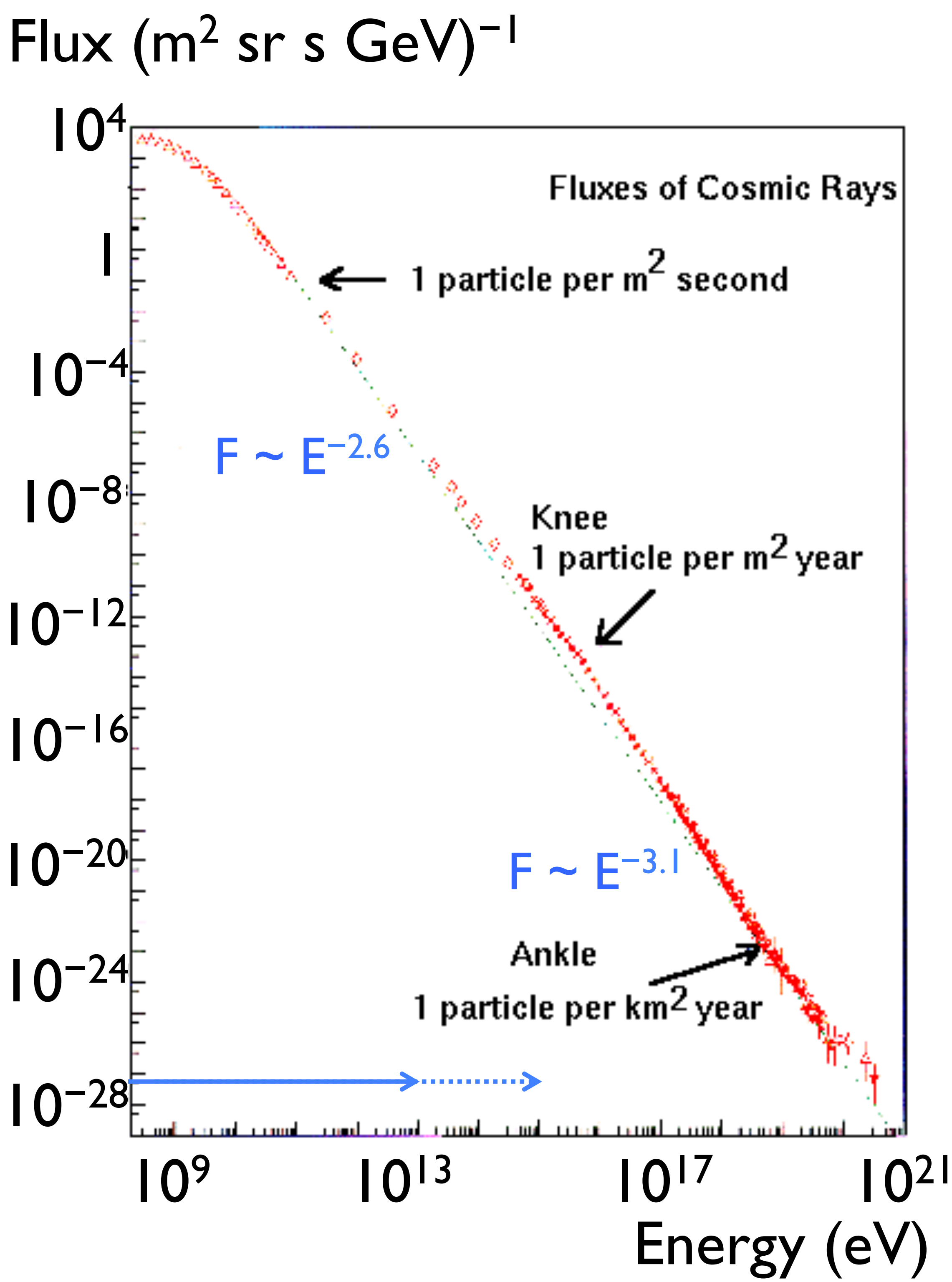
Constraints on Particle Acceleration from Optical Spectra of Fast Shocks in Supernova Remnants

Jack Hughes
Rutgers University

Luke Hovey (LANL), Curtis McCully (LCO, UCSB), Viraj Pandya (UCSC), and Kristoffer Eriksen (LANL)

Cosmic Rays (CR)



Diffusive Shock Acceleration

First order Fermi acceleration:

Worked out in the 1970's by several groups (Axford, Leer, & Skadron 1977, Krymsky 1977, Bell 1978, Blandford & Ostriker 1978).

Particles gain energy each time they cross a strong shock.

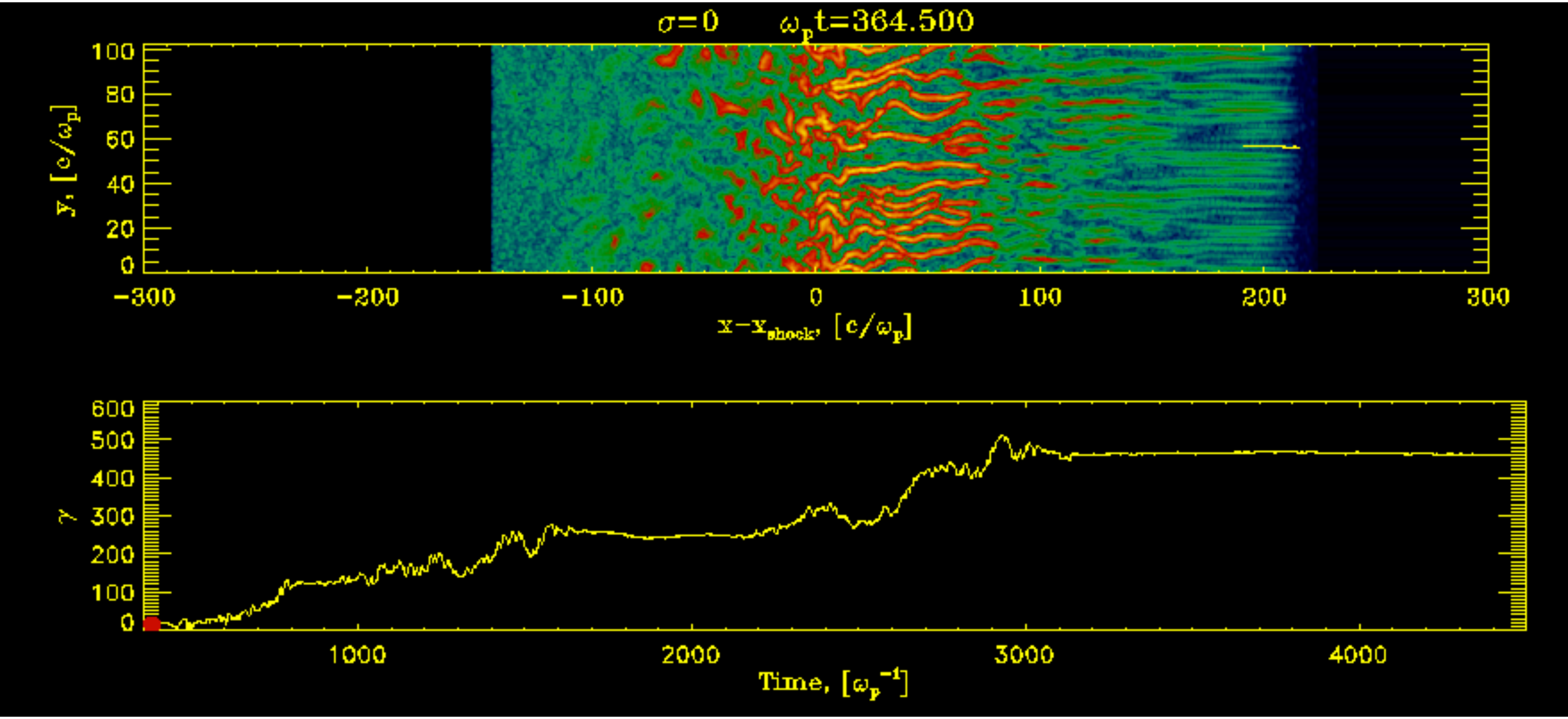
Results in power law spectrum with energy index approx. −2

Acceleration is typically limited by time (i.e., number of shock crossings), so SNR shocks probably can only account for CRs up to energies of $10^{13} - 10^{15}$ eV.

A key component is that SNR shocks are mediated by magnetic fields (not collisions)

Acceleration Mechanism

Spitkovsky 2008 – Particle Acceleration in a Relativistic Shock
2D particle-in-cell simulation, magnetic energy density (color)



