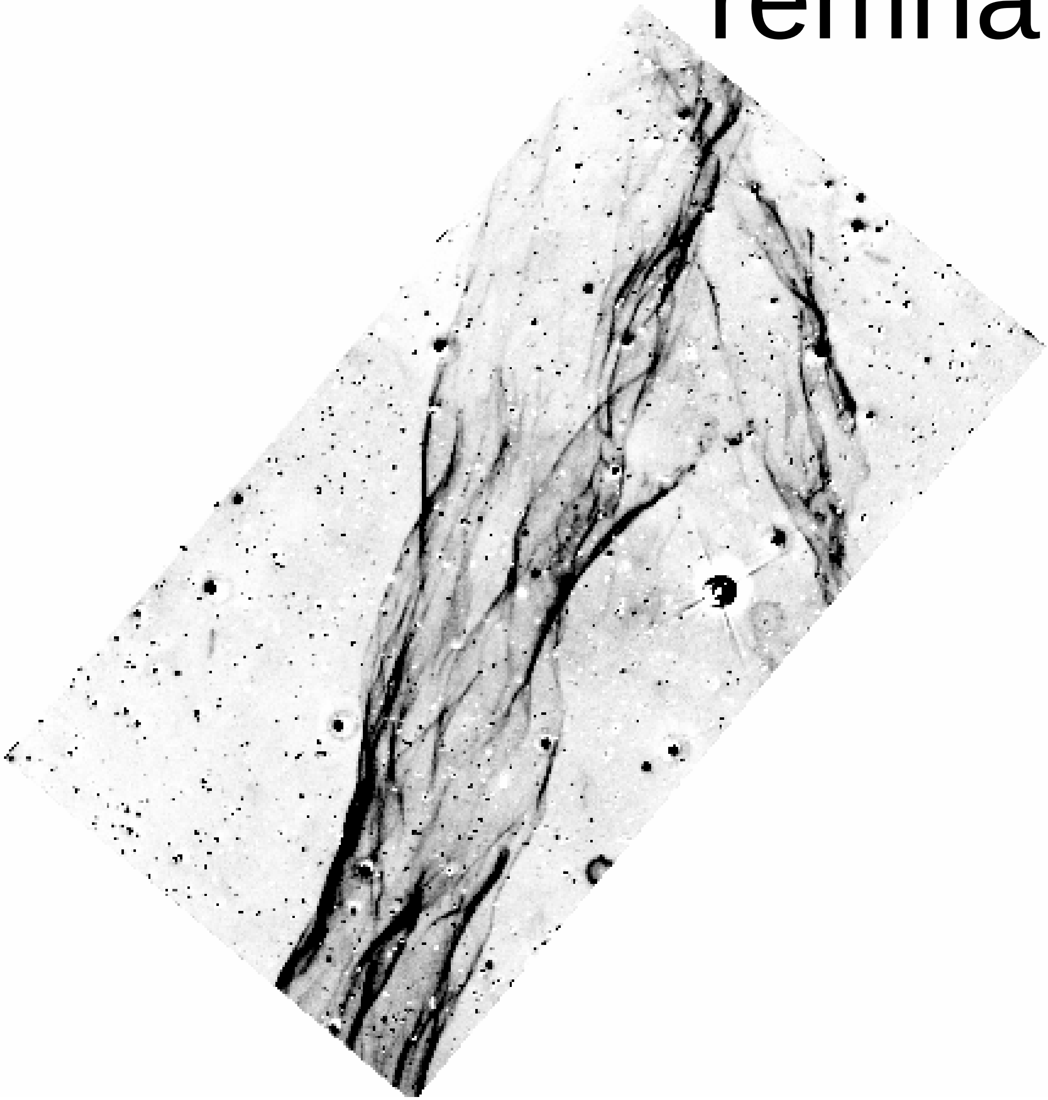
Hα emission of supernova remnants



