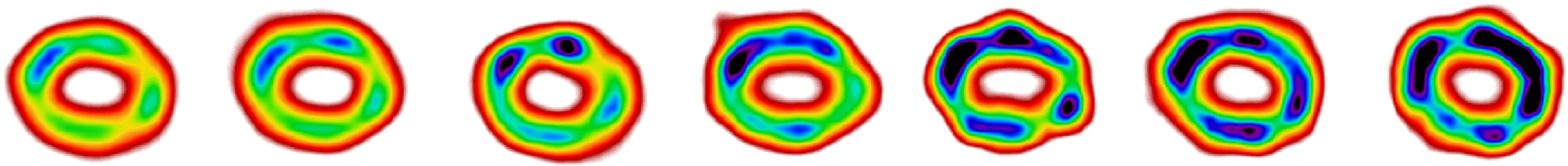
David Burrows
Svet Zhekov
Sangwook Park
Dick McCray
Eli Dwek

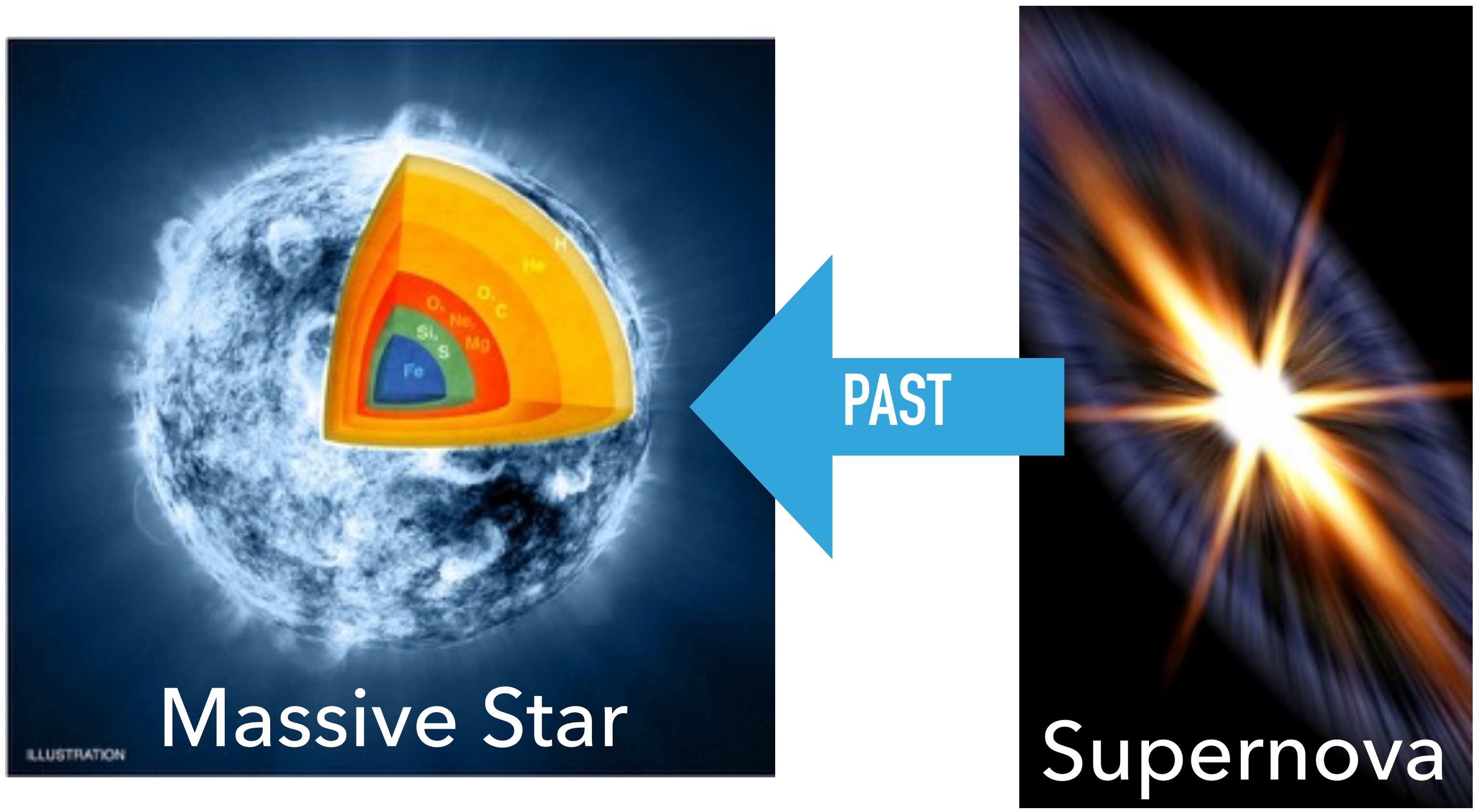
Kari A. Frank
Penn State University



CHANDRA OBSERVATIONS OF SN 1987A

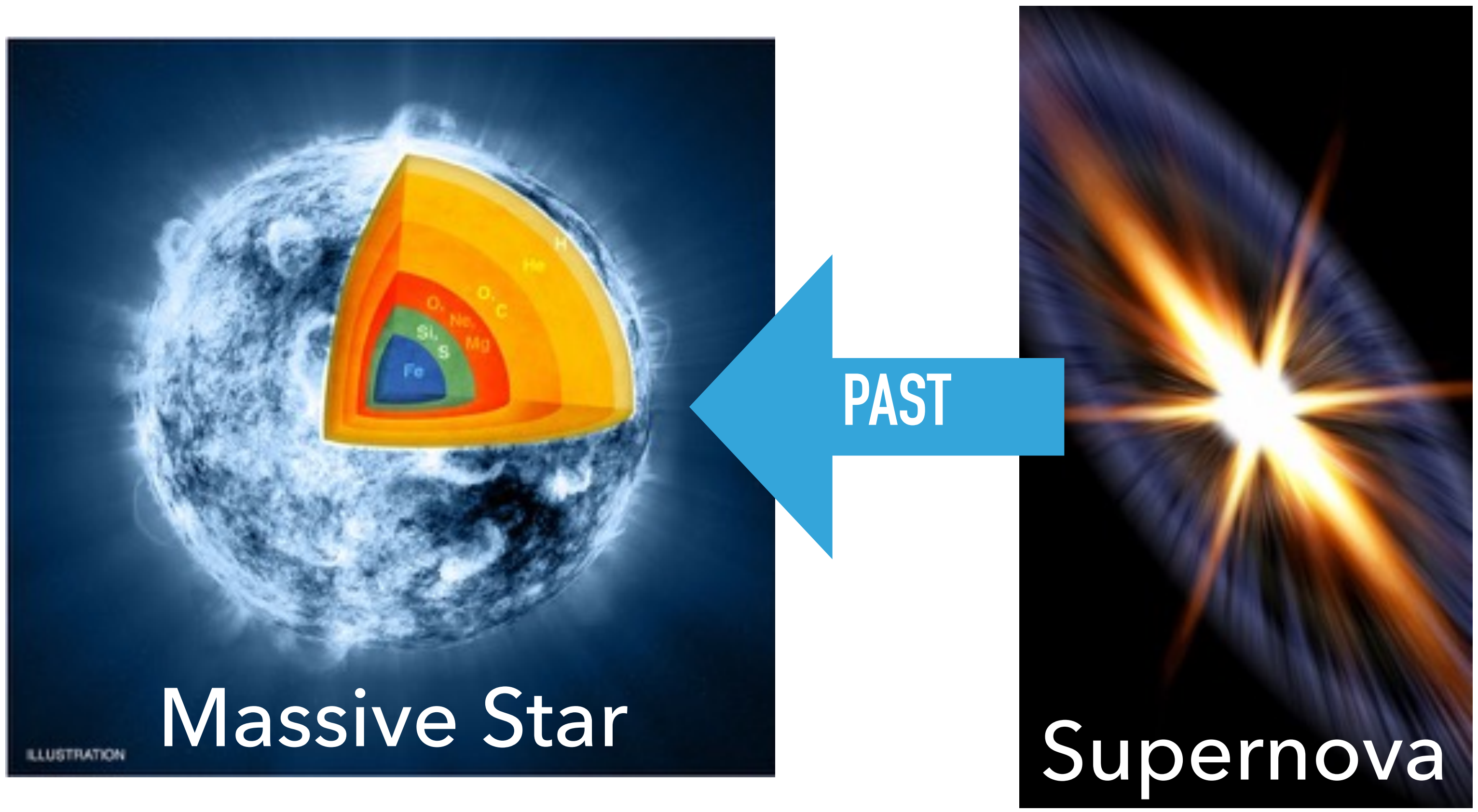
An unprecedented view of the life and death of a blue supergiant

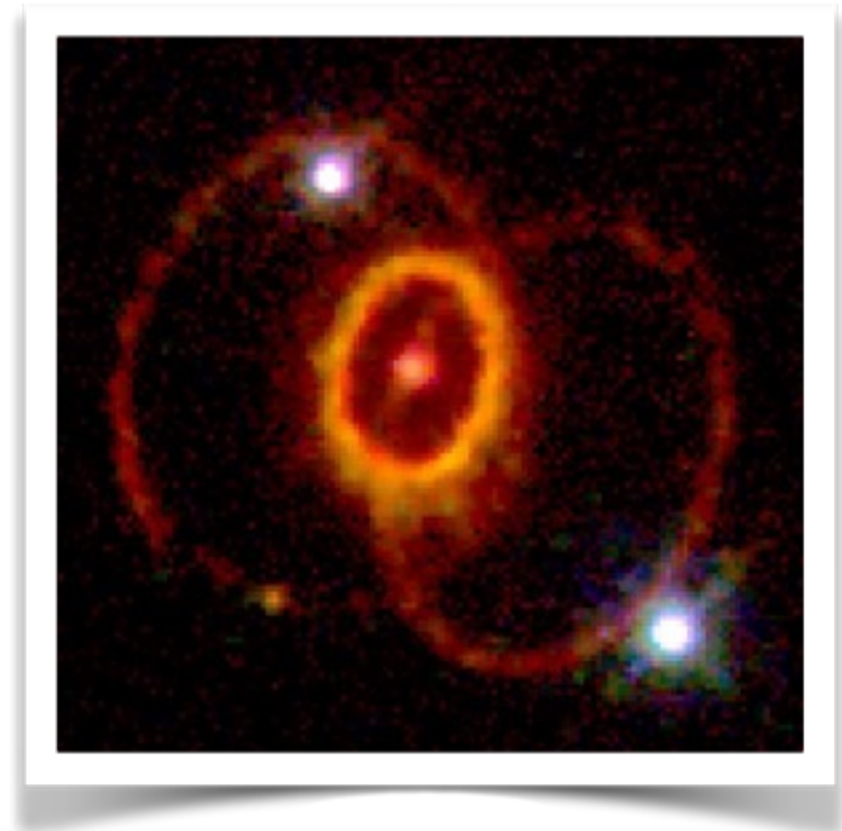
WINDOW INTO THE PAST



- Probe CSM Structure
- Ejecta morphology/abundances linked to
  => Explosion mechanism
  => Progenitor properties

WINDOW INTO THE PAST





- Probe CSM Structure
- Ejecta morphology/abundances linked to
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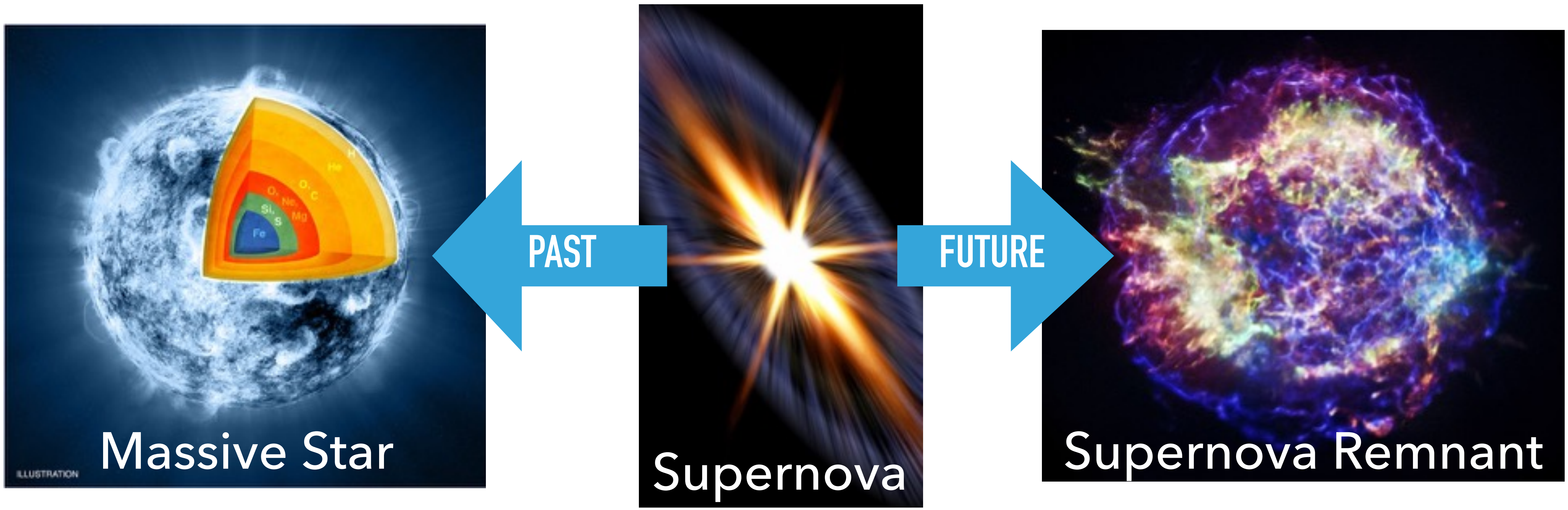
WINDOW INTO THE PAST AND FUTURE



- Probe CSM Structure
- Ejecta morphology/abundances linked to
  => Explosion mechanism
  => Progenitor properties

- Destruction of CSM
- Dust formation/destruction?
- Evolution of ejecta
- Shock physics
- Cosmic rays
- Effect of SN/CSM on later SNR?
- Pulsar/PWN formation?

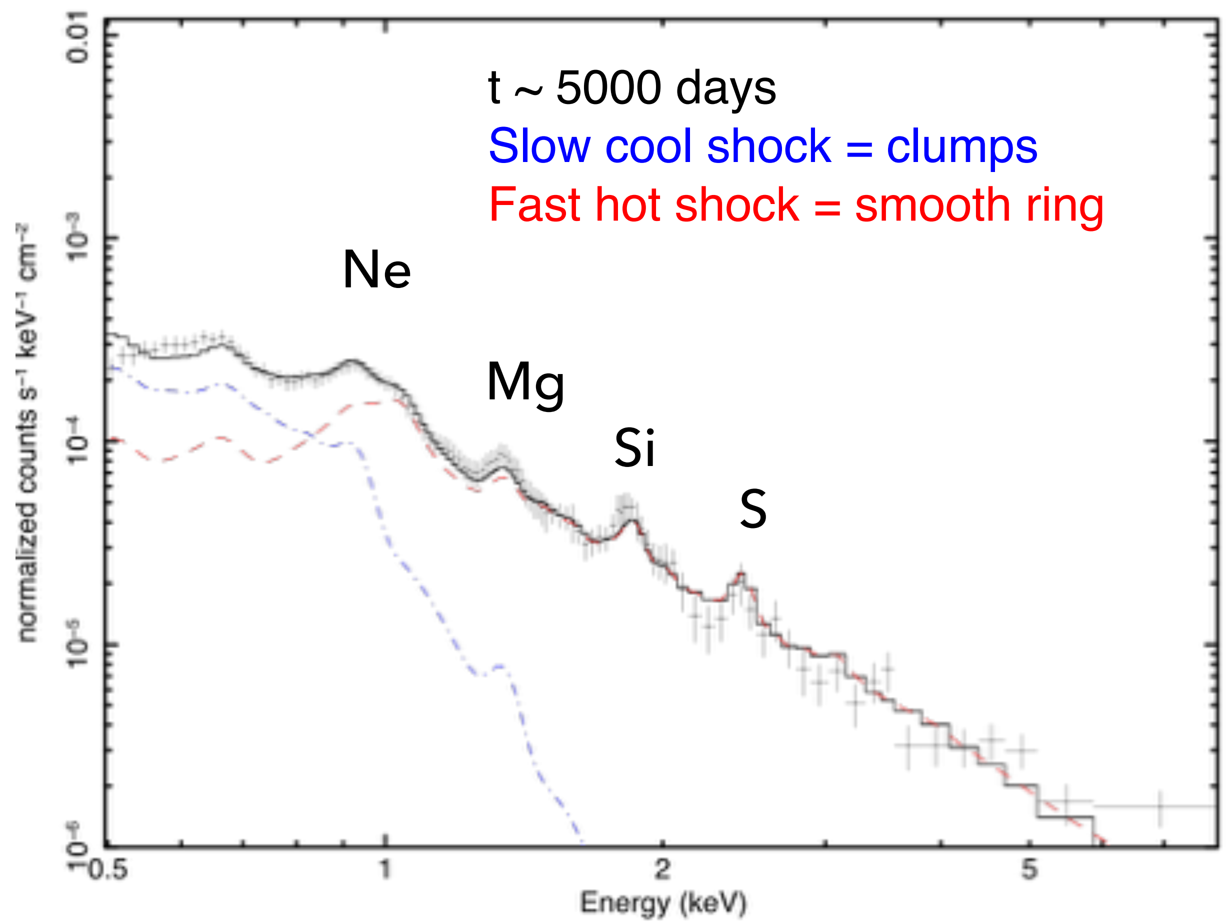
CHANDRA ACIS MONITORING CAMPAIGN

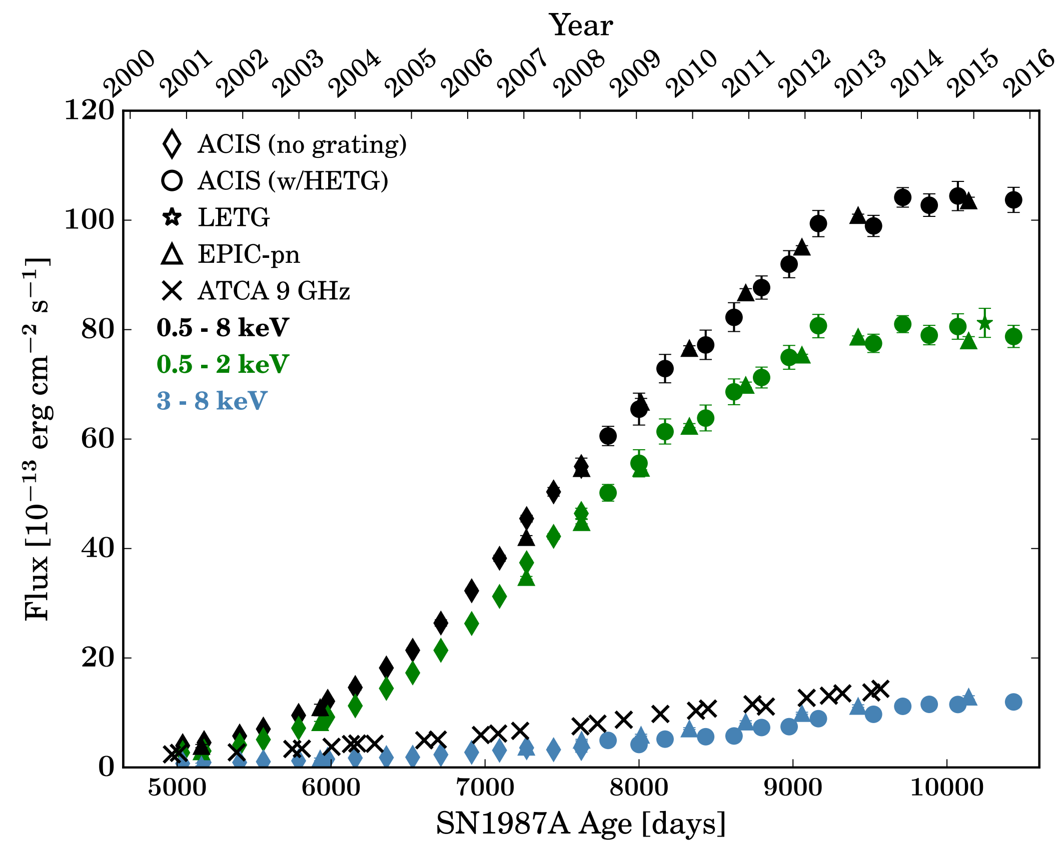
- ~6 month intervals for 16 years = 32 epochs
- Complementary to monitoring campaigns in optical, IR, radio, submm
- Burrows+(2000), Michael+(2002), Park+(2002,2004,2005,2006,2007,2011), Zhekov+ (2005,2006,2009), Racusin+(2009), Dewey+(2012), Helder+(2013), **Frank+(2016)**

Date	Age	Grating
1999-10-06	4608	HETG
2000-01-17	4711	NONE
2000-12-07	5036	NONE
2001-04-25	5175	NONE
2001-12-12	5406	NONE
2002-05-15	5559	NONE
2002-12-31	5789	NONE
2003-07-08	5978	NONE
2004-01-02	6157	NONE
2004-07-22	6358	NONE
2005-01-09	6529	NONE
2005-07-11	6713	NONE
2006-01-28	6913	NONE
2006-07-27	7094	NONE
2007-01-19	7270	NONE
2007-07-13	7445	NONE
2008-01-09	7624	NONE
2008-07-01	7799	HETG
2009-01-18	8000	HETG
2009-07-06	8169	HETG
2010-03-28	8232	HETG
2010-09-28	8433	HETG
2011-03-25	8617	HETG
2011-09-21	8975	HETG
2012-03-28	9165	HETG
2013-03-21	9523	HETG
2013-09-28	9713	HETG
2014-03-19	9885	HETG
2014-09-20	10071	HETG
2015-03-14	10246	HRC/LETG
2015-09-17	10433	HETG
2016-03-28	10626	HRC/LETG

SPECTROSCOPY

- temperatures
- densities
- ionization timescales
- abundances
- fluxes in multiple bands
- changes in all these over time





