Explosive Ideas about Massive Stars - from Observations to Modeling, Stockholm, Sweden, August 12, 2011

X-Ray Emission from Supernova Remnant 1987A

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SNR 1987A: X-Ray Observations

- Brightest supernova observed by mankind since 1604 (Kepler's SN)
- Distance: 50 kpc, in the Large Magellanic Cloud
- Age: 24 years and 6 month old as of 2011-8
- Type II SN
- Progenitor: Blue supergiant (Sk -69 202, B3 I)
- Neutrino burst: Core-collapse explosion → creation of a neutron star/black hole.
- Most intensively studied SN of all time:
  - Optical/UV: HST and many ground-based
  - Radio: initial detection, turned on again in ~1990
  - **X-ray**: no initial detection, turned on in ~1990 → ROSAT, **Chandra,** XMM, Swift, Suzaku
  - γ-ray: detected decay lines from ^{56}Co decay of ^{56}Ni, confirming explosive nucleosynthesis

→ ADS: 1100 (~ 1/week) refereed papers (since 1987) with "1987A" in the Title

◆ Chandra observations since 1999:

- Monitoring: ACIS, HETG, twice a year, separated by ~6 months
- Spectroscopy: HETG, LETG
- As of 2011-3, 29 Chandra observations performed:

  23 ACIS, HETG monitoring

  5 HETG, LETG deep spectroscopy

  2 HRC imaging

  → >2 Ms exposure in total

SNR 1987A: Chandra Observations

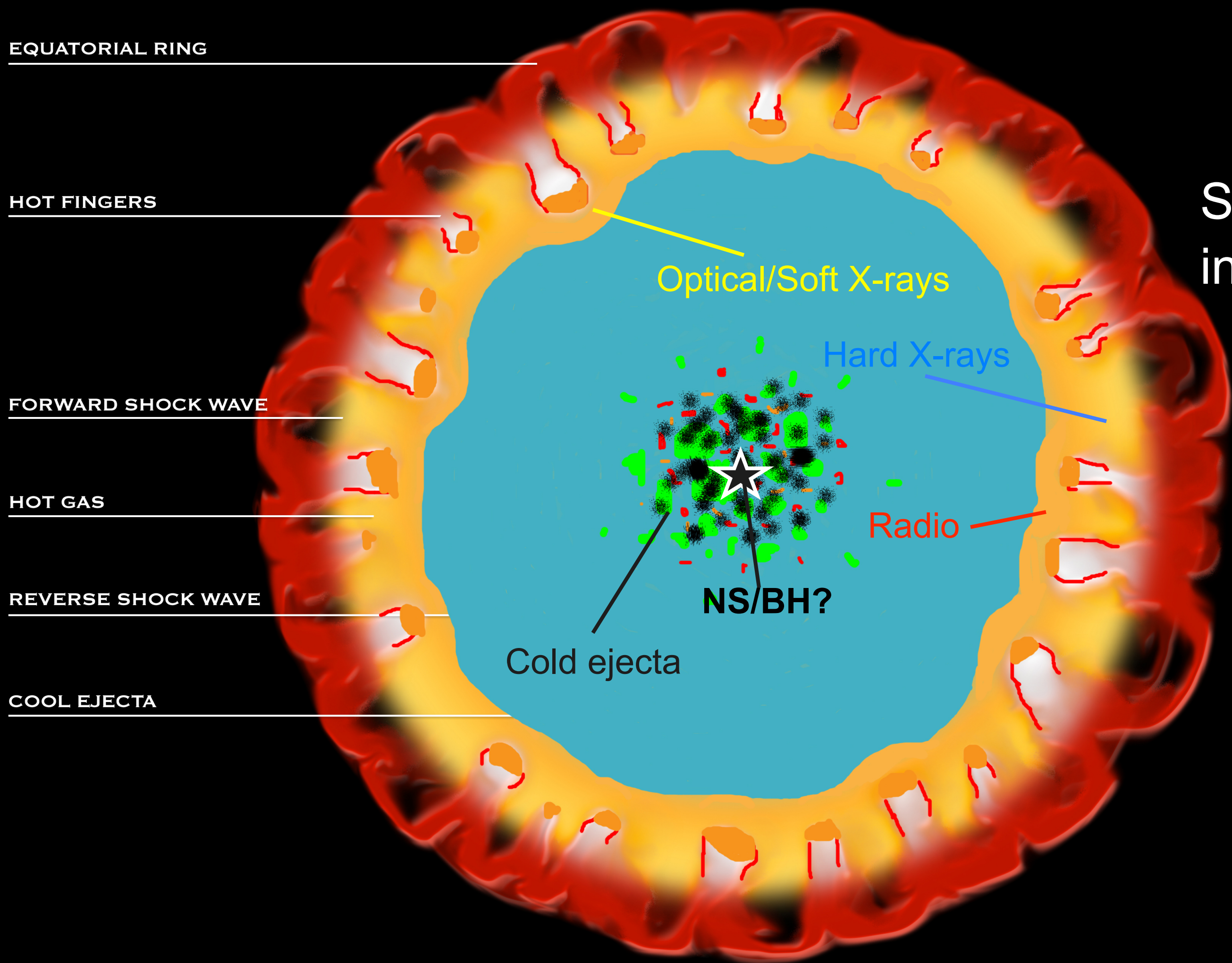
Date (age [days])	Inst.	Exp (ks)	Frame (s)
1999-10-6 (4609)	HETG	116	3.1
2000-1-17 (4711)	ACIS-S3	9	3.2
2000-12-7 (5038)	ACIS-S3	99	3.2
2001-4-25 (5176)	ACIS-S3	18	3.2
2001-12-12 (5407)	ACIS-S3	49	3.2
2002-5-15 (5561)	ACIS-S3	44	3.2
2002-12-31 (5791)	ACIS-S3	49	3.2
2003-7-8 (5980)	ACIS-S3	45	3.2
2004-1-2 (6157)	ACIS-S3	46	3.2
2004-7-22 (6359)	ACIS-S3	49	1.6
2004-9-1 (~6400)	LETG	289	1.0
2005-1-9/13 (6533)	ACIS-S3	48	0.4
2005-7-11/16 (6716)	ACIS-S3	44	0.4
2006-1-28 (6914)	ACIS-S3	42	0.4
2006-7-27 (7095)	ACIS-S3	40	0.4
2007-1-19 (7271)	ACIS-S3	38	0.4
2007-3-11/4-17 (~7340)	HETG	355	2.5
2007-7-13 (7446)	ACIS-S3	26	0.4
2007-9-4/16 (~7504)	LETG	285	3.2
2008-1-10 (7626)	ACIS-S3	9	0.2
2008-4-28 (7736)	HRC-I	46	0.016
2008-7-4 (7802)	ACIS-S3/HETG	9/43	0.2/1.1
2009-1-5 (7987)	ACIS-S3/HETG	6/72	0.2/1.1
2009-7-6/9-8 (~8200)	HETG	58	1.1
2010-3-17/28 (8429)	HETG	64	1.0
2010-8-18 (8577)	HRC-I	35	0.016
2010-9-28 (8619)	HETG	54	1.0
2011-3-1/13 (~8778)	HETG	180	2.5
2011-3-25 (8796)	HETG	56	1.0
2011-9	*HETG*	*52*	*1.0*

- Publications:

Burrows et al. 2000, ApJ, 543, L149
Park et al. 2002, ApJ, 567, 314
Michael et al. 2002, 574, 166
Park et al. 2004, AdSpR, 33, 386
Park et al. 2004, ApJ, 610, 275
Park et al. 2005, AdSpR, 35, 991
Zhekov et al. 2005, ApJ, 628, L127
Park et al. 2005, ApJ, 634, L73
Zhekov et al. 2006, ApJ, 645, 293
Park et al. 2006, ApJ, 646, 1001
Dewey et al. 2008, ApJ, 676, L131
Zhekov et al. 2009, ApJ, 692, 1190
Racusin et al. 2009, ApJ, 703, 1752
Ng et al. 2009, ApJ, 706, L100
Zhekov et al. 2010, MNRAS, 407, 1157
Park et al. 2011, ApJ, 733, L35

more to come..

SNR 1987A: Physical Picture



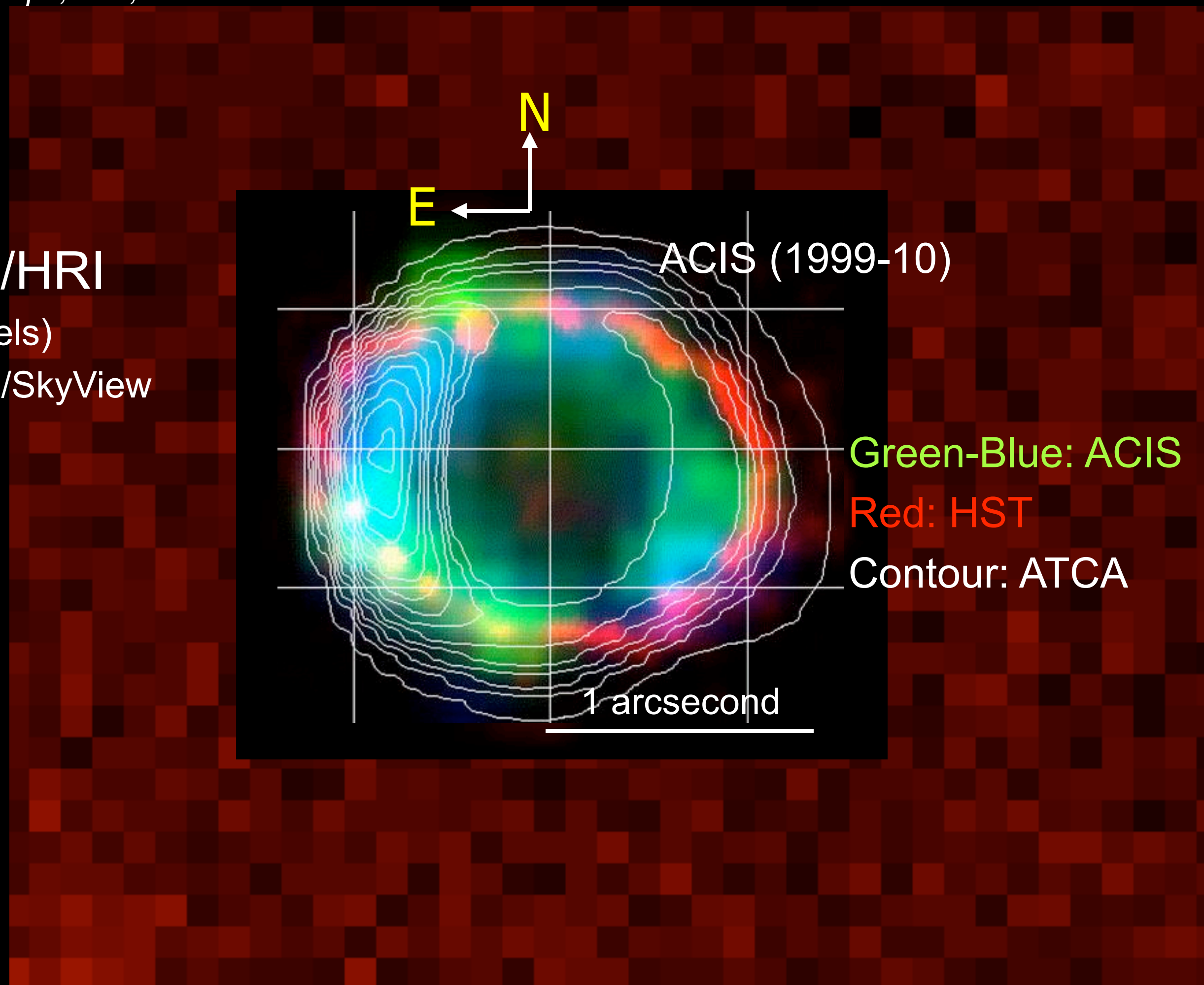
Shock-CSM interaction

Artistic presentation of SNR 1987A (SAO/CXC)
(e.g., *Michael et al. 1998*)

SNR 1987A: Multi-Wavelengths Images

Burrows+ 2000, ApJ, 543, L149

ROSAT/HRI
(5” pixels)
HEASARC/SkyView



Green-Blue: ACIS
Red: HST
Contour: ATCA

SNR 1987A: Chandra Images 1999–2010

Park+ 2002, ApJ, 567, 314
Park+ 2004, ApJ, 610, 275
Park+ 2005, ApJ, 634, L73
Park+ 2006, ApJ, 646, 1001
Racusin+ 2009, ApJ, 703, 1752
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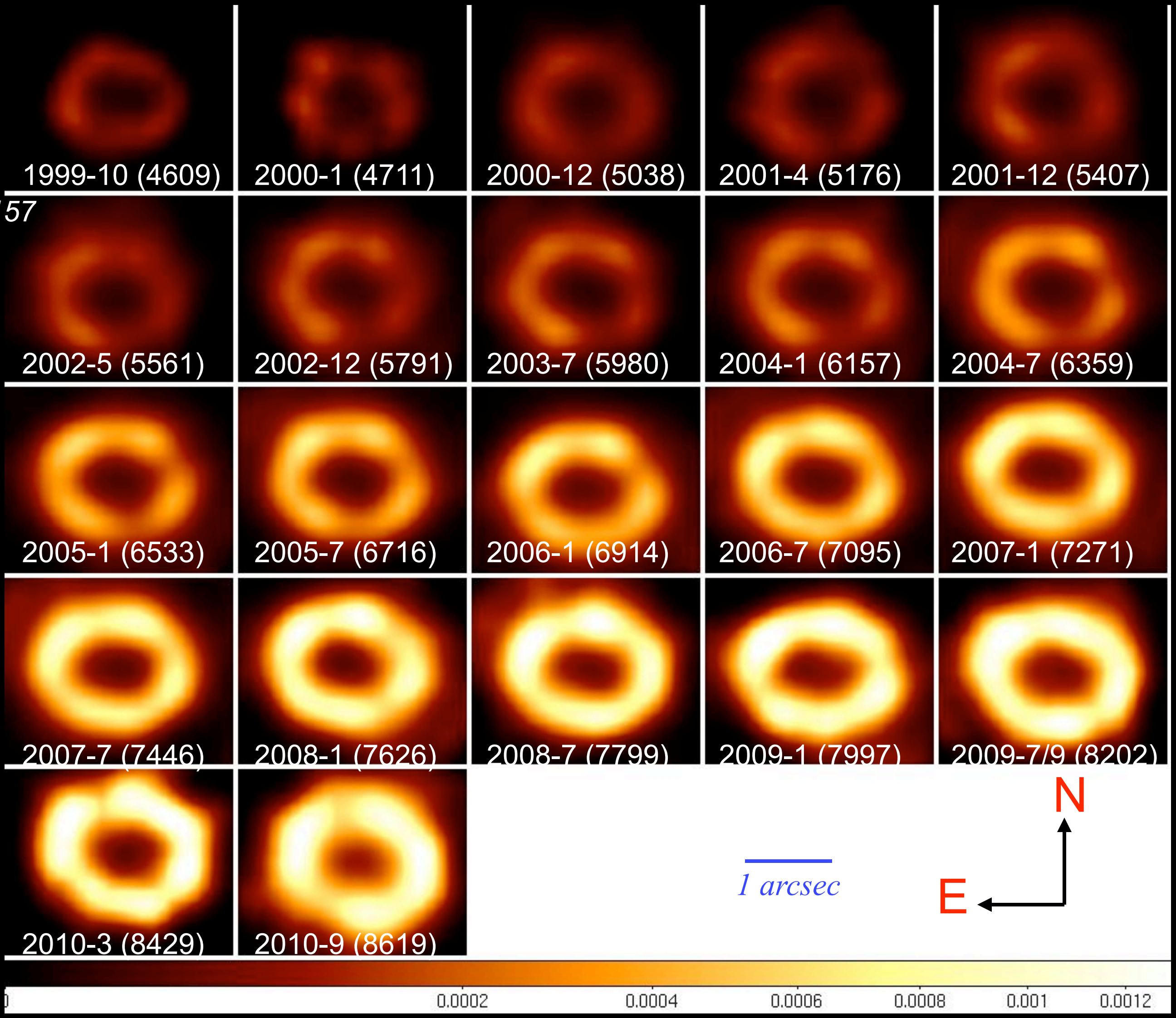
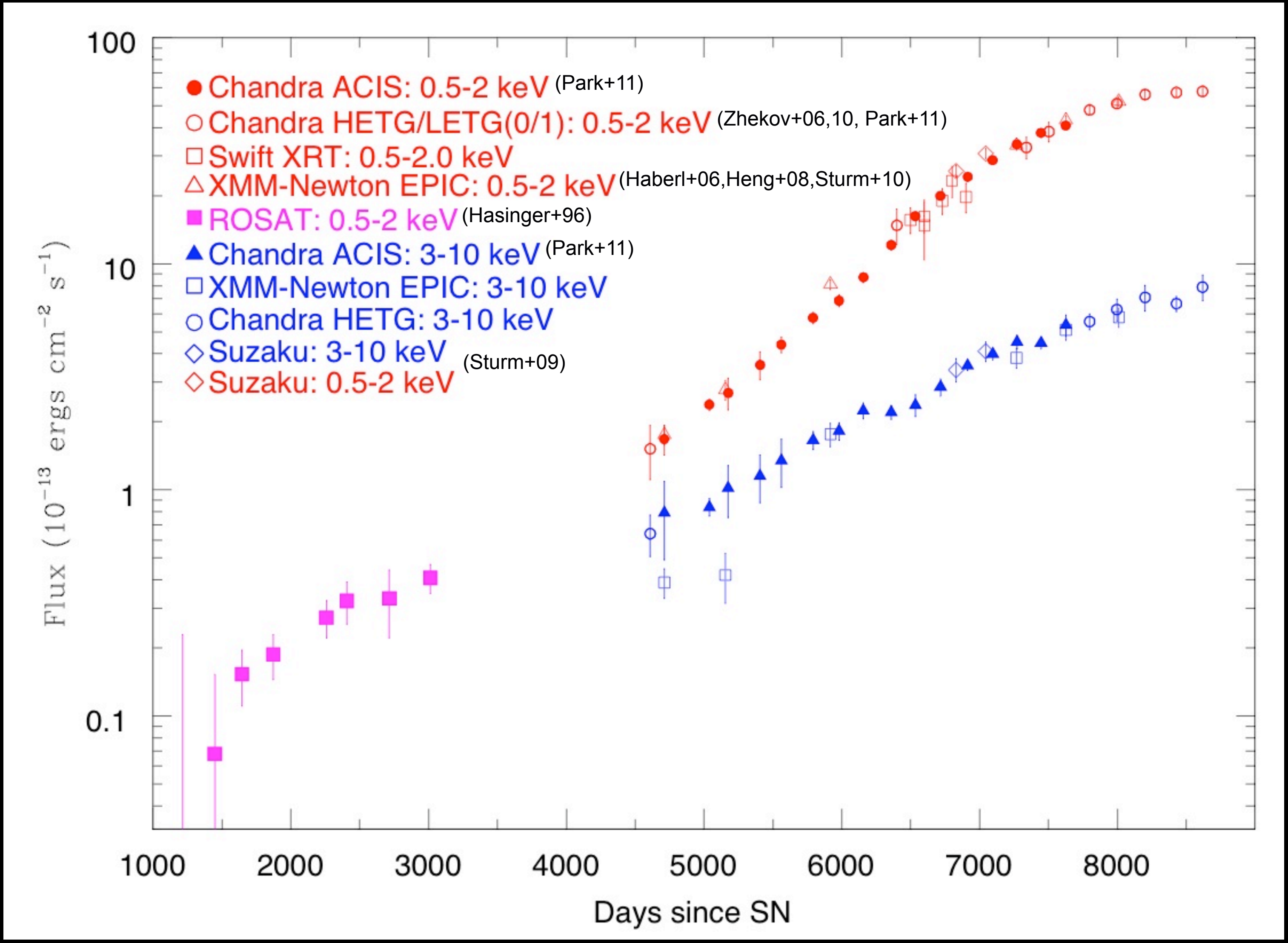
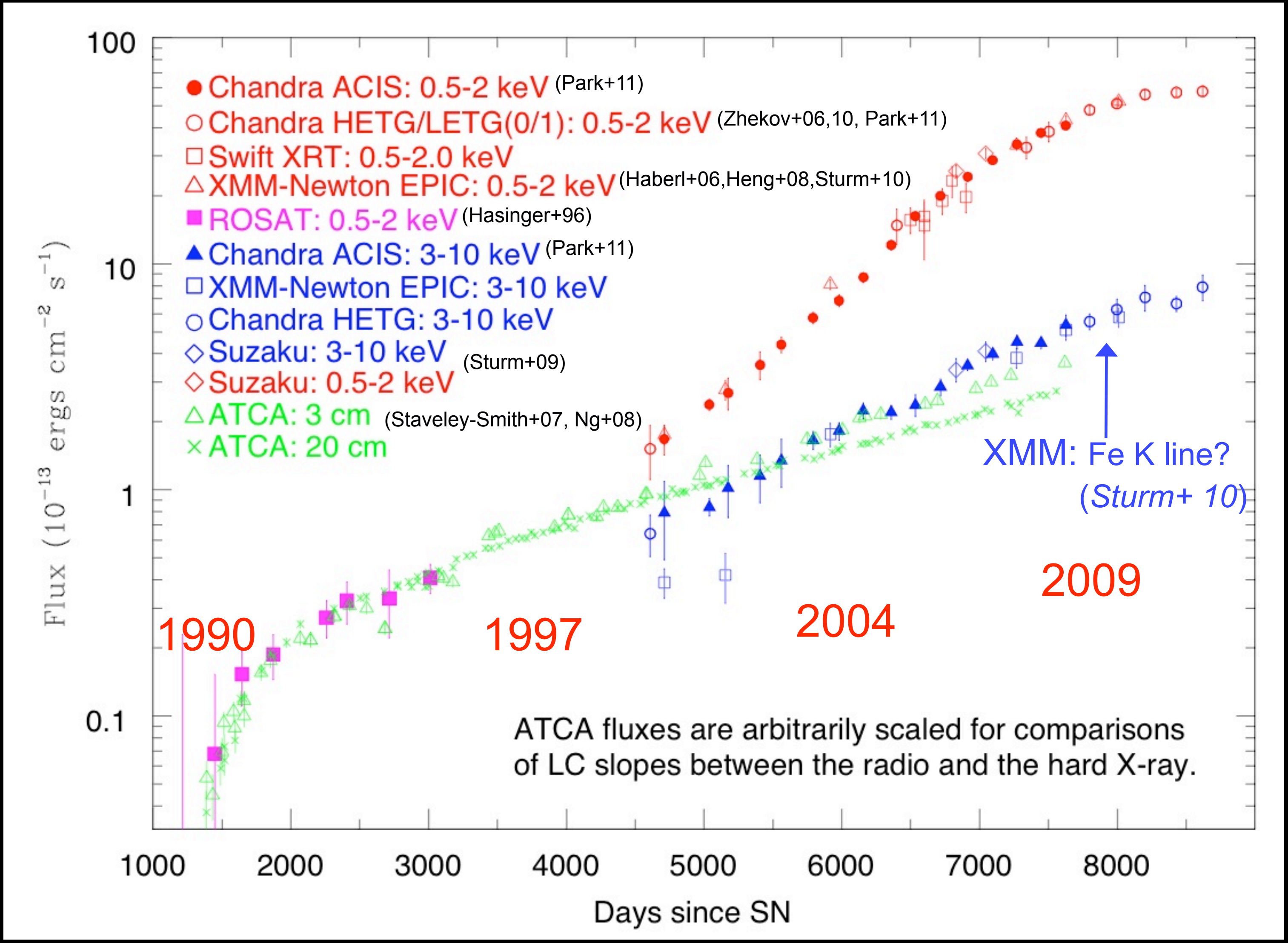
Park+ 2011, ApJ, 733, L35



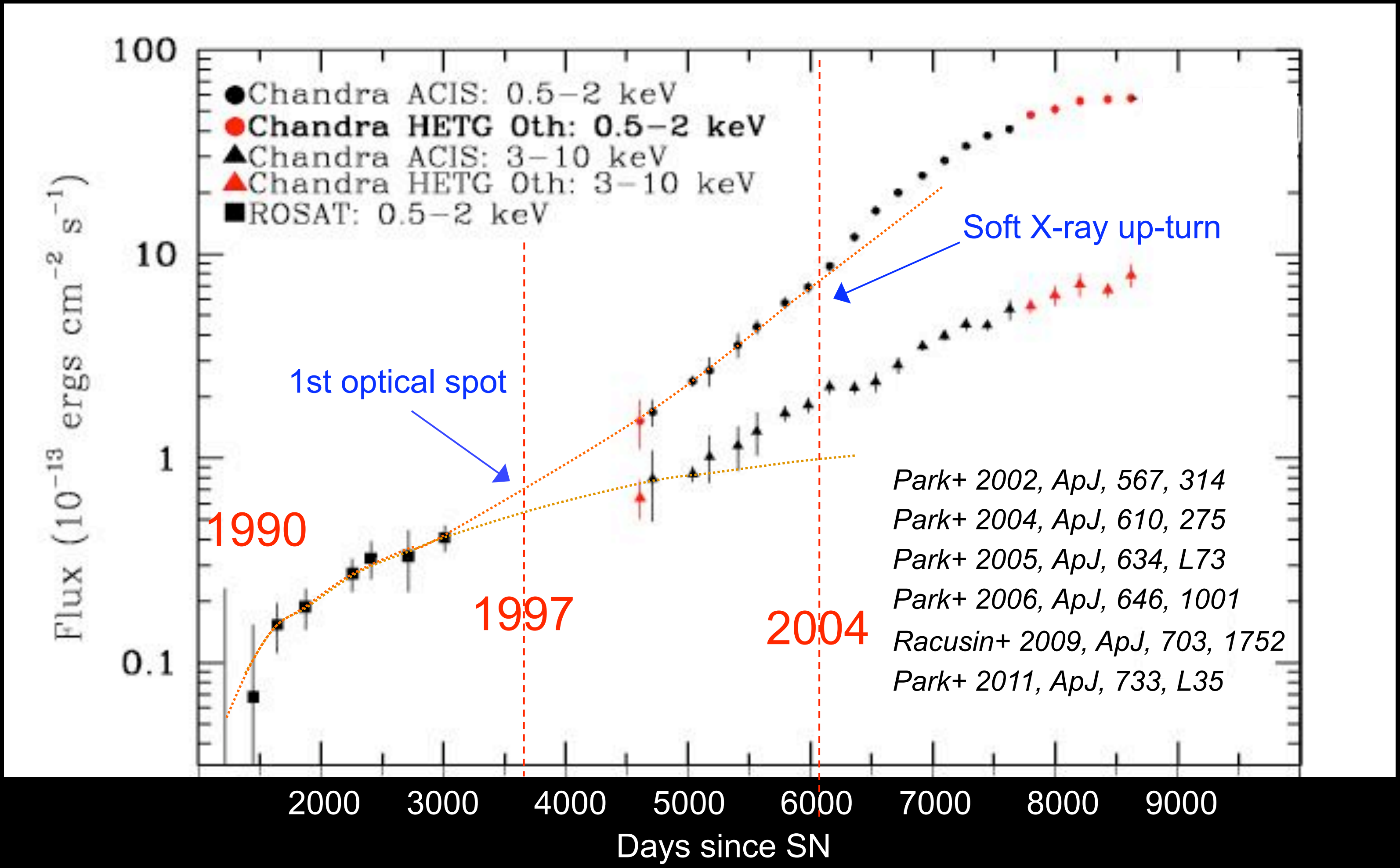
SNR 1987A: X-Ray Light Curves 1990-2010



SNR 1987A: X-Ray Light Curves 1990-2010



SNR 1987A: Chandra Light Curves 1999-2010

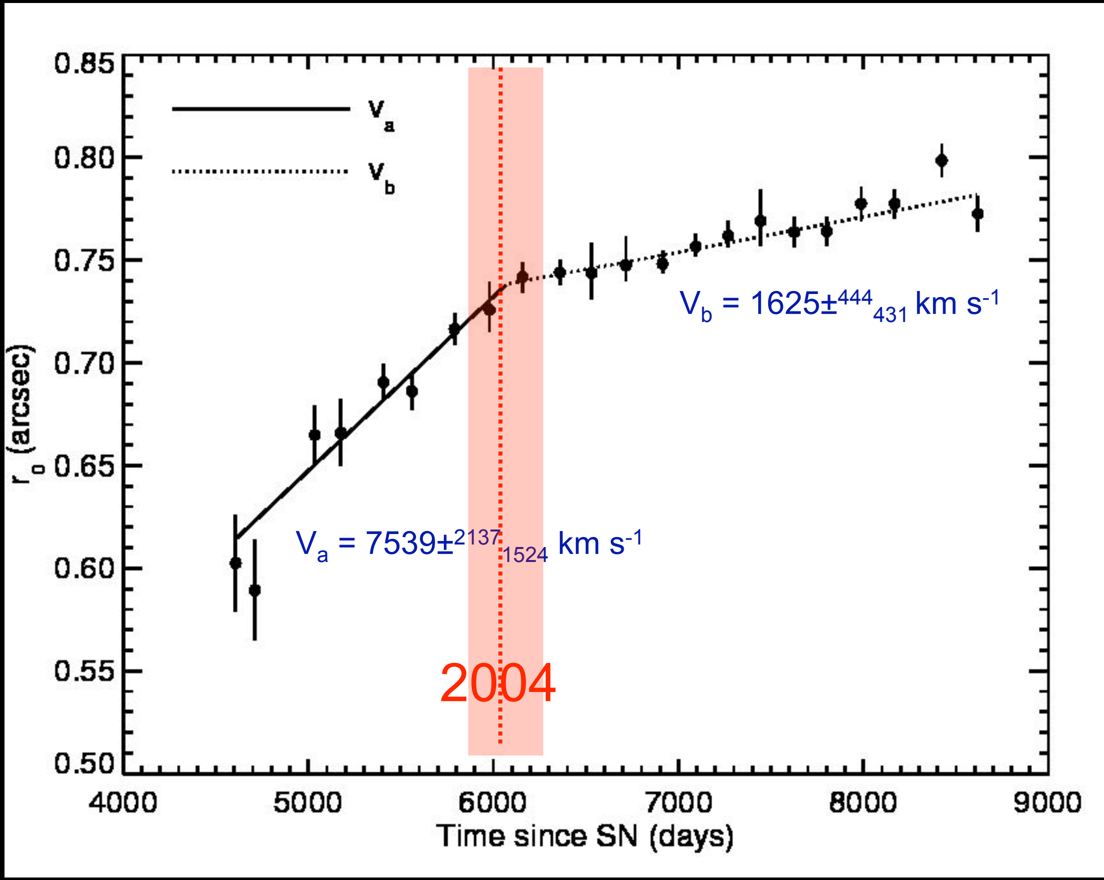


SNR 1987A: X-ray Radial Expansion 1999-2010

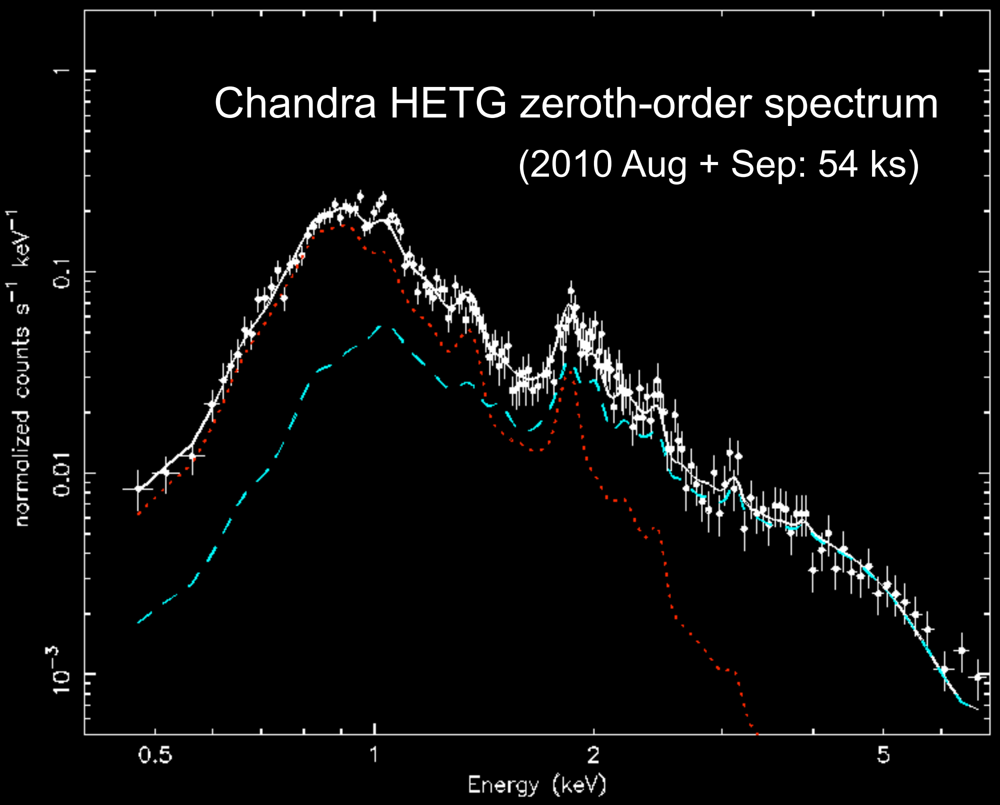
Racusin+ 2009, ApJ, 703, 1752
Park+ 2011, ApJ, 733, L35

X-ray radius vs time:

Broadband deconvolved image for each epoch is de-projected (43º) and fitted to an empirical model (a torus + 4 lobes) to estimate the radius of the SNR as a function of time. The expansion slows down to ~1600 km s^{-1} from ~7500 km s^{-1} at day ~6060. The current peak radius is R = 0.78”.



SNR 1987A: X-Ray Spectrum 2010-9



kT_{soft} ~ 0.56 keV

kT_{hard} ~ 2.4 keV

$n_e t_{soft}$ ~ 4 x 10^{11} cm^{-3} s

$n_e t_{hard}$ ~ 3 x 10^{11} cm^{-3} s

=> Shock interacting with density gradient

Abundances (*Zhekov+ 09, Russell & Dopita 92*)

N=0.56, O=0.08

Ne=0.29, Mg=0.28

Si=0.33, S=0.30

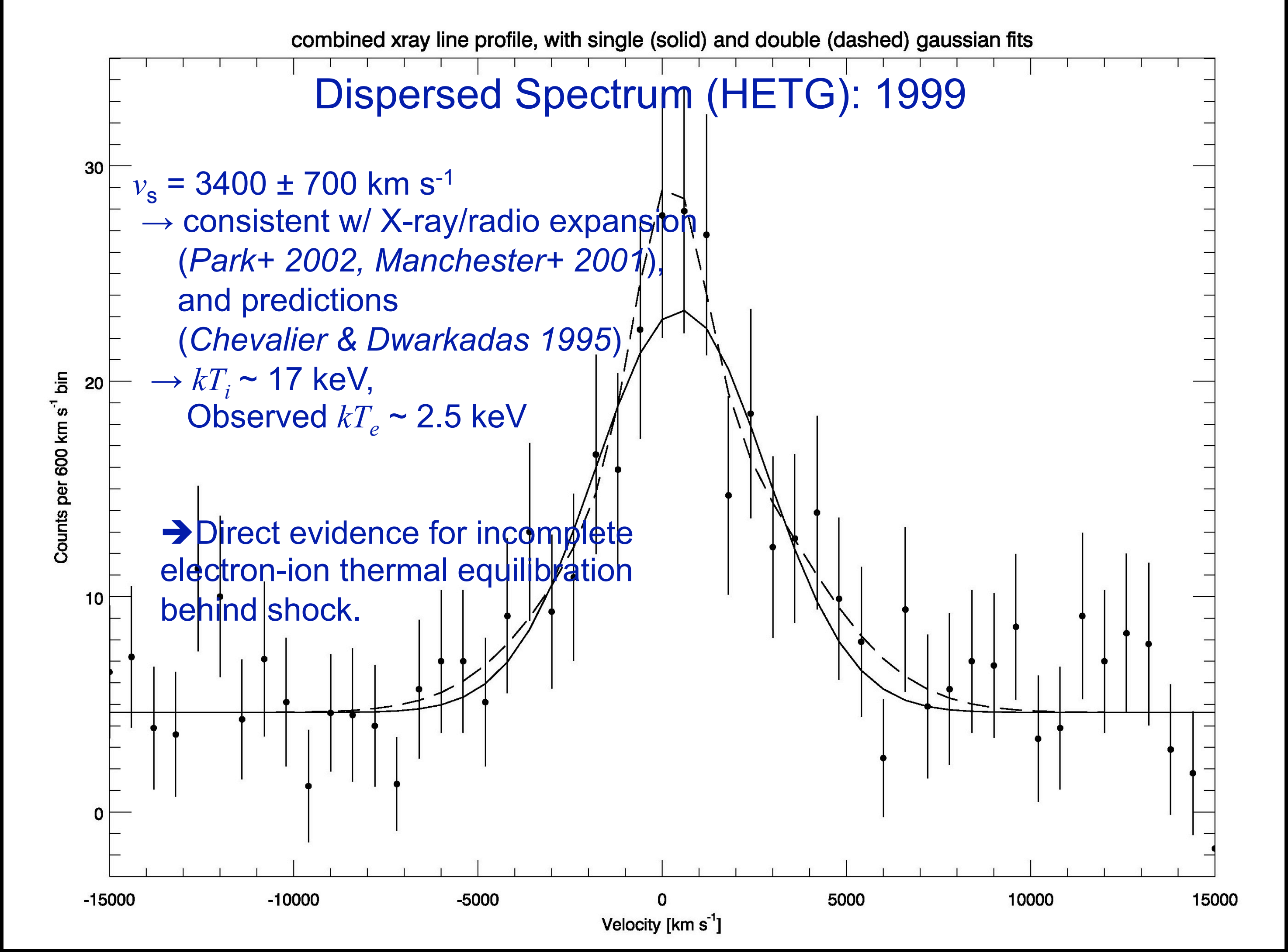
Ar=0.54, Ca=0.34

Fe=0.19, Ni=0.62

=> Shocked CSM (no ejecta)

SNR 1987A: Dispersed Spectrum 1999

Michael+ 2002, ApJ, 574, 166



SNR 1987A: Dispersed Spectrum 2004

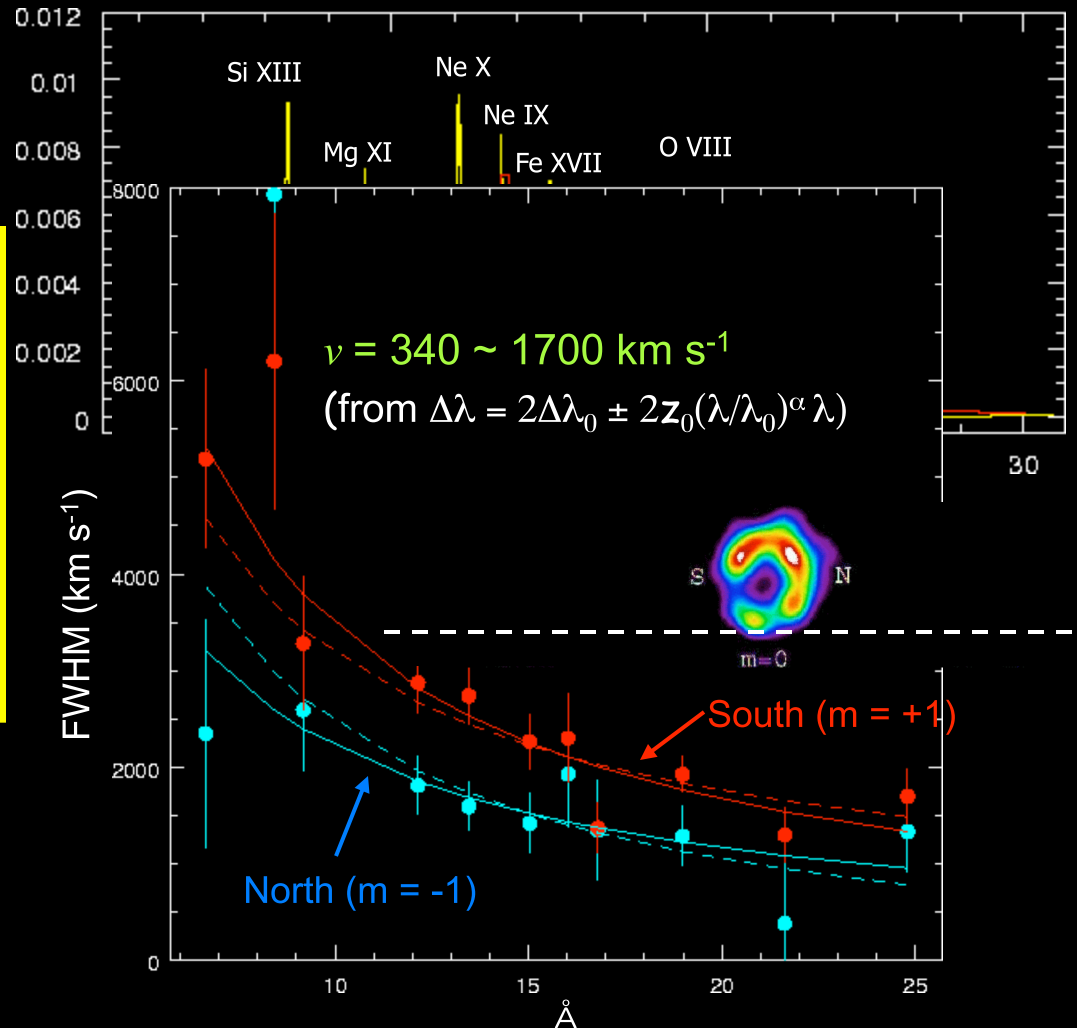
Zhekov+ 2005, ApJ, 628, L127
Zhekov+ 2006, ApJ, 645, 293

(Line Profiles & Kinematics)

LETG/ACIS-S:
289 ks in 2004-8/9
(day 6400)

X-ray lines are resolved w/ good photon statistics.

Individual line widths are measured.

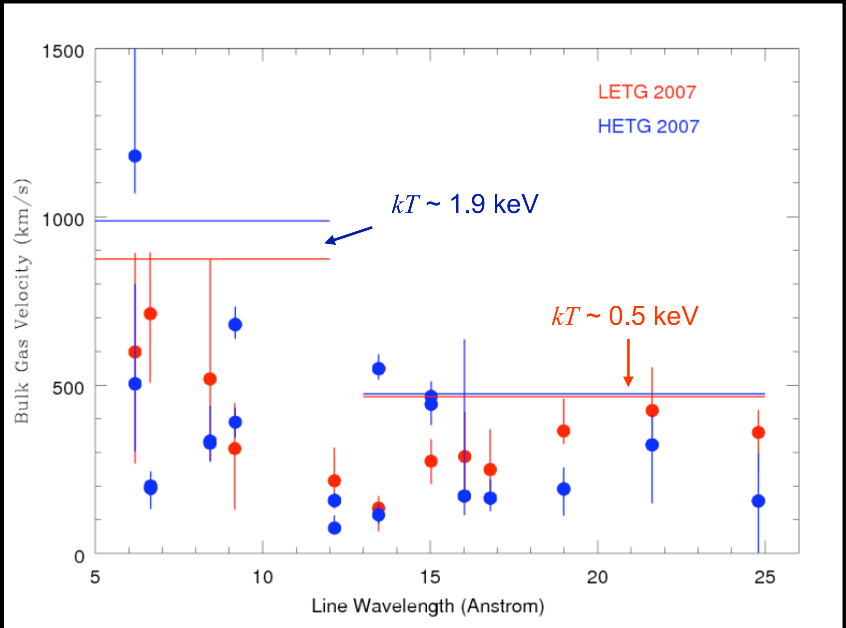


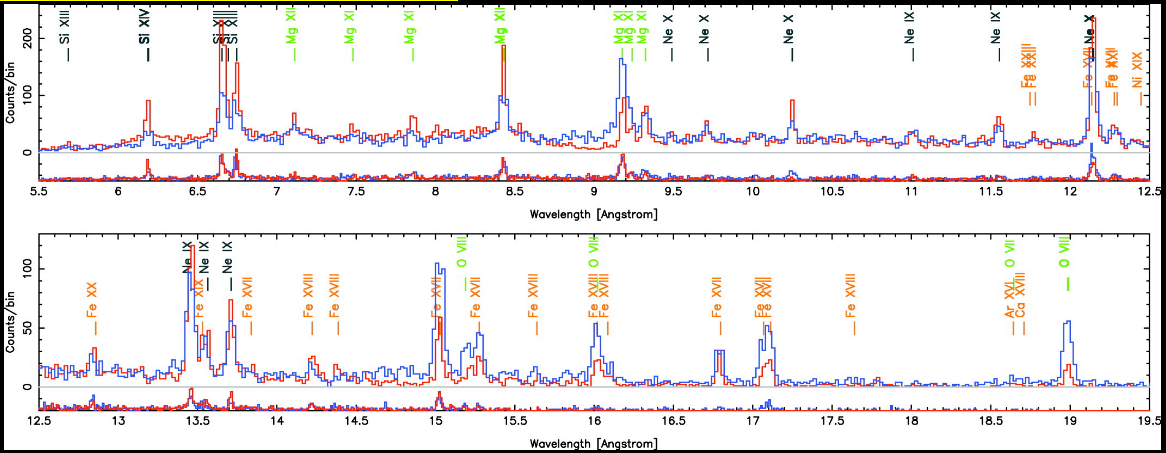
SNR 1987A: Dispersed Spectrum 2007

Dewey+ 2008, ApJ, 676, L131
Zhekov+ 2009, ApJ, 692, 1190

Deep HETG (355 ks) & LETG (285 ks) observations in 2007.
Two characteristic shock model fit: kT ~ 0.5 and 2 keV.
- Soft kT is constant (~0.5 keV).
- Hard kT decreases (2.7 → 1.9 keV).

Bulk gas velocities measured by the line widths are v ~ 150-700 km s^{-1}, while v ~ 500-1000 km s^{-1} as derived from the fitted electron temperatures.
Lower bulk motion velocities suggest a contribution from the reflected shock.



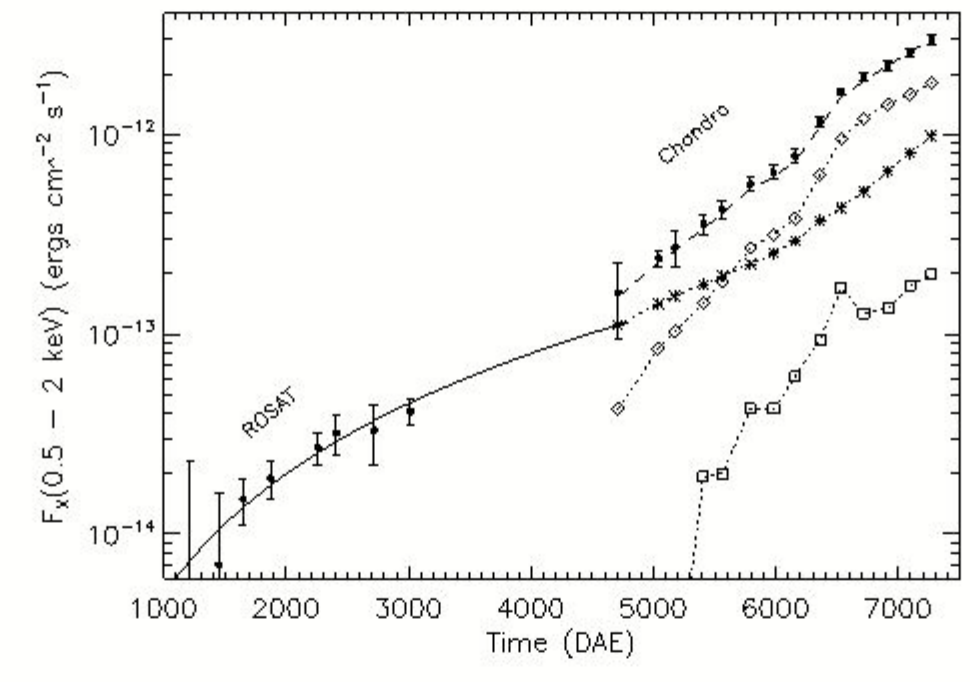


SNR 1987A: 3-Shock Structure?

Zhekov+ 2009, ApJ, 692, 1190
Zhekov+ 2010, MNRAS, 407, 1157

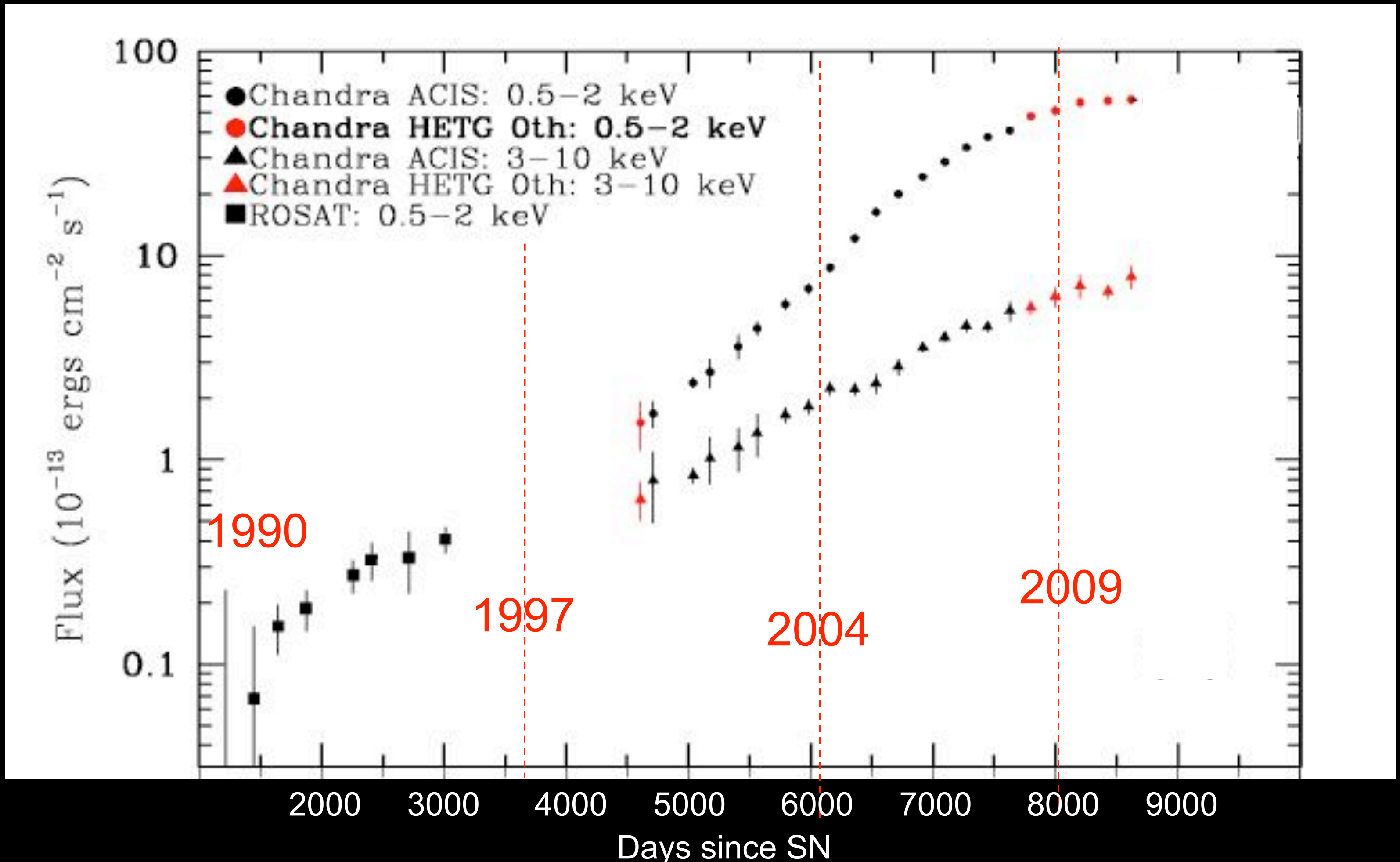
- 1-D picture of Blast wave + Transmitted + Reflected Shocks: EM ratios between components are related with T, $n_e\, t$, and n jump condition using standard solutions for strong plane shock (*Zhekov+ 2009, 2010*).

→ A steep increase of transmitted (and reflected) shock comp at ~6000 days BW comp can be extrapolated back to early ROSAT fluxes.



SNR 1987A: Flattening of Soft X-Ray Light Curve since ~2009

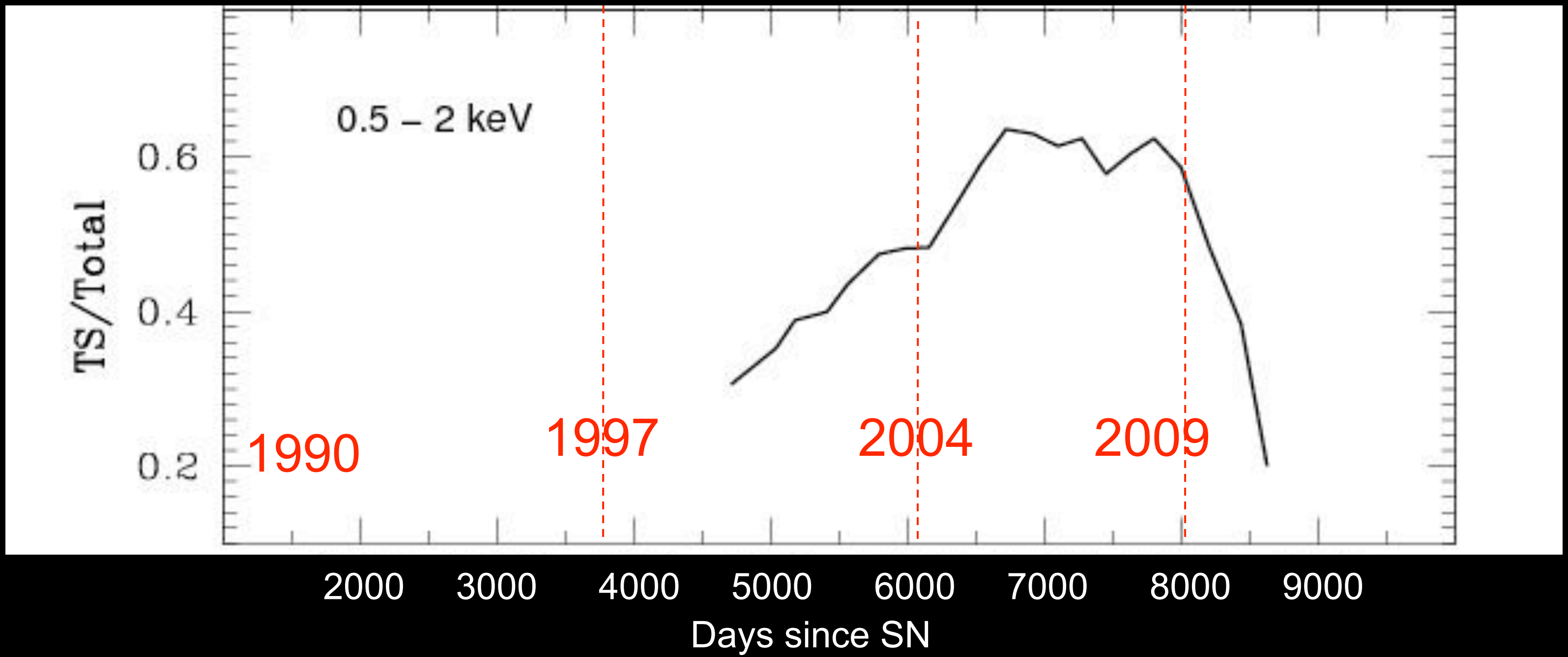
Park+ 2011, ApJ, 733, L35



Has the blast wave reached a density peak of the inner ring?

SNR 1987A: Decrease of Slow Shock Emission since ~2009

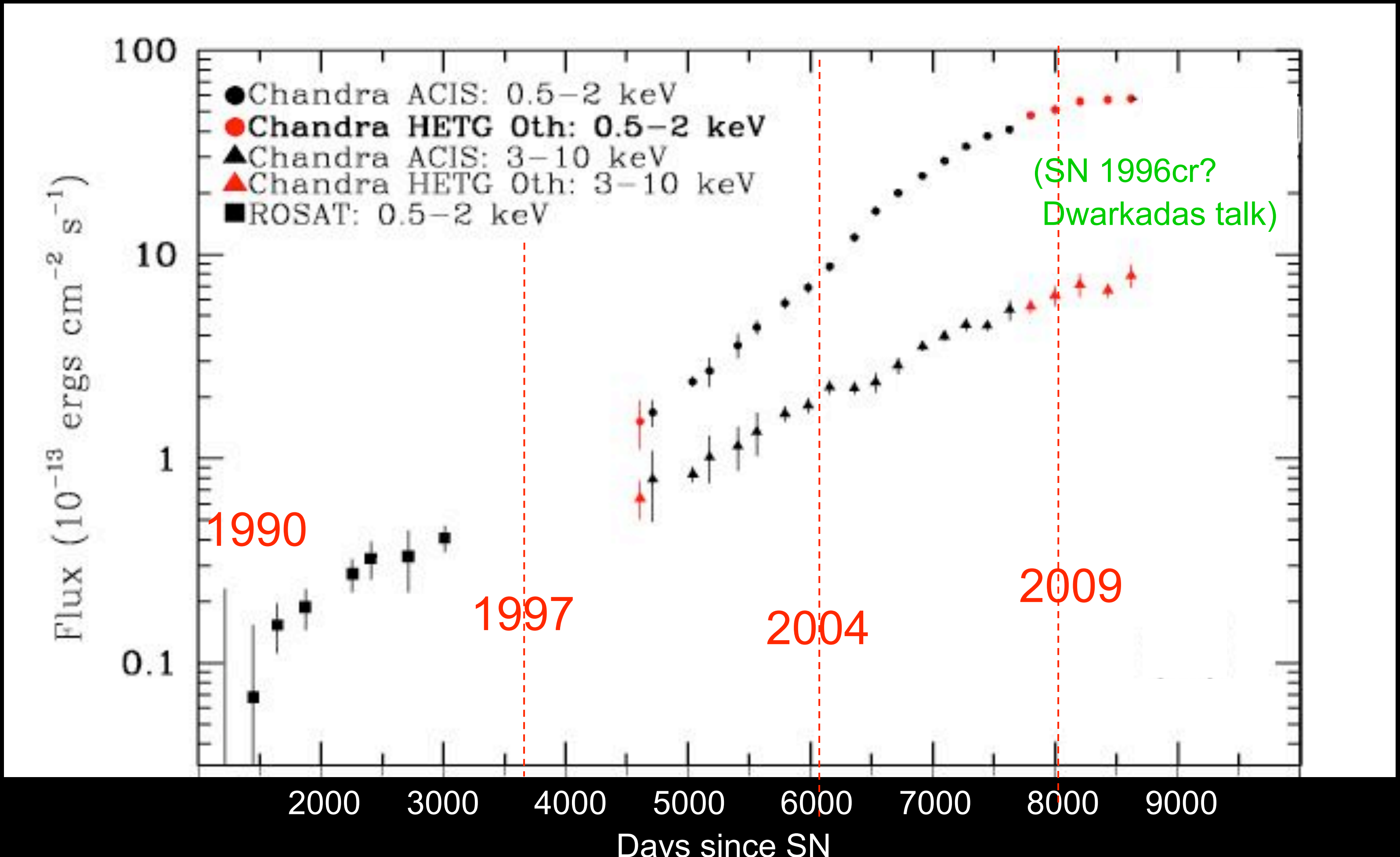
Park+ 2011, ApJ, 733, L35



The 3-shock component model (transmitted, BW, and reflected shocks, *Zhekov+ 2010*) fit shows a significant drop of the fractional contribution from the transmitted shock into the highest density since ~2009.

SNR 1987A: A New Phase

Park+ 2011, ApJ, 733, L35



The soft LC may decrease ($f \propto t^{-1}$) **IF** the shock is entering RSG wind ($\rho \propto r^{-2}$).

SNR 1987A: Probing RSG/BSG/LBV Winds

SNR is dominated by emission from blast wave interaction with dense equatorial CSM ("the inner ring").

Blast wave reached dense "protrusions" in ~1997.

Blast wave reached the main body of inner ring in ~2004.

Since ~2009, the soft X-ray light curve has flattened: Possibilities include the case that the blast wave may be propagating into the progenitor's RSG wind ($\rho \propto r^{-2}$) beyond the inner ring.

With our continuing Chandra monitoring, we will directly probe the nature of the progenitor's winds (density and chemical structures), thus trace back what was going on with the progenitor star before SN explosion – true evolutionary path of the star.

We are searching for the neutron star at the SNR's center!

SNR 1987A: Compact Remnant?

The central point source has not been detected. Stellar ejecta at the center of the SNR might still be optically thick in X-rays.

Assuming a PL spectrum (Γ = 1.7–3.0), upper limits on the embedded point source has been placed:

- Based on the ACIS image on 2004-7, a point source upper limit is $L_{X,\text{2-10 keV}} \sim 10^{34}$ erg s^{-1} for $N_H = 2 \times 10^{21}$ cm^{-2}.

- Based on the HRC image on 2008-4, a point source upper limit is $L_{X,\text{2-10 keV}} \sim 3 \times 10^{34}$ erg s^{-1} for $N_H = 1.3 \times 10^{21}$ cm^{-2} (Ng+ 09).

→ Will ALMA help (unless an AXP) ?

SNR 1987A: ACIS Time-lapse movie 2000–2009

Thank you

and

60 More Happy Returns, Claes!

To be continued..