetric bases (FWHM ~ 9000 km/s). These features are typical of late-time SNe interacting with dense circumstellar material. This combination suggests that the rapidly moving SN material is running into CSM clumps and is driving slower shock fronts into them.

An estimate from the narrow Hα/Hβ lines suggests Av~5, which is probably a lower limit for components of the SN explosion itself.



SN1996cr LIGHT CURVE

Only upper limits at early times, so no strong constraints!

Optical fall-off is typical, but eventually shows up-tick.

Radio does not have characteristic turn-on, but appears to “jump” by a factor of 1000. Then relatively flat light curve.

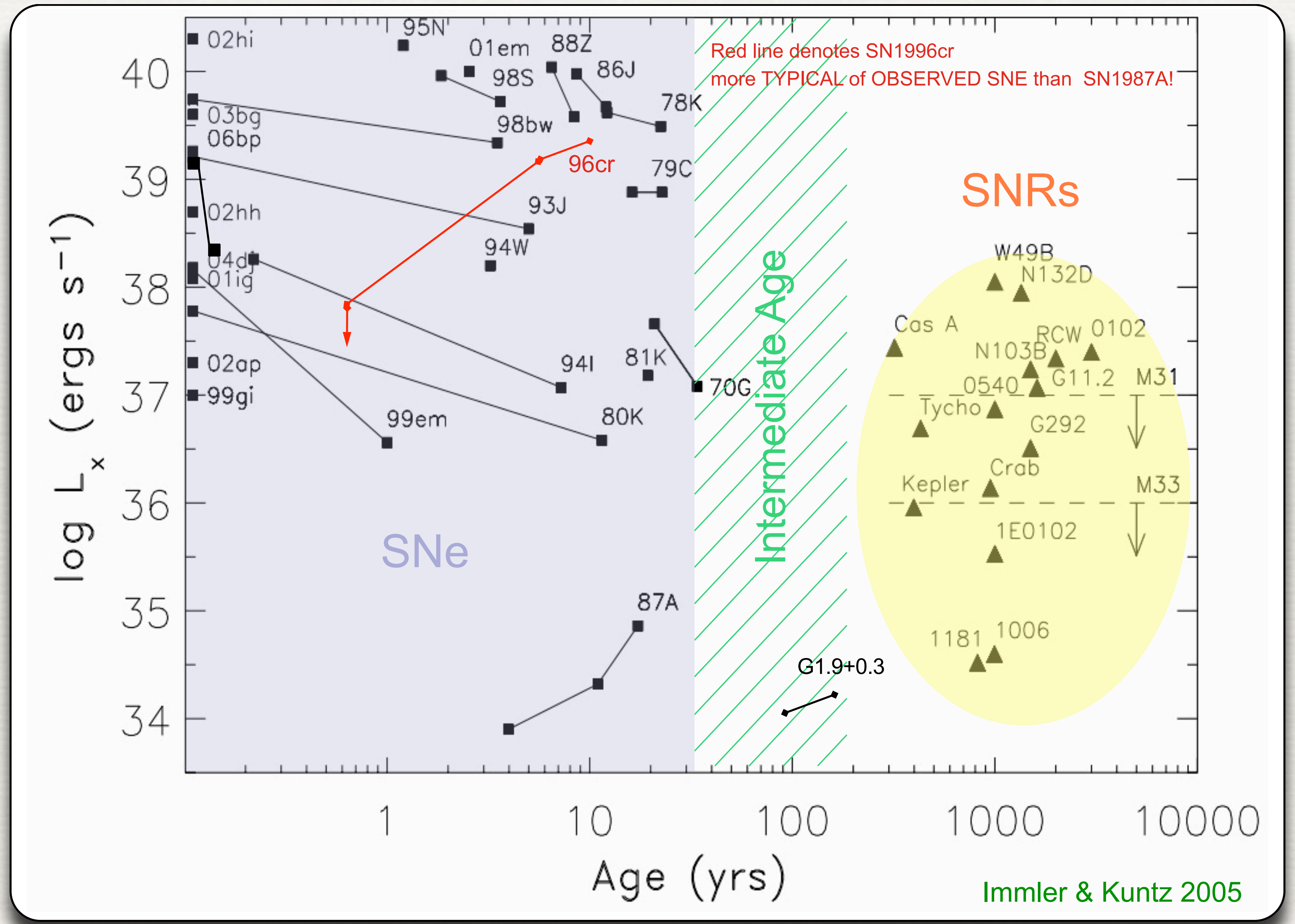
X-rays likewise are unusually missing early on and seen to rise at late times. See modest spectral variability (cooling as expands? decrease in NH?)

