Studying shock and ambient ISM properties in Balmer-dominated

Sladjana Knežević

(maiden Nikolić)

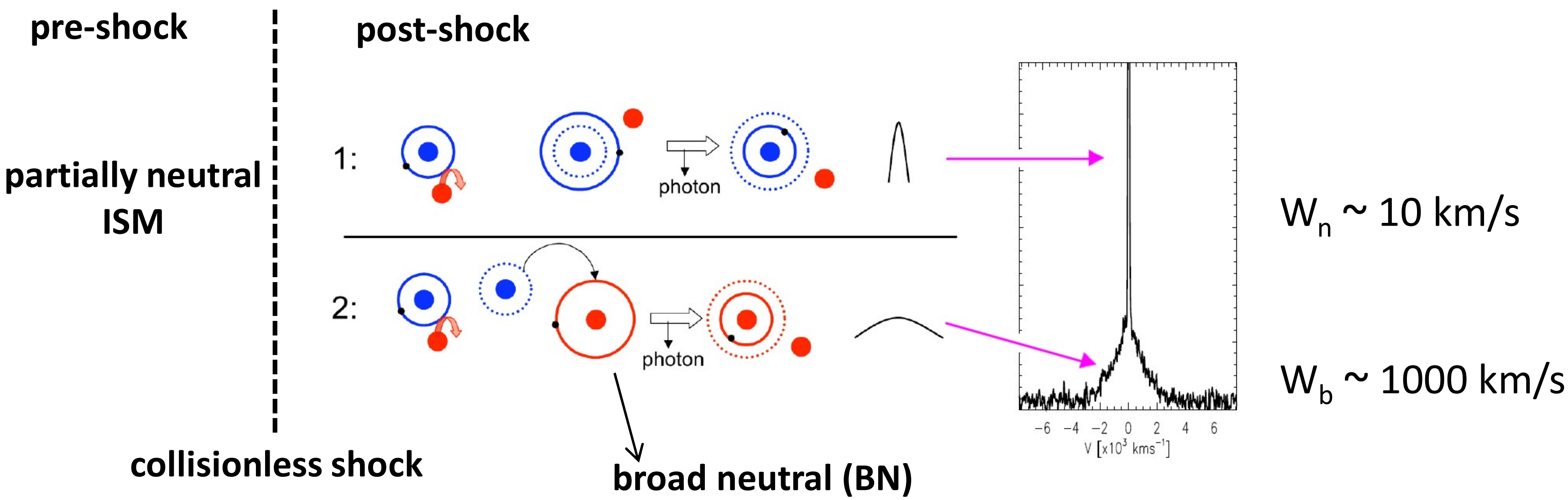
Astronomical Observatory, Belgrade

<u>In collaboration with</u>:

Rino Bandiera, Giovanni Morlino (INAF Arcetri, Italy)
John Raymond (Harvard CfA, USA)
Steve Schulze (Stockholm University, Sweden)

Balmer-dominated shocks (BDSs)

- **Collisionless** (~ 1000 km/s), **non-radiative shocks** propagate in **partially neutral** and diluted **(0.1-1cm^{-3})** medium.
- **Filaments** are sheets of shocked gas seen **edge-on.** Strong hydrogen lines with narrow (~ **10km/s**) and broad (~ **1000 km/s**) components.
- **Absence** or weak presence **of forbidden lines** of lowly ionized metals.



1: The narrow line is produced by excitation of cold hydrogen atoms downstream;

2: The broad line is produced by excitation of hydrogen atoms that have undergone charge exchange with hot protons (broad neutrals).

Studying physical conditions in the shocks

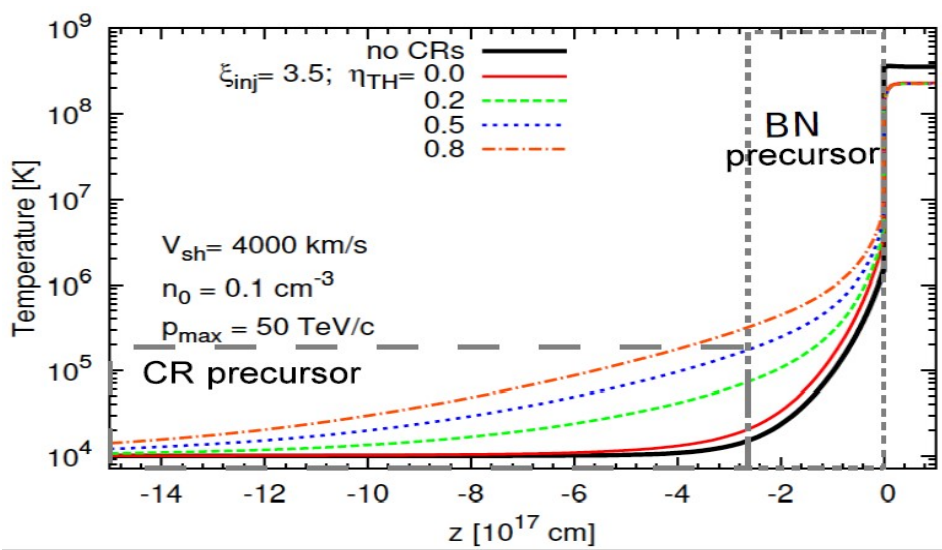
- Each line represented by a Gaussian.

$W_b \sim V_{sh}$ —prop. mot.→ d (distance) —prop. mot.→ V_{sh} → CR acc. eff.

$(W_b, I_b/I_n)$ → T_e/T_p

Hα line profile and widths → shock precursors

Morlino, G., et al., 2013, ApJ, 768, 148



CR precursor: W_b ↓, I_b/I_n ↓, non-Gaussianity

BN precursor: W_b ↓, I_b/I_n ↓, non-Gaussianity

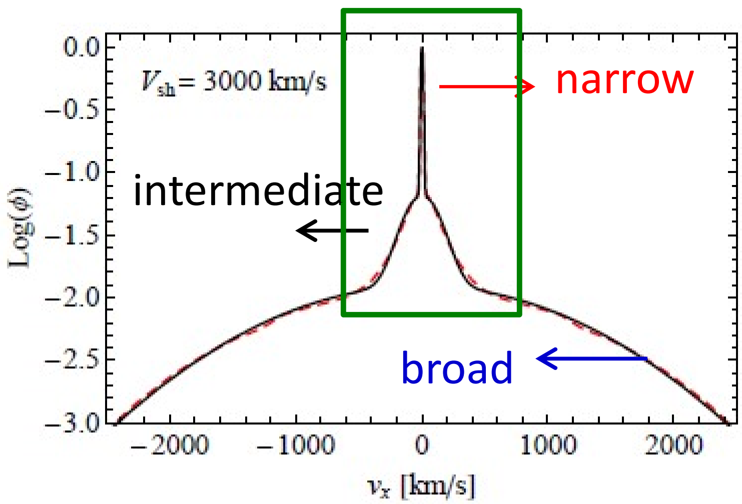
not significant

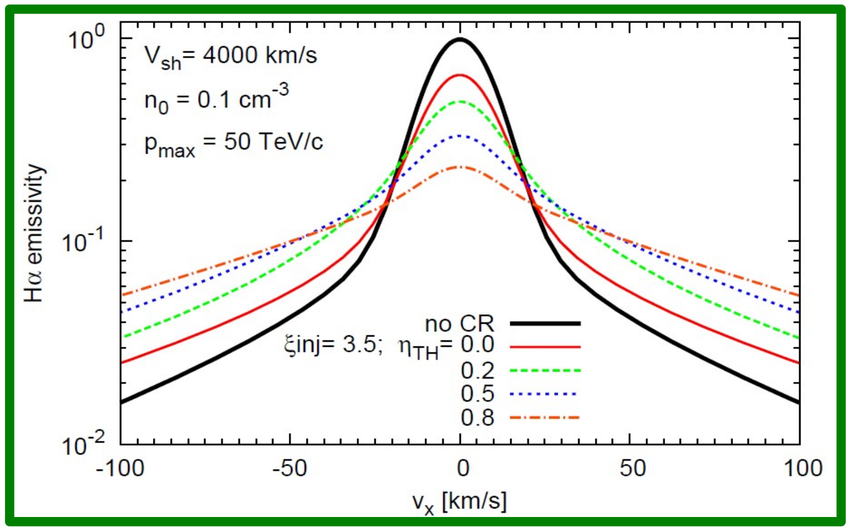
Spectroscopic signatures of precursors

• **CR precursor**: W_n = 21 km/s $(T_0/10^4\ K)^{1/2}$ >> 21 km/s (damping of the magnetic turbulence in the CR precursor) and splitted NL (inclined shocks)

• **BN precursor**: W_i ~ 100 km/s (charge exchange in the BN precursor); W_n = const

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





$W_n = W_n(V_{sh}, T_e/T_p, \varepsilon_{CR}, p_{max}, \eta_{TH})$ $\qquad$ $W_i = W_i(V_{sh}, T_e/T_p, \varepsilon_{CR}, \eta_{TH}, f_n)$

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

Observations of BDSs

- Very faint ~ 10^{-16} $ergs^{-1}cm^{-2}arcsec^{-2}$ –> we need very good instrument efficiency;
- W_b ~ 1000 km/s –> we need a large spectral coverage;
- W_n ~ 10 km/s –> we need high spectral resolution: R ~ 10 000;
- Extended objects (~ 1') –> we need a large FOV;
- Often have a complex structure –> we need high spatial resolution (~ 0.1").

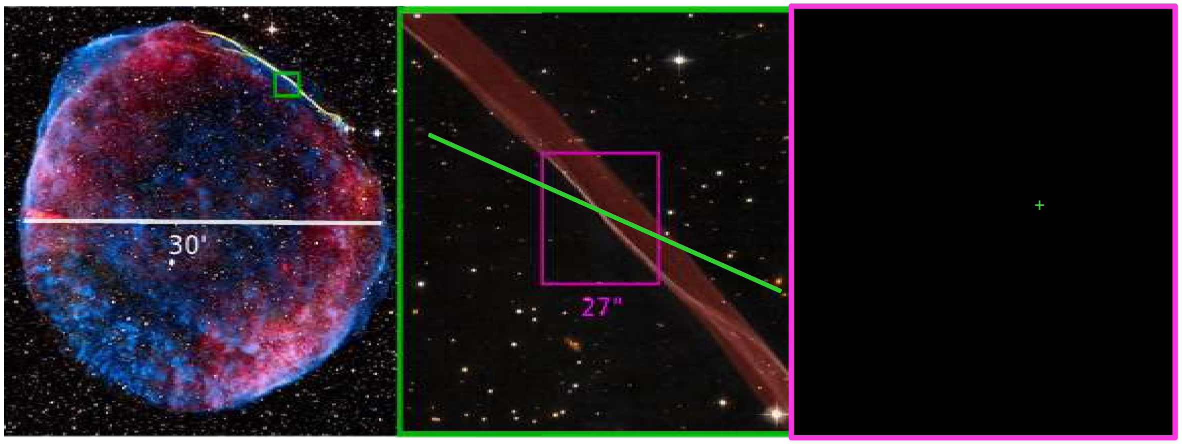
Our research goal:

➢ Minimize shock geometry contribution to the Hα-line profiles using the available instruments/techniques.

➢ Correct for spatial variations in the line parameters and look for a possible physical explanation.

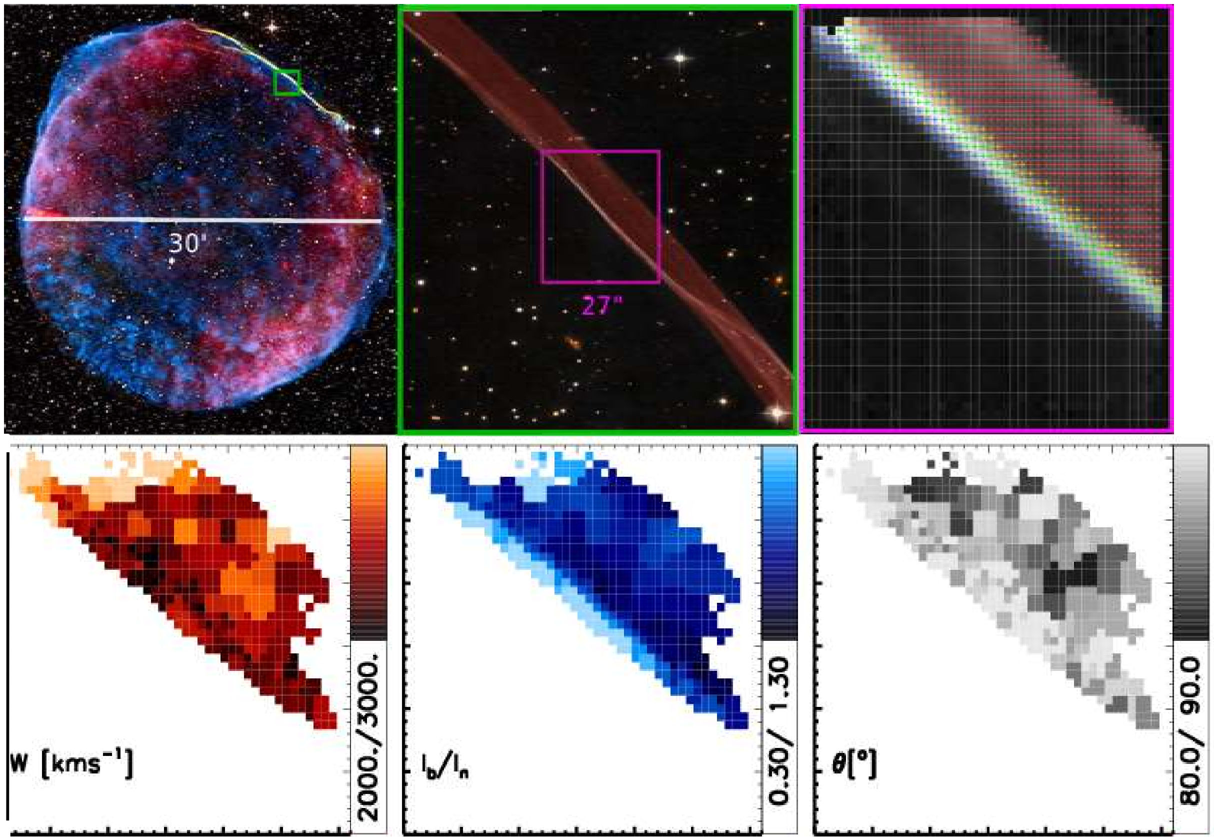
VIMOS-IFU/VLT observations of SN 1006

(Nikolić S. et al., Science, 2013, 340, 45)



SN 1006: spectro-spatially resolved broad line

(Nikolić et al., 2013, Science, 340, 45)



Spatial resolution: 0.66''
1.7x10[16] cm

Spectral resolution: 110 km/s
NL not resolved

Wavelength coverage: 5250-7400Å

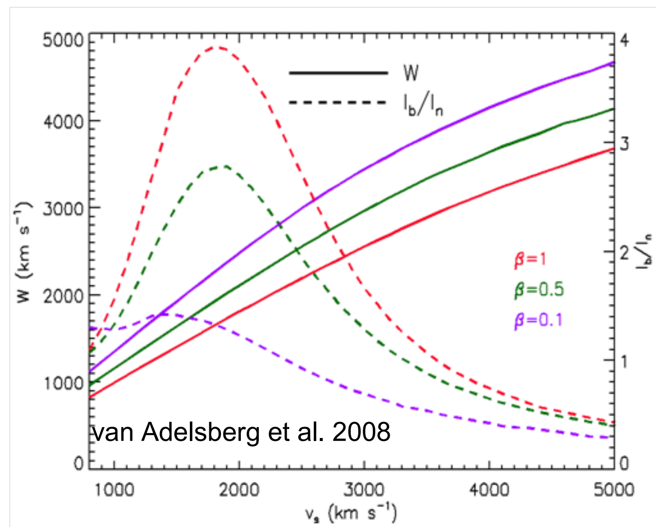
Hα very faint: 6 hours on-source

2000 spaxels → **133 spectral bins**

$\Delta V = \frac{3}{4} V_s \cos\theta$

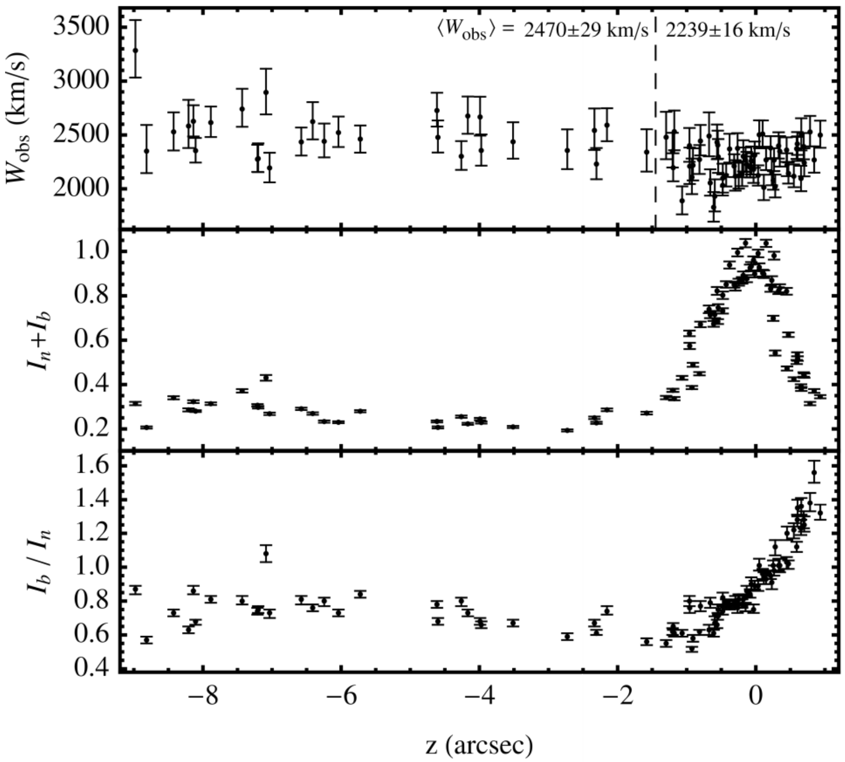
Observed: W_b, I_b/I_n, ΔV ⇨ Derived: V_s, $\beta \equiv T_e/T_p$
(van Adelsberg et al. model 2008)

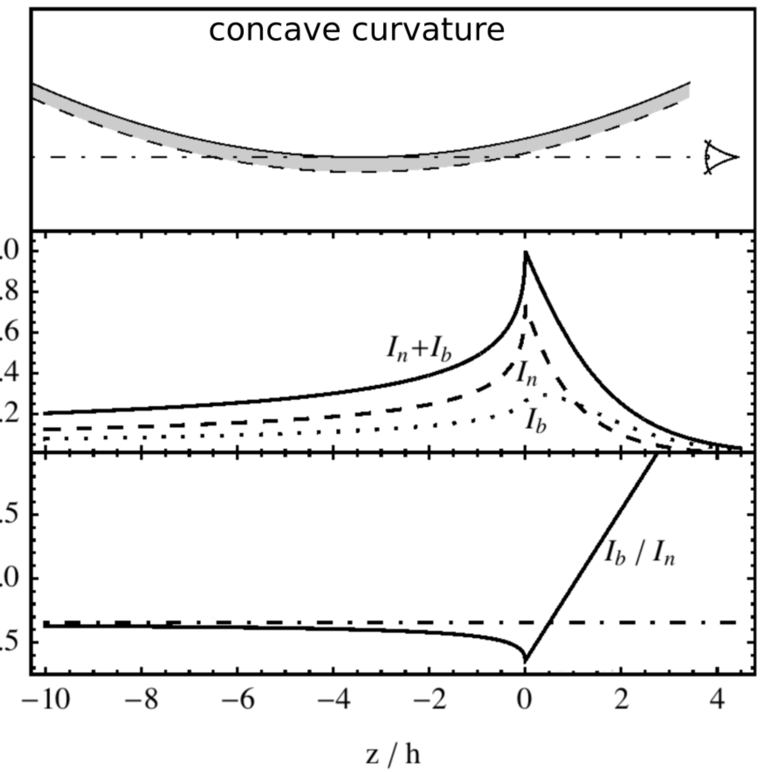
➢ 85% of the bins are not accounted for by the model without precursors.



SN 1006: physics or geometry

(Bandiera et al., 2019, MNRAS, 483, 1537)



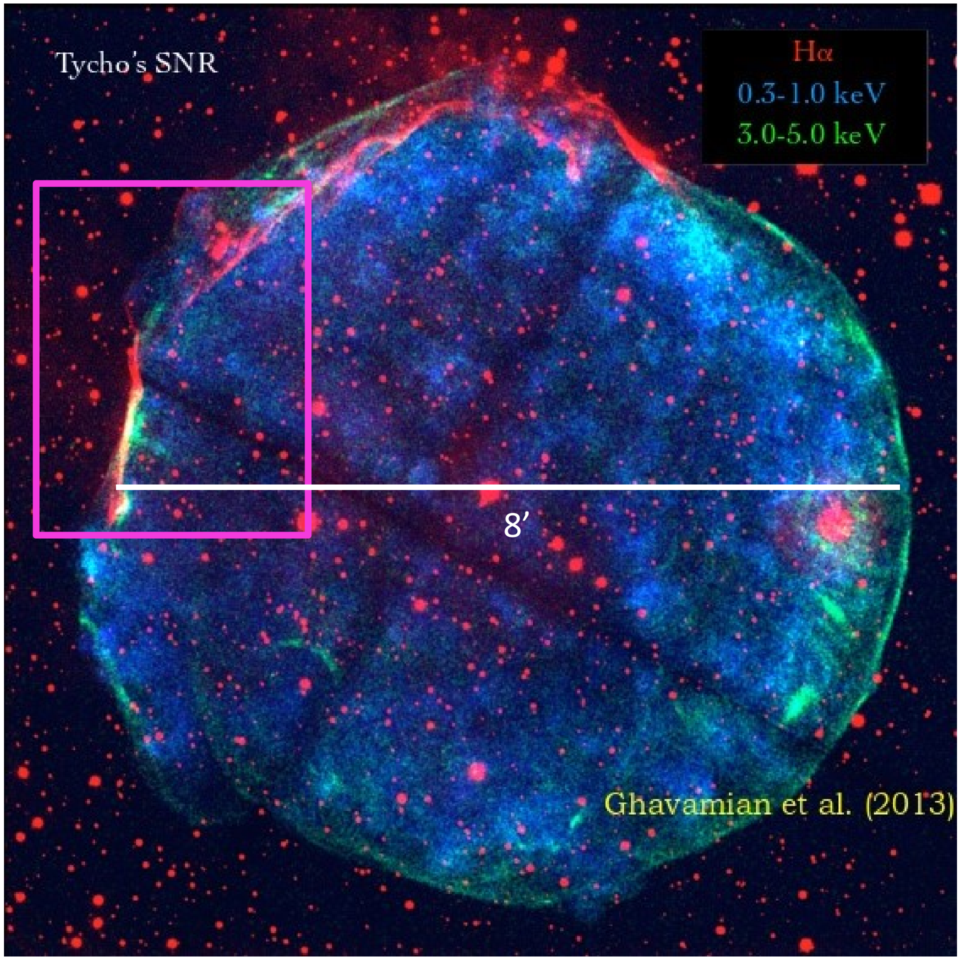


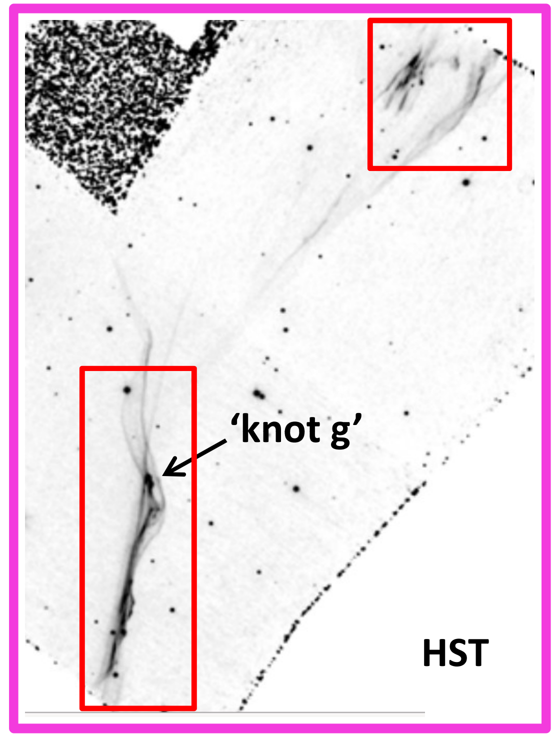
The type of bending of the shock surface may affect the observed spatial profile of: I_b+I_n, I_b/I_n, W_b, ΔV.

Concave curvature with ripples (multiple shock intersection along the LOS).
Evidence of the presence of ambient density variations over ~ 0.1 pc.

Tycho's SNR: spectro-spatially resolved narrow line

(Knežević et al, 2017, ApJ, 846, 167)





GHαFaS on the WHT (Fabry-Pérot):

FoV: 3.4'x3.4'

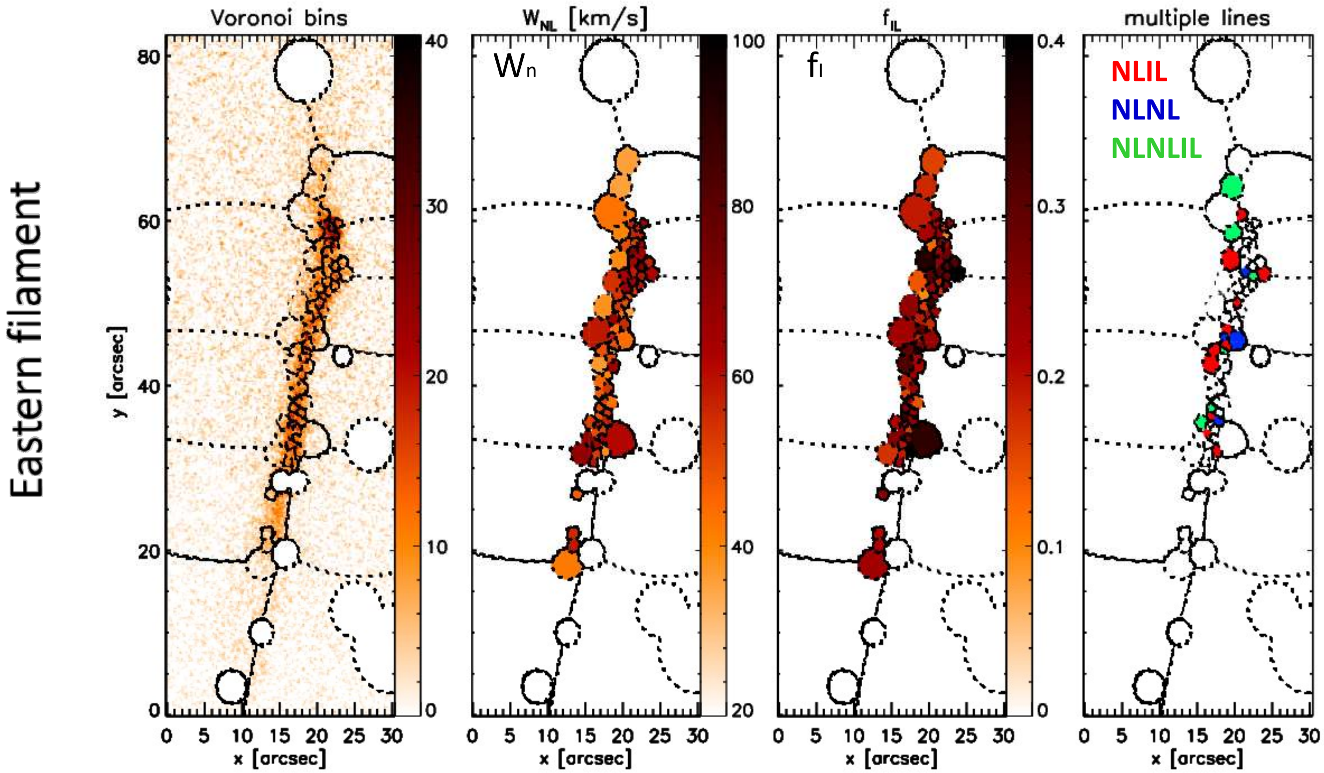
Spatial sampling: 0.2"; angular resolution: 1"

Spectral resolution: 19 km/s

Spectral coverage: 400 km/s

BL not resolved

Tycho's SNR: evidence for CR and BN precursor



9.6 h on-source

82 Voronoi bins with S/N≈10 (Capellari & Copin 2003)

$W_n \in [35,72]$ km/s

↓

Varying amount of neutrals.

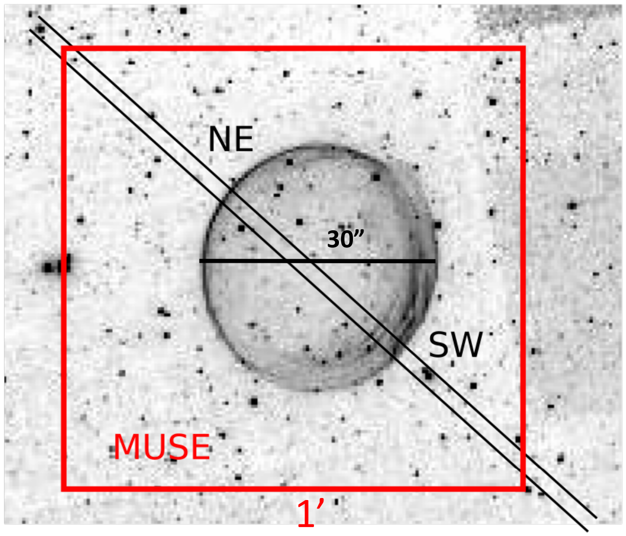
- **Spectro-spatially resolved the 'knot g' and the entire filament.**
  Bayesian analysis: parameter estimation & model comparison.

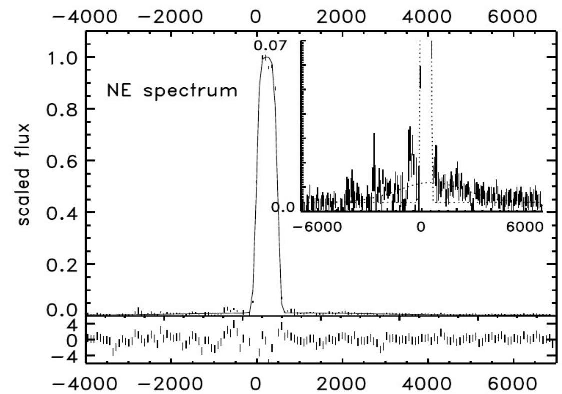
- Suprathermal NL widths ($W_n \approx 55$ km/s) + NLNL in 18% of the bins ($W_n \approx 49$ km/s, $\Delta V \approx 38$ km/s)
  → **presence of a CR precursor.**

- Need for additional (intermediate) component (Bayes factor): 24% of the bins with $W_i \approx 185$ km/s and $f_i/f_n \approx 0.4$ on average → **presence of a BN precursor**.

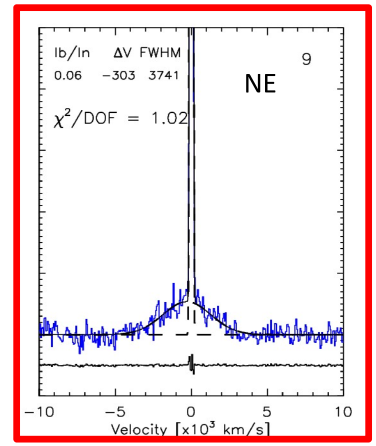
SNR0509-67.5: MUSE/VLT WFM observations

(Knežević et al, 2021, Publ. Astron. Obs. Belgrade , 100, 267)



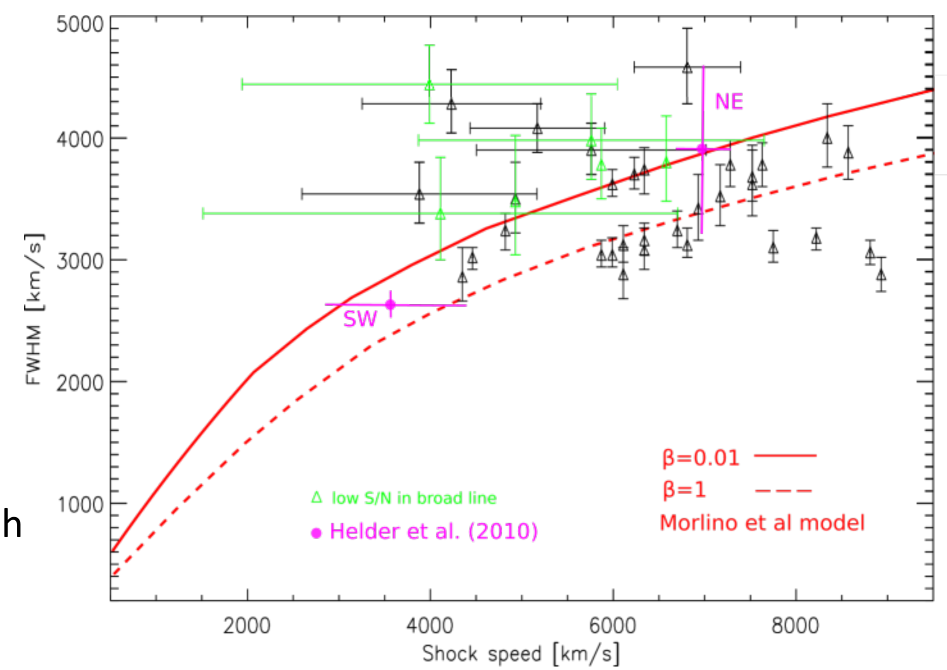


Helder et al., 2010, ApJL, 719, L140

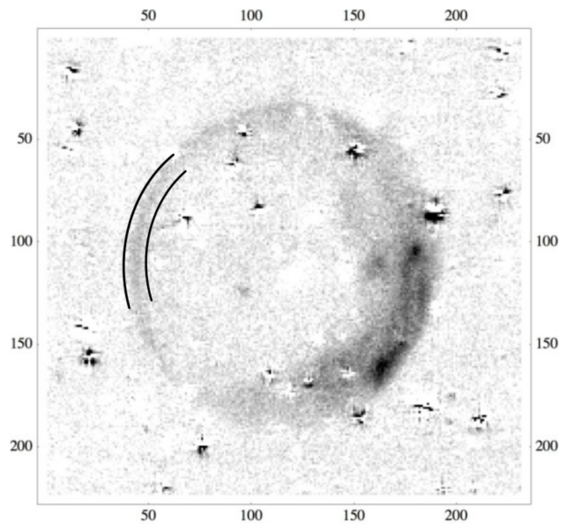


Knežević et al. 2021

- 3h on-source
- Spatial sampling: 0.2”; angular resolution: 1”.
- Spectral resolution: 110 km/s
  NL not resolved
- Wavelength coverage: 4750 - 9350Å
- Best candidate to study CRs: known distance with measured proper motions gives shock speed.

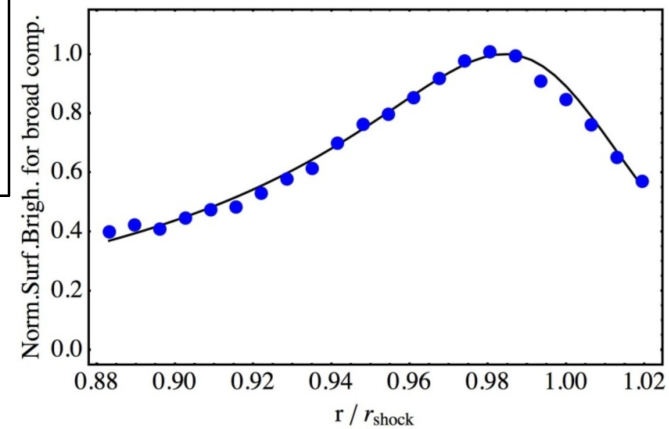


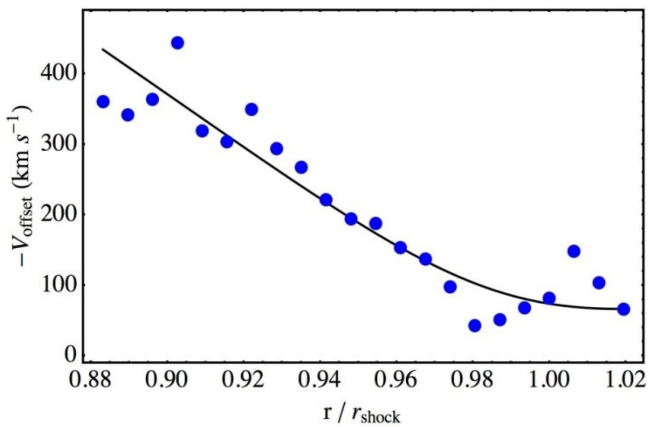
SNR0509-67.5: Geometry of the NE rim

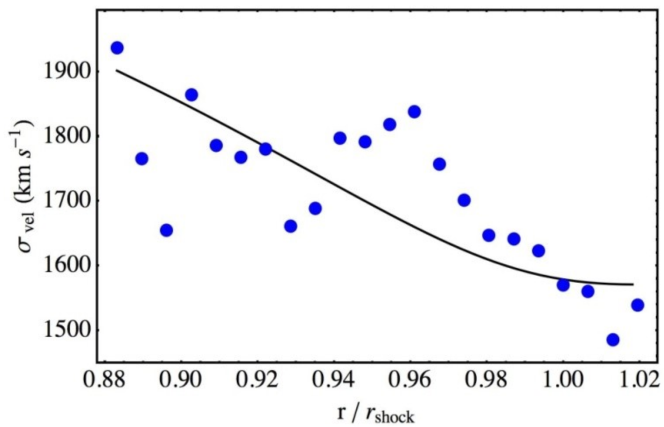


Pixel selection
along circular arcs

P.A. = {45°,105°}
Rad = {13.6",15.7"}
Radial width ≅ 0.2"







Courtesy of Rino Bandiera

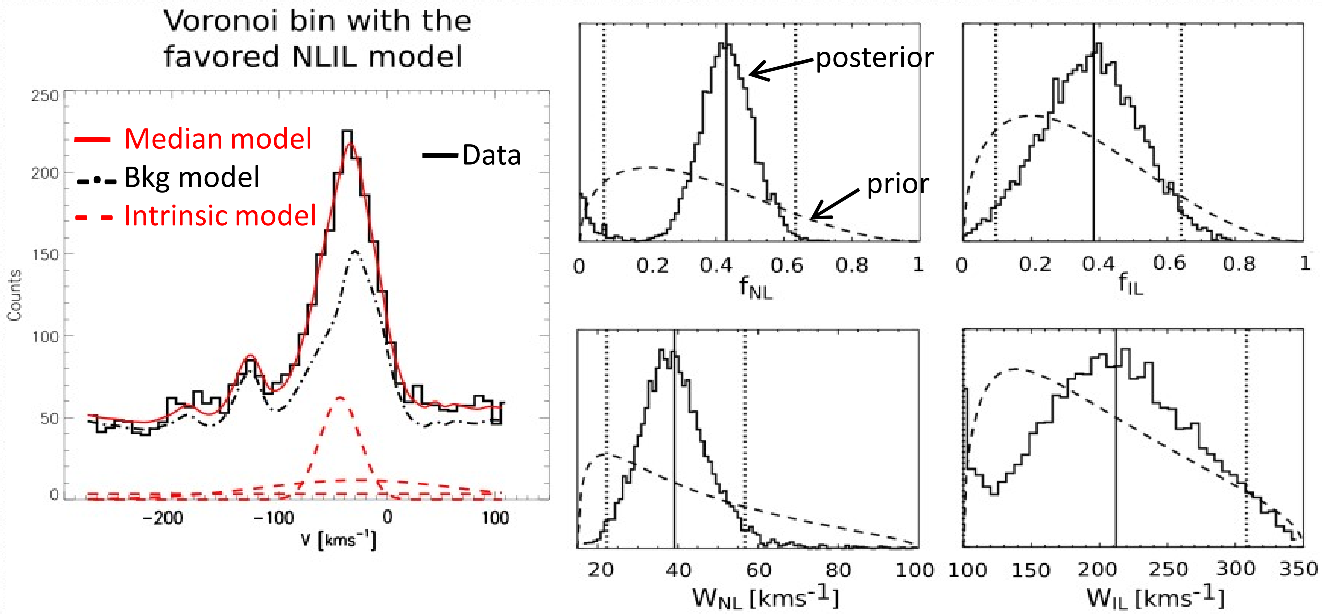
Best-fit model: $r_{sh} \cong 15.4$ arcsec; $\sigma_{vel} \cong 1500$ km s^{-1};$V_{bulk} \cong 3000$ km s^{-1}
$grad_{skyplane} \cong +6.5\ r_{sh}^{-1}$;$grad_{LOS} \cong -0.85\ r_{sh}^{-1}$

Summary

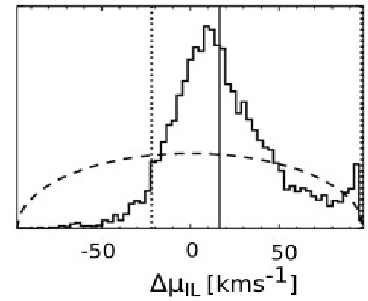
- Balmer-dominated shocks are an important diagnostic tool for shock parameters.
- Apart from pion-decay gamma emission, Balmer emission can also trace CR *protons*.
- We showed the importance to disentangle geometrical effects from the shock dynamics.
- Our data allow distinguishing between different shock models.
- We find evidences for CR and broad-neutral precursors in the Galactic SNR of Tycho, and CR efficient acceleration in the SNR 0509-67.5 remnant in the LMC.

Thank you for your attention.

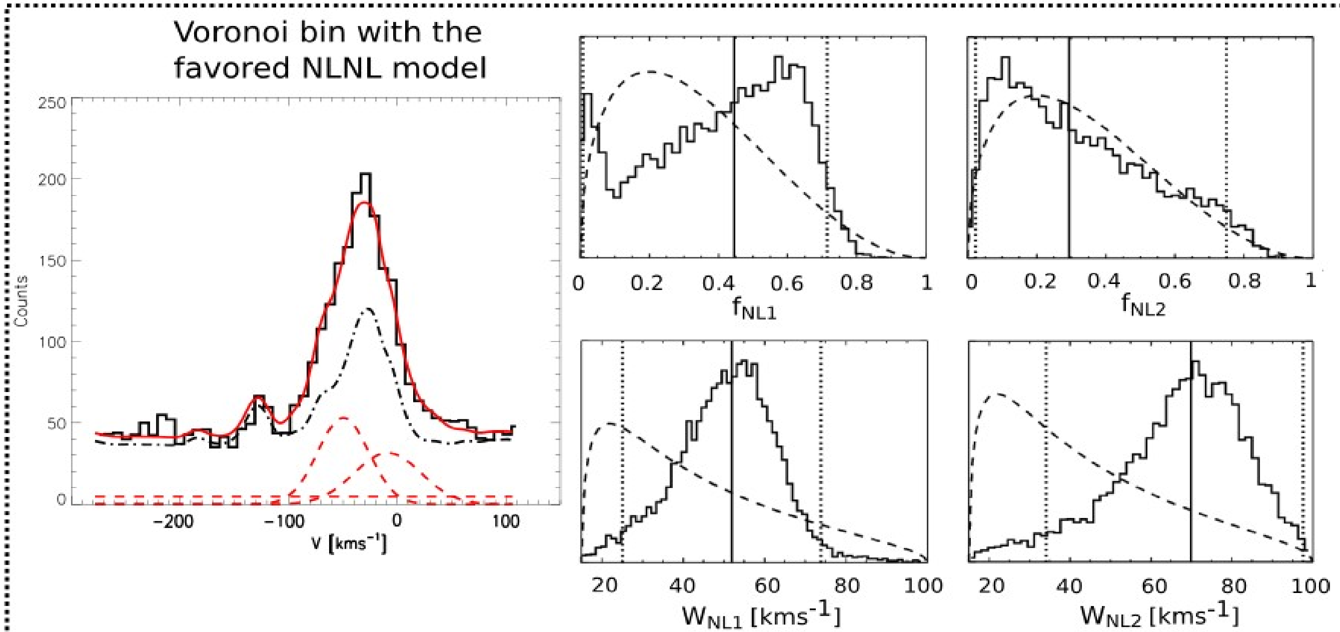
1D-marginalized posteriors



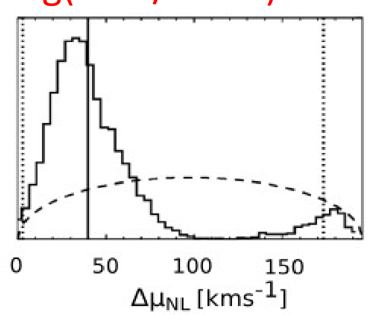
$Log(E_{NLIL}/E_{NL}) > 1$ dex
$Log(E_{NLIL}/E_{NLNL}) > 1$ dex



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

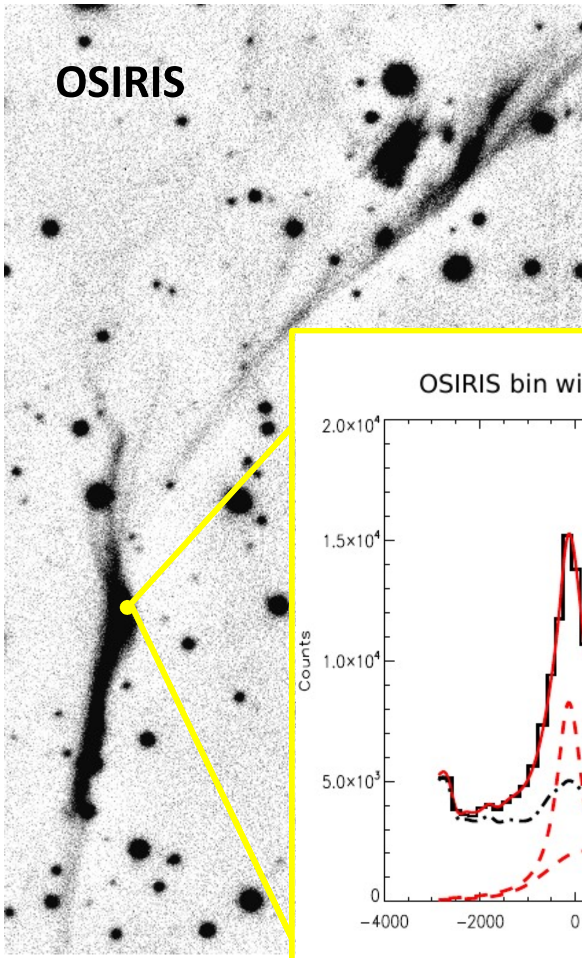


$Log(E_{NLNL}/E_{NL}) > 1$ dex
$Log(E_{NLNL}/E_{NLIL}) > 0.5$ dex
$Log(E_{NLNL}/E_{NLNLIL}) > 0.5$ dex



$W_{NL1} \approx 52$ km/s
$W_{NL2} \approx 70$ km/s
$\Delta\mu_{NL} \approx 40$ km/s

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

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