SPECTROSCOPY

- temperatures
- densities
- ionization timescales
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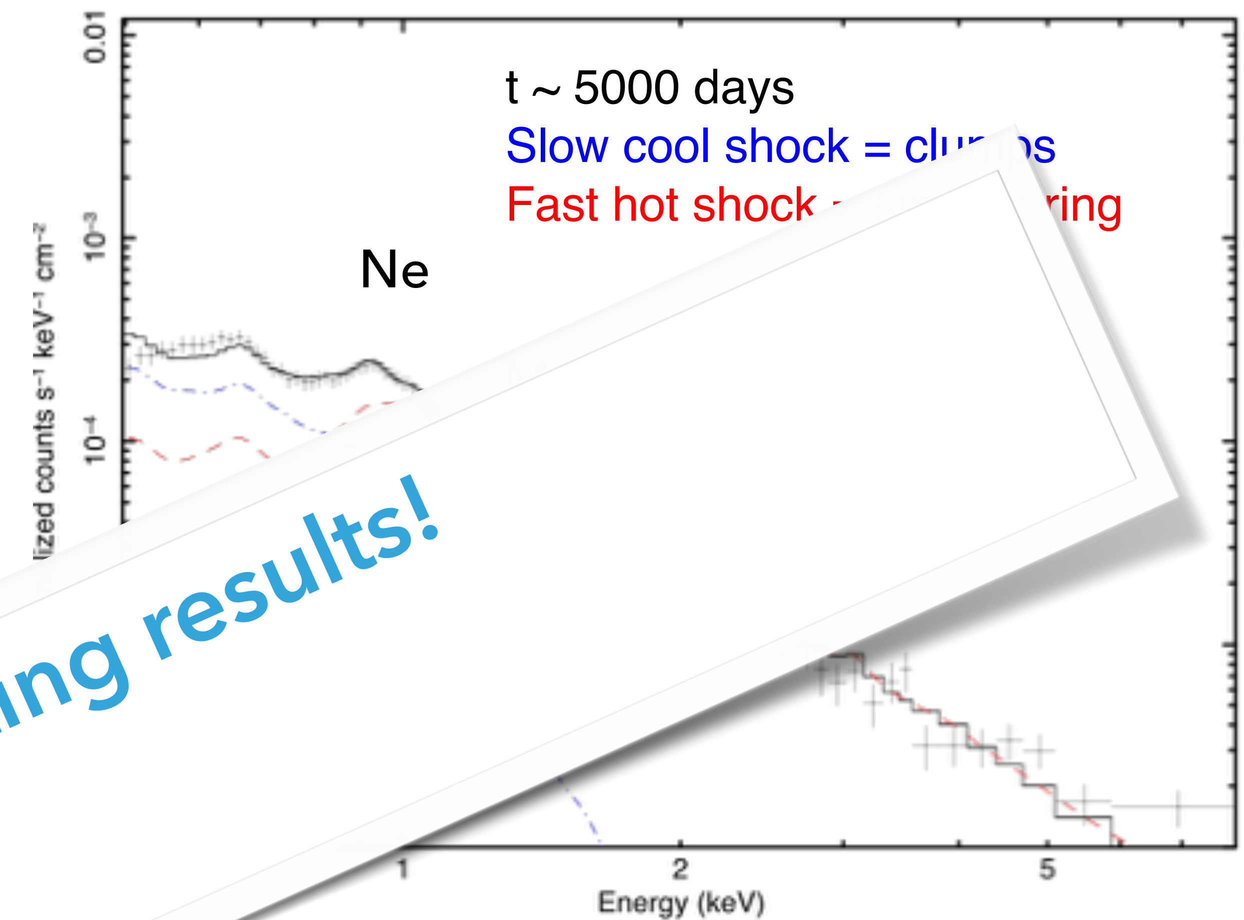
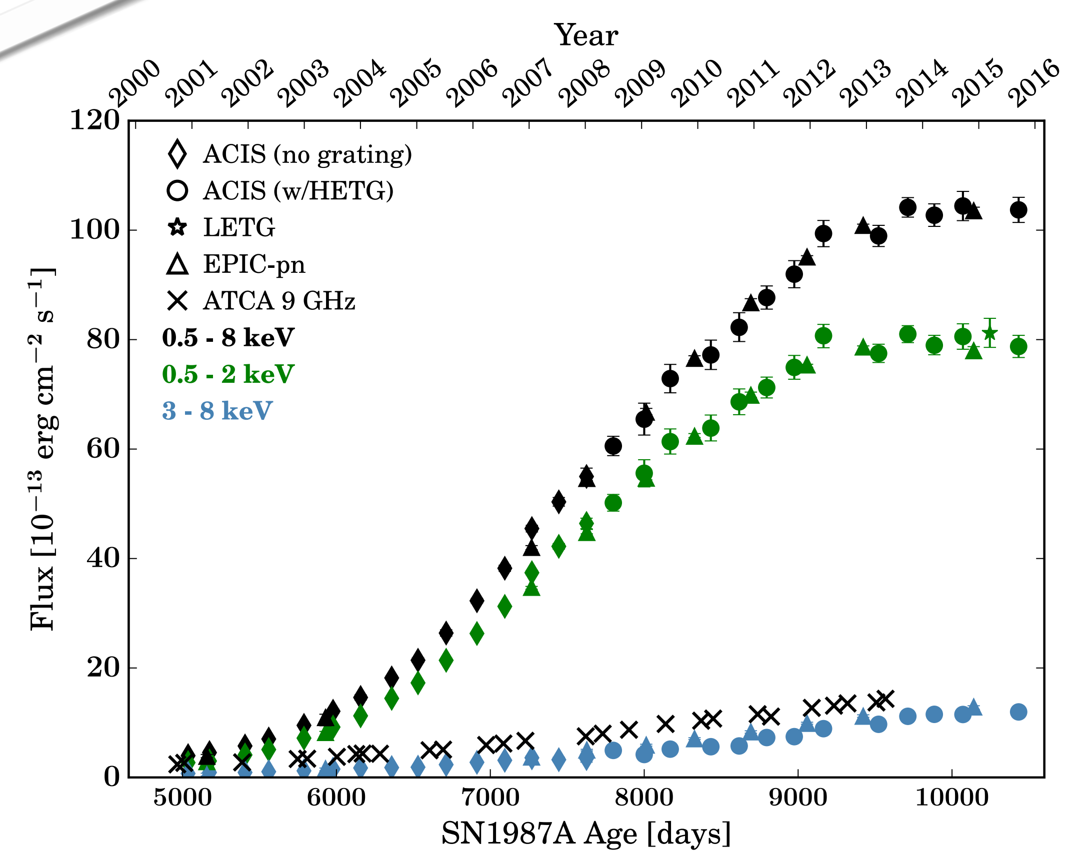
- f
- these over time





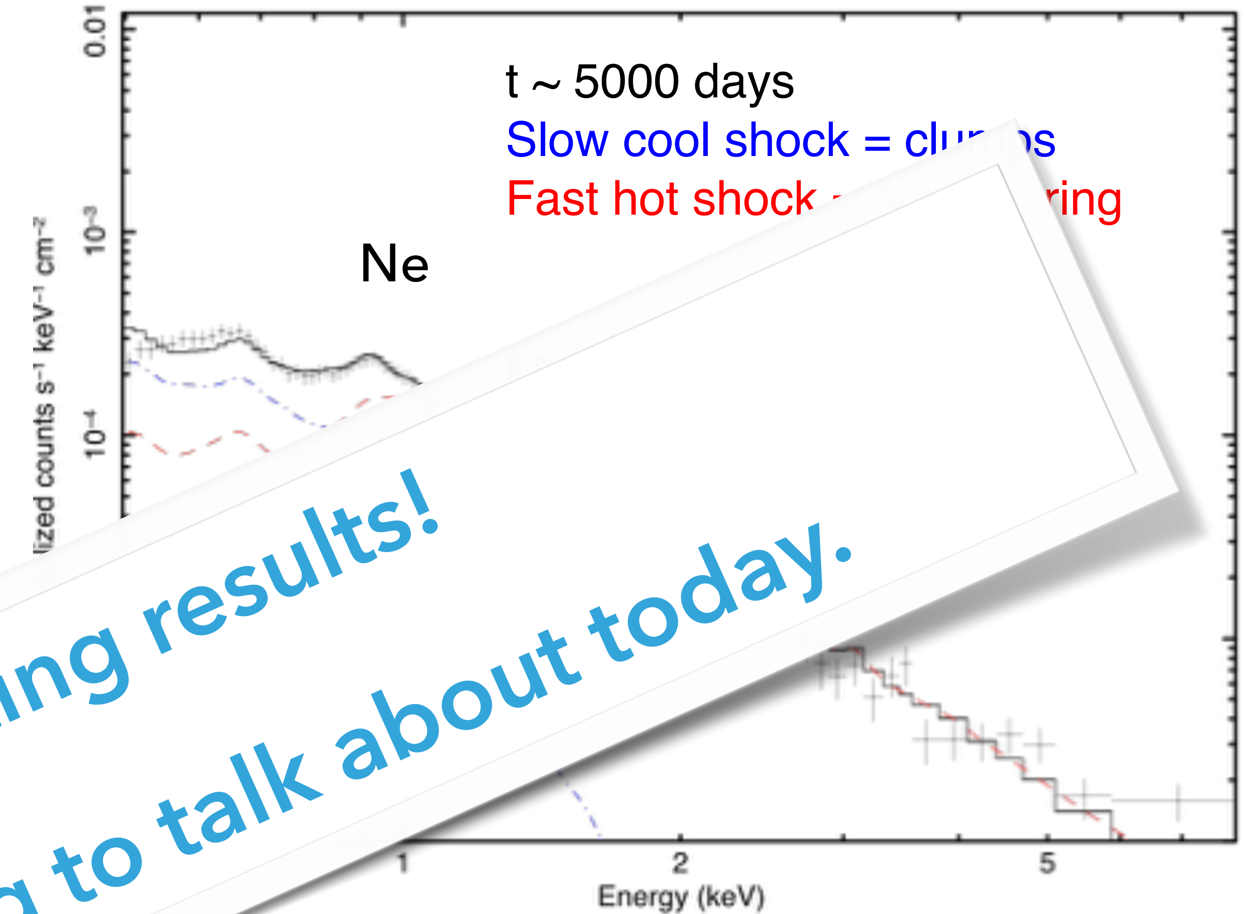
Lots of interesting results!

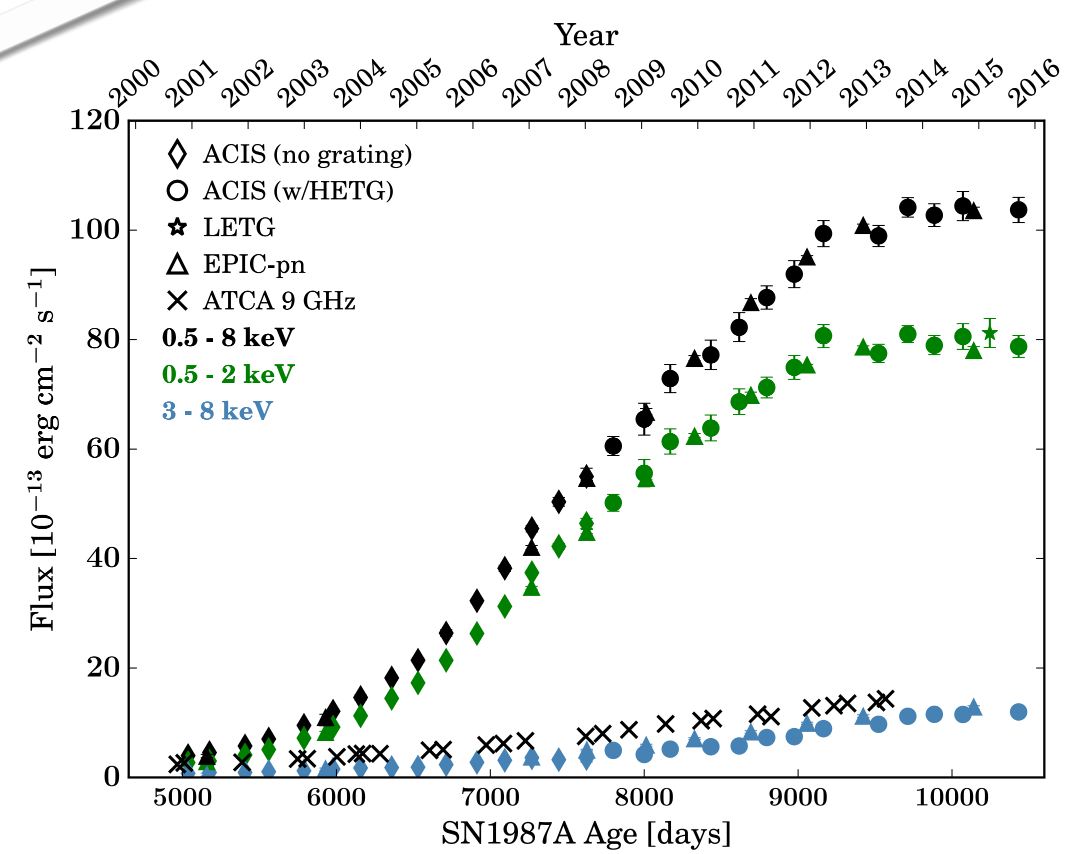
SPECTROSCOPY

- temperatures
- densities
- ionization timescales
- abundanc
- fl
- these over time

Lots of interesting results!

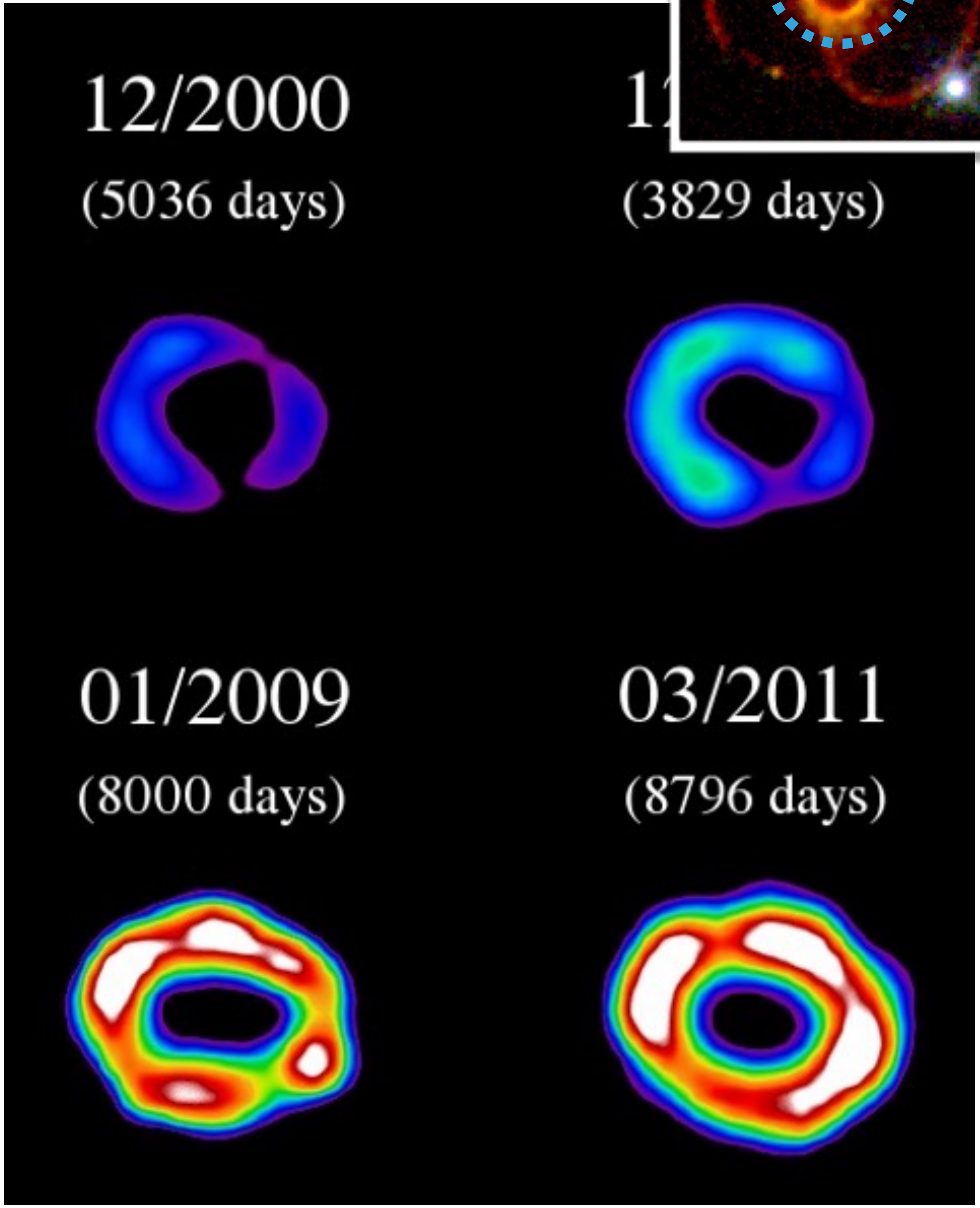
…which I'm not going to talk about today.

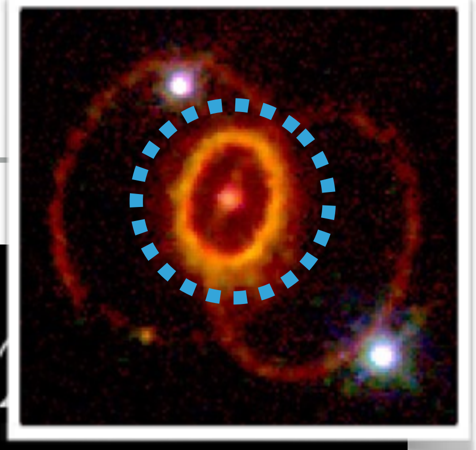




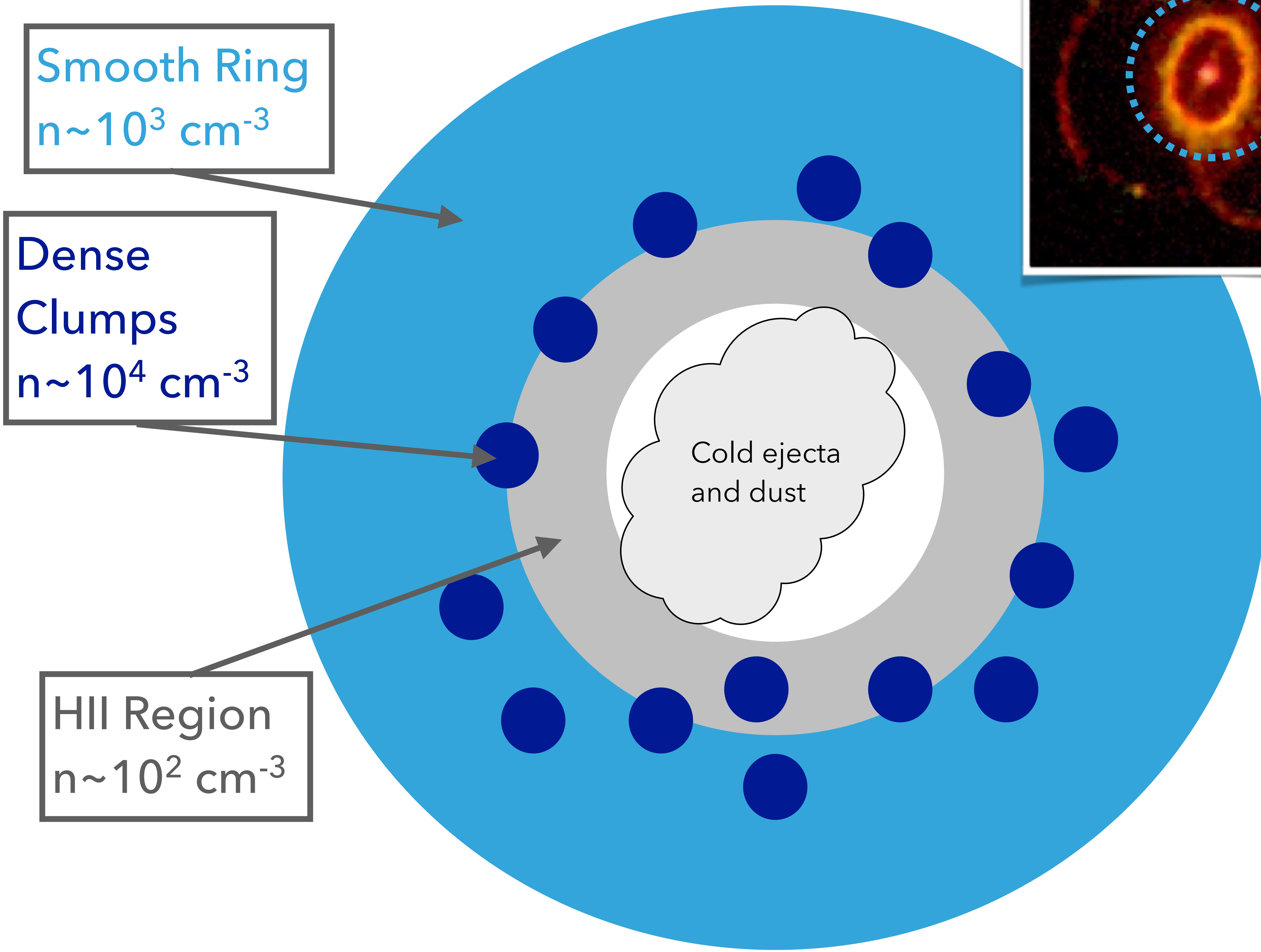
IMAGING+TIME COVERAGE

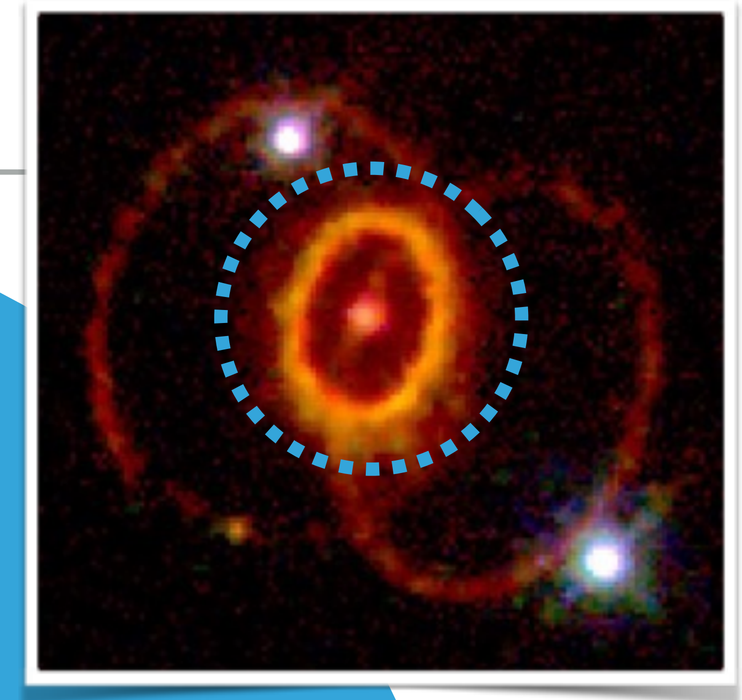
- morphology evolution
  - asymmetries
  - expansion velocities
- comparisons with other wavelengths
- timescales ~1 year





THE PICTURE SO FAR: THE EQUATORIAL RING





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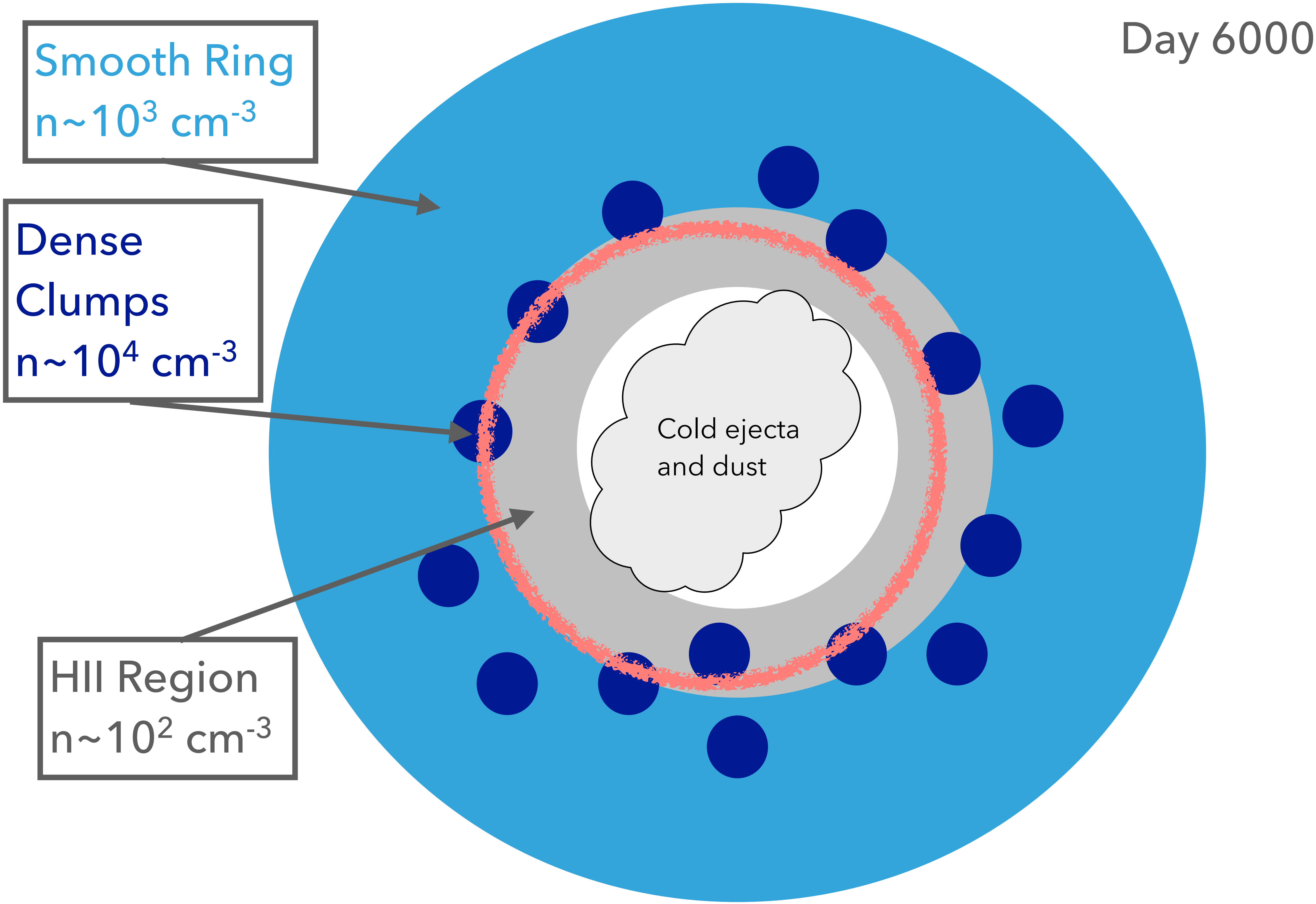