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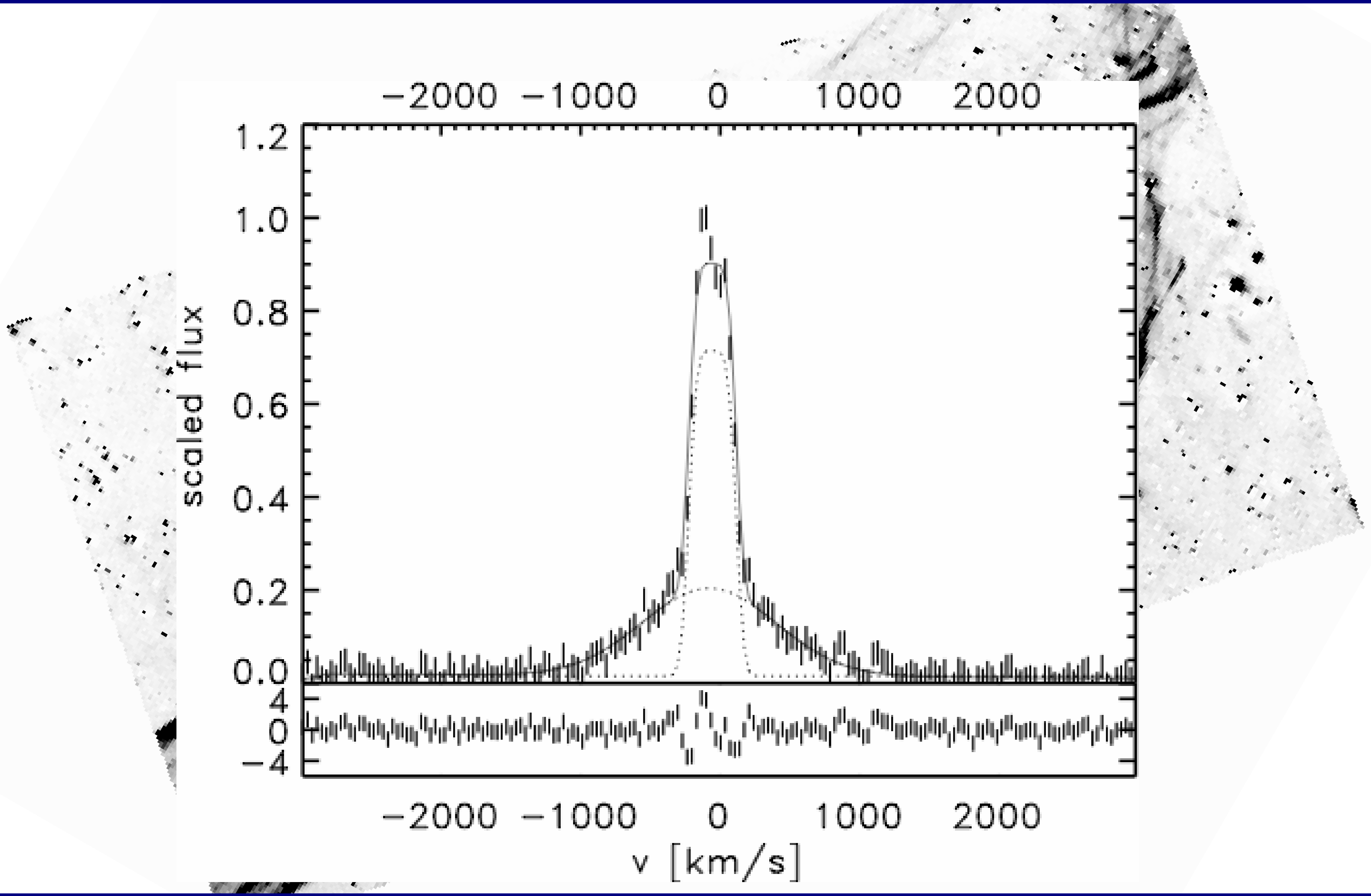
