Rings of Metal-Rich Ejecta in Puppis A: Hints of a SN Interaction in a Binary?

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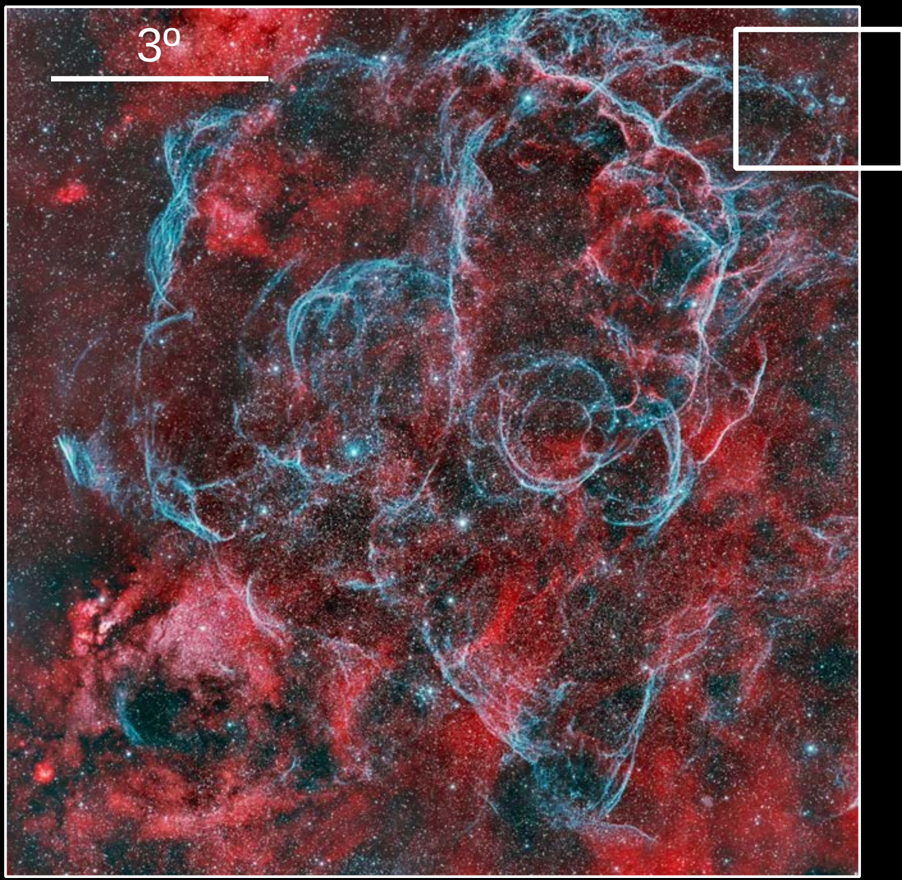
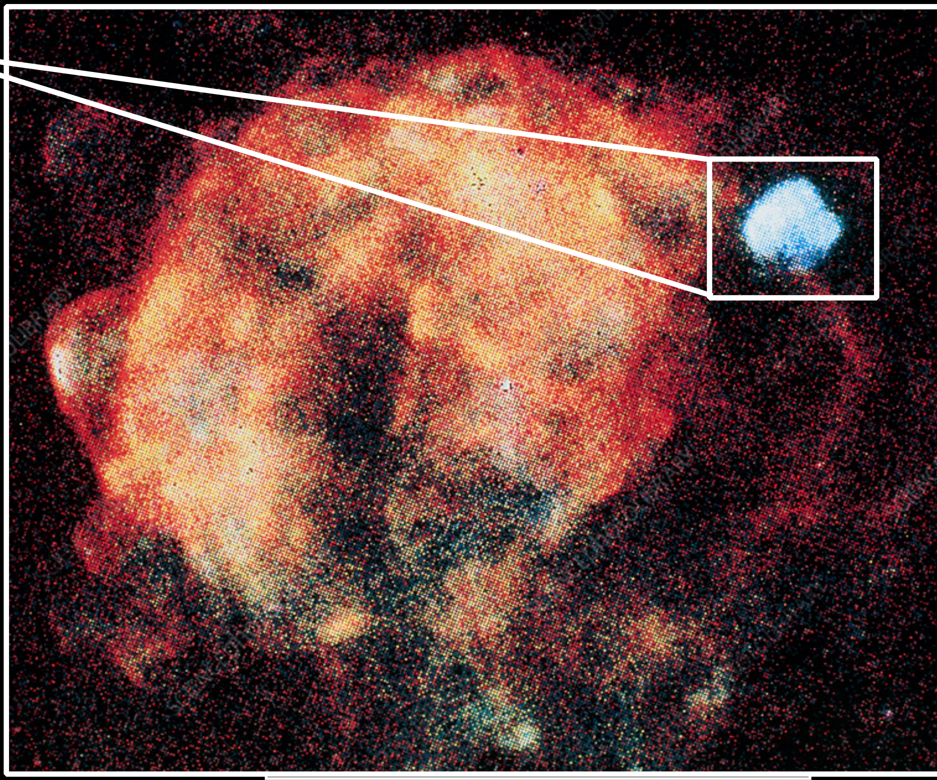
M. A. Dopita (1946-2018)

Puppis A is Nested Within the Vela SNR

Ha [O III]

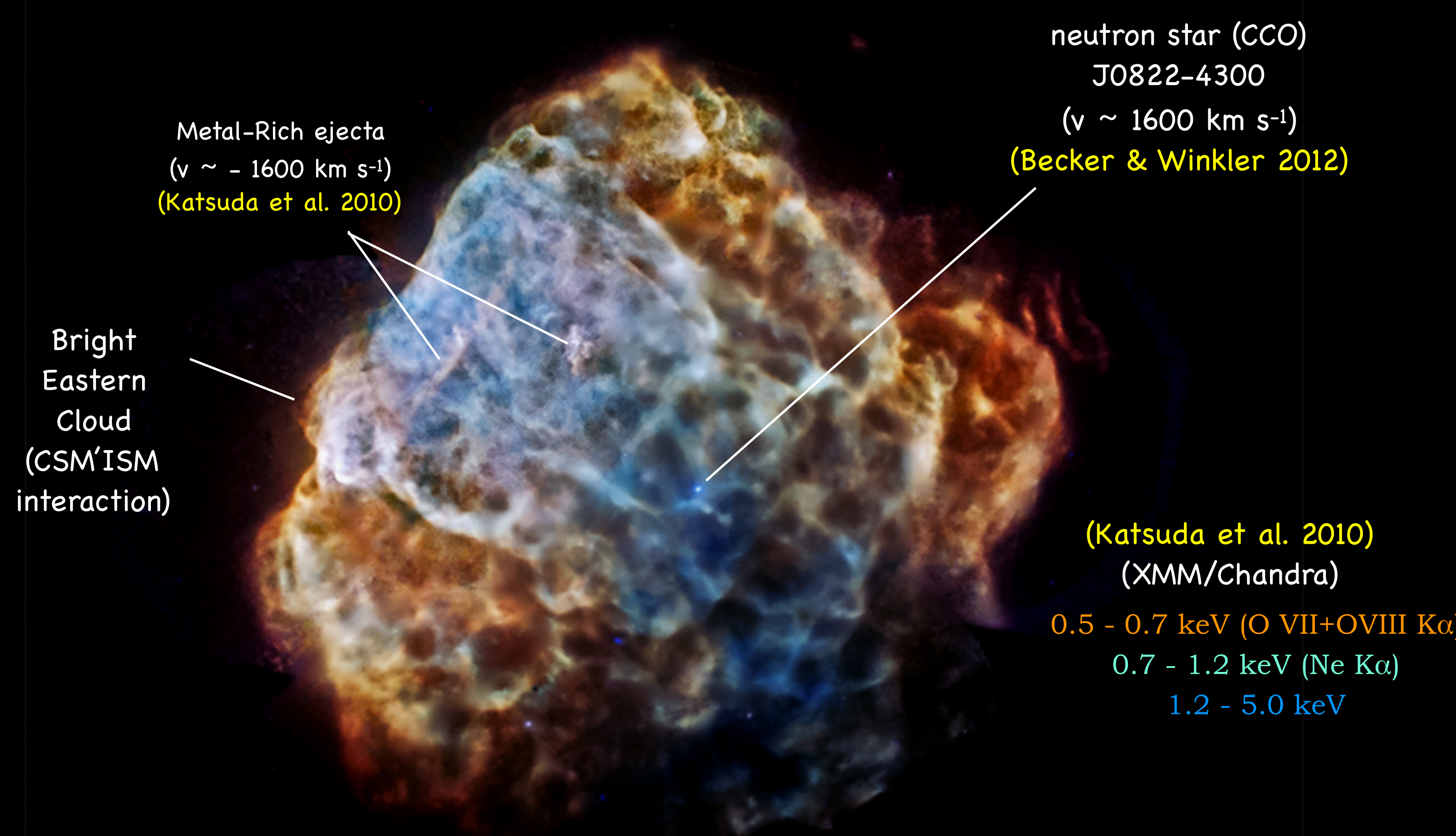


Vela: D = 250 pc
(Cha et al. 1995)



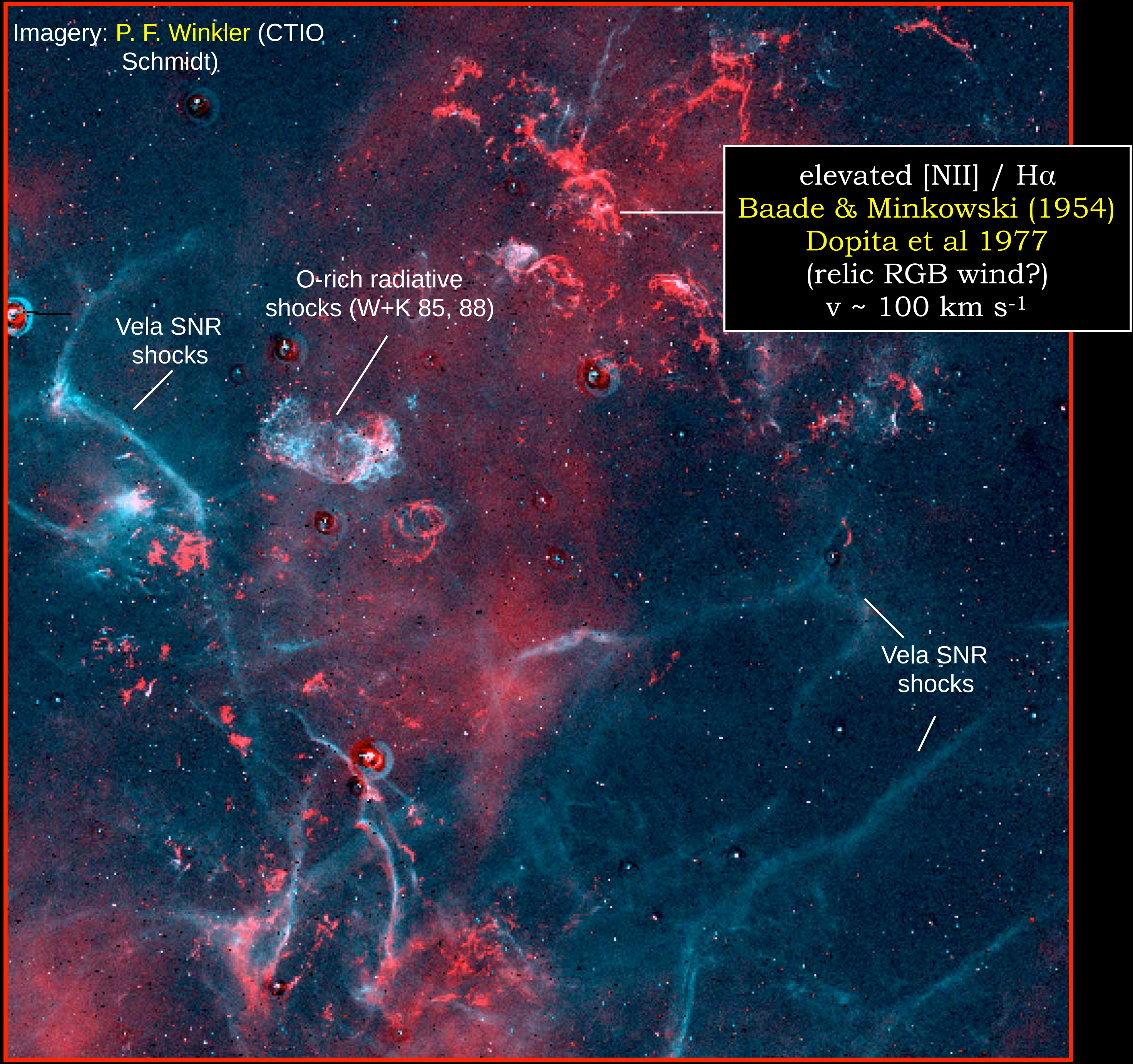
ROSAT HRI (Aschenbach 1995)