All point to strong CSM interaction most similar to SN1987A, but >1000x brighter

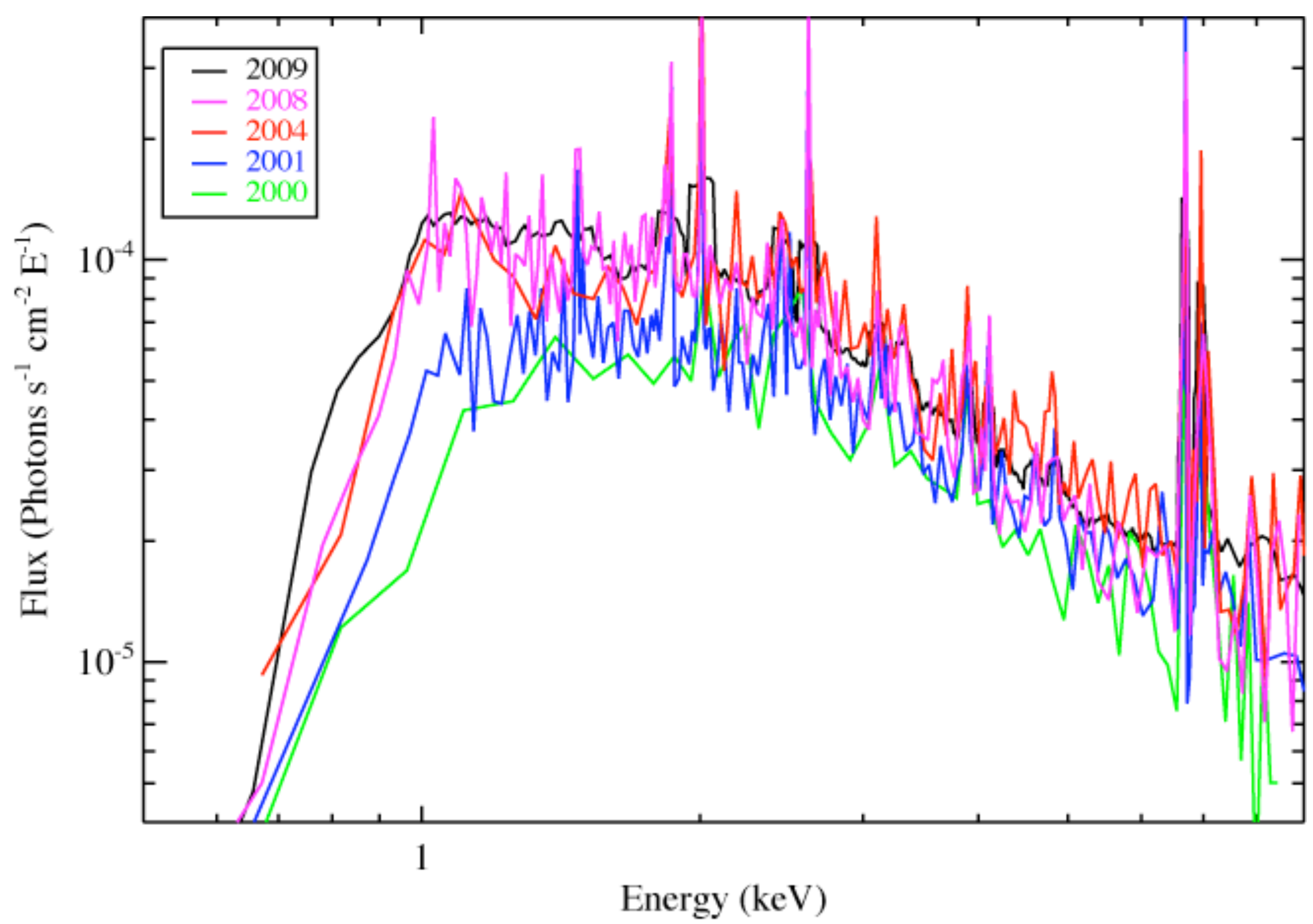
While the optical data are limited, archival X-ray and radio data have proven invaluable for estimating the rough date of the explosion. We have plotted together the soft and hard X-ray fluxes, as well as radio flux densities in a variety of bands (see figure). In both the radio and X-ray bands, we have not yet observed the rollover and decline universally seen from other type II SNe. Notably, the 0.5-2 and 2-10 keV X-ray data are best-fitted by $Fx \propto t^{0.7}$ and $t^{0.5}$, whereas nearly all Sne decline as t^-1 when free-free emission dominates and t^-0.4 when line emission does.

Moreover, the ROSAT HRI upper limits imply an even stronger rise at early times. For the radio data, we have applied the model of Weiler et al. 2001, which has successfully modeled several recent SNe. However, our limited set of radio data hint at complex structure not entirely addressed by this model. The radio data clearly show a sharp turn-on between 1996 and 1997. Since the explosion typically pre-dates the emergence of the radio emission by months to years, CG X-2 likely went off sometime before 1996. Weiler et al. 1998 suggest that the peak 6cm luminosity can be used as a rough tracer of the explosion date. If we assume the 6cm peak from the crude model fit, this implies an explosion date of 1995 October, albeit with large errors toward earlier times. Such a date is in line with comparable type IIn SNe, and thus we have adopted it for the time being.

XRAY Lightcurves of SNe

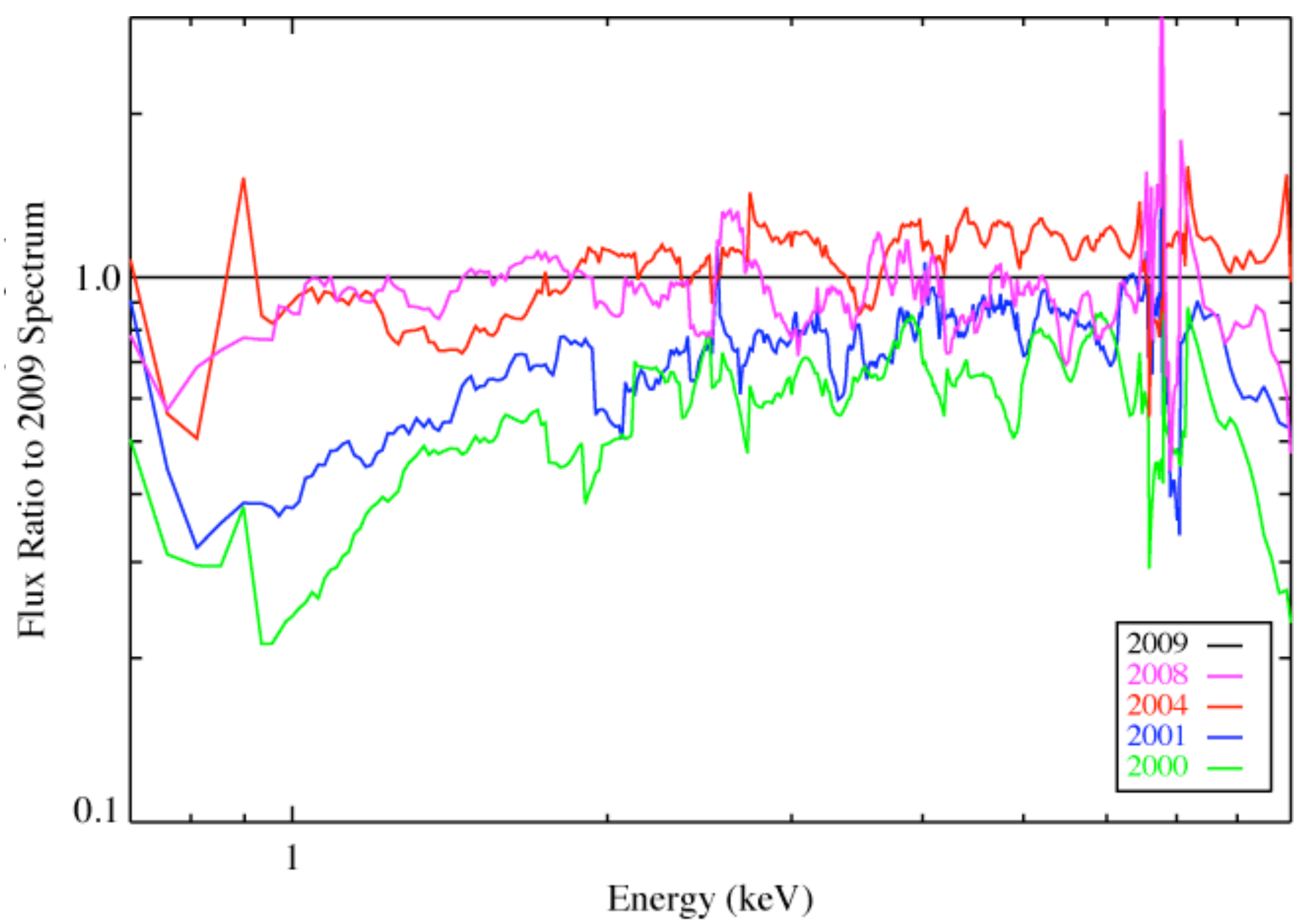


SN1996cr X-ray Spectrum



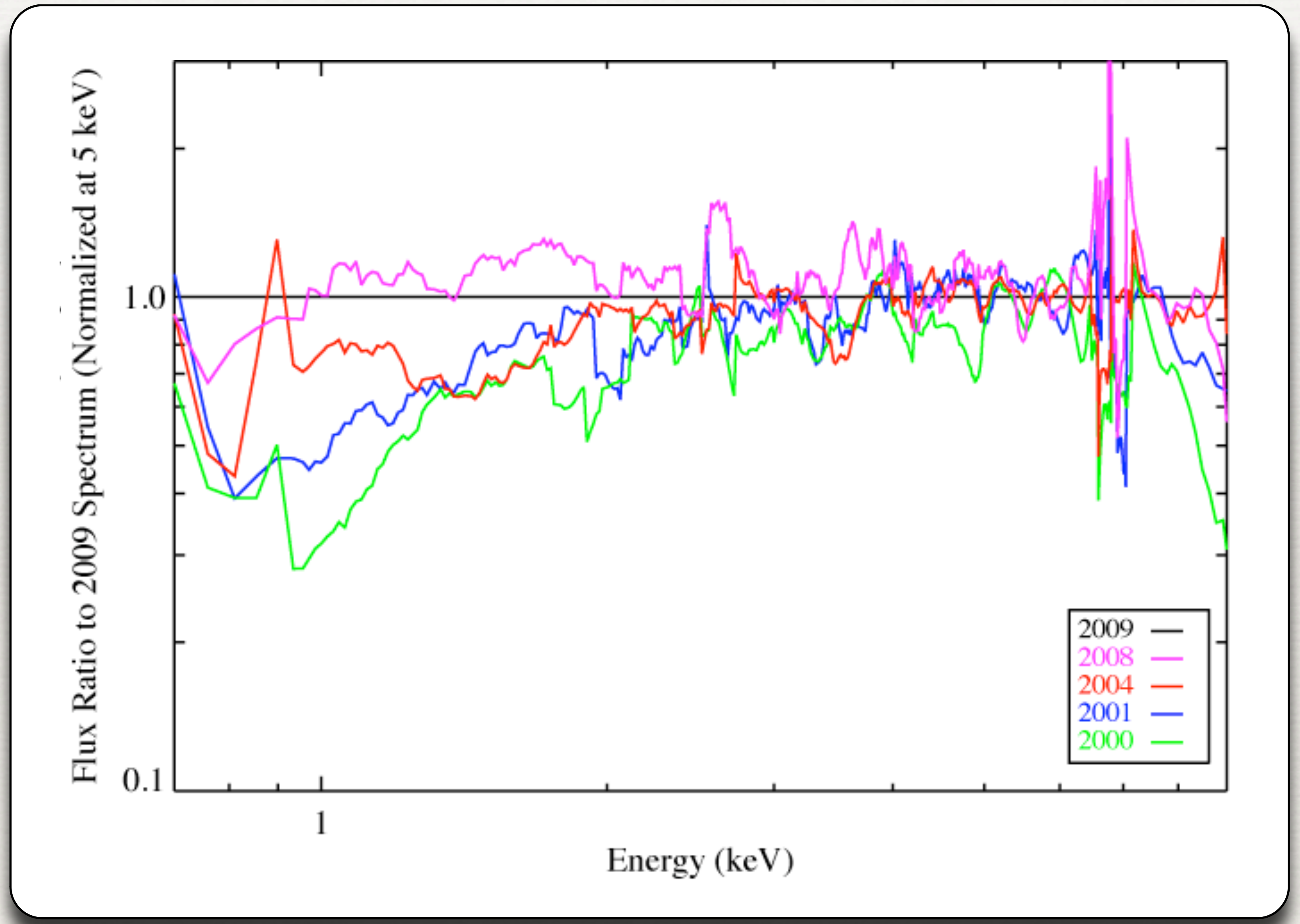
CCD spectra from 5 epochs. Note strong emission lines, relatively hot thermal component and high NH.

SN1996cr X-ray Spectrum



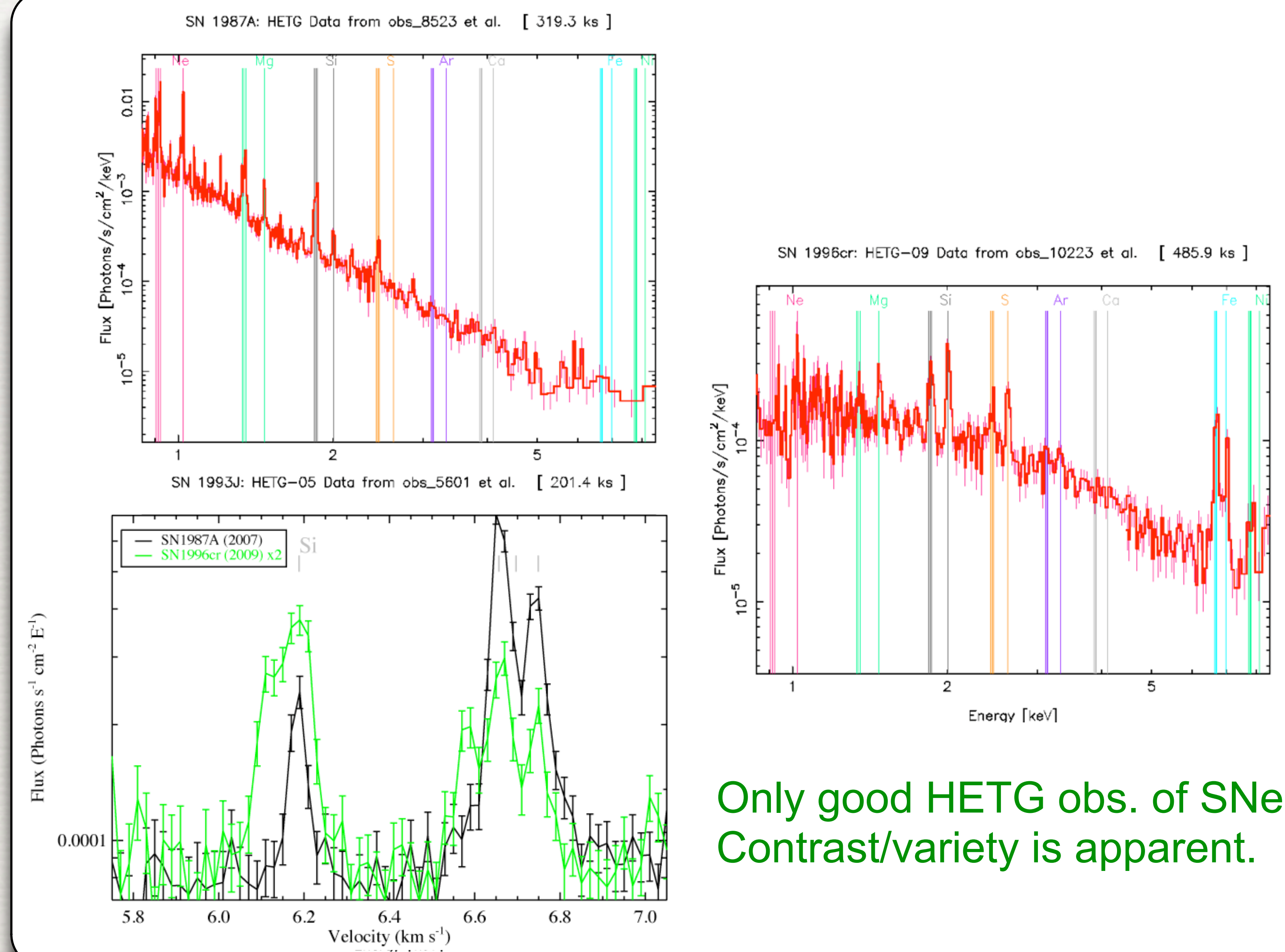
Normalized to 2009 spectrum, we can now see variations better.
Note the luminosity changes above 2keV and potential NH changes below 2keV.

SN1996cr X-ray Spectrum



Normalizing at 5keV, we can now look at NH and spectral changes better
Not much change in spectrum in 9 yrs above 2keV.
Clearly large change in <2keV spectrum, but unclear it is NH or new reverse shock component (or both)

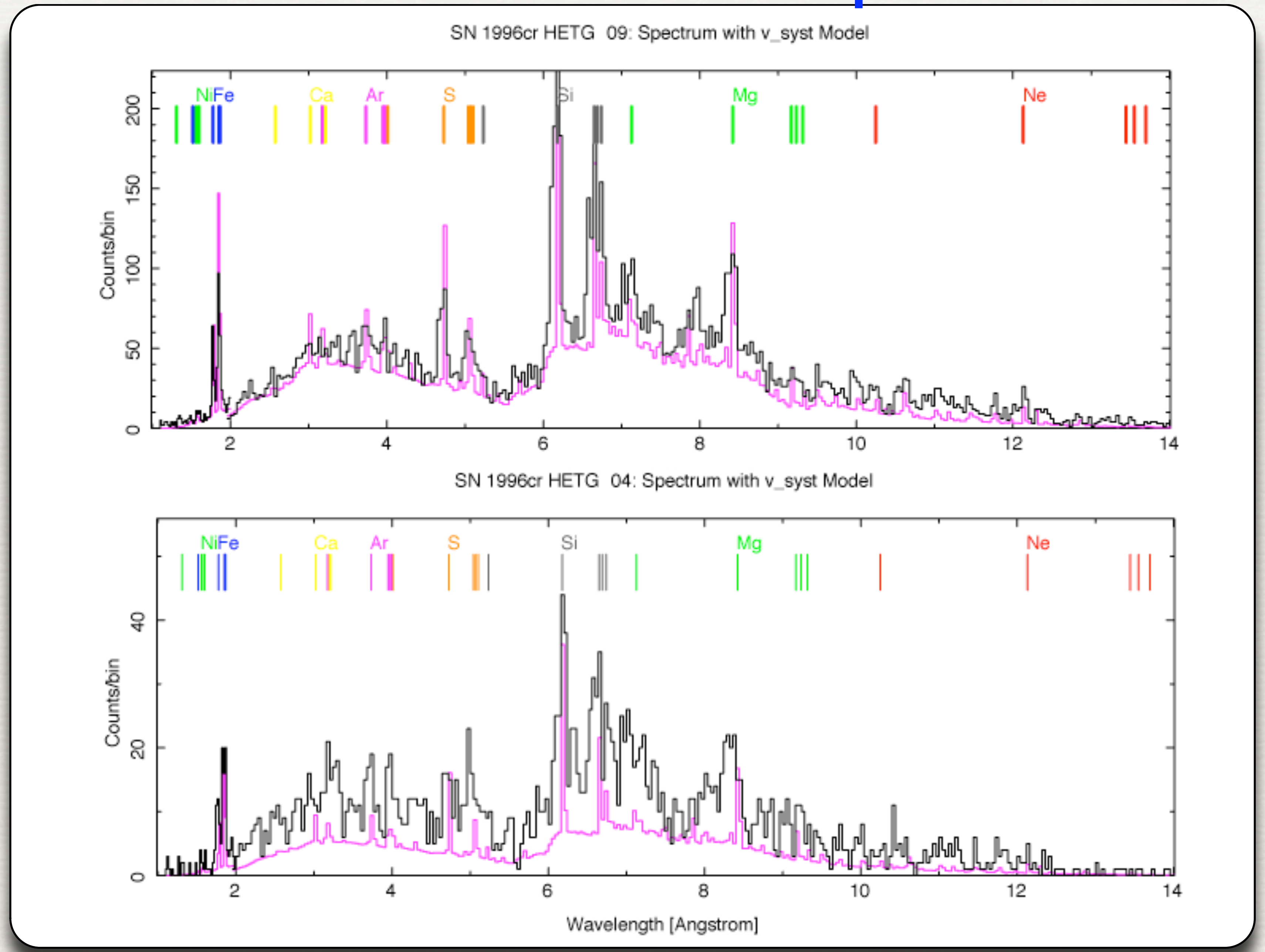
SN1996cr HETG Spectrum



Only good HETG obs. of SNe.
Contrast/variety is apparent.

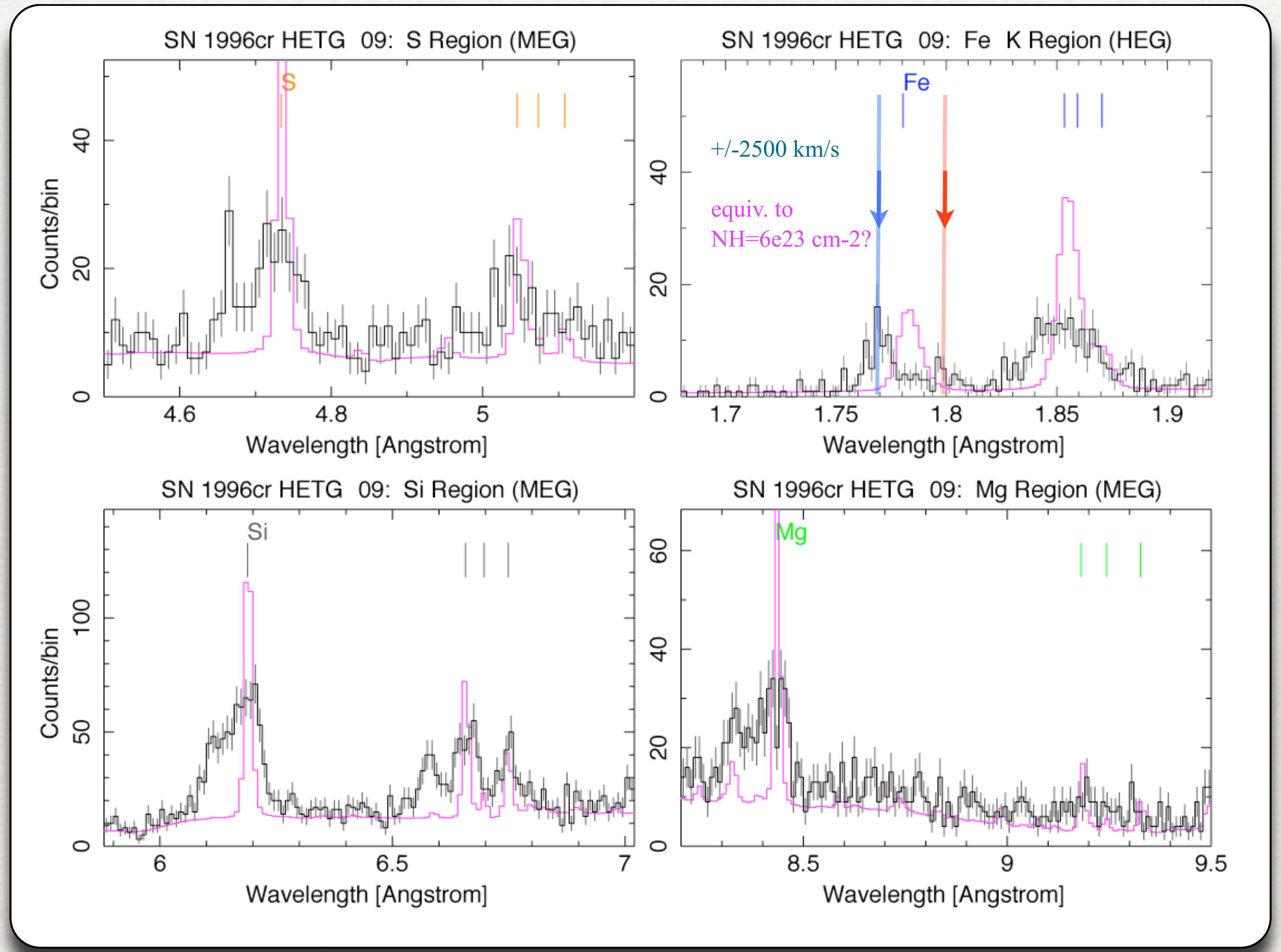
HETG has resolution of 400-1000, ~4-100 times better than regular ACIS spectra.

SN1996cr HETG Spectrum



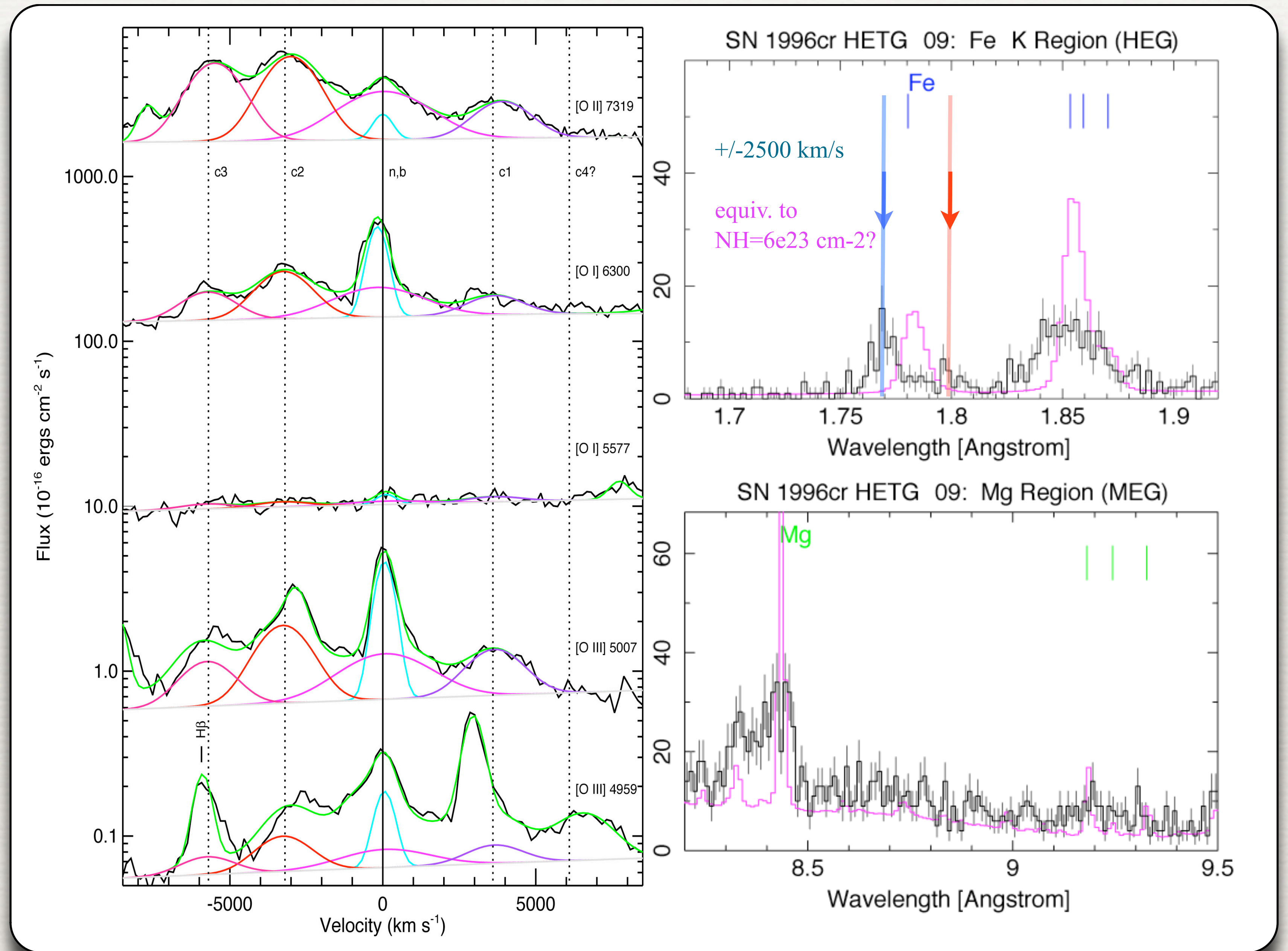
Have multiple epoches, but 485ks in ’09 is first time we have REALLY good statistics to confirm features in earlier data.
Thank TAC for giving time. Very useful for confirming ratty spectral features.

SN1996cr HETG Spectrum



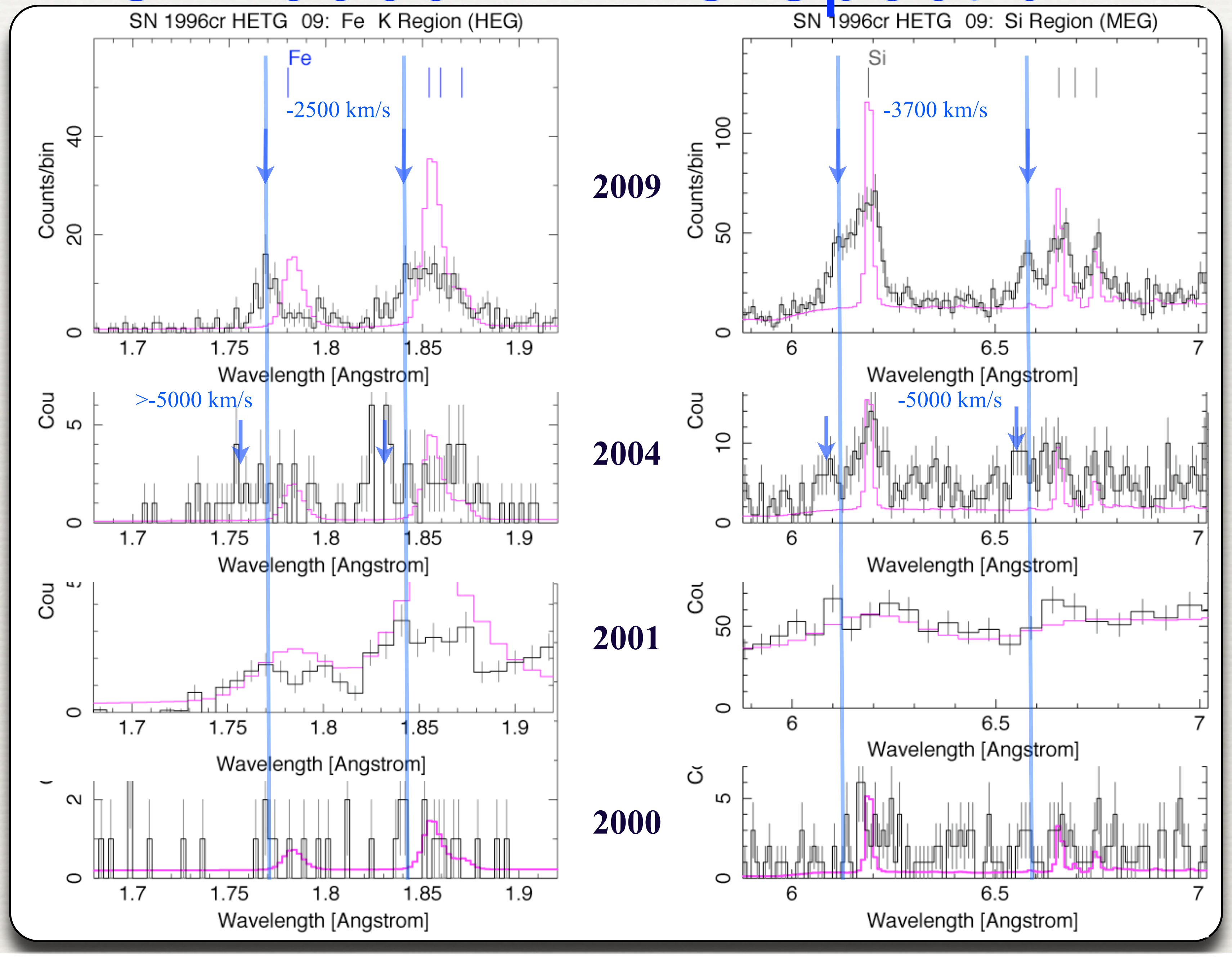
Here is zoom-ins of main lines. Can see H-like and He-like lines, both have quick broad, blue-shifted components.
We SEE faint red component in Fe only, suggesting something like NH=6e23 if we assume solar abundances. This is unlikely to be the case though, as ejecta is HIGHLY supersolar. Along with hydro predictions of abundances/structure, we can use this constraint to derive eject mass.

SN1996cr HETG Spectrum



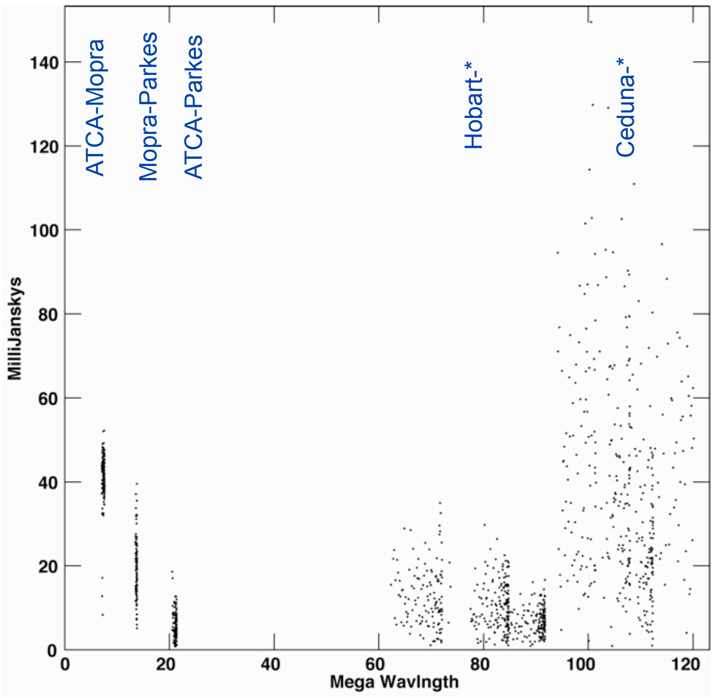
Line structure is a lot like optical O lines. Suggests we could monitor with optical spectrum and come back to HETG if something interesting happens.

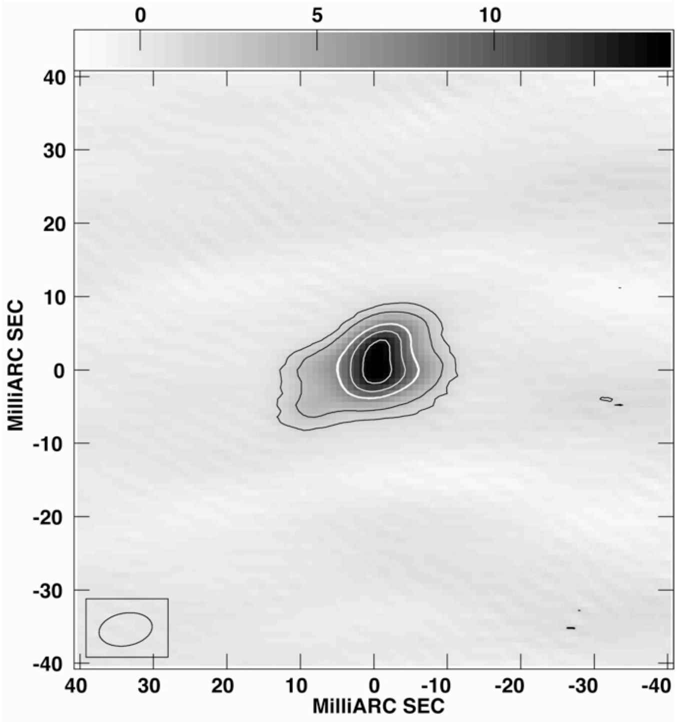
SN1996cr HETG Spectrum



Line evolution is apparent, even in earlier ratty data. Hydro predicts this!

22GHz VLBA observations





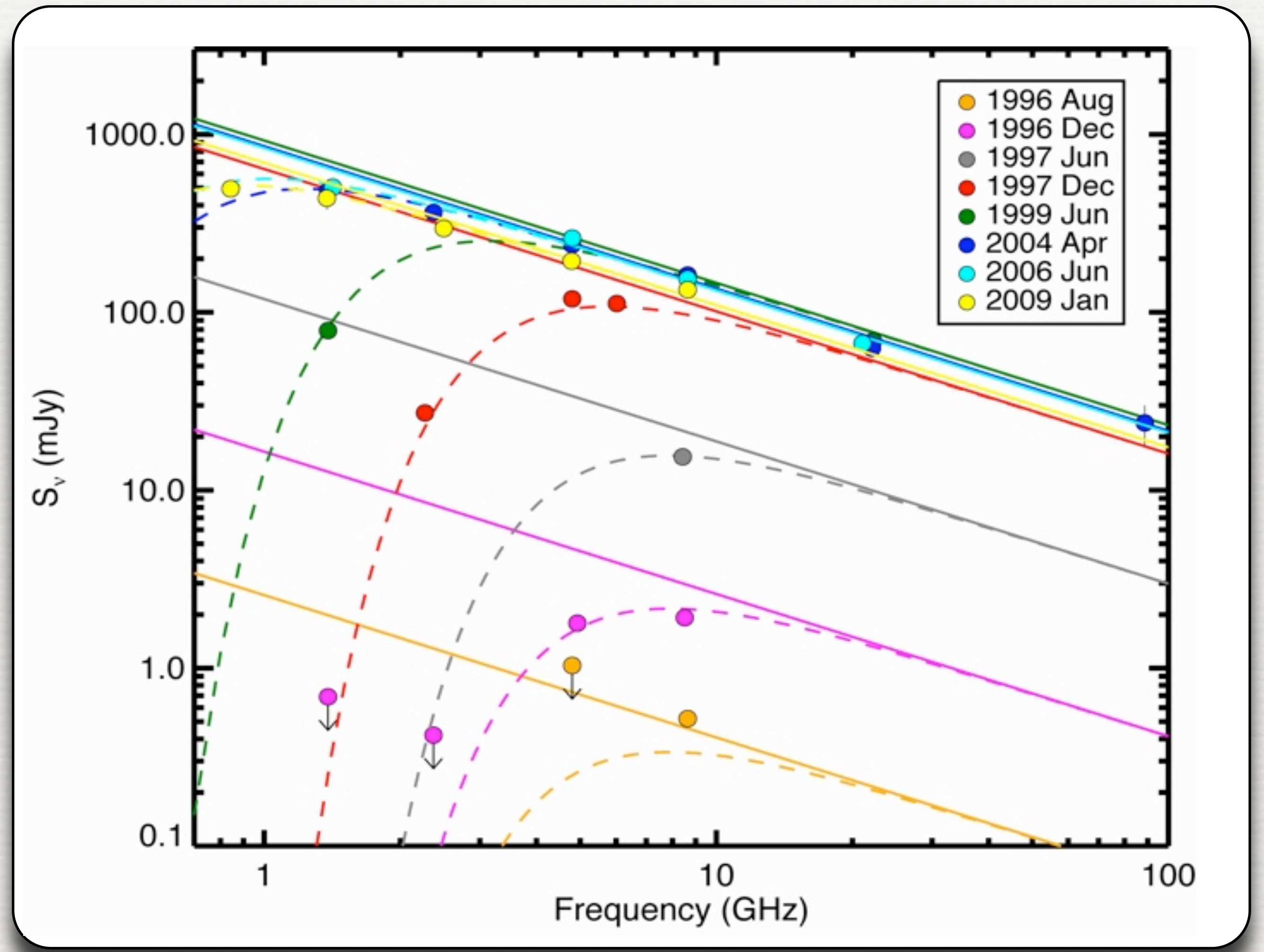
Inner baselines detect and resolve

Resolved in image as well, although "structure" likely artifact of baselines

provide measure of RADIUS as ~5 mas = ~2.8e17 cm = 0.1 pc @12 yrs

Awaiting new VLBA observations for more radius/velocity/morphology constraints...

SN1996cr Radio LIGHT CURVE



radio absorption traces IONIZED e^- ⇨ allows constraints on CSM density

⇨ Radio gives $N_e \sim 10^{22}$ cm^{-2}
X-ray gives $N_H \sim 3\text{-}5 \times 10^{21}$ cm^{-2} ?

INPUT FOR HYDRO

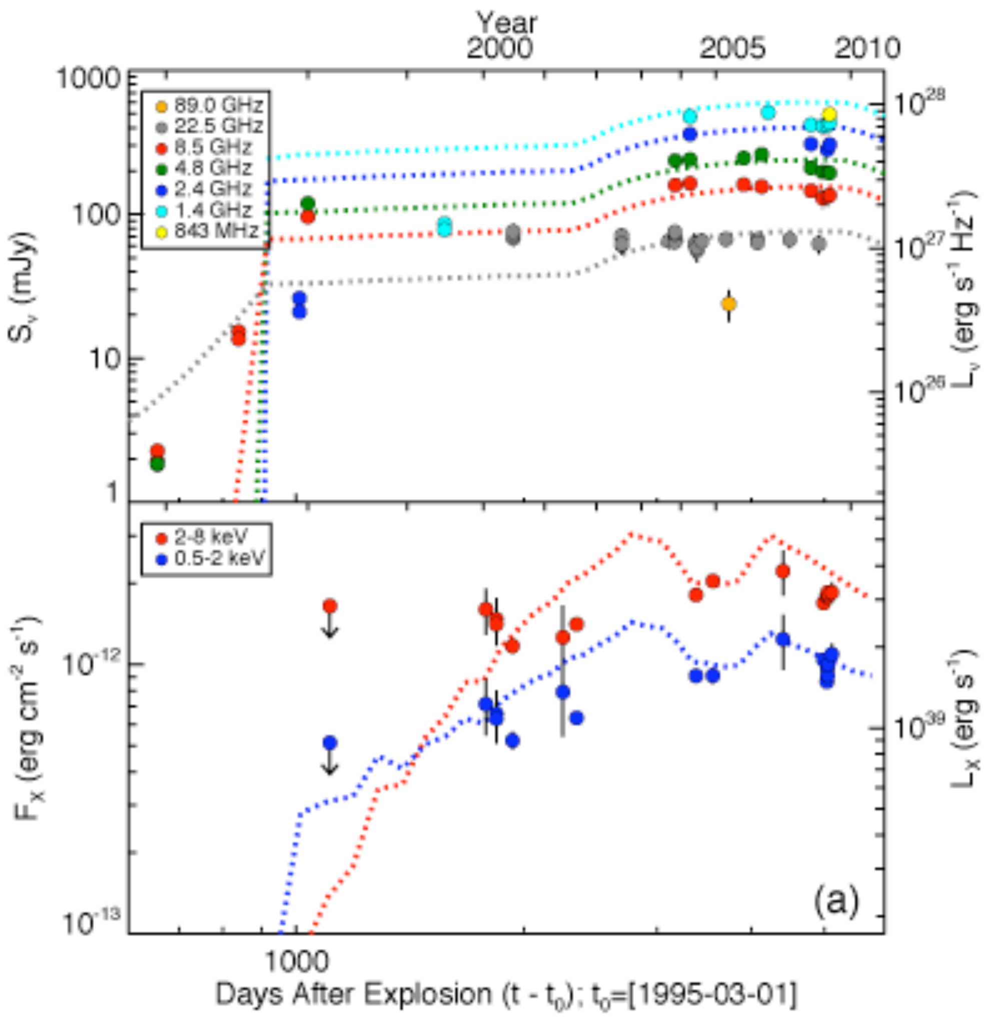
So we have the following time-dependent physical constraints:

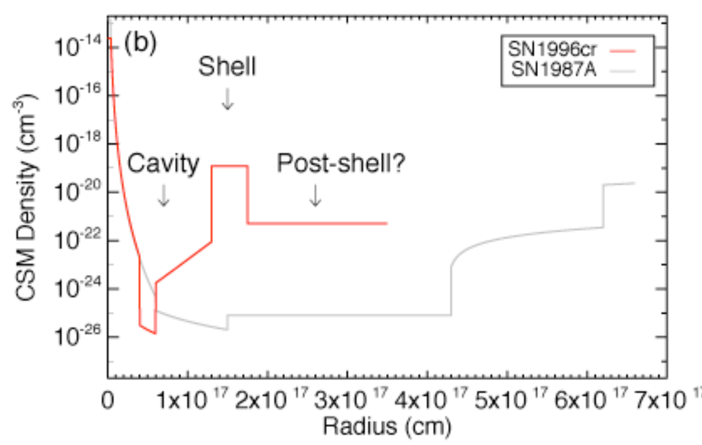
luminosity (=> explosion power, CSM density/structure)
radius (=> forward shock velocity)
line velocities (=> ejecta/reverse shock velocity)
decreasing f-f absorption, N_H (=> CSM density/structure)
He-like, H-like line strengths (=> temperature)
abundances, variations with velocity? (=> asymmetries?)
blue/red strengths of Fe (X-ray), O (optical) (=> ejecta mass?)
eventually morphology? (=> asymmetries?)

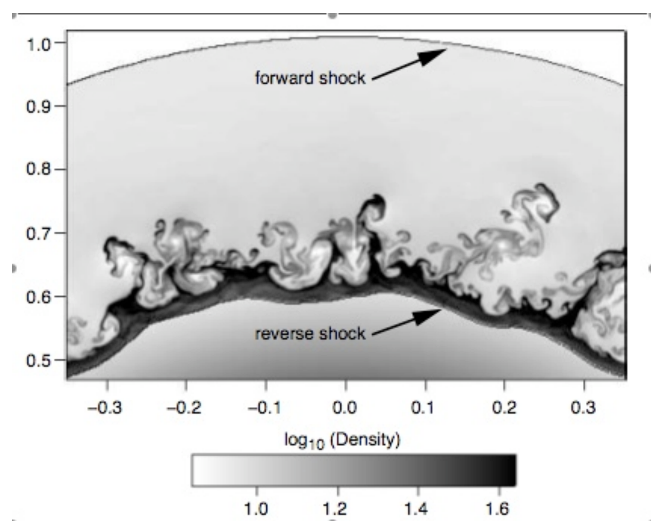
Hope hydro can inform us about limits to:

initial shock velocity, ejecta mass, CSM mass+loss rate, and provide insight into the last gasps of progenitor.

HYDRODYNAMICAL MODELING







Blondin & Ellison 2001

Dotted lines on light curve show current hydro model...constrained by X-ray observations only at present. Radio just along for the ride currently, and does pretty well, although absorption needs to change to fit data better.

Also shown is our 1-D density profile. Once we have looked down the rough CSM structure and parameters, we can move to 2-D hydro to try to explain velocity structure of emission lines, range of temperatures and ionization states, etc.

DISCUSSION/CONCLUSIONS

Quite unfortunate to miss SN1996cr early on, because all of the available data suggest that it is an extreme example of the CSM-interacting type IIn class. Would we miss such a SN today? Unlikely, as it was missed primarily because SN monitoring was still in its adolescence 10 years ago.

It already has archival X-ray data surpassed only by a few SNe and future observations could provide some important constraints on the nature of ejecta expanding into dense CSM and the development of the forward/reverse shock. ONLY SN1987A and SN1993J allow more detailed study. However, while SN1987A constraints remain more robust, SN1996cr provides important bridge to more common nearby SNe and may inform us in a few years what we can expect from SN1987A in the coming decades.

SN1996cr's flux makes it a unique target for a wide variety of detailed follow-up studies (VLBI expansion, HST light echo, HI absorption, IR dust production)

•Although we cannot say with absolute confidence, the deeper, more regular automated searches carried out today would almost certainly catch such a source now.