Role of reflected shocks in particle acceleration in supernova remnants

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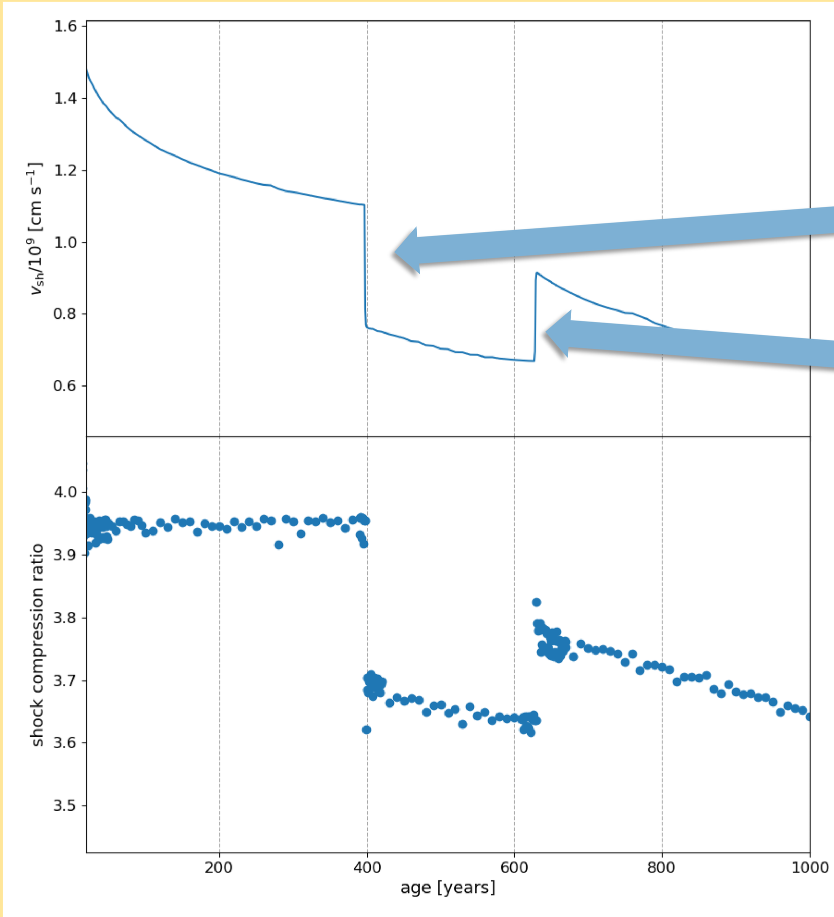
Majority of supernova remnants expand into a complex environment of the stellar wind bubble blown up either by their progenitor or their companion star, where forward shock might interact with various density inhomogeneities. Such interactions would cause formation of fast reflected shocks propagating back and forth between the forward shock, the contact discontinuity in the interior of the remnant and the reverse shock. Current investigations of particle acceleration at supernova remnant shocks usually ignore the complexity of the hydrodynamic picture. On the other hand, rapidly improving observational facilities allow now for precise spatially and temporally resolved measurements that do not always agree with a simplified modelling. It is intuitive that many irregularities as compared to the classical view of non-thermal emission from supernova remnants could be connected to the particulars of the environment. This work investigates the impact of the interaction of a reflected shock with a forward shock of an SNR on the particle acceleration in the source and examines observational signatures that could potentially arise from such interactions.