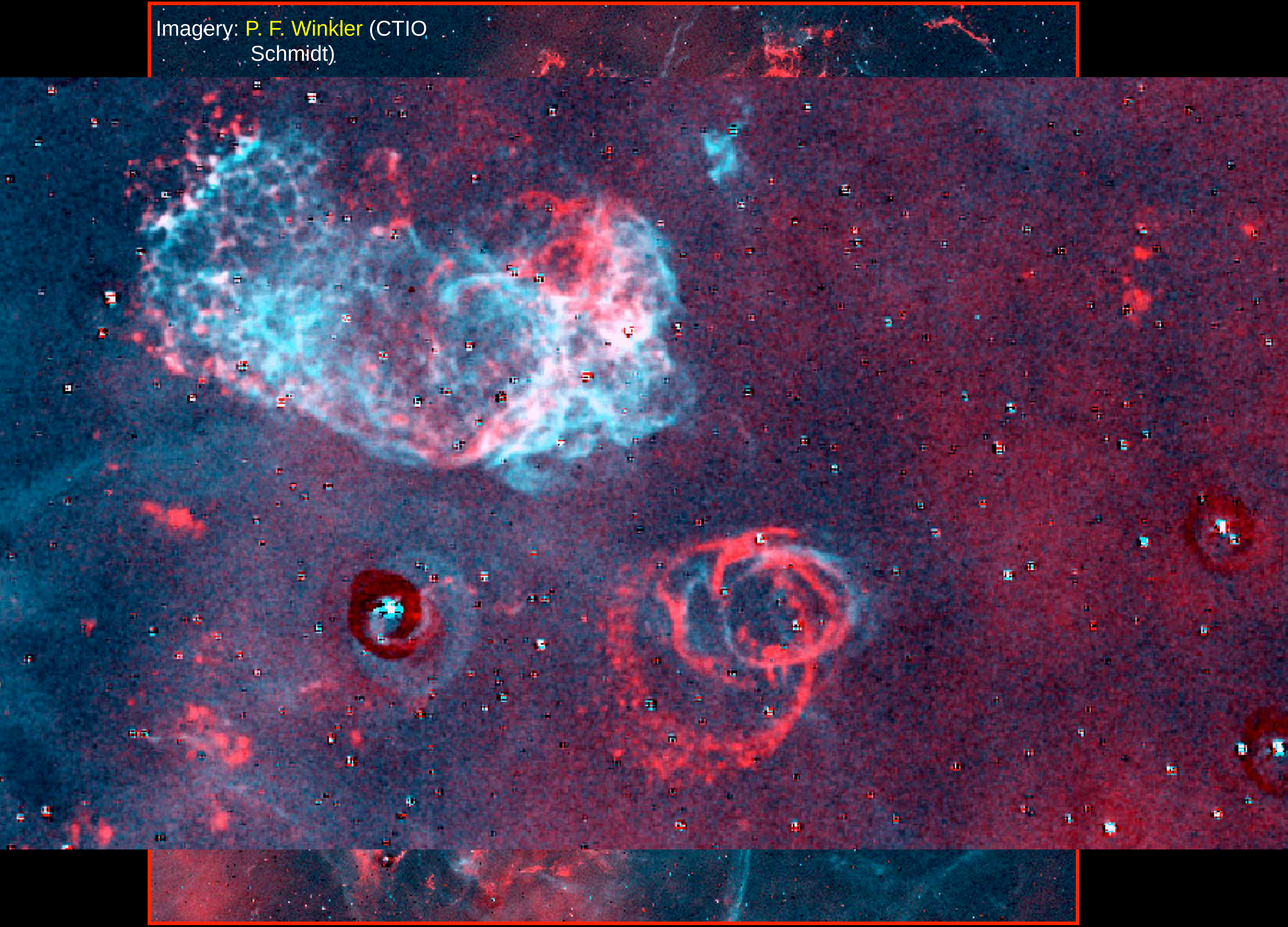
Puppis A is a Middle-Aged SNR



- Age ~ 3700 yrs (optical; Winkler & Kirshner 1988) - 4400 yrs (X-rays)
- Strong interaction w/H I and CO clouds on eastern side (Dubner 1988; Reynoso et al 1995; Blair et al. 1995)
- R ~ 25′ (~ 16 pc assuming D = 2.2 kpc)
- Si-rich (Hwang et al. 2008) and O/Ne/Mg-rich X-ray ejecta (Katsuda et al. 2008; 2010)
- Progenitor mass ~ 25 $M_\odot$ inferred from abundance ratios (Katsuda et al. 2010)

Hα
[O III]


