The Expansion of 1E 0102.2-7219

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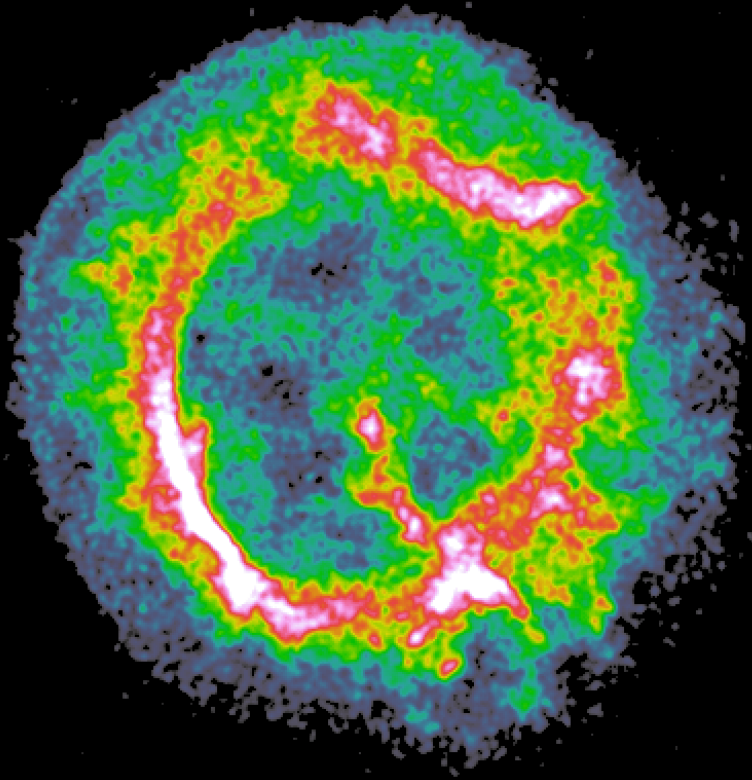
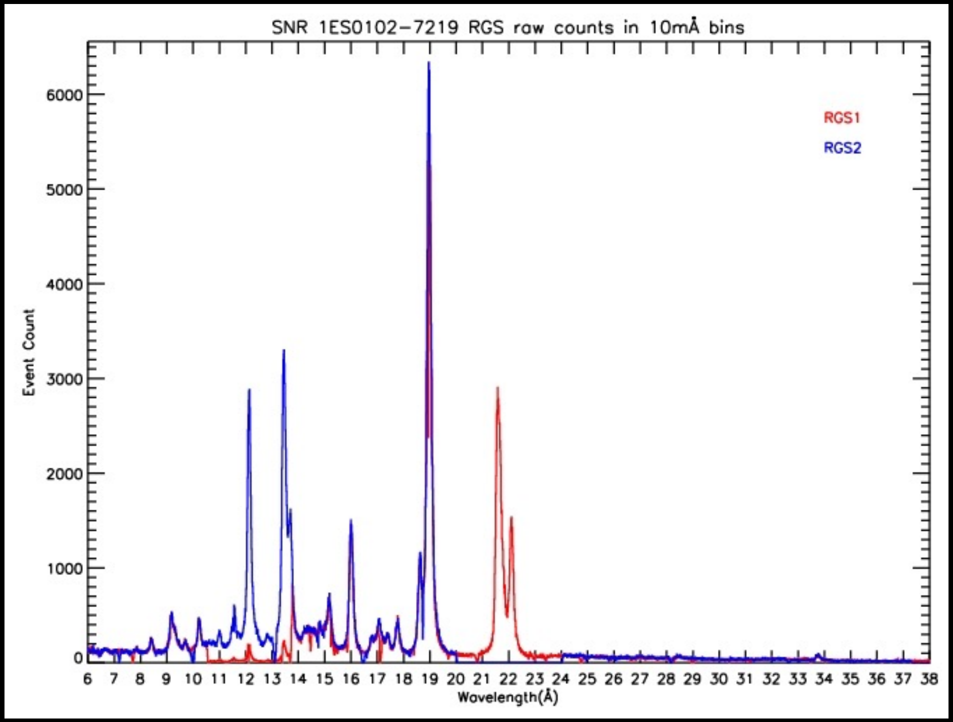
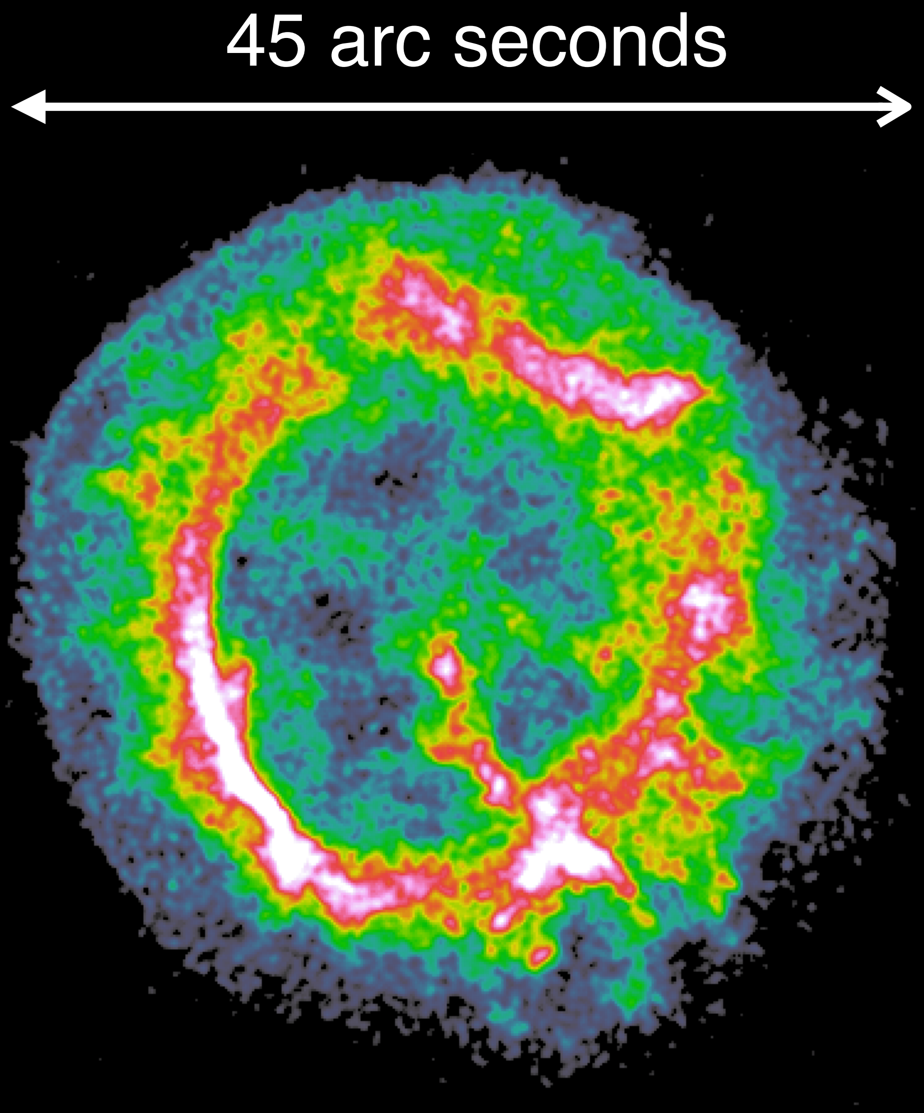