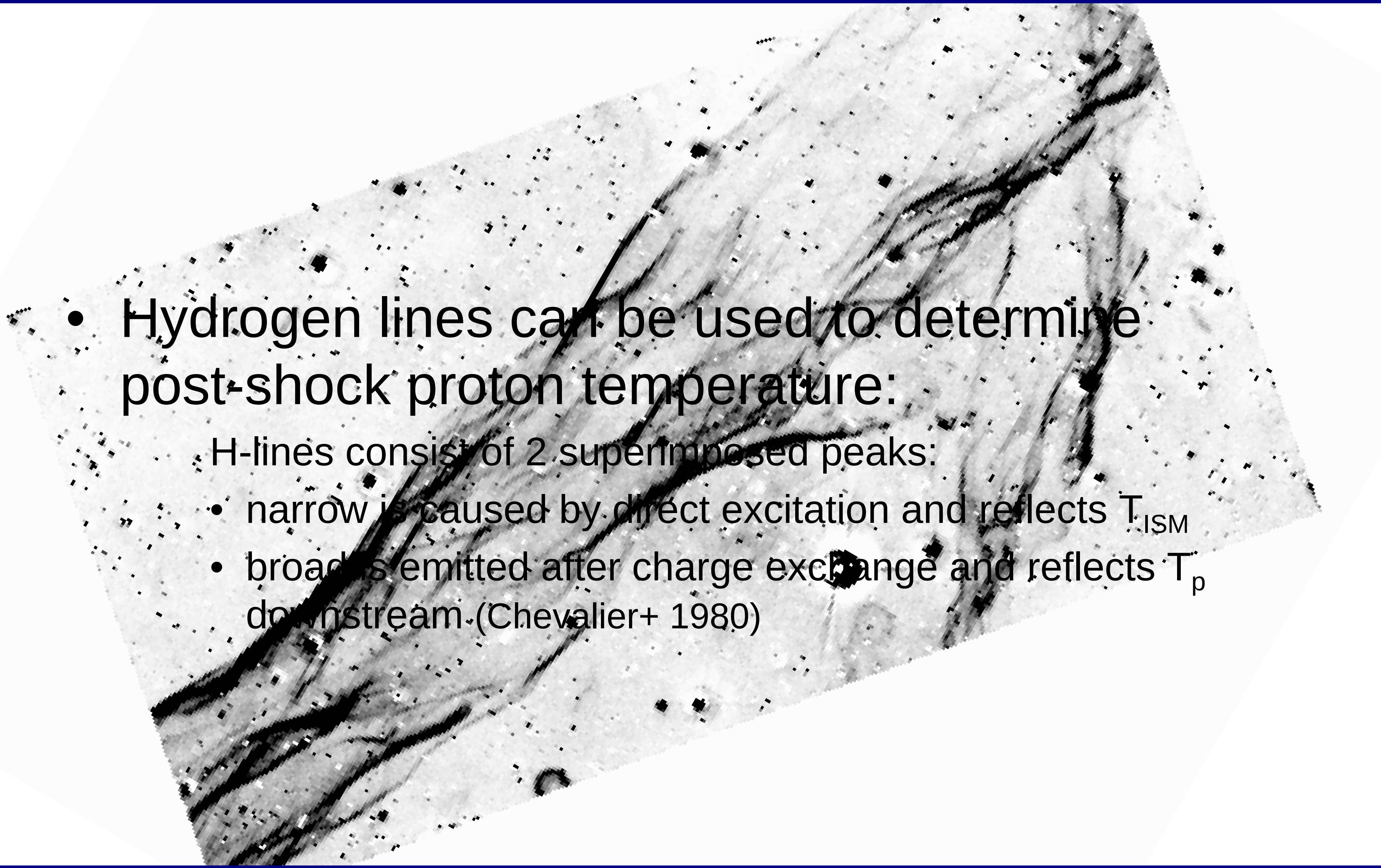
Hα emission of supernova remnants

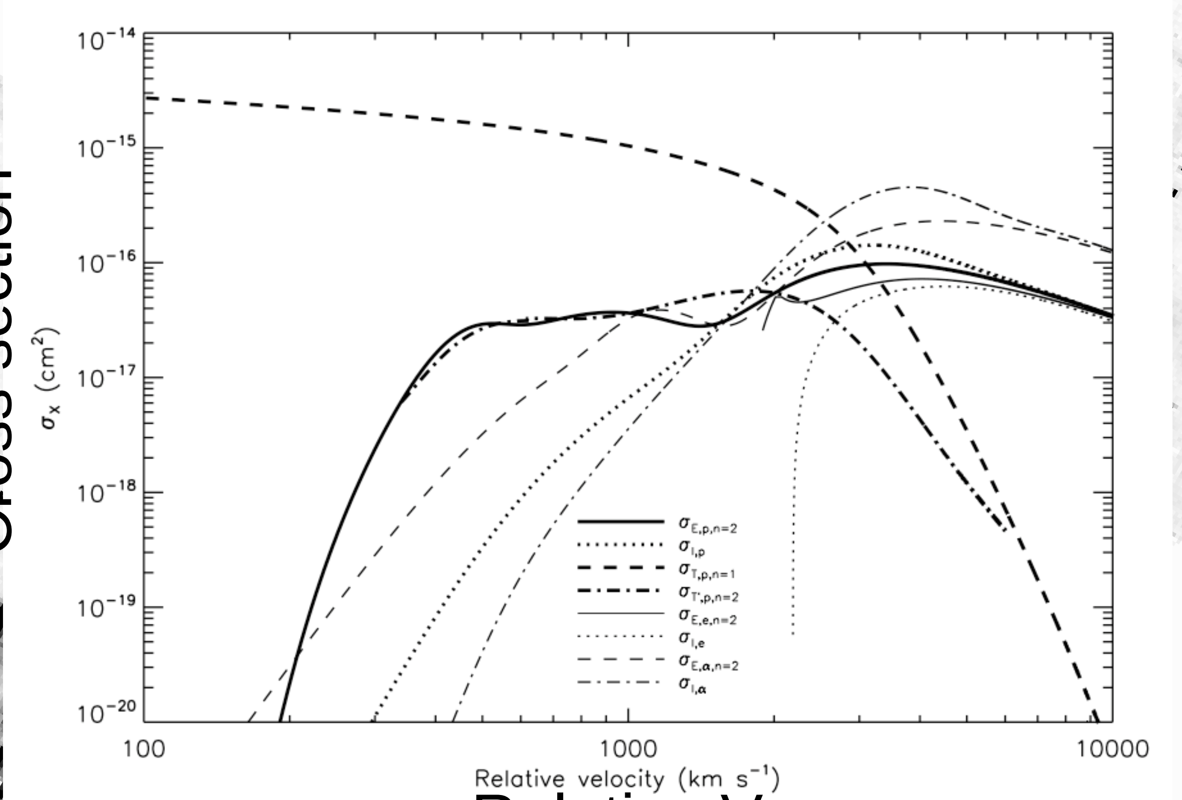


Hα emission of supernova remnants



- Hydrogen lines can be used to determine post-shock proton temperature:
  - H-lines consist of 2 superimposed peaks:
    - narrow is caused by direct excitation and reflects T_{ISM}
    - broad is emitted after charge exchange and reflects T_p downstream (Chevalier+ 1980)

Interpreting line widths



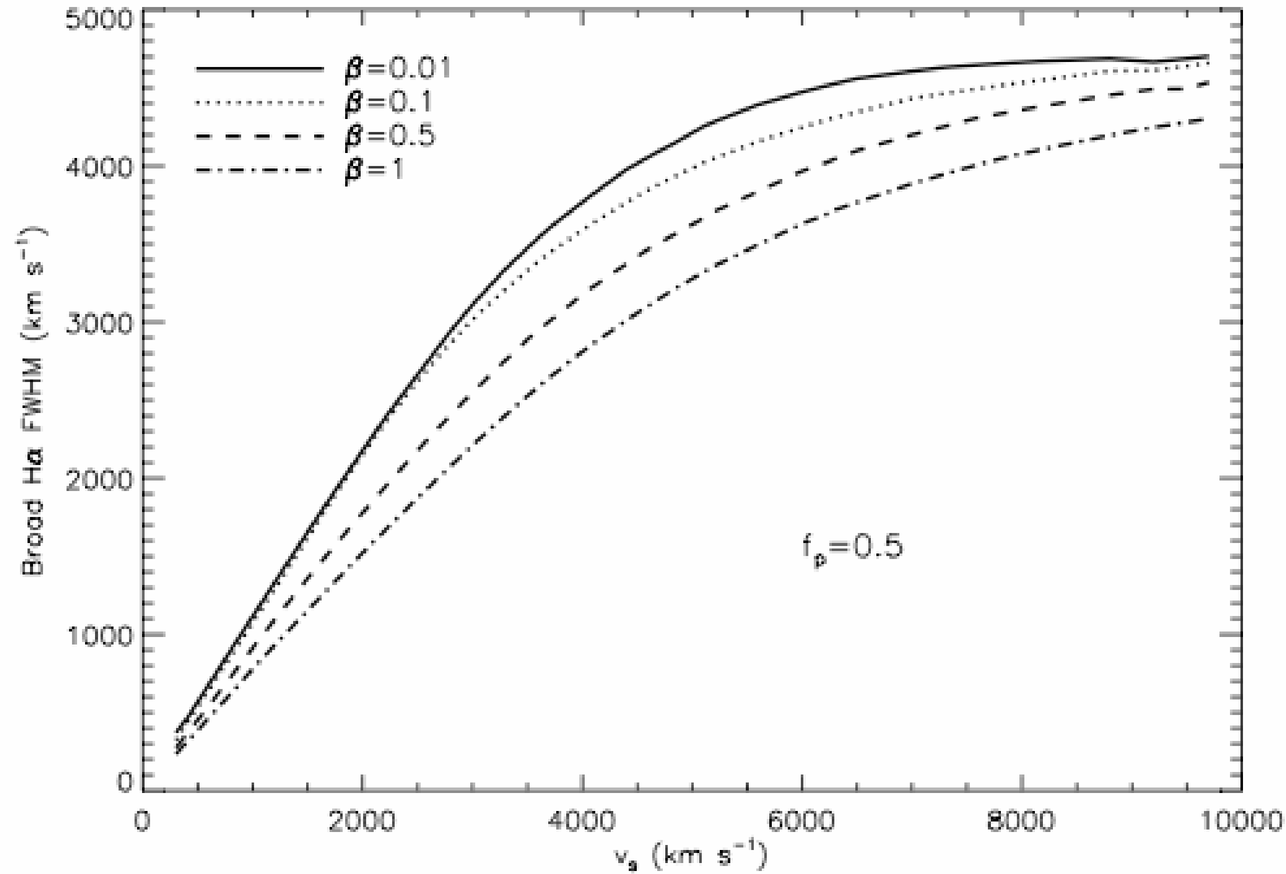
Cross section

Relative V

Heng+ 2007

Interpreting line widths

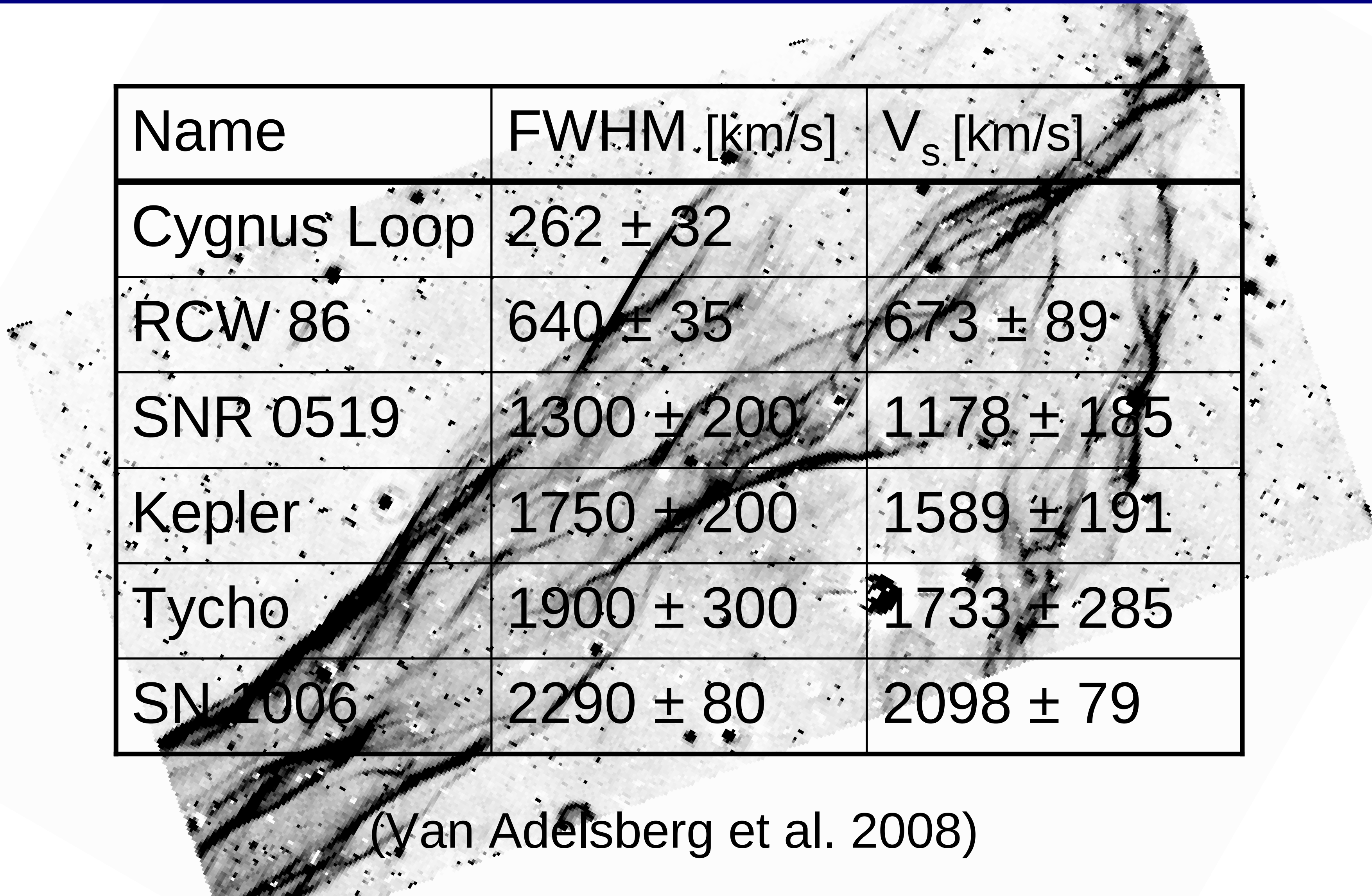
FWHM



V_s

Van Adelsberg+ 2008

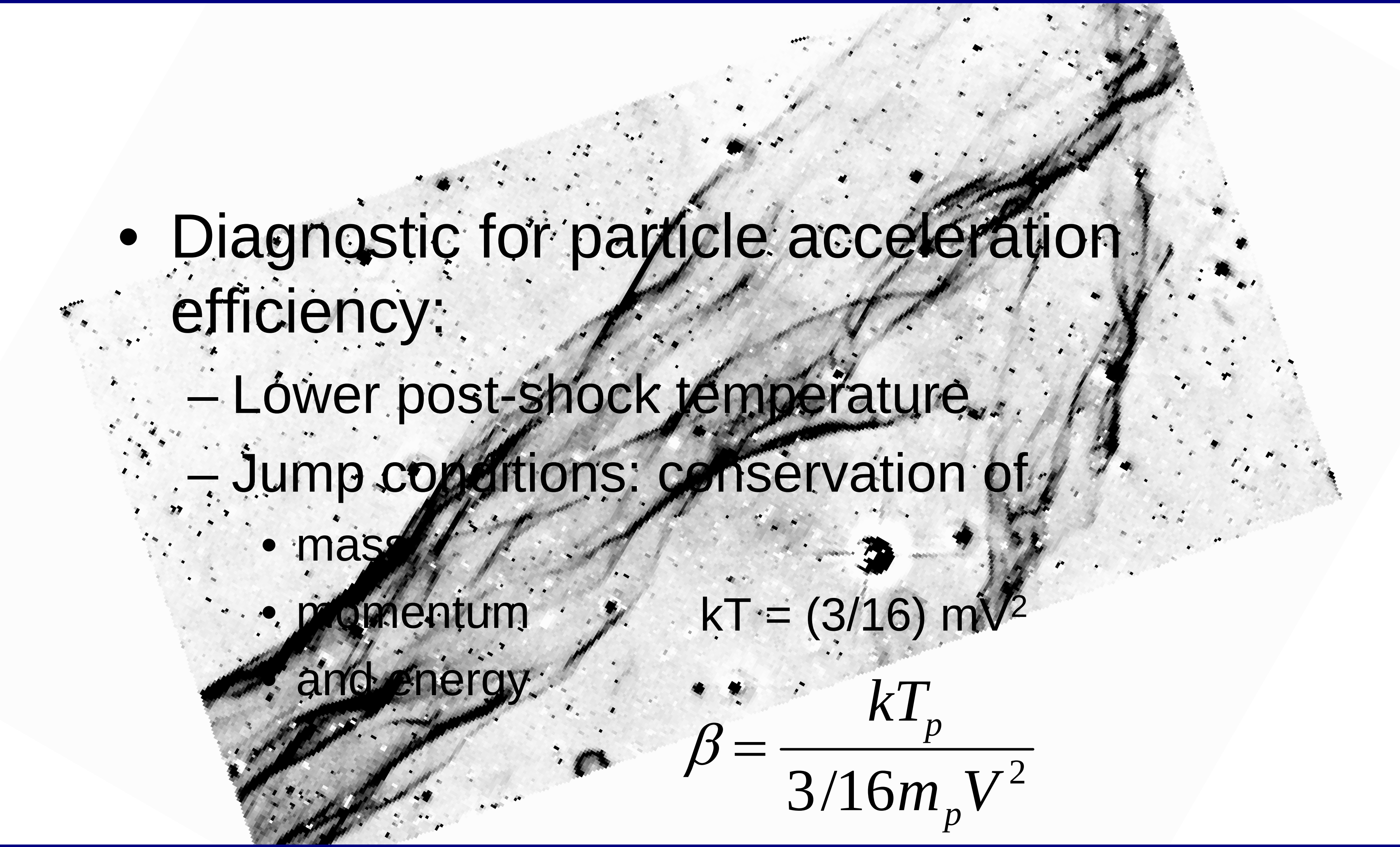
Hα emission of supernova remnants



Name	FWHM [km/s]	V_s [km/s]
Cygnus Loop	262 ± 32	
RCW 86	640 ± 35	673 ± 89
SNR 0519	1300 ± 200	1178 ± 185
Kepler	1750 ± 200	1589 ± 191
Tycho	1900 ± 300	1733 ± 285
SN 1006	2290 ± 80	2098 ± 79

(Van Adelsberg et al. 2008)

