Measurement of shock velocities of N132D based on the thermal X-ray emission

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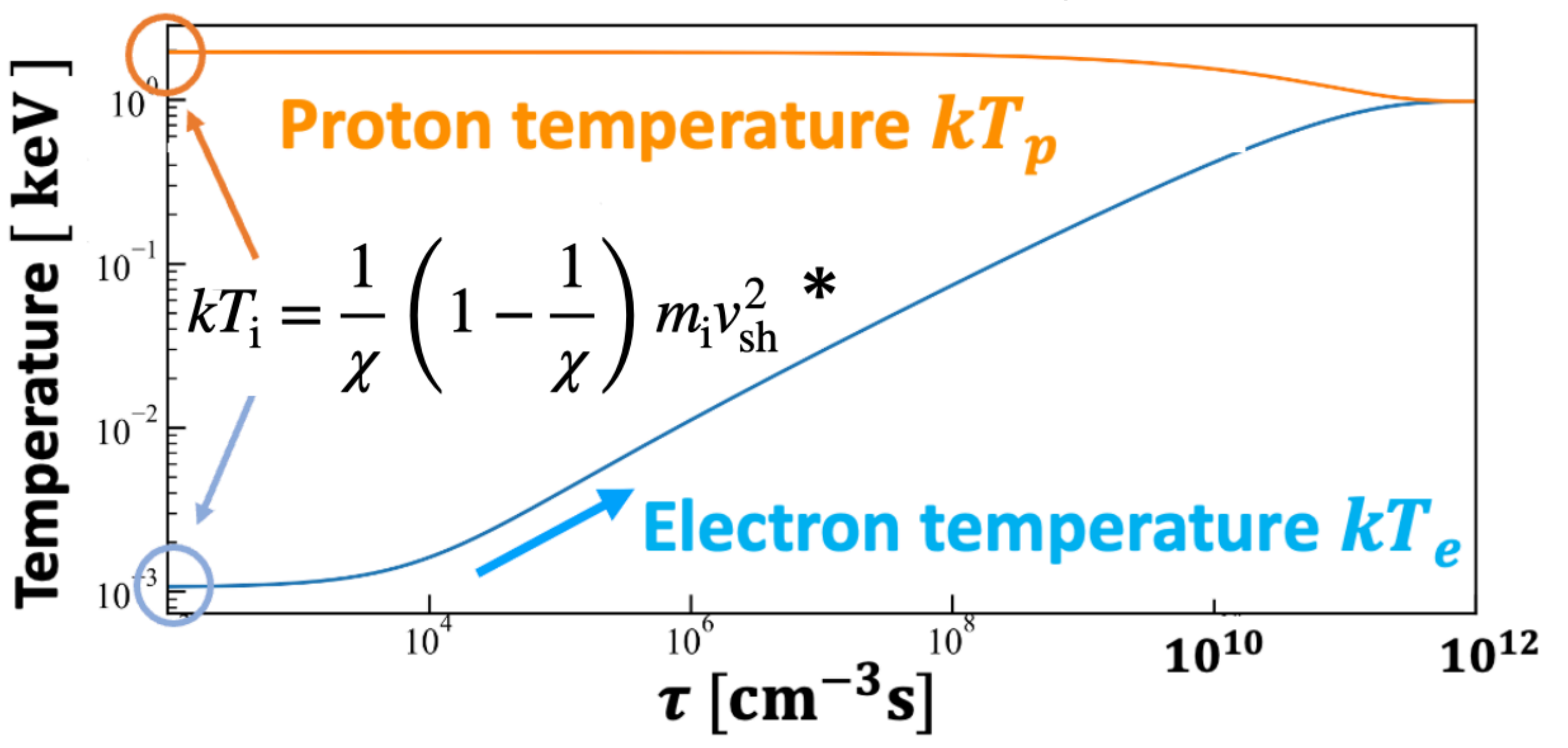
Summary

Shock velocities and their spatial variation provide insight into the evolution of supernova remnants (SNRs). Shock velocity can be estimated from the electron temperature and ionization degree of the shock-heated plasma by solving the thermal relaxation process via Coulomb collisions. We focus on the supernova remnant N132D. Our comprehensive spectral analysis of the rim regions using Chandra revealed that shock velocities range from 800 to 1500 $\mathrm{km\ s^{-1}}$. We compare these estimates with proper motion velocity. The velocities from our spectroscopy and from the proper motion measurement are consistent with each other in the southern part. However, they differ by up to a factor of 4 in the northern regions. This surprising discrepancy cannot be explained by the adiabatic cooling of the plasma or effects of the magneto-hydrodynamic or oblique shocks, and can be explained by a highly efficient particle acceleration (reaching $\approx 90\,\%$).

Introduction

- ◆Shock velocities and their spatial variation provide insight into the evolution of supernova remnants (SNRs).
- ◆ Shock velocity has been measured based on proper motion, which is mainly applicable for galactic and young SNRs.
- ◆Shock velocity can be estimated from thermal X-ray by tracing back postshock processes (i.e., thermal equilibration and ionization).
- ◆We develop a spectral model (`IONTENP`), which estimates shock velocity by simultaneously solving the two postshock processes [1].



Ionization timescale τ

$$\tau = \int_0^t n(t')dt$$

t' : elapsed time just after shock heating

*in the extreme case of collisionless shock
$kT_{\rm e}/kT_{\rm p} = m_{\rm e}/m_{\rm p}$

Fig. 1: Thermal equilibration process. non-equilibrium temperature state immediately after the shock gradually approaches equilibrium via Coulomb collisions.

Observation and Data Reduction

- ◆We used archival Chandra data of N132D from 2019 March 27 to 2020 July 16 (868 ks in total).
- ◆We reprocessed data following the standard procedure using `chandra_repro`.

Results

Shock velocity estimated from thermal X-rays

- ◆We fit the spectra extracted from the source regions (Fig. 2b) with `IONTENP` model.
- ◆Shock velocities are found to have a significant variation in the range of 800-1500 km s⁻¹(Fig. 3).

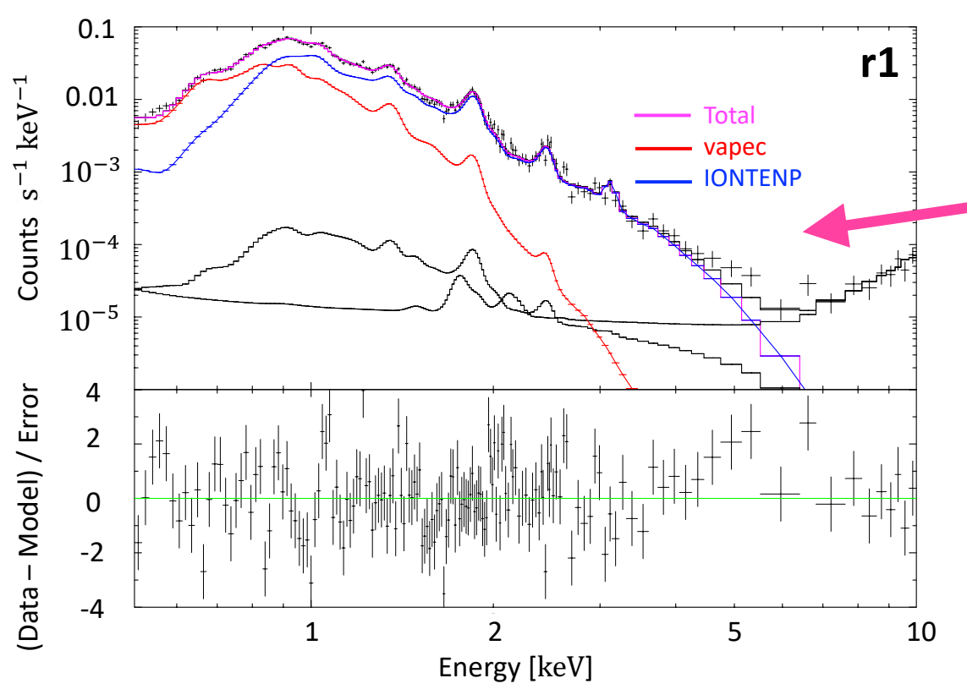


Fig. 2a

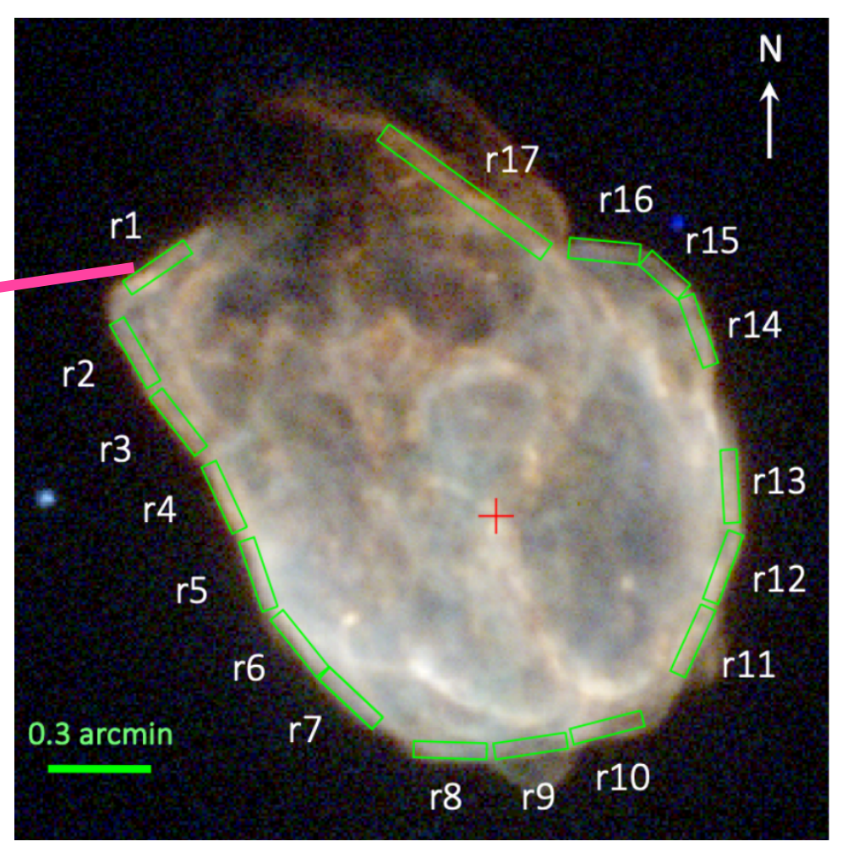


Fig. 2b

Fig. 2a: The X-ray spectrum and best-fit model for the region r1.
Fig.2b:Chandra ACIS-S three colour image (red: 0.5-1.2 keV, green: 1.2–2.0 keV, blue: 2.0–7.0 keV) with analysis regions (green box). The red cross indicates the inferred centre of explosion.

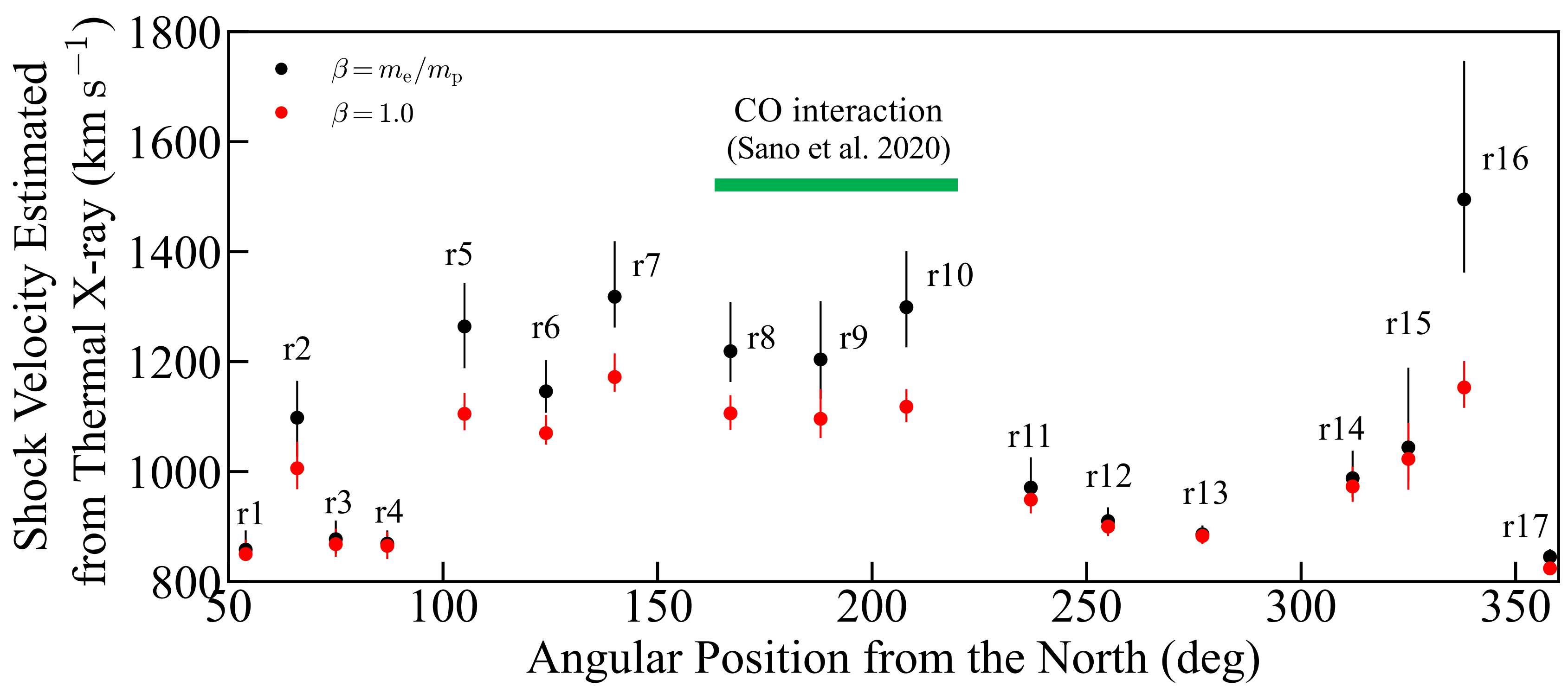


Fig. 3: Spatial distribution of shock velocity estimated from thermal X-ray along the rim in N132D. The fitting results of shock velocity for $\beta = m_{\rm e}/m_{\rm p}$ (red) and $\beta = 1.0$ (black) are summarised. These practically indicates upper and lower limit value of the shock velocity.

Discussion

Comparison with Doppler velocities

- ◆Doppler broadening of the silicon and sulphur Heα lines for the entire N132D region is $\sigma_v \approx 450\ \mathrm{km\ s^{-1}}$, which corresponds to a shock velocity of $\approx 1200\ \mathrm{km\ s^{-1}}$ [2].
- ◆The velocity can be treated as a representative forward-shock velocity in the southern half (5–r10), where Si and Si emission is the brightest.
- ◆This is consistent with our velocity estimation in r5-r10.

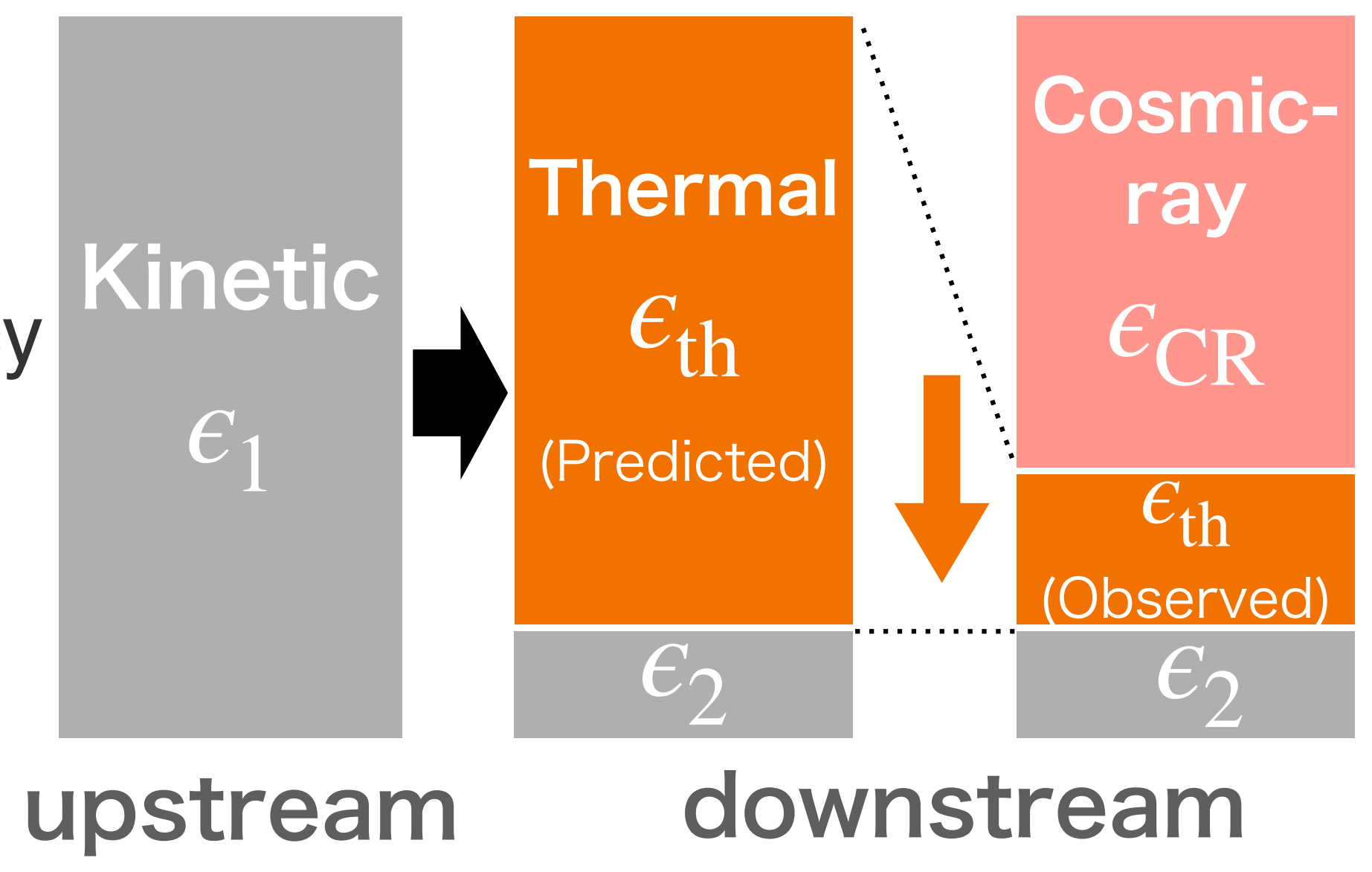
Discussion

Comparison with proper motions

- ◆Proper motions were measured by comparing Chandra images obtained in 2006 and in 2019–2020 [3].
- ◆The propagation velocities of the shell are $v_{\rm prop} \approx 3700\ \mathrm{km\ s^{-1}}$ in the north (r1) and $v_{\rm prop} \approx 1700\ \mathrm{km\ s^{-1}}$ in the south (r5-r13).
- ◆Our estimated velocities $v_{\rm th}$ are generally lower than the proper motion velocities $v_{\rm prop}$.
- ◆The discrepancy between $v_{\rm prop}$ and $v_{\rm th}$ indicates that the energy transferred from the shock wave to the heating of the ISM is less than that expected from the proper motion measurements.
- ◆Possible effects which can explain the measured discrepancies between $v_{\rm prop}$ and $v_{\rm th}$:
  - Adiabatic cooling : $v_{\rm th}/\ v_{\rm prop} \geq 0.93$
  - MHD shock : $v_{\rm th}/\ v_{\rm prop} \geq 0.9$
  - Oblique shock :$v_{\rm th}/\ v_{\rm prop} \geq 0.77 - 0.95$ [4]
- ◆**The discrepancy in r5-r10 (0.7-0.8) can be explained by these effects.**

Highly efficient cosmic-ray acceleration

- ◆ The regions other than r5–r10 show larger discrepancies of $v_{\rm th}/\ v_{\rm prop} \geq$ 0.23 (r1). Such discrepancies cannot be explained by the effects considered above.
- ◆Here we examine the effect of particle acceleration at the shock front.



- ◆Energy flux conservation

$$\epsilon_1 v_1 = \left(\epsilon_2 + \epsilon_{\rm th} + \epsilon_{\rm CR}\right) v_2$$

- ◆Cosmic-ray acceleration efficiency

$$\eta = \frac{\epsilon_{\rm CR}}{\epsilon_{\rm th} + \epsilon_{\rm CR}} = \frac{\chi\epsilon_1 - \epsilon_2 - \epsilon_{\rm th}}{\chi\epsilon_1 - \epsilon_2}$$

- ◆The parameter set $v_{\rm prop} = 3700\ \mathrm{km\ s^{-1}}$ and $v_{\rm th} = 860\ \mathrm{km\ s^{-1}}$ (r1) can be explained with the efficiency is $\eta \approx 90\,\%$ ($\gamma = 5/3$).

Implication from γ-ray observations

- ◆The total energy of accelerated protons is estimated to be $W_{\rm p} = 4 \times 10^{50}$ erg.
- ◆This can be translated to an acceleration efficiency of $\eta \sim 40\,\%$ (assuming a typical kinetic energy of the explosion, 10^{51} erg).
- ◆This supports our suggestion that N132D is an efficient cosmic-ray accelerator.

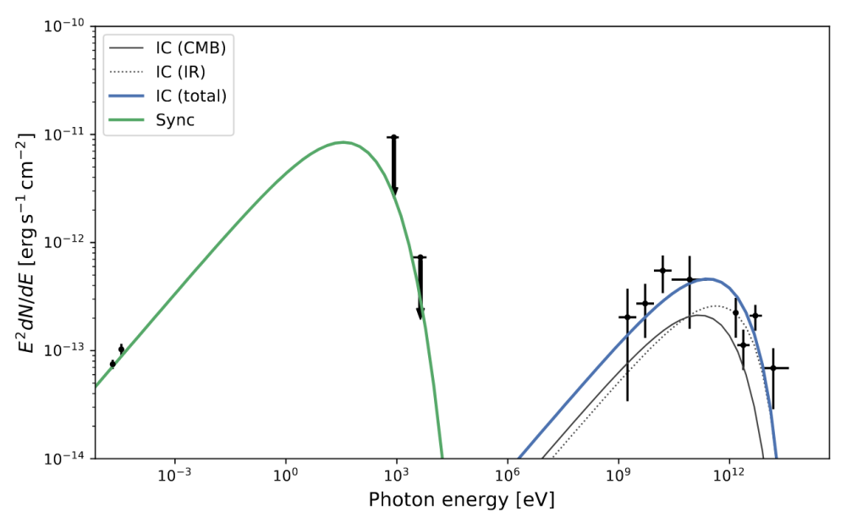


Fig. 6a

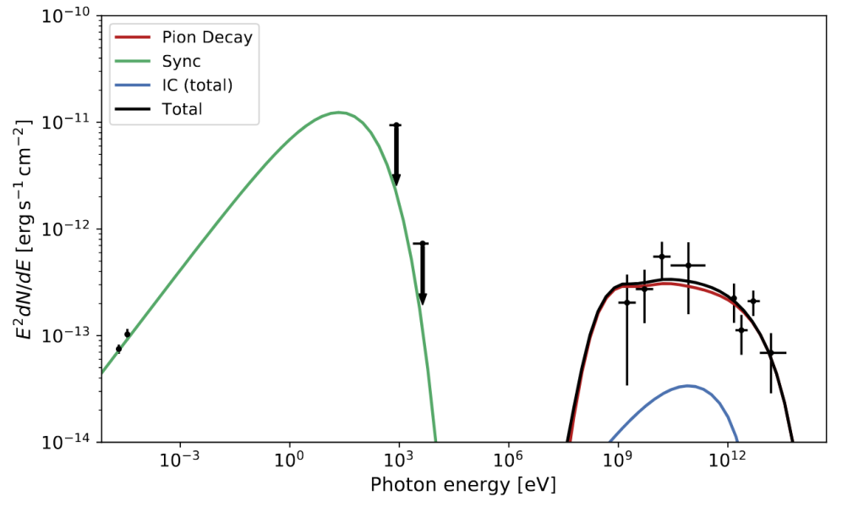


Fig. 6b

MODEL	W_e(> 1 GeV) erg	Γ	$E_{c_{elec}}$ TeV	B μG	W_p(> 1 GeV) erg	n_p cm^{-3}	$E_{c_{prot}}$ TeV
Leptonic	4.5×10^{49}	2.2	8	20	–	–	–
Hadronic	4×10^{48}	2.1	2.5	100	4×10^{50}	10	120

Fig. 6a: Leptonic model considering an electron distribution following a power law with an exponential cutoff.
Fig. 6b: Hadronic model considering a proton distribution following a power law with an exponential cutoff [4].

Multi-messenger aspect

Neutrino emission from SNR

- ◆Assuming $D = 50$ kpc, $t_{\rm cool} = 2700$ yrs, $v_{\rm sh} = 3700\ \mathrm{km\ s^{-1}}$ and $\eta = 90\,\%$, the energy flux of neutrino emission is $E_\nu F_{E_\nu} \approx t_{\rm cool} t_{\rm pp}^{-1}\ 4\pi R^2 m_p n_{\rm ISM} v_{\rm sh} \eta\ D^{-2} \approx 3 \times 10^{-12}$ erg/ s/ cm^2.
- ◆Detection with IceCube will be challenging.

References

[1] Ohshiro, Y., Suzuki, S., Okada, Y., Suzuki, H., & Yamaguchi, H. 2024, ApJ. [2] XRISM Collaboration. 2024.
[3] Plucinsky, P., Long, X., Kashyap, V., et al. 2024, AAS meeting. [4]Shimoda, J., Inoue, T., Ohira, Y., et al. 2015, ApJ [5] H. E. S. S. Collaboration, Abdalla, H., Aharonian, F., et al. 2021