Importance of Richtmyer-Meshkov Instability on Measurements of Cosmic-Ray Acceleration Efficiency at Supernova Remnants

reference: Shimoda et al. 2015 ApJ 803, 98

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Introduction

Using MHD simulations, we have studied SNR shocks propagating into inhomogeneous upstream region.

- ISM density fluctuation:

  Power spectrum ; $\rho_k^2 k^2 \propto k^{-5/3}$ (Armstrong 1995)

  Dispersion ; $\frac{\Delta\rho}{\langle\rho\rangle} \approx 1.0$ at $L_{injection} \sim 100$ pc (de Avillez & Breitschwerdt 2007)

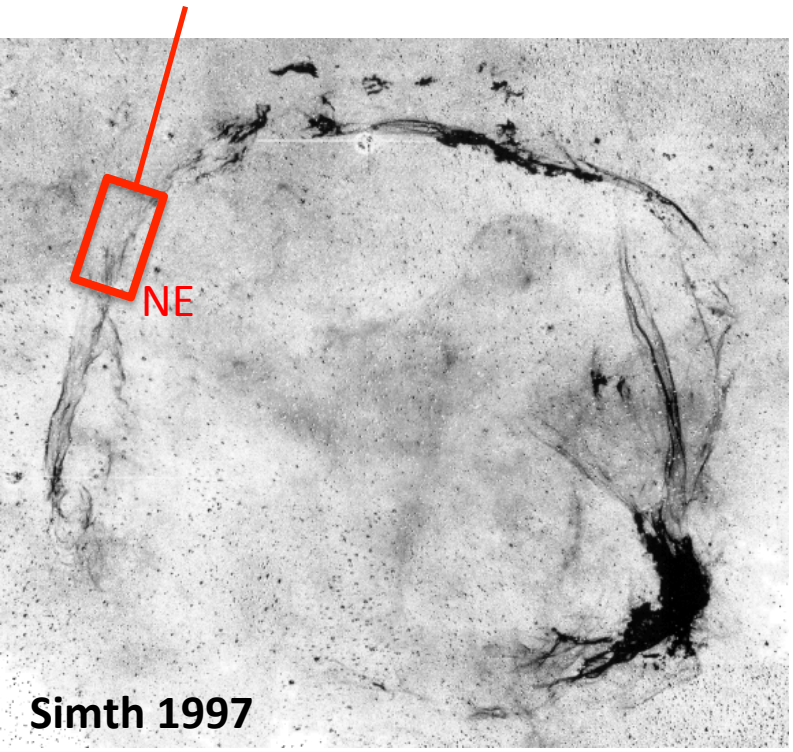
- In this context, several observational results on SNRs have been explained, which gives new insights into CR acceleration.

e.g.) RXJ1713 : X-ray variability (Inoue+ 09,10,12 , Gicalone & Jokipii 07)
No thermal X-ray lines (Inoue+ 12, Zirakashvili & Aharonian 10)
IC-like Gamma-ray spectrum (Inoue+ 12, Zirakashvili & Aharonian 10, Gabici & Aharonian 14)
SN1006 : Sudden change of polarization angle (Inoue & Shimoda+ 13)
middle aged SNRs : GeV break of γ-ray spectra (Inoue+ 10)

The CR production efficiency at SNR

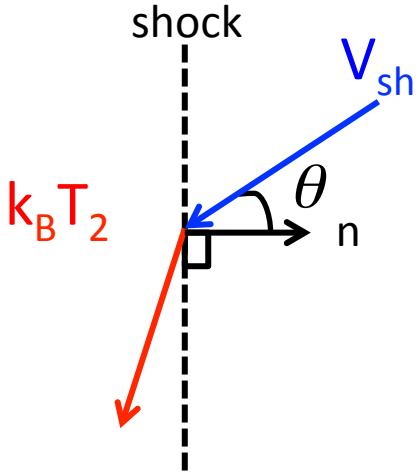
The energy density of Galactic CR around the Earth is explained if ~ 10 % of SN explosion energy is used for CR acceleration.

Observations of the northeastern region of the young SNR RCW 86 imply that the efficiency is higher than ~ 50 % (Helder+ 09, 13)!?



The Hα image of RCW 86, whose radius is ~10 pc.

