A Monte Carlo Simulation on Resonant Scattering of X-Ray Line Emission in Supernova Remnants

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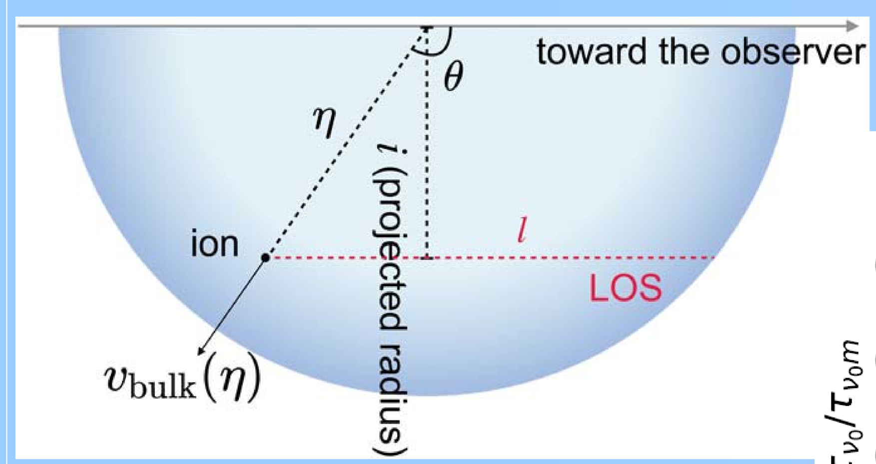
Resonant scattering (RS) of X-ray line emission in supernova remnants (SNRs) may modify the observed line profiles and fluxes and has a potential impact on estimating the physical properties of the hot gas and hence on understanding the SNR physics. RS events usually happen in the lines with large oscillation strength, such as the Lyα and Heα r lines. It was detailed only for elliptical galaxies and galaxy clusters, but has not been theoretically modeled ever for SNRs. This work presents our Monte Carlo simulation of the RS effect on X-ray resonant-line emission, typified by the O VII Heα r and O VIII Lyα lines, from SNRs. We employ the physical conditions that are characterized by the Sedov–Taylor phase and ejecta-dominance phase, with some basic parameters similar to those in Cygnus Loop and Cas A, respectively. We show that the impact of RS (on the line-of-sight optical depth, the surface brightness, line-ratios, etc.) is most significant near the edge of the remnant in Sedov phase and near the reverse shock of the remnant in the ejecta-dominance phase. The line profiles are predicted to be asymmetric because of scattering of the photons emitted by the ions in bulk motion at different radii with different emissivity. It is predicted that the surface brightness of the line emission would decrease in the outer projected region but is slightly enhanced in the inner. The G-ratio of the O VII Heα triplet can be effectively elevated by RS in the outer region. We show that the RS effect of the O VII Heα r line in the southwestern boundary (SW-Knot) region of Cygnus Loop is nonnegligible. The observed O VII G-ratio of ~1.8 of the region could be achieved with RS taken into account for O abundance properly elevated from the previous estimates. For young SNR like Cas A, the ratio between O VIII Lyβ and the resonant line O VIII Lyα is shown to be elevated in the shocked ejecta. This could qualitatively explain the enhanced O VIII Lyβ/Lyα ratio and O VIII Lyα deficit in the southeastern blob of Cas A.