Radiation Acceleration Transport Parallel Code

Powered by RATPAC

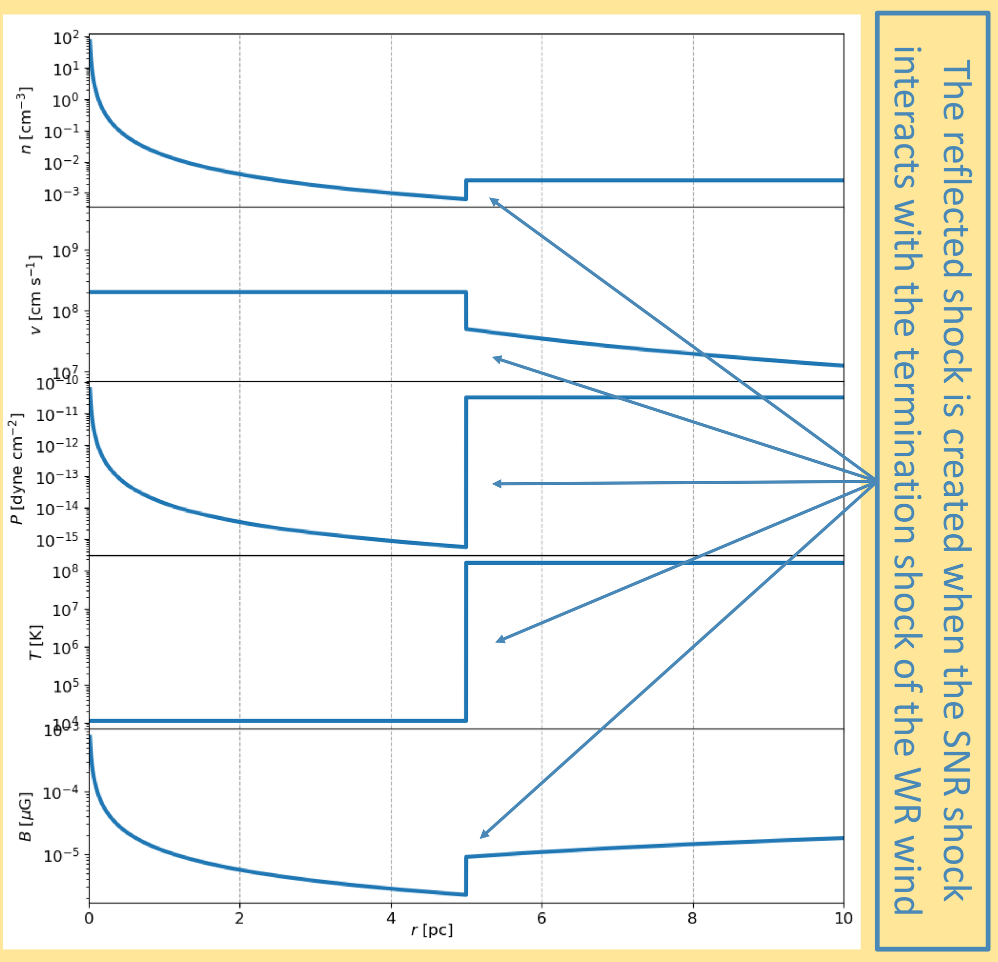
- Kinematic approach to particle acceleration
- Solves the particle transport equation time-dependently in 1-D spherical symmetry
- Coupled to 1-D hydrodynamic simulations which are performed on-the-fly with PLUTO
- Products:
  - time- and spatially-dependent spectra of accelerated particles
  - spectra of non-thermal emission through synchrotron, inverse Compton scattering, and hadronic interactions

Forward shock evolution



- Shock velocity decreases as the shock hits the termination shock of the wind
- Shock velocity increases again once the reflected shock reaches it after bouncing of the contact discontinuity in the SNR interior
- Compression ratio at the shock decreases as the shock moves into the hot medium of the shocked wind
- Particles are assumed to be injected into the acceleration process only at the forward shock