Imagery: P. F. Winkler (CTIO Schmidt)
elevated [NII] / Hα
Baade & Minkowski (1954)
Dopita et al 1977
(relic RGB wind?)
v ~ 100 km s-1
O-rich radiative shocks (W+K 85, 88)
Vela SNR shocks
Vela SNR shocks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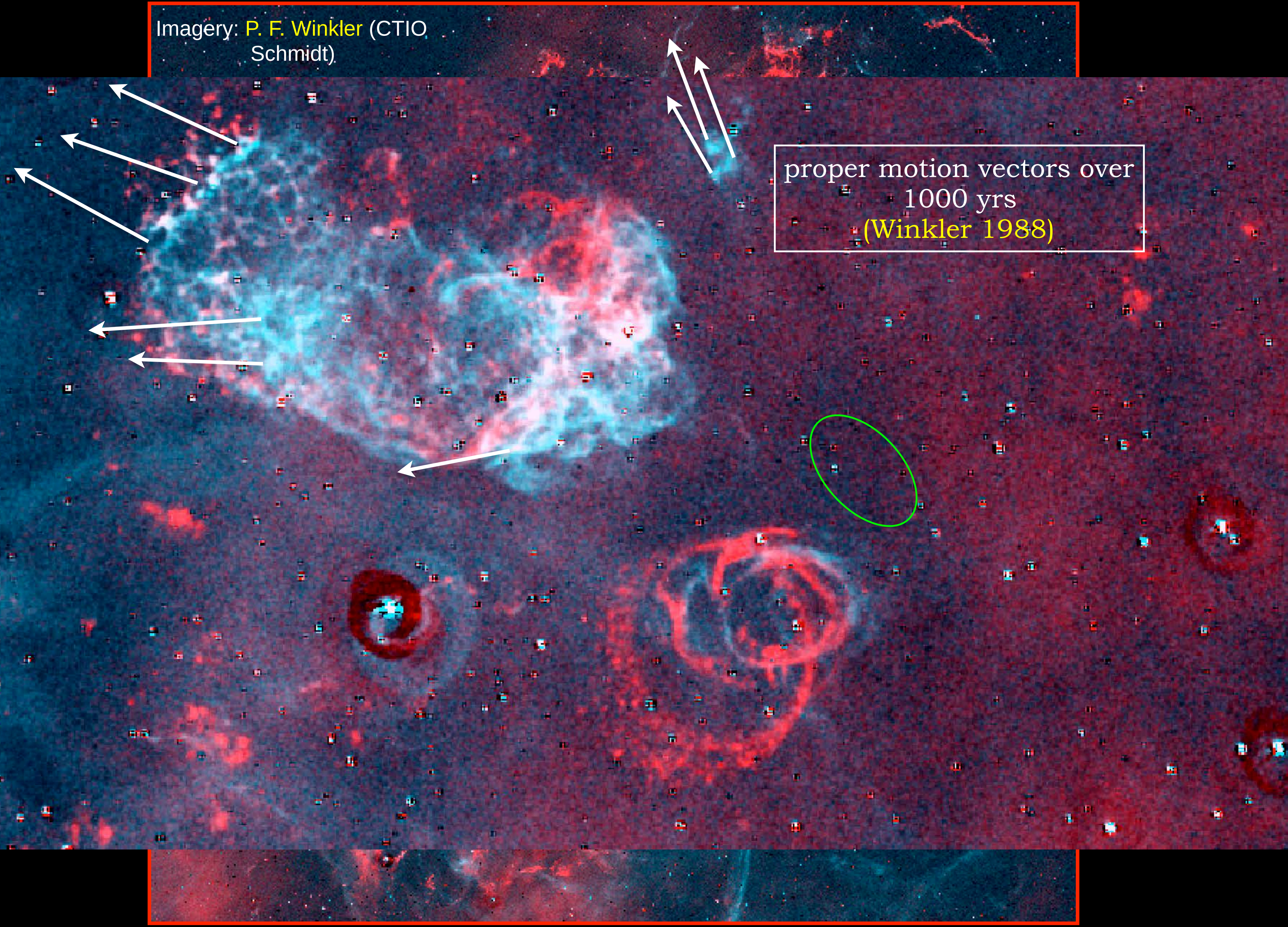
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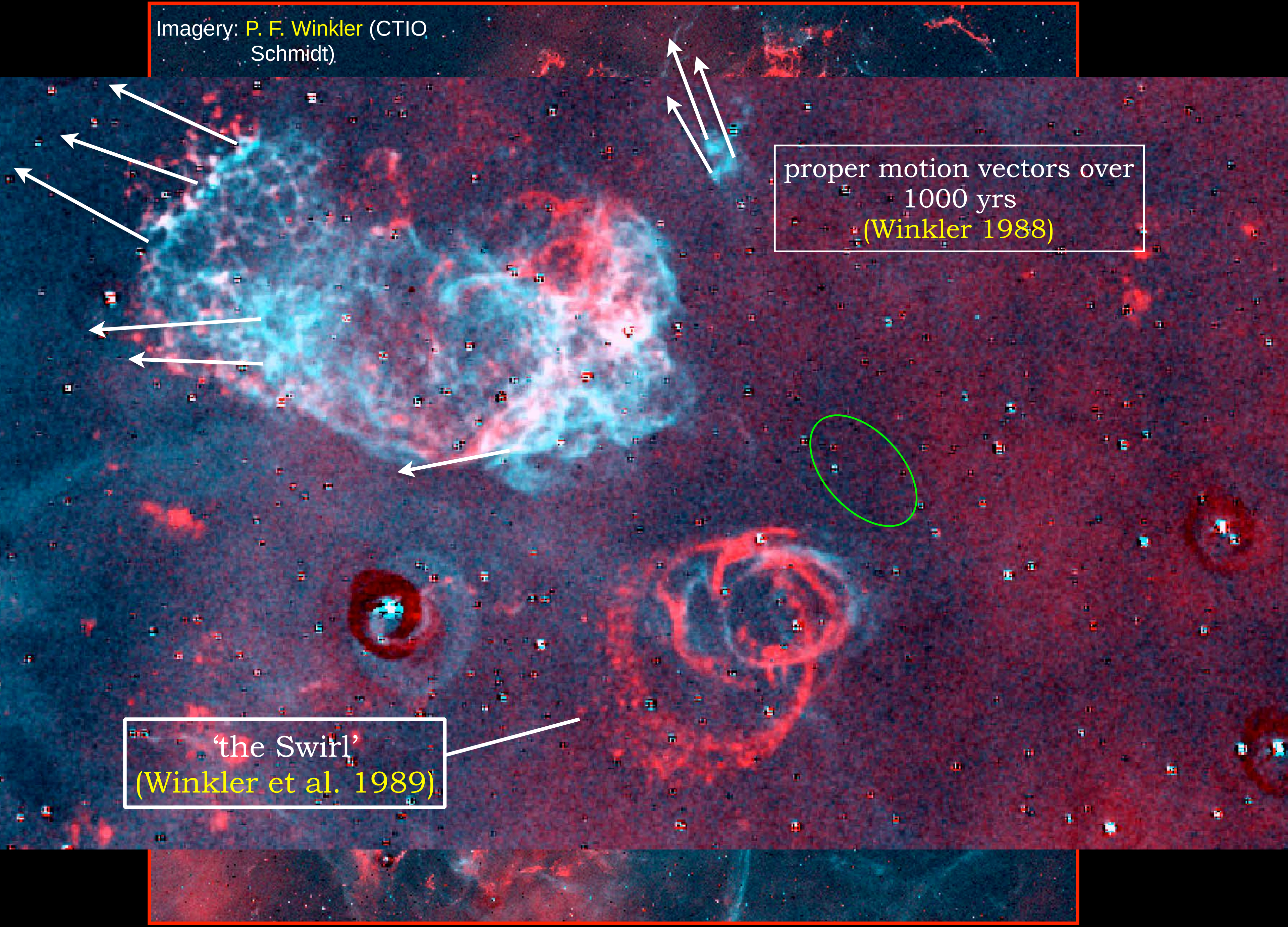
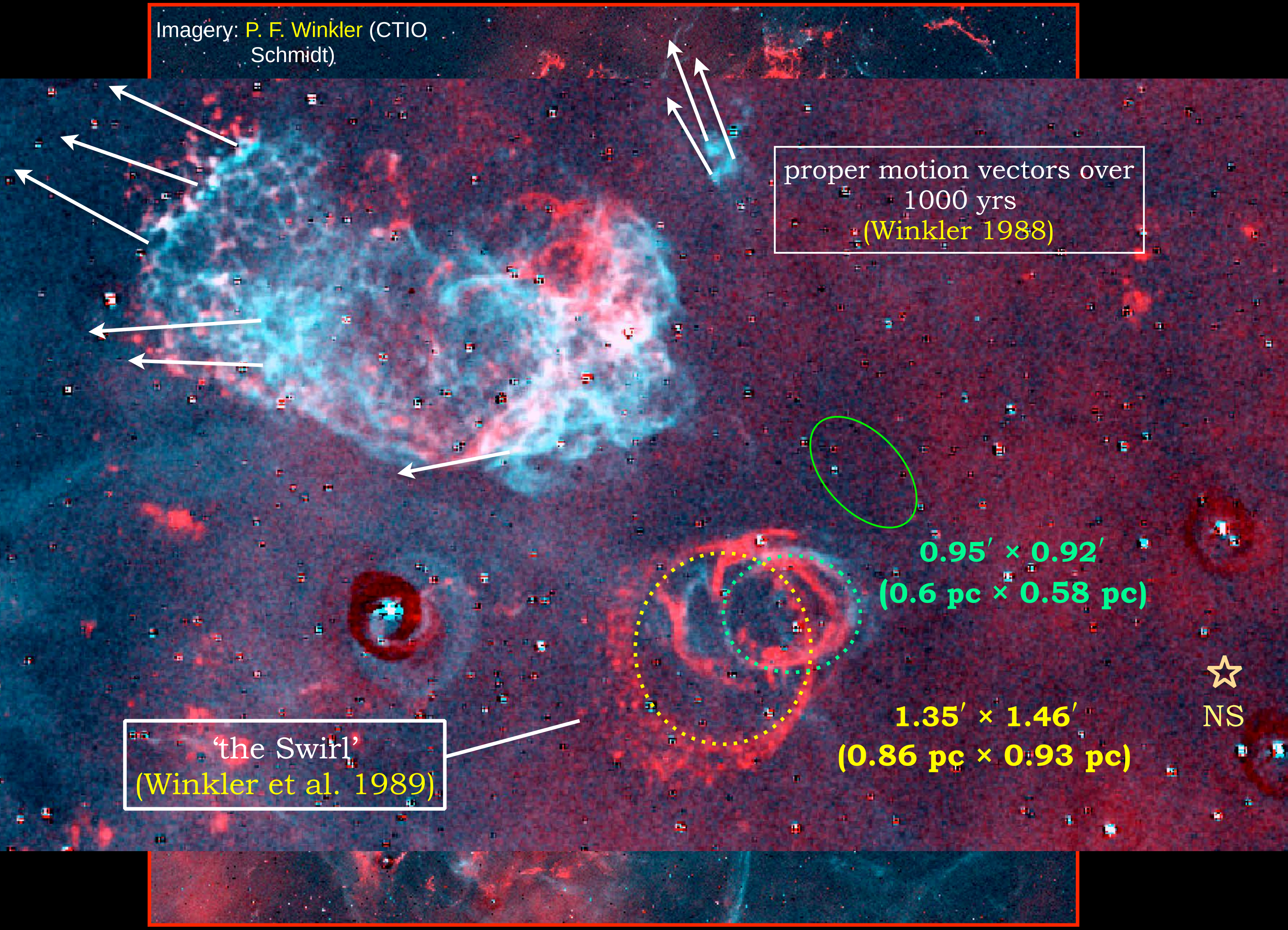
proper motion vectors over 1000 yrs (Winkler 1988)

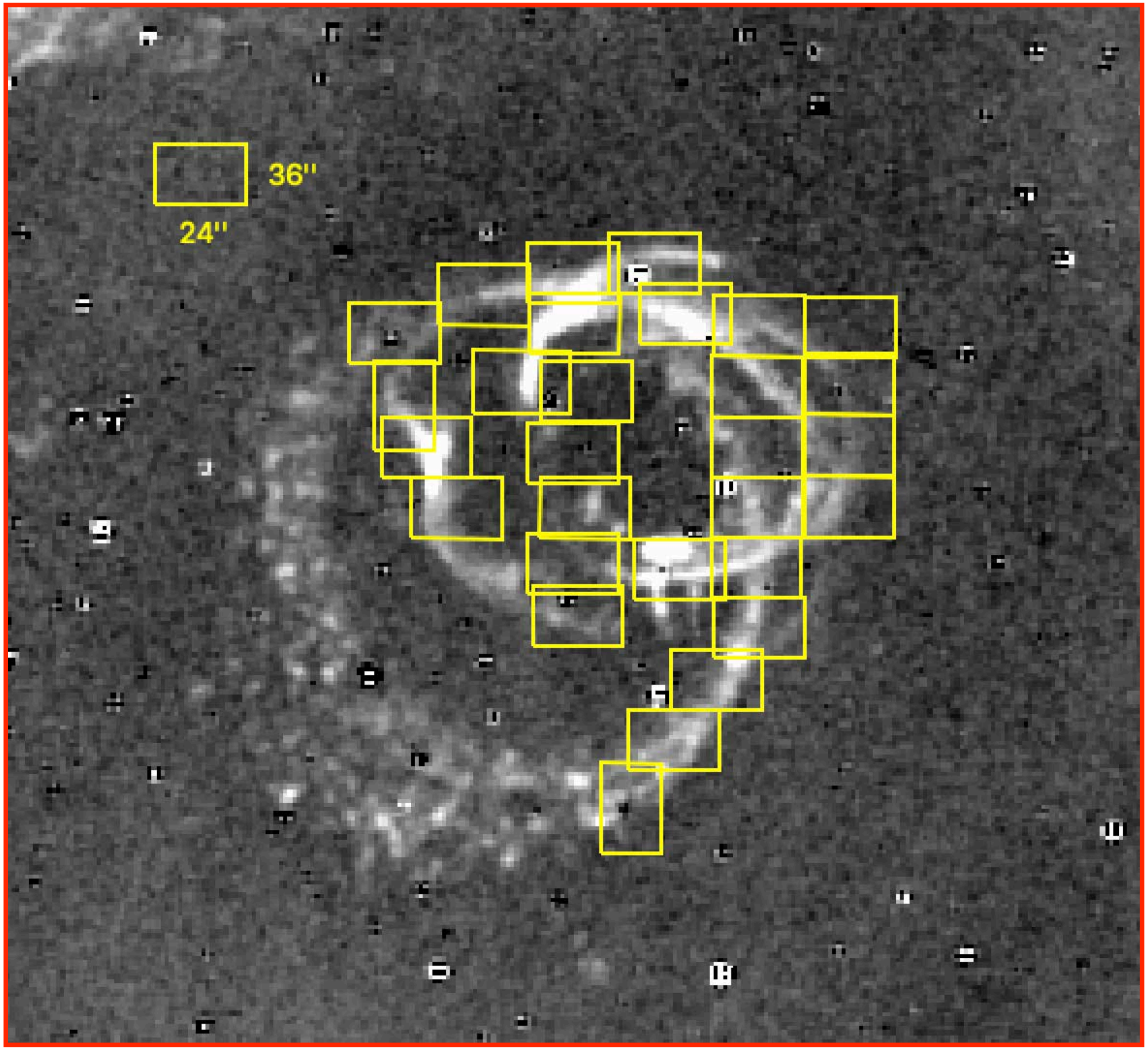

Imagery: P. F. Winkler (CTIO Schmidt)
proper motion vectors over 1000 yrs
(Winkler 1988)
'the Swirl'
(Winkler et al. 1989)