1. Sedov-Taylor case

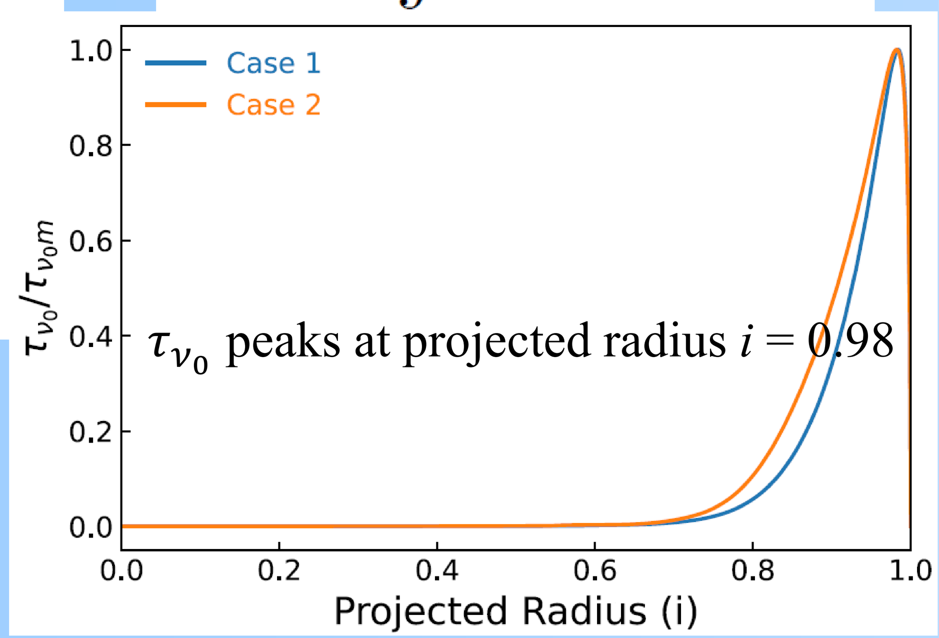
(Exemplified by Cygnus Loop)

Parameter values used in simulations

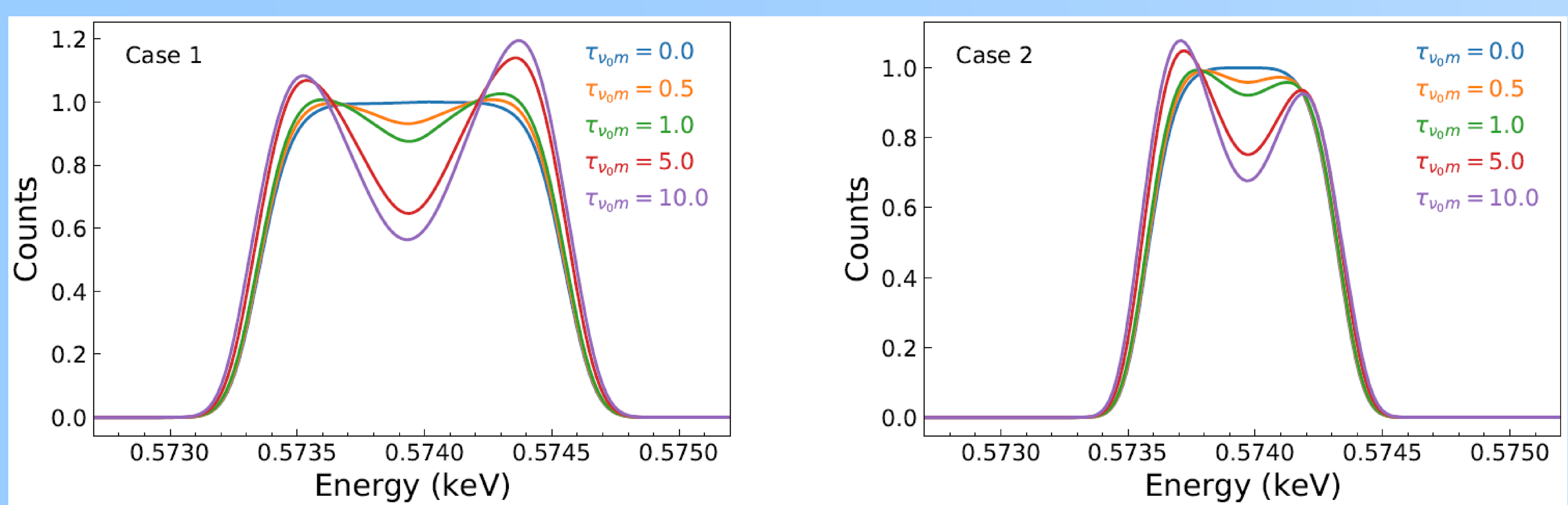
	R_s (pc)	V_s ($\mathrm{km\,s^{-1}}$)	E (10^{51} erg)	n_0 ($\mathrm{cm^{-3}}$)	$n_e t_i{}^a$ ($10^{10}\,\mathrm{cm^{-3}s}$)	t (10^4 yr)	T_s (keV)
Case 1	13	450	0.33	0.35	~4.8	~ 1.1	~ 0.24
Case 2	13	300	0.42	1.0	~ 20	~ 1.7	~ 0.11



$$\tau_\nu(i) = R_s \int n_{\rm ion}(\eta, Z)\, s(\eta, x)\, dl$$



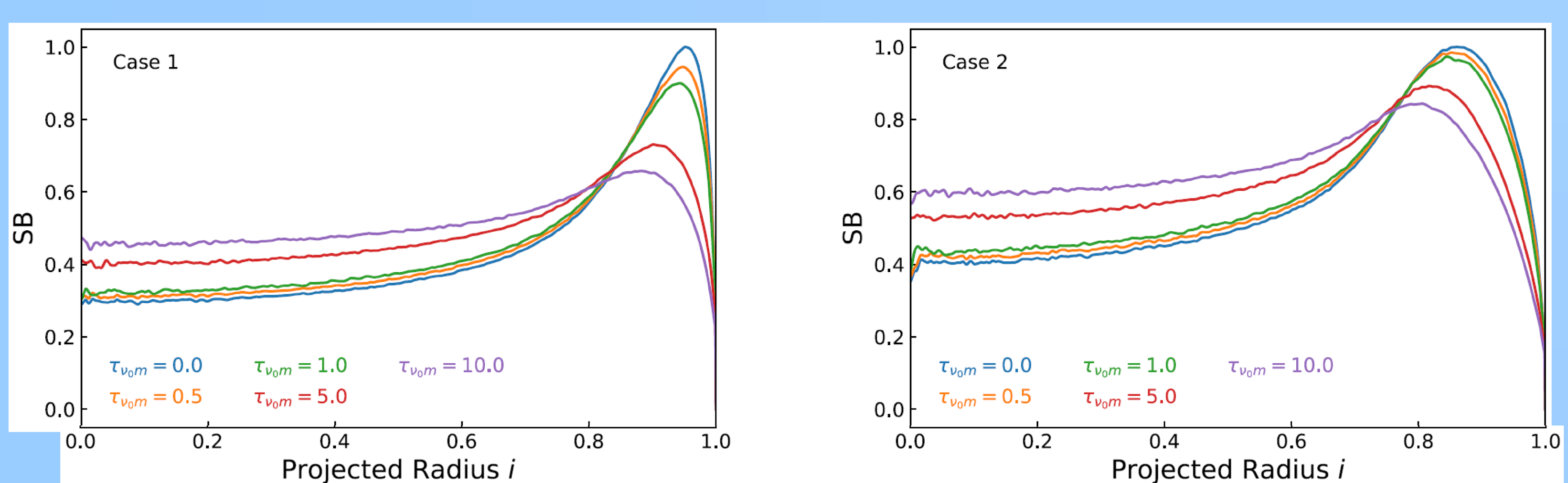
Right figure: Optical depth at the line center of O VII r line $\nu_0 = 573.95$ eV, normalized by the maximum depth $\tau_{\nu_0 m}$.



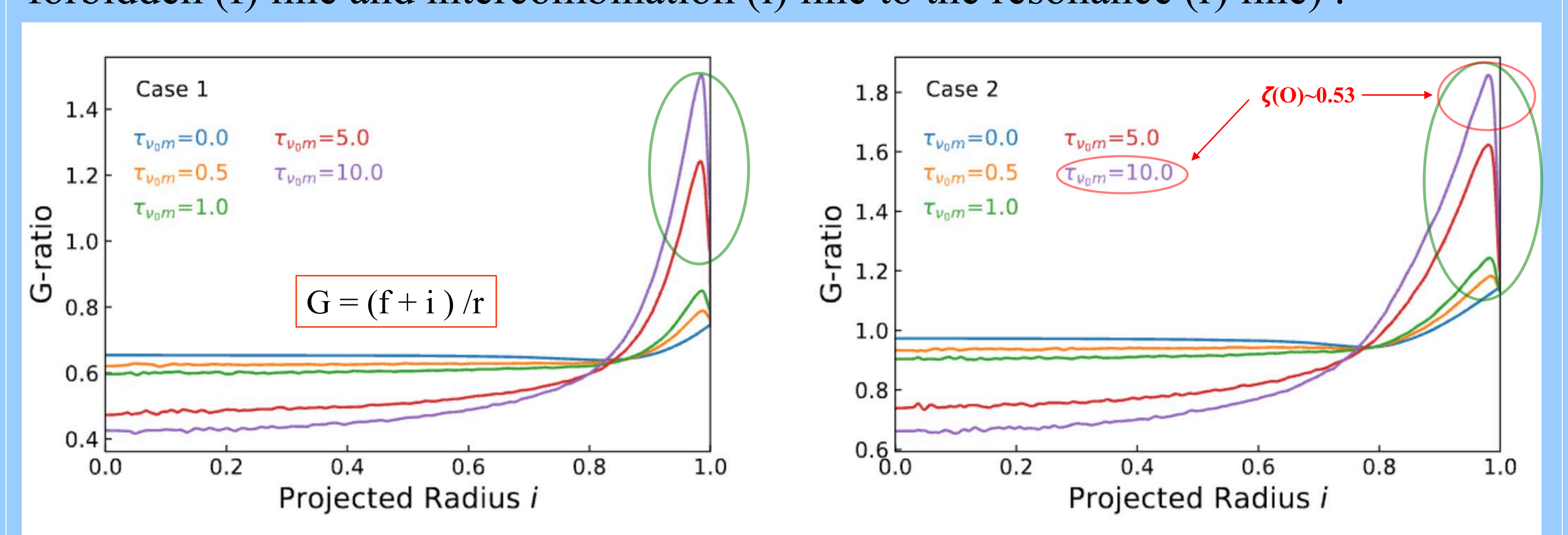
Above figure: Line profiles of O VII Heα r photons received from the entire SNR.

- As $\tau_{\nu_0 m}$ increases, the line profiles get increasingly deformed: the photon counts at the line core keep being reduced.
- The line broadening resulting fron the RS effect is slight compared with the Doppler broadening.
- The asymmetry of the line profiles reflects the total effect of scattering of the photons emitted by the O VII ions in bulk motion at different radii with different emissivity.

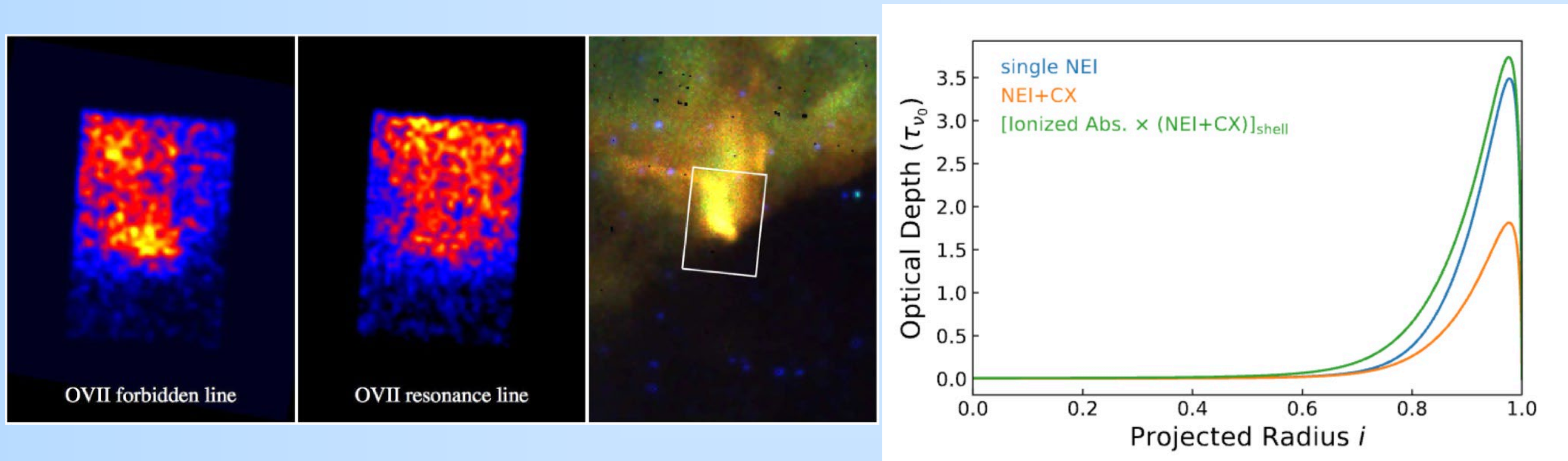
Below figure: Projected **radial surface brightness (SB) distribution** of the O VII Heα r line: SB is reduced in the outer region but enhanced in the inner.



