On Cosmic-ray Production Efficiency at Realistic Supernova Remnant Shocks

reference: Shimoda et al. 2015 ApJ 803, 98

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ICRC2015, 5, August, 11:45 – 12:00

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)

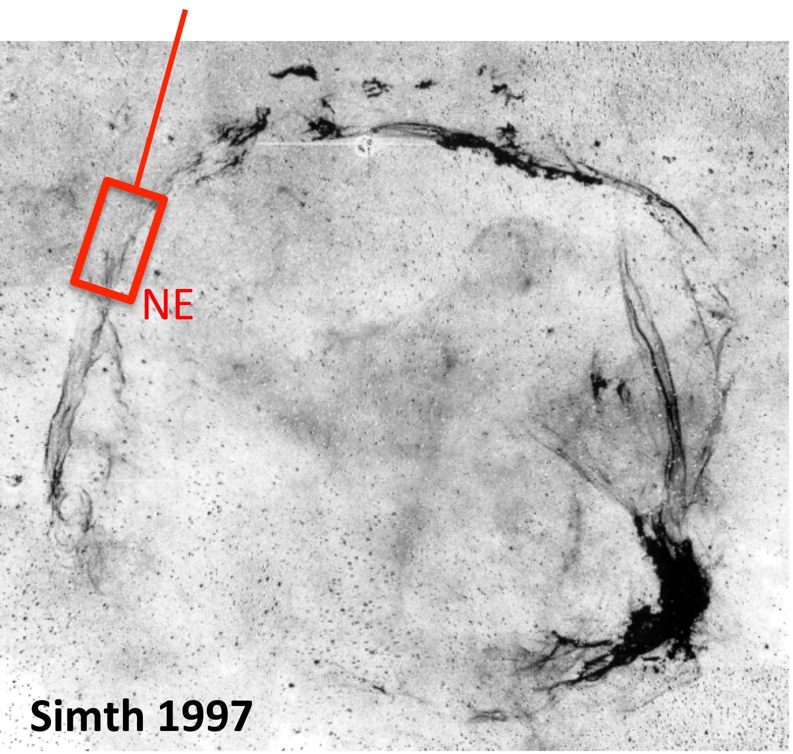
SN1006 : Sudden change of polarization angle (Inoue & Shimoda+ 13)

middle aged SNRs : GeV break of γ-ray spectra (Inoue+ 10)

The CR production efficiency at SNR

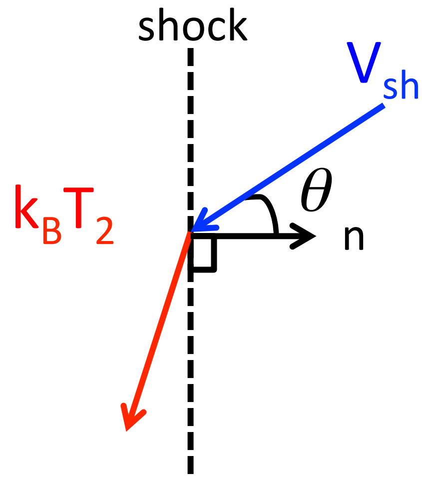
The energy density of Galactic CR around the Earth is explained if ~ 10 % of SN explosion energy is used for CR acceleration.

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



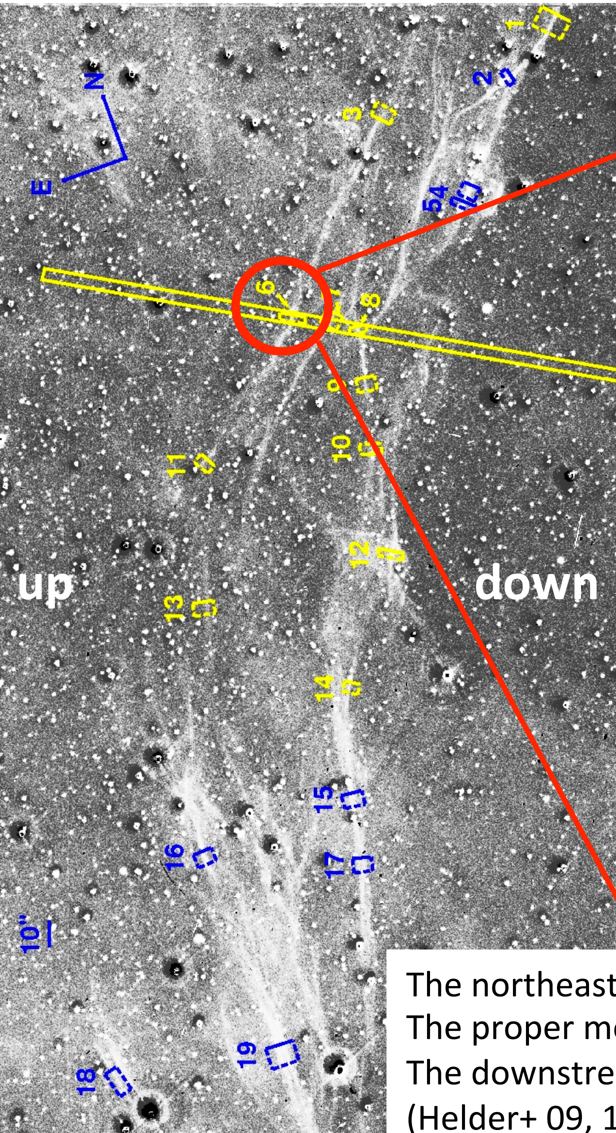
Rankine-Hugoniot relations

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

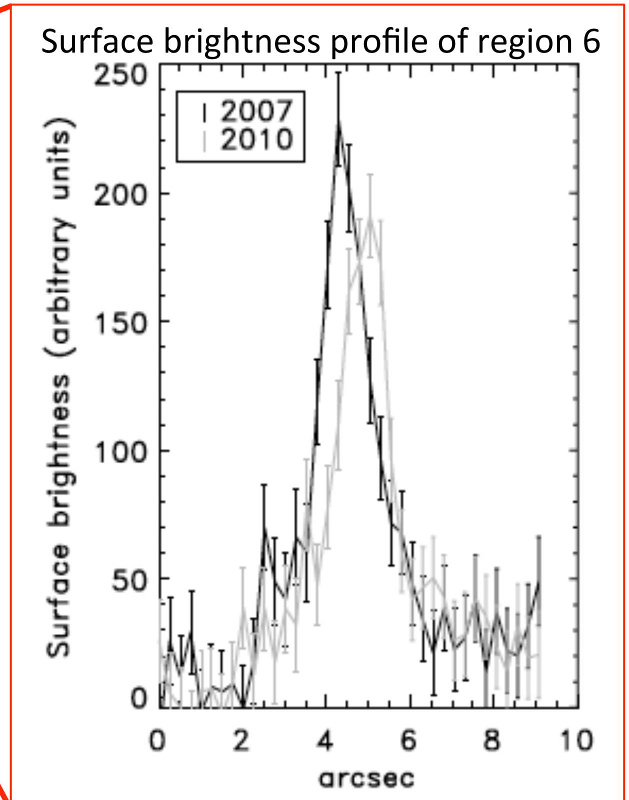
✓ The SNRs shock is loosing the energy due to the CR production.

✓ If the actual downstream temperature and the shock velocity can be measured individually, we get the CR production efficiency as a missing thermal energy.

Measurements of the shock velocity



- ✓ The shock velocity is measured by the proper motion of Hα filaments.



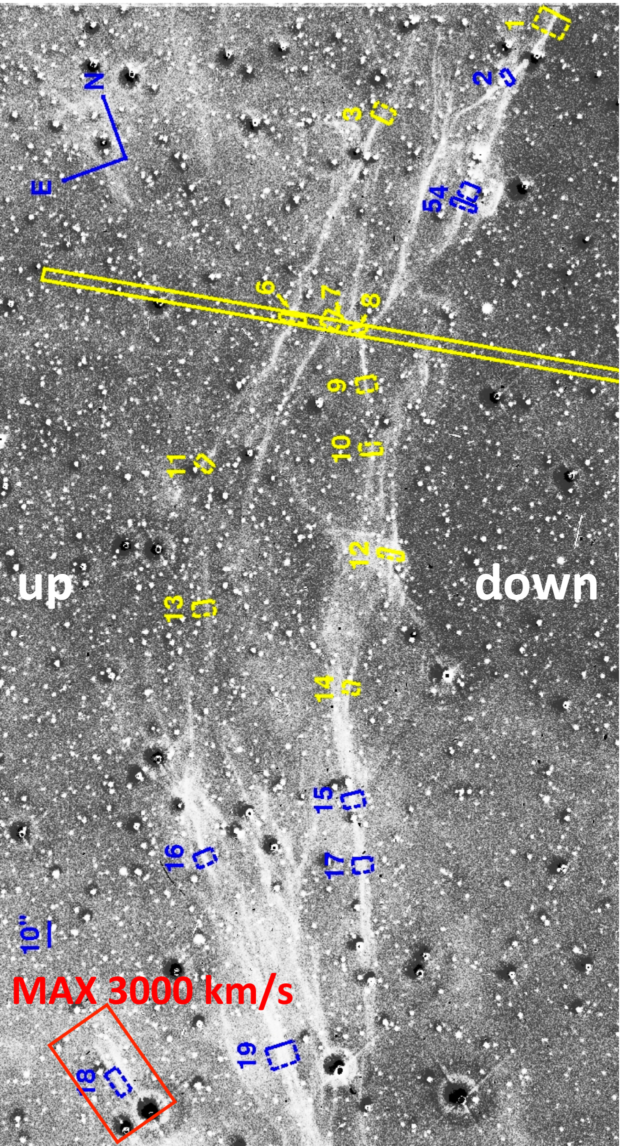
- ✓ The proper motion measured by the shift of surface brightness profile.

$$\chi^2 = \int dx \left(L_{2010}(x - \Delta x) - L_{2007}(x) \right)^2$$

- ✓ The shift is determined so that the χ^2 takes minimum value (Helder+ 13).

The northeastern region of RCW 86.
The proper motion is measured in boxes.
The downstream temperature measured along the long slit.
(Helder+ 09, 13)

Measurements of the shock velocity



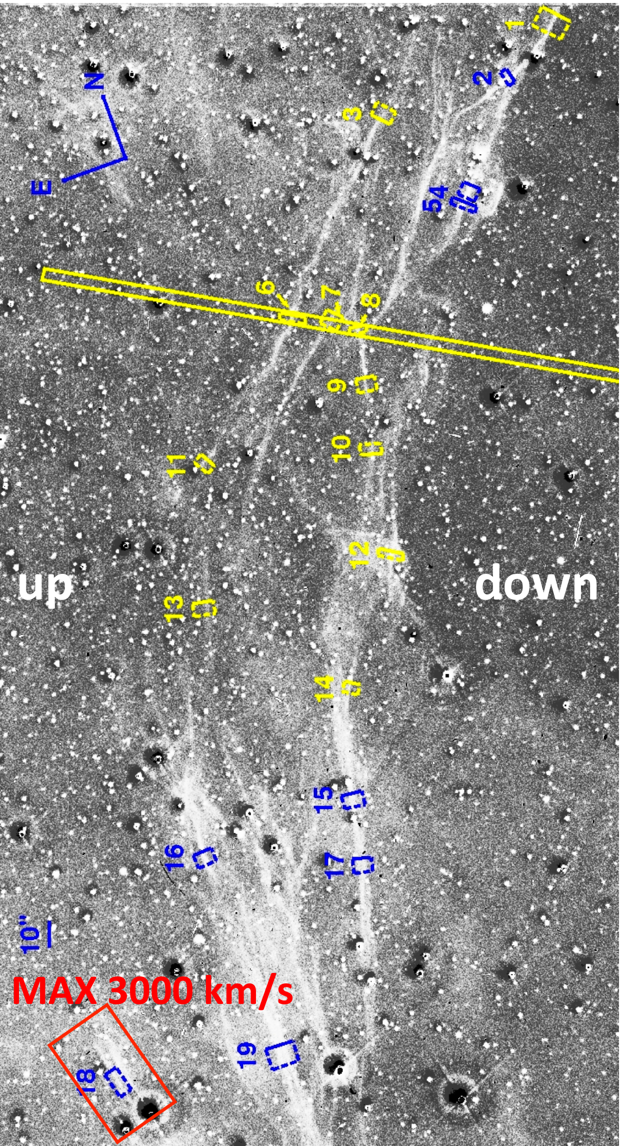
✓ The shock velocity is measured by the proper motion of Hα filaments.

Filament #	shift [''] in 1135 days	V_s km s^{-1}	@ ±	2.5 kpc stat. err.
1	0.20 ± 0.04	745	±	136
2	0.14 ± 0.07	543	±	280
3	0.31 ± 0.09	1172	±	347
4	0.25 ± 0.05	948	±	174
5	0.28 ± 0.05	1067	±	186
6	0.49 ± 0.07	1871	±	250
7	0.31 ± 0.10	1196	±	367
8	0.35 ± 0.06	1325	±	221
9	0.34 ± 0.05	1299	±	191
10	0.08 ± 0.11	317	±	437
11	0.31 ± 0.09	1192	±	351
12	0.26 ± 0.04	991	±	133
13	0.39 ± 0.12	1493	±	475
14	0.21 ± 0.10	800	±	371
15	0.26 ± 0.07	1001	±	256
16	0.37 ± 0.05	1422	±	175
17	0.29 ± 0.06	1096	±	219
18	0.81 ± 0.23	3071	±	878
19	0.35 ± 0.04	1349	±	151
Mean/std. dev.	0.31/0.08	1204	/	575

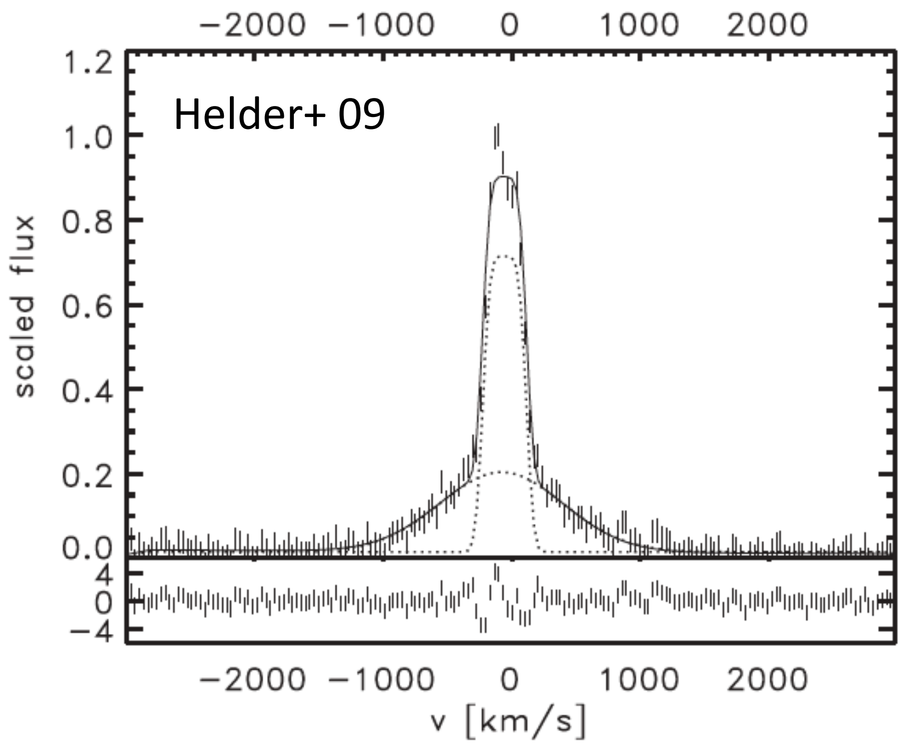
MAX ~ 3000 km/s
MIN ~ 300 km/s
MEAN ~ 1200 km/s

Helder+ 13

Measurements of downstream temperature

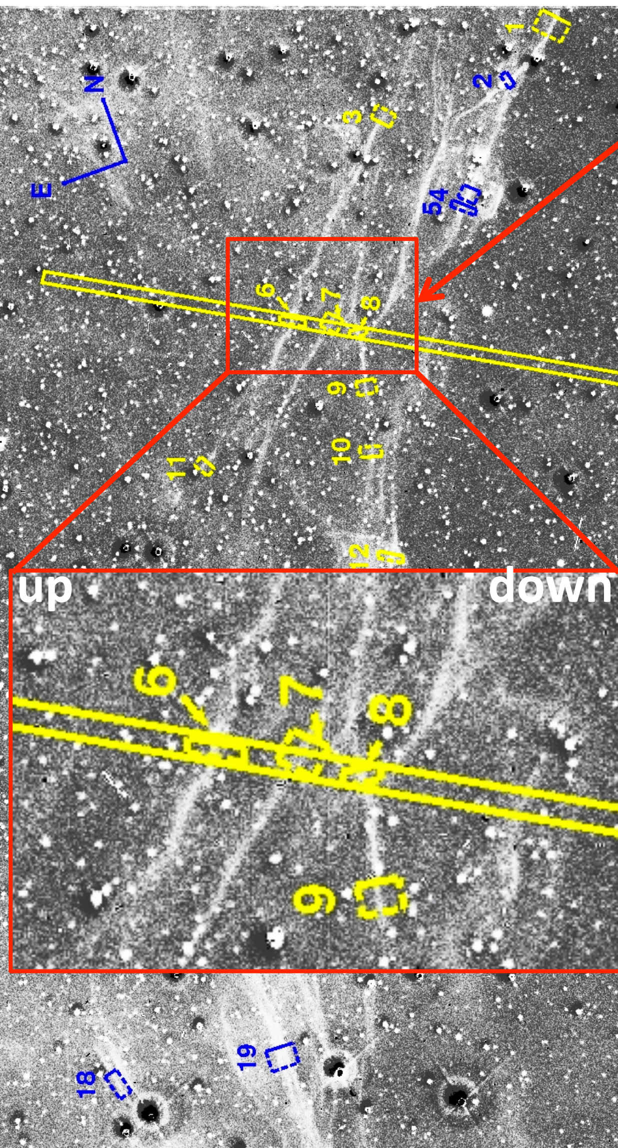


- ✓ The downstream temperature measured by the broad component of Hα which emitted by hot hydrogen atoms undergoing charge exchange process with downstream protons.



The observed downstream proton temperature $k_B T_{down}$ = 2.3 keV (Helder+ 09).

Consider the filaments on the slit



How about the production efficiency at the slit ?

Filament #	shift ["] in 1135 days	V_s km s^{-1}	@ ±	2.5 kpc stat. err.
1	0.20 ± 0.04	745	±	136
2	0.14 ± 0.07	543	±	280
3	0.31 ± 0.09	1172	±	347
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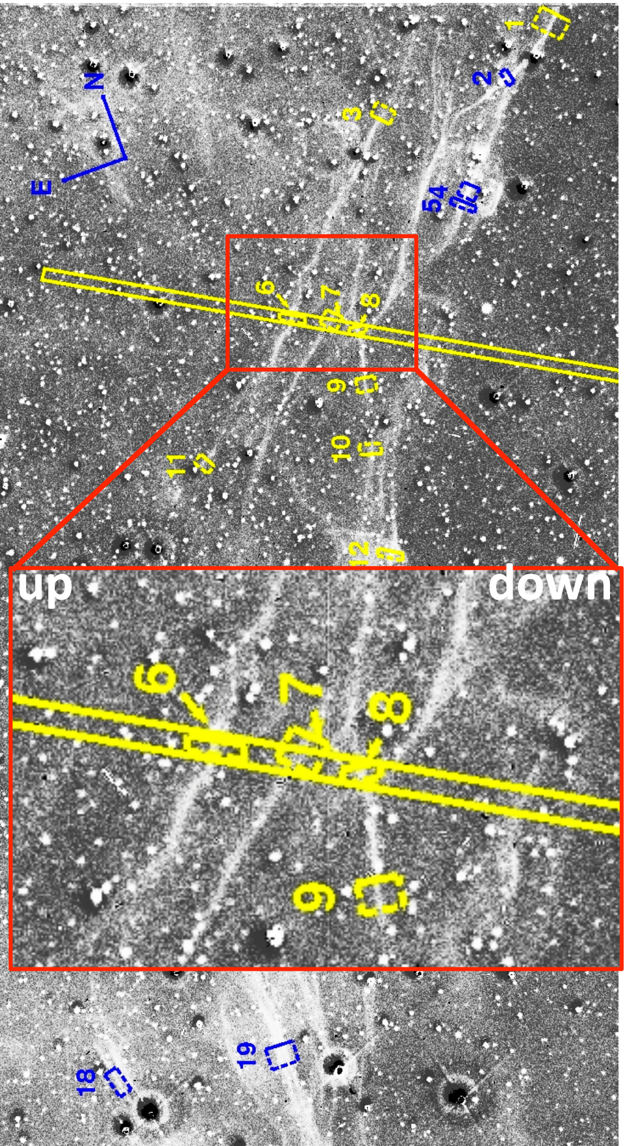
Helder+ 13

The estimation of the CR production efficiency.



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

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

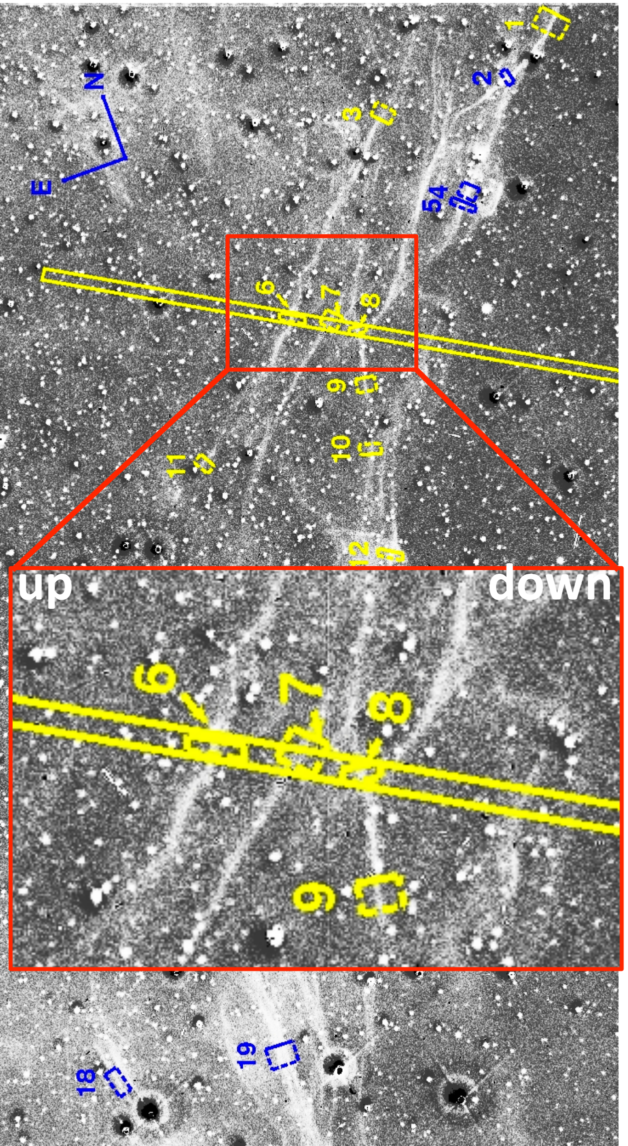
$$k_B T_{proper} = \frac{3}{16} m_p V_{proper}^2 \approx 6.8\ keV \quad (\ \theta = 0\ )$$

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

- ✓ The CR production efficiency:

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

Consider the filaments on the slit



$$k_B T_{proper} \approx 6.8\ keV \left(\frac{V_{sh}}{1871\ km/s} \right)^2$$: for region 6, $\eta \approx\ 0.66$

$$k_B T_{proper} \approx 2.8\ keV \left(\frac{V_{sh}}{1196\ km/s} \right)^2$$: for region 7, $\eta \approx\ 0.18$

$$k_B T_{proper} \approx 3.4\ keV \left(\frac{V_{sh}}{1325\ km/s} \right)^2$$: for region 8, $\eta \approx\ 0.32$

- ✓ The CR production efficiency seems to be ubiquitously high.
- ✓ Other SNRs also imply the high efficiency of CR acceleration (e.g., Morlino+ 13, 14) 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.

Observed expansion speed

Filament #	shift [″] in 1135 days	V_s km s^{-1}	@ $\pm$	2.5 kpc stat. err.
1	0.20 ± 0.04	745	$\pm$	136
2	0.14 ± 0.07	543	$\pm$	280
3	0.31 ± 0.09	1172	$\pm$	347
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Mean/std. dev.	0.31/0.08	1204	/	575

Helder+ 13

Observed expansion speed of RCW 86 is dispersed (Helder et al. 2013).
→This implies that the shock is propagating into an inhomogeneous medium.

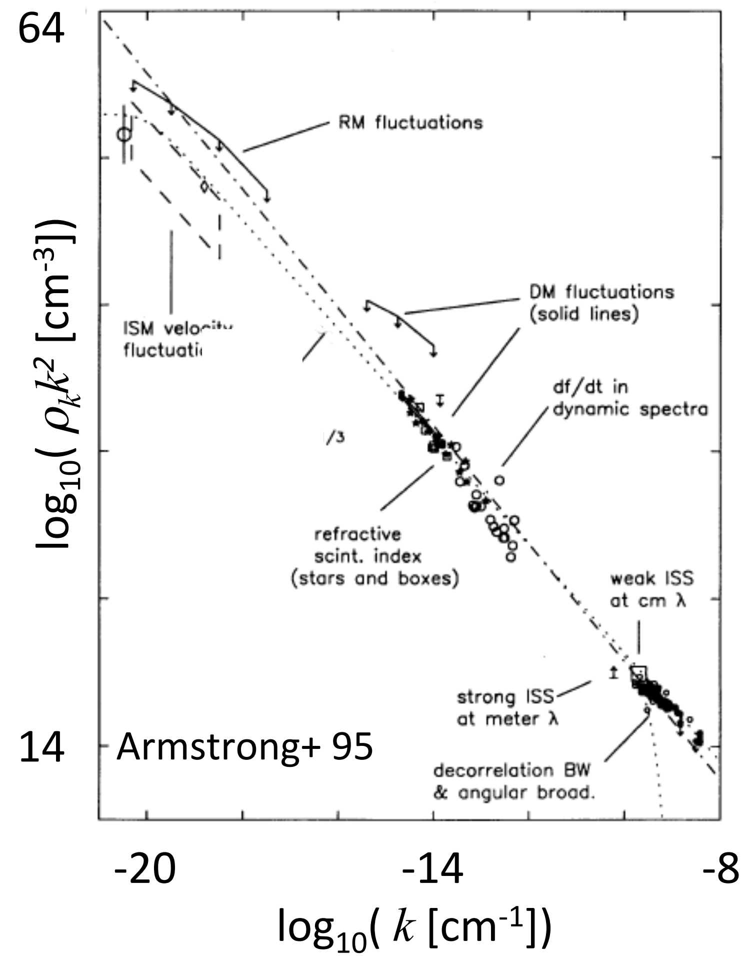
Realistic density fluctuations of ISM

- ✓ 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

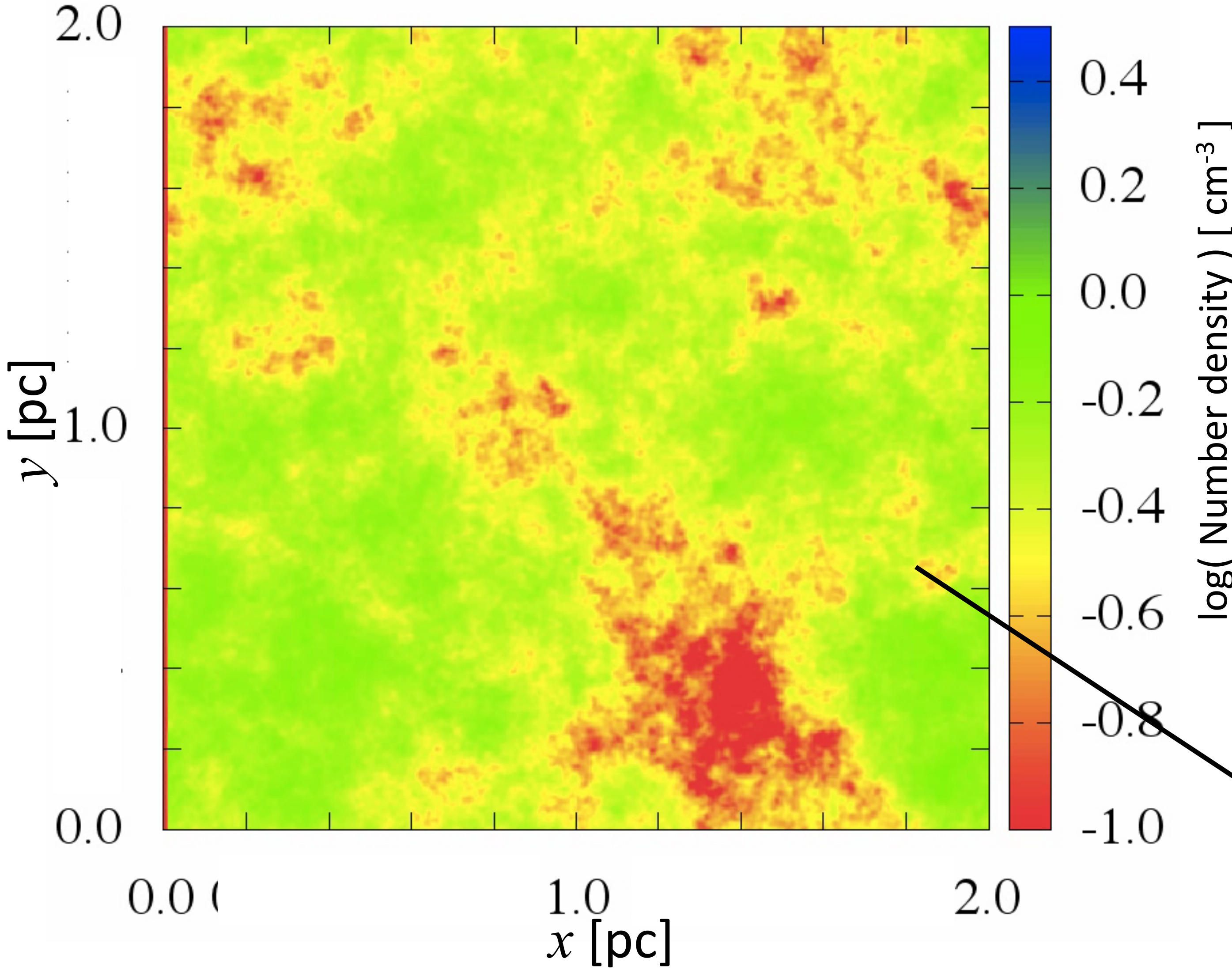


It is widely accepted that the ISM is highly inhomogeneous.
The shock interacting with fluctuations may has a velocity dispersion.
We demonstrate it by using 3-dimensional MHD simulation.

Shock propagation into realistic ISM

Result of 3D MHD simulation :

Two-dimensional slice of the number density（ Inoue & Shimoda+ 2013 ）.

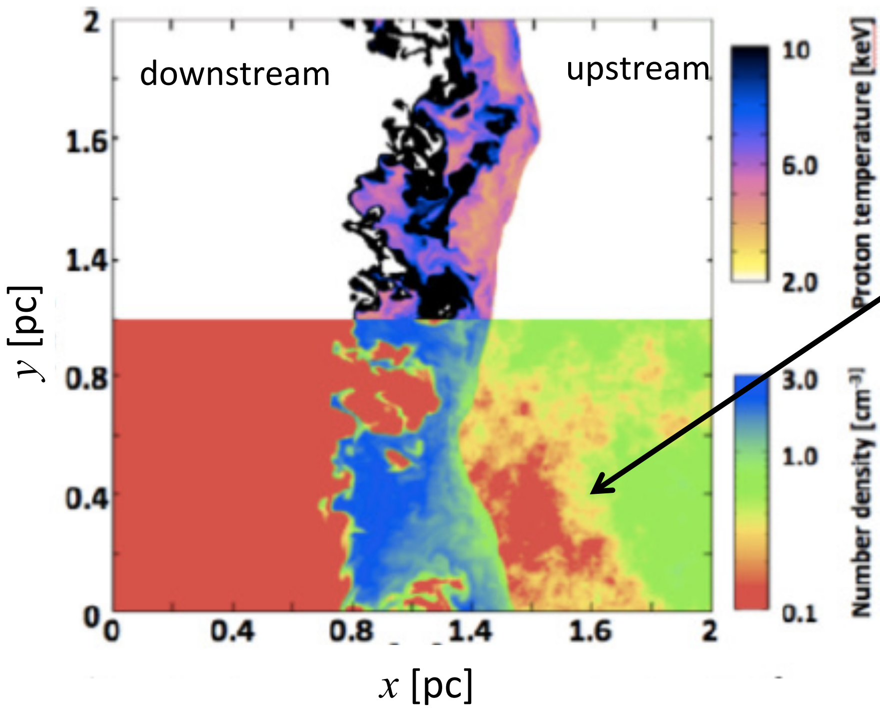


We realized realistic ISM density fluctuations in upstream medium.

$$\rho_k^2 k^2 \propto k^{-5/3}$$

$$\frac{\Delta\rho}{\langle\rho\rangle} \approx 0.3$$

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.

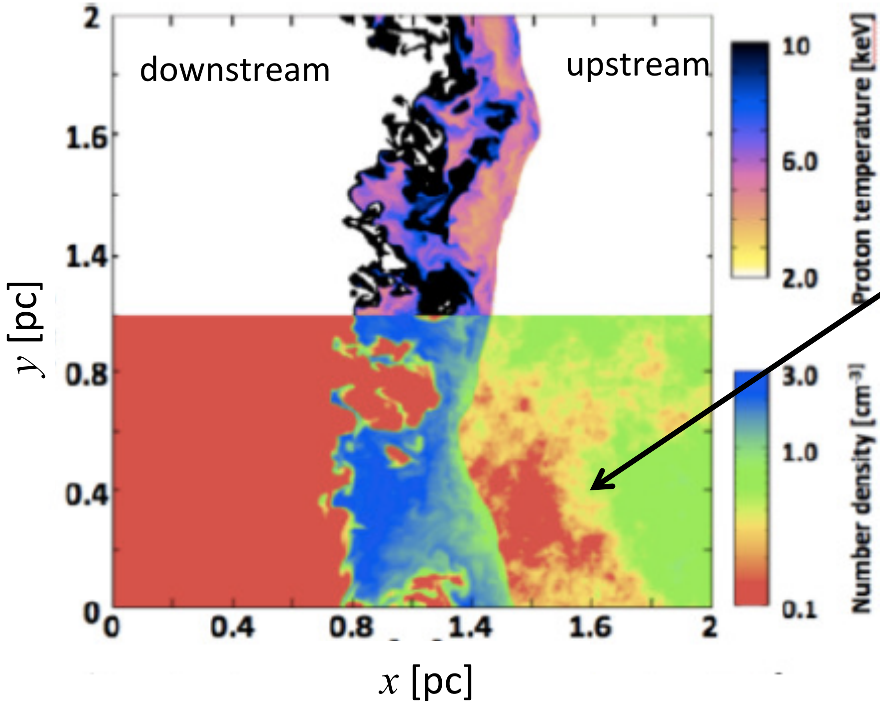
We realized realistic density structure of ISM.

$\rho_k^2 k^2 \propto k^{-5/3}$ (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 , <$V_{sh}\cos\theta$> ~ 1300 km/s.
- ✓ **The shock is oblique almost everywhere (i.e. $\theta \neq 0$).**

Shock propagation into realistic ISM



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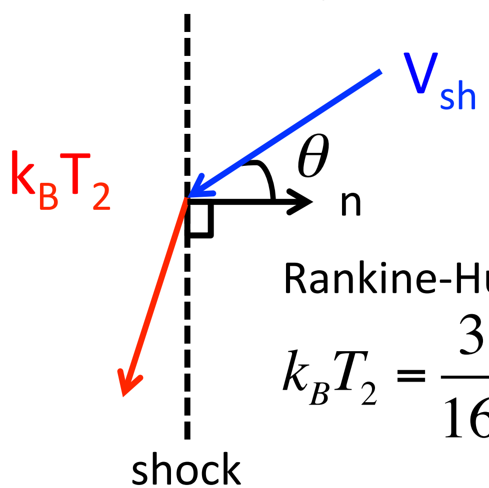
$$\frac{\Delta\rho}{\langle\rho\rangle} \approx 0.3$$ (de Avillez & Breitschwerdt 2007)

- ✓ 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 $\mathrm{H}\alpha$ emission from the simulation data and measured the expansion speed of $\mathrm{H}\alpha$ filaments on the celestial sphere.**



Rankine-Hugoniot relation

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

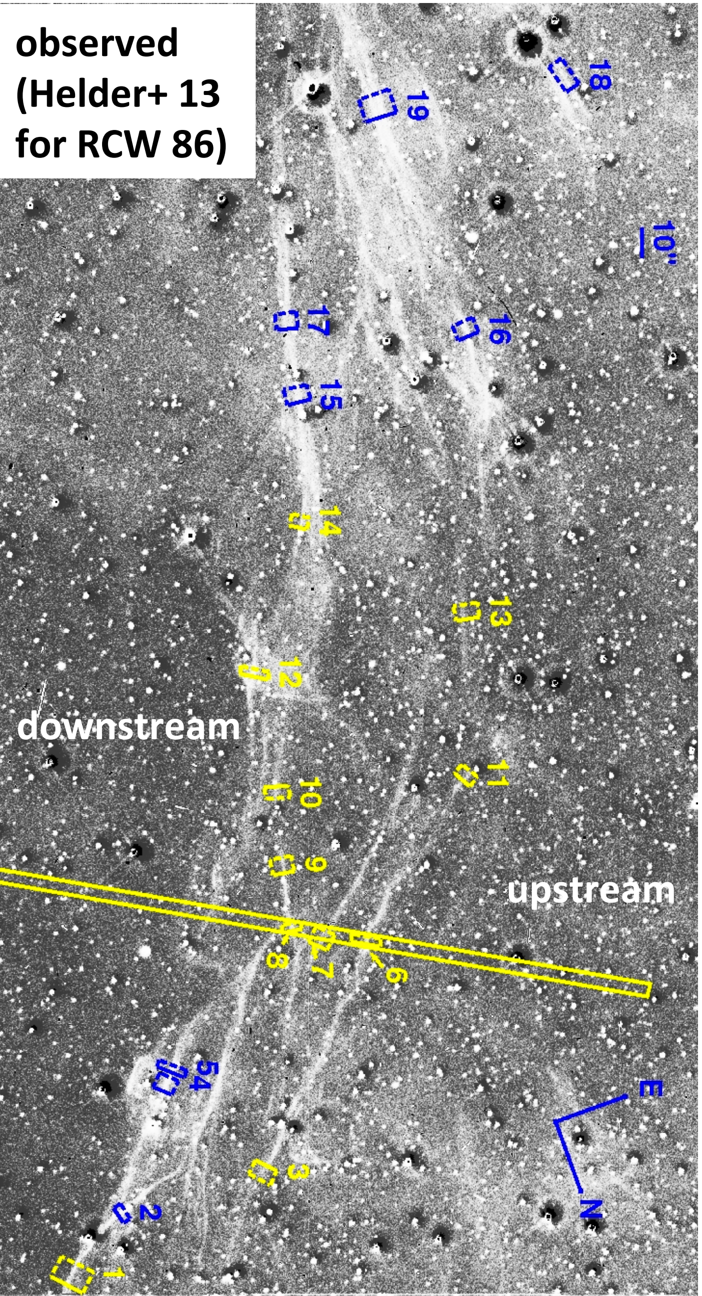
Calculation of Hα

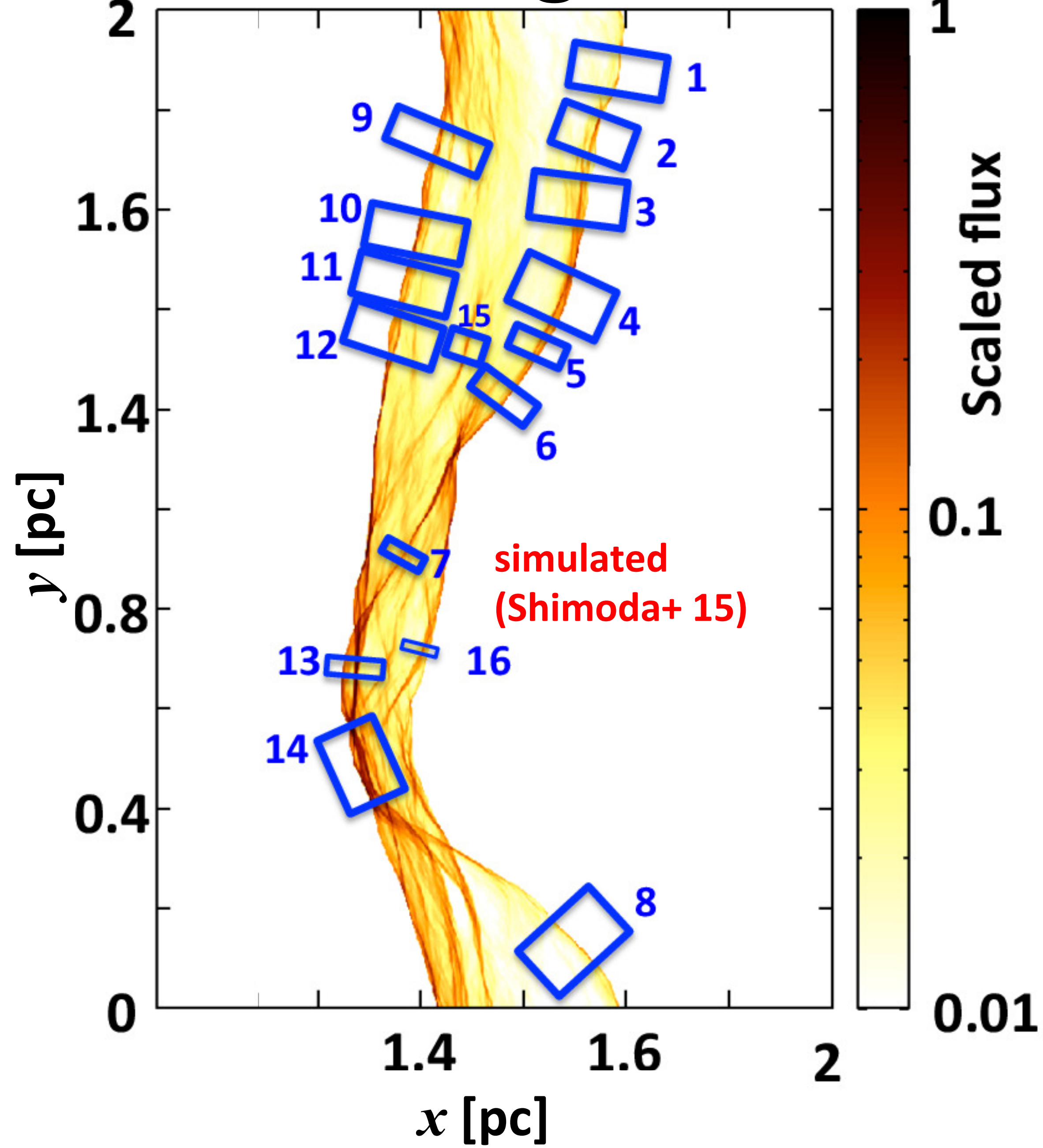
For simplicity, we calculated the reaction rate of excited hydrogen emitting narrow component of Hα line.

- ✓ **For almost all cases, the contribution of the narrow component is non-negligible : e.g. The flux of the narrow component is four times as large as the broad component for RCW86 (Helder+ 09) :**
  The narrow component is better for observation than the broad one.

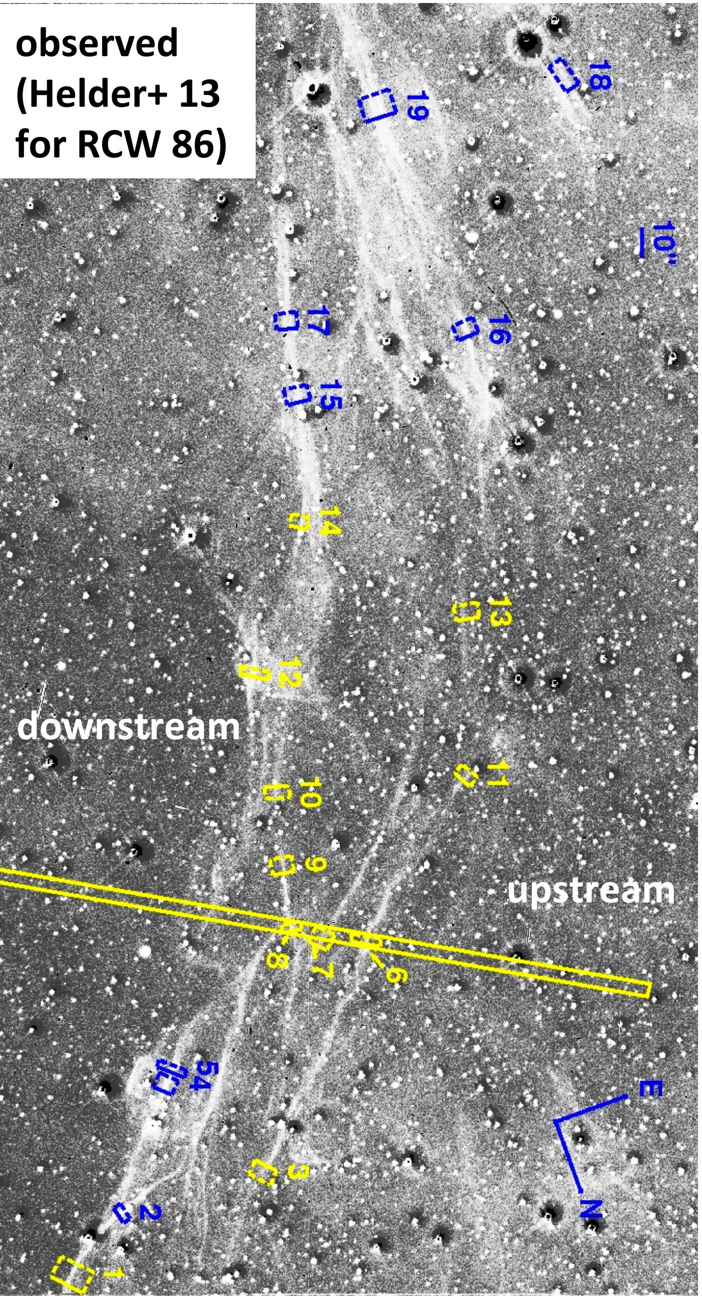
- ✓ **The broad component is emitted from hot hydrogen atoms undergoing charge exchange. They have the same distribution function as downstream protons :**
  Computation of the broad component needs much time.

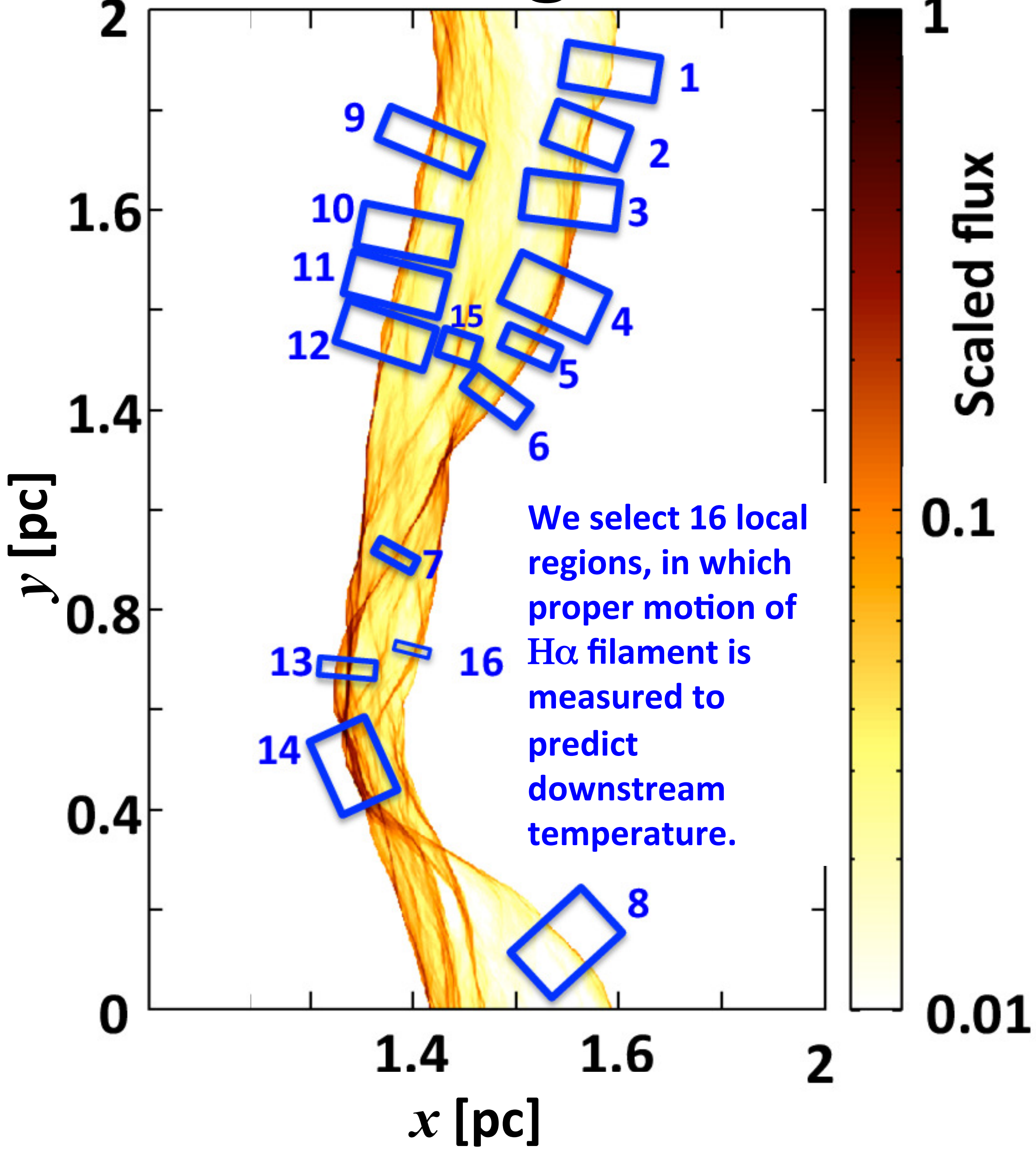
Simulated Hα image





Simulated Hα image

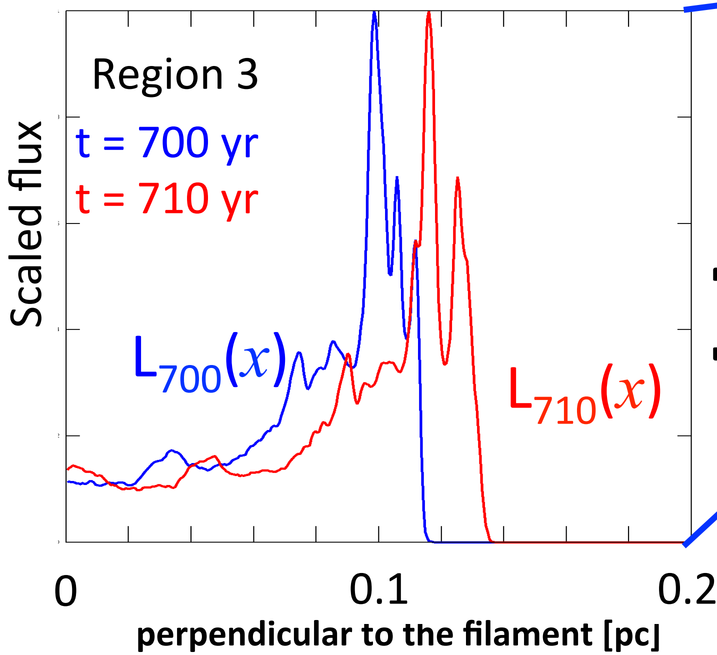




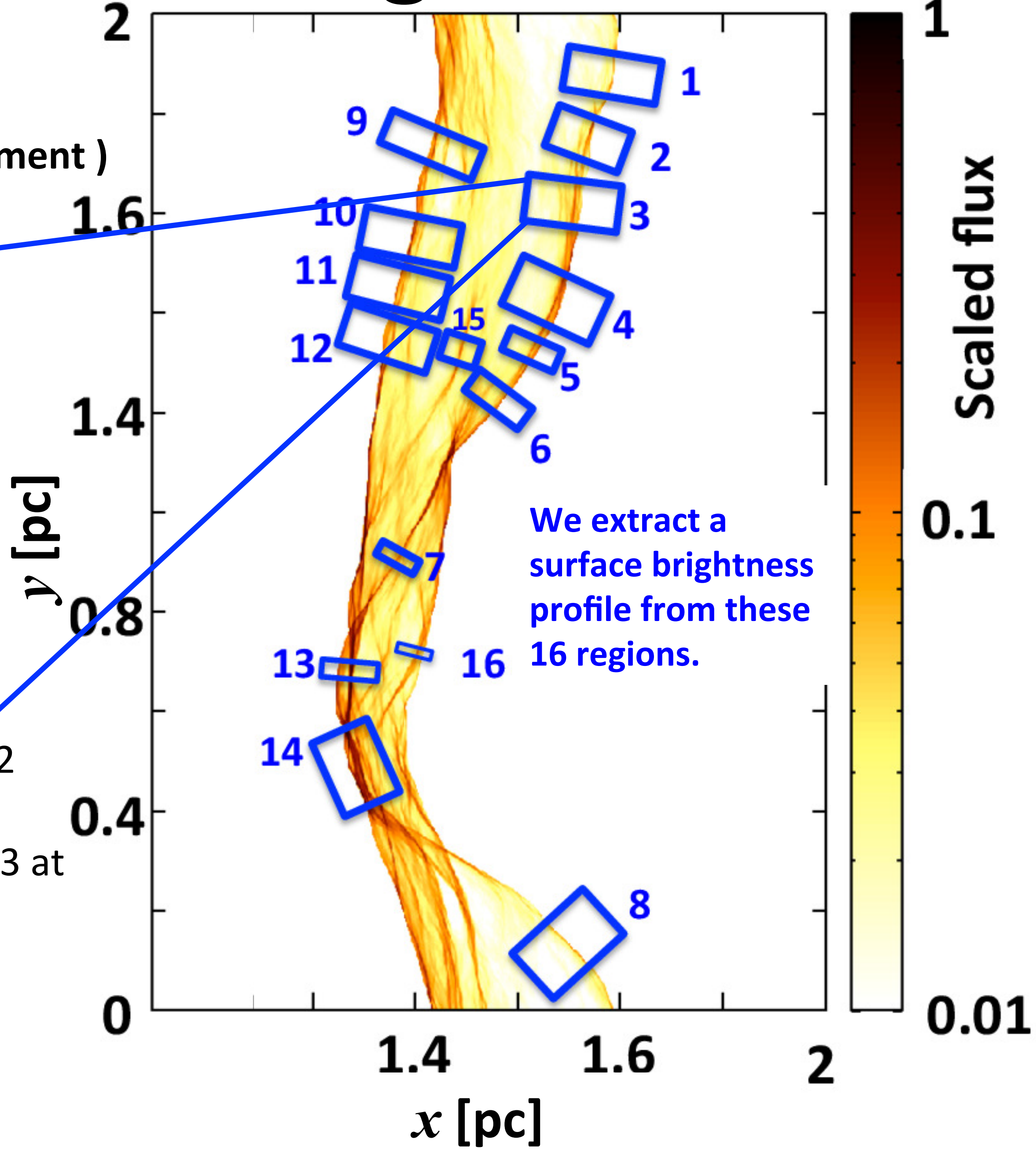
We select 16 local regions, in which proper motion of Hα filament is measured to predict downstream temperature.

Results for Region 3

Surface brightness profiles (in the direction perpendicular to the filament)

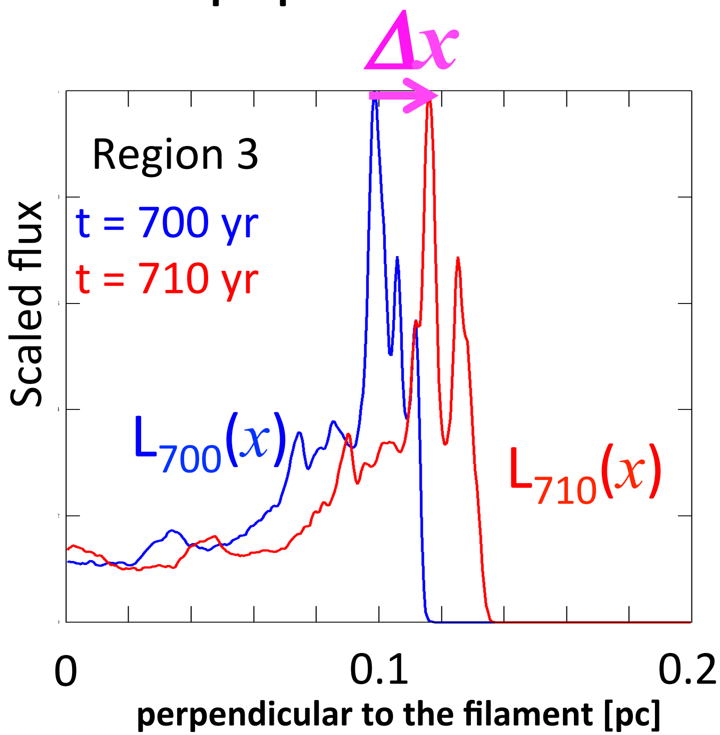


Surface brightness profiles of region 3 at 700 years and 710 years from the beginning of the simulation.



Results for Region 3

Surface brightness profiles (in the direction perpendicular to the filament)



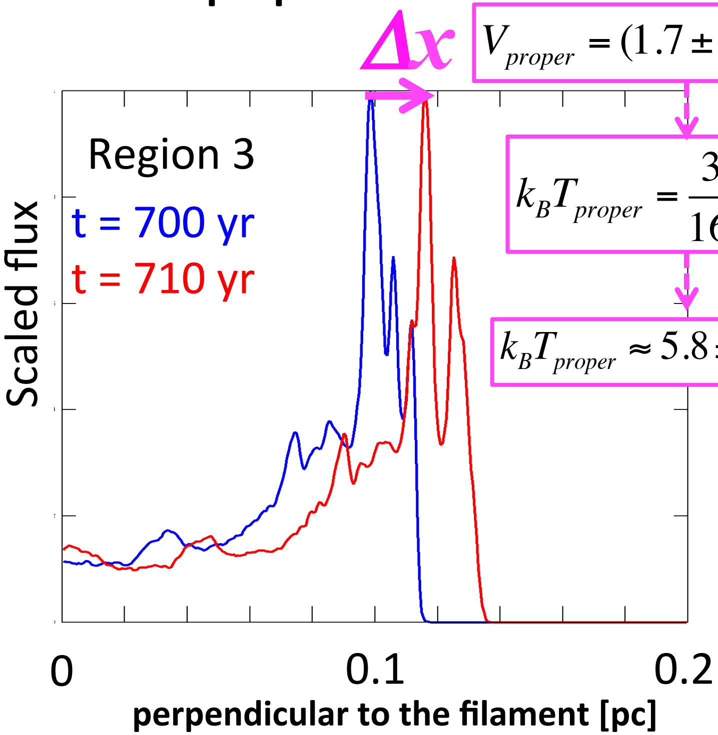
Surface brightness profiles of region 3 at 700 years and 710 years from the beginning of the simulation.

✓ We analyzed a proper motion of Hα filament in the same way as Helder et al. 2013 and measured the proper motion so that the χ^2 takes minimum value and evaluated the 1-σ error.

$$\chi^2 = \int dx \left(L_{700}(x - \Delta x) - L_{710}(x) \right)^2$$

Results for Region 3

Surface brightness profiles (in the direction perpendicular to the filament)



$V_{proper} = (1.7 \pm 0.1) \times 10^8 \, cm/s$

$k_B T_{proper} = \frac{3}{16} m V_{proper}^2$

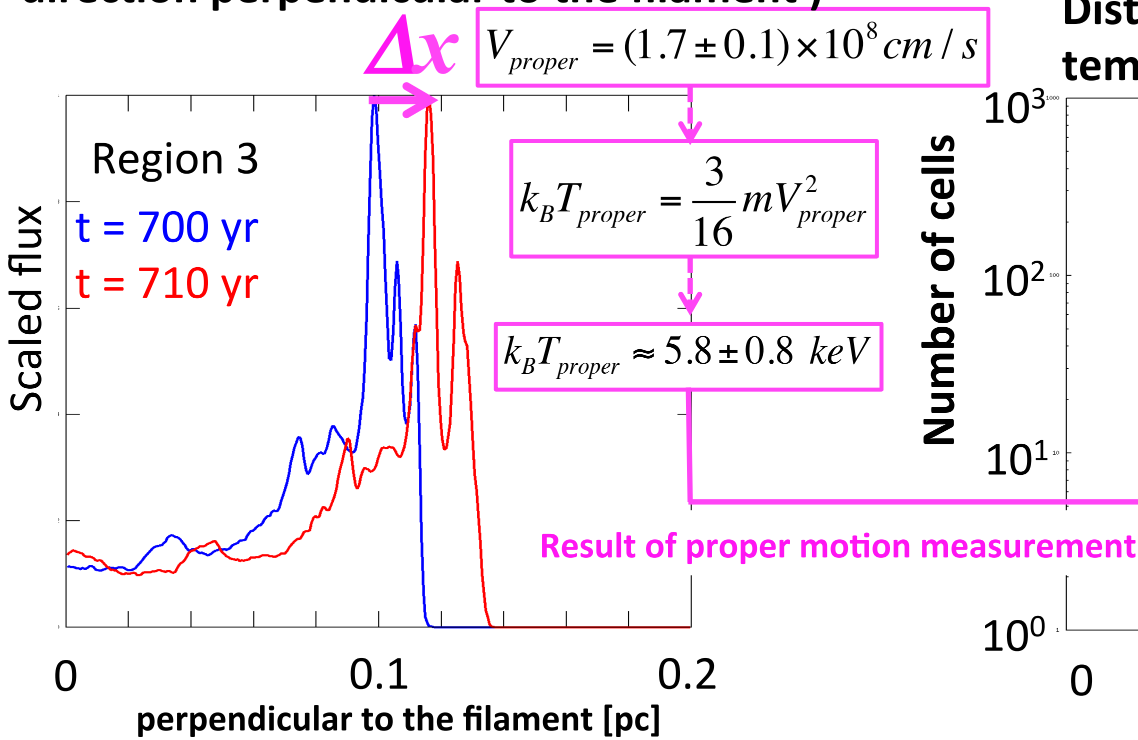
$k_B T_{proper} \approx 5.8 \pm 0.8 \; keV$

Surface brightness profiles of region 3 at 700 years and 710 years from the beginning of the simulation. We measured the proper motion so that the χ^2 takes minimum value and evaluated the 1-σ error.

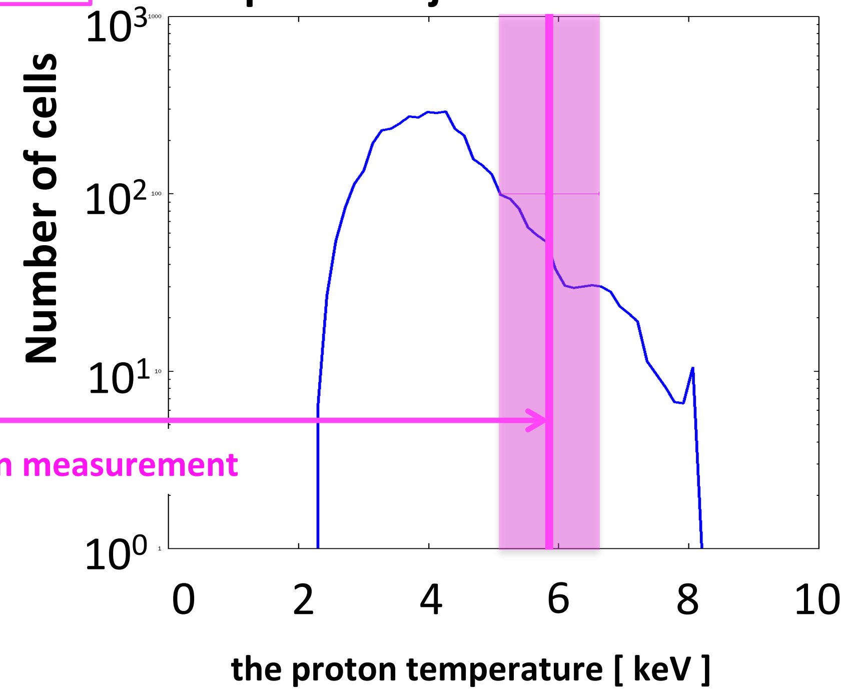
✓ We got the proper motion velocity as about 1700 km/s and predicted the downstream temperature is about 6 keV with assuming a plane-parallel shock-jump conditions.

Results for Region 3

Surface brightness profiles (in the direction perpendicular to the filament)



Distribution of downstream proton temperature just on the filament



Surface brightness profiles of region 3 at 700 years and 710 years from the beginning of the simulation. We measured the proper motion so that the χ^2 takes minimum value and evaluated the 1-σ error.

The proton temperature estimated from proper motion is higher than the mean (typical) downstream proton temperature.

Results for Region 3

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

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

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

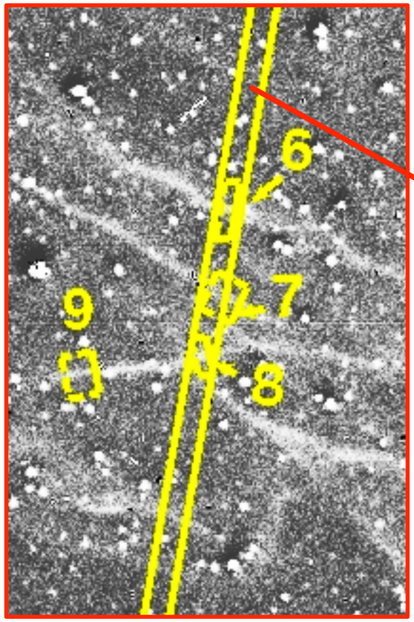
- ✓ The mean of downstream proton temperature just on the filament :

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

- ✓ The apparent CR acceleration efficieny :

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

For RCW 86 case



$k_B T_{down} = 2.3\ keV$

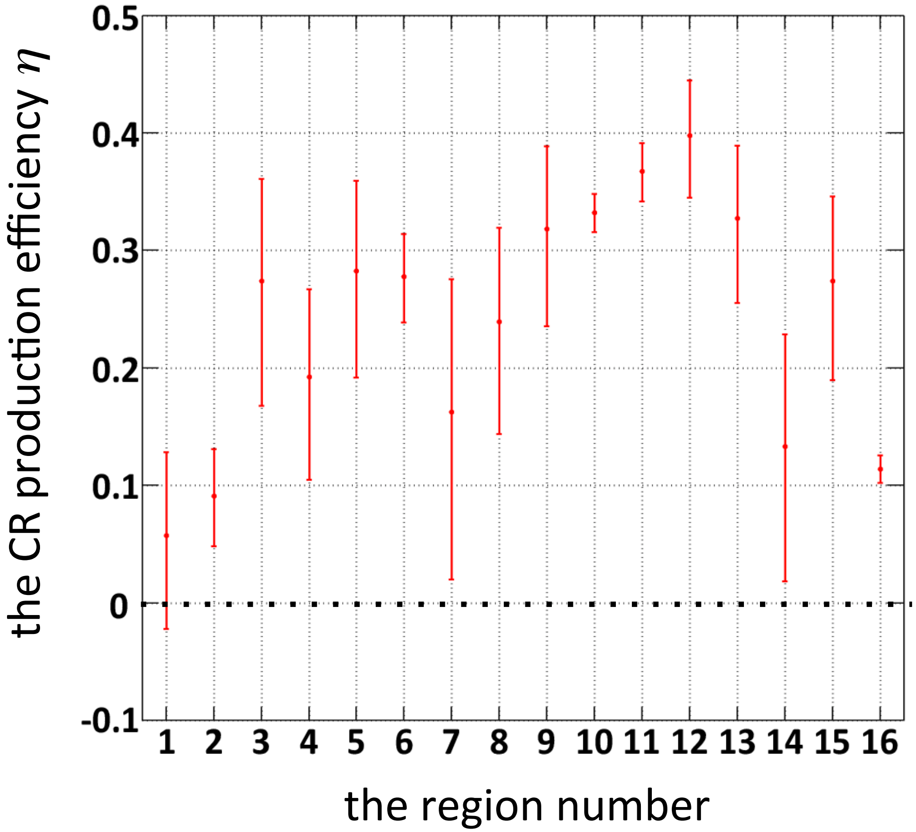
region 6, $\eta \approx$ 0.66 $V_{proper} \approx 1871\ km/s$

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 $T_{proper} > T_{down}$

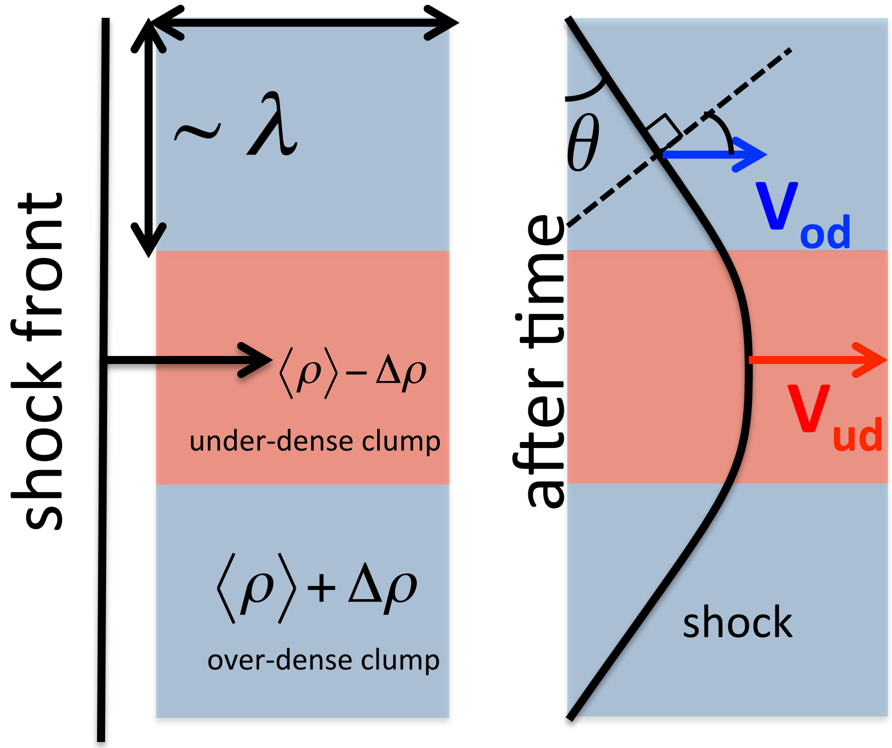
T_{proper} : the predicted temperature from proper motion measurements

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

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

The apparent CR production efficiency η happens to be 10 - 40% in spite of no CR acceleration.

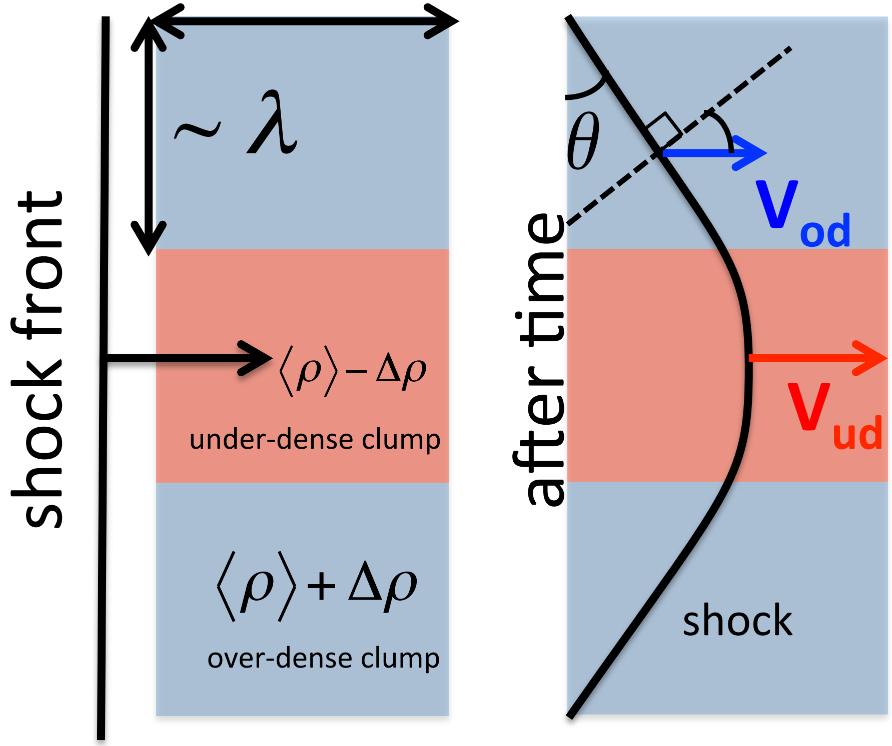
The analytical estimation of η



- ✓ We simplify the upstream medium as a mixture of two component, under dense clump (red) and over dense clump (blue).
- ✓ The characterized size of clump is λ.
- ✓ Assuming momentum conversation, we find the relation between the shock deforming angle θ and the amplitude of a fluctuation.

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

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

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

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

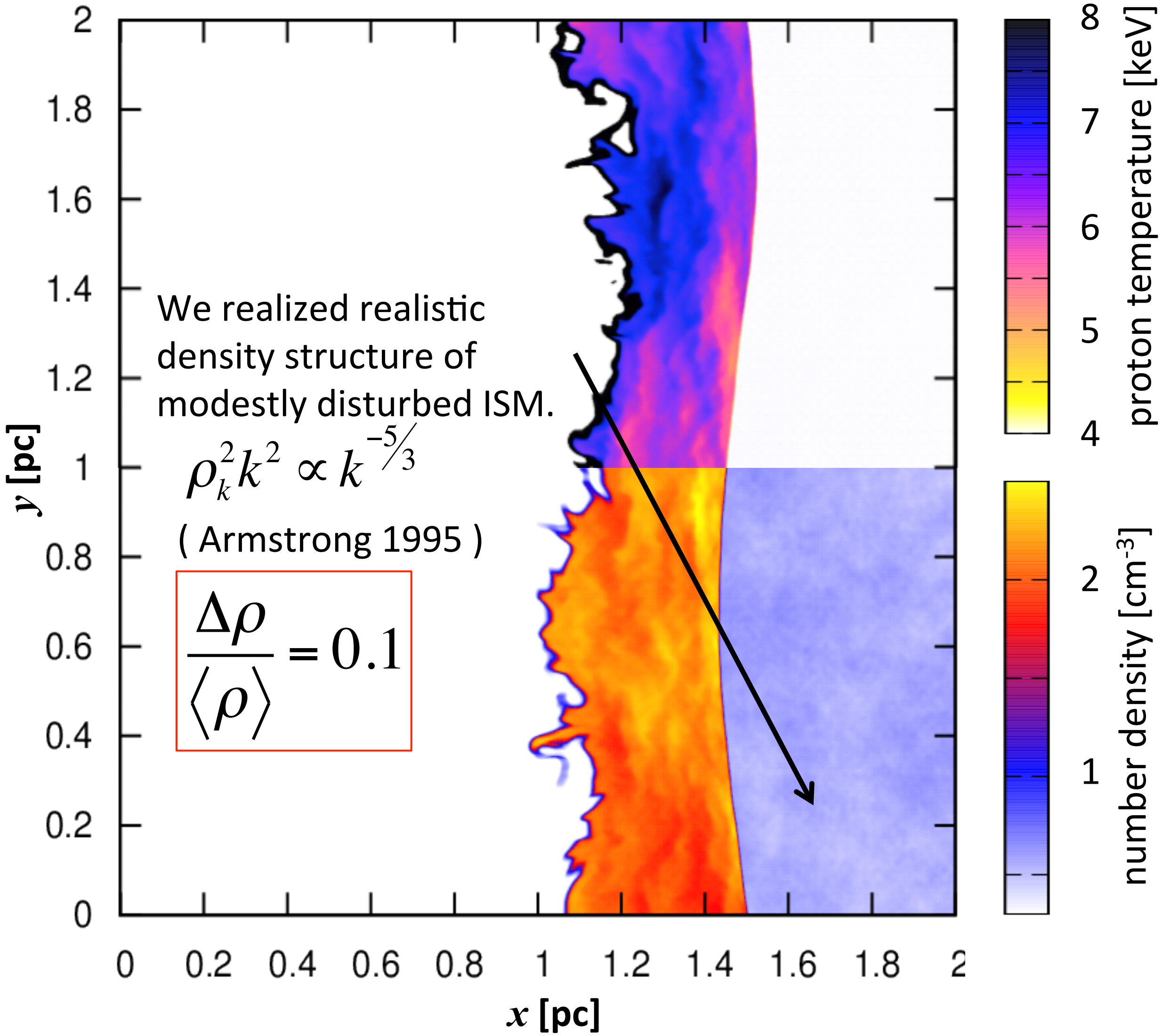
In the present case, $\Delta\rho/\langle\rho\rangle = 0.3$,

$$0.09 \le \eta \le 0.6$$ analytical

$$0.1 \le \eta \le 0.4$$ numerical

roughly consistent

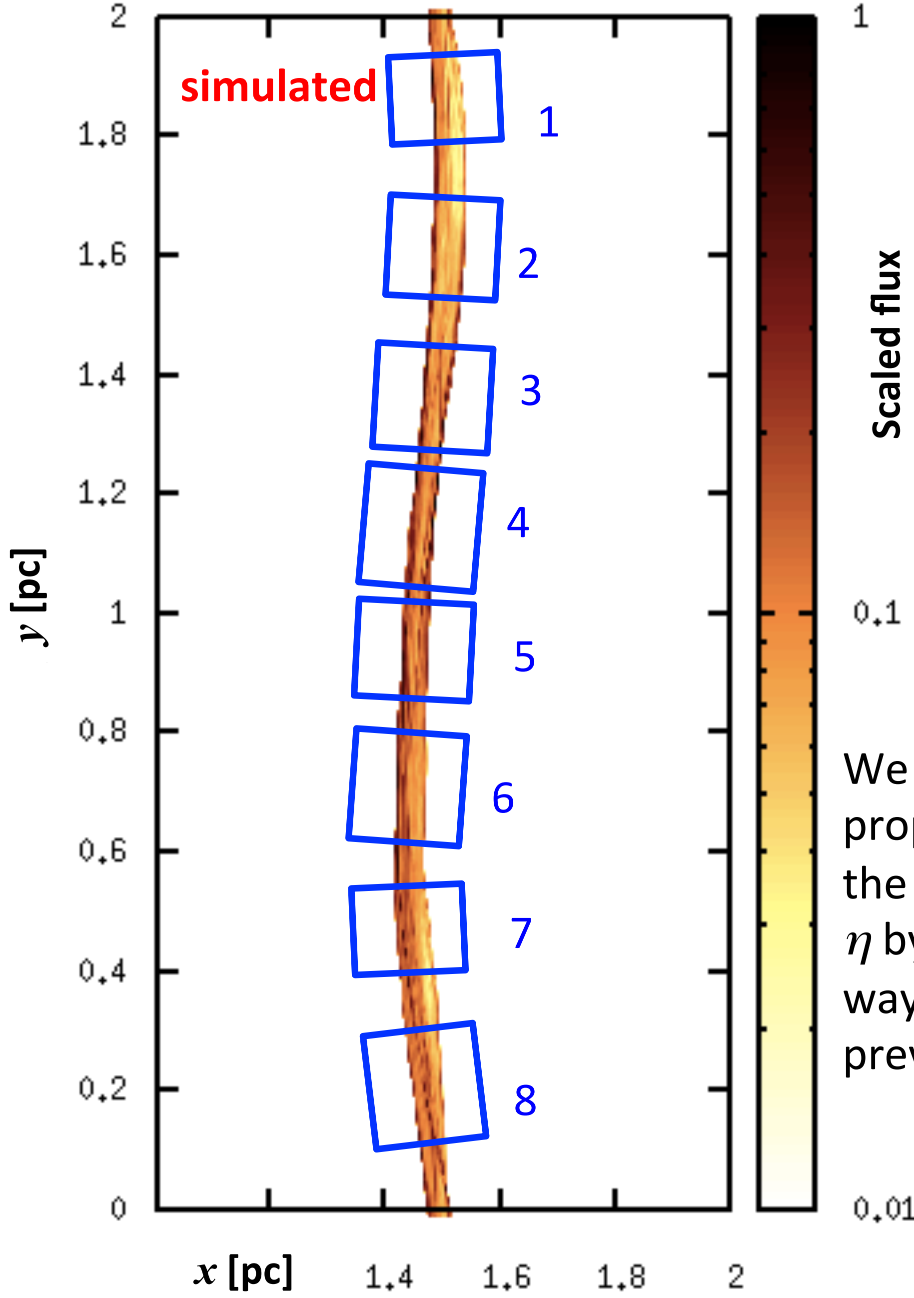
Shocks propagating into modestly disturbed ISM



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

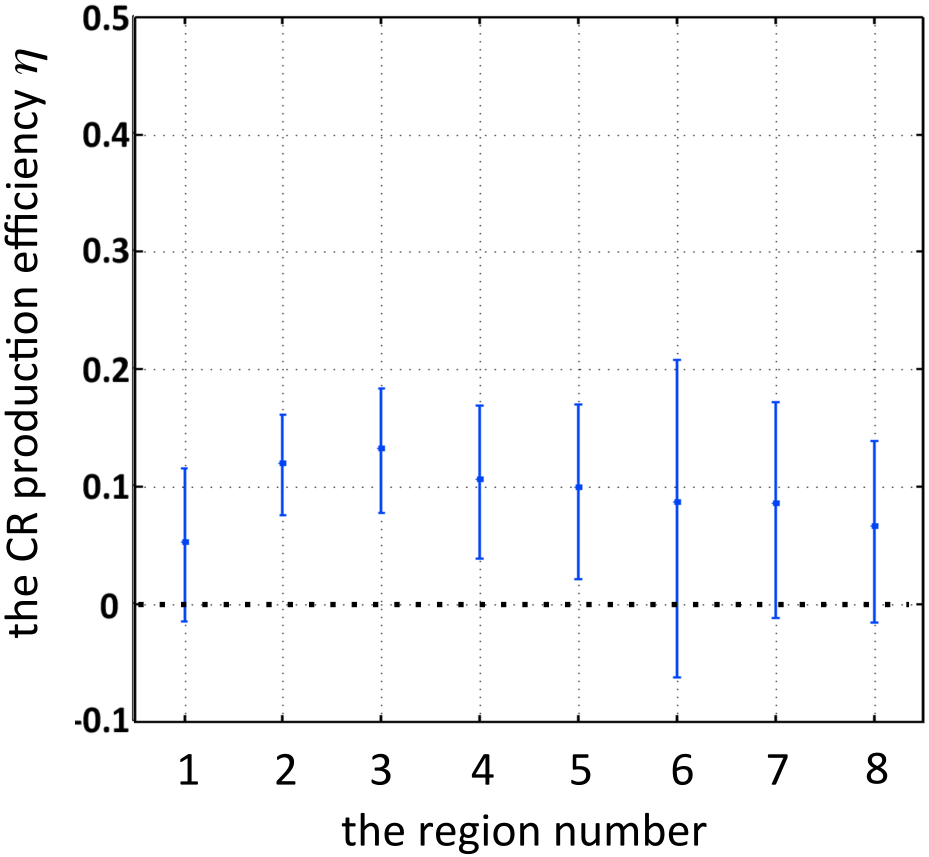
✓ The shock is oblique despite of the case of Δρ/<ρ> = 0.1.

Simulated Hα image for $\Delta\rho/<\rho>=0.1$



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

Results for 8 Regions ($\Delta\rho/<\rho>=0.1$)



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 $\Delta\rho/<\rho> = 0.1$, the efficiency η is roughly consistent to our analytical estimation.

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

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.
- ✓ Hα proper motion velocity (V_{proper}) is almost identical to the shock velocity component perpendicular to line of sight.
- ✓ The downstream temperature is given by the velocity component normal to the shock surface ($V_{sh}\cos\theta$).
- ✓ 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.