Imagery: P. F. Winkler (CTIO Schmidt)
proper motion vectors over 1000 yrs (Winkler 1988)
0.95′ × 0.92′ (0.6 pc × 0.58 pc)
1.35′ × 1.46′ (0.86 pc × 0.93 pc)
NS
'the Swirl' (Winkler et al. 1989)

WiFeS Fields in Puppis A

29 Fields observed
(2×1800 s per field)

- B3000 (blue channel) + R3000 (red channel)
- Coverage 3500-9500 Å
- 100 km s^{-1} resolution
- Surface brightness limit ~ 10^{-17} ergs cm^{-2} s^{-1} $arcsec^{-2}$
- 10 nights (2016/2017)



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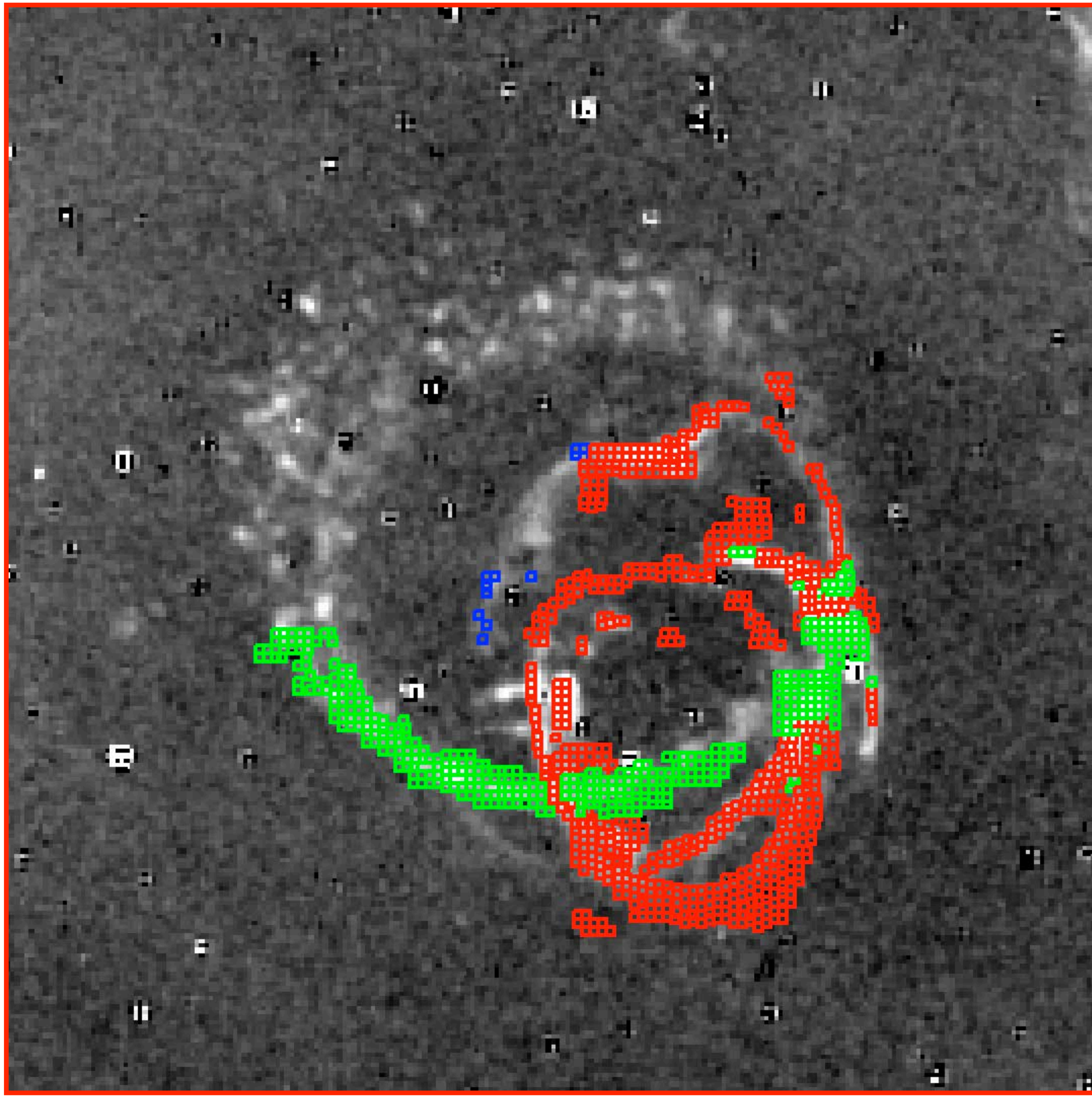
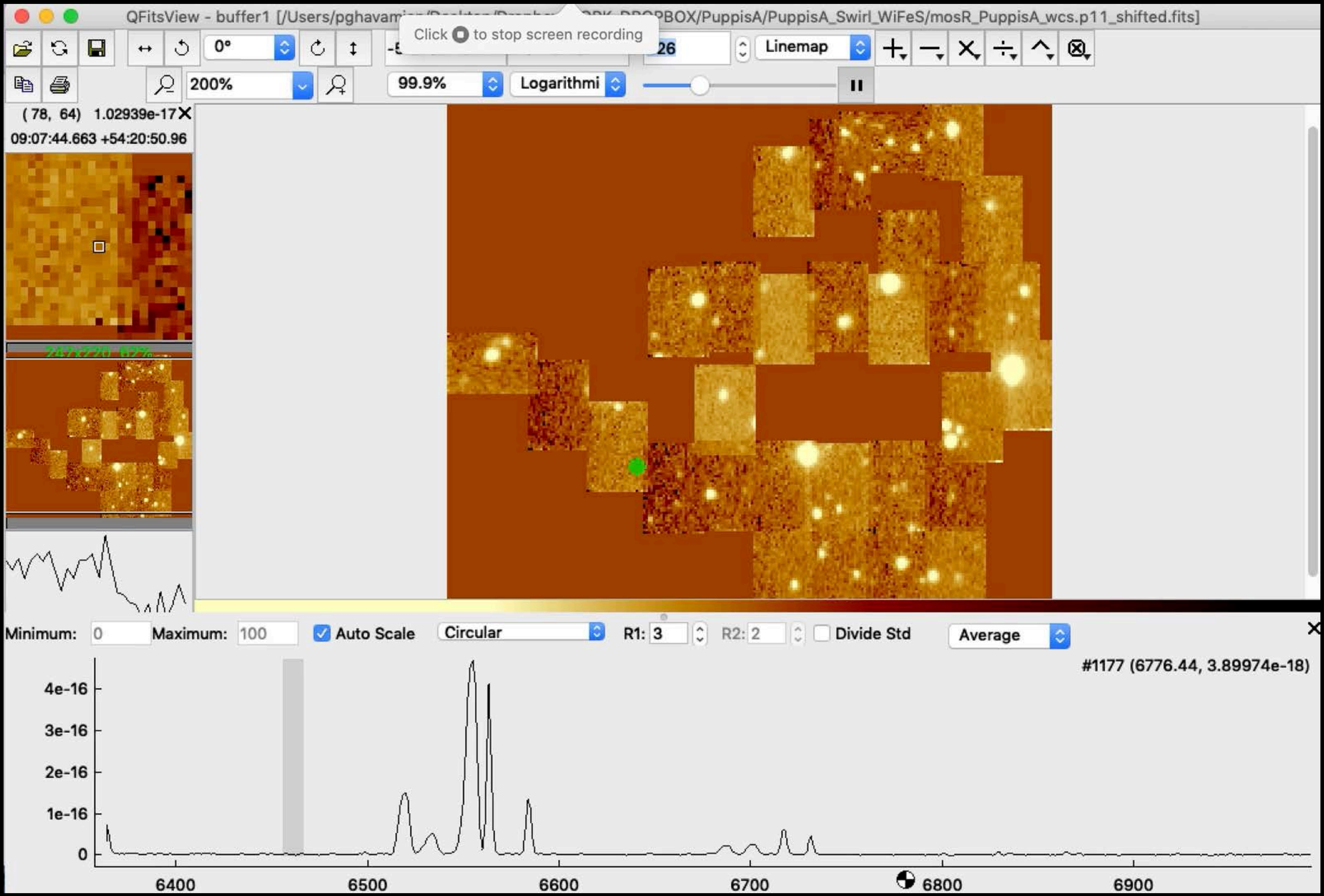


Stepping Through the Red Channel Datacube of the Swirl



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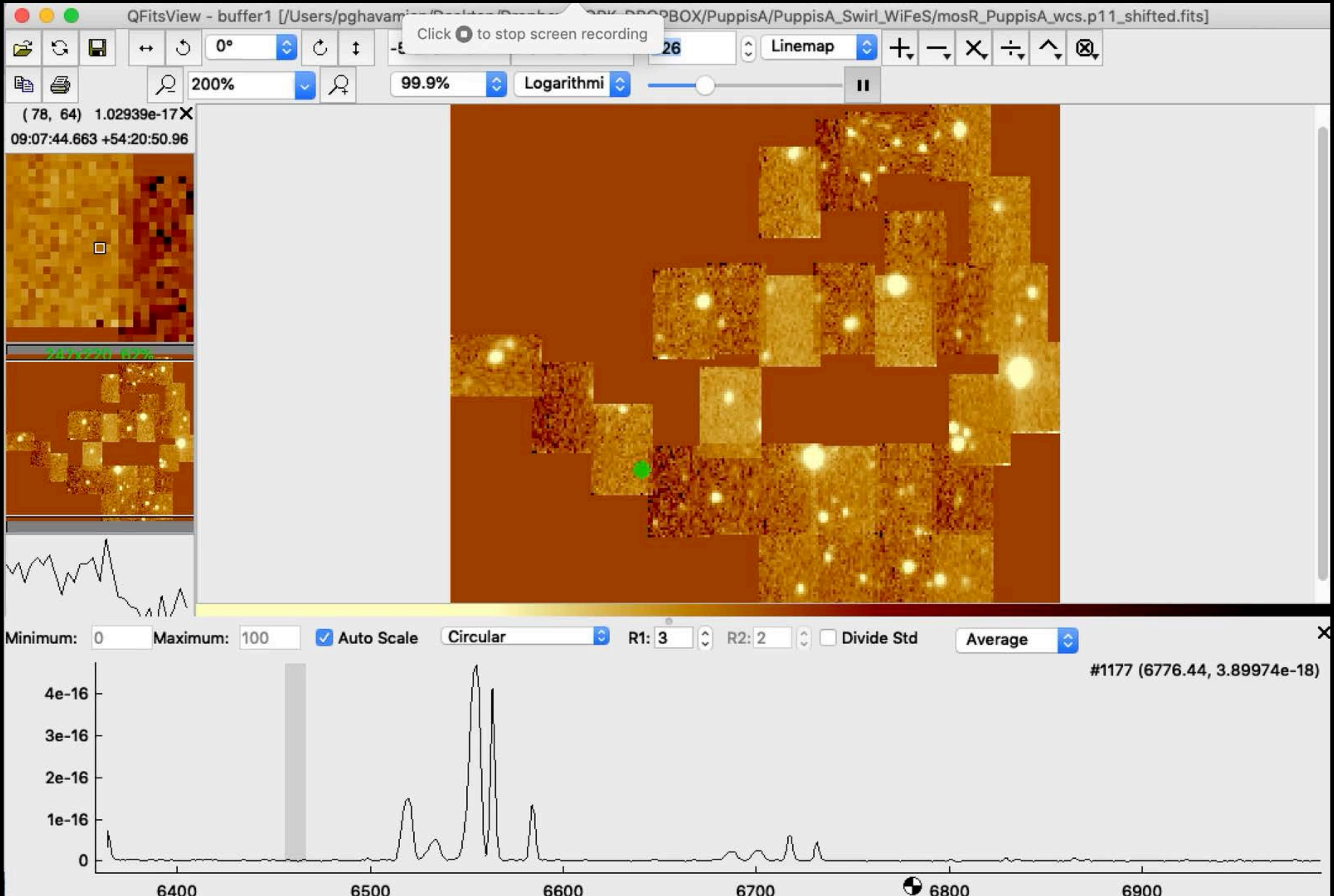


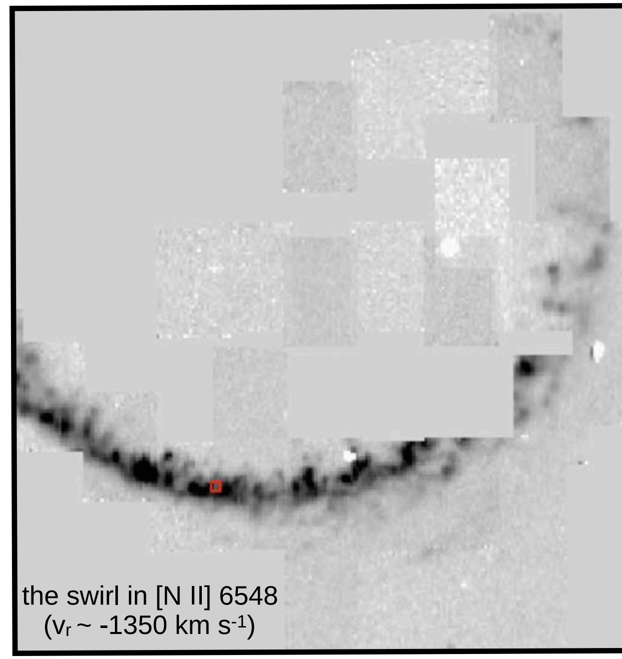
Background Subraction is Tricky for Some Lines

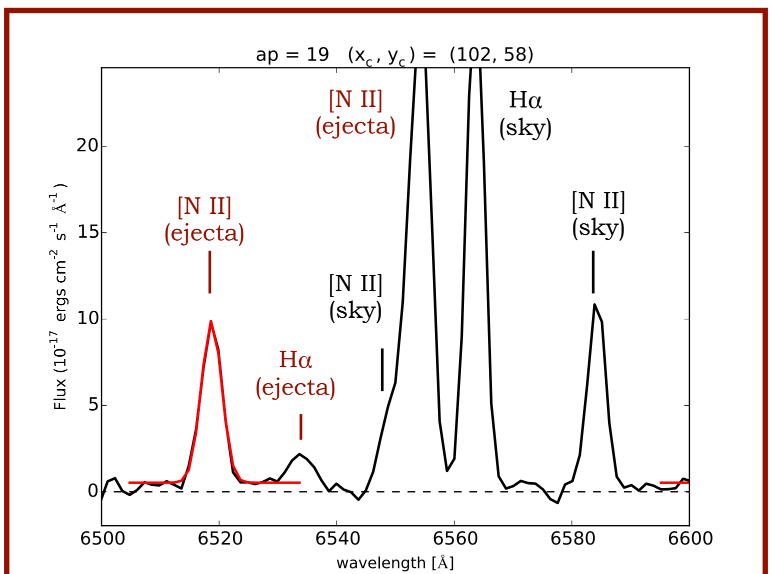
Background/ejecta line blending is a challenge in the Swirl data:

- Some ejecta **Hα** (v_r ~-780 km s^{-1}) blueshifted to background [N II] 6548
- Some ejecta **[N II] 6583** (v_r ~-1350 km s^{-1}) blueshifted to background [N II] 6548

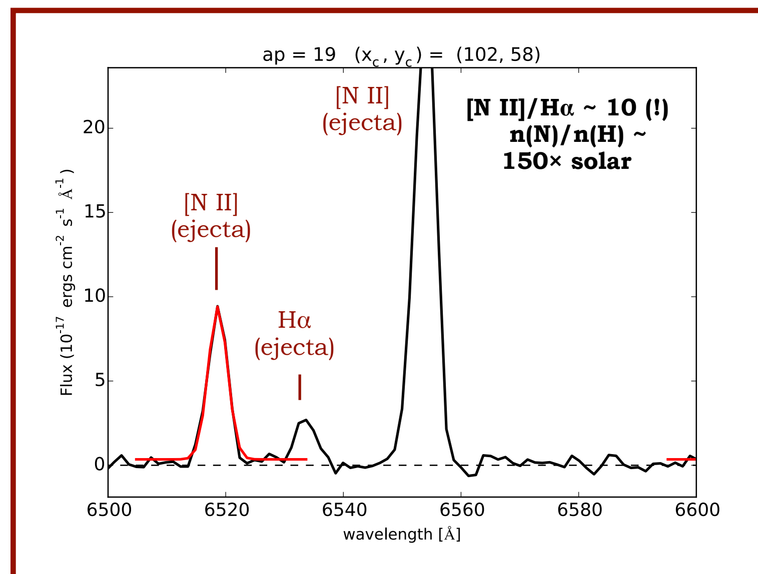
… this necessitates careful background subtraction in many locations

- Automated line-profile fitting to <u>1065 spectra</u>



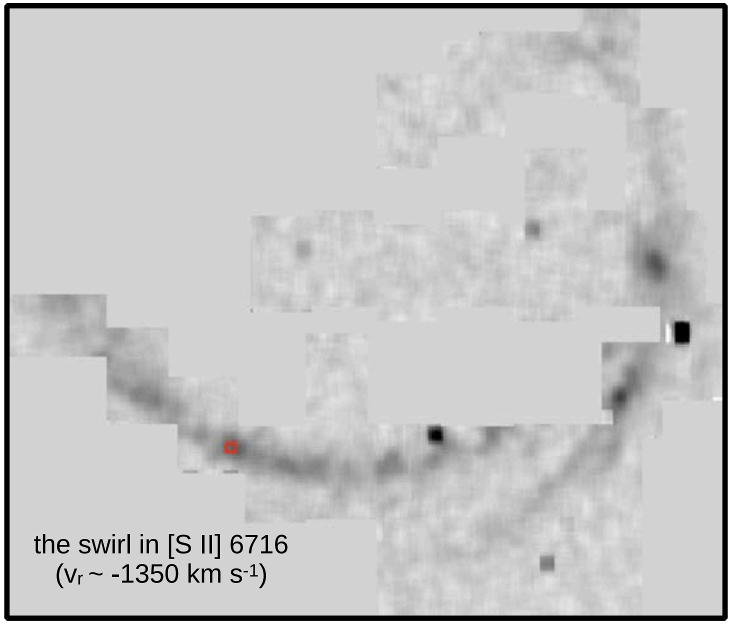


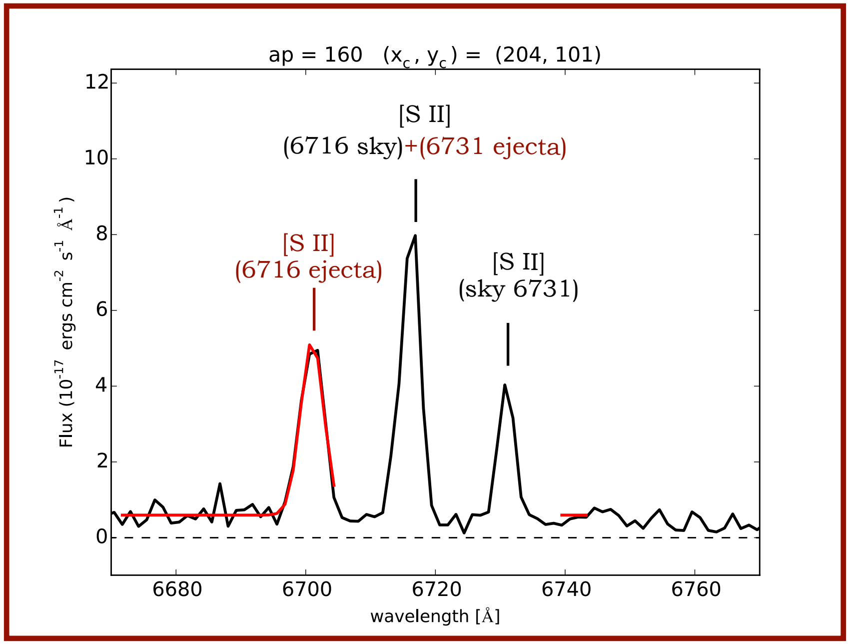
SKY
SUBTRACTION



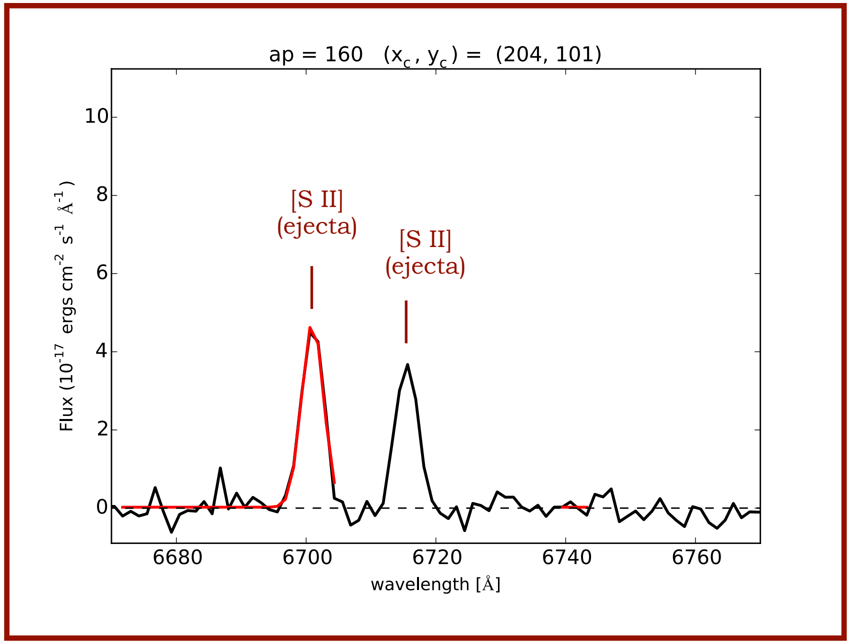
Another Example

Ejecta **[S II] 6731** (v_r ~ -780 km s^{-1}) blueshifted to background [S II] 6716



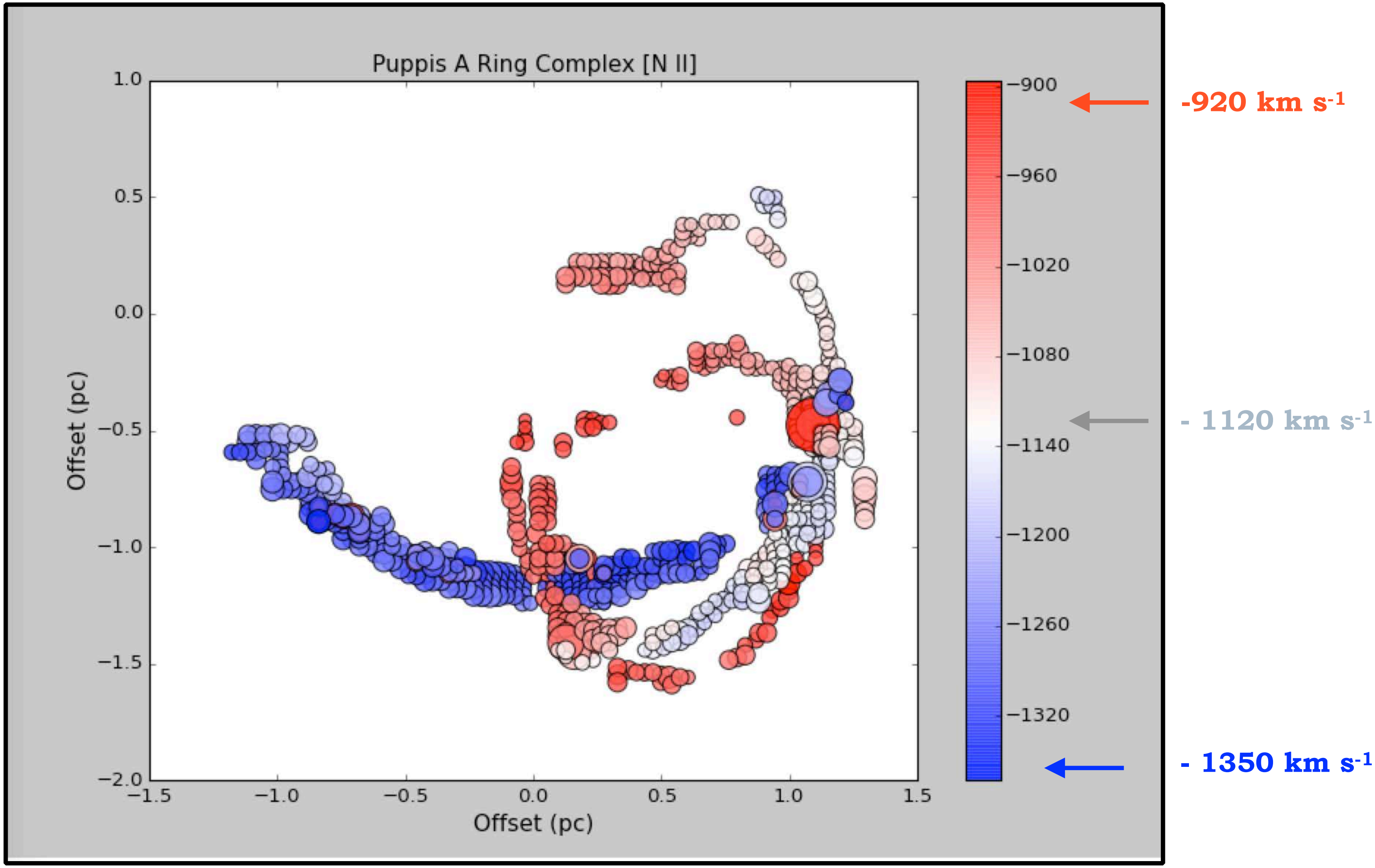


SKY SUBTRACTION



[S II] 6716/6731 ~ 1.1
n_e ~ 500-1000 cm^{-3}

[N II] Radial Velocities of the Swirl from WiFeS



dot radii ∝ line FWHM

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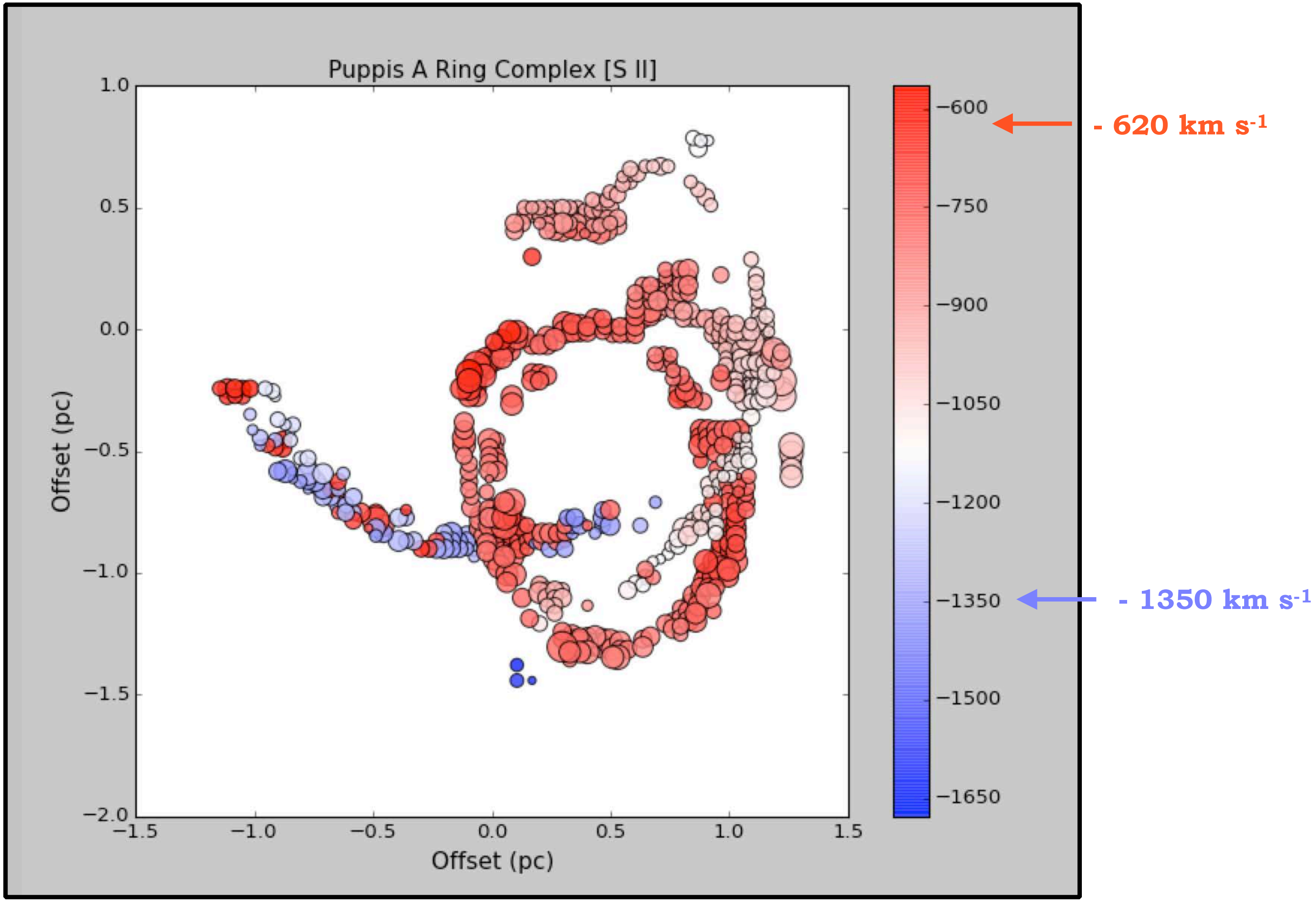
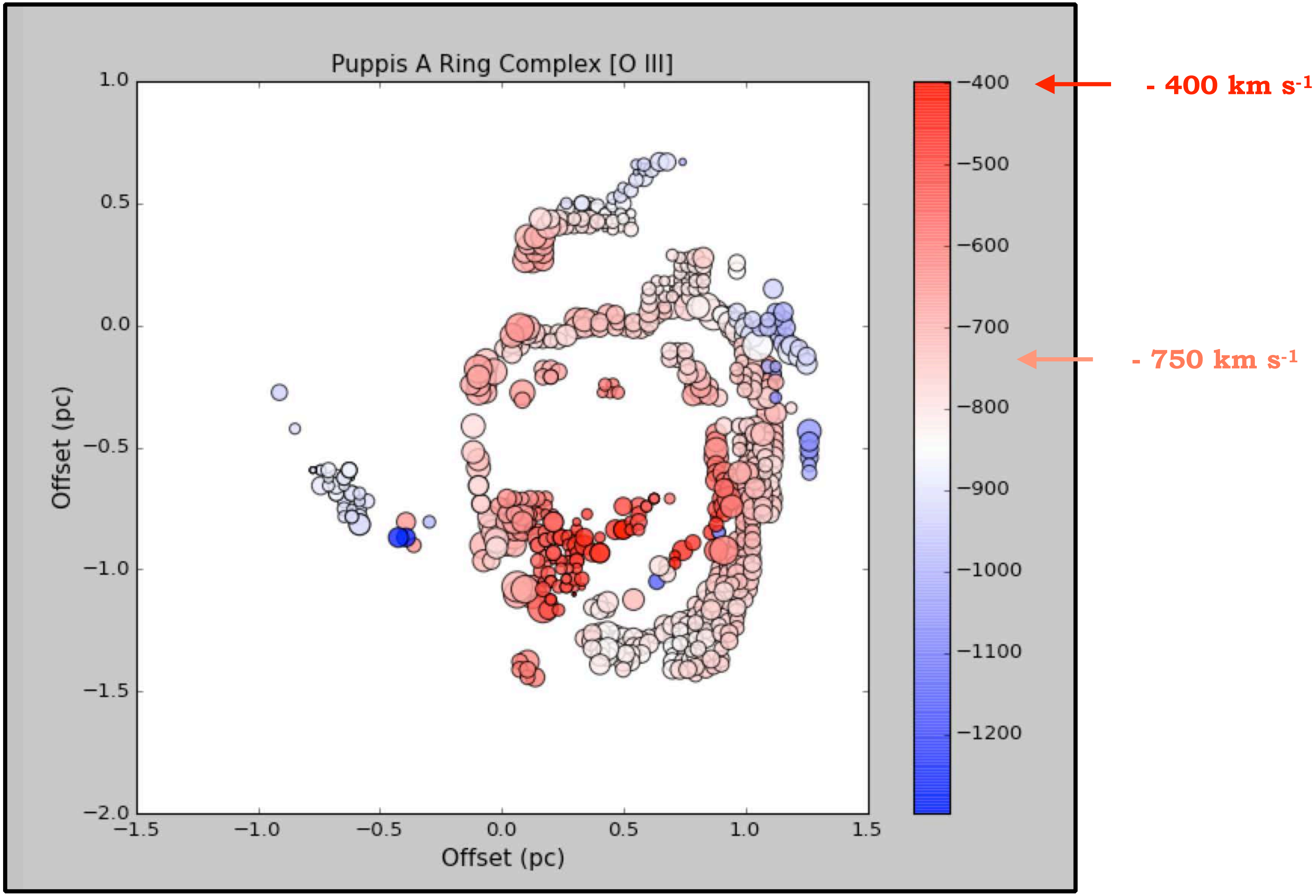


dot radii ∝ line FWHM

[O III] Radial Velocities of the Swirl from WiFeS



dot radii ∝ line FWHM

Why the Rings Are So Unusual

- Their velocities seem quantized. Are they even associated with Puppis A? Expansion speeds, central location in Puppis A suggest yes

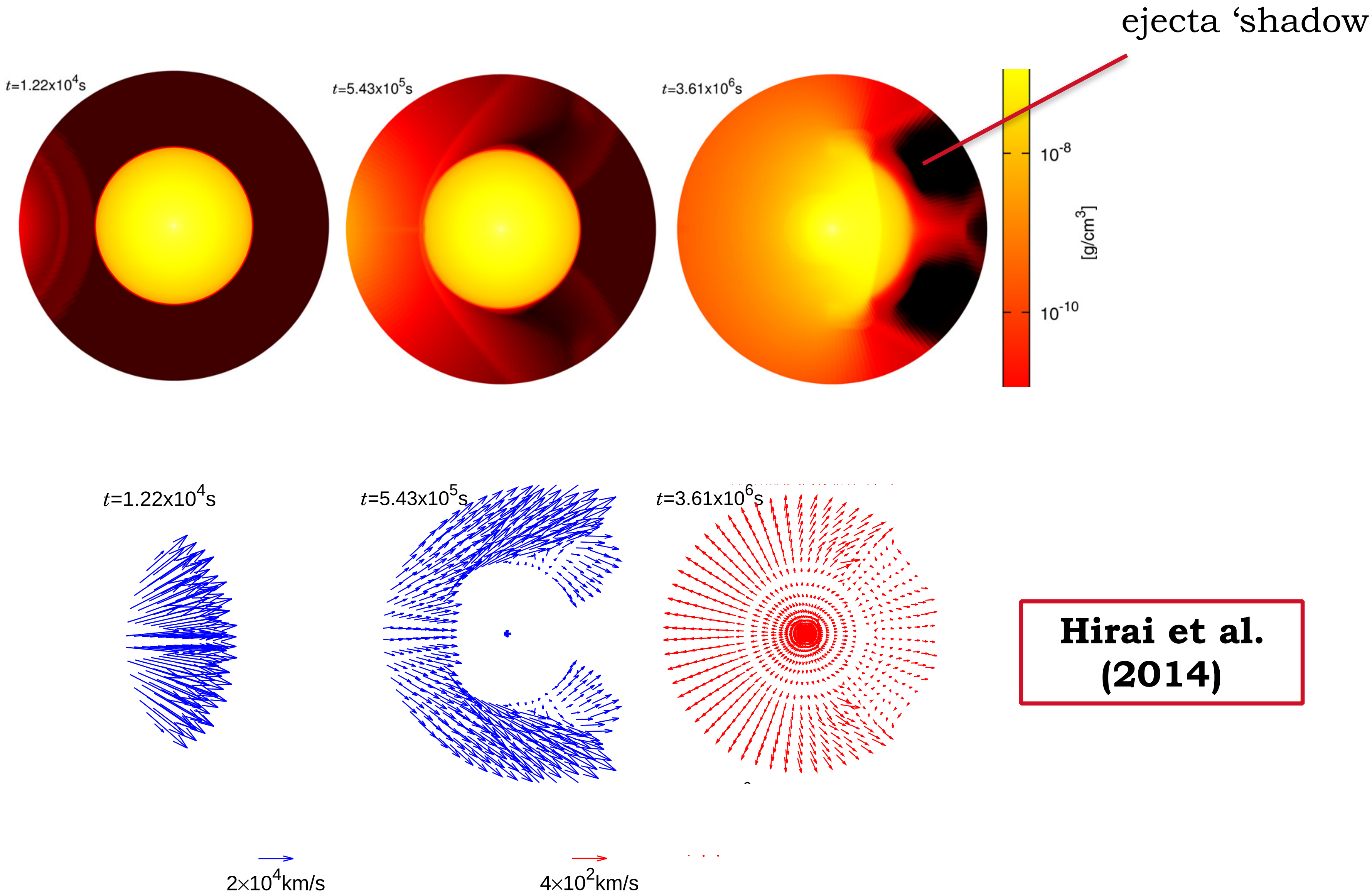
- Swirl shows only blue shifted emission, consistent with a binary explosion picture (secondary located between us and the primary during SN)

- Dynamical timescale of knots: typical radiatively shocked clump ~ 10^{17} cm (limited by seeing), gives survival time τ ~ 100-150 yrs

  … *Implies: what we're seeing has been recently shocked!*

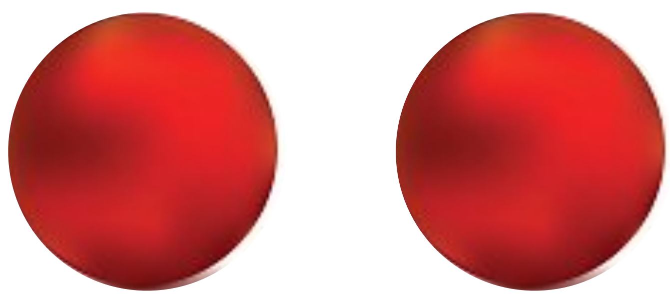
- Rings similar in abundances to FMFs in Cas A **(Fesen et al. 1987)**, though probably slower than the main body of ejecta

Nearly 70% of all Massive Star Systems are Multiple!
Numerical Simulation of a 10 $M_{\odot}$ Binary Interaction



Hirai et al. (2014)

One Possible Scenario: A Massive Binary System



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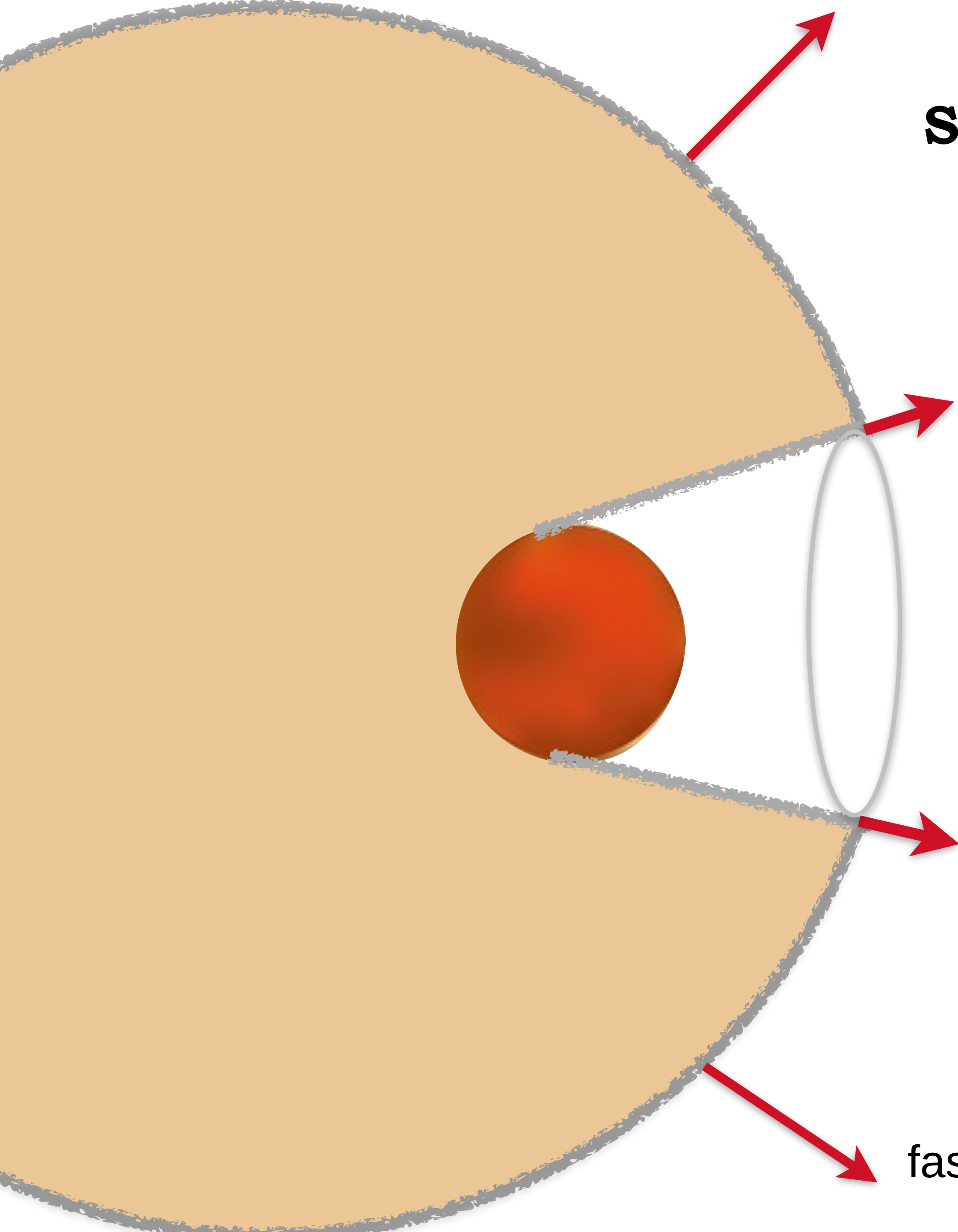

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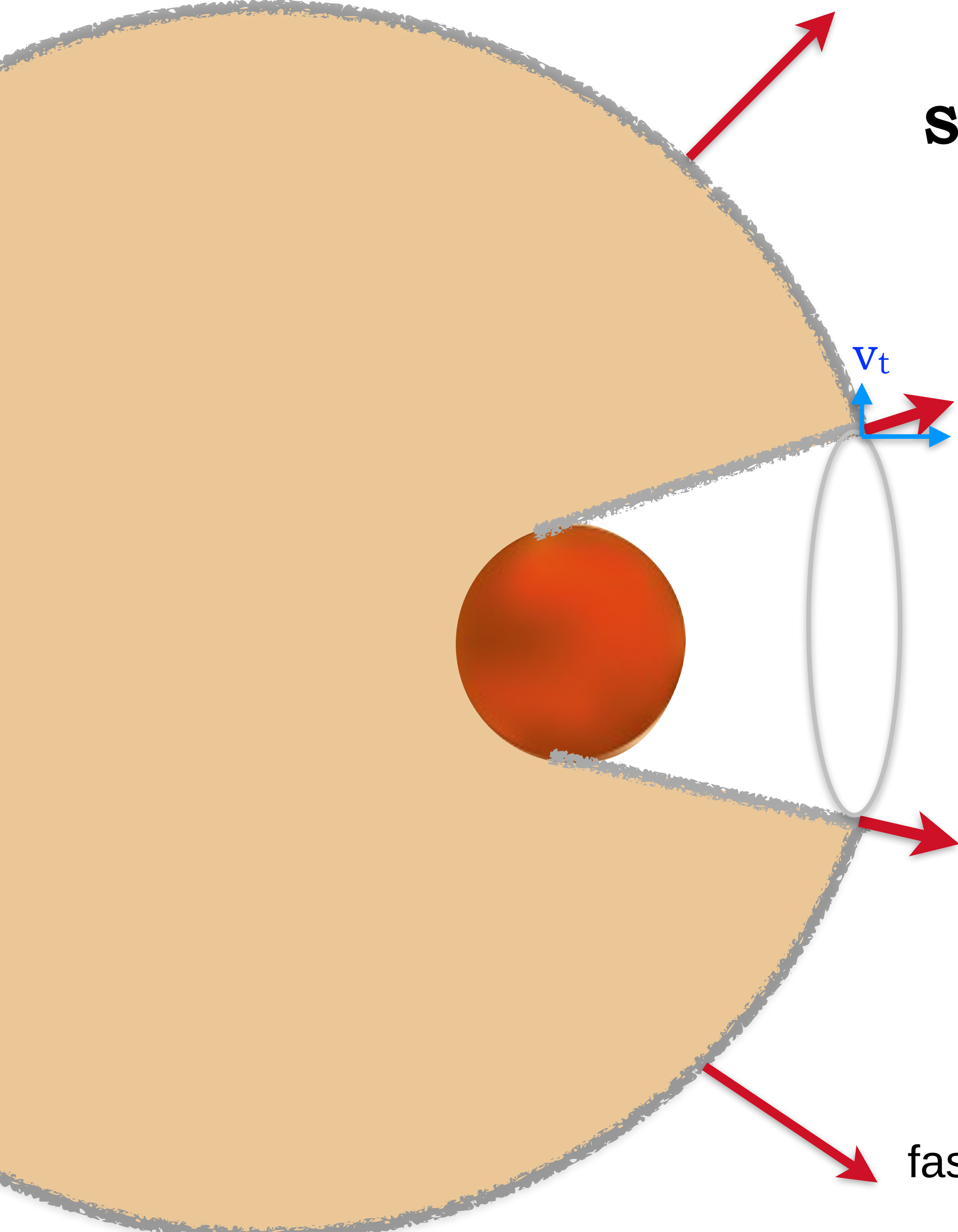

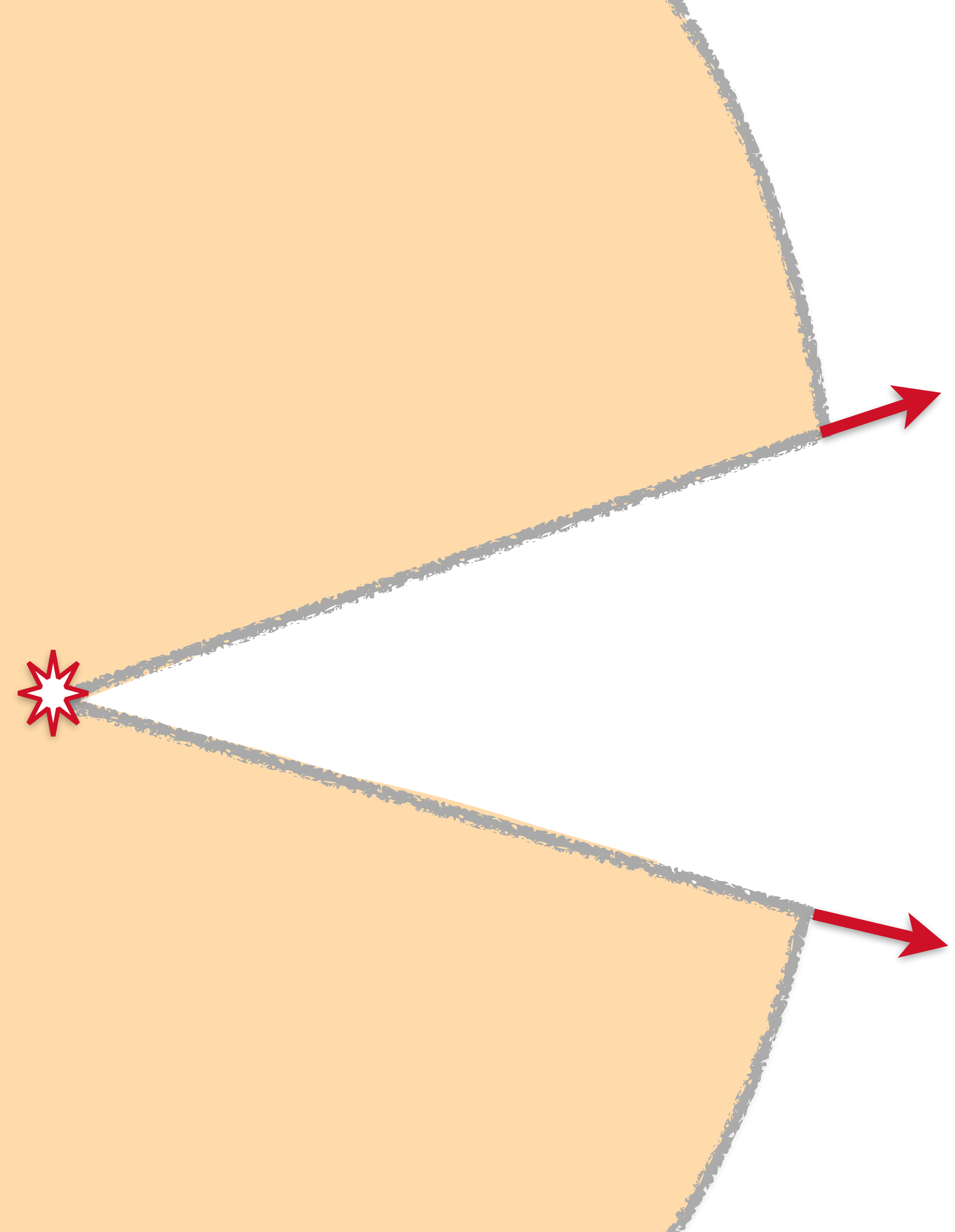

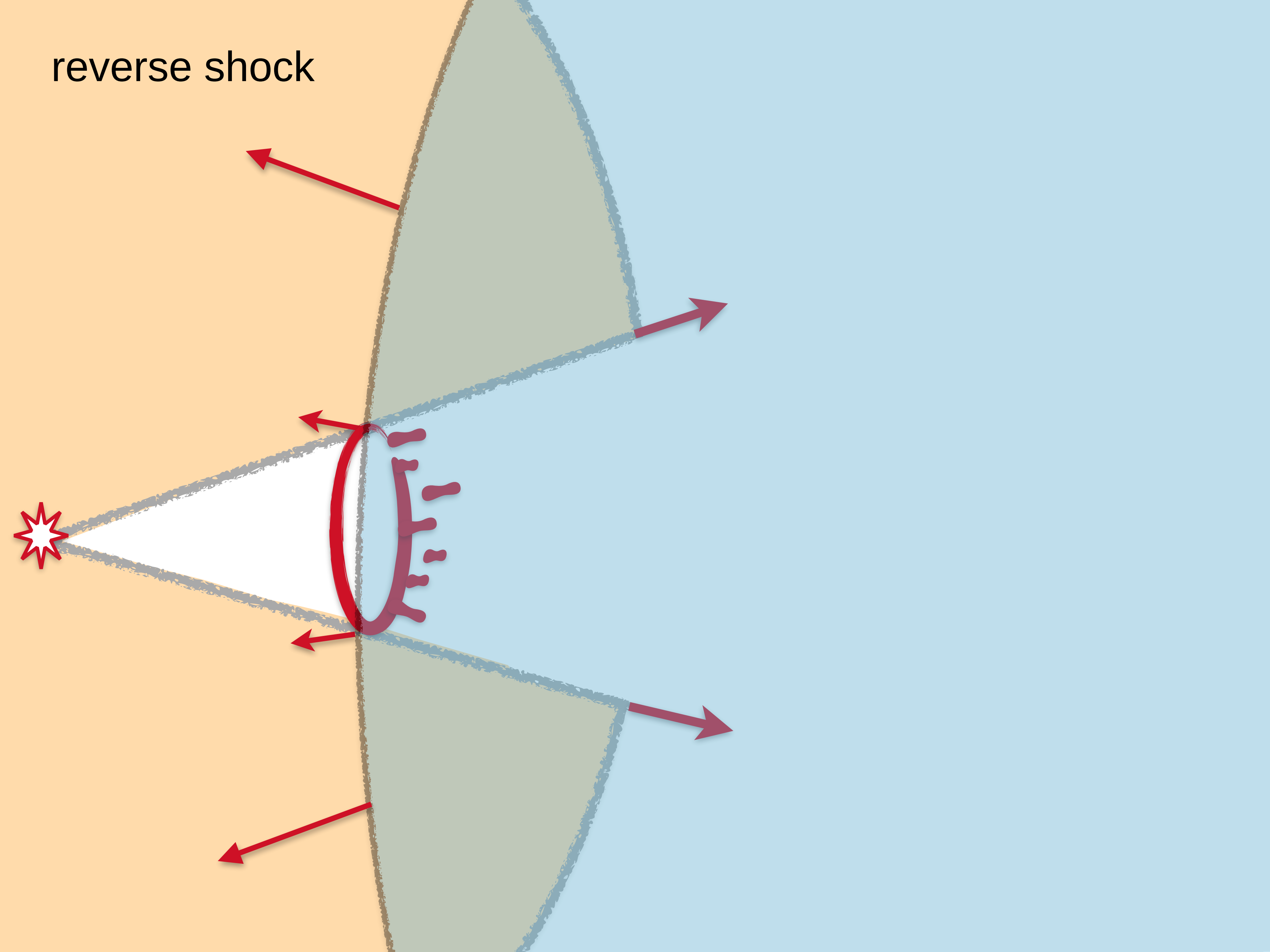
reverse shock

Conclusions

- A conical ejecta pattern may produce slow lateral expansion of rings if they are approaching us

  (… may be why **Winkler et al (1989)** get such a short dynamical age for rings (~ 800 yrs), so may make 2nd supernova unnecessary)

- Assuming v ~ 1350 km/s for outer N-rich ring, t = 3700 - 4400 year lifetime of the SNR gives a Swirl distance ~ v t = 5 - 6 pc from center of Puppis A (assuming *undecelerated* ejecta)

  … This is well inside Puppis A (R ~ 16 pc)

- Weak H emission within the rings and O-rich ejecta suggests a star that lost most of its H mass before the explosion, and maybe some mixing between layers (SN Type IIb/L: **Chevalier 2005**) (SN 1993J-type)

- Pre-SN wind explanation for Swirl? (how to get v ~ 1350 km s^{-1}?)

- Could the H have been donated to secondary star?

- Faint Ca, Ar, Ni, He also detected in WiFeS data of Swirl: ongoing analysis

- Proper motions for the ring complex must be measured

Optical/X-Ray Comparison of Swirl