Setup: the circumstellar medium



Typical for the Wolf-Rayet wind right before the explosion

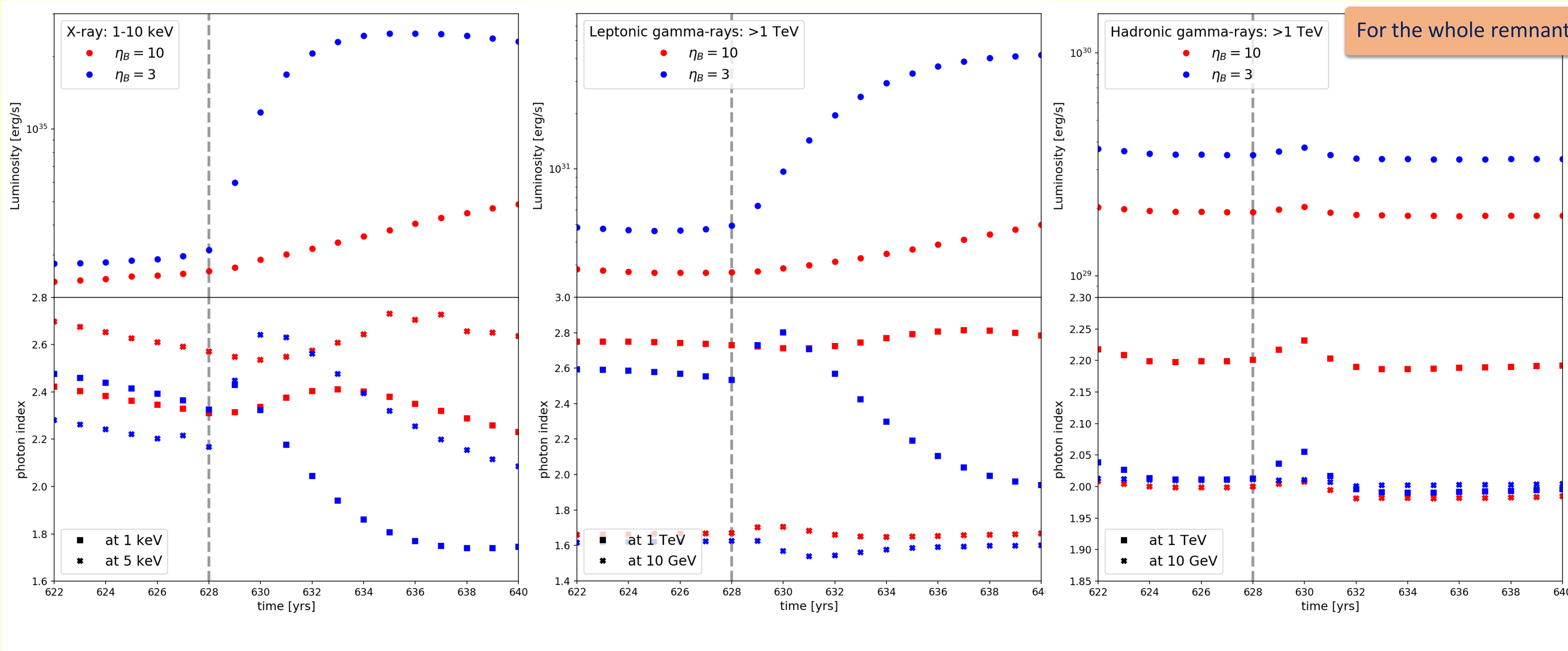
Setup: magnetic field amplification and diffusion

- Magnetic field amplified by a factor of 5 at the shock
- Exponentially decrease to the medium value along the precursor of $0.05R_{sh}$
- Compressed at the shock by a factor of $\sqrt{11}$
- Passively transported with the plasma flow downstream
- Bohm-like diffusion assumed:

$$D(p) = \eta_B \frac{pc^2}{3eB}$$

$$\left.\begin{array}{ll}\eta_B = 10 & (G1.9+0.3, SN1006) \\ \eta_B = 3 & (Tycho, Cas\ A)\end{array}\right\} \text{- for young SNRs}$$

A boost given by the reflected shock to the forward shock results in the increase of the maximum energy that reflects in X-ray and TeV emission

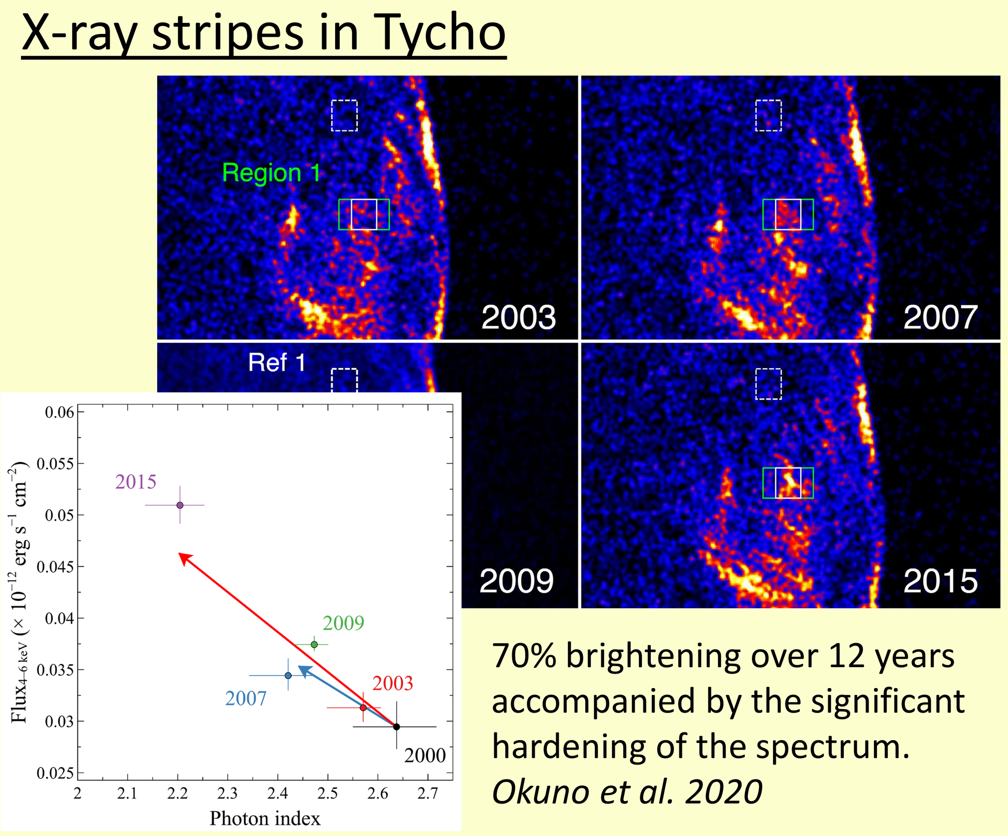


X-rays: Significant increase of the luminosity accompanied by hardening of the spectrum. The effect is more pronounced for slower diffusion

Leptonic gamma-rays: The effect is similar to X-rays, but somewhat weaker. No change of the spectral shape in the GeV energy range

Hadronic gamma-rays: the effect is negligible, because unlike electrons, protons are not affected by radiation losses prior to the interaction

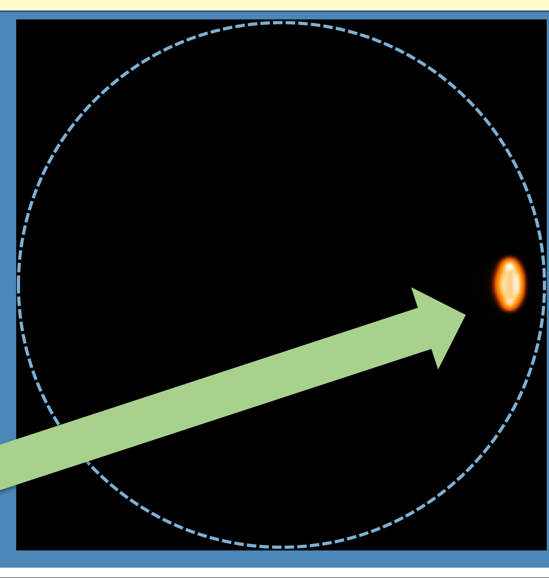
X-ray stripes in Tycho

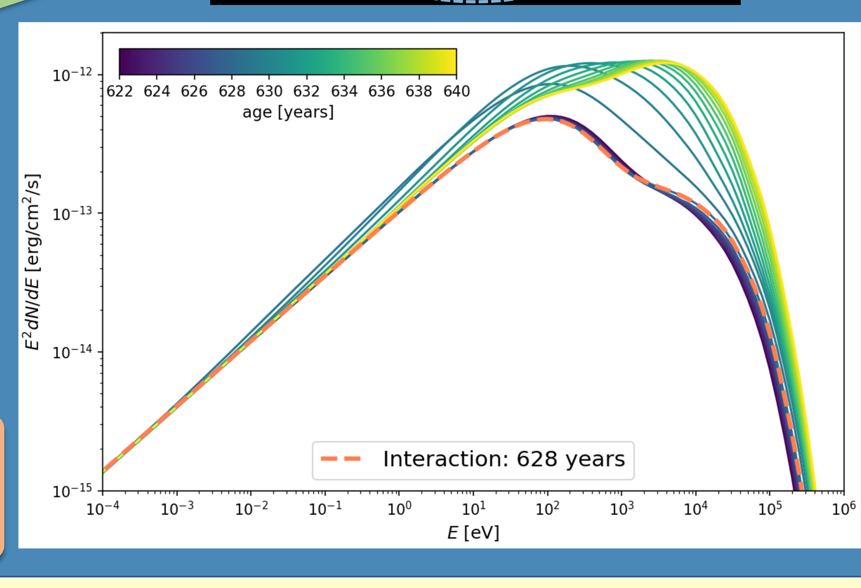


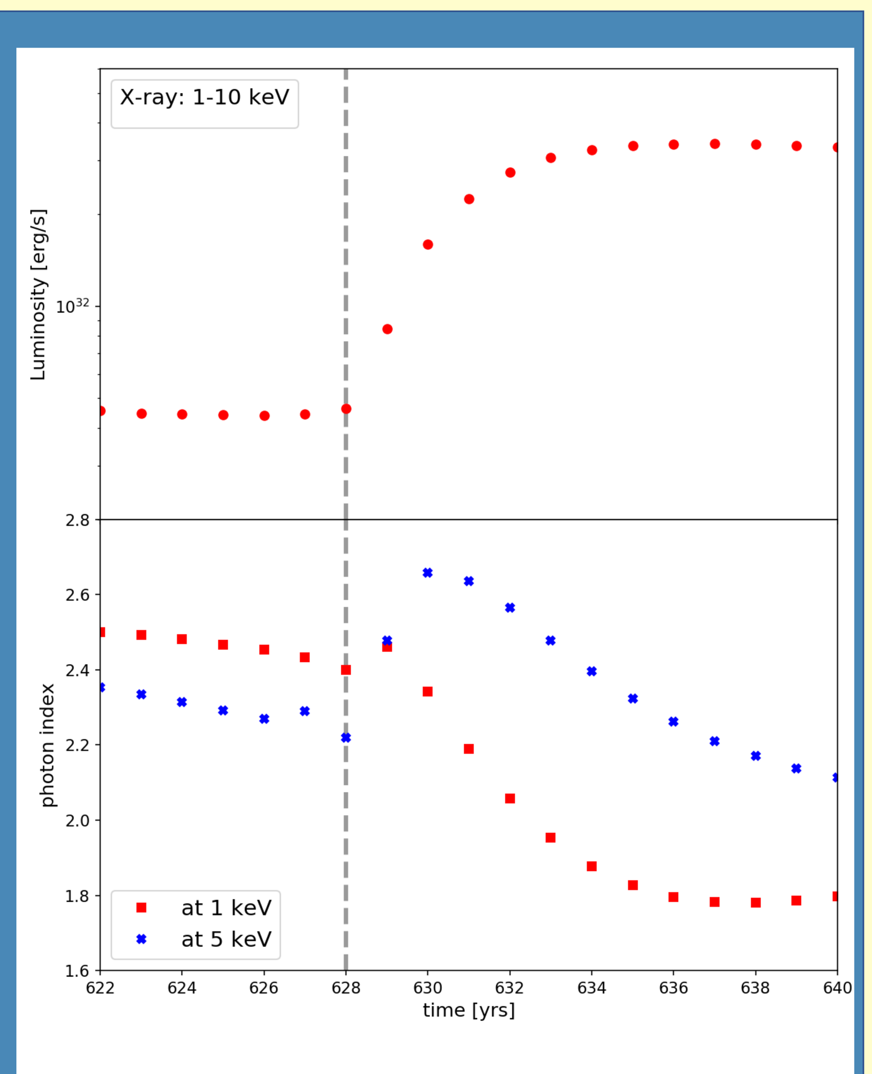
70% brightening over 12 years accompanied by the significant hardening of the spectrum.
Okuno et al. 2020

Modeling of the X-ray stripe/knot

- The emission is considered only within the cone with the opening angle of 5 degrees (instead of the whole sphere)
- The cone is rotated by 30 degrees and the calculated X-ray emission projected on the 2d plane
- X-ray fluxes and spectra are extracted from the stripe-like emitting region for the times around the reflected shock-forward shock interaction
- $\eta_B = 3$ and the distance to the source of 1 kpc are assumed







Resembles brightening of the X-ray stripe detected in the Tycho SNR

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