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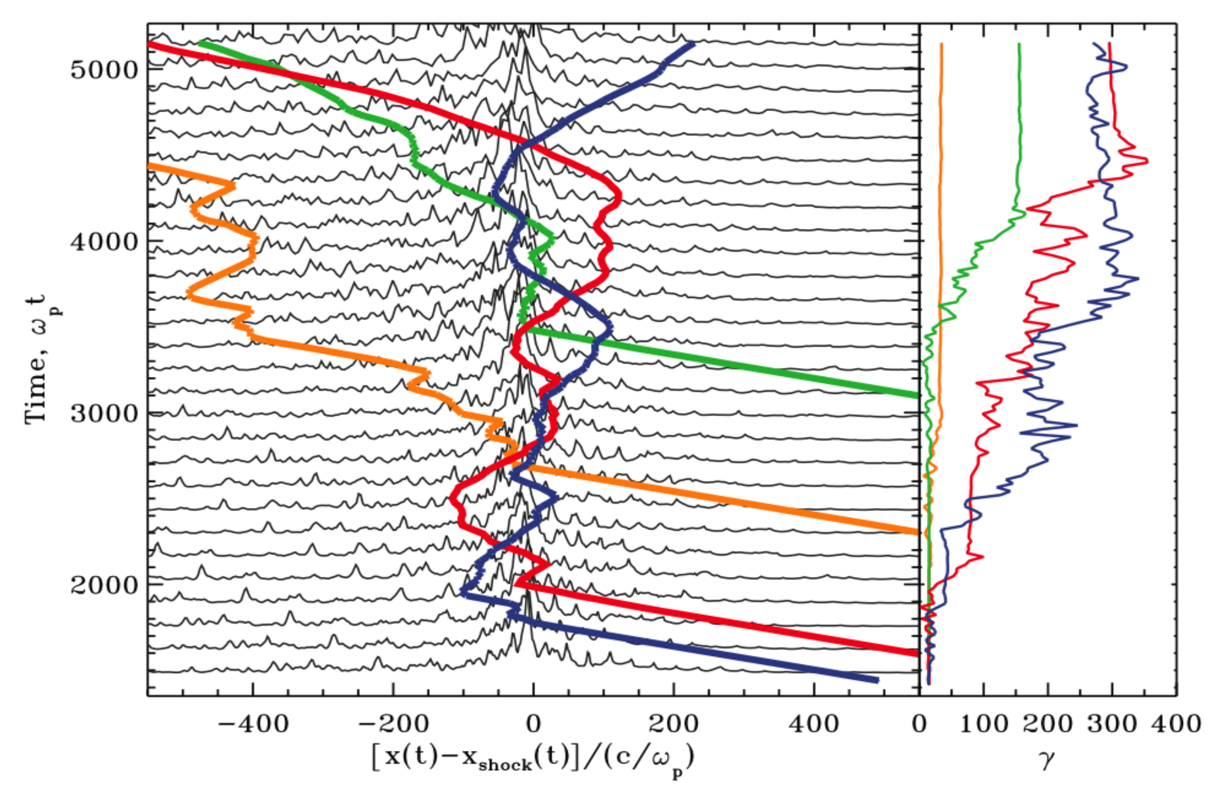
Selected particle trajectories

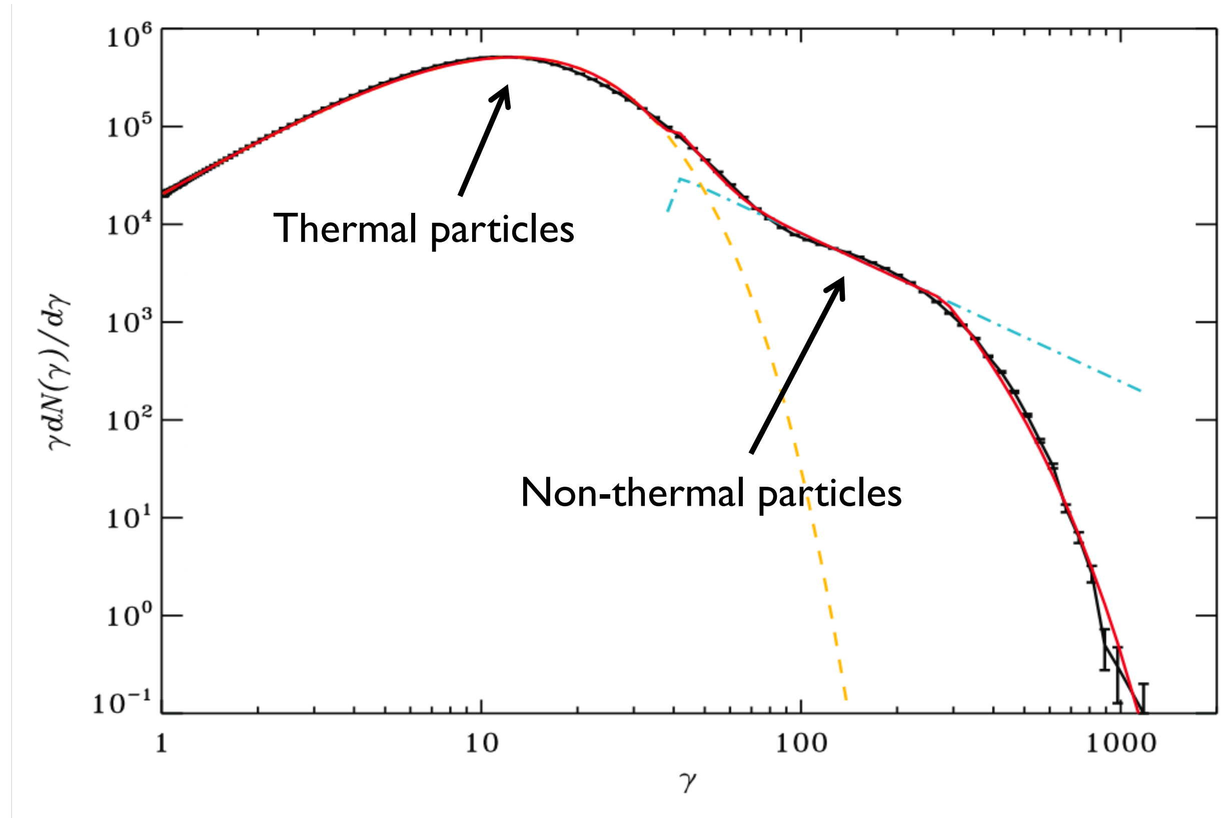


Post-shock (downstream)

Shock front

Pre-shock (upstream)