1E 0102.2 -7219: Introduction



hereafter called “E0102”

X-ray brightest SNR in the SMC

~0.75 arcmin diameter, ~13 pc

t ~ 2,050 yr (Finkelstein et al. 2006)

L_X(0.3-10.0 kev) = $2.5\text{x}10^{37}$ ergs s^{-1}

“O-rich” SNR, core-collapse SNe (Dopita et al. 1981)

O, Ne, Mg, & Si abundances most consistent with a ~25 $M_\odot$ progenitor (Blair et al. 2000)

compact object, $L=1.4\text{x}10^{33}$ ergs s^{-1} [1.2-2.0 keV] (Vogt et al. 2018)

X-ray morphology is roughly symmetric

ACIS S3 (0.35-8.0 keV), OBSID 1423, 19 ks, 10/1999

X-ray vs. Optical Morphology

Finkelstein et al. 2006

X-ray and optical are sometime correlated, sometimes anti-correlated, in general the optical is more complicated

HST ACS [O III]   Chandra ACIS S3

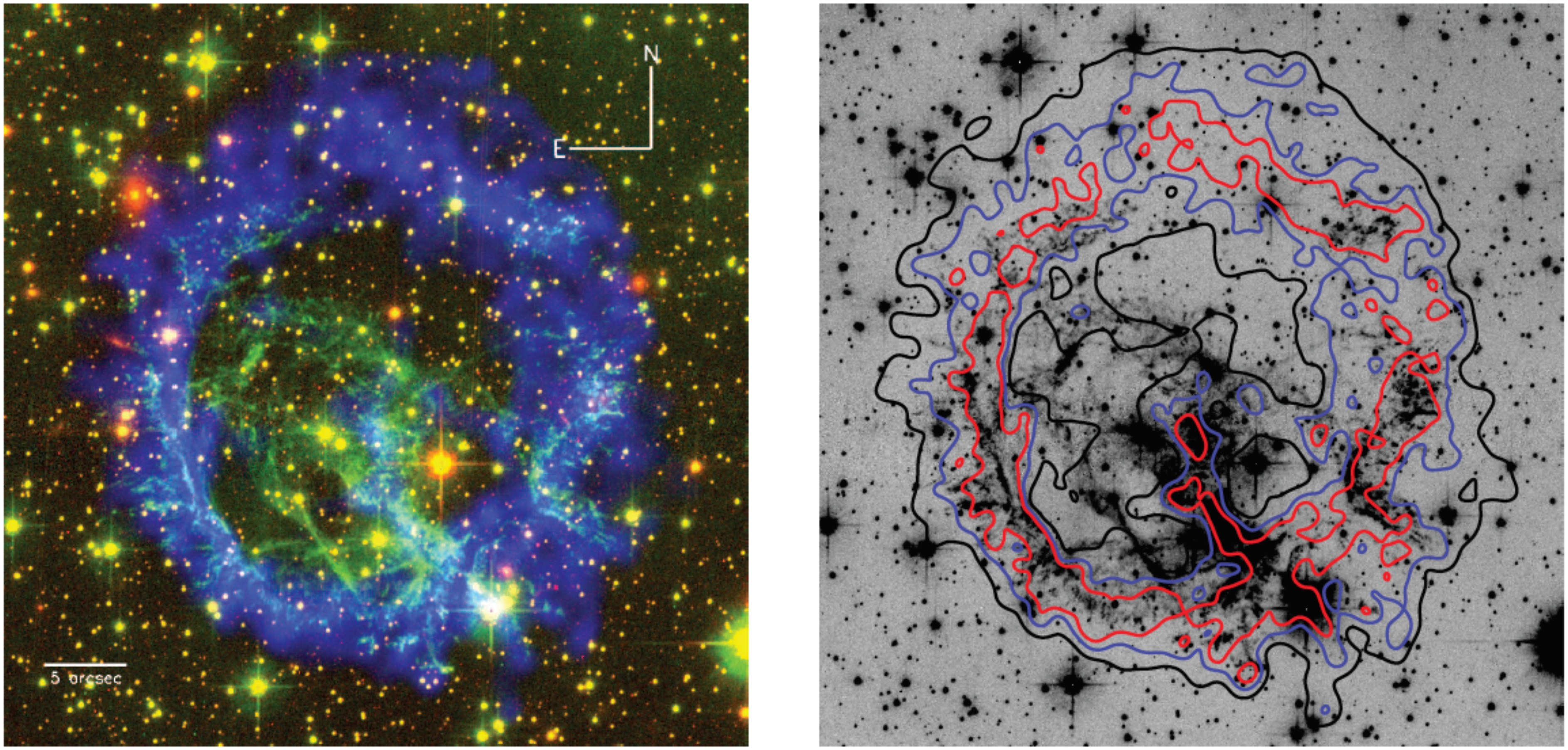
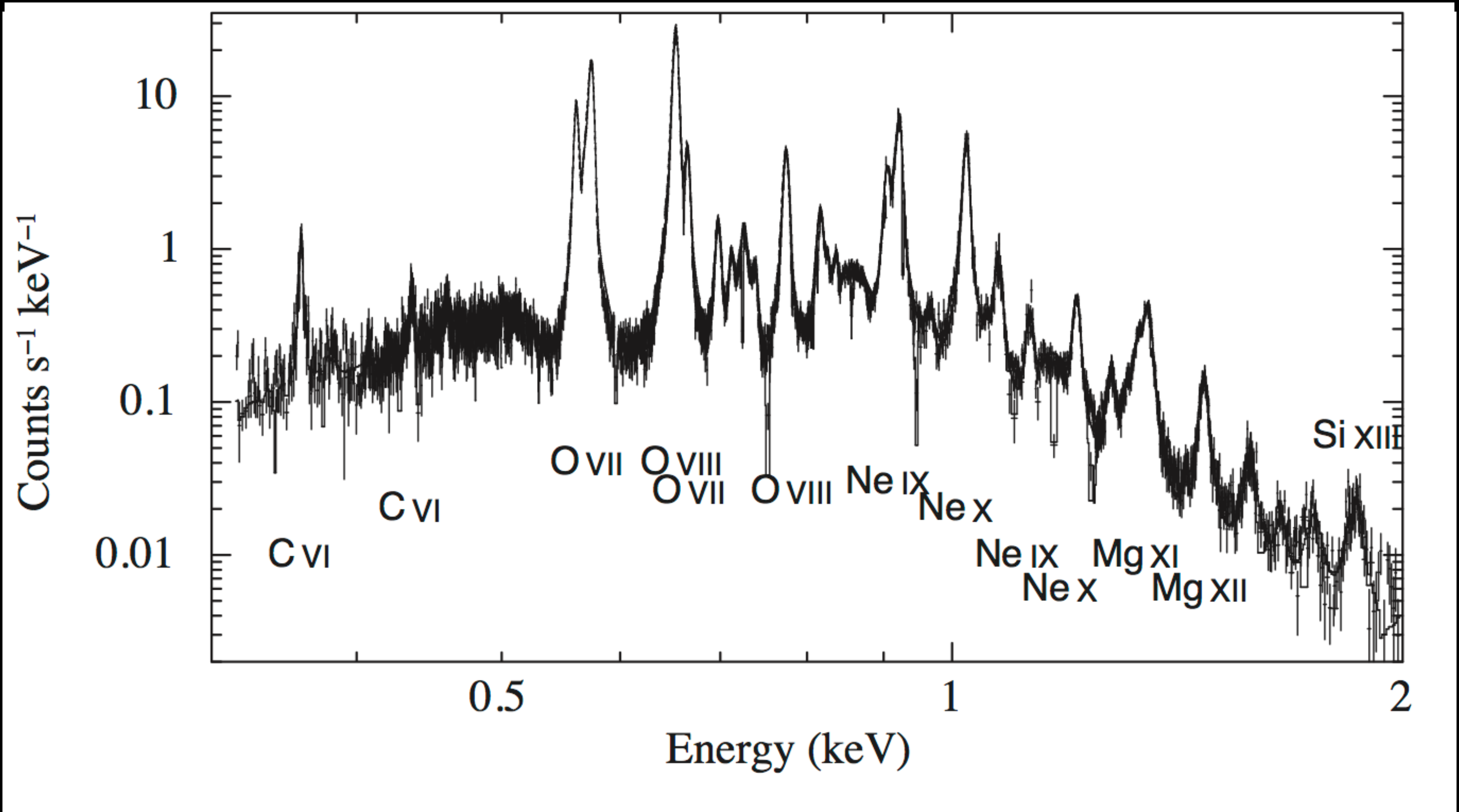