- ✓ The measurement principle of the efficiency

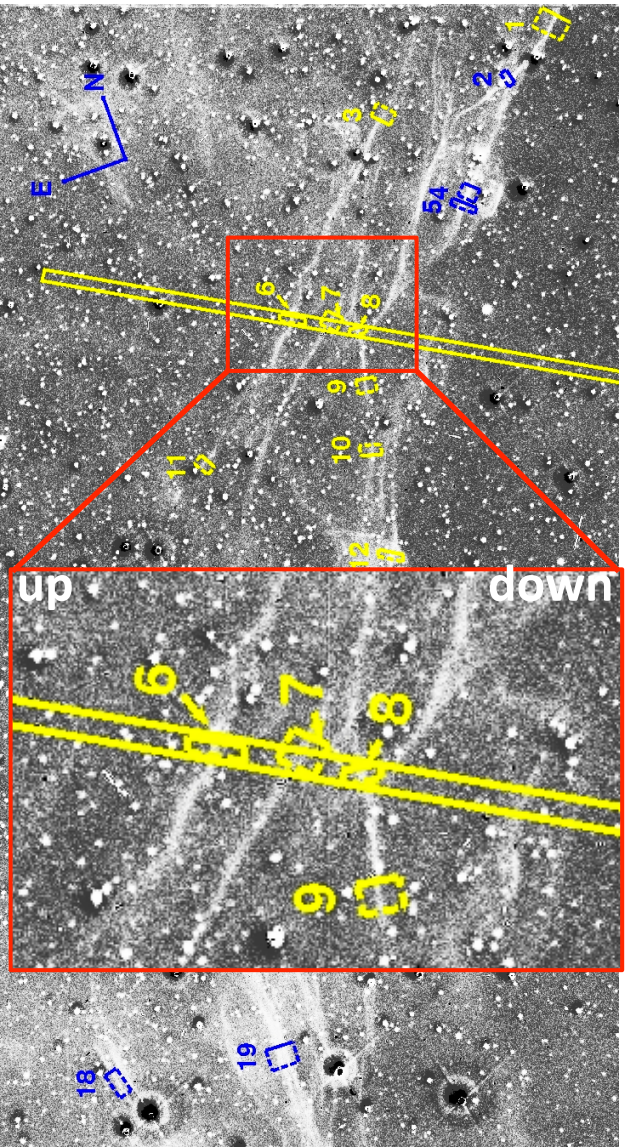


Rankine-Hugoniot relations

$$k_B T_2 = \frac{3}{16} m V_{sh}^2 \cos^2\theta$$

- ✓ The SNRs shock is loosing the energy due to the CR acceleration.
- ✓ If the actual downstream temperature and the shock velocity can be measured individually, we get the CR acceleration efficiency as a missing thermal energy.

The estimation of the CR acceleration efficiency.



- ✓ The expansion speed measured by the proper motion of the Hα filament:

$$V_{proper} \approx 1871 \ km/s \quad \text{(for Region 6)}$$

$$k_B T_{proper} = \frac{3}{16} m_p V_{proper}^2 \approx 6.8 \ keV \quad (\theta = 0)$$

- ✓ The downstream temperature : $k_B T_{down} = 2.3 \ keV$

- ✓ The CR acceleration efficiency:

$$\eta = \frac{T_{proper} - T_{down}}{T_{proper}} \approx 0.66$$

- ✓ The CR acceleration efficiency seems to be ubiquitously high.
- ✓ Other SNRs also imply that $\eta > 0$ based on the same argument.

Assumptions of previous studies

- ✓ The shock is plane parallel（i.e. θ = 0）.

$$k_B T_2 = \frac{3}{16} m V_{sh}^2 \cos^2 \theta$$

- ✓ All of the missing thermal energy goes into CR acceleration.

$$\eta = \frac{T_{proper} - T_{down}}{T_{proper}}$$

- ✓ These assumptions would be suitable for a spherically symmetric shock wave propagating into a homogeneous medium.

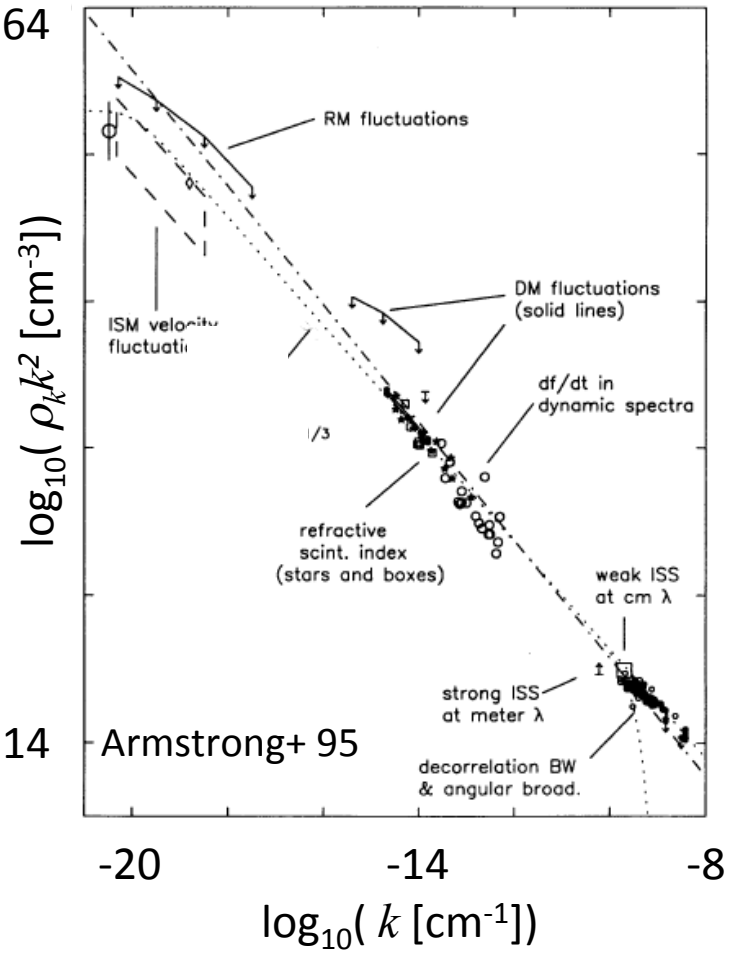
Realistic density fluctuations of ISM

- ✓ The density power spectrum of ISM measured by several radio observations.

$$\rho_k^2 k^2 \propto k^{-5/3}$$ (Armstrong+ 1995)