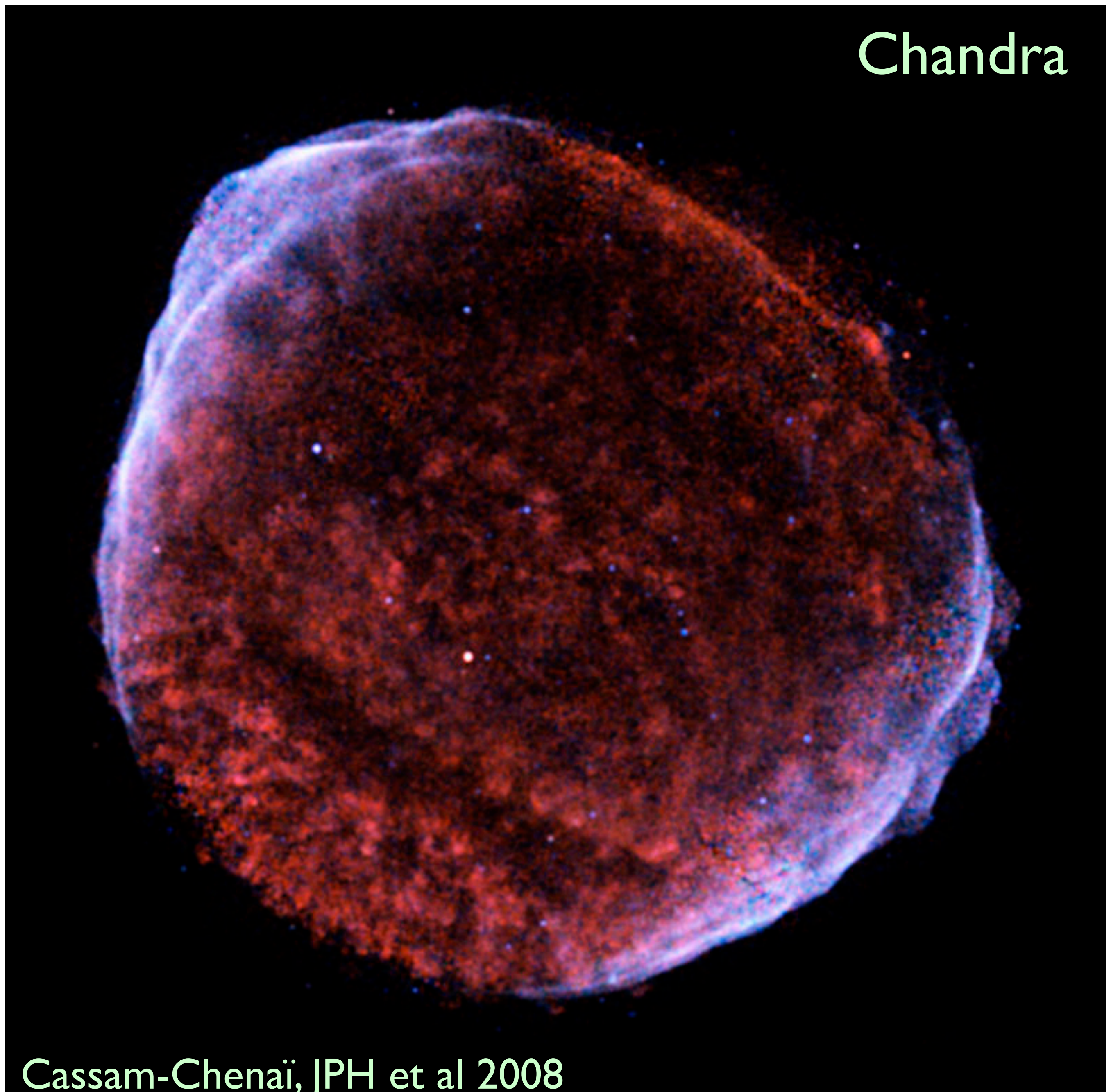
Particle spectrum



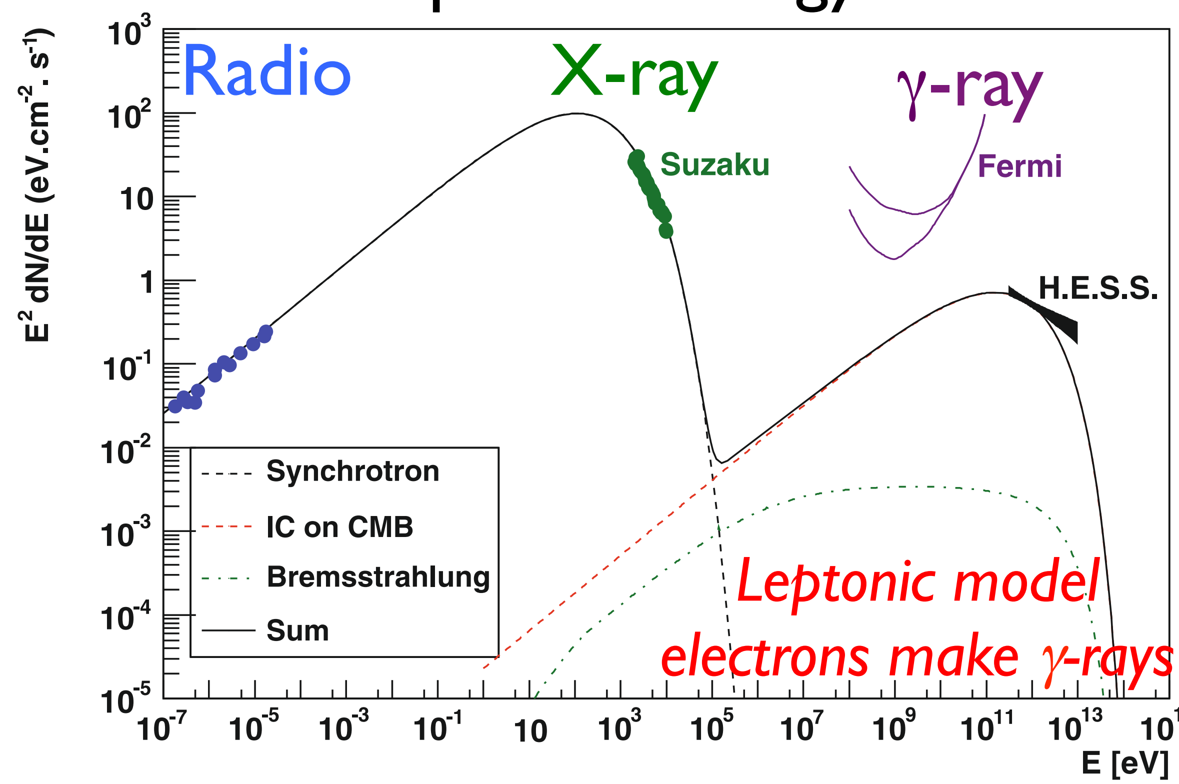
This process is *efficient*:
of order 50% of the shock energy can go into nonthermal particles

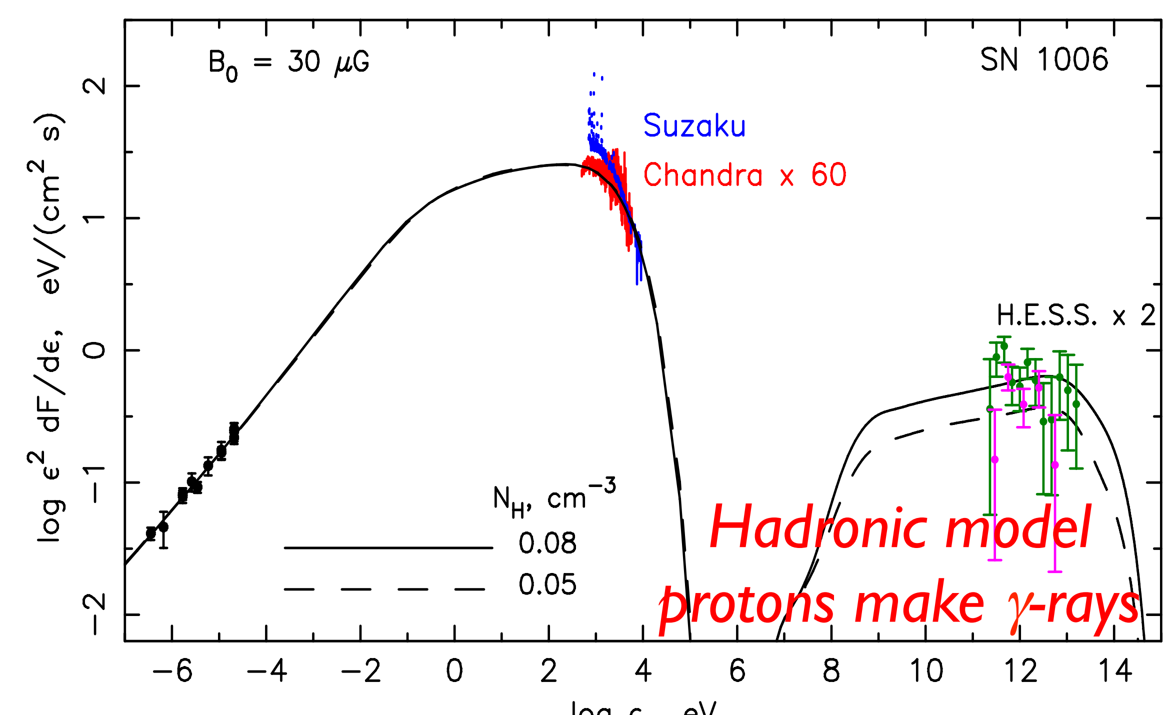
Spectral Evidence for CR Acceleration at Shocks: the Case of SN1006

Nonthermal synchrotron rims



Broadband spectral energy distribution





A Different Approach: Evidence from Energetics

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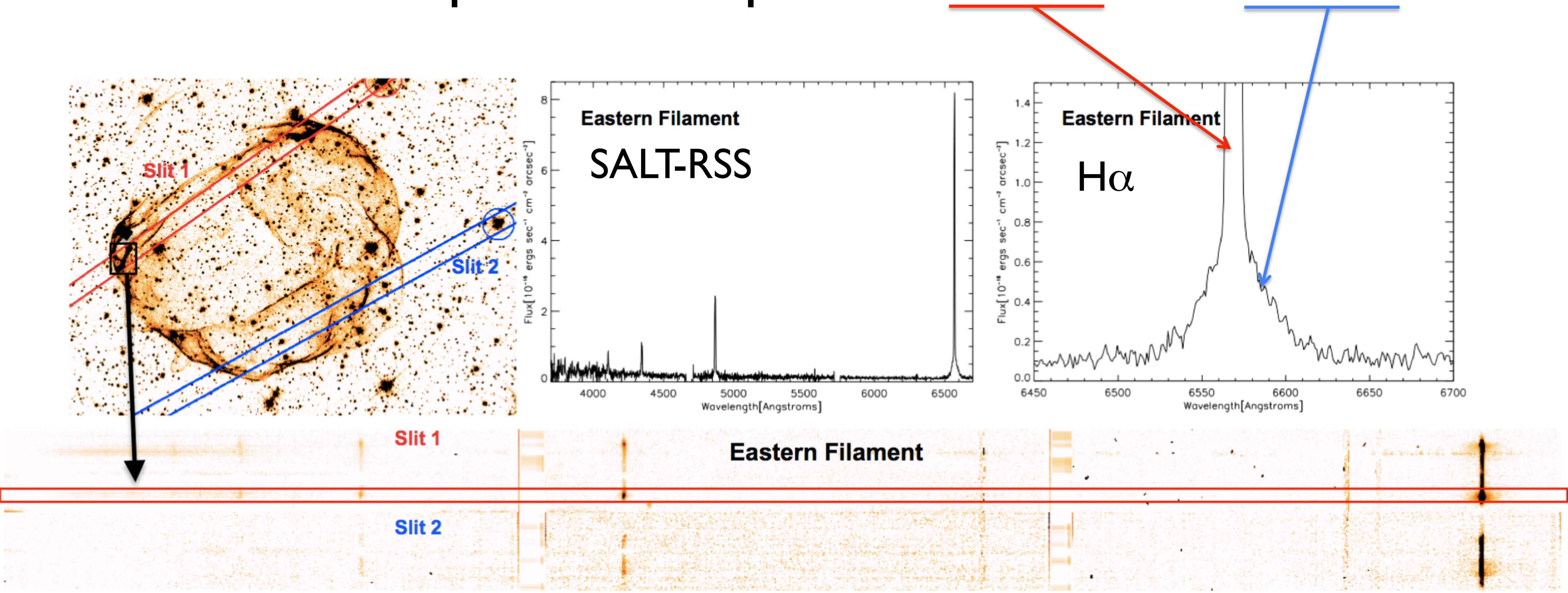
proton temperatures are possible for a special type of "Balmer-dominated" shock

Balmer-dominated Shocks

Observational characteristics

- Hydrogen emission (e.g., optical Balmer lines) dominates
- No emission from metal line species: [O III], [S II]
- Two component line profile: narrow and broad