Below figure: Projected radial profiles of the **O VII Heα triplet G-ratio** (the forbidden (f) line and intercombination (i) line to the resonance (r) line) .



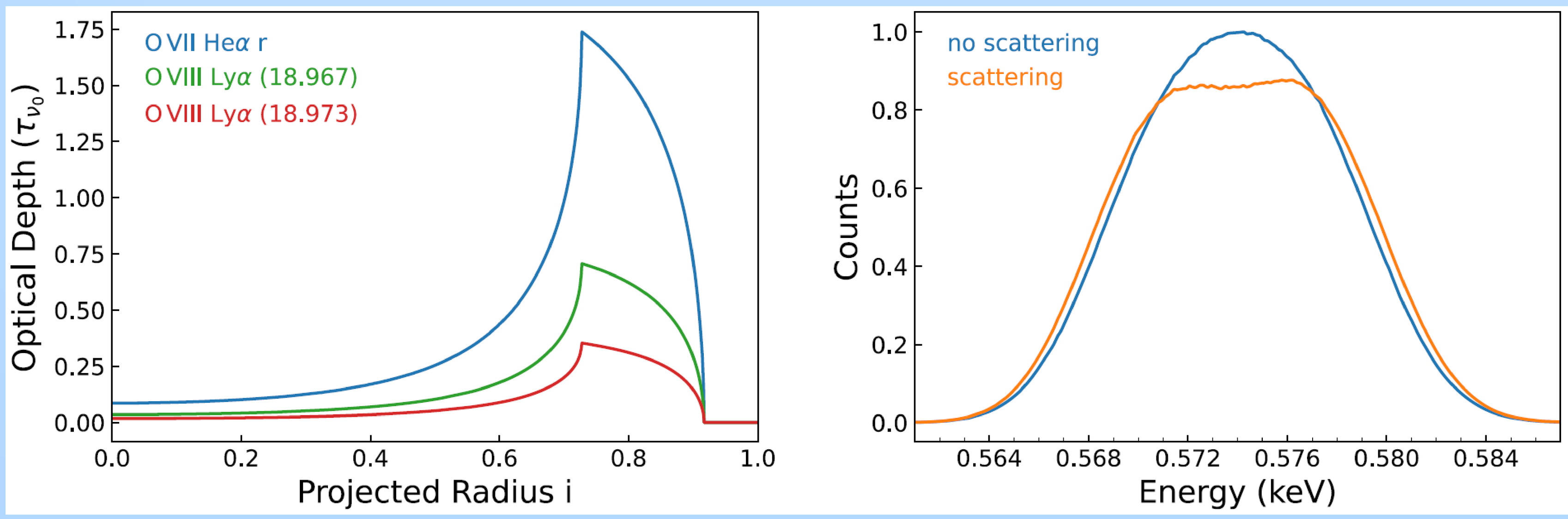
(in continuation of the left column bottom) G-ratio rises evidently in the outer region ($i > 0.8$) and drop in the inner region. In Case 2, a G-ratio of >~1.8 as observed in SW-Knot (Uchida et al. 2019) can be achieved if $\tau_{\nu_0 m} \sim 10$, which corresponds to an O abundance $\zeta(\mathrm{O}) \sim 0.53$, moderately elevated from previous estimates.



Above figure: X-ray images of the SW-Knot of Cygnus Loop (from Uchida et al. 2019). For interpretation of O VII G-ratio as high as 1.8, Uchida et al. (2019) discuss models including "single NEI", "NEI+charge exchange (CX)", and "ionized absorbed (NEI+CX)" in that RS effect is mimicked; it is here shown that τ_{ν_0} values are above 1 near the SNR edge for these models, indicating that RS is nonnegligible.

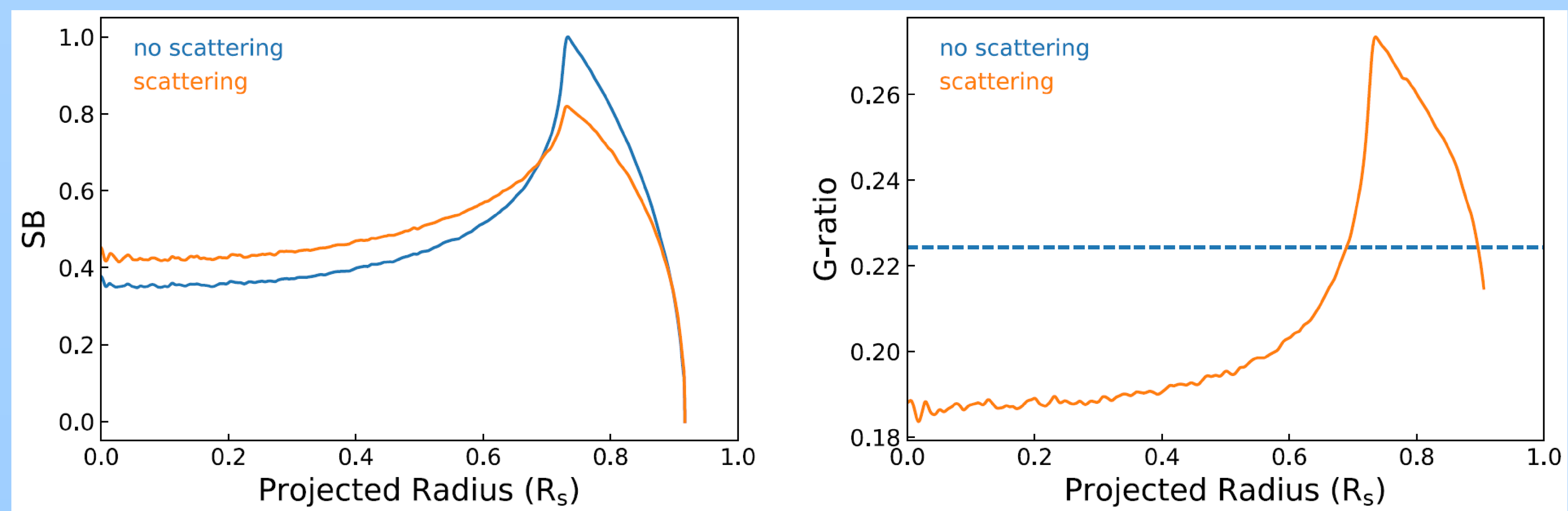
2. Ejecta-dominance case

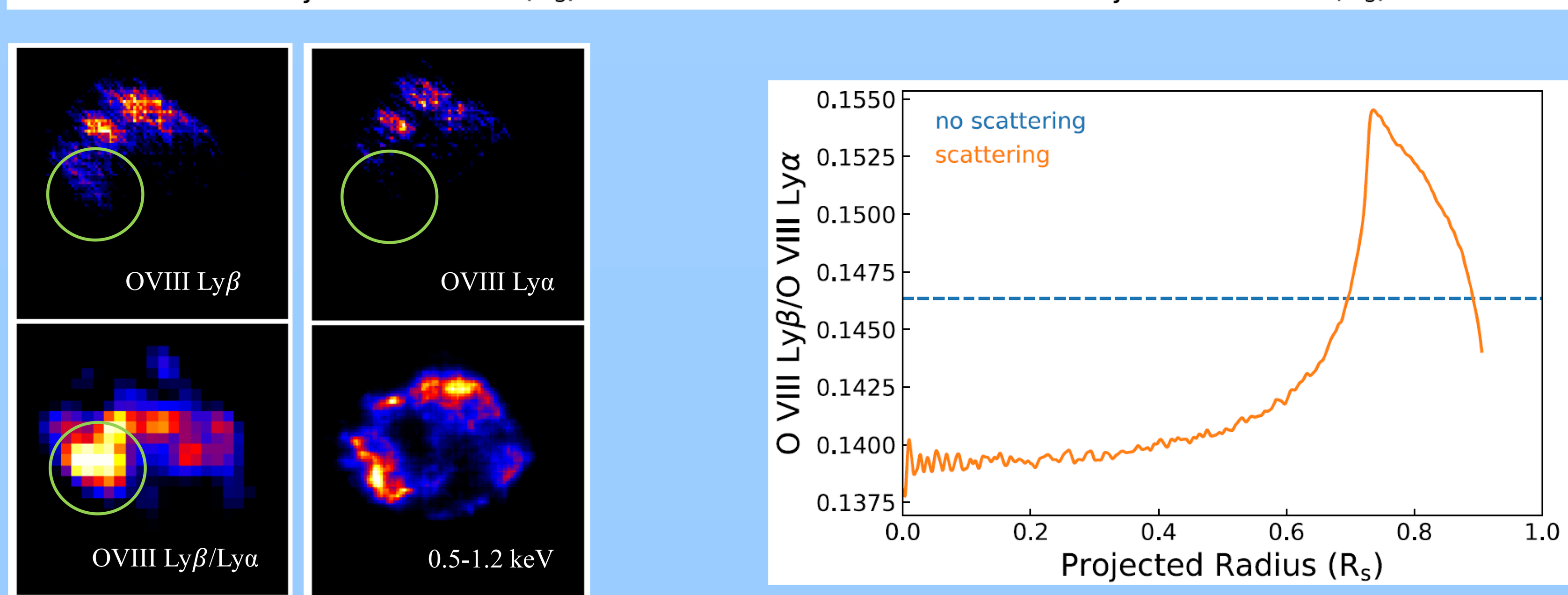
(Exemplified by Cas A)



Above figure: (Left) The line-center **optical depths** of O VII Heα r and O VIII Lyα. (Right) Line profiles of O VII Heα r photons with and without RS modeled for the entire SNR. Here the parameters adopted are: $R_s \approx 2.2$ pc, $R_r \approx 1.6$ pc, $V_r \sim 3000$ km/s (local frame), $T_e \approx 1$keV, $T_{\rm O\ ion} \approx 280$ keV, $n_e \approx 0.9\ \mathrm{cm^{-3}}$, $n_e t \sim 1\times10^{10}\ \mathrm{cm^{-3}}$ s, oxygen mass $\approx 0.36 M_\odot$, oxygen ion fraction ≈ 0.46 for O VII and ≈ 0.47 for O VIII.

Below figure: (Left) Projected **radial surface brightness distribution** of O VII Heα r; (Right) **O VII Heα triplet G-ratio**.





Above figure: X-ray images of the SE-Blob of Cas A (from Bleeker et al. 2001) and the **projected O VIII Lyβ /Lyα ratio distribution**. The calculated line ratio qualitatively explains the enhanced O VIII Lyβ/Lyα ratio and O VIII Lyα deficit in the SE blob.

References

Bleeker et al., 2001, A&A, 365, L22
Uchida et al., 2019, ApJ, 871, 234