Fig. 7.—*Left*: Three-color image, with the ACS 2003 [O III] in green and the F775W filter in red. The 1999 *Chandra* image is represented in blue. *Right*: ACS 2003 epoch shown with contours from the 1999 *Chandra* image overlaid. The red contour marks the brightest X-ray emission and is coincident with the reverse shock, while the black contour outlines the faintest emission with the outer edge at the position of the forward blast wave. The X-ray and optical ejecta emissions correspond in many areas, but are also anticorrelated in several regions.

1E 0102.2 -7219: X-ray Spectrum

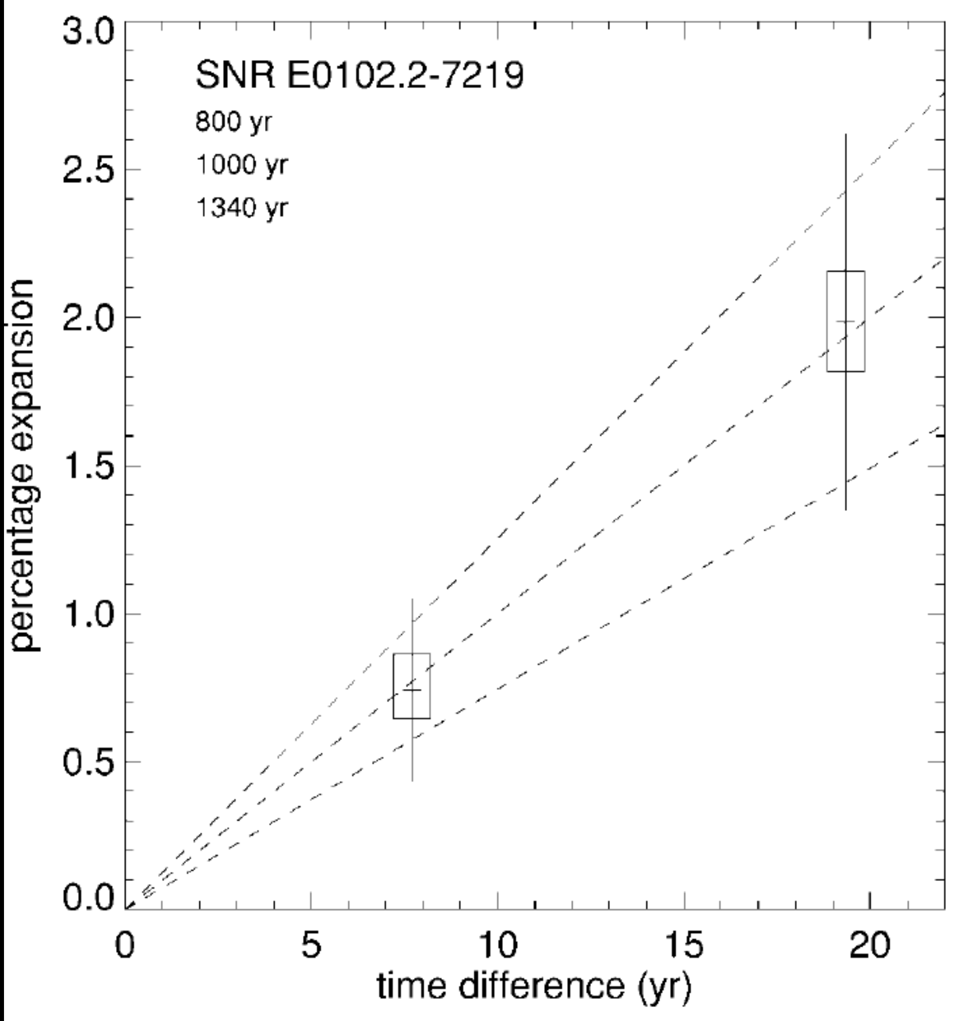
XMM-Newton RGS spectrum Pollock (Sheffield), Rasmussen et al. 2000
Spectrum is dominated by strong lines of O, Ne and Mg with *little or no Fe emission*
This is the simplest known SNR spectrum in the 0.5 - 1.0 keV band



The Expansion of E0102 in X-rays

- Hughes et al. 2000 compared an early (1999) Chandra image to ROSAT/HRI to Einstein/HRI images and derived an expansion of 0.100 %/yr +/- 0.025 %/yr or 0.022 arcsec/yr which implies a shock velocity of v_S~6,000 km/s
- X-ray spectral fits give kT=0.4 - 1.0 keV for the shock, while a v_S~6,000 km/s naively indicates a temperature kT~45 keV
- Nonequipartition between electrons and ions can explain part of this discrepancy but they can't get the electron temperature below 2.5 keV even assuming no equipartition
- Hughes et al. 2000 conclude that a significant fraction of the shock's energy must be going into the acceleration of cosmic rays (CRs)
- Their fitting method estimates the "global mean expansion" and assumes that the expansion rate is uniform over the entire remnants both radially and azimuthally.
- They estimate an age of ~1000 yr.

Hughes et al. 2000



Complications with a Global Expansion Measurement

1. Compare data from different telescopes and detectors (Einstein/HRI, ROSAT/HRC,Chandra/ACIS). If the expansion rate is 0.10 %/yr and the radius is 22 arcsec, in 19 years the outer blast wave would have moved 0.43 arcseconds. Chandra has a 50% EE radius of ~0.4 arcsec but Einstein and ROSAT are more like 4.0 arcsec.

2. Hughes measured a “global expansion”. But the X-ray emission is dominated by the ejecta heated by the reverse shock. The forward shock and reverse shock most likely have different velocities and the velocity of each may vary with azimuthal position.

3. E0102 has a complex 3D structure. The bright ejecta ring contains most of the X-ray counts and will provide most of the constraint for a fit of the global expansion. But optical and X-ray data indicate that the ring is composed of two rings or is a cylinder viewed at slight angle with respect to the major axis.

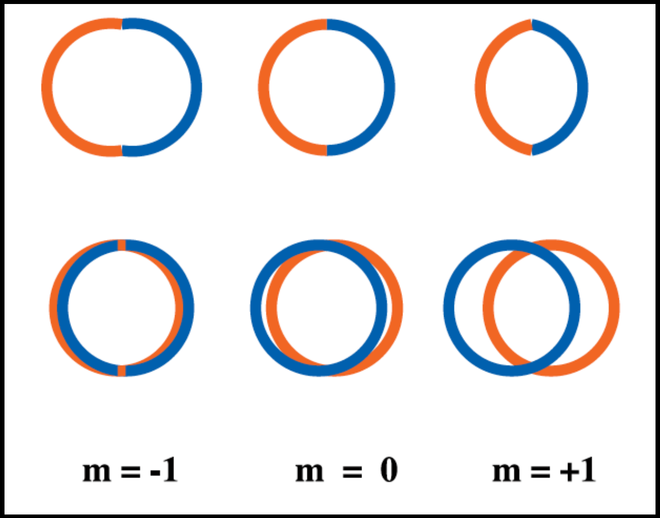
4. ACIS data in full-frame mode suffer from pileup in the bright ring that suppress the count rate.

E0102's Complex 3D Structure

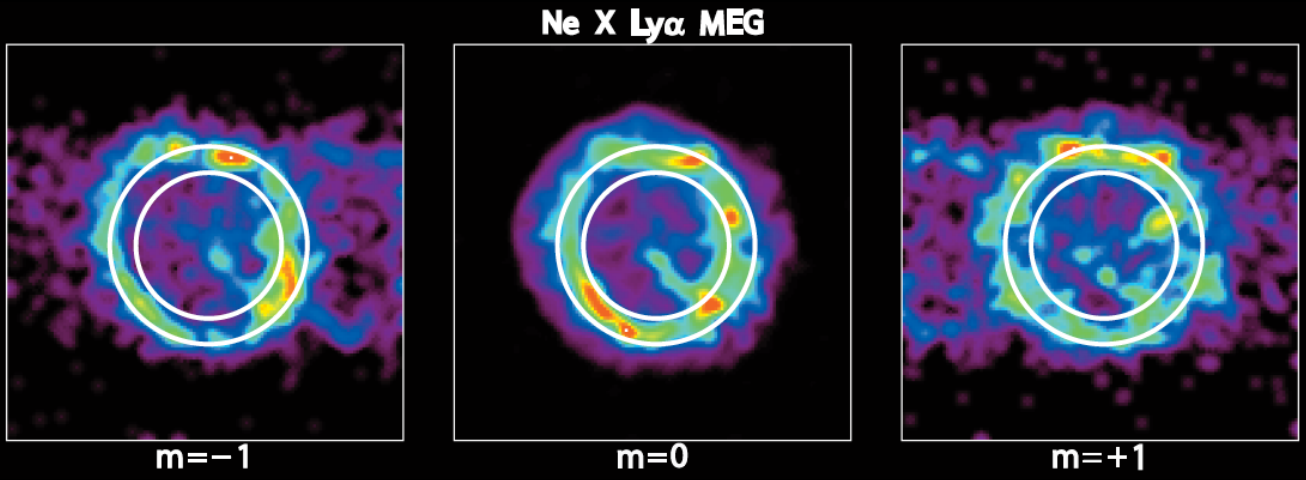
- Flanagan et al. 2004 used the HETG to determine that there is redshifted and blue shifted material in the bright X-ray ring. They model the structure as thick ring or cylinder.

Example: one half of the ring is red-shifted and the other half is blue-shifted.

Idea for E0102: two whole or mostly whole rings, one red-shifted and one blue-shifted



Flanagan et al. 2004

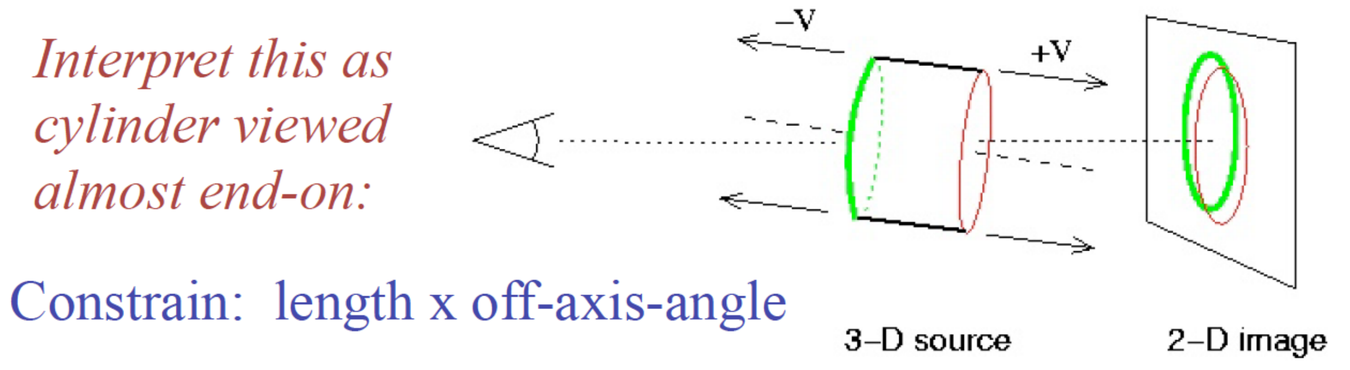


- Vogt and Dopita 2010 conclude E0102 has an asymmetric bipolar structure with the major axis of the explosion inclined at 40 degrees to the LOS. Most of the ejecta are blue-shifted with -2,500 km/s and the red-shifted material has velocities as high as +3,500 km/s

E0102's Complex 3D Structure

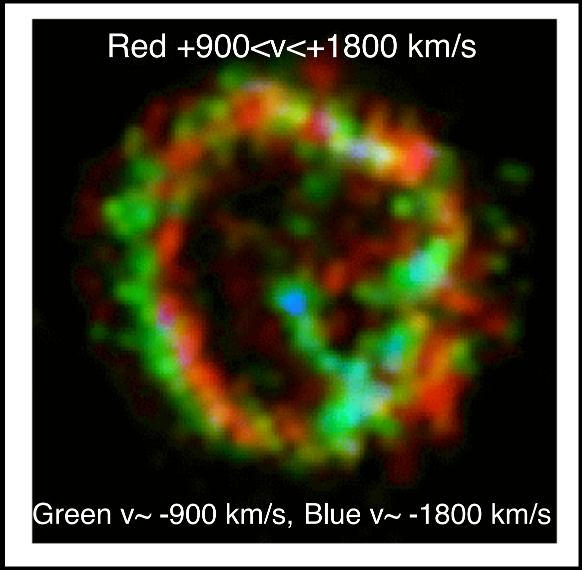
Dewey et al. 2003

- Dan Dewey discussed this idea in 2003 SNORE talk at CfA. The idea is that our viewing geometry for E0102 is somewhat special. IF we were able to view E0102 from a different angle it might look more like other O-rich SNRs like Cas A, G292.0+1.8, N132D, etc.



Interpret this as cylinder viewed almost end-on:

Constrain: length x off-axis-angle



Flanagan et al. 2004

Cylinder in blastwave sphere

- If you accept the ‘Cylinder in a spherical blastwave’ model, then measuring the expansion of the outer blast wave should be possible with Chandra if the Hughes et al. expansion values are correct
- Assuming 0.022 arcsec/yr for 19 years, the outer blast wave should have moved 0.43 arcsec

A Different and Hopefully Simpler Approach

1. Use only Chandra data and compare Chandra data to Chandra data. Remove systematic uncertainties in ROSAT and Einstein data.

2. Measure the expansion of the *outer blast wave*, exclude the bright ring. Exploit Chandra's angular resolution to separate the blast wave from the ejecta ring.

3. Minimize or eliminate pileup by looking at the outer blast wave and/or using subarray data with a shorter frametime.

Complications with Our Approach

1. The mirror is certainly the same for each measurement but ACIS is a different detector every time it observes E0102 due to the time-variable contamination layer.

2. The outer blast wave is faint and the statistics can be poor for an 8 ks observation.

3. Subarray data may have no point sources to register on. We must find another way to register the images. All data since 2006 are in subarray mode.

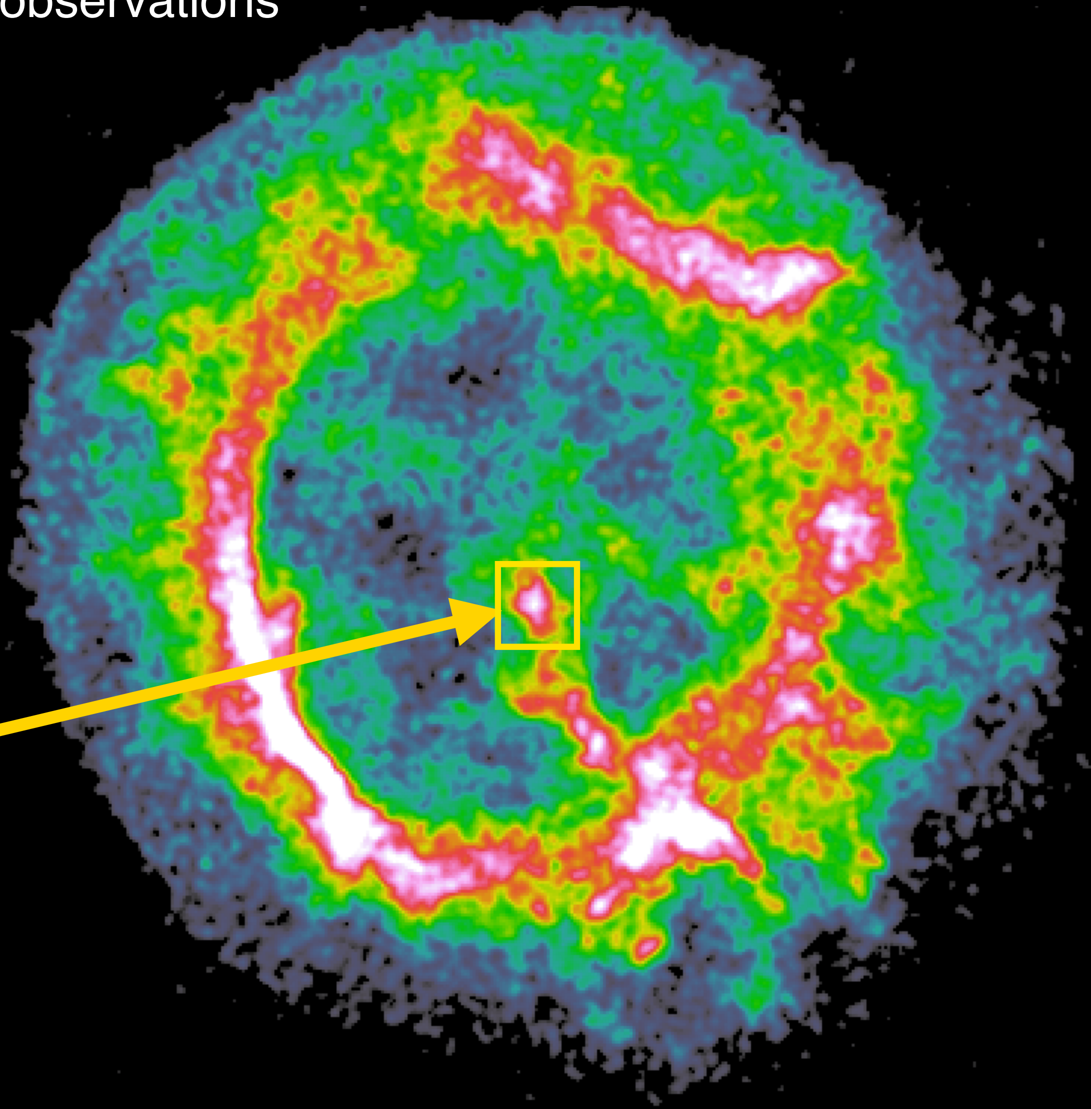
Long XI (IHEP,CAS) does all the hard work

Complications with Our Approach

Register on the bright central knot, since subarray data of 10-20 ks may not have any sources that are bright enough to register on.

There are 11 ACIS S3 on-axis subarray observations from 2003 to 2016.

HST WFPC3/UVIS data, courtesy of D. Milisavljevic (Purdue)
[O III]
Blue == blue-shifted (v< -1500 km s^{-1})
Red == red-shifted (v> 1500 km s^{-1})
Green == ~zero velocity
(-2000 < v < 2000 km s^{-1})

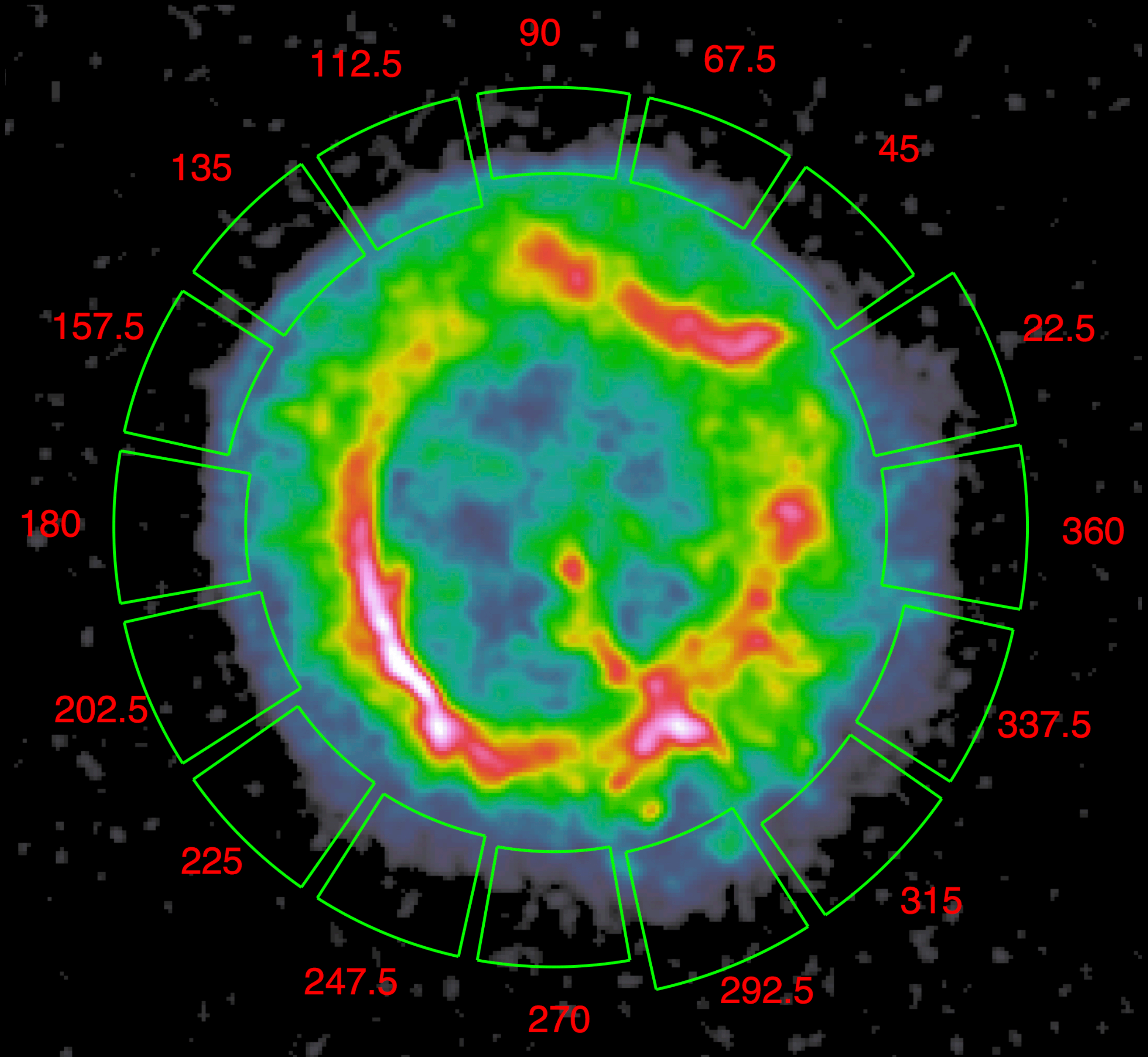


Central Knot to register on

Definition of Annular Regions

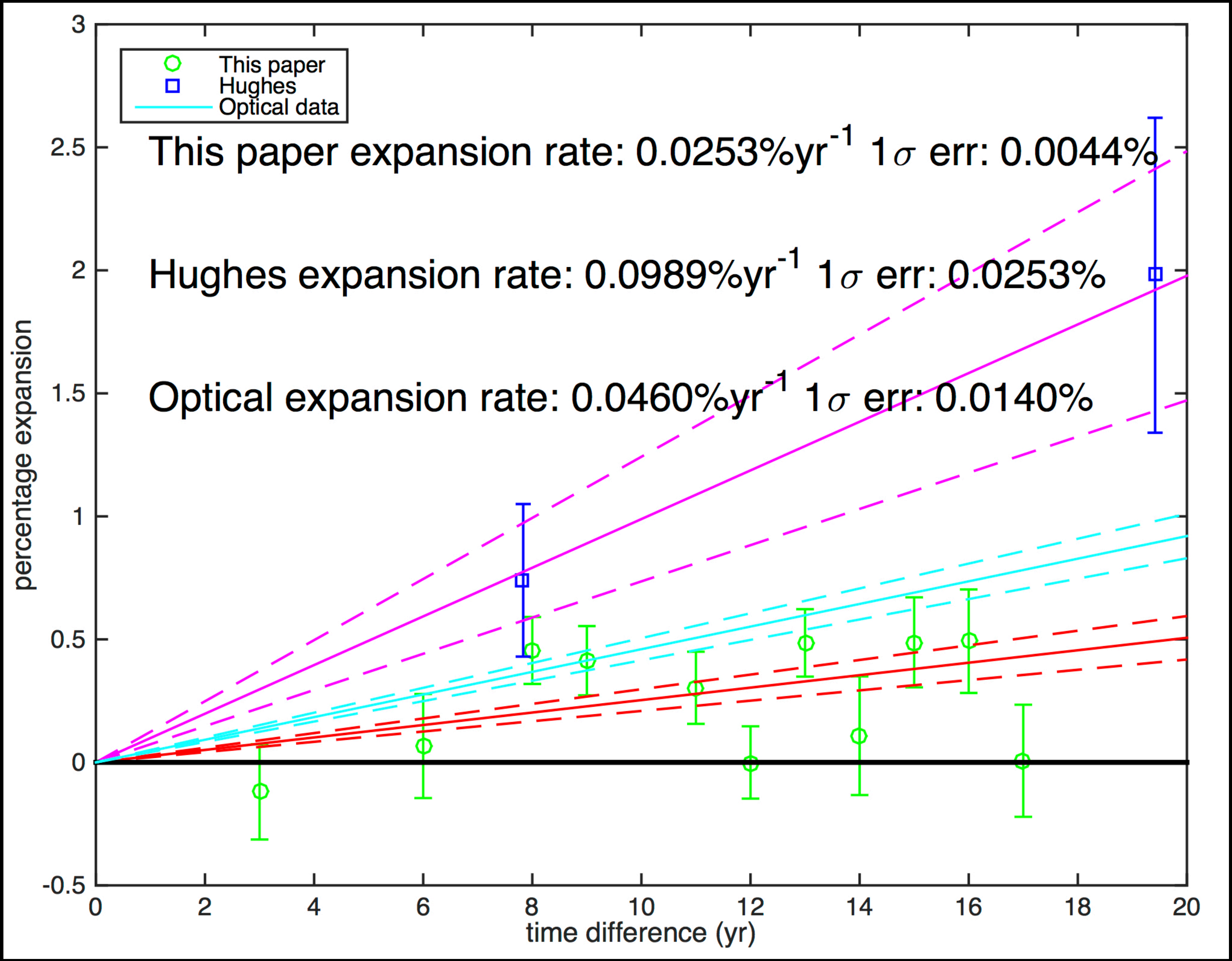
Xi et al. 2018

A model is constructed based on early mission data. Later subarray observations are registered relative to that image. Radial profiles are extracted and fit in the following regions.



Expansion Rate Results

Xi et al. 2018



This paper expansion rate: 0.0253%yr^{-1} 1σ err: 0.0044%

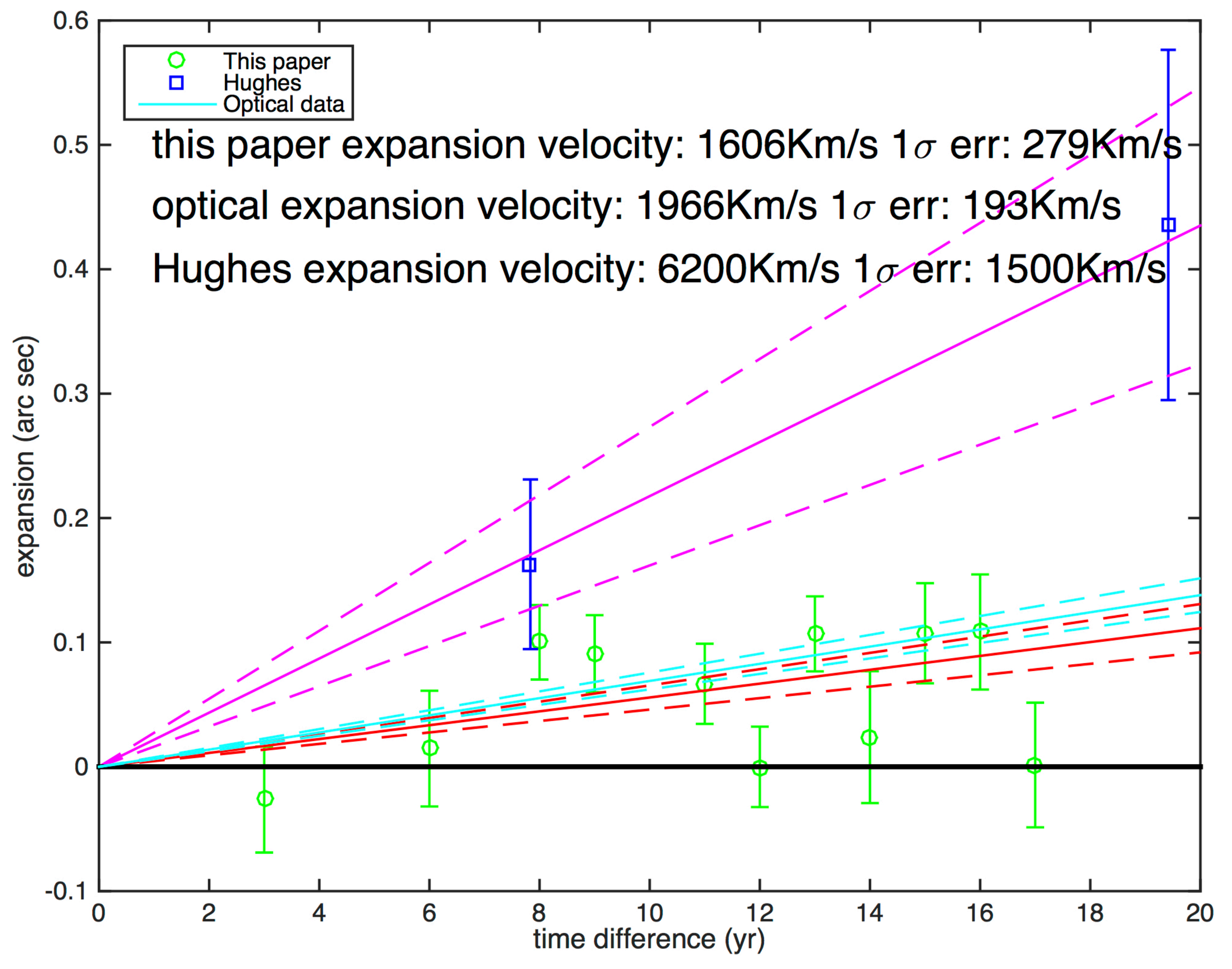
Hughes expansion rate: 0.0989%yr^{-1} 1σ err: 0.0253%

Optical expansion rate: 0.0460%yr^{-1} 1σ err: 0.0140%

Expansion Velocity Results Xi et al. 2018

- the fact that the X-ray and optical expansion velocities are so close to each other is a coincidence. The x-ray emitting material at the outer blast wave must have decelerated more than the optical filaments.

- assuming no significant deceleration of the optical filaments and R_{opt}/R_{BW}~0.6, the deceleration parameter is 0.6, intermediate between free expansion and the Sedov phase $R \sim t^{2/5}$.



Forward and Reverse Shock Radii

Xi et al. 2018

We can take advantage of E0102's simple geometry and *Chandra*'s superb resolution to measure the position of the forward and reverse shocks. Ellipses were fit to determine the forward and reverse shock radii.

Fitted Values:

v_s = 1606 +/- 279 km s^{-1}

R_{fs} = 6.40 +/- 0.17 pc

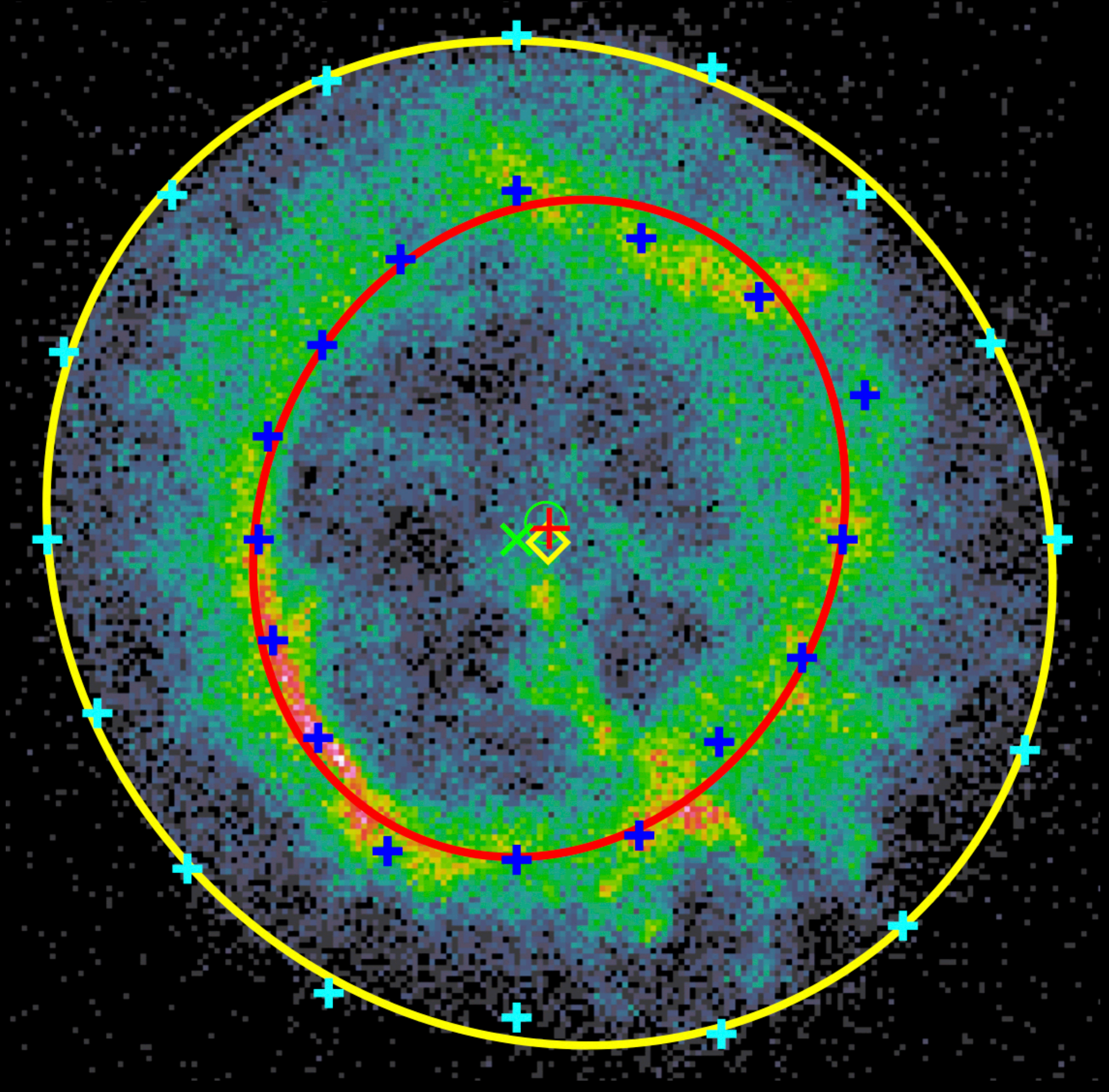
R_{rs} = 4.17 +/- 0.12 pc

X Milisavljevic center

O Finkelstein center

+ reverse shock center

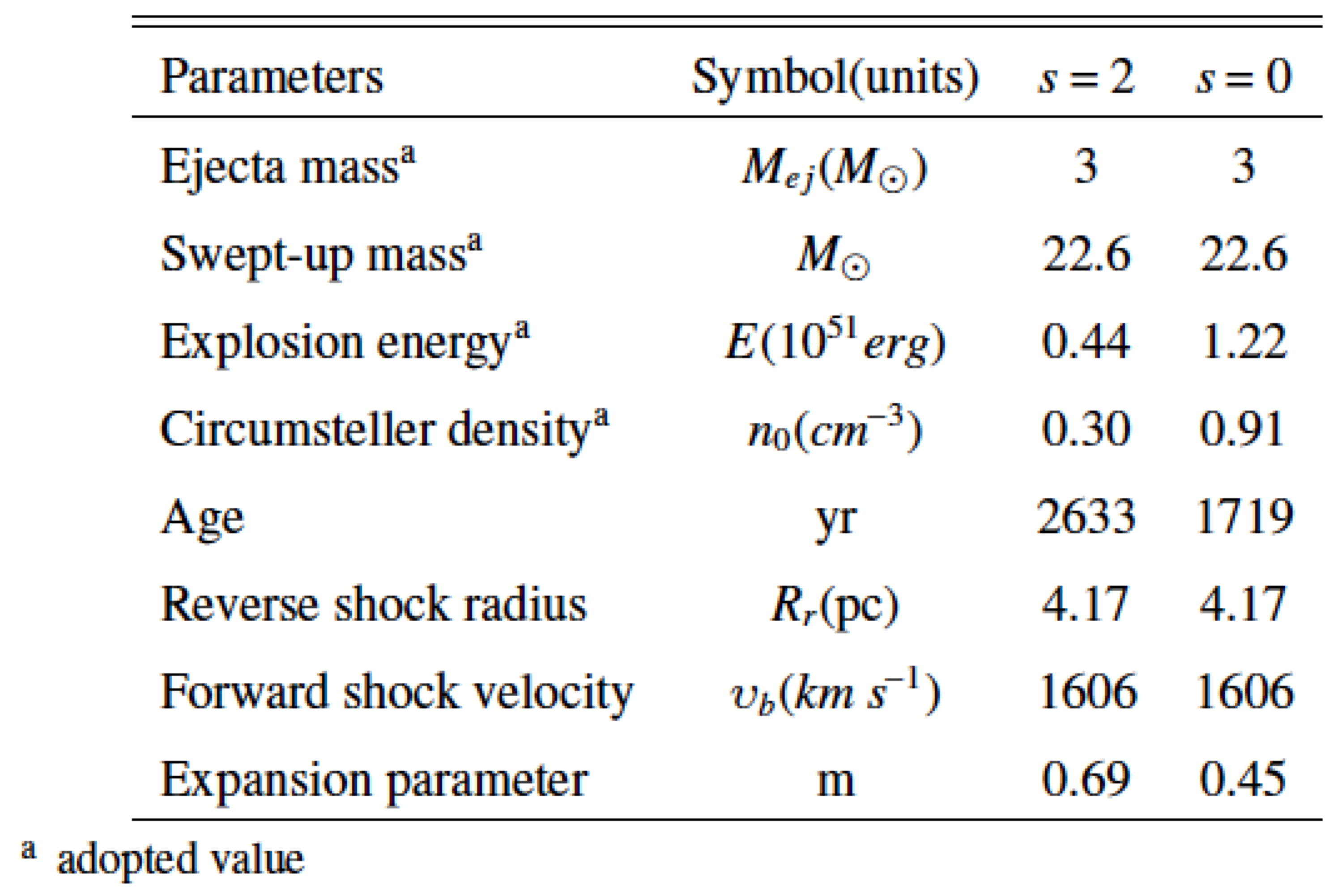
◇ forward shock center



Evolutionary Models

Xi et al. 2018

- a grid of models were run for different ejecta masses (M_{ej}), density profiles (s=0,2), circumstellar densities (n_0), ejecta profiles (n=9) based on Truelove & McKee (1999), Laming & Hwang (2003), and Micelotta et al. (2016)
- explosion energy E_0 was varied to match the R_f, R_r, and v_s
- solutions with M_{ej}=3 solar masses match the observed values



Parameters	Symbol(units)	$s = 2$	$s = 0$
Ejecta mass[a]	$M_{ej}(M_\odot)$	3	3
Swept-up mass[a]	$M_\odot$	22.6	22.6
Explosion energy[a]	$E(10^{51} erg)$	0.44	1.22
Circumsteller density[a]	$n_0(cm^{-3})$	0.30	0.91
Age	yr	2633	1719
Reverse shock radius	R_r(pc)	4.17	4.17
Forward shock velocity	$v_b(km\ s^{-1})$	1606	1606
Expansion parameter	m	0.69	0.45

[a] adopted value

Conclusions

- Expansion measured with Chandra data alone is significantly less than the Hughes et al. result
- Chandra analysis give a v_s= 1606 +/- 279 km s^{-1}, optical expansion velocity is v_s= 1966 +/- 193 km s^{-1}
- There has been significant deceleration of the blastwave and the remnant is evolving from the free expansion phase to the Sedov phase
- E0102's electron/ion equilibration appears similar to other remnants with similar shock velocities. There is no need to have a large fraction of the shock's energy going into CR acceleration.
- Evolutionary models can reproduce the observed values of the forward shock radius, the reverse shock radius, and the shock velocity
- Evolutionary models assuming M_{ej}=3 can not distinguish between a constant density medium or a medium shaped by the stellar wind of the progenitor