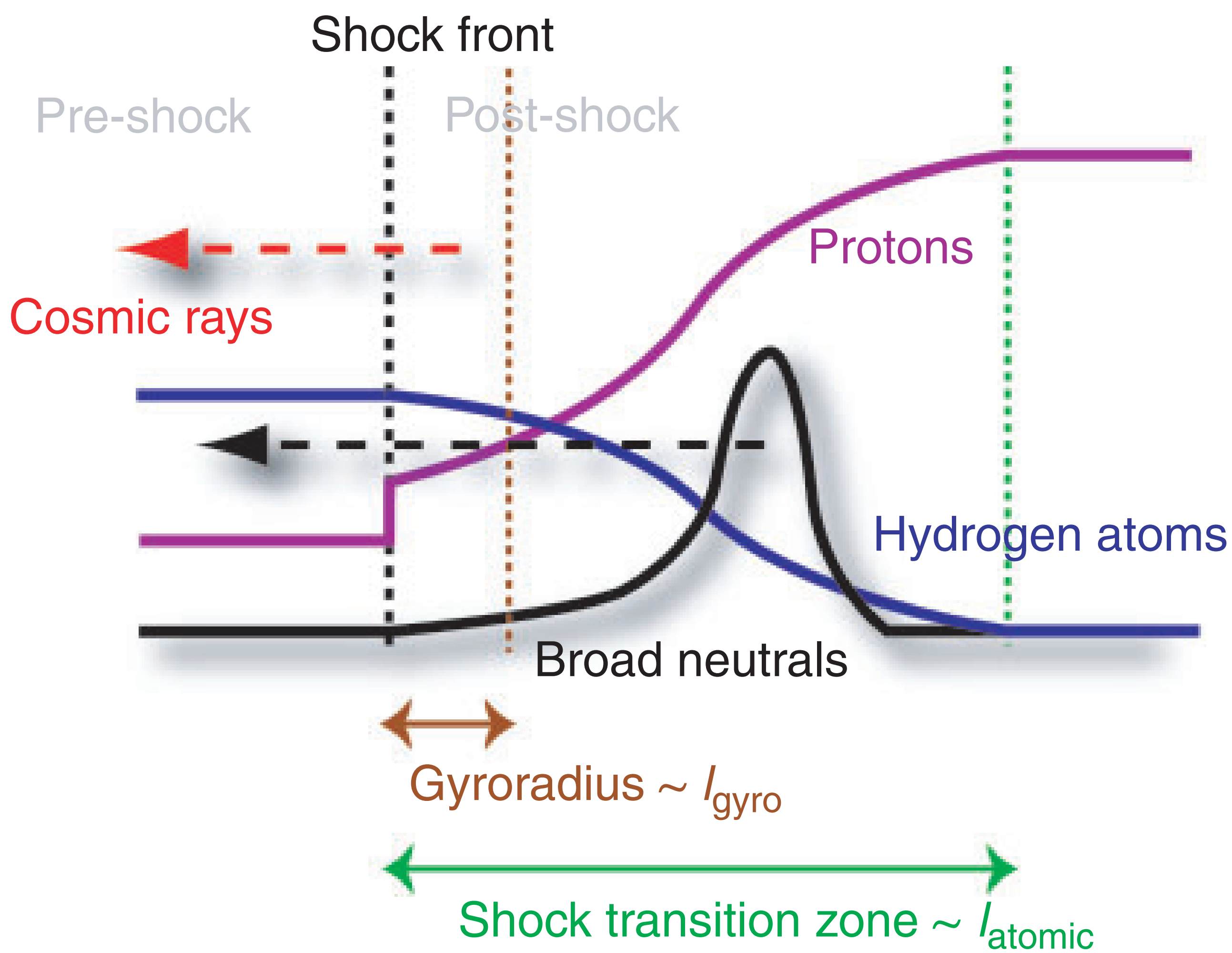


Balmer-dominated Shocks

Physical explanation

Chevalier & Raymond 1978

- Fast shock in a partially neutral medium
- Narrow line: excitation of neutral H atoms
- Broad line: H atoms charge exchange with hot protons to produce broad neutrals, that are excited and emit



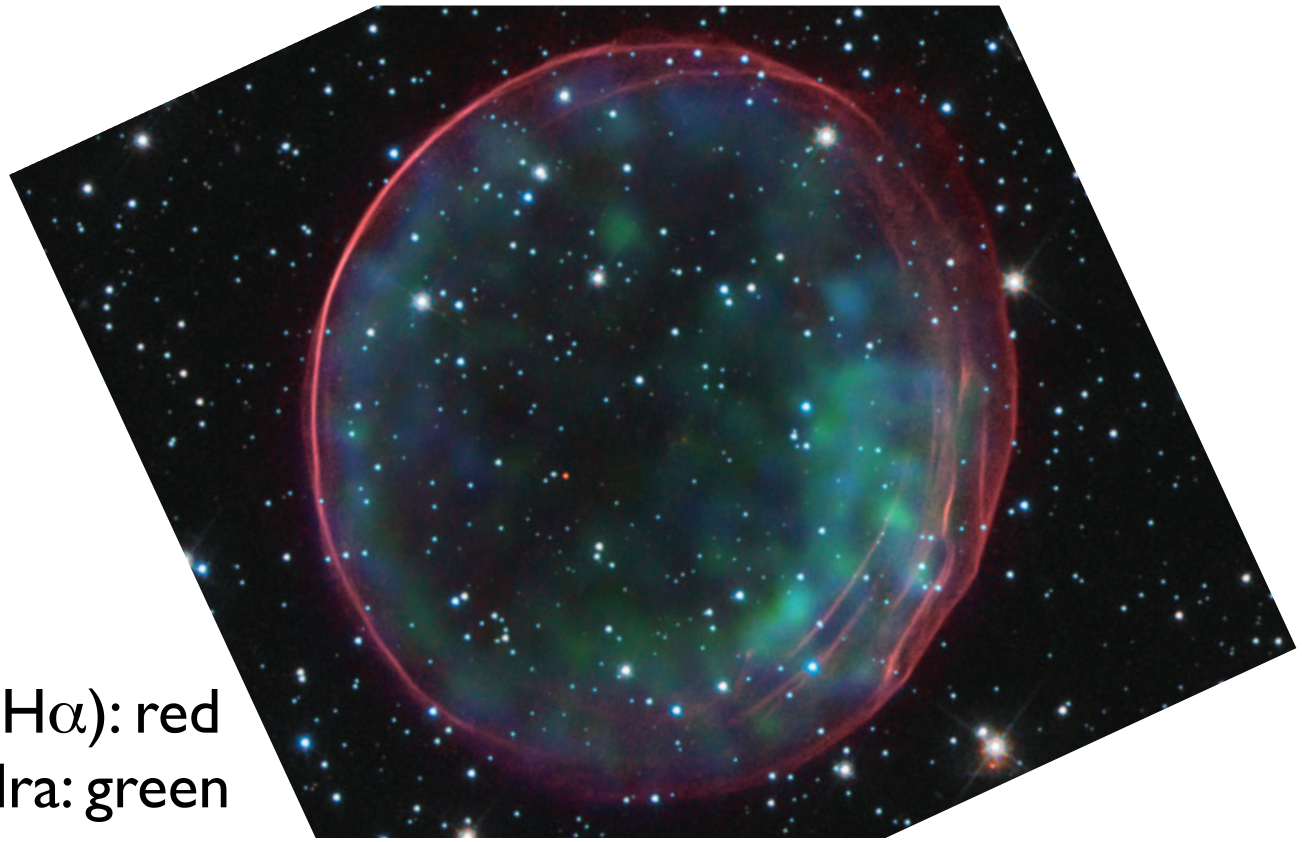
cartoon from Heng 2010

Narrow line diagnoses the velocity distribution of the pre-shock hydrogen atoms

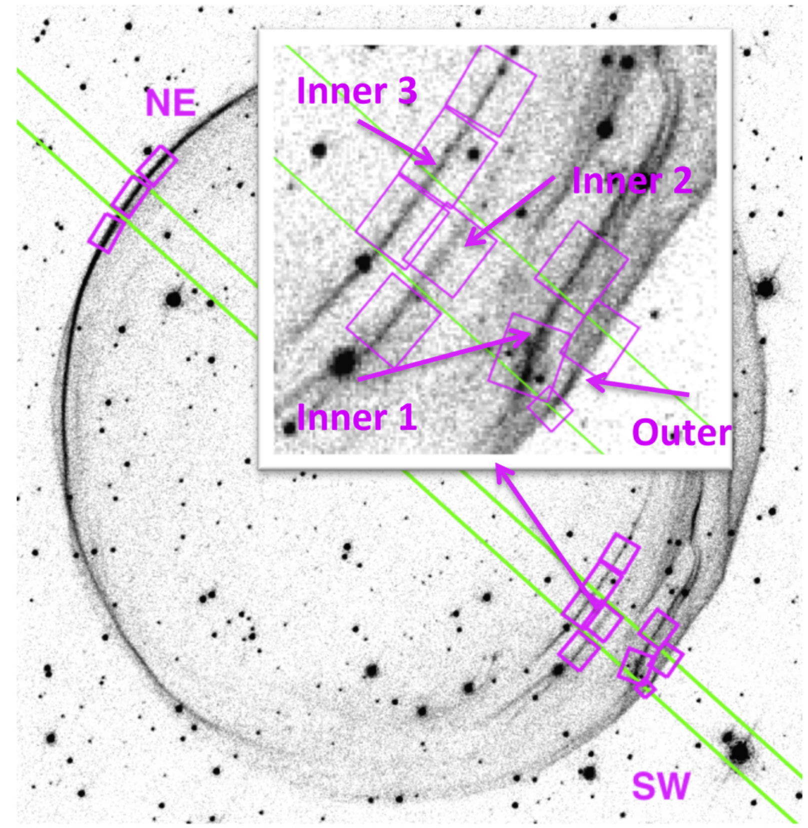
Broad line diagnoses the velocity distribution (temperature) of the post-shock protons

