Shock precursors in the north-eastern rim of Tycho's supernova remnant

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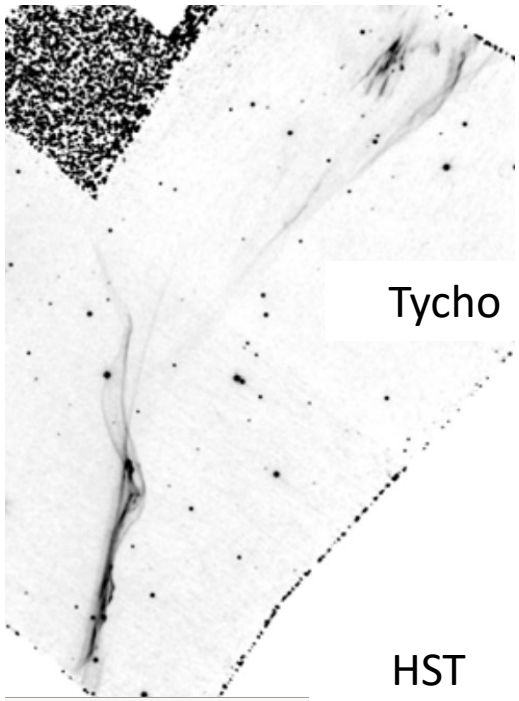


Knežević et al, 2017, ApJ, 846, 167

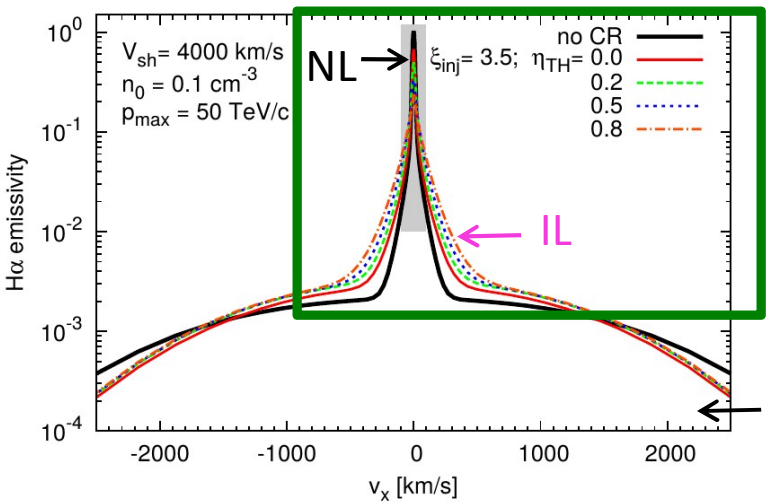
Balmer-dominated shocks

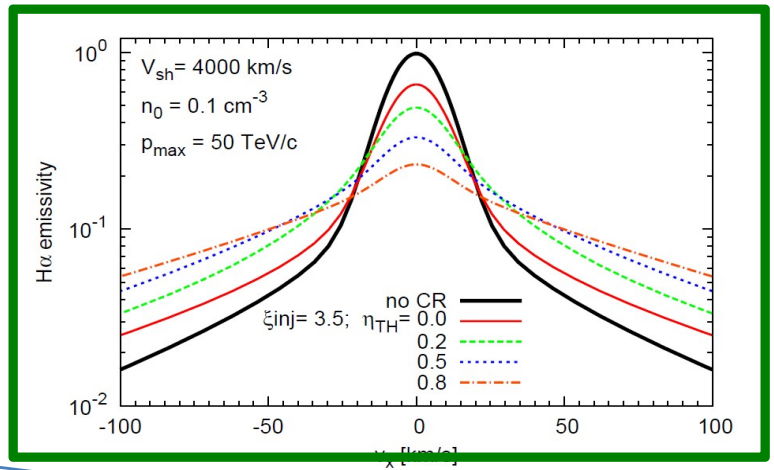
- **Characteristics:** collisionless, non-radiative shocks in partially ionized ISM, strong narrow (W_{NL} ~ 10 km/s) + broad (W_{BL} ~ 1000 km/s) Hα.

- **Shock models**: estimating shock velocity (V_{sh}), electron-proton equilibration (T_e/T_p), effect of precursors.

- **CR precursor**: W_{NL} = 21 km/s $(T_0/10^4\ K)^{1/2}$ >> 21 km/s (damping of the magnetic turbulence in the CR precursor) .

- **BN precursor**: W_{IL} ~ 100 km/s (charge exchange in the BN precursor); W_{NL} = const.



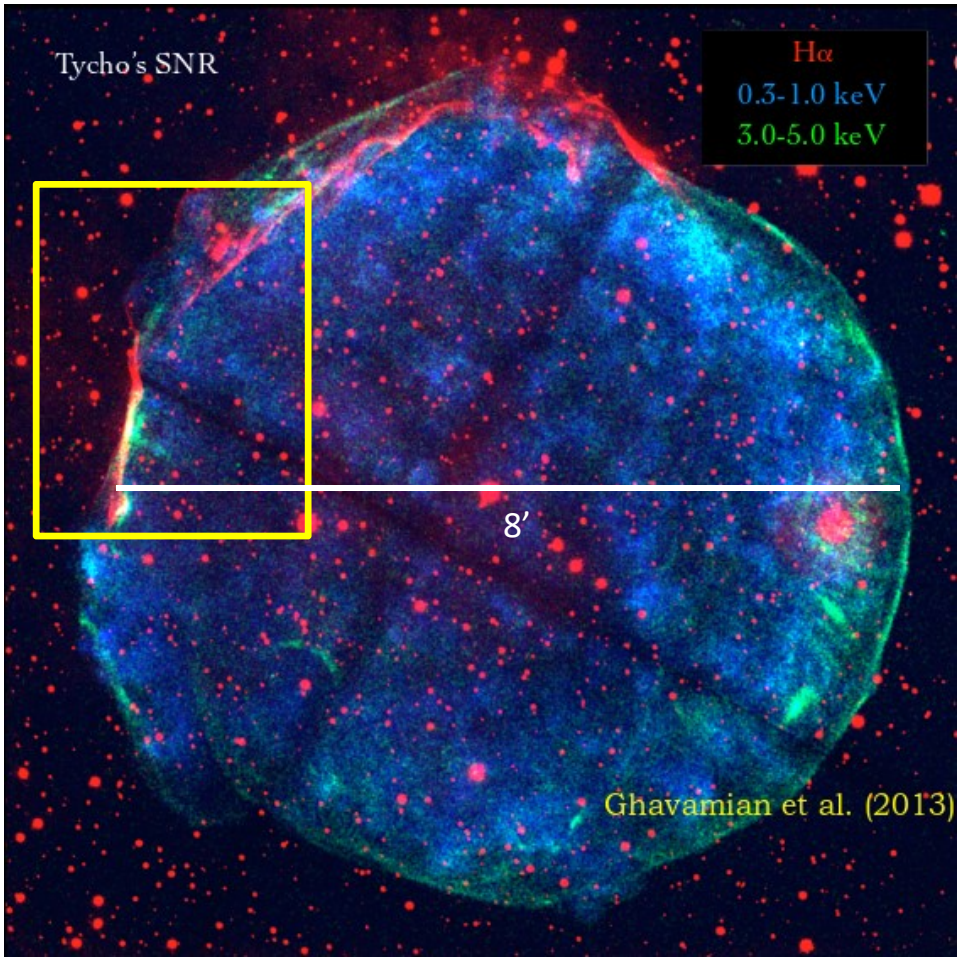


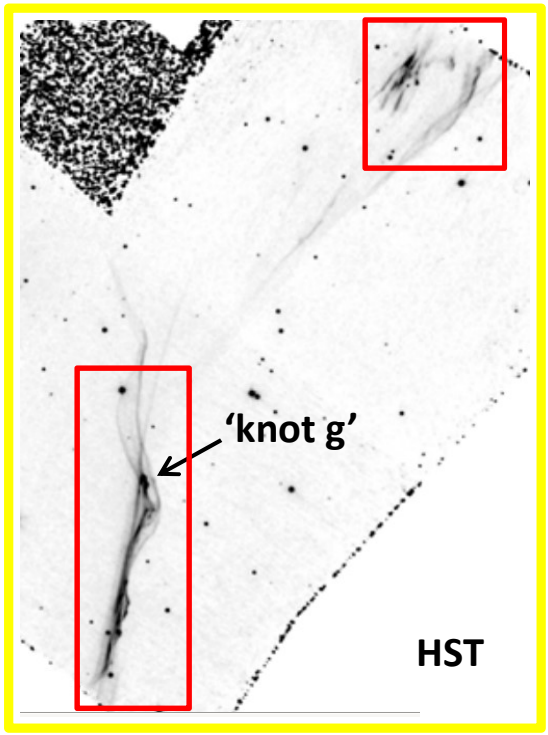
Morlino et al., 2012, ApJ, 760, 137
Morlino et al., 2013, ApJ, 768, 148

$W_{NL} = W_{NL}\ (V_{sh}, T_e/T_p, \varepsilon_{CR}, p_{max}, \eta_{TH})$

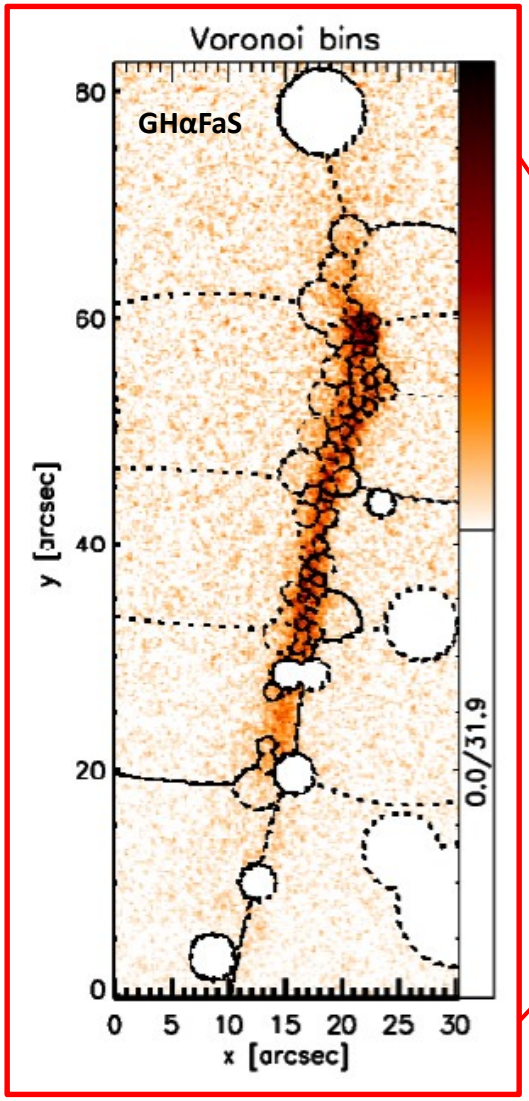
$W_{IL} = W_{IL}\ (V_{sh}, T_e/T_p, \varepsilon_{CR}, \eta_{TH}, f_n)$

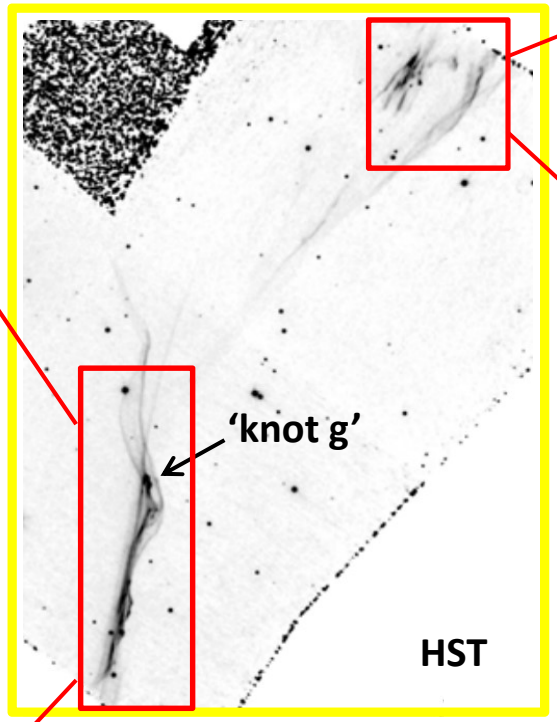
Tycho: Minimizing contribution of projection effects and correction for spatial variation

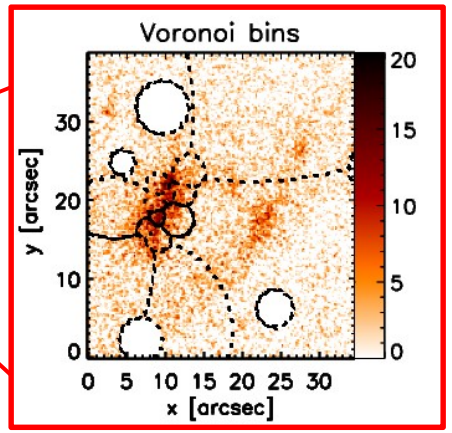




GHαFaS on the WHT (Fabry-Pérot interferometer) observations: 82 spatial-spectral bins







FoV: 3.4'x3.4'
Angular resolution: 1''
Spectral resolution: 8 km/s
Spectral coverage: 400 km/s

Voronoi binning by Capellari & Copin (2003) for S/N≈10: 82 bins
→ **spectro-spatially resolved the 'knot g' and the entire filament.**

Bayesian analysis: parameter estimation & model comparison

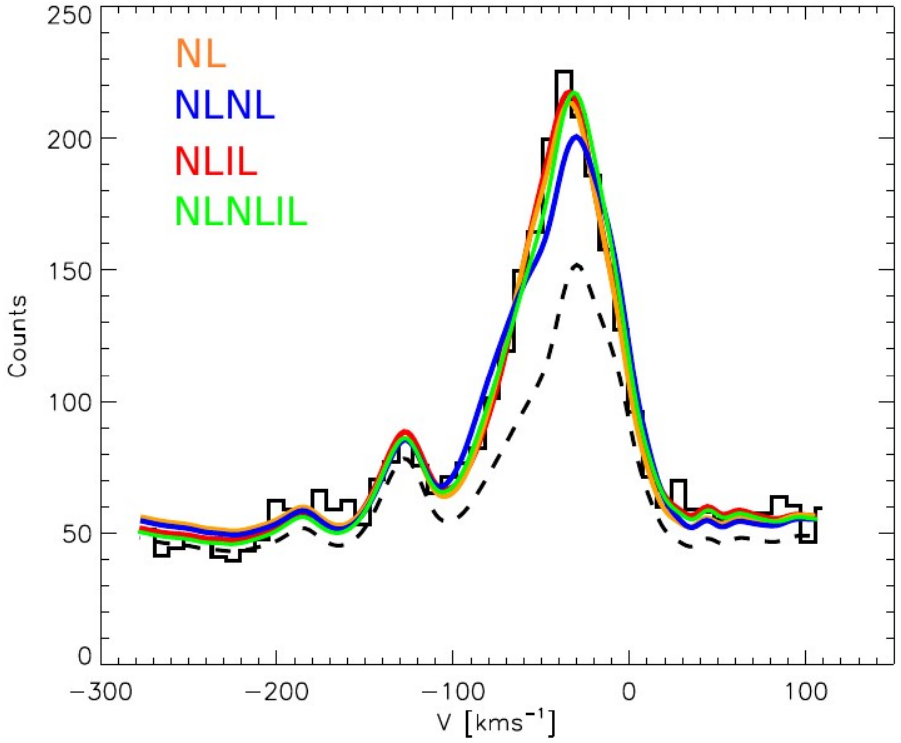
Models (Gaussians + continuum) to account for geometry and physics:

1. **NL** – single narrow line (homogeneous pre-shock medium, no differential bulk velocity components, no precursors);

2. **NLNL** – double narrow line (inclined shocks with CR precursor);

3. **NLIL** – narrow + intermediate line (BN precursor);

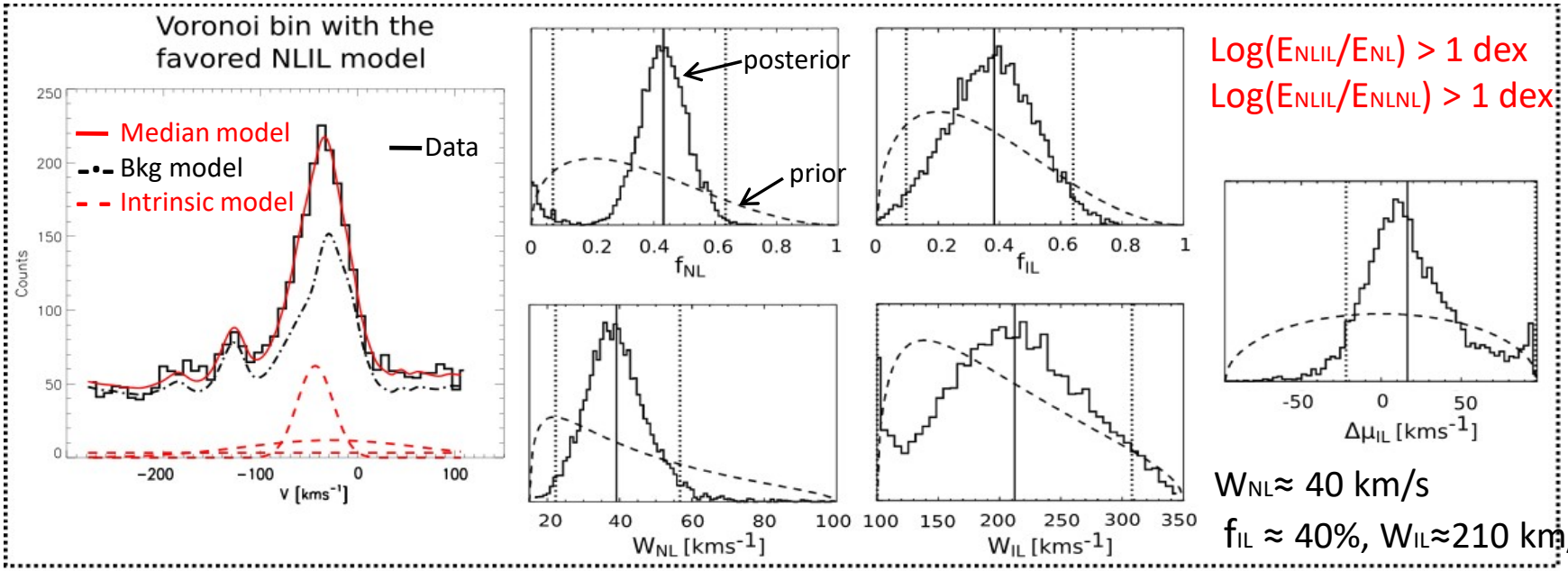
4. **NLNLIL** - double narrow + intermediate line (inclined shocks with CR and BN precursor);



W_{NL} = [15, 100] km/s
W_{IL} = [100, 350] km/s

We use **MCMC** to calculate posterior from data and prior (tested for different priors), and calculate **Bayesian evidences** to compare the models.

1D-marginalized posteriors

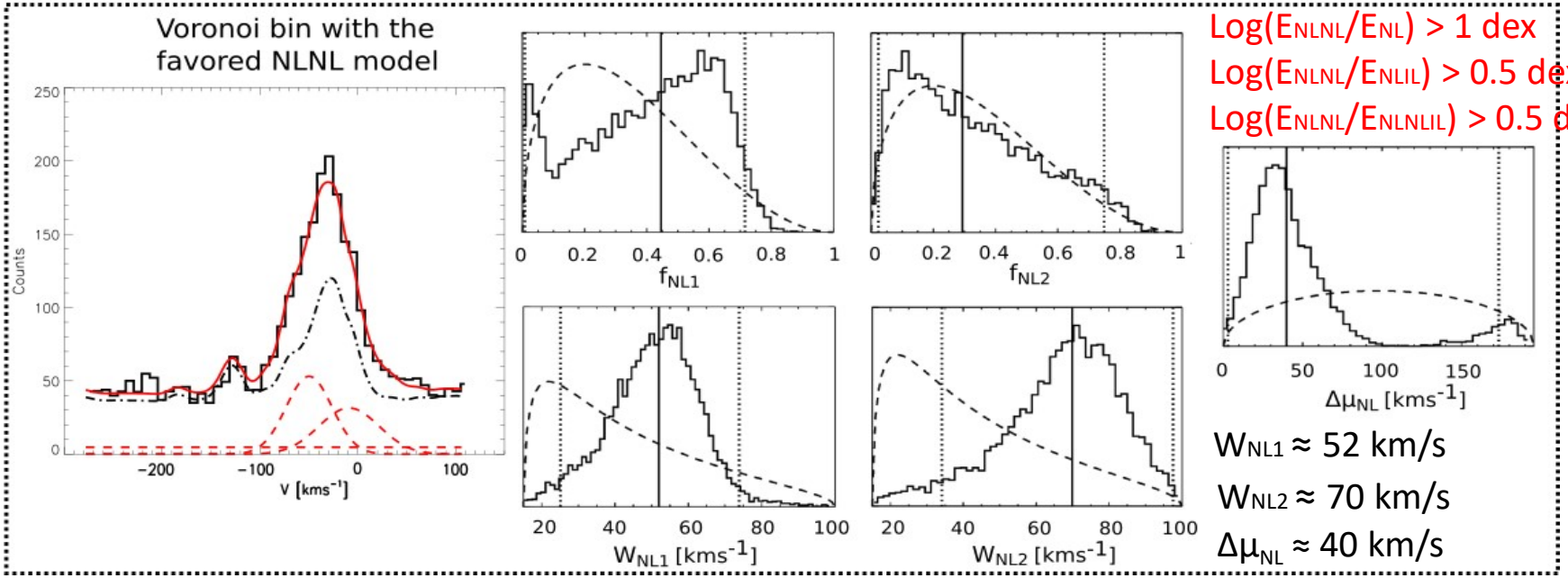


$\mathrm{Log}(E_{NLIL}/E_{NL}) > 1$ dex

$\mathrm{Log}(E_{NLIL}/E_{NLNL}) > 1$ dex

$W_{NL} \approx 40$ km/s

$f_{IL} \approx 40\%$, $W_{IL} \approx 210$ km/s



$\mathrm{Log}(E_{NLNL}/E_{NL}) > 1$ dex

$\mathrm{Log}(E_{NLNL}/E_{NLIL}) > 0.5$ dex

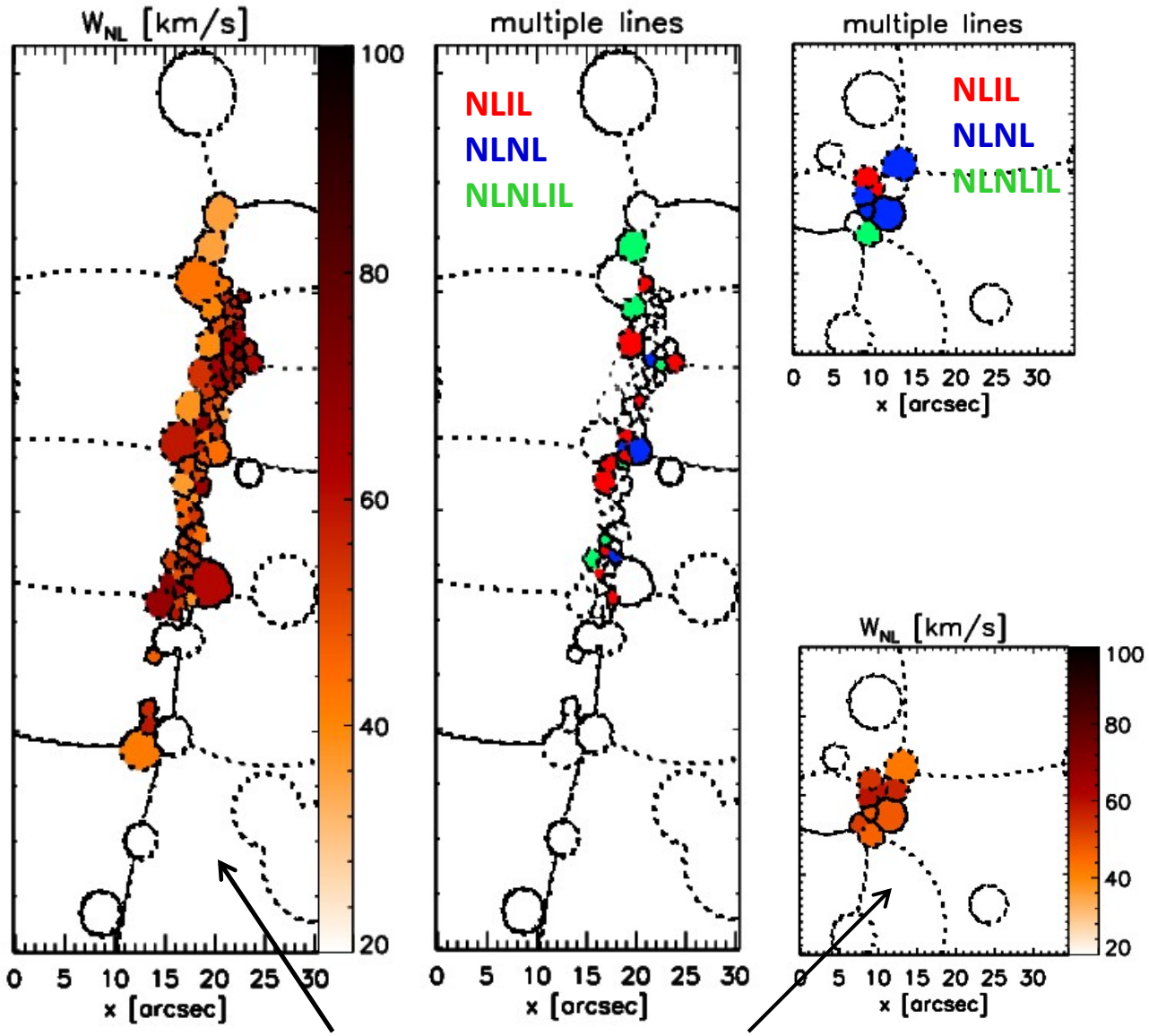
$\mathrm{Log}(E_{NLNL}/E_{NLNLIL}) > 0.5$ dex

$W_{NL1} \approx 52$ km/s

$W_{NL2} \approx 70$ km/s

$\Delta\mu_{NL} \approx 40$ km/s

Spatial variation of W_{NL} and favored models



Median of evidence-weighted 1D posteriors of all models

W_{NL} = 54.8 ± 1.8 km/s
(Cross-bin median)

Double-NL models:

W_{NL} >> 21 km/s

$\Delta\mu_{NL}$ = 38.5 ± 5.1 km/s

IL models:

W_{IL} = 180.5 ± 14.3 km/s

f_{IL} / f_{NL} = 0.41 ± 0.07

Summary

- **Spectro-spatially resolved NL** in the entire projected NE rim including lower-surface brightness parts of the filaments.

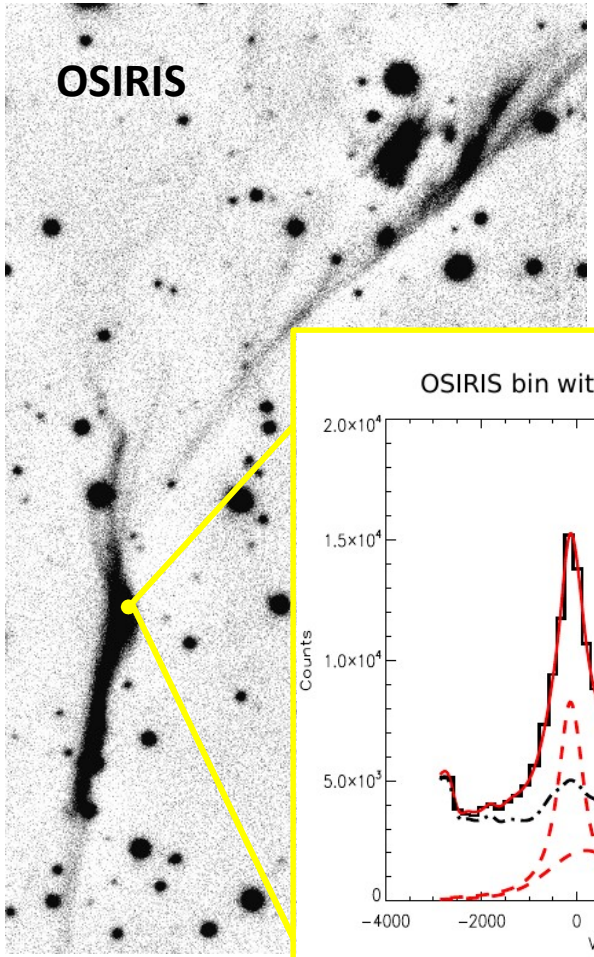
- Parameter estimation and model comparison using **Bayesian inference.**

- Suprathermal NL widths (W_{NL} >> 21 km/s) + NLNL in 18% of the bins (also with W_{NL} >> 21 km/s) → **presence of a CR precursor.**

- 24% of the bins show need for IL → **presence of a BN precursor**.

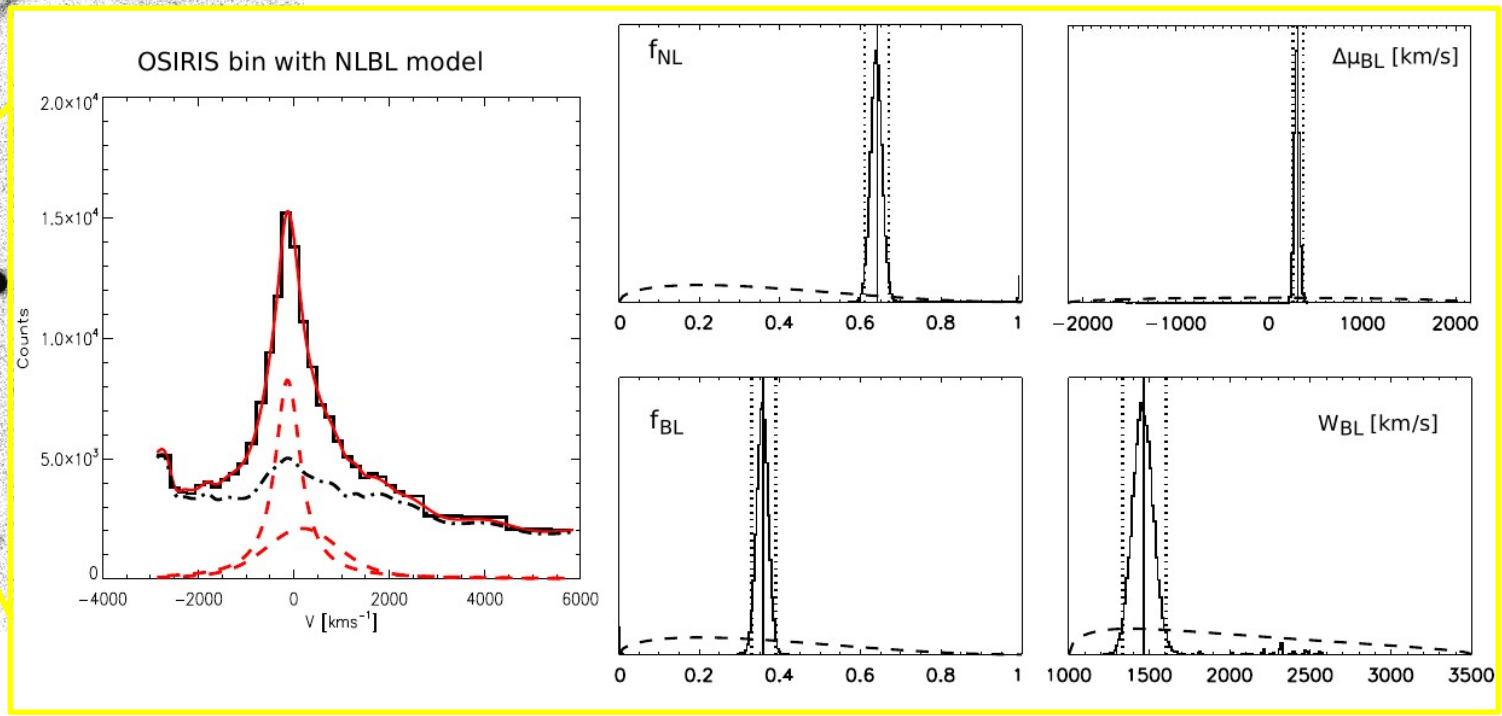
- Assuming $V_{sh} \in$ [2500, 3000] km/s , we get p_{max} > 10 TeV, η_{TH} > 10% , ε_{CR} > 15%.

OSIRIS on the GTC (narrow-band tunable filter) observations of Tycho's SNR



FoV: 4' x 4'
Angular resolution: 1''
Spectral resolution: 300 km/s

$$W_{BL} = W_{BL}(V_{sh}, T_e/T_p, \varepsilon_{CR})$$

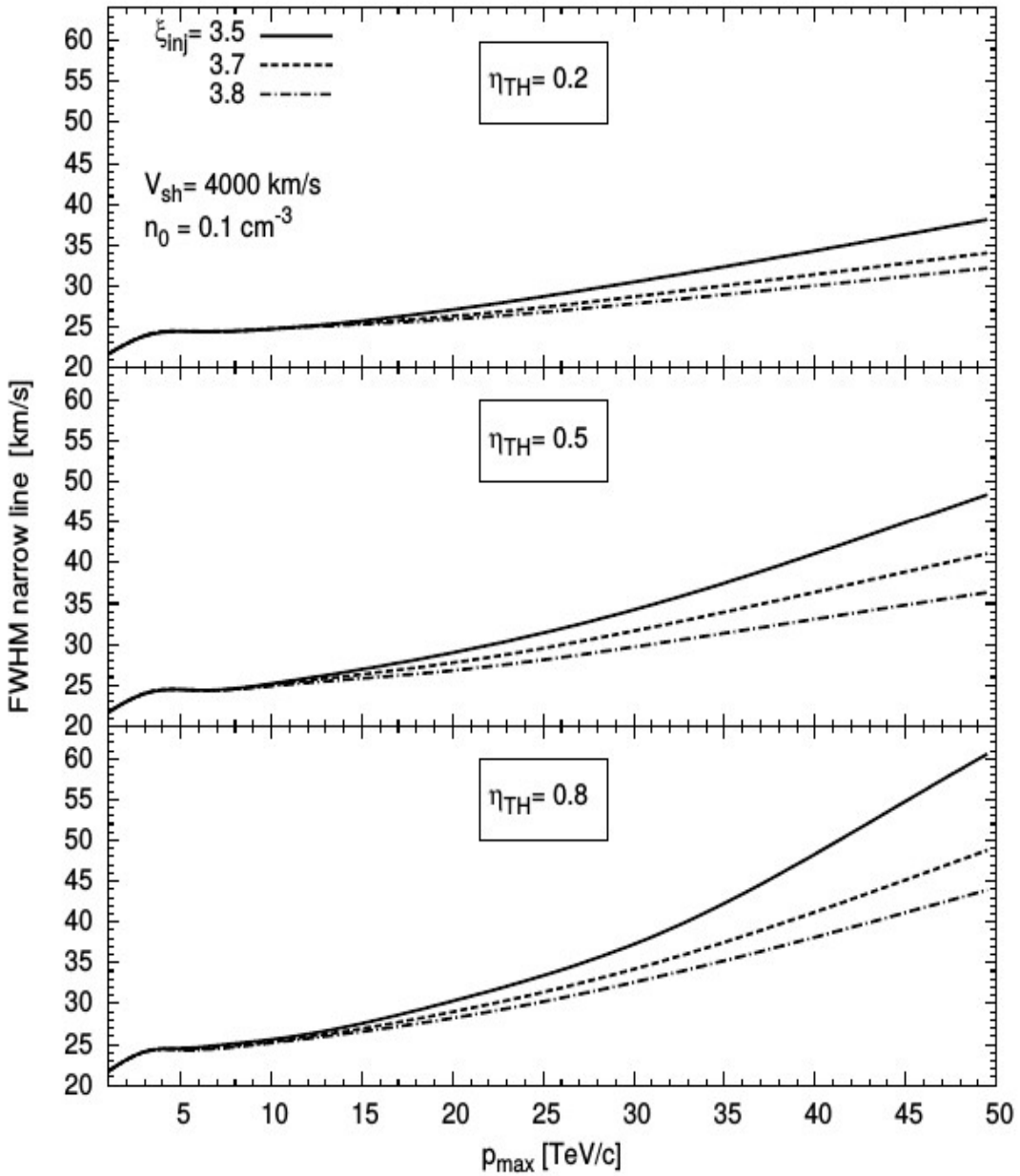


Future

- Include the observations of BL (OSIRIS observations):
  (W_{BL}, I_{BL}/I_{NL}) → (V_{sh} , T_e/T_p);
- Combination with non-thermal X-ray/gamma emission → maximum energy of accelerated particles (p_{max});
- → Rim-mapping of ε_{CR}

THANK YOU FOR YOUR ATTENTION!

Intermediate line (Morlino et al, 2013)



Intermediate line (Morlino et al, 2012)