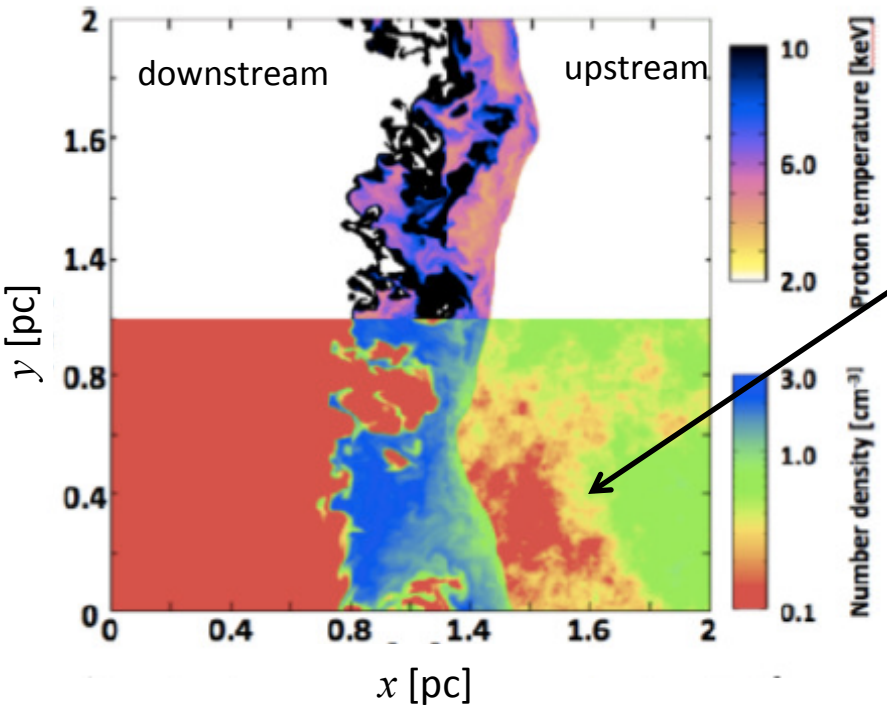
- ✓ The amplitude at 2 pc-scale is expected by simulations.

$$\frac{\Delta\rho}{\langle\rho\rangle} \approx 0.3$$ (de Avillez & Breitschwerdt 2007



It is widely accepted that the ISM is highly inhomogeneous.
The shock interacting with fluctuations may has a velocity dispersion.
We demonstrate it by using 3-dimensional MHD simulation.

Shock propagation into realistic ISM



2-dimensional slice of the proton temperature (upper half) and number density (lower half) in the z = 0 pc plane.

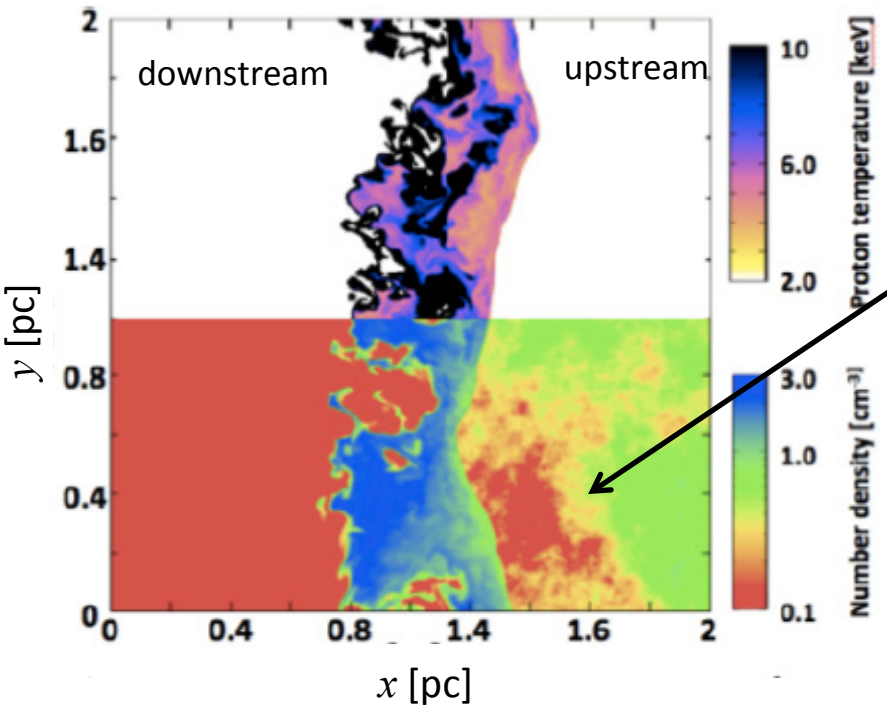
We realized realistic density structure of ISM.

$\rho_k^2 k^2 \propto k^{-5/3}$ (Armstrong 1995)

$\frac{\Delta\rho}{\langle\rho\rangle} \approx 0.3$ (de Avillez & Breitschwerdt 2007)

- ✓ Density fluctuations of realistic ISM causes the shock wave to become rippled and generate turbulence. (Giacalone & Jokipii 07; Inoue & Shimoda+ 13)
- ✓ The shock velocity differs according to location : 100 km/s < $V_{sh}\cos\theta$ < 2300 km/s , $\langle V_{sh}\cos\theta\rangle$ ~ 1300 km/s.
- ✓ **The shock is oblique almost everywhere (i.e. $\theta \neq 0$).**

Shock propagation into realistic ISM



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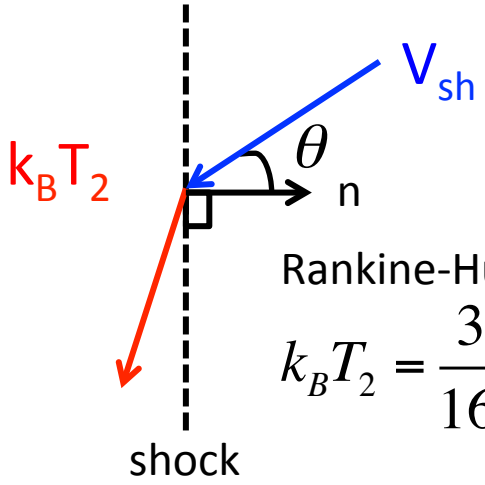
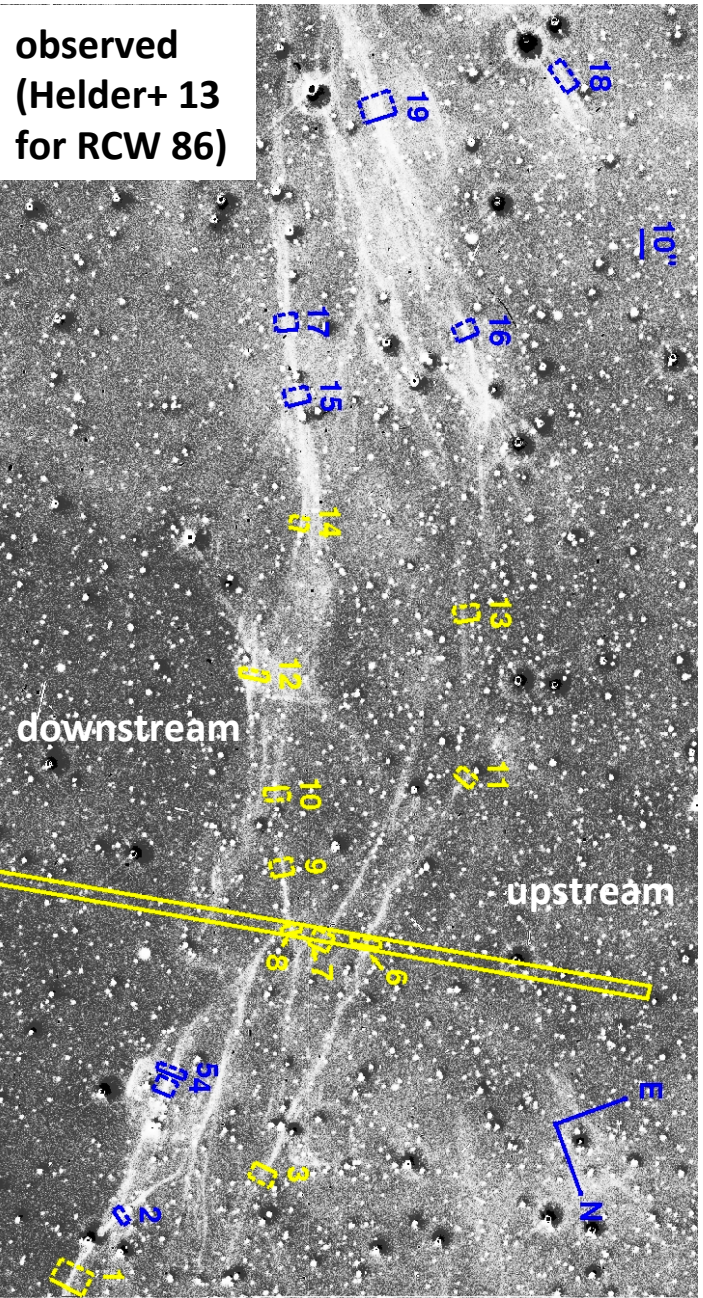


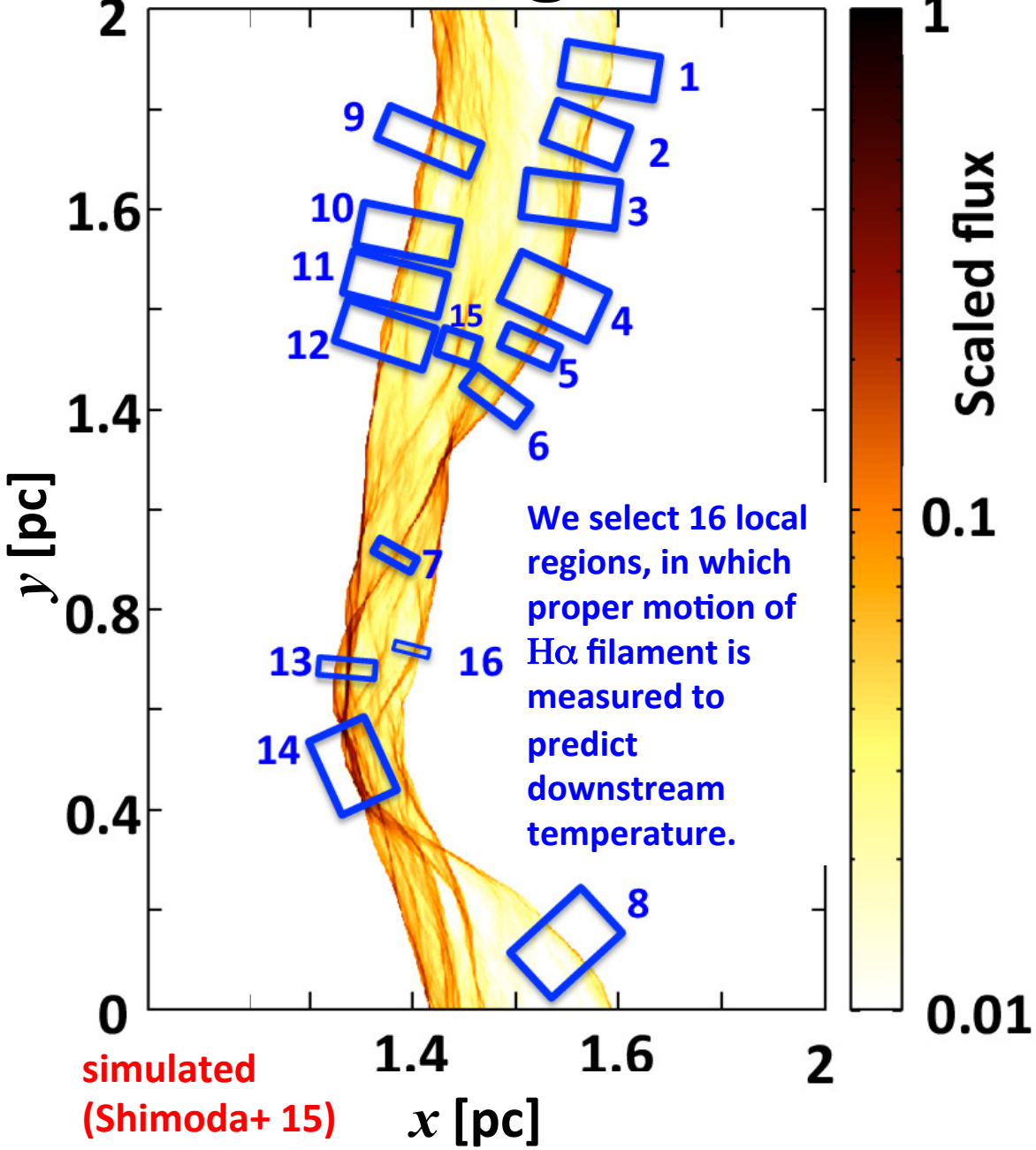
Rankine-Hugoniot relation

$k_B T_2 = \frac{3}{16} m V_{sh}^2 \cos^2\theta$

- ✓ The kinetic energy of the shock wave is transferred into downstream turbulence as well as thermal energy related to the $V_{sh}\cos\theta$.
- ✓ **To estimate influence of the shock obliqueness on η, we have calculated the Hα emission from the simulation data and measured the expansion speed of Hα filaments on the celestial sphere.**

Simulated Hα image





Results for Region 3

- ✓ The expansion speed measured by the proper motion of the Hα:

$$V_{proper} \approx 1700 \ km/s$$

$$k_B T_{proper} = \frac{3}{16} m_p V_{proper}^2 \approx 5.8 \ keV \quad (\theta = 0)$$

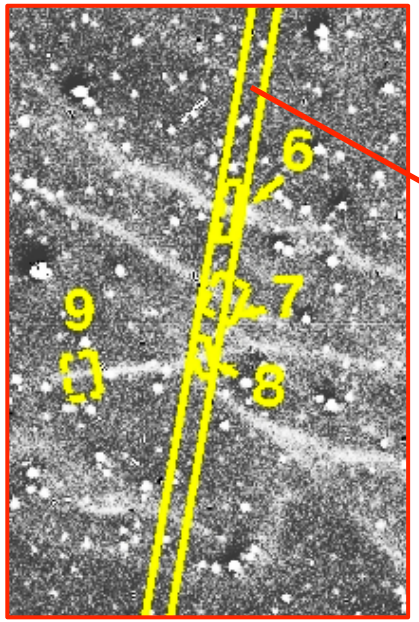
- ✓ The mean of downstream proton temperature just on the filament :

$$k_B T_{down} = 4.2 \ keV$$

- ✓ The apparent CR acceleration efficieny :

$$\eta = \frac{T_{proper} - T_{down}}{T_{proper}} \approx 0.27$$

For RCW 86 case



$k_B T_{down} = 2.3 \ keV$

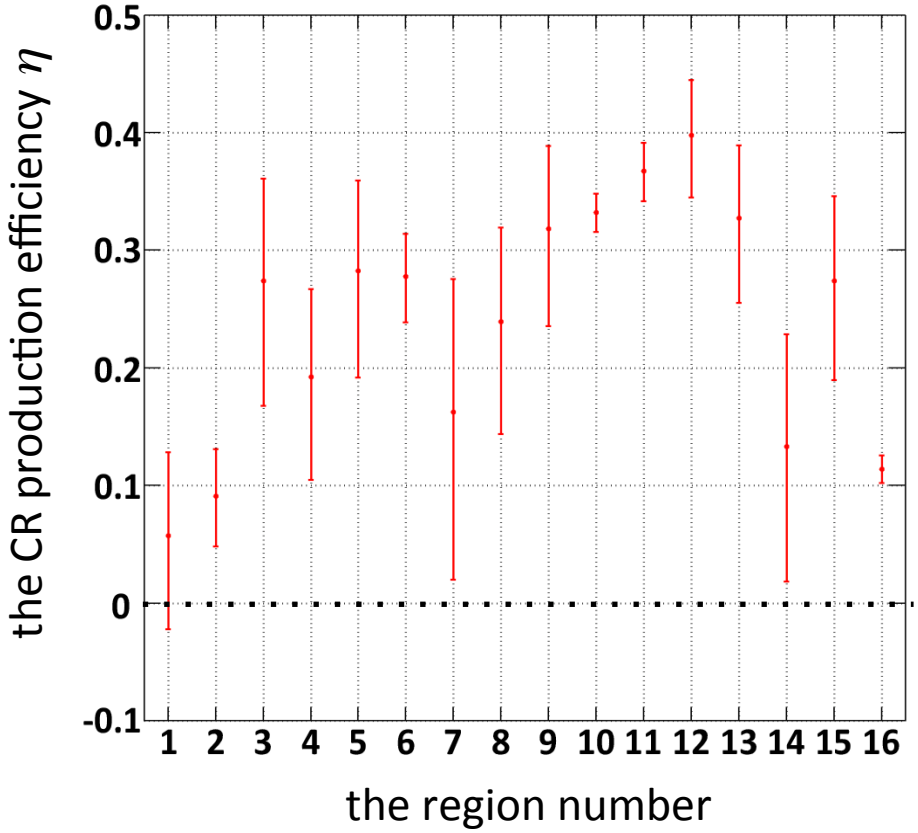
region 6, $\eta \approx$ 0.66 $V_{proper} \approx 1871 \ km/s$

region 7, $\eta \approx$ 0.18 $V_{proper} \approx 1196 \ km/s$

region 8, $\eta \approx$ 0.32 $V_{proper} \approx 1325 \ km/s$

For region 3, the influence of the shock obliqueness on the efficiency η can be significant.

Results for 16 Regions



All regions show $T_{proper} > T_{down}$

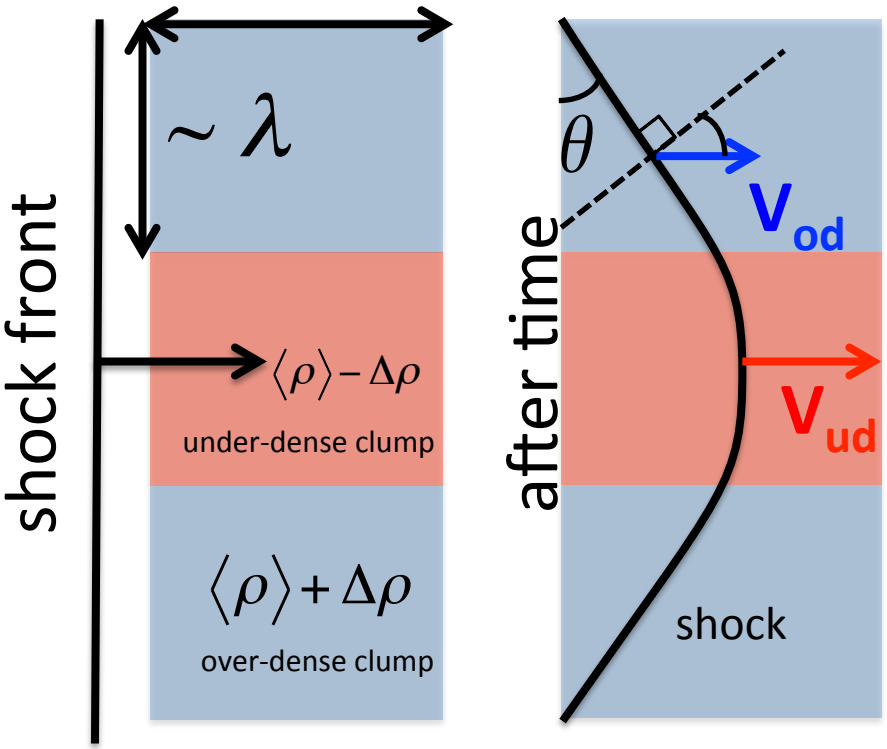
T_{proper} : the predicted temperature from proper motion measurements

T_{down} : the actual downstream temperature just on the filament.

$$\eta = \frac{T_{proper} - T_{down}}{T_{proper}}$$

The apparent CR acceleration efficiency η happens to be 10 – 40%.

The analytical estimation of η



$$\theta \approx \frac{V_{ud}t - V_{od}t}{\lambda} \sim \frac{\Delta\rho}{\langle\rho\rangle}$$

- ✓ If we observe the proper motion velocity of the shock surface propagating into the over-dense clump, then $V_{proper} \approx V_{od}$, the efficiency η is estimated as

$$\eta = 1 - \left(\frac{V_{od}\cos\theta}{V_{od}}\right)^2 \sim \left(\frac{\Delta\rho}{\langle\rho\rangle}\right)^2.$$

- ✓ While, if we get $V_{proper} \approx V_{ud}$, the efficiency η is estimated as

$$\eta = 1 - \left(\frac{V_{od}\cos\theta}{V_{ud}}\right)^2 \sim \frac{2\Delta\rho}{\langle\rho\rangle}.$$

$$\left(\frac{\Delta\rho}{\langle\rho\rangle}\right)^2 \le \eta \le \frac{2\Delta\rho}{\langle\rho\rangle}$$

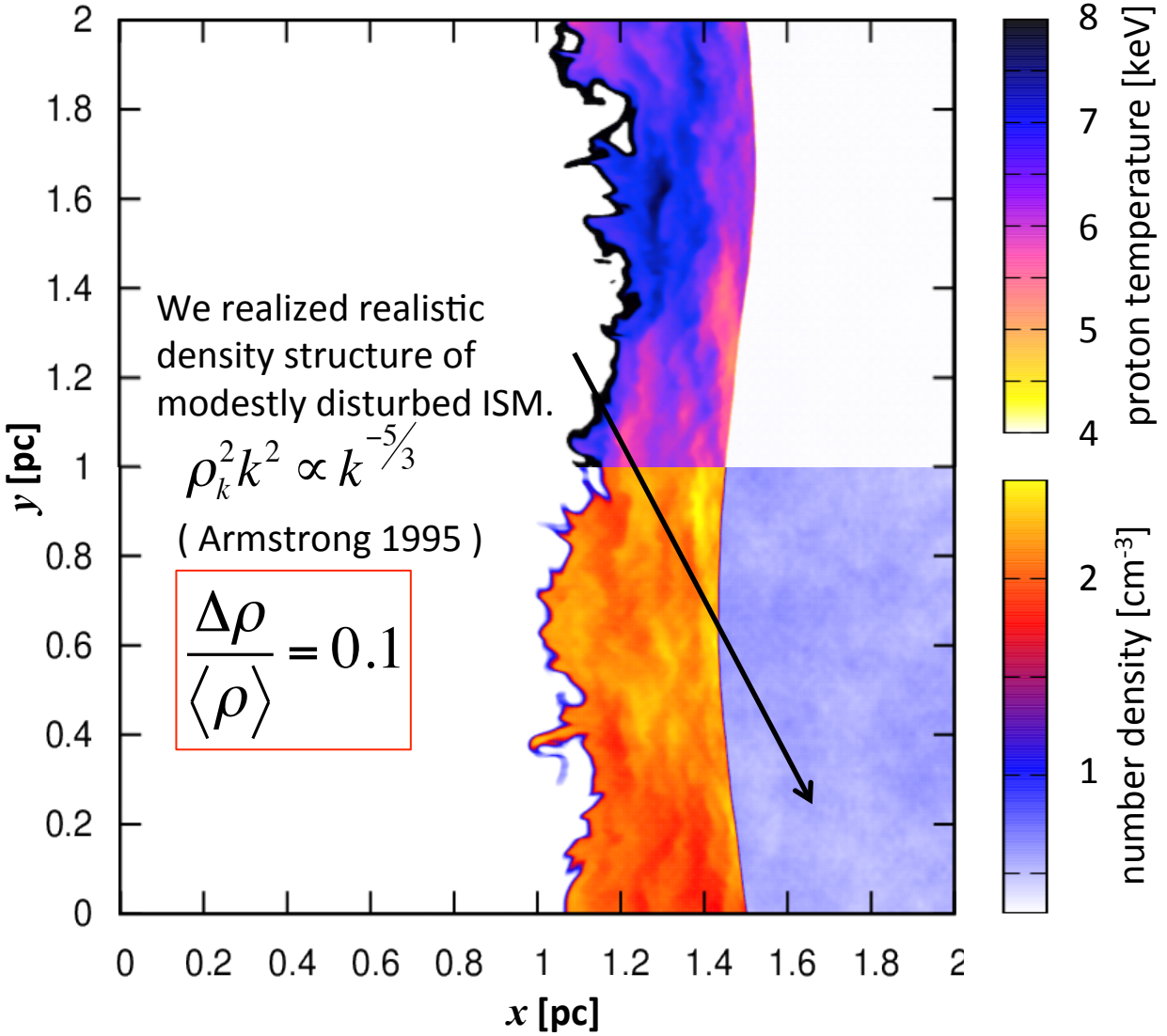
In the present case, $\Delta\rho/\langle\rho\rangle = 0.3$,

$0.09 \le \eta \le 0.6$ analytical

$0.1 \le \eta \le 0.4$ numerical

roughly consistent

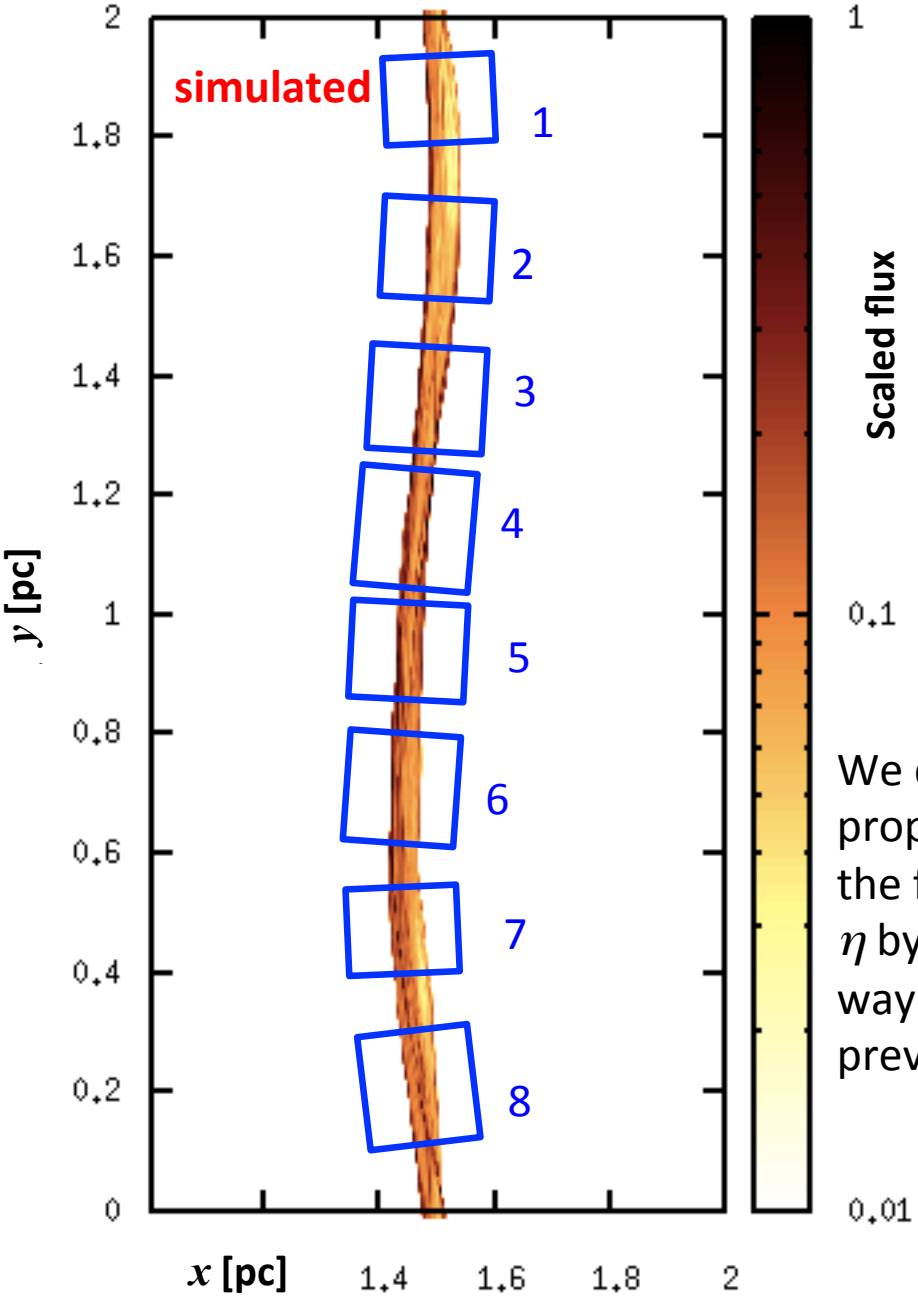
Shocks propagating into modestly disturbed ISM



2-dimensional slice of the proton temperature (upper half) and number density (lower half) in the z = 1 pc plane.

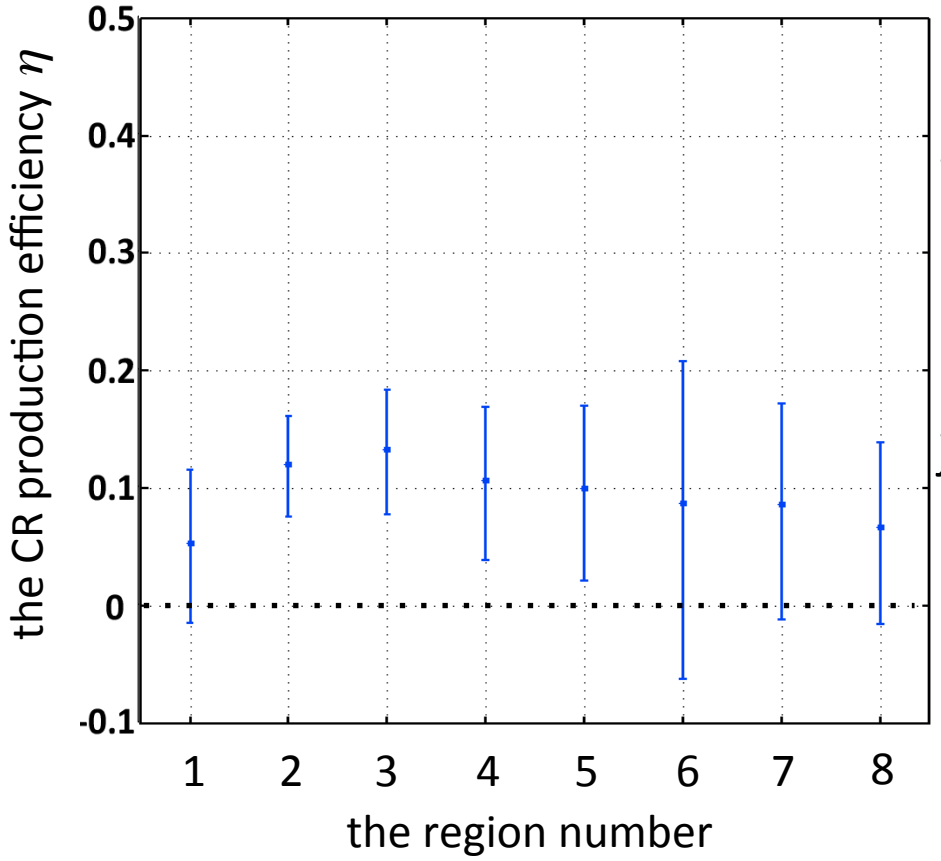
✓ The shock is oblique despite of the case of $\Delta\rho/\langle\rho\rangle = 0.1$.

Simulated Hα image for $\Delta\rho/\langle\rho\rangle$=0.1



We calculate proper motion of the filament and η by the same way as the previous case.

Results for 8 Regions ($\Delta\rho/\langle\rho\rangle$=0.1)



All regions show $T_{proper} > T_{down}$

T_{proper} : the predicted temperature from proper motion measurements

T_{down} : the actual downstream temperature just on the filament.

$$\eta = \frac{T_{proper} - T_{down}}{T_{proper}}$$

In the case of $\Delta\rho/\langle\rho\rangle$ = 0.1, the efficiency η is roughly consistent to our analytical estimation.

$$\left(\frac{\Delta\rho}{\langle\rho\rangle}\right)^2 \le \eta \le \frac{2\Delta\rho}{\langle\rho\rangle}$$

Conclusion & Summary

- ✓ The energy density of Galactic CRs around the Earth is explained if 1 - 10 % of SNe explosion energy is used into CR acceleration.
- ✓ The CR production efficiency η is estimated as the ratio of missing downstream thermal energy (= $T_{proper} - T_{down}$) to downstream thermal energy predicted by proper motion measurements.
- ✓ In previous study, the efficiency η is estimated as ~ 20 - 66 % with assuming the plane-parallel shock jump conditions ($\theta = 0$), which may be suitable for shock propagation into homogeneous medium.
- ✓ The shock wave propagating into realistic ISM has a velocity dispersion and that are oblique almost everywhere.
- ✓ The downstream temperature is given by $V_{sh}\cos\theta$.
- ✓ In the typical ISM case ($\Delta\rho/\langle\rho\rangle=0.3$), the efficiency η appears to be as high as 10 - 40 % in spite of no CR acceleration because of $V_{proper} > V_{sh}\cos\theta$, while $\Delta\rho/\langle\rho\rangle=0.1$ case shows $\eta \sim 10$ %.
- ✓ The analytical estimation of η is roughly consistent to the numerical result for both cases.