Broad-to-narrow flux ratio tells us about the post-shock electron temperature

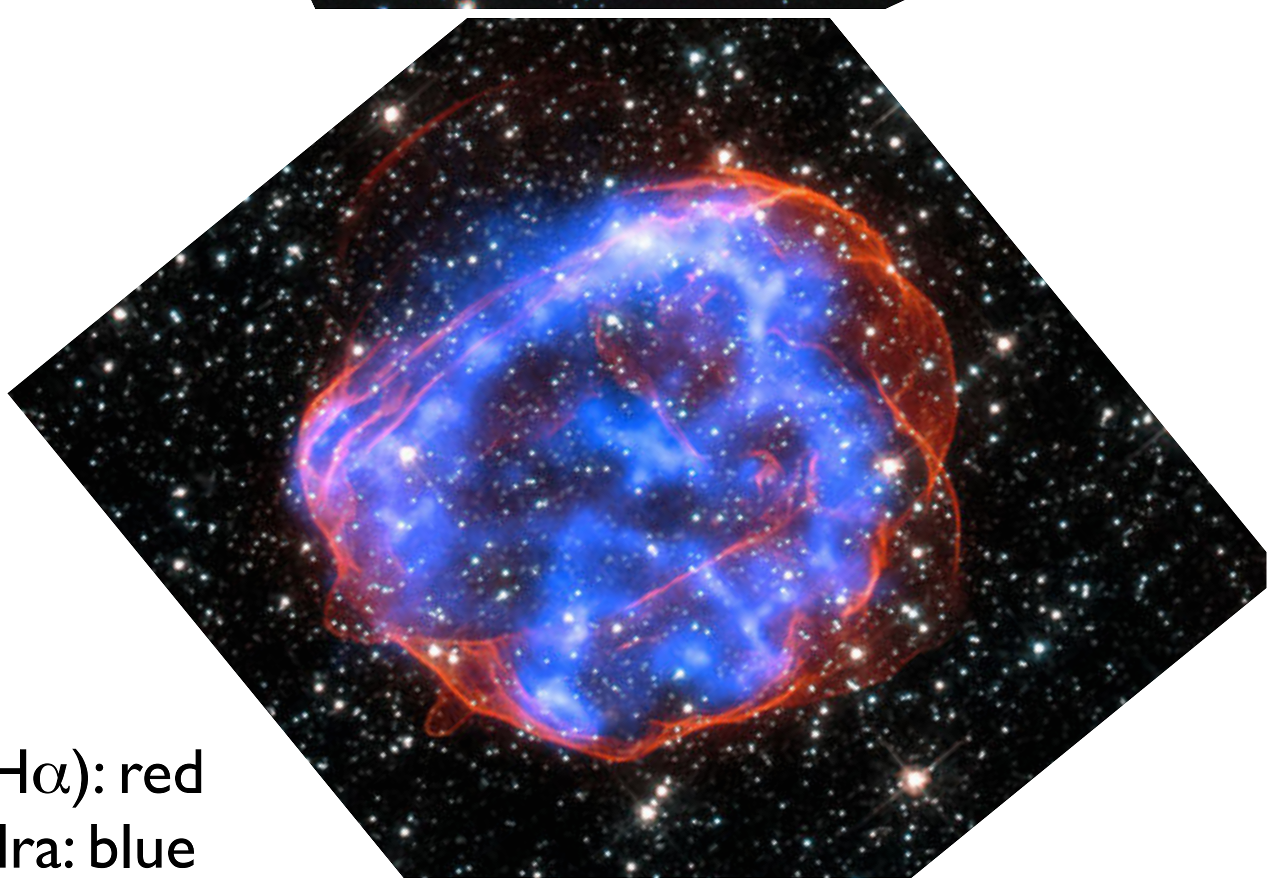
LMC SNRs 0509-67.5 & 0519-69.0



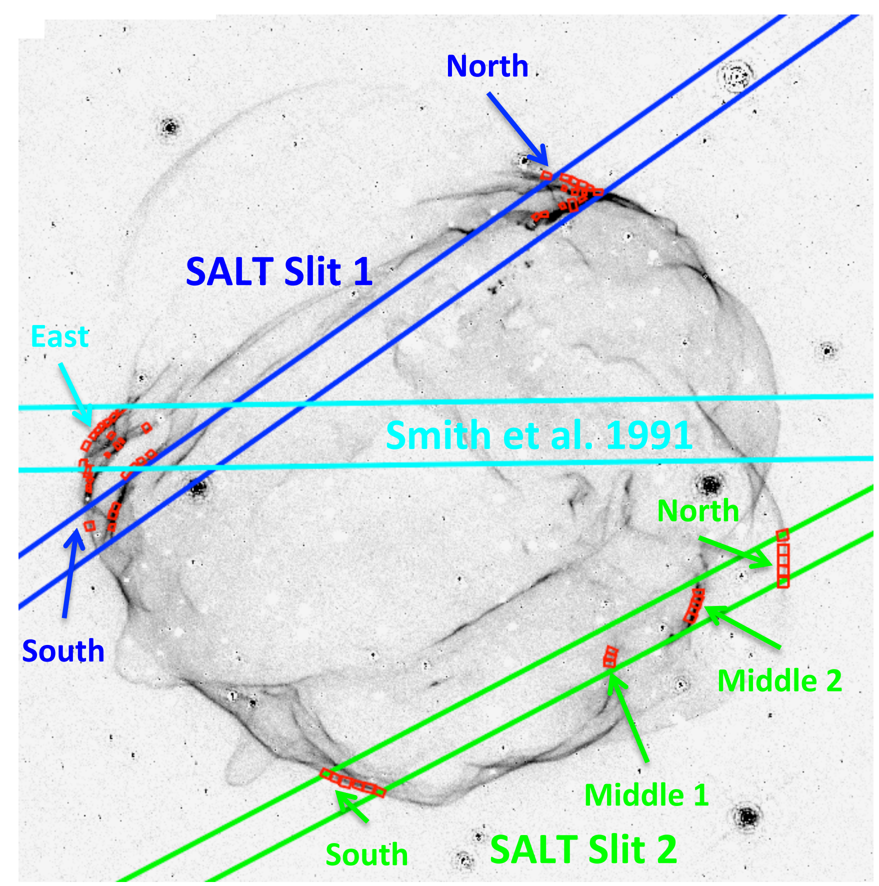
HST (Hα): red
Chandra: green



~30”