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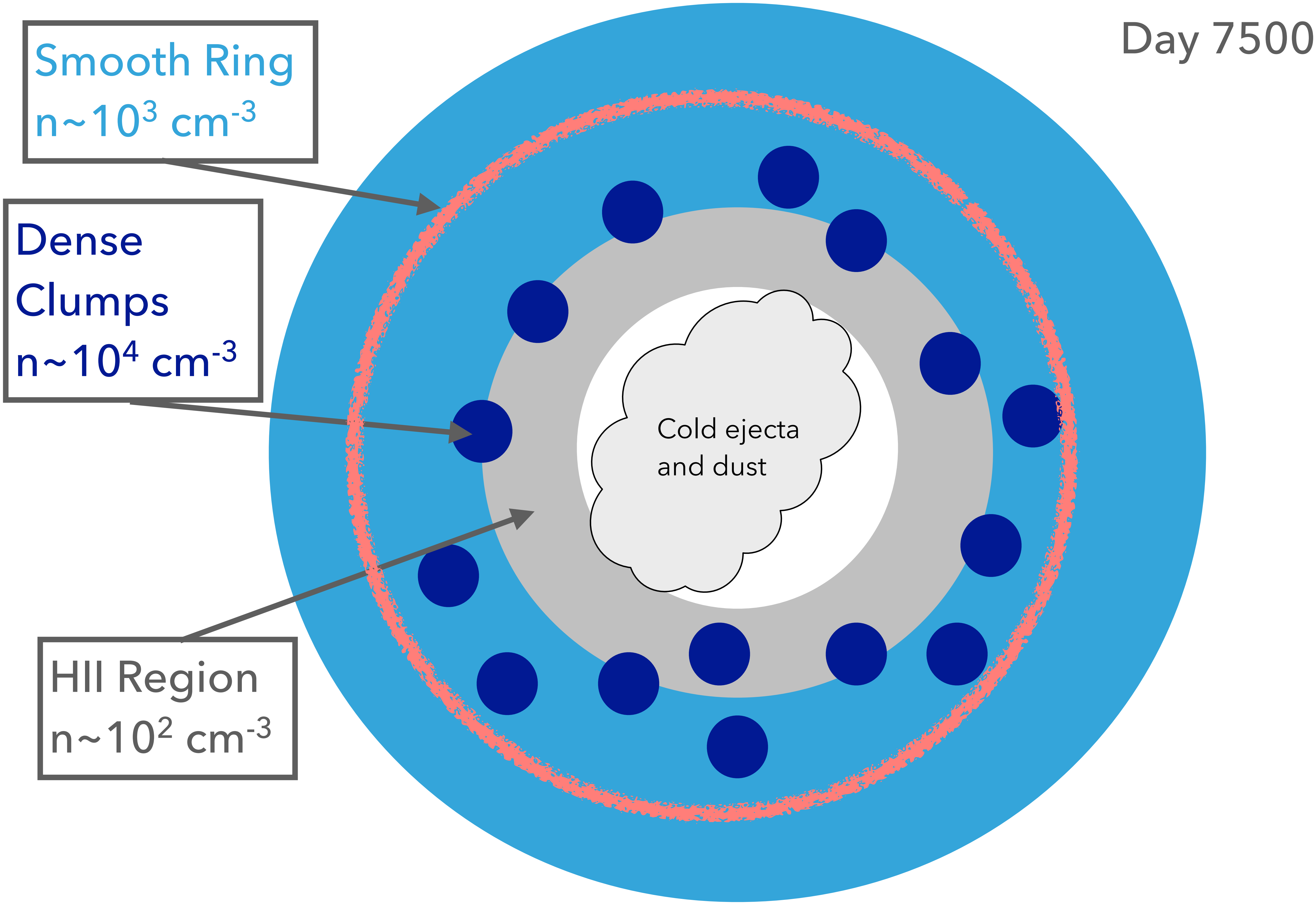
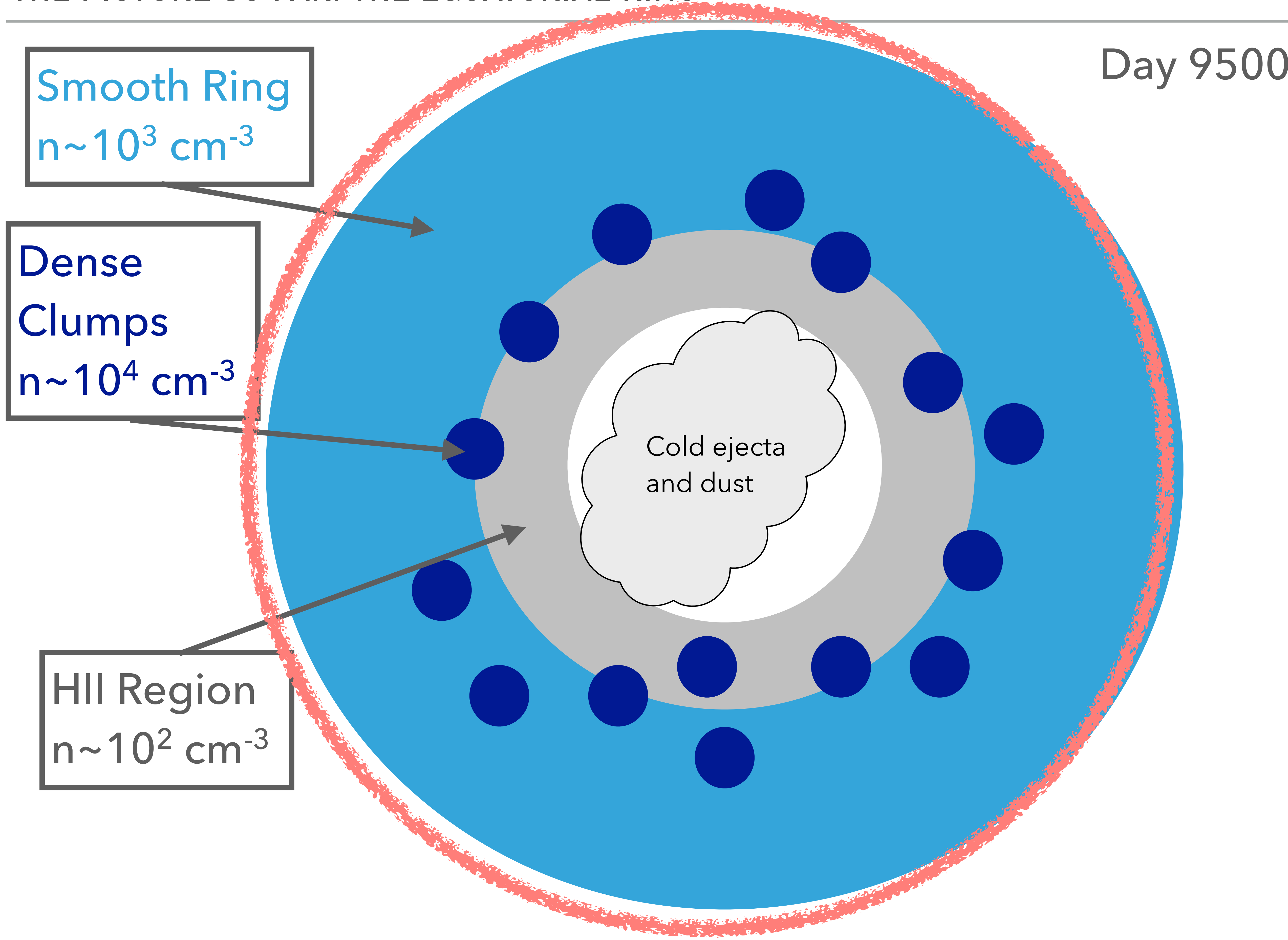
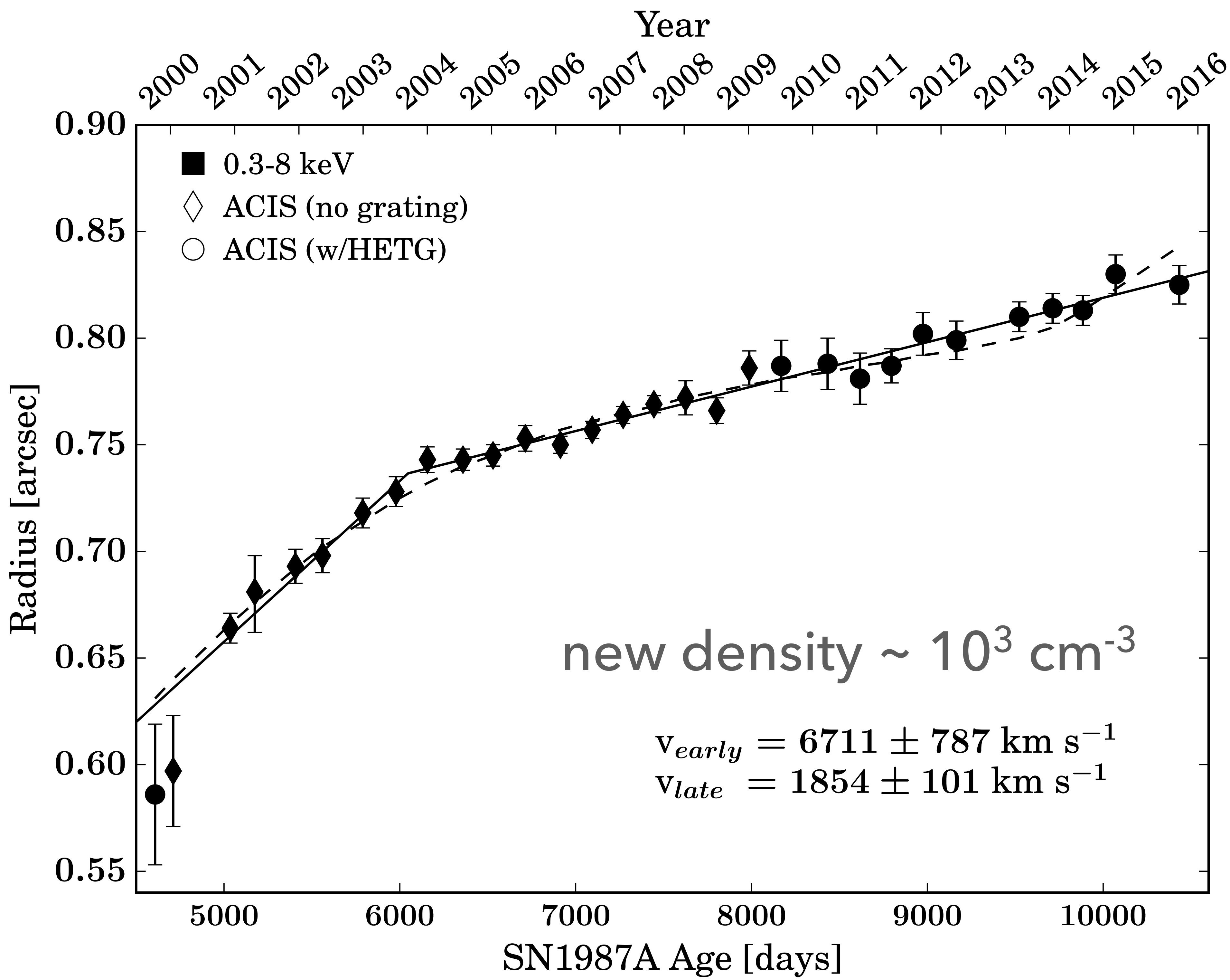


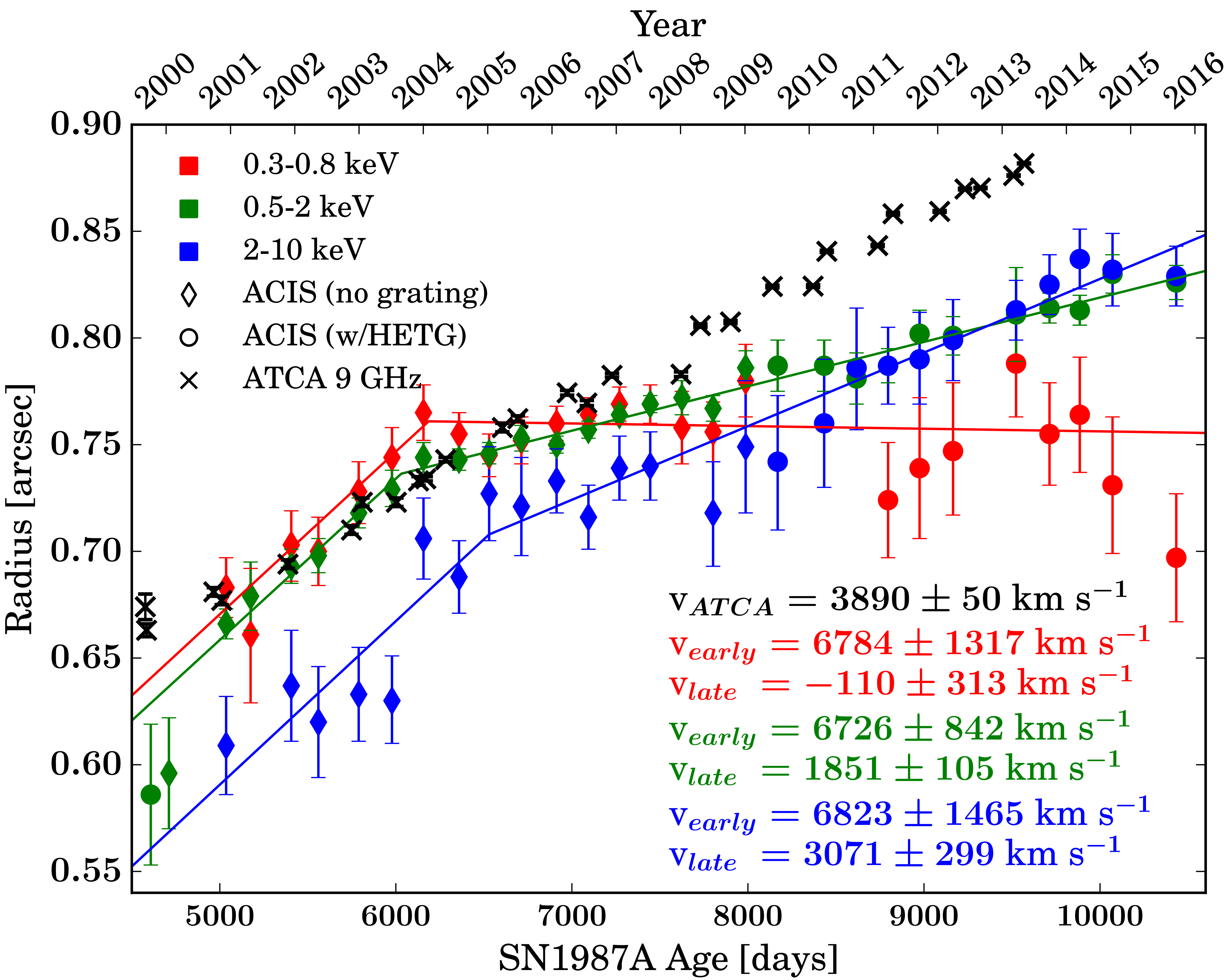
THE PICTURE SO FAR: THE EQUATORIAL RING



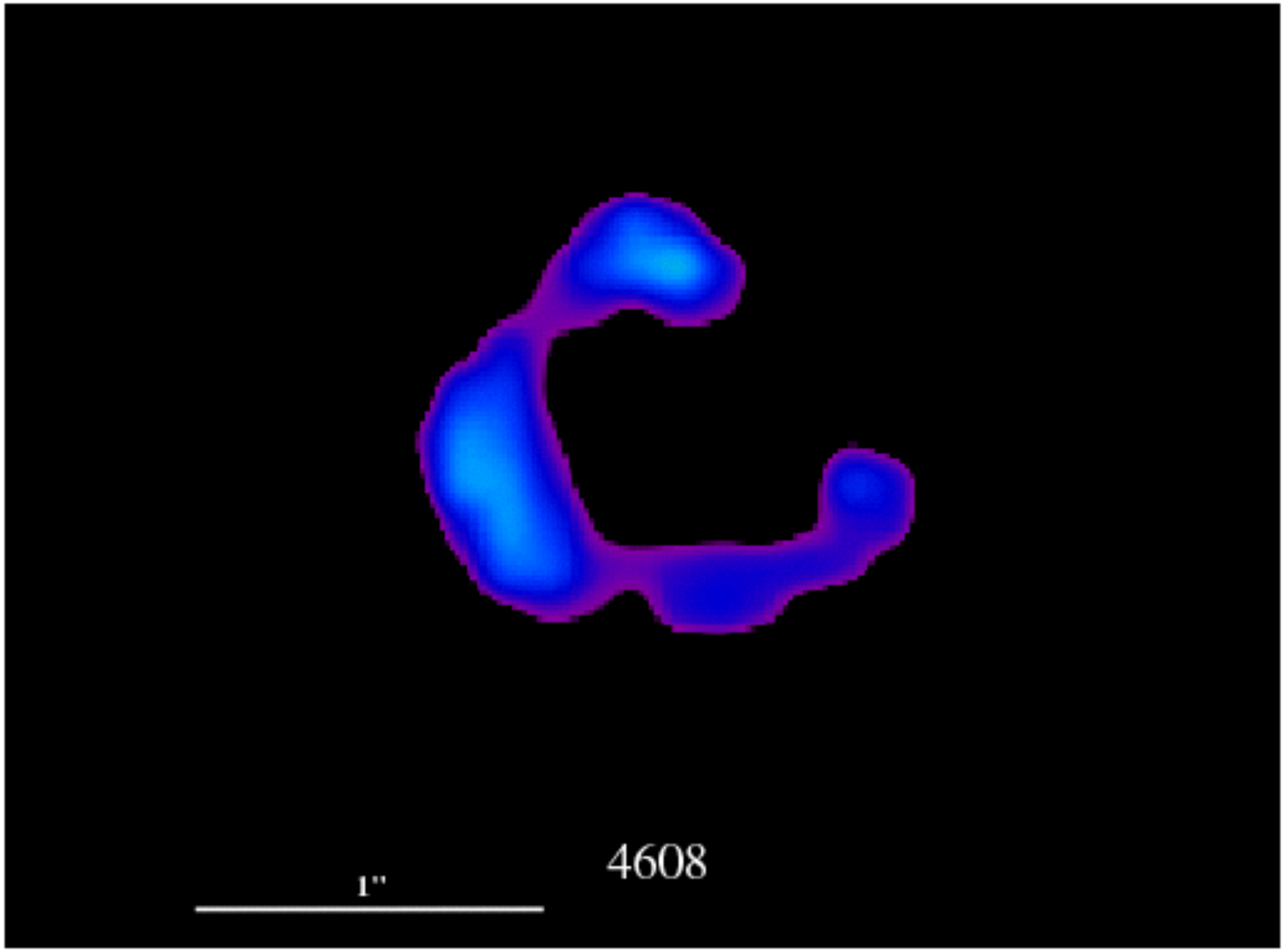
COLLISION WITH SMOOTH RING



ENERGY DEPENDENT EXPANSION



ASYMMETRIC EVOLUTION AND END OF CLUMP INTERACTION



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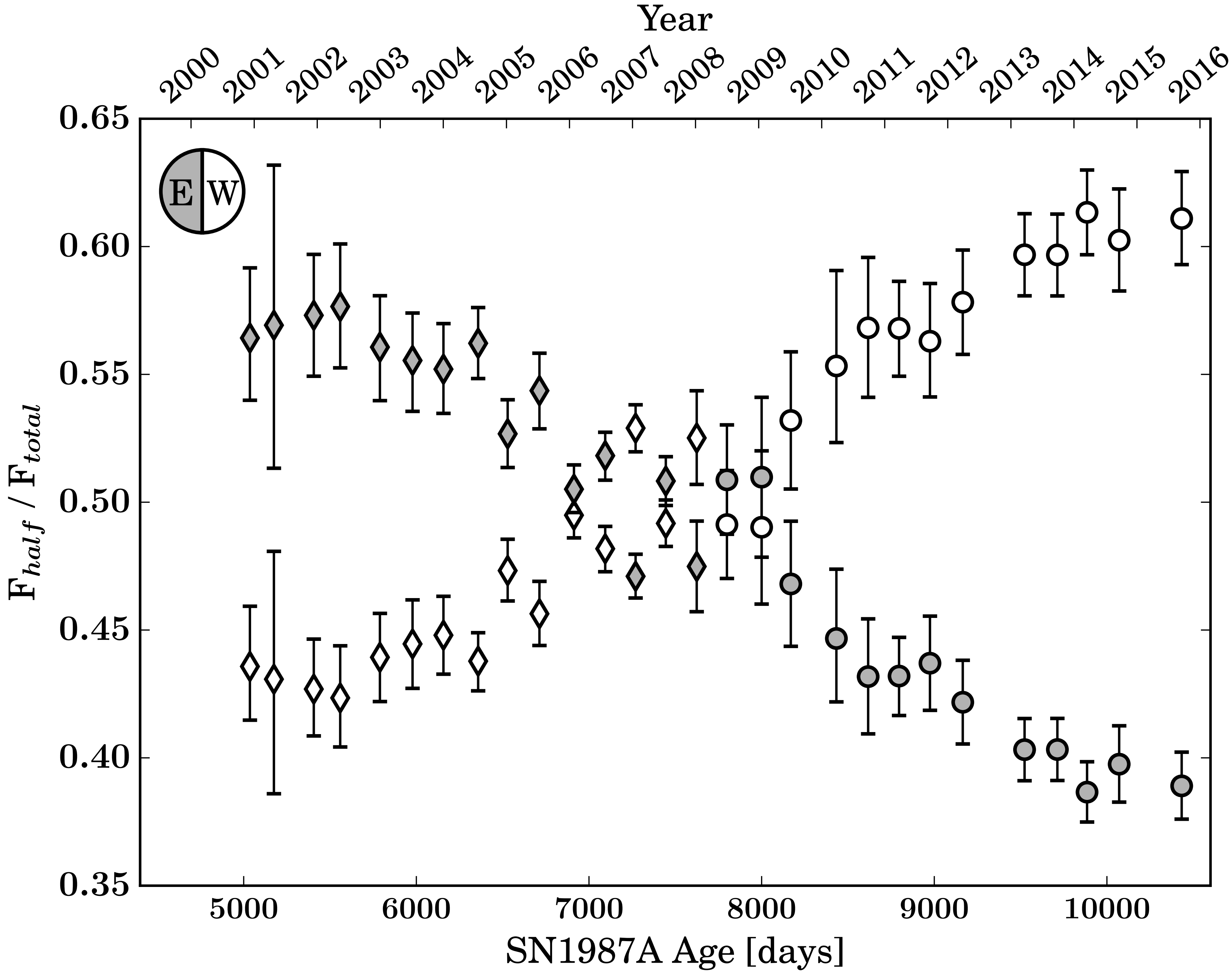
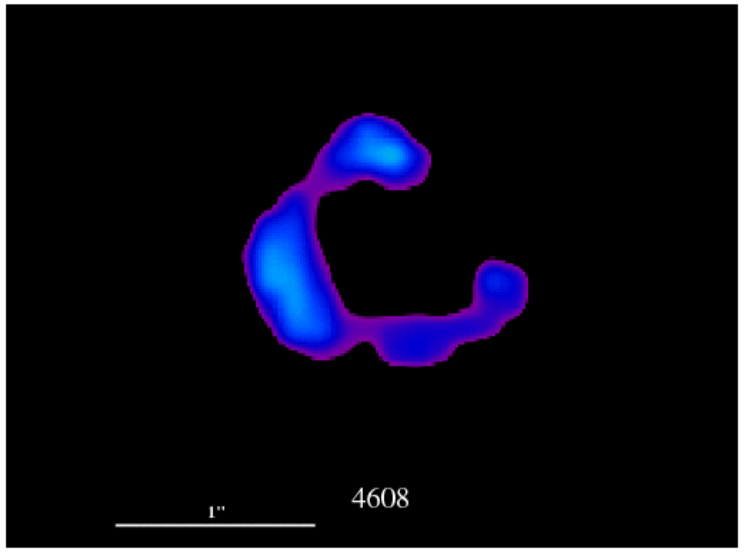
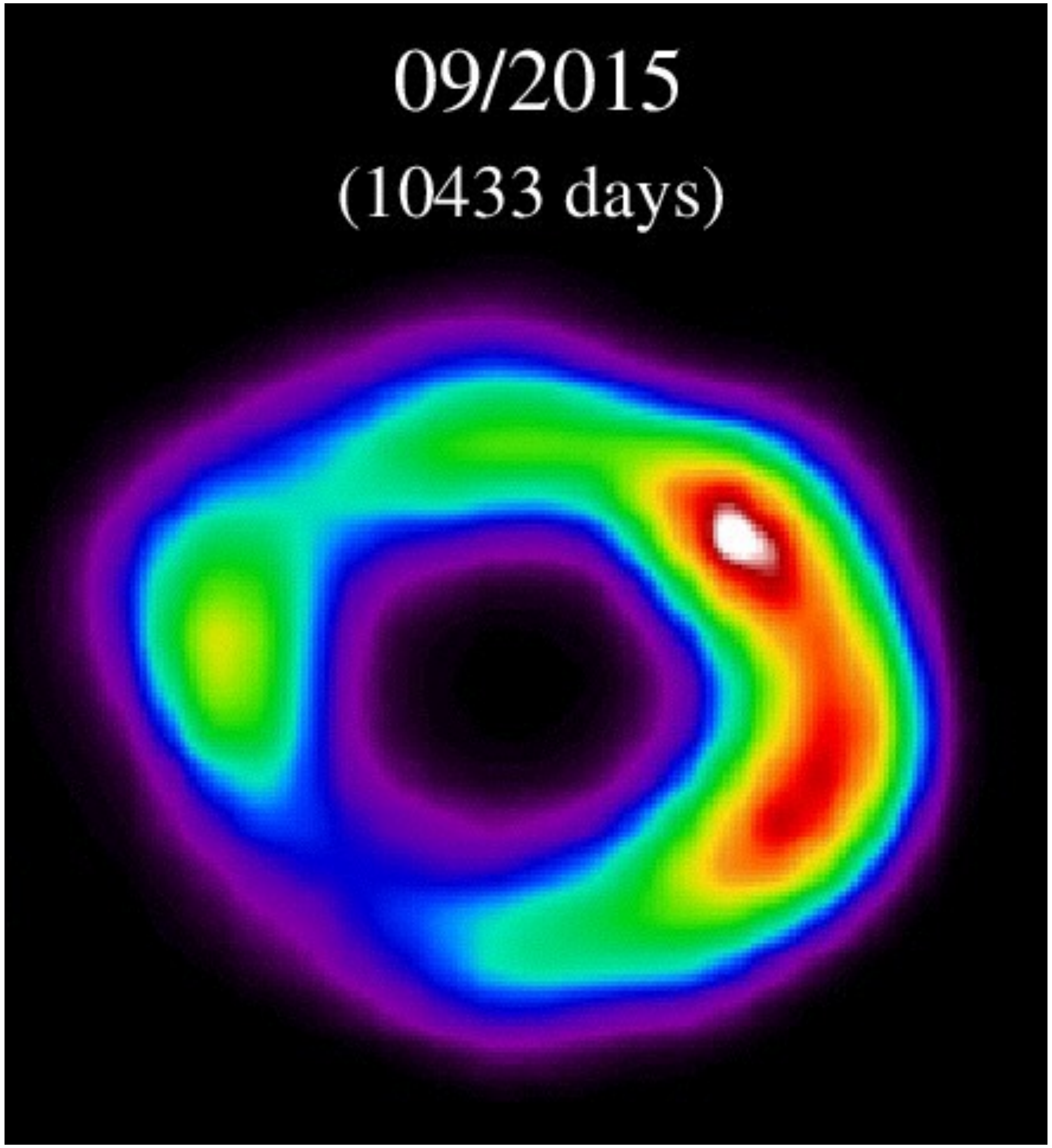




EXITING THE RING



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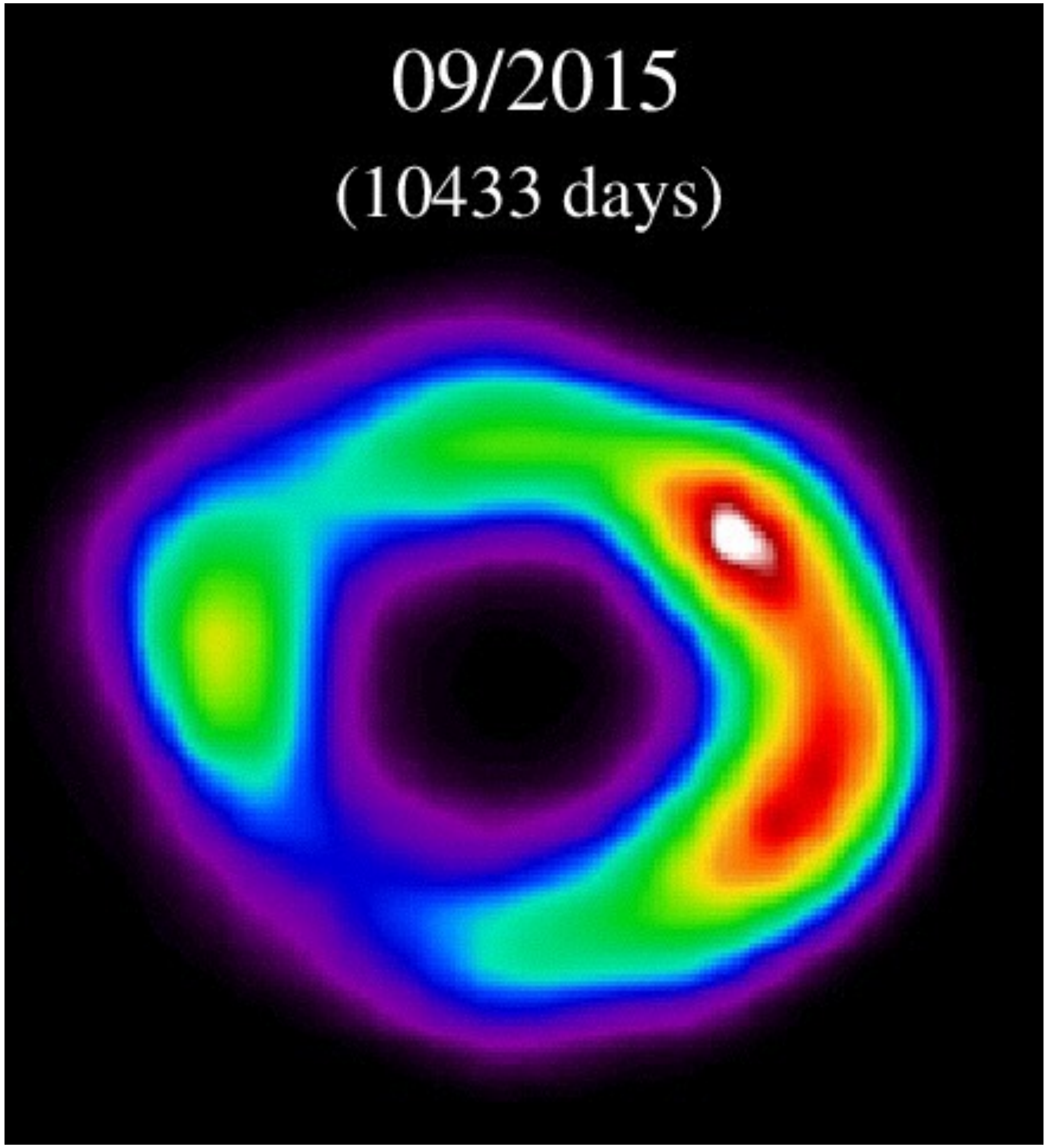
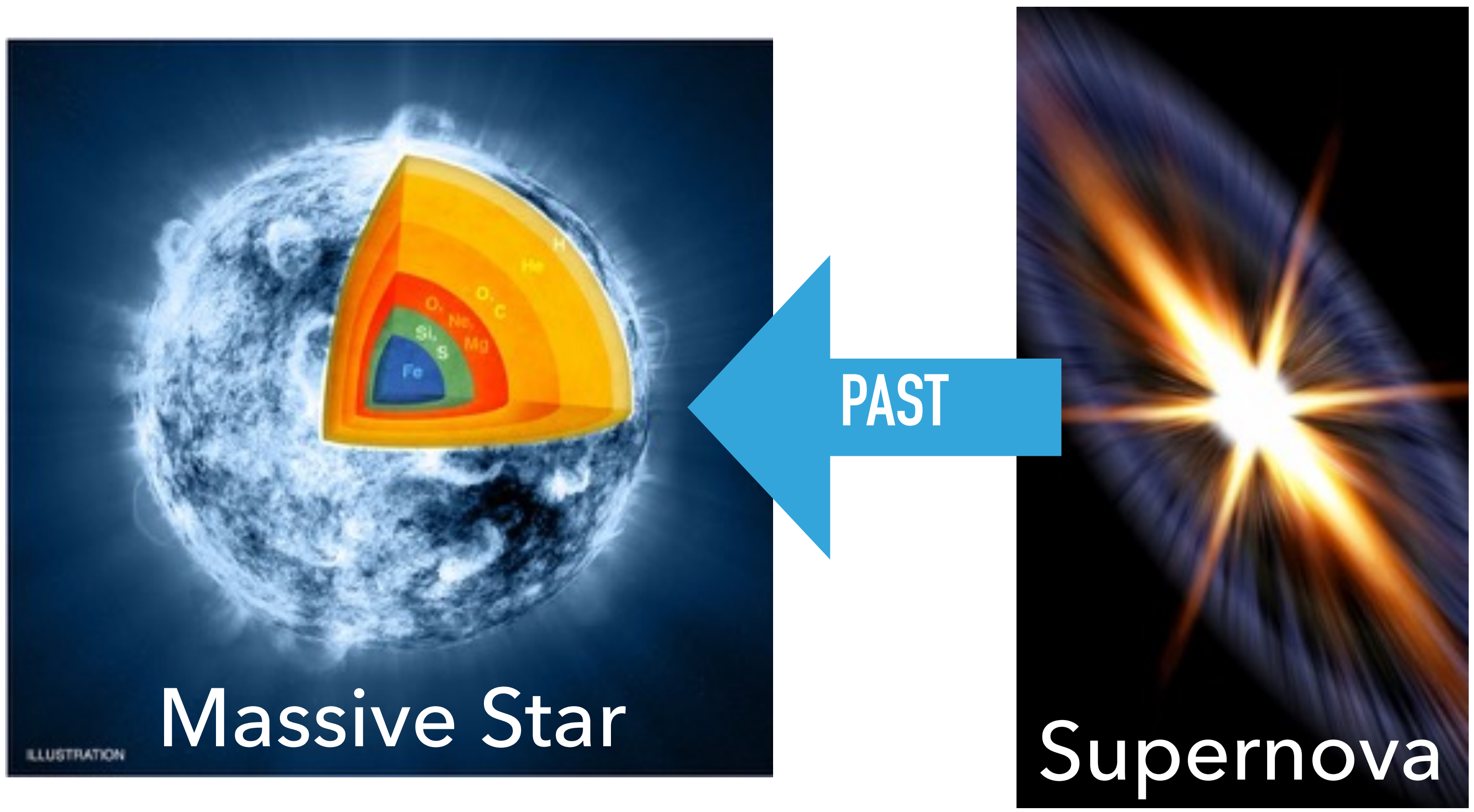
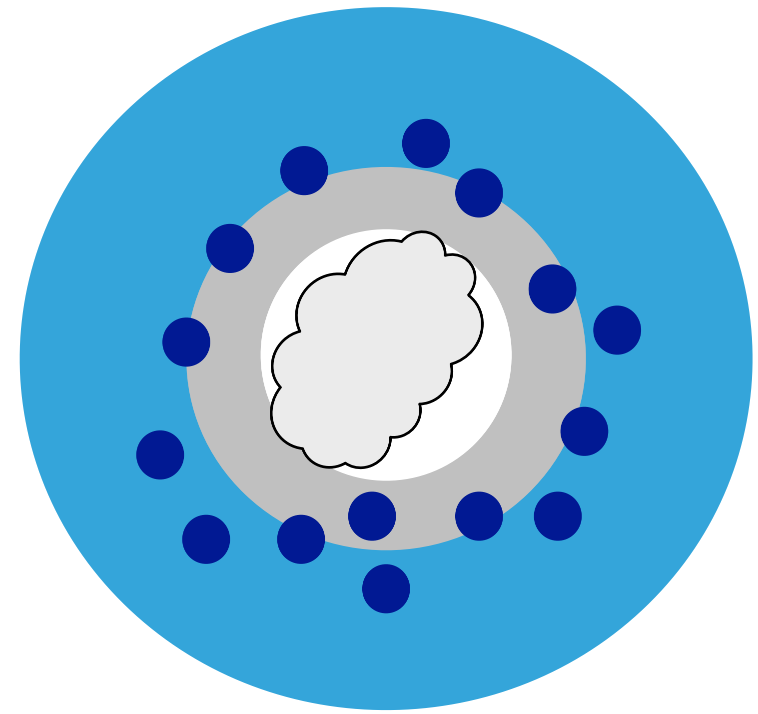


NEUTRON STAR NON-DETECTION

- 2-10 keV Flux < 6×10^{-4} counts/s
- most likely a combination of high internal absorption + too much glow from the ring

WINDOW INTO THE PAST AND FUTURE

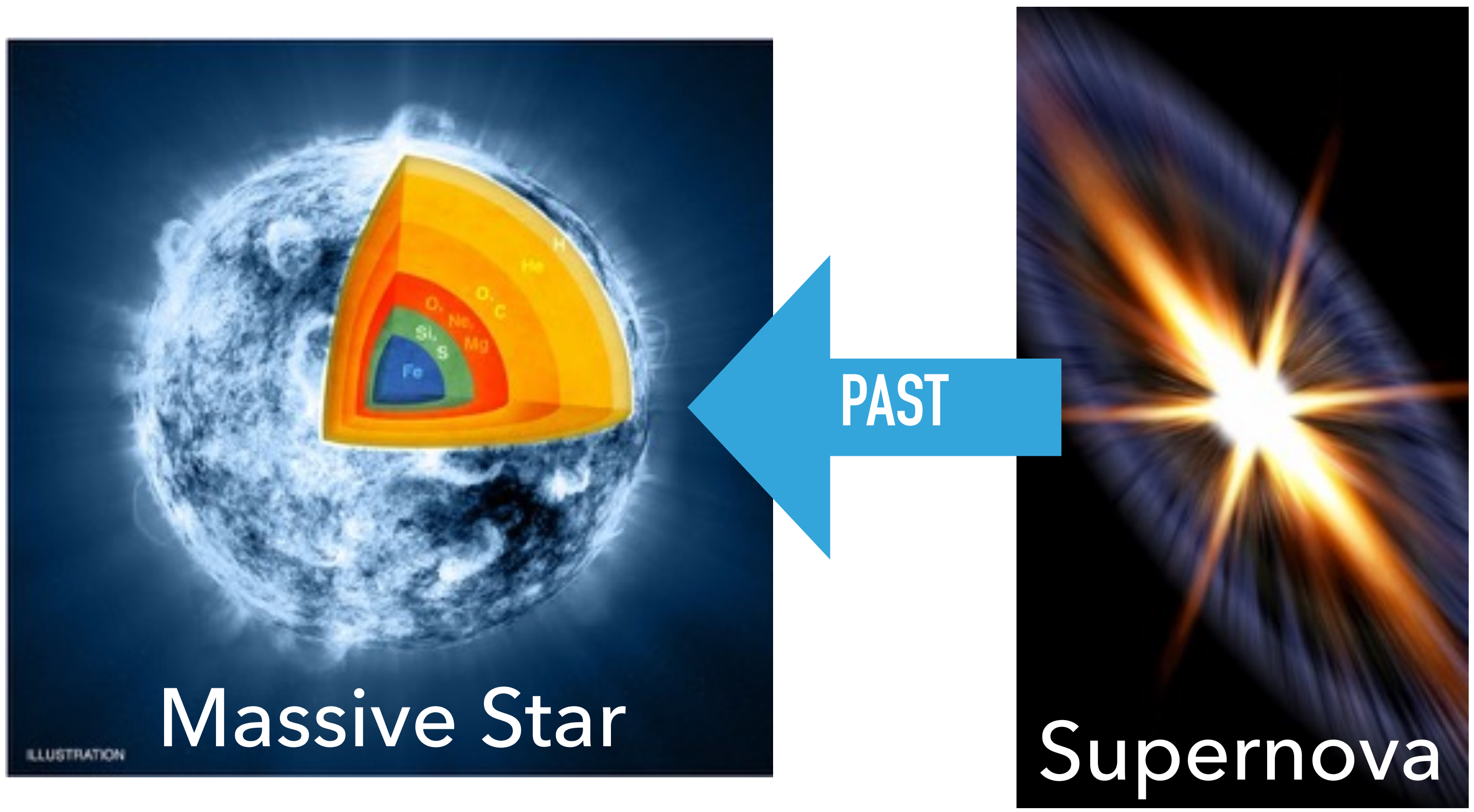




What we have learned

- HII region
- structure of inner ring
- asymmetric SN or CSM

WINDOW INTO THE PAST



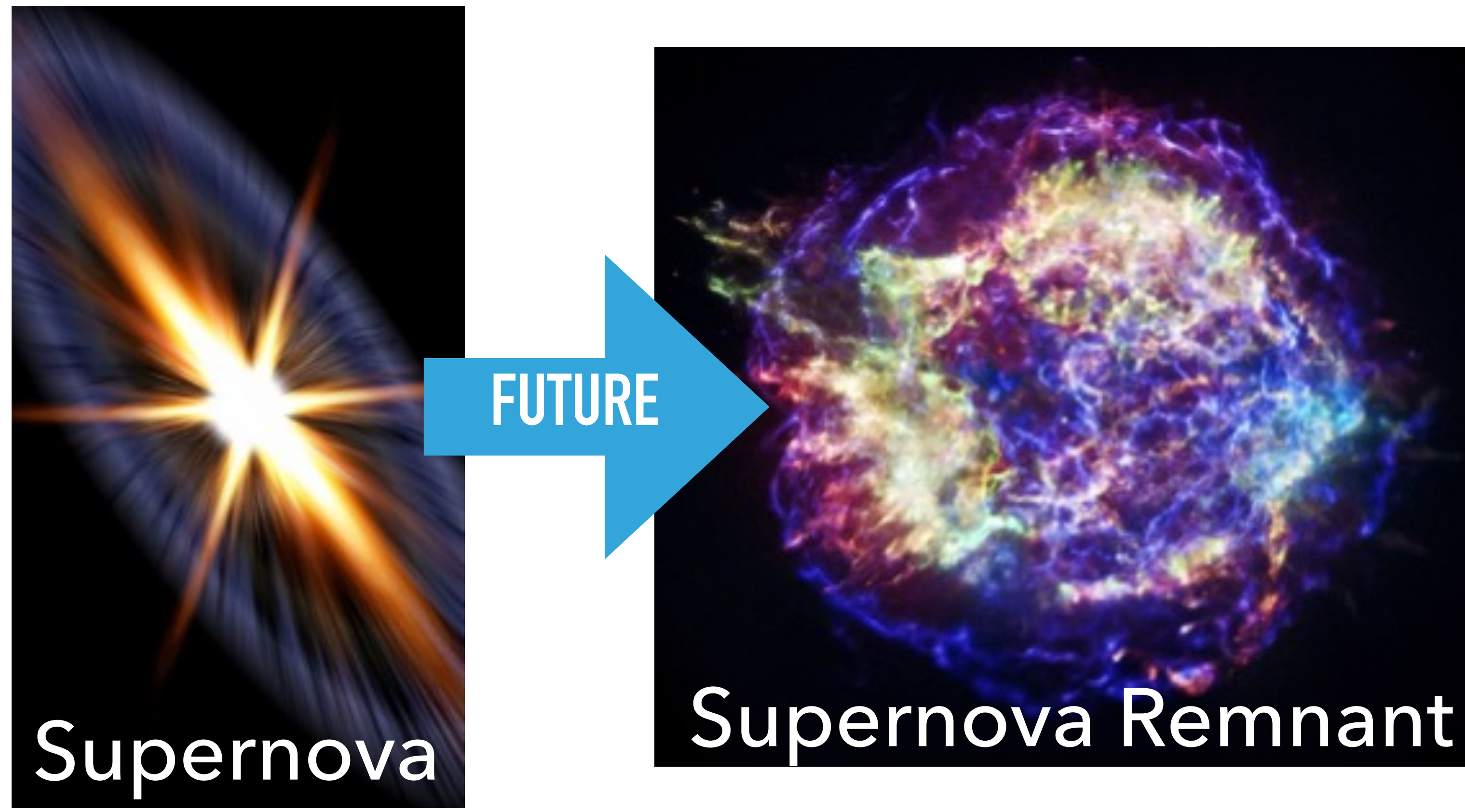
What we have learned

- HII region
- structure of inner ring
- asymmetric SN or CSM

What's next?

- CSM between inner and outer rings?
  - starting to probe now
- outer rings? - 20 years

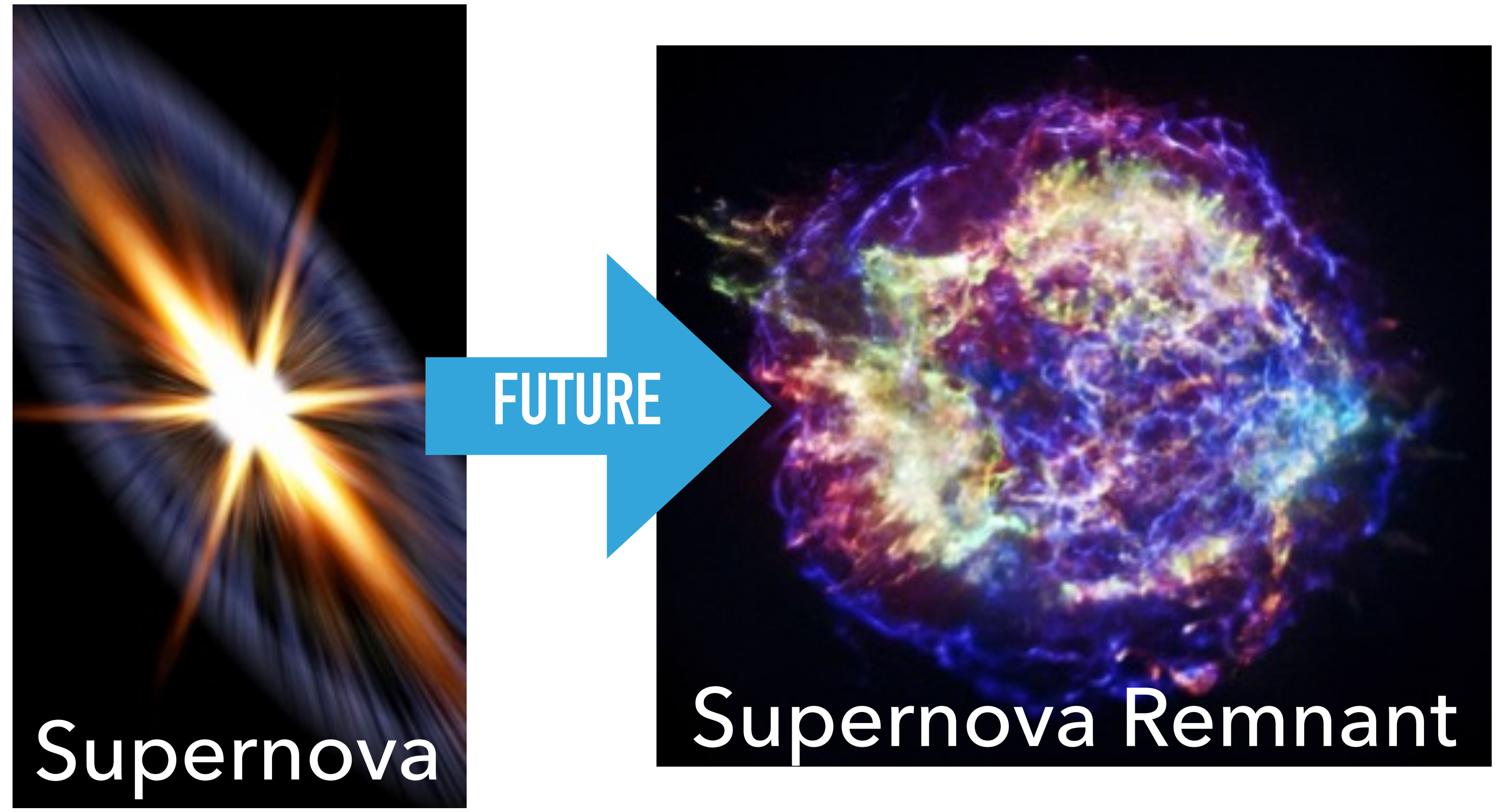
WINDOW INTO THE PAST AND FUTURE



What we have learned

- X-ray heating of cold ejecta and dust
- asymmetric SN?
- radio and hard X-ray share origin
- high internal absorption and/or no neutron star

WINDOW INTO THE PAST AND FUTURE



What's next?

- destruction of ring – already started!
- shocking and evolution of ejecta - within next decade
- effect of SN/CSM on later SNR? - several decades
- pulsar/PWN formation? - any time

What we have learned

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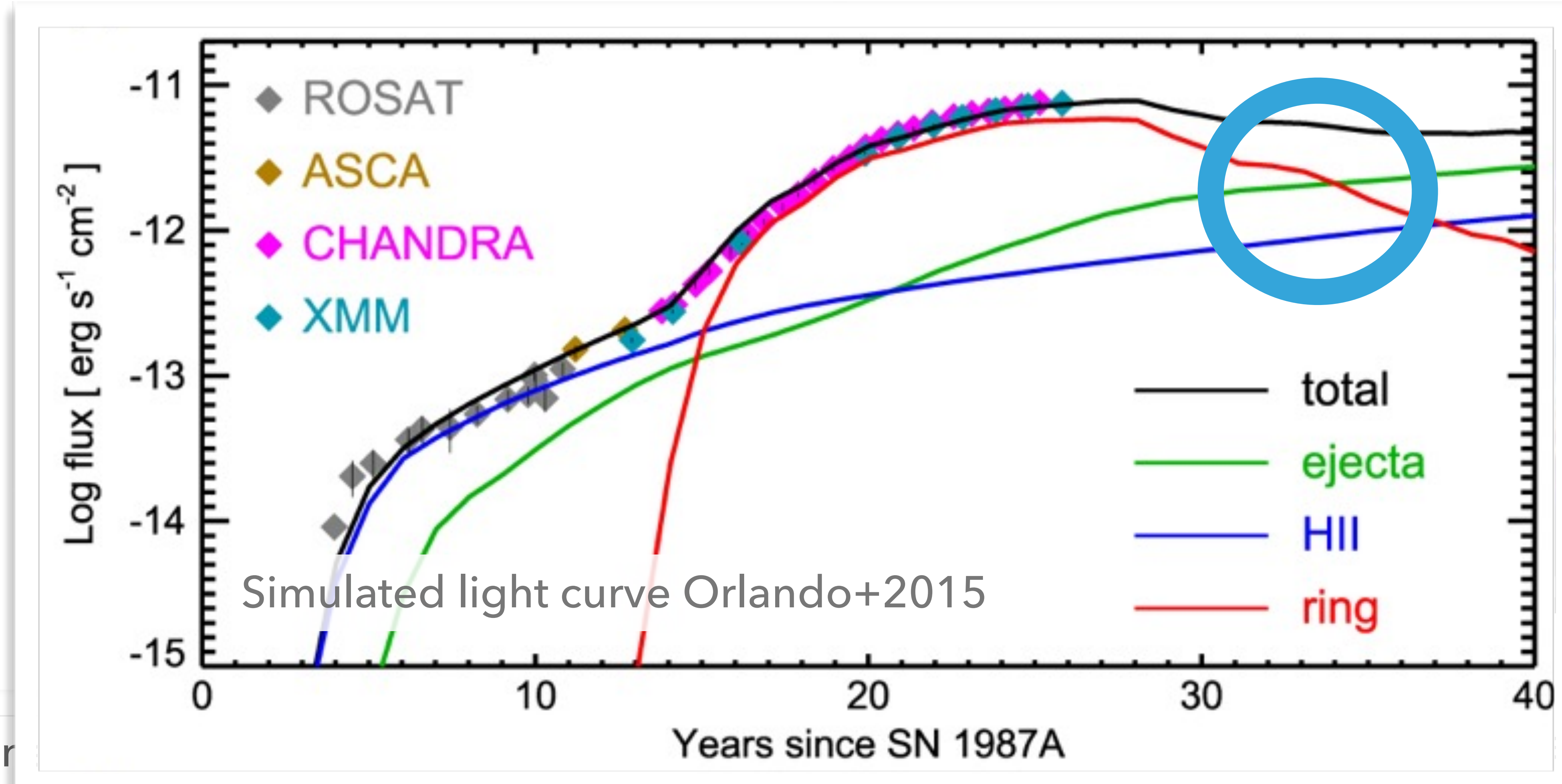

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ant

ecta
and dust

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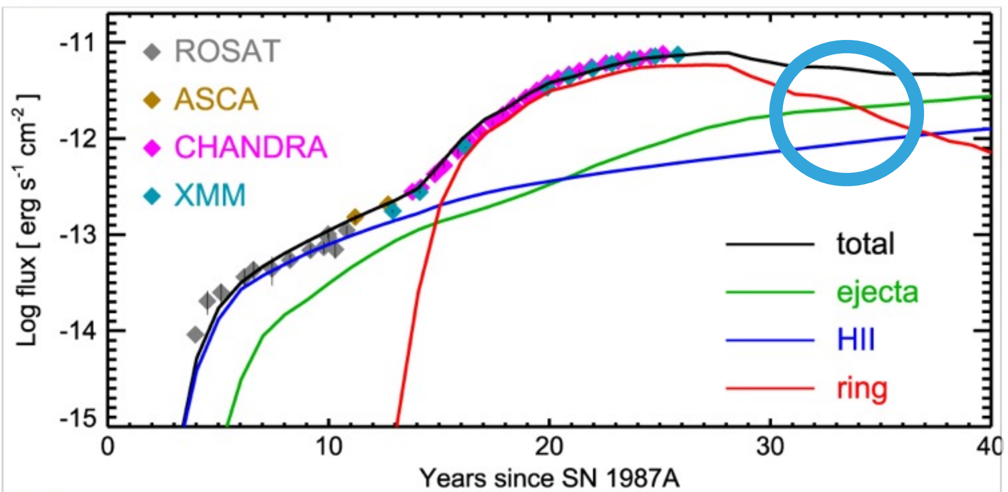


Simulated light curve Orlando+2015

FUTURE

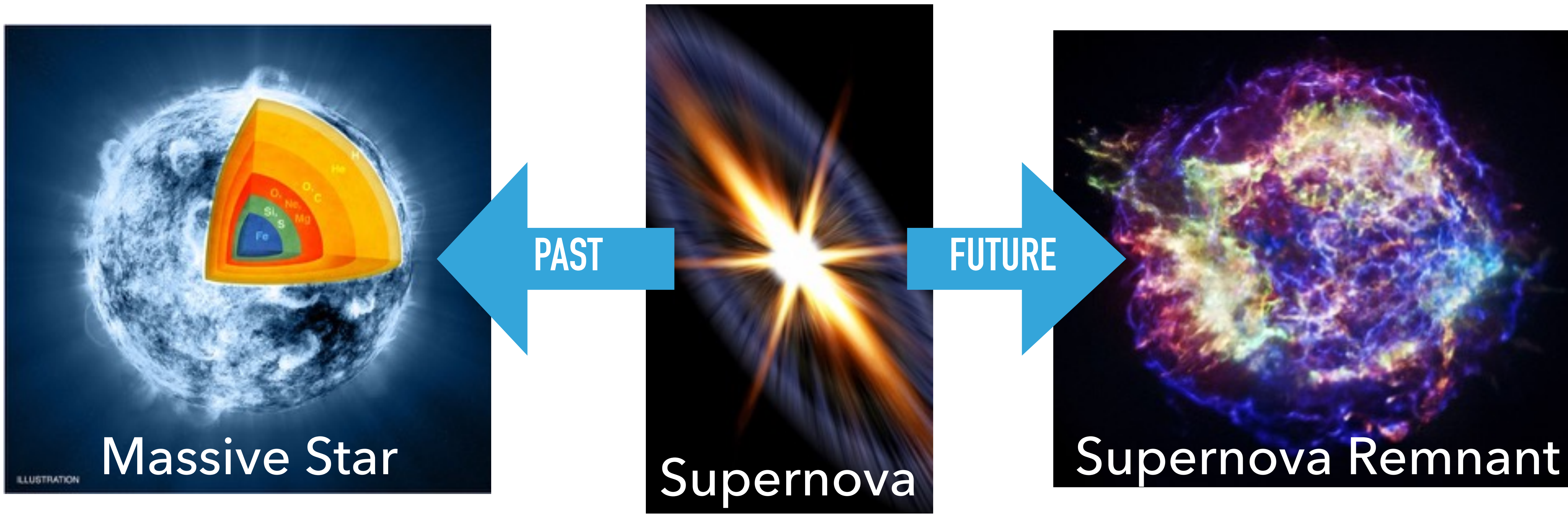
What's next?

- destruction of CSM – already started!
- shocking and evolution of ejecta - over next decade
- effect of SN/CSM on later SNR? - several decades
- pulsar/PWN formation? - any time

What we have learned

- X-ray heating of cold ejecta and dust
- asymmetric SN?
- radio and hard X-ray share origin
- high internal absorption and/ or no neutron star

WINDOW INTO THE PAST AND FUTURE



Story is only just beginning!

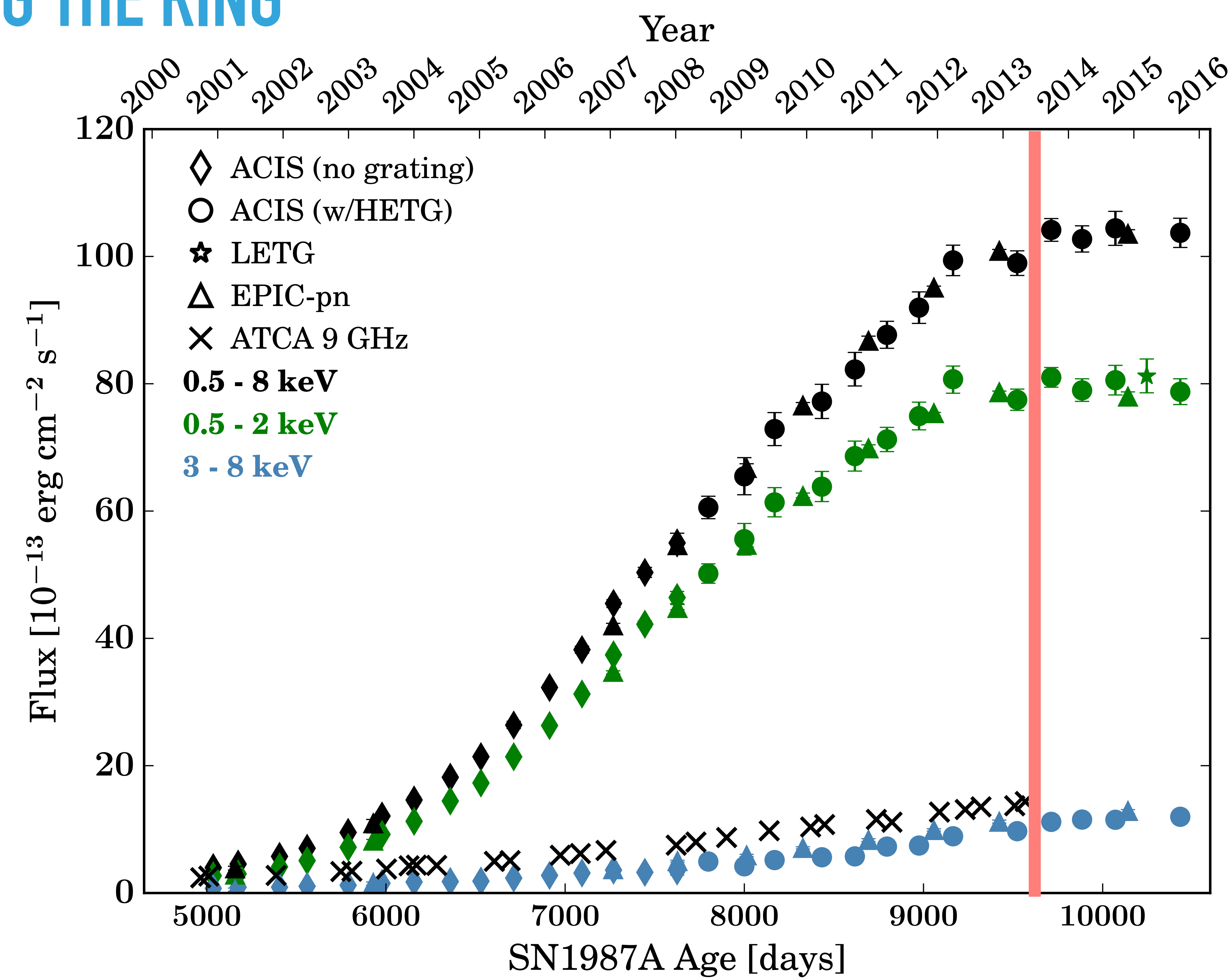
Chandra has been critical in telling the full story so far, and will continue to be in the future.

BONUS SLIDES

ADS SEARCH RESULTS

- Refereed with 1987A in title: 1190
- Refereed with 1987A in abstract: 1939
- All publications with 1987A in abstract: 4339
- All publications with 1987A and Chandra in abstract: 115

EXITING THE RING



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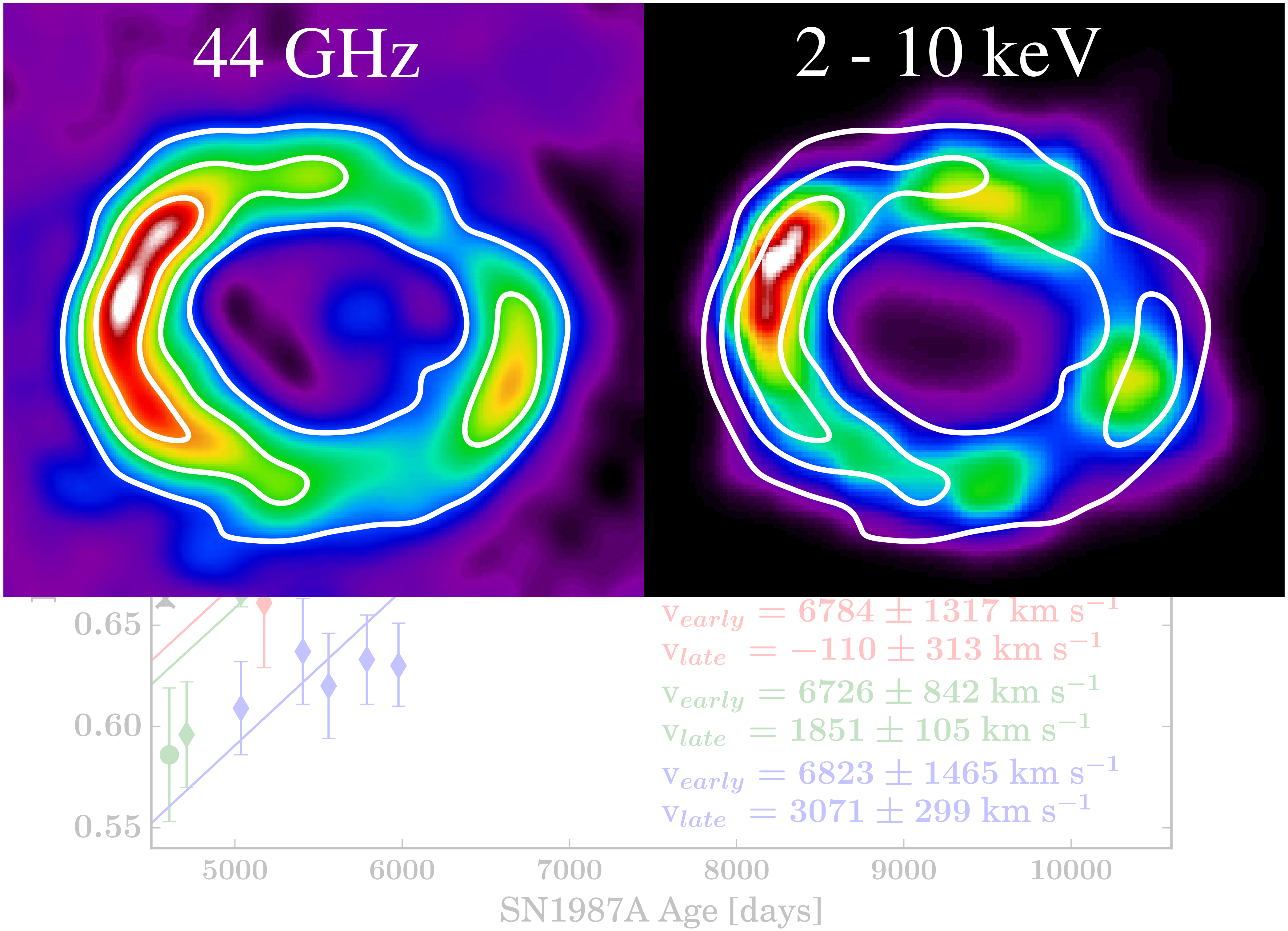

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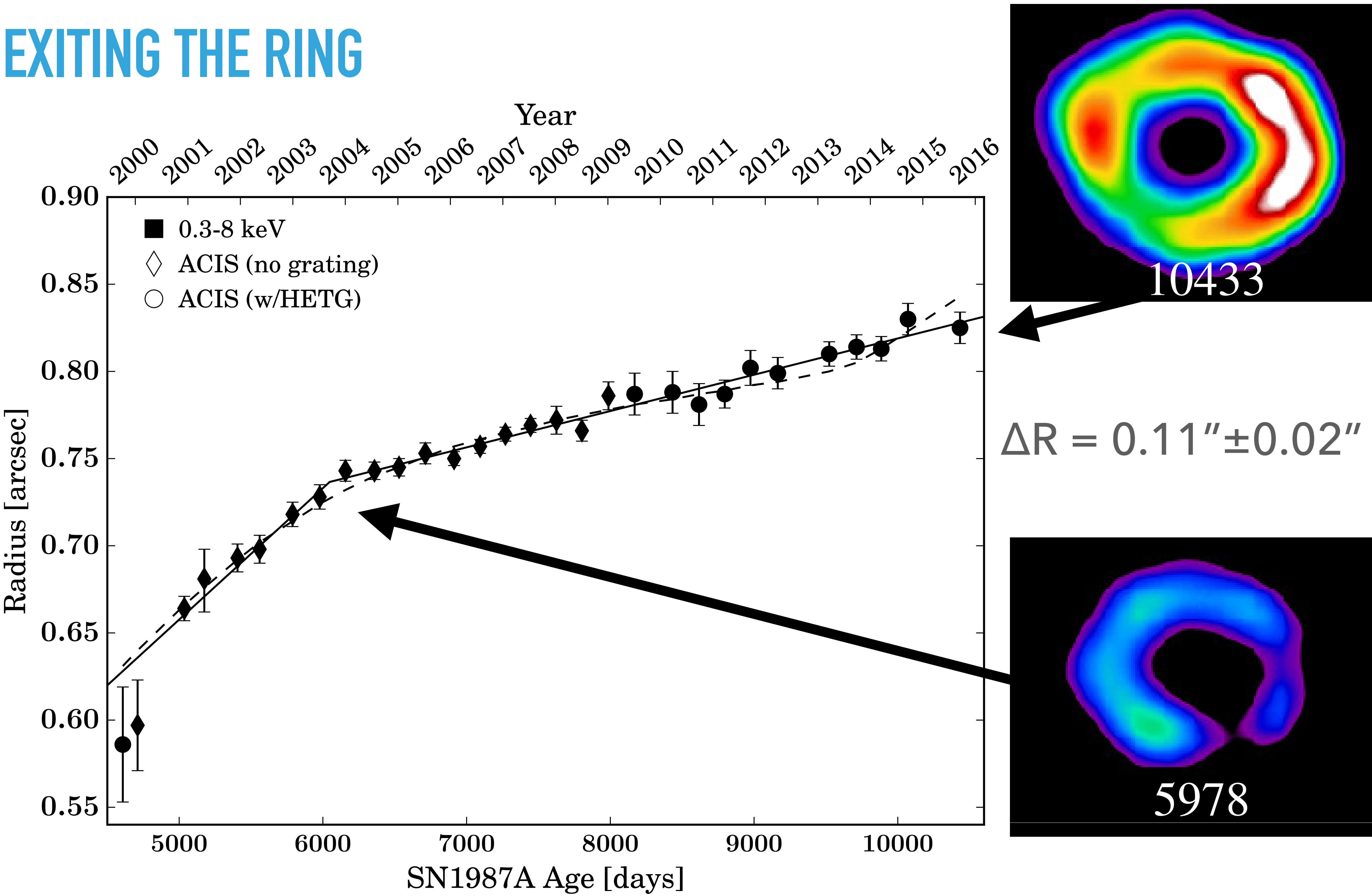
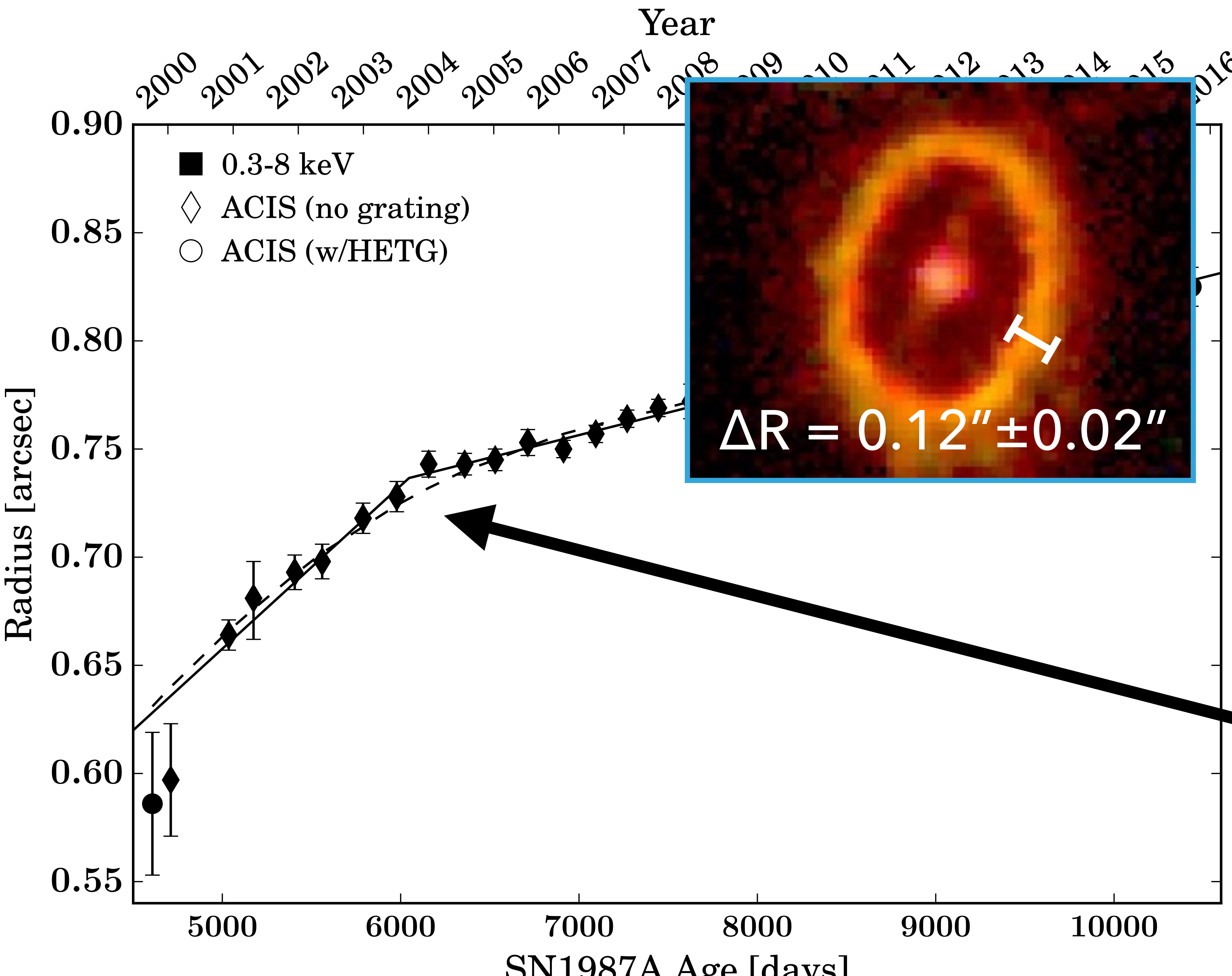
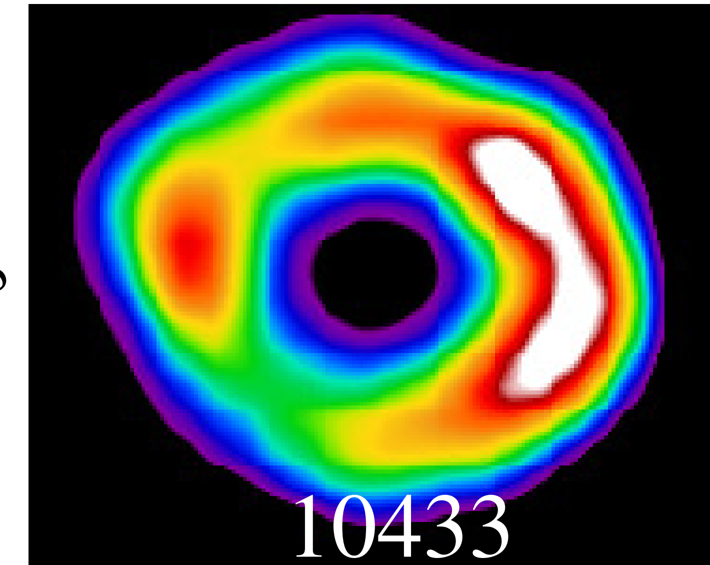


ΔR = 0.11″±0.02″

EXITING THE RING





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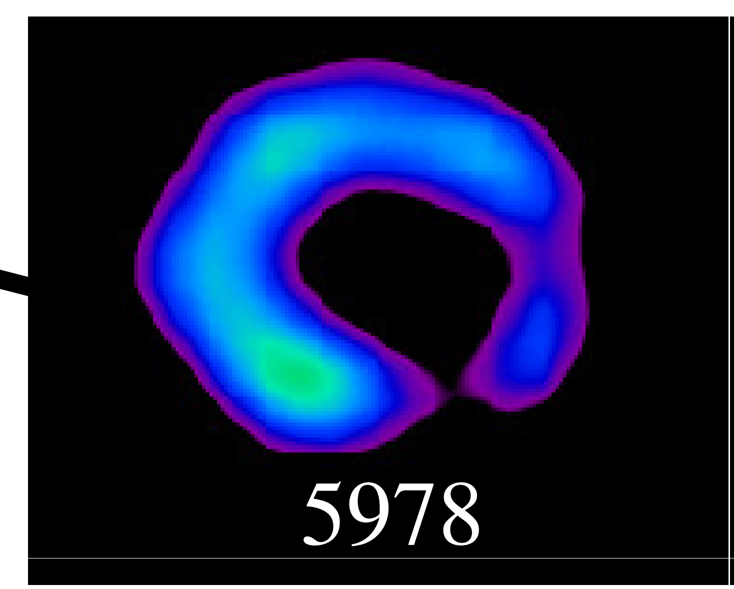
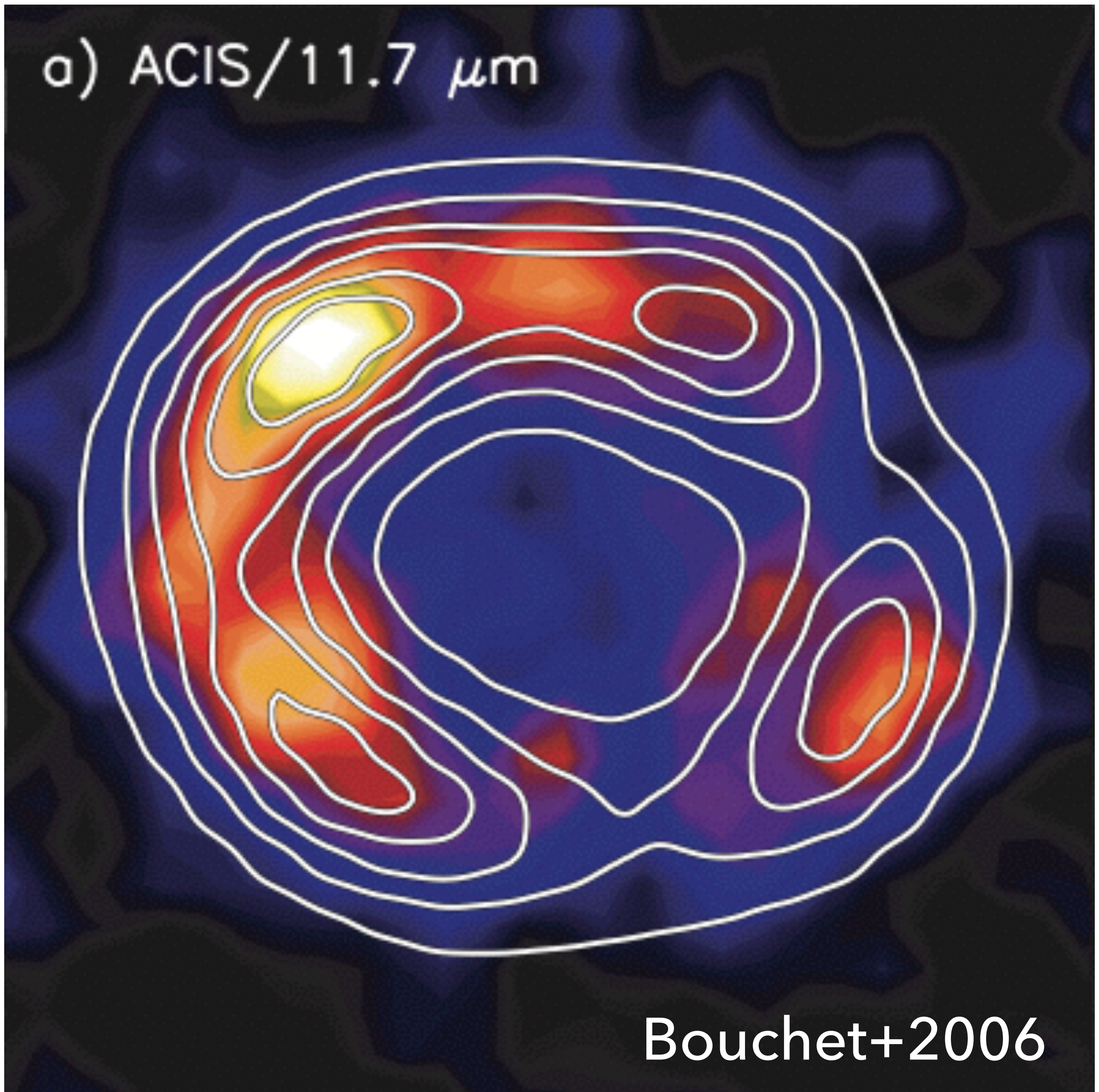


COLLISIONAL HEATING OF DUST IN RING

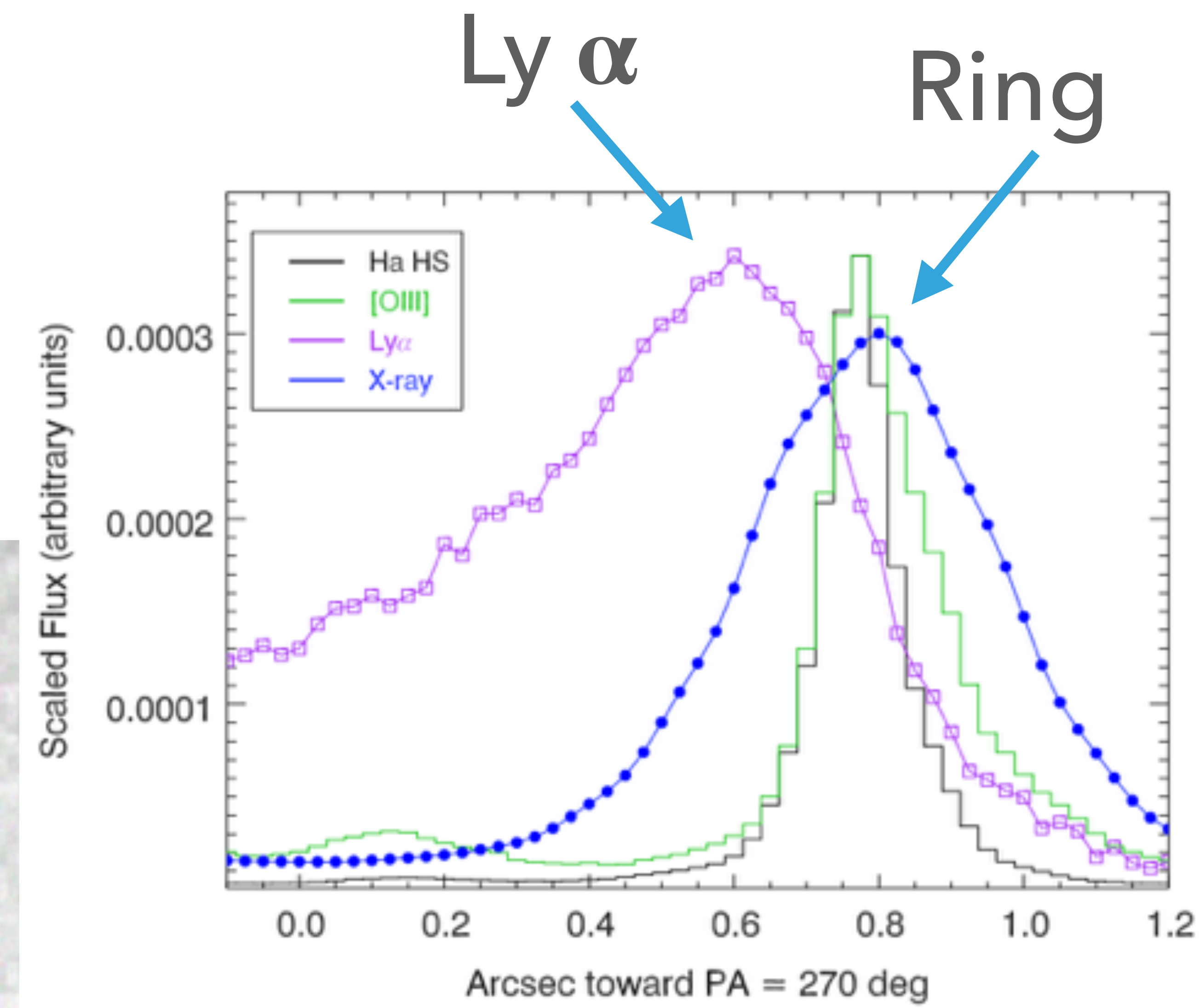


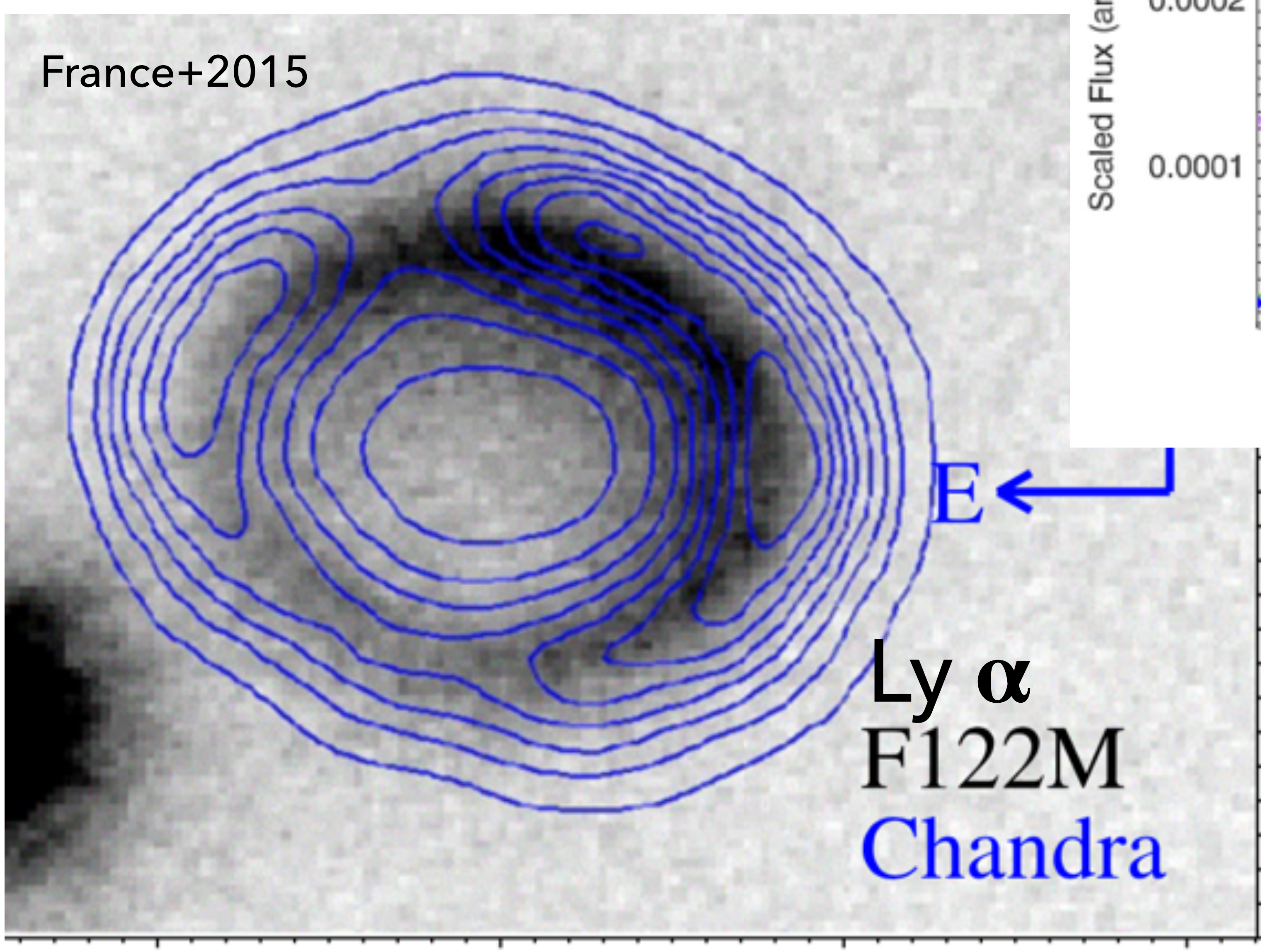
Gemini T-ReCS 11.7μm

Chandra contours

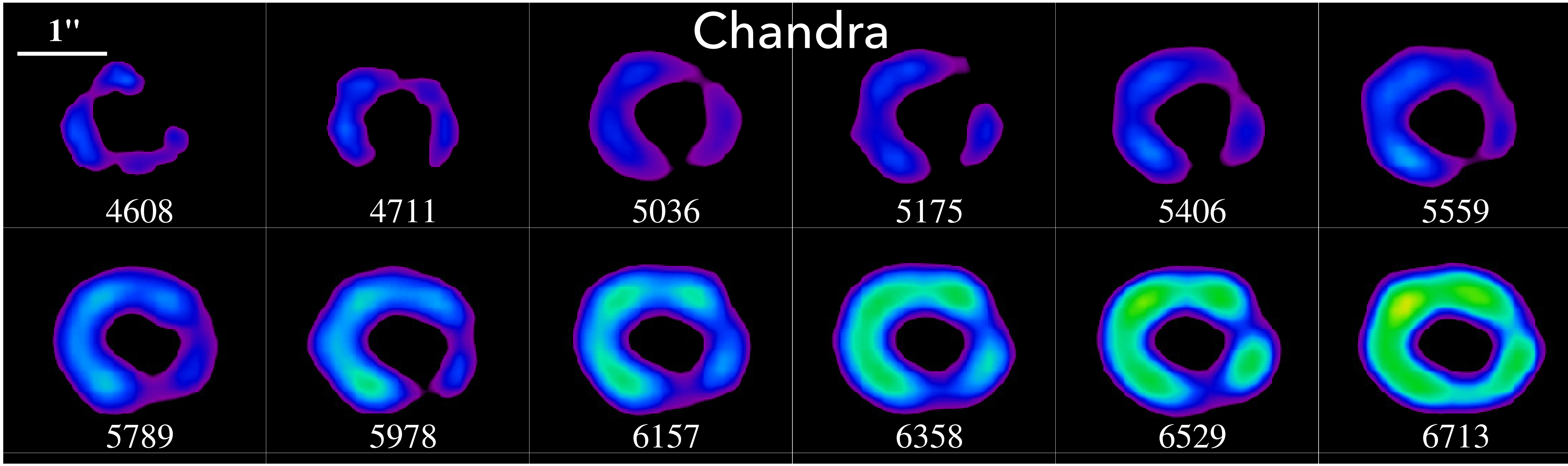
age~6500 days

RADIATIVE HEATING OF EJECTA

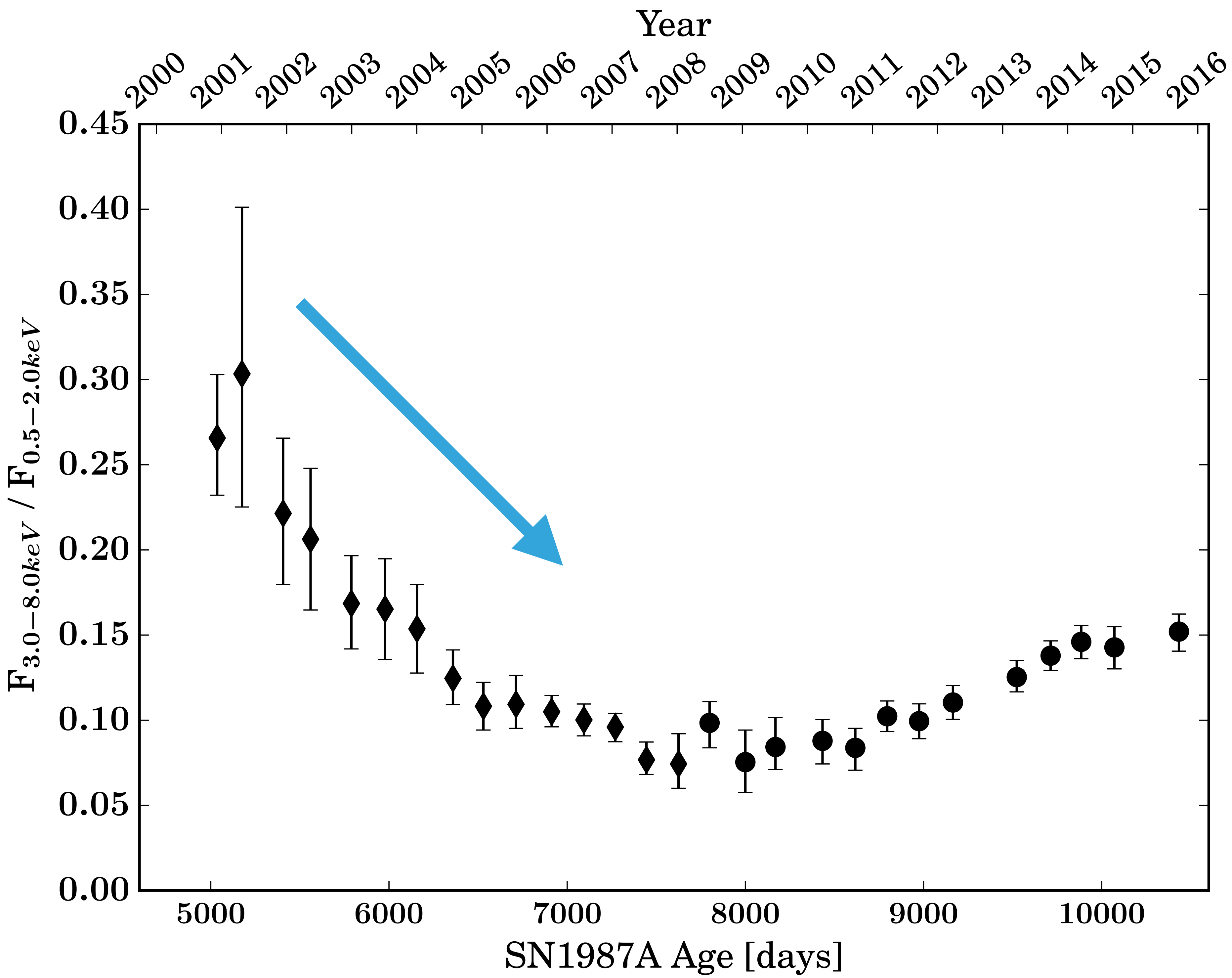




COLLISION WITH CLUMPS AND SMOOTH RING



END OF CLUMP INTERACTION



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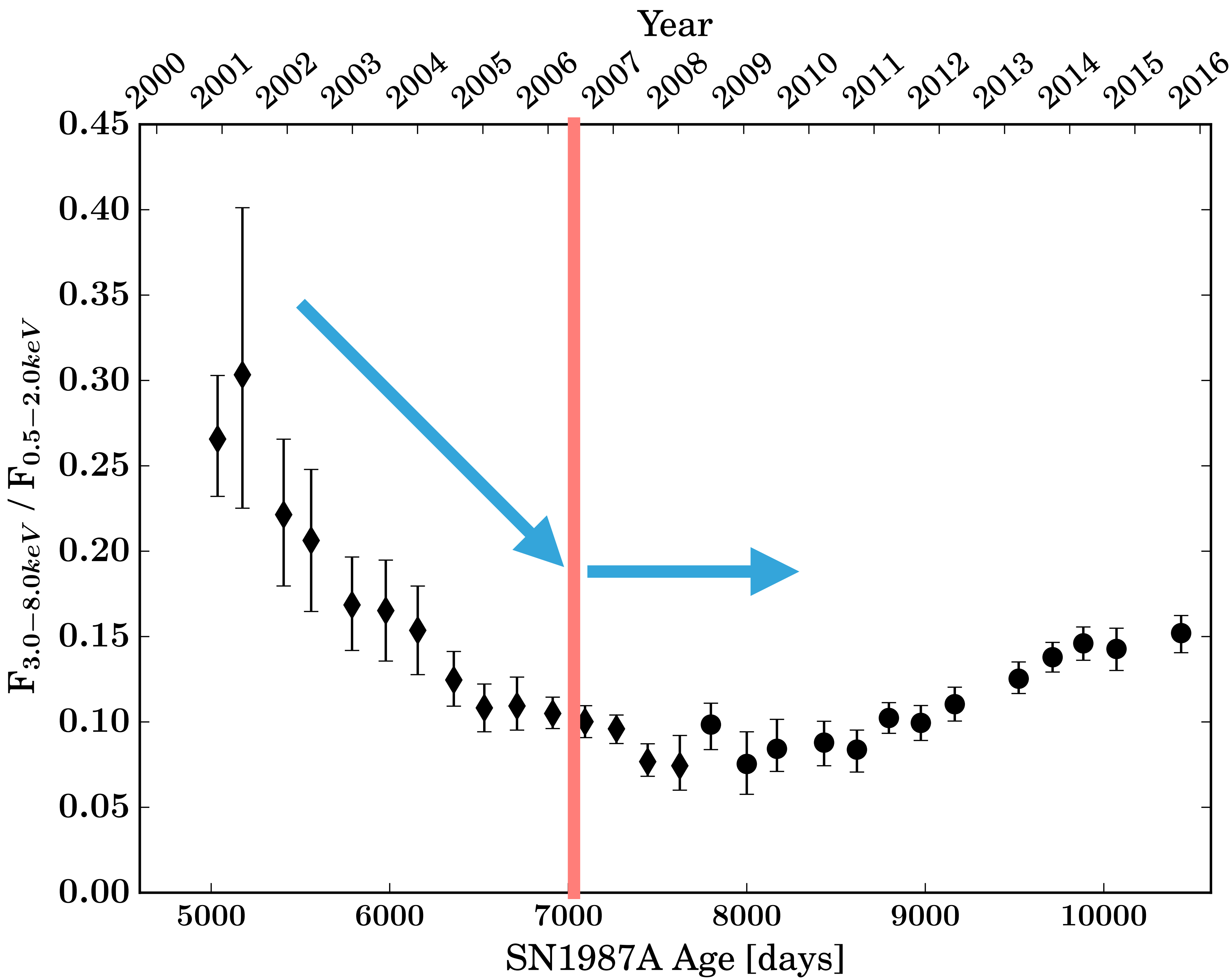

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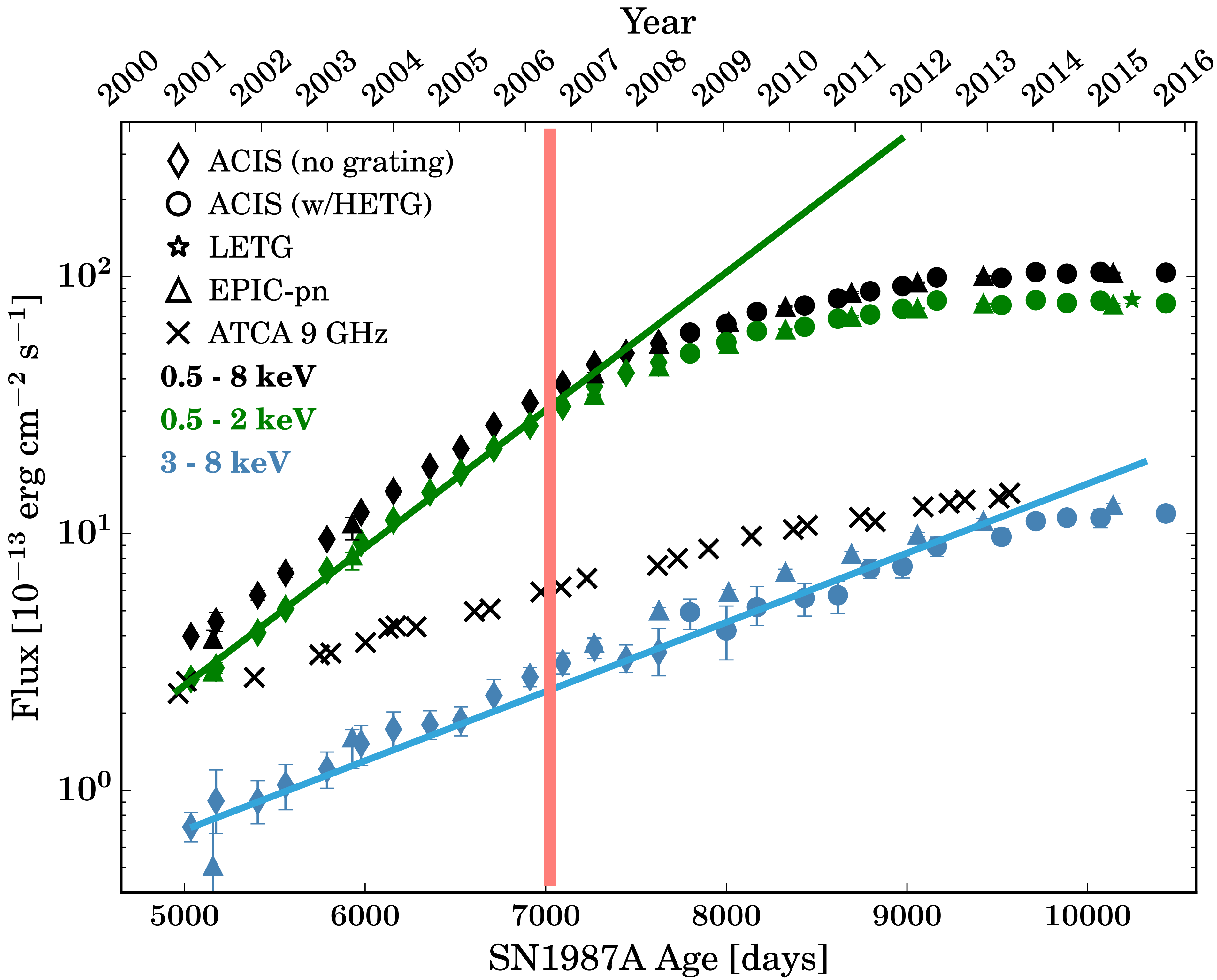
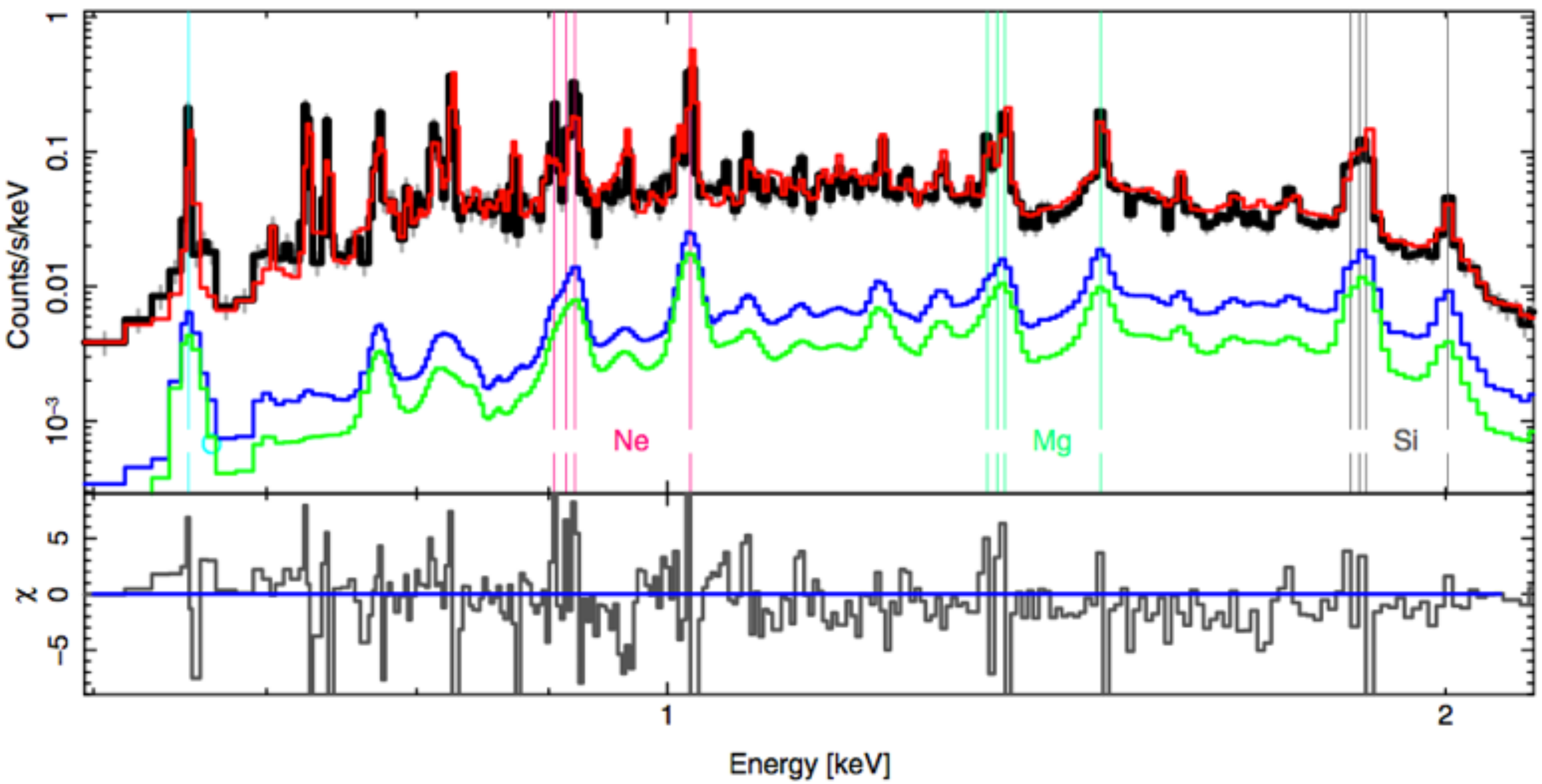


POINT SOURCE FLUX LIMITS

- Procedure
  - stack 2-10 keV images (those with sufficient counts)
  - fit model image then add point source with increasing flux until delta chi2 = 2.706 (90% limit)
- Flux < 6×10^{-4} counts/s in 2-10 keV
- assuming standard gamma=1.5 power law
  - $N_H = 0.235e22\ cm^{-2}$=> observed L_X<3.1e33 erg/s
  - $N_H = 5e22\ cm^{-2}$=> intrinsic L_X<1.2e34 erg/s

GRATING SPECTROSCOPY



From LETG spectrum:
(Zhekov+ 2006)

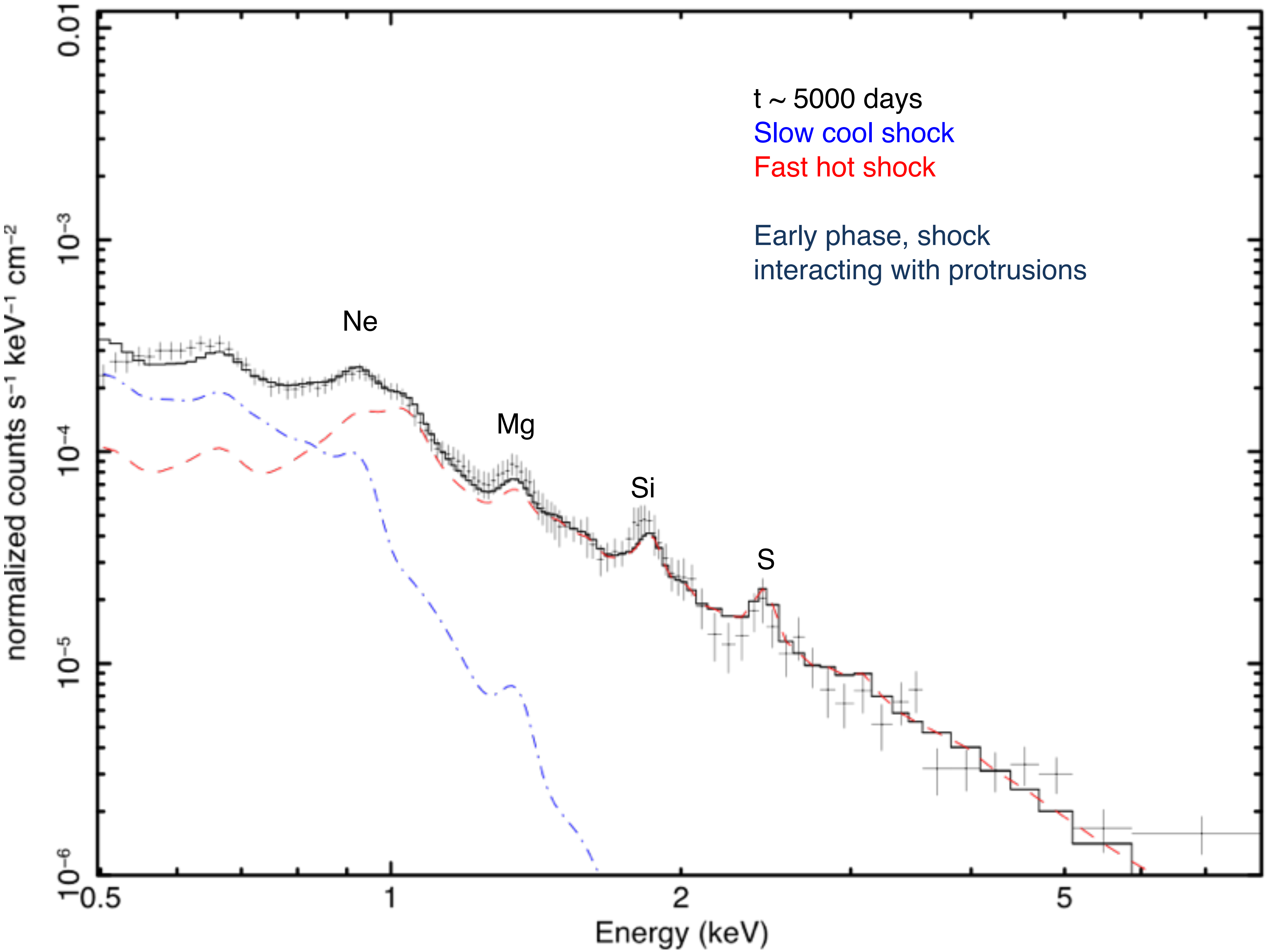
N = 0.76
Ne = 0.29
Mg = 0.24

Si = 0.28
S = 0.45
Fe = 0.16

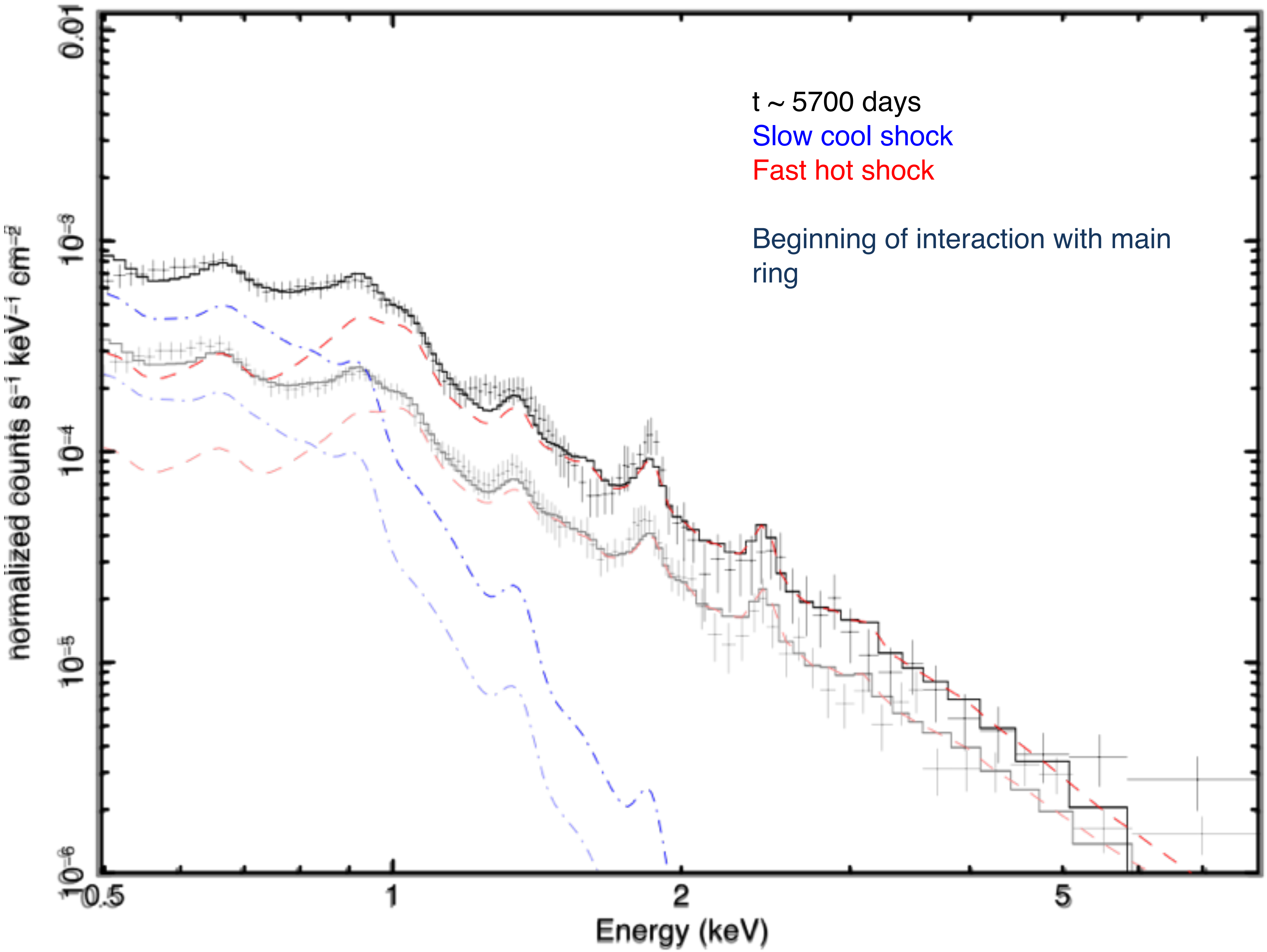
CCD SPECTROSCOPY

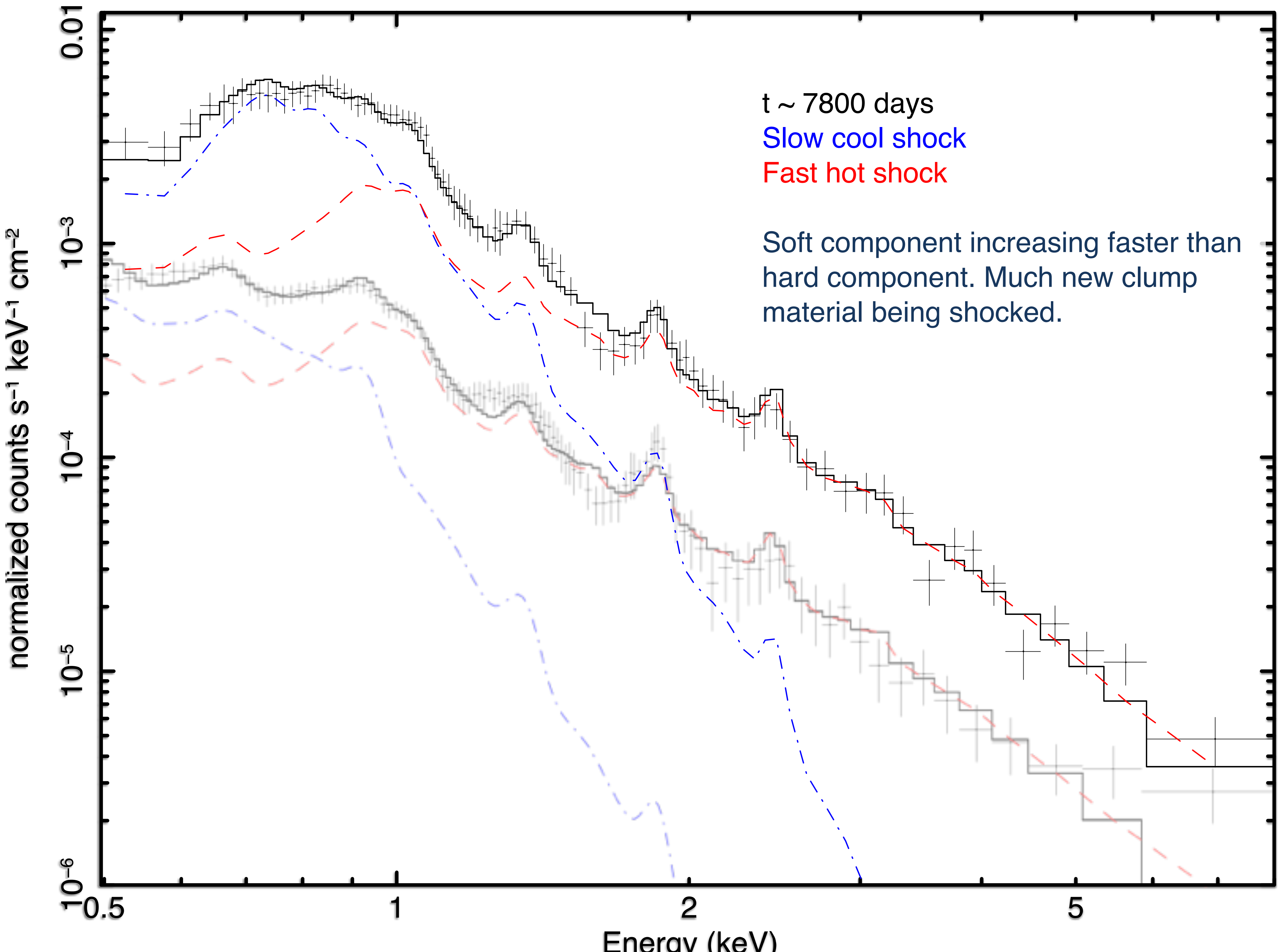
- 1- or 2-component NEI thermal shock model
  - Soft component:
    - kT ~ 0.3 keV
    - $n_e t > 10^{12}$ s/cm^3 (~CIE)
  - Hard component:
    - kT ~ 1 – 3 keV
    - $n_e t = 2 – 3 \times 10^{11}$ s/cm^3
- Simplification of very complex, multi-shock system

CHANDRA SPECTROSCOPY

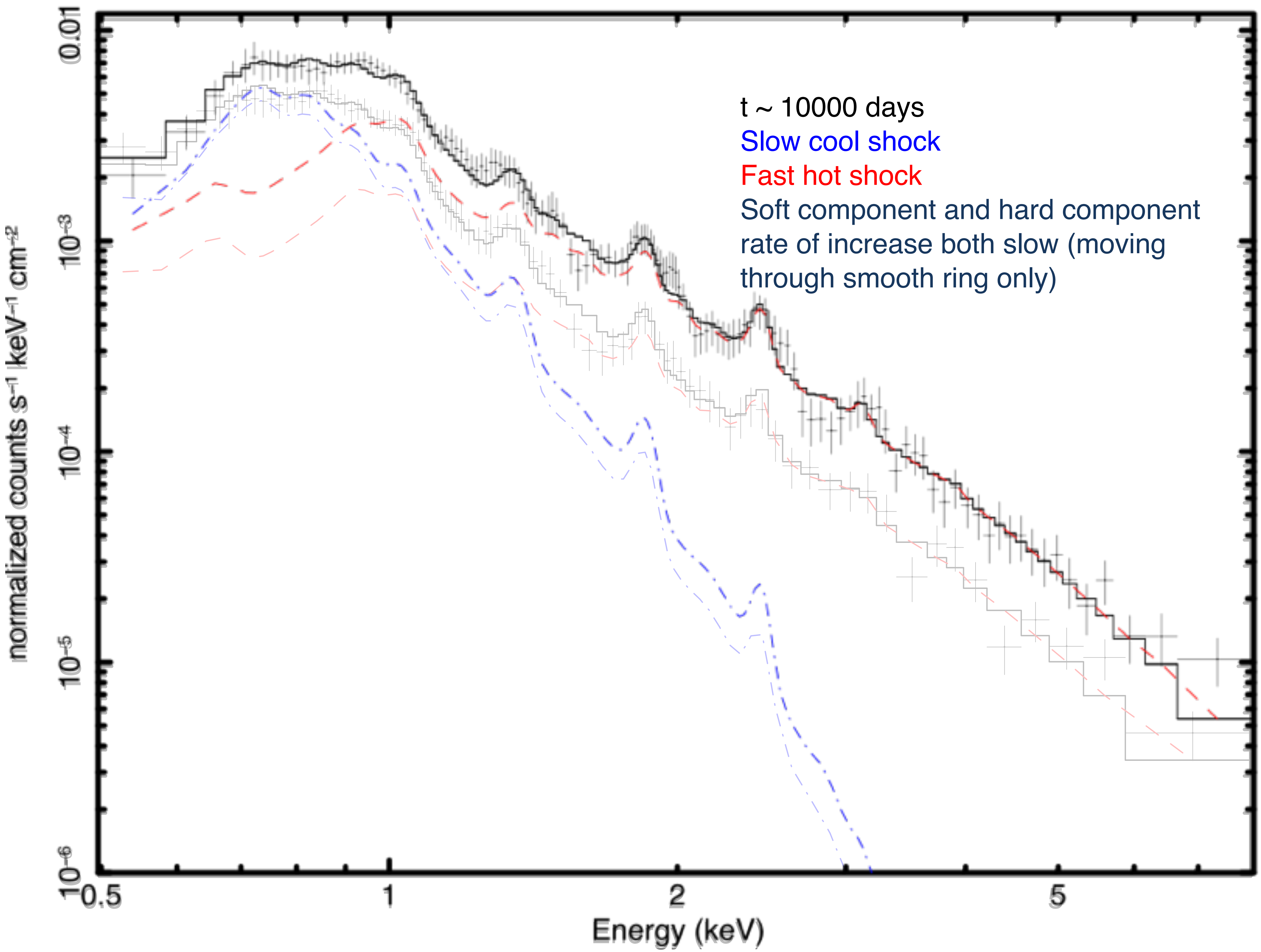


CHANDRA SPECTROSCOPY



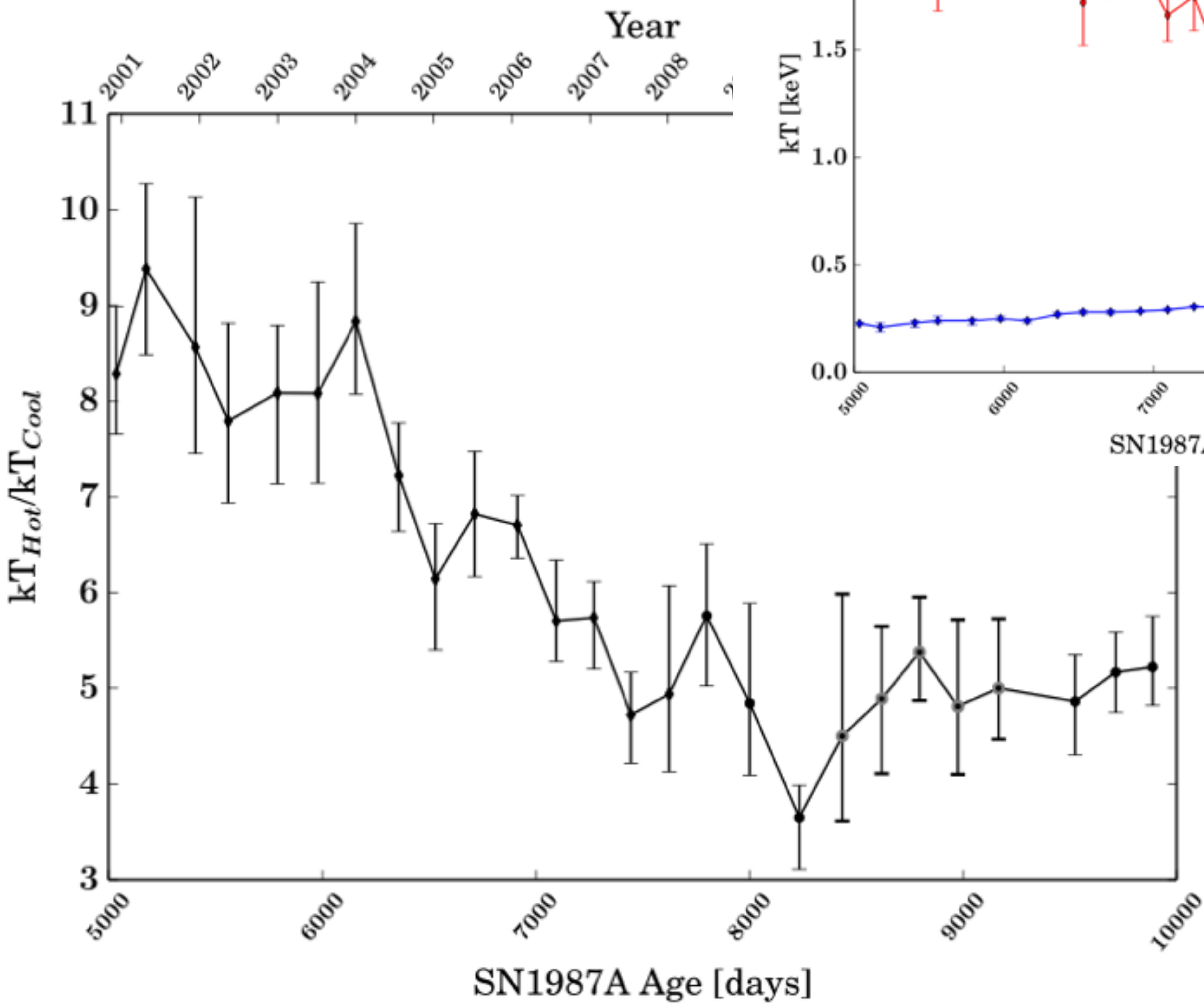

normalized counts s⁻¹ keV⁻¹ cm⁻²
0.01
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.5
1
2
5
Energy (keV)
t ~ 7800 days
Slow cool shock
Fast hot shock
Soft component increasing faster than hard component. Much new clump material being shocked.

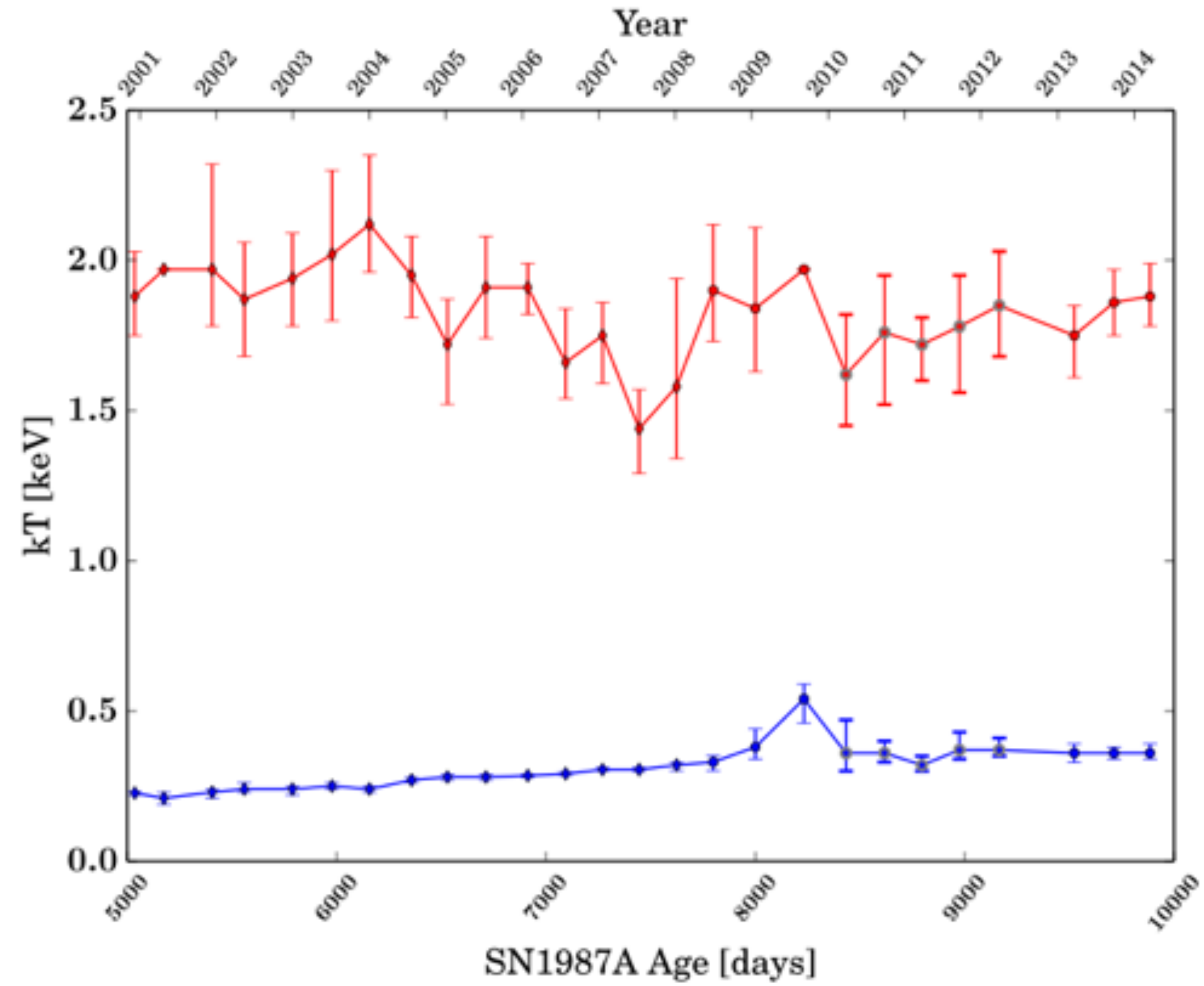
CHANDRA SPECTROSCOPY



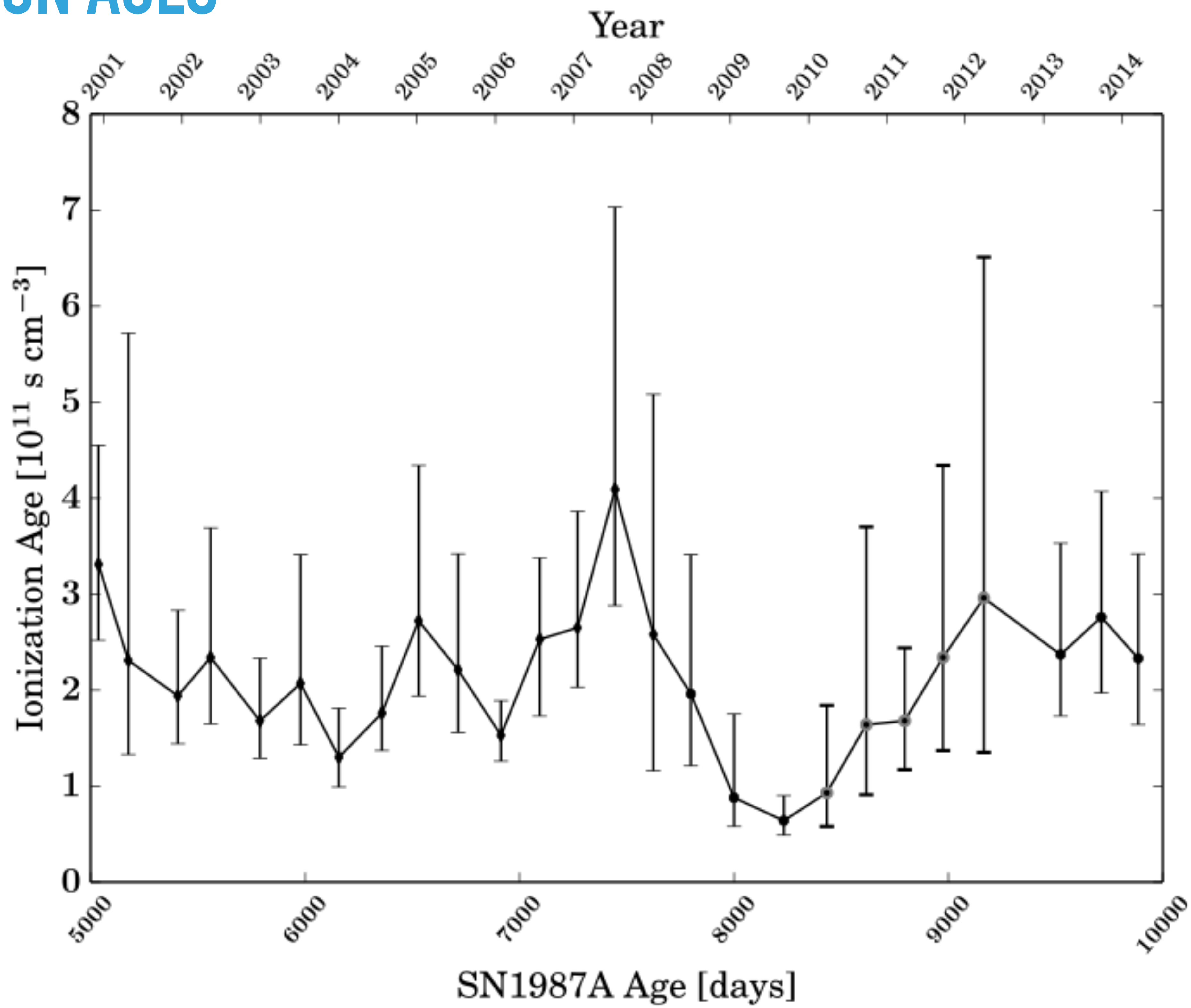
t ~ 10000 days
Slow cool shock
Fast hot shock
Soft component and hard component rate of increase both slow (moving through smooth ring only)

TEMPERATURE RATIO

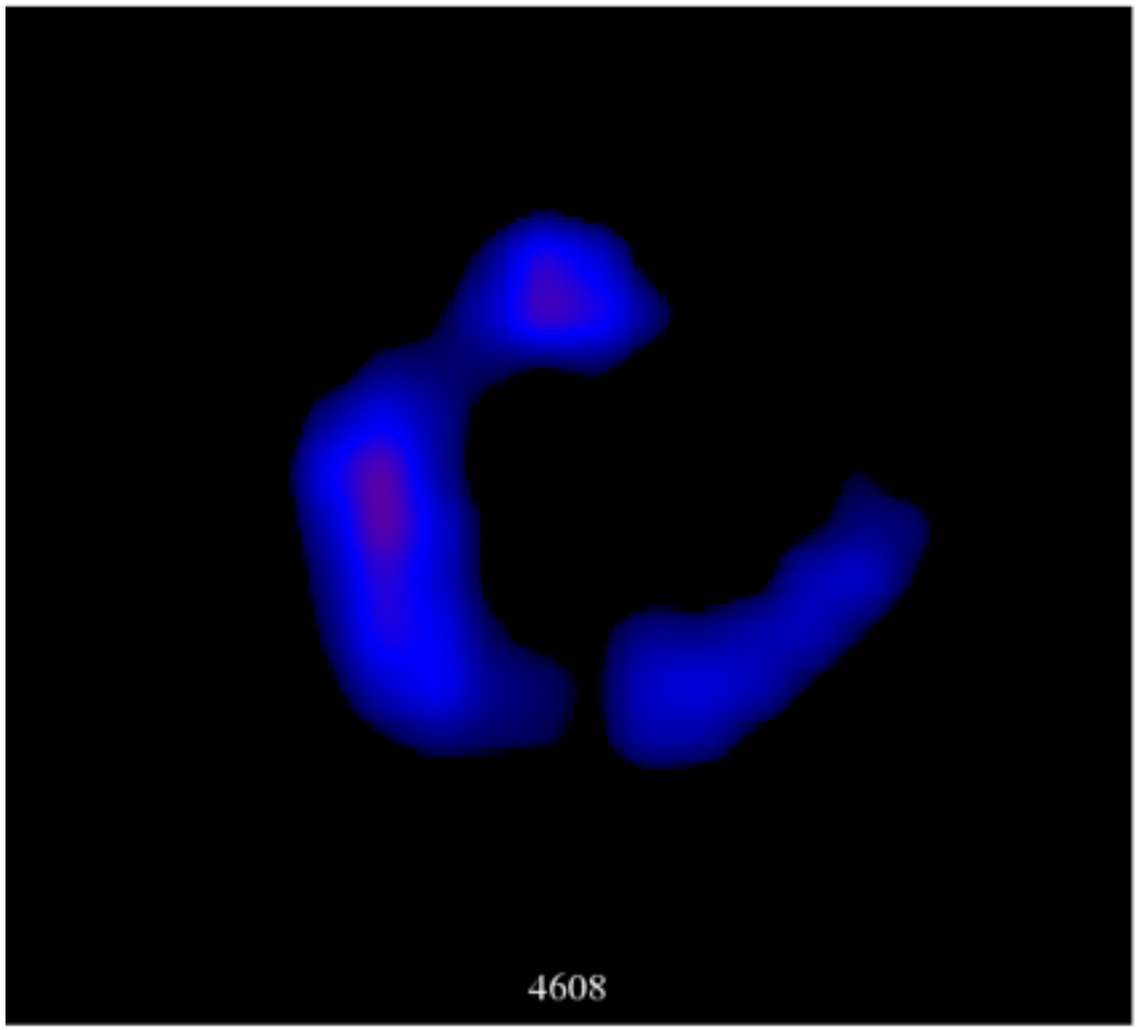


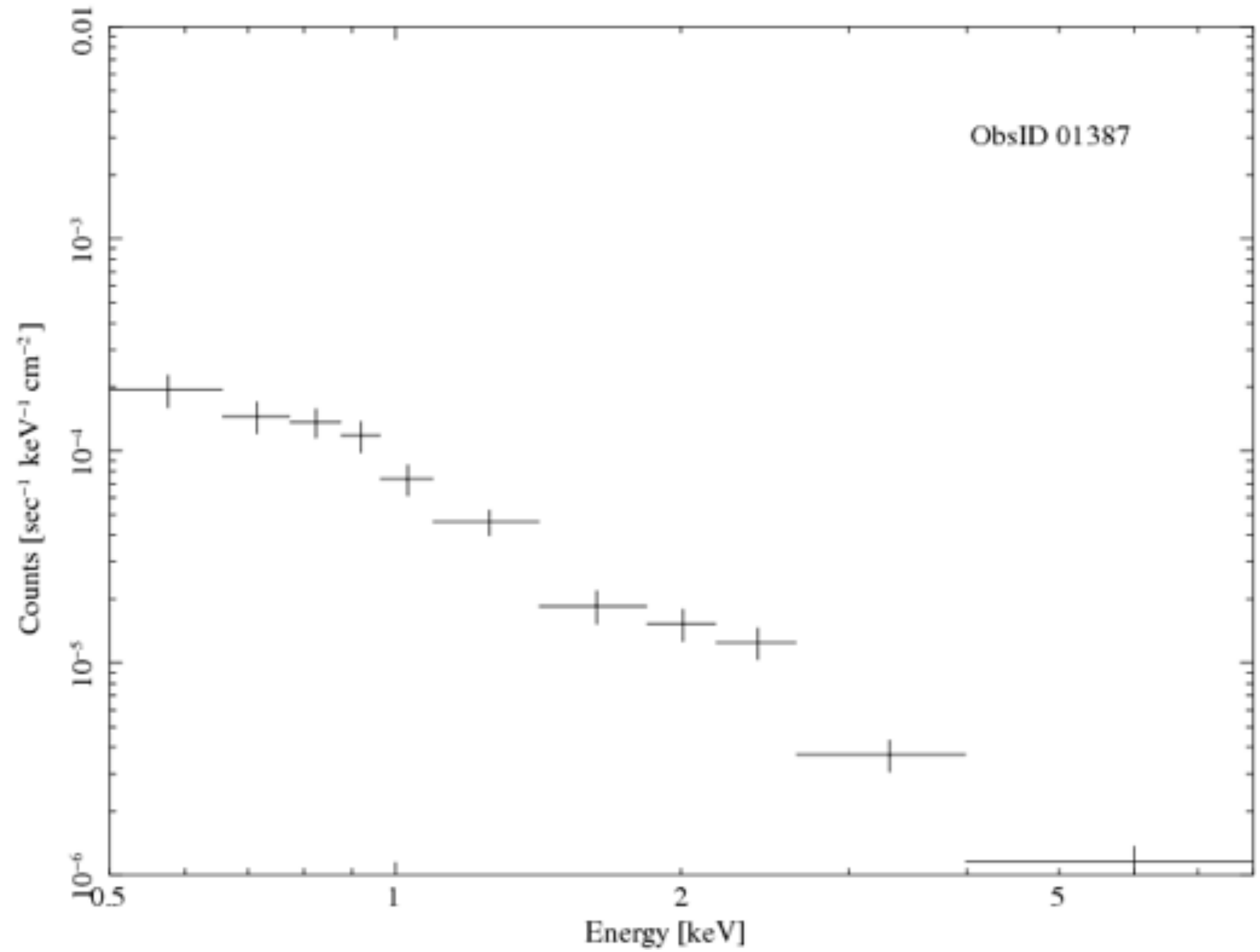


IONIZATION AGES

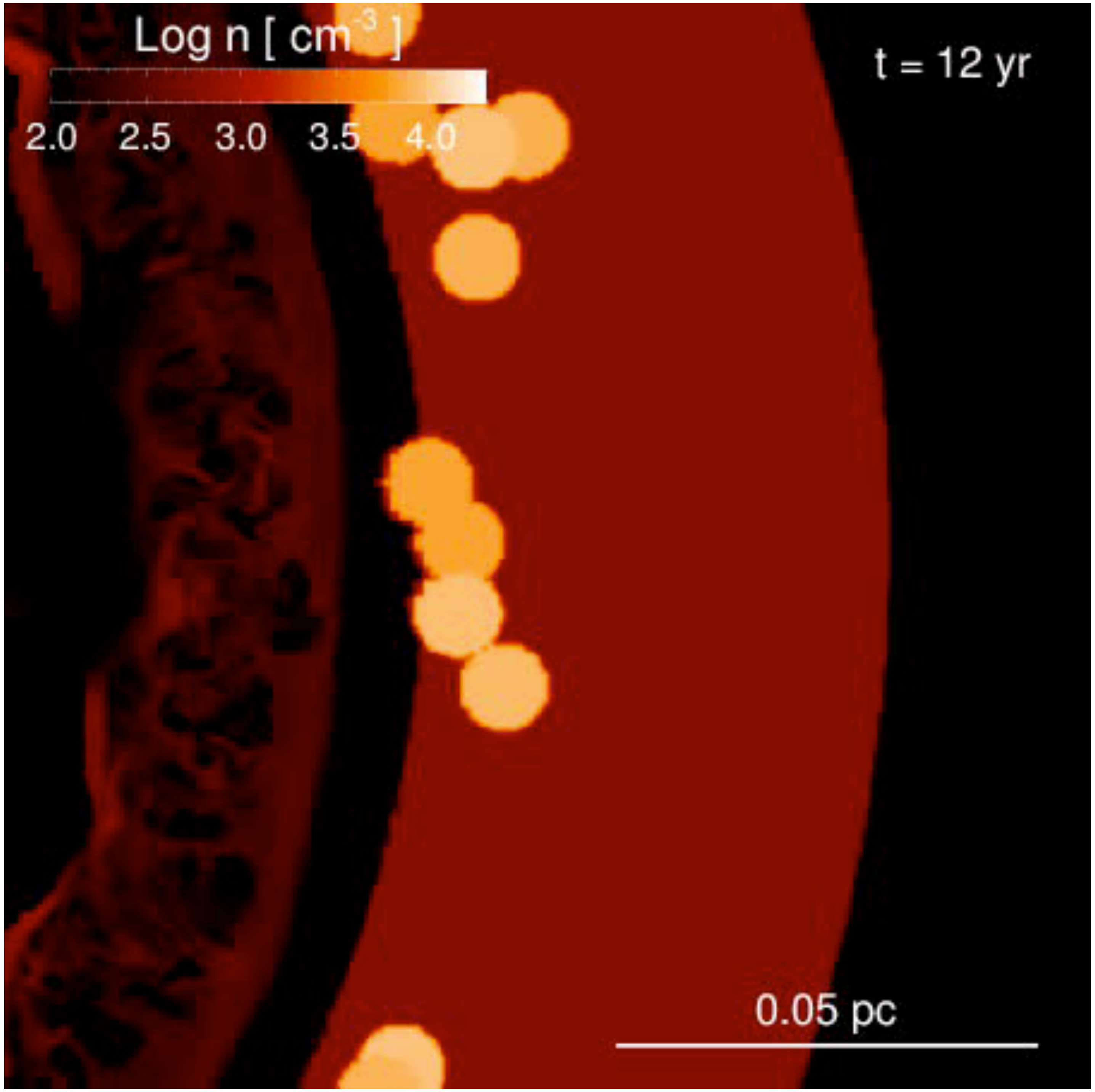


CHANDRA IMAGING AND SPECTROSCOPY MOVIE

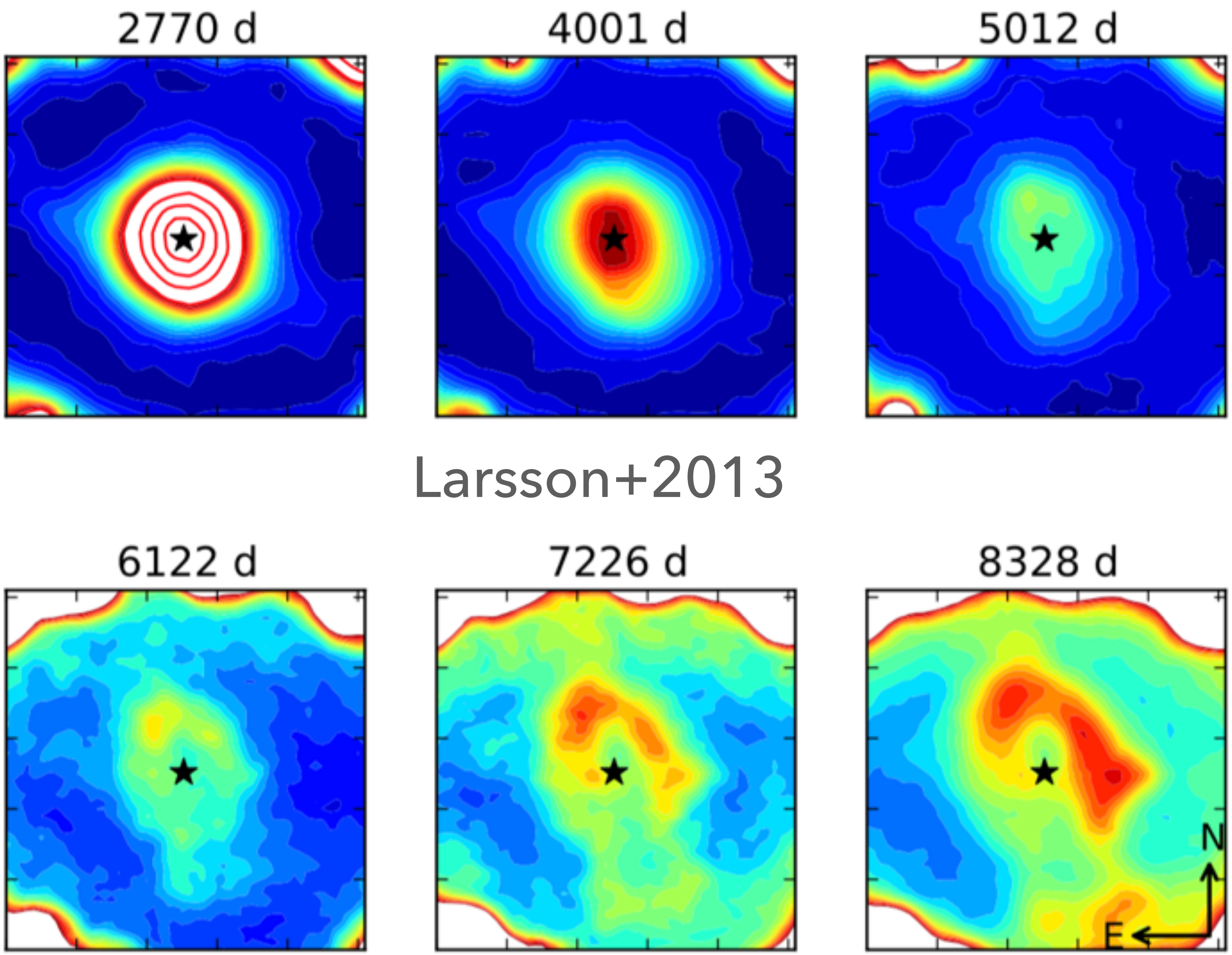




ORLANDO+2015 SIMULATION

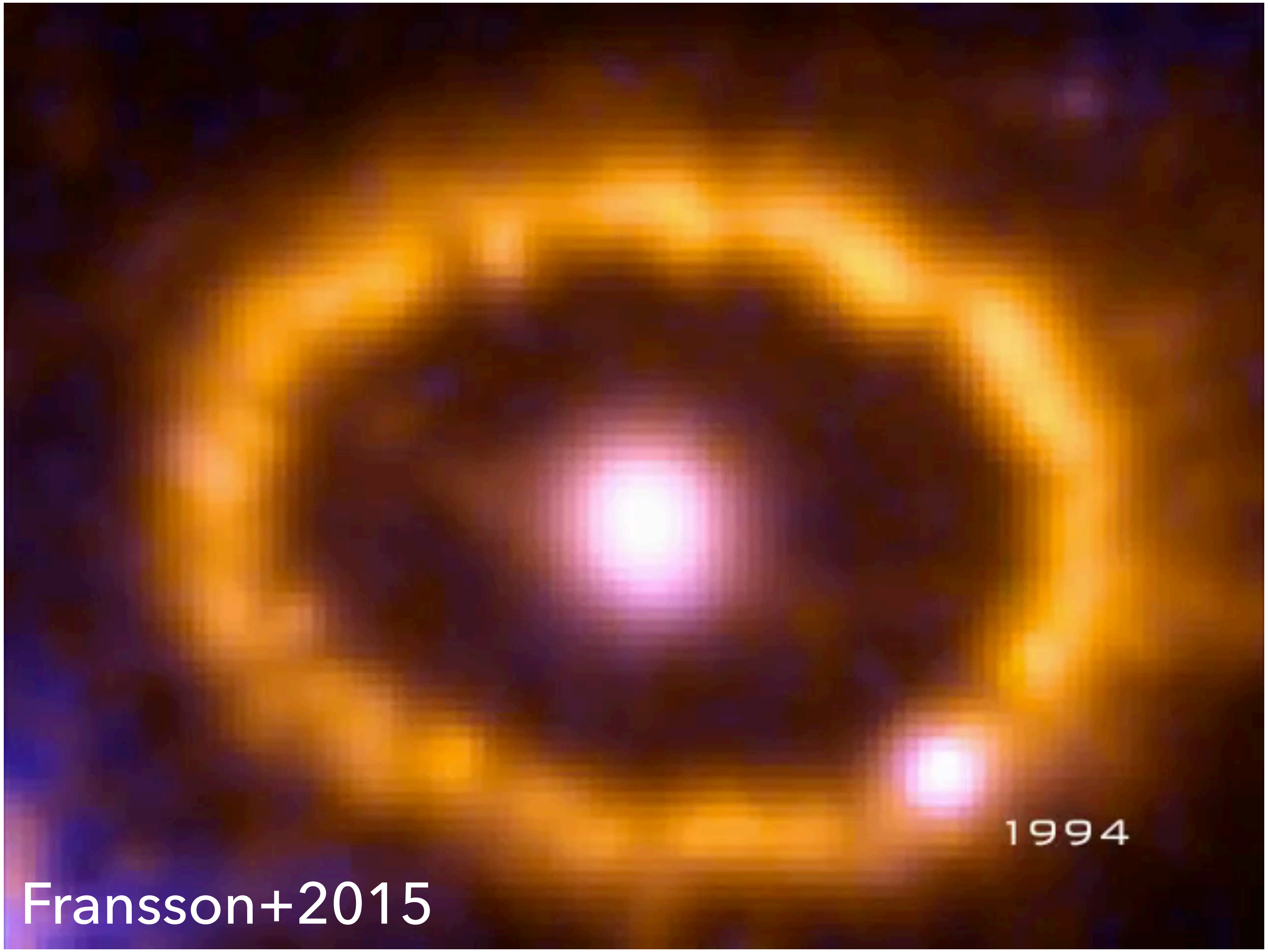


X-RAYS RADIATIVELY HEAT OUTER LAYER OF DEBRIS



Larsson+2013

OPTICAL (RE)BRIGHTENING OF RING, EJECTA EXPANDS AND FADES



SOFT/ OPTICAL=CLUMPS

HARD/RADIO=HII