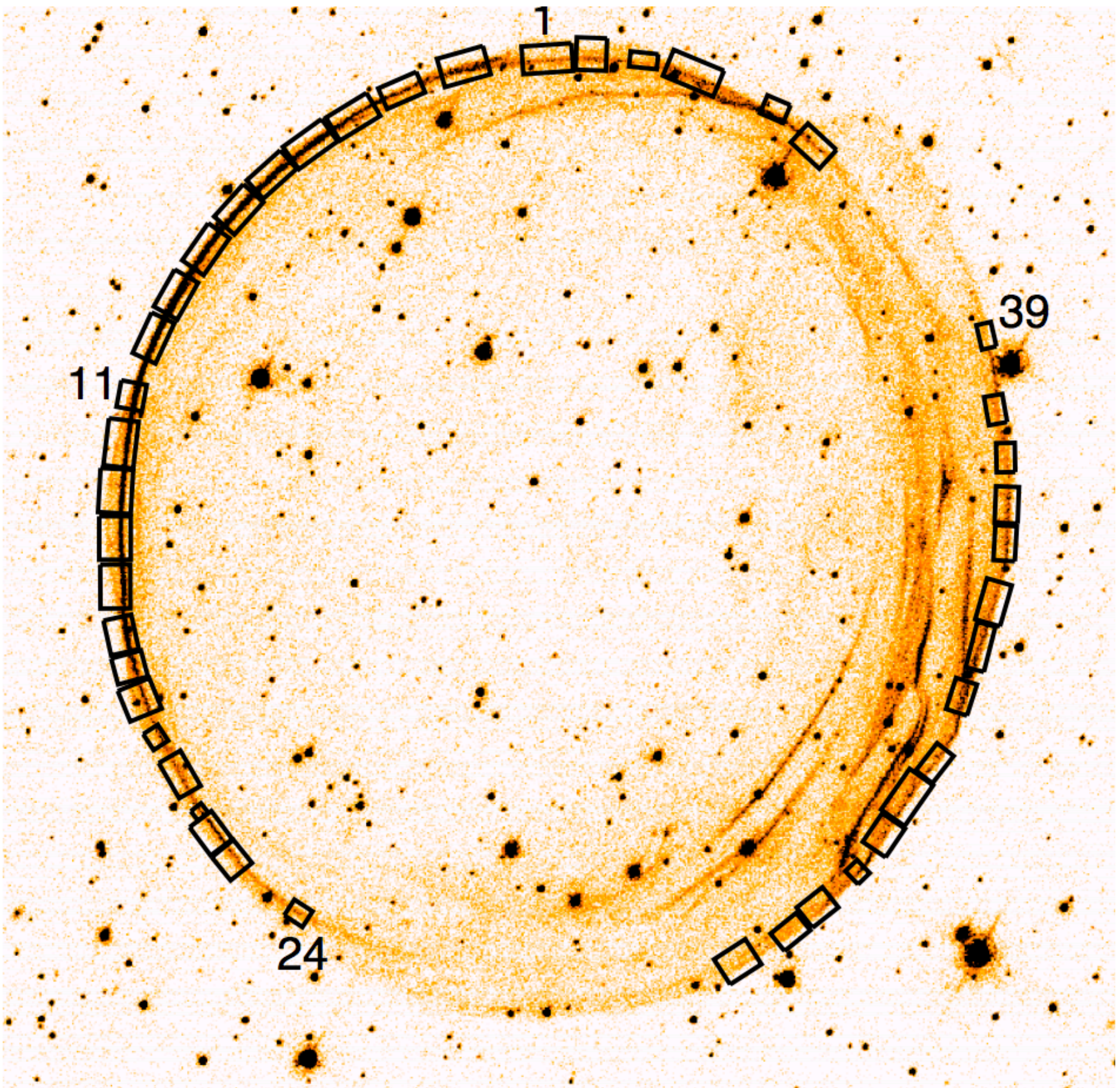
HST (Hα): red
Chandra: blue



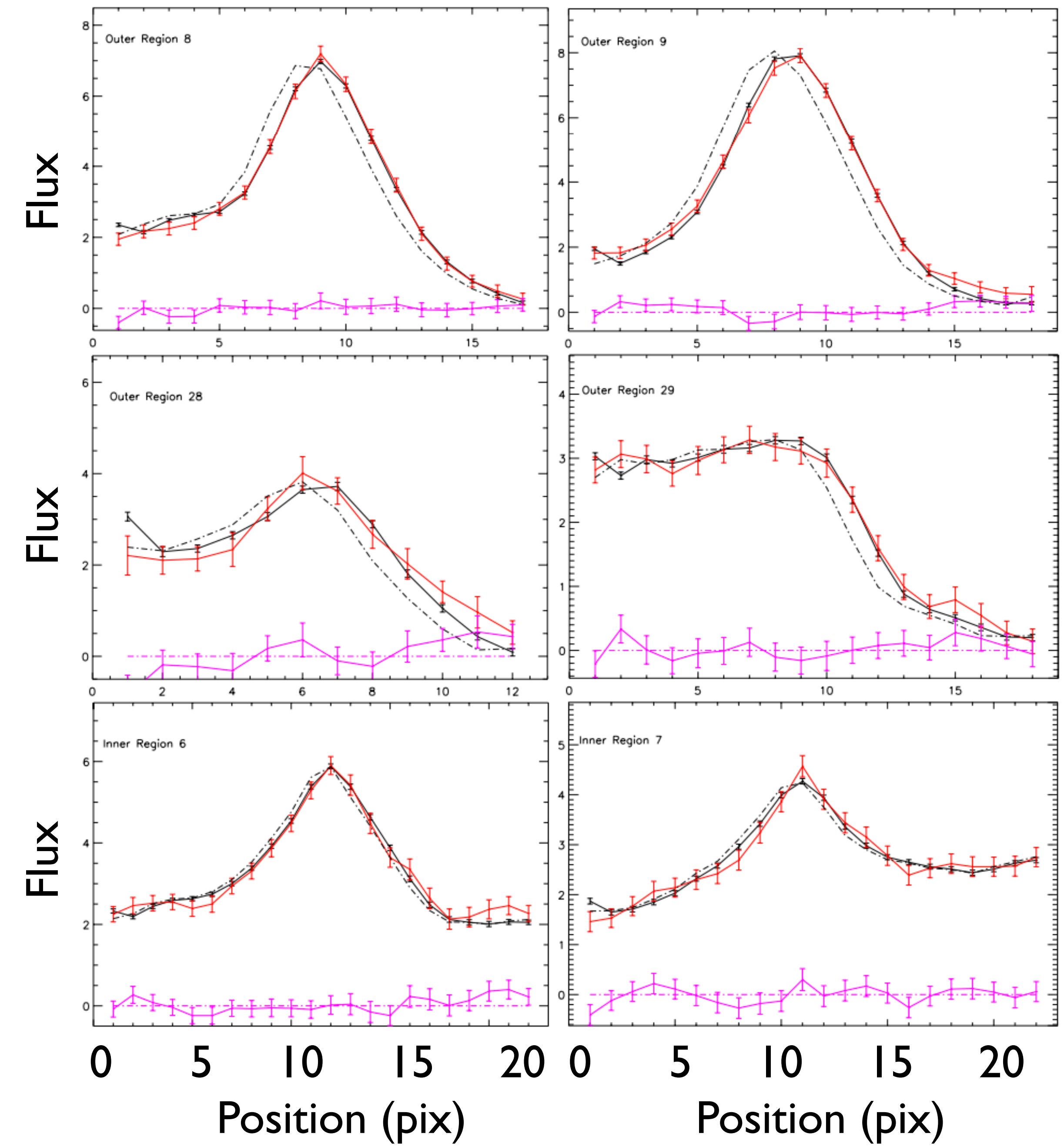
~30”

HST Proper Motion of Shock

Two epochs separated by ~1 yr



Shift flux profiles in each region to measure proper motion around rim



Distance to LMC is 50 kpc with 4% uncertainty (Clementini et al. 2003)

Measure Shock Speed

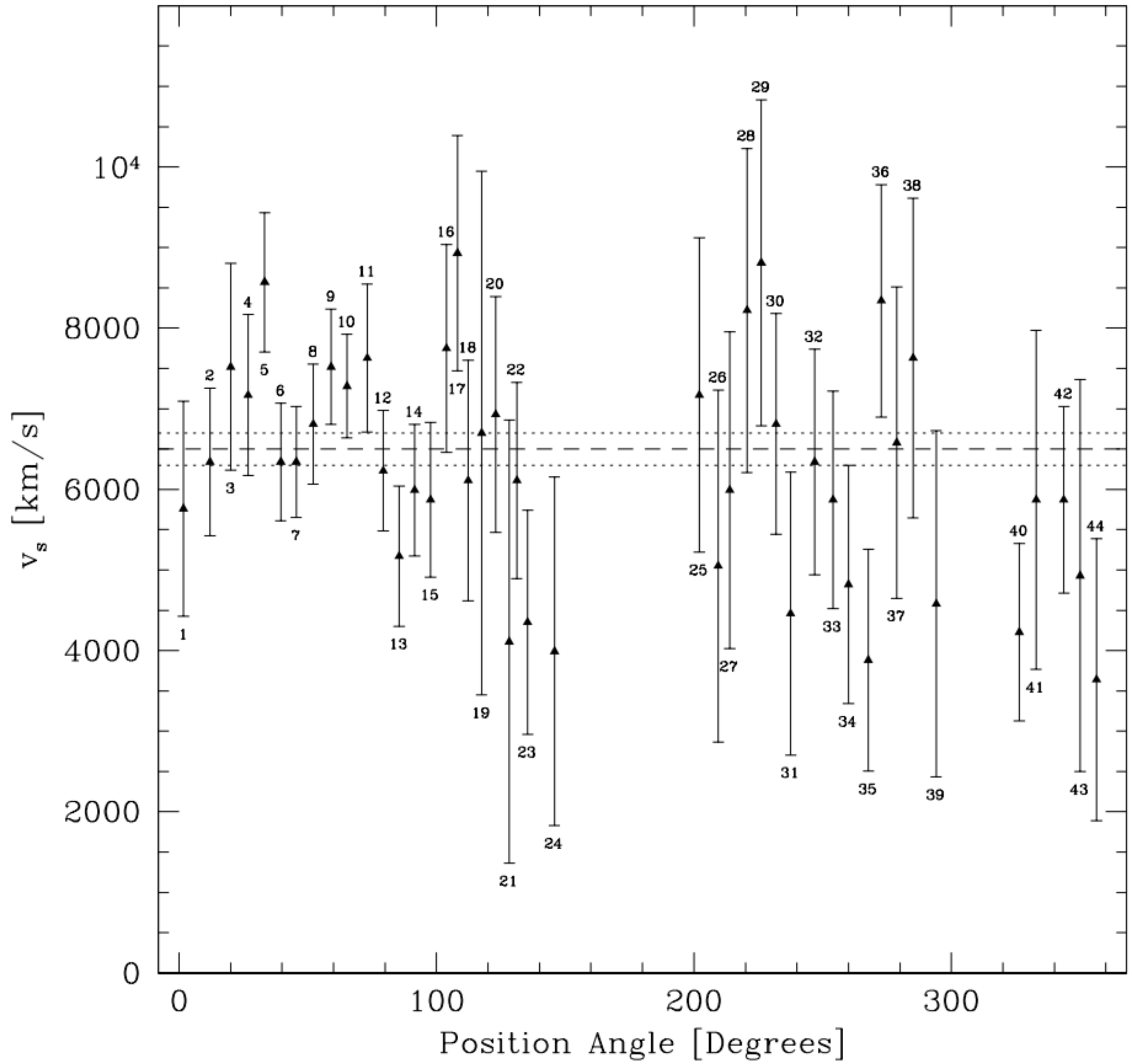
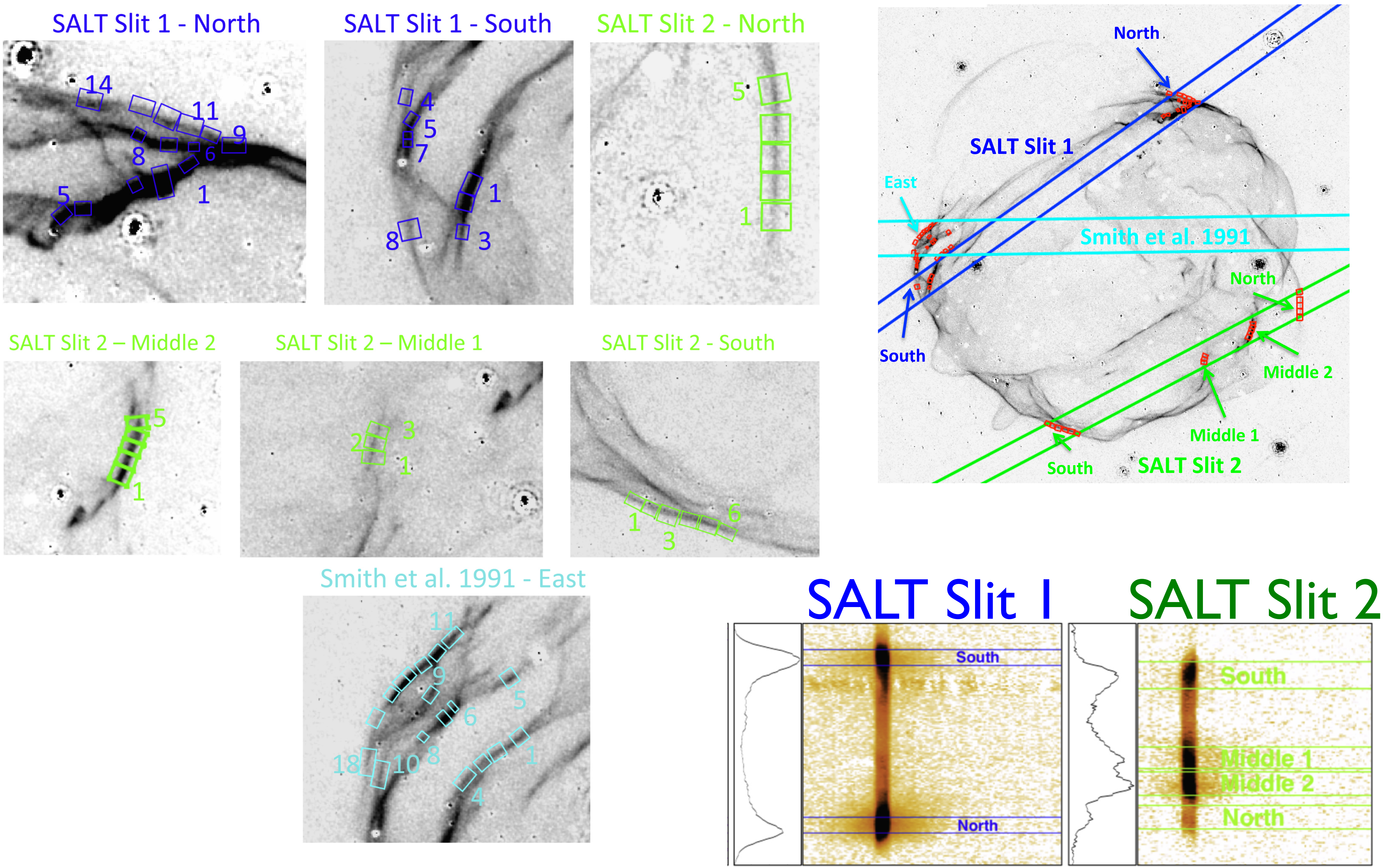


FIG. 4.— Expansion velocity vs. position angle for the 44 Hα profiles we consider. Each point is labeled with its corresponding identification number. The global average velocity and $\pm 1\sigma$ uncertainty range are shown with a dashed line and dotted lines respectively.

Global average expansion speed is 6500 ± 200 km/s (χ_r^2 = 1.1)

Connect shock speeds to spectra



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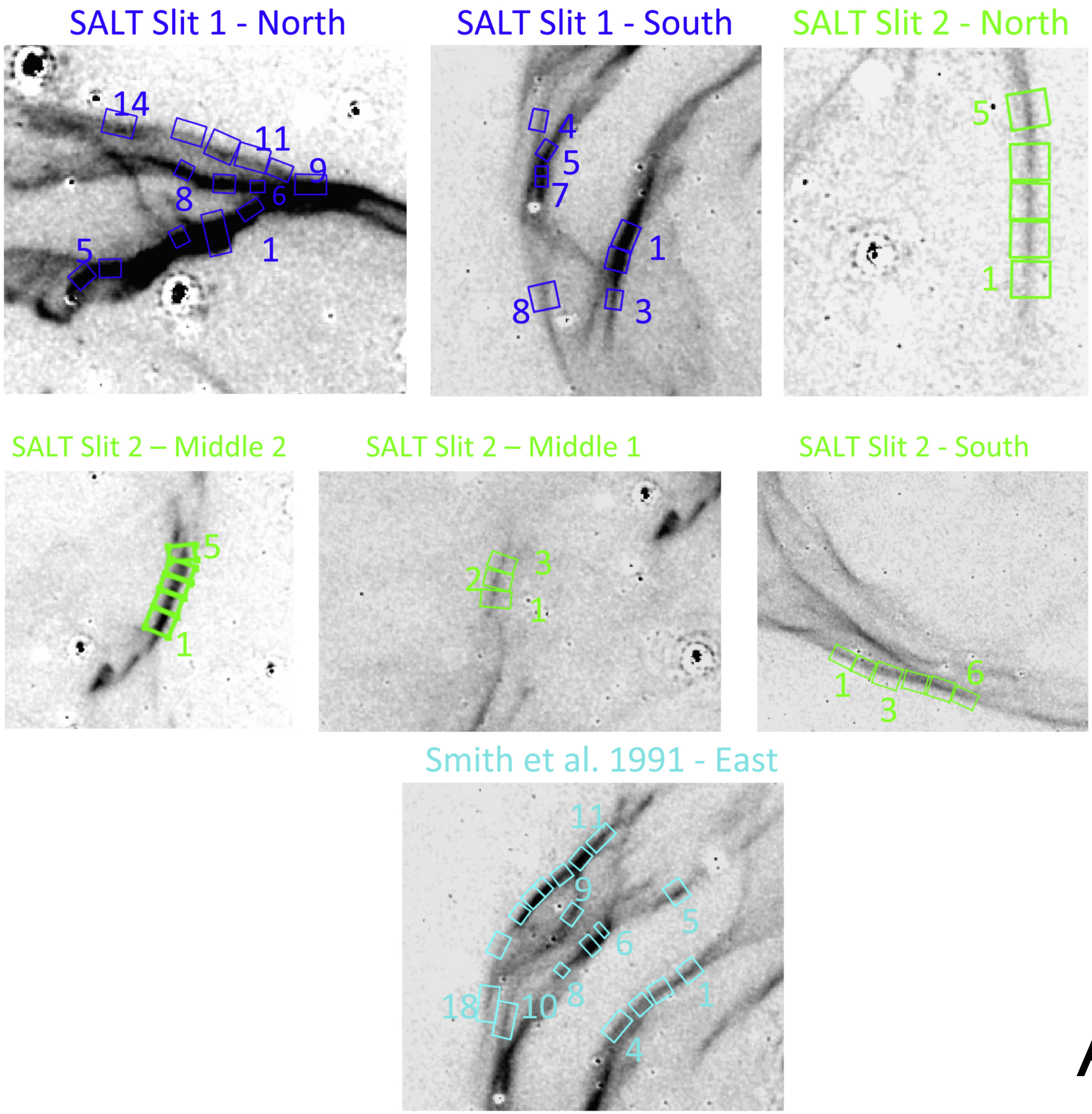
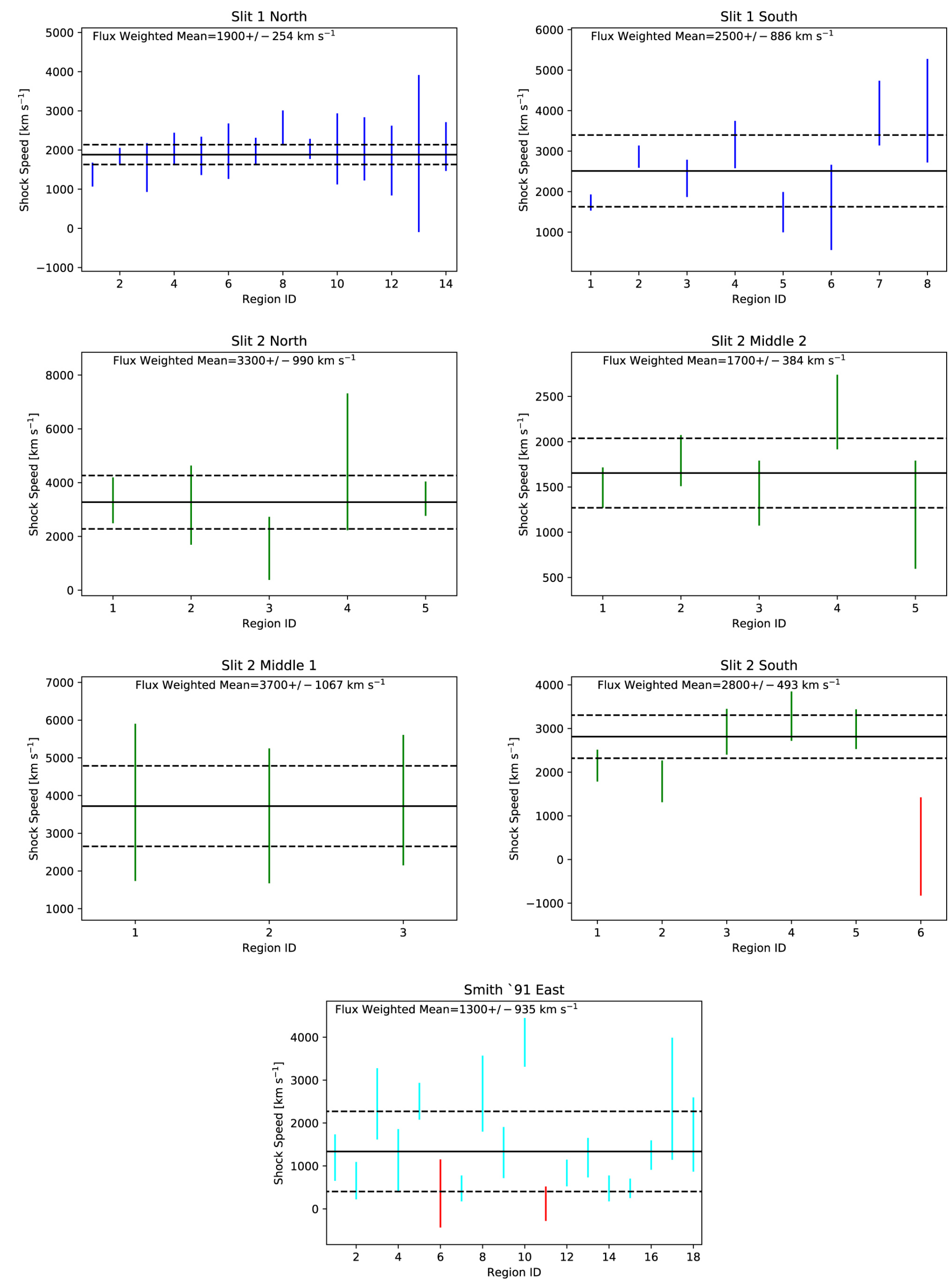
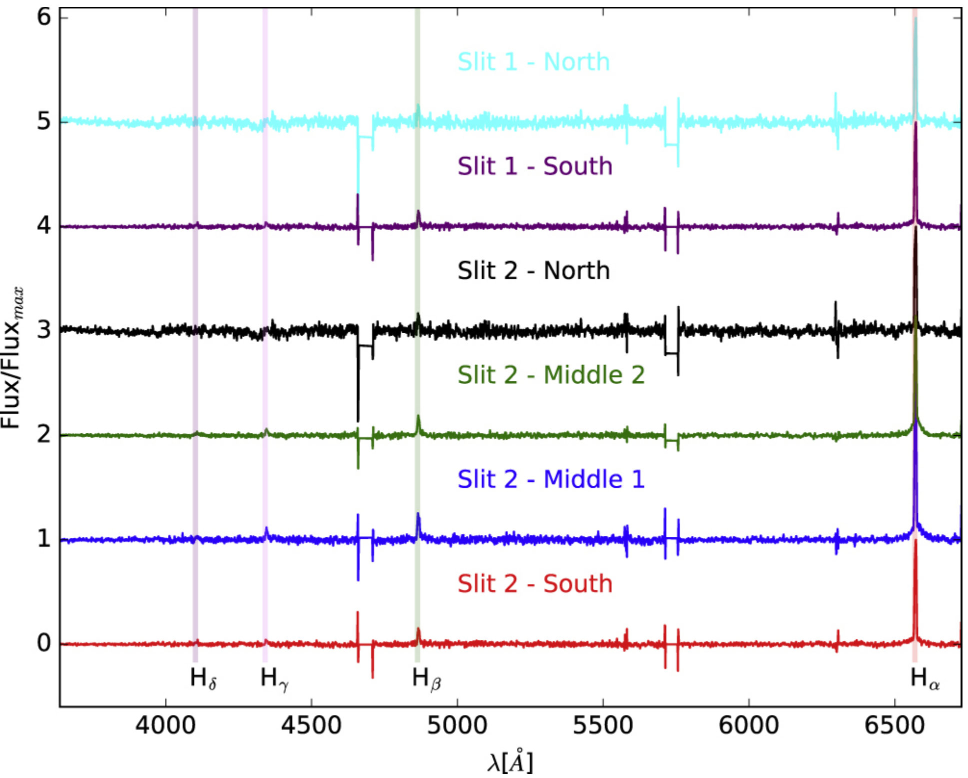
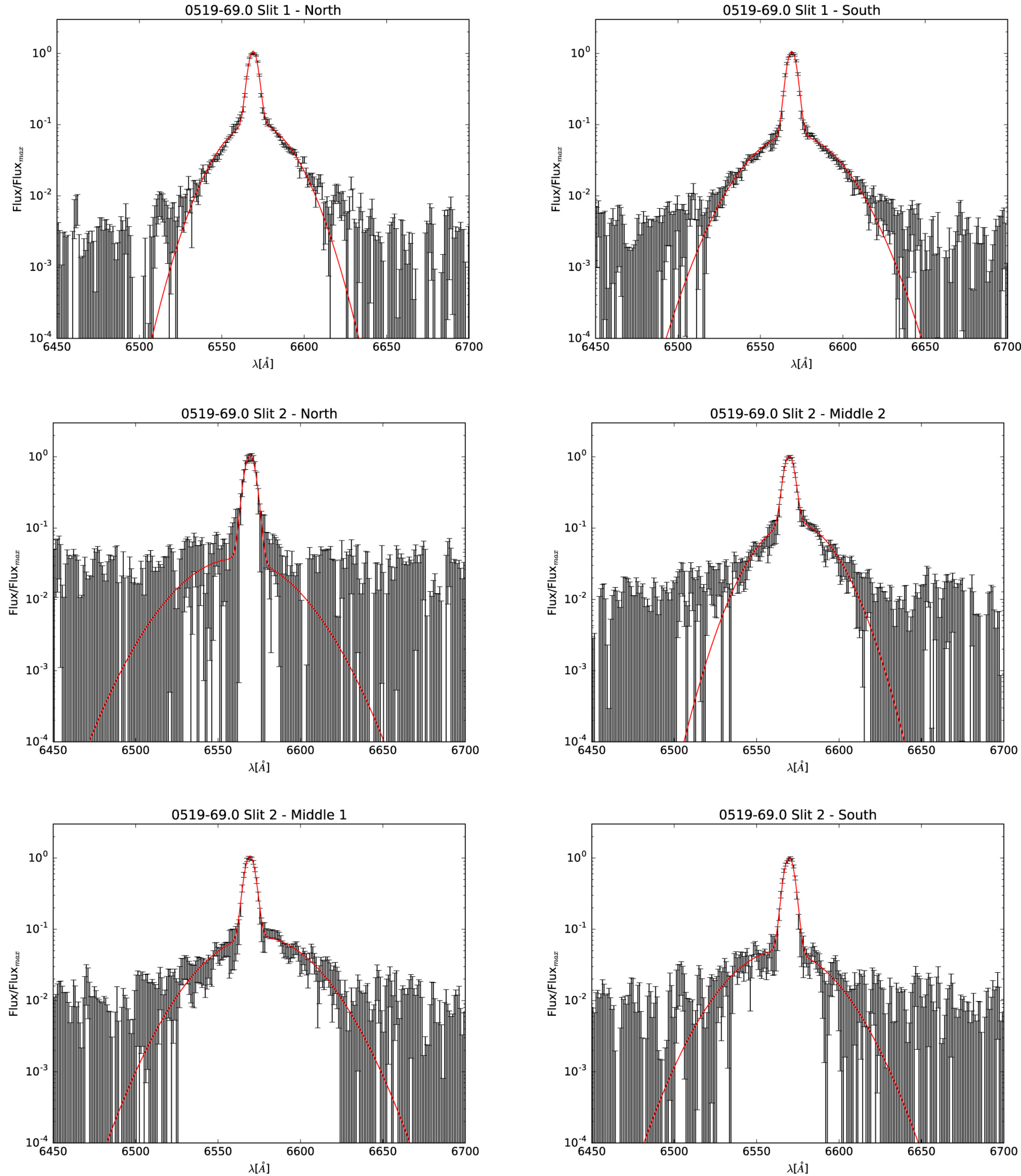




Ave shock speeds:
1300 – 3700 km/s

SALT RSS Spectra

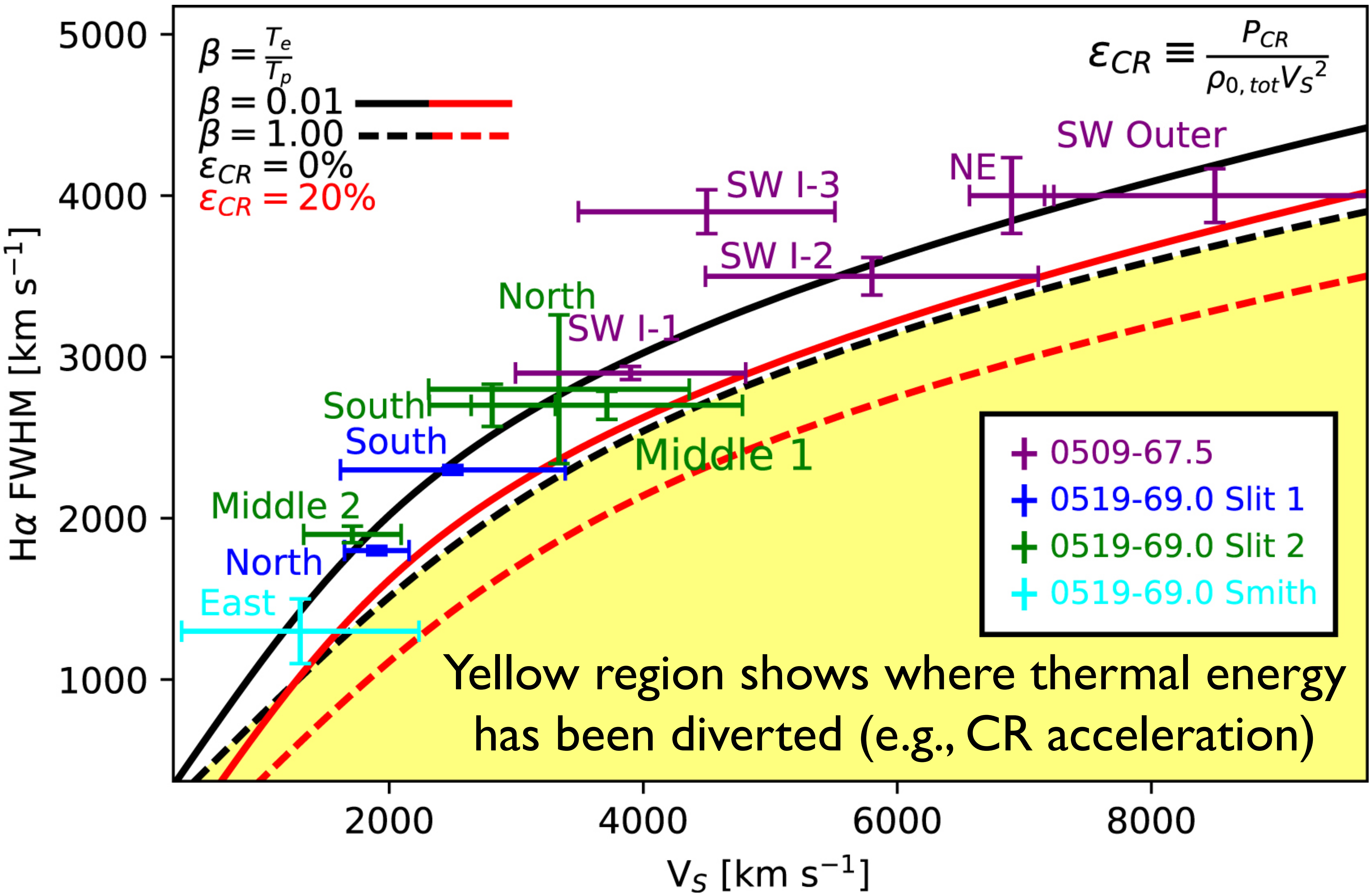




Hα broad widths: 1300 to 2800 km/s

Broad-narrow centroid offsets: −240 to 370 km/s

Compare to shock models



Ensemble limit on CR acceleration efficiency: <7% (95% C.L.)

models from Morlino et al 2013

Summary

- Measured shock speeds for two young LMC SNRs
  - Two epochs of HST imaging (Hα) separated by ~1 yr
  - Location in LMC key to convert proper motions to speeds
- Measured Hα broad line widths from VLT/FORS2 and SALT/RSS for 11 separate shock locations (plus one from the literature)
- Broad Hα line widths consistent with shock speeds: implies minimal energy loss to CR acceleration
  - CR efficiency limit ($<7\%$ at 95%CL) far below value of 13% required to explain spectral energy distribution of Tycho's SNR

Published as Hovey et al 2018, ApJ, 862, 148

S·A·L·T

Los Alamos
NATIONAL LABORATORY
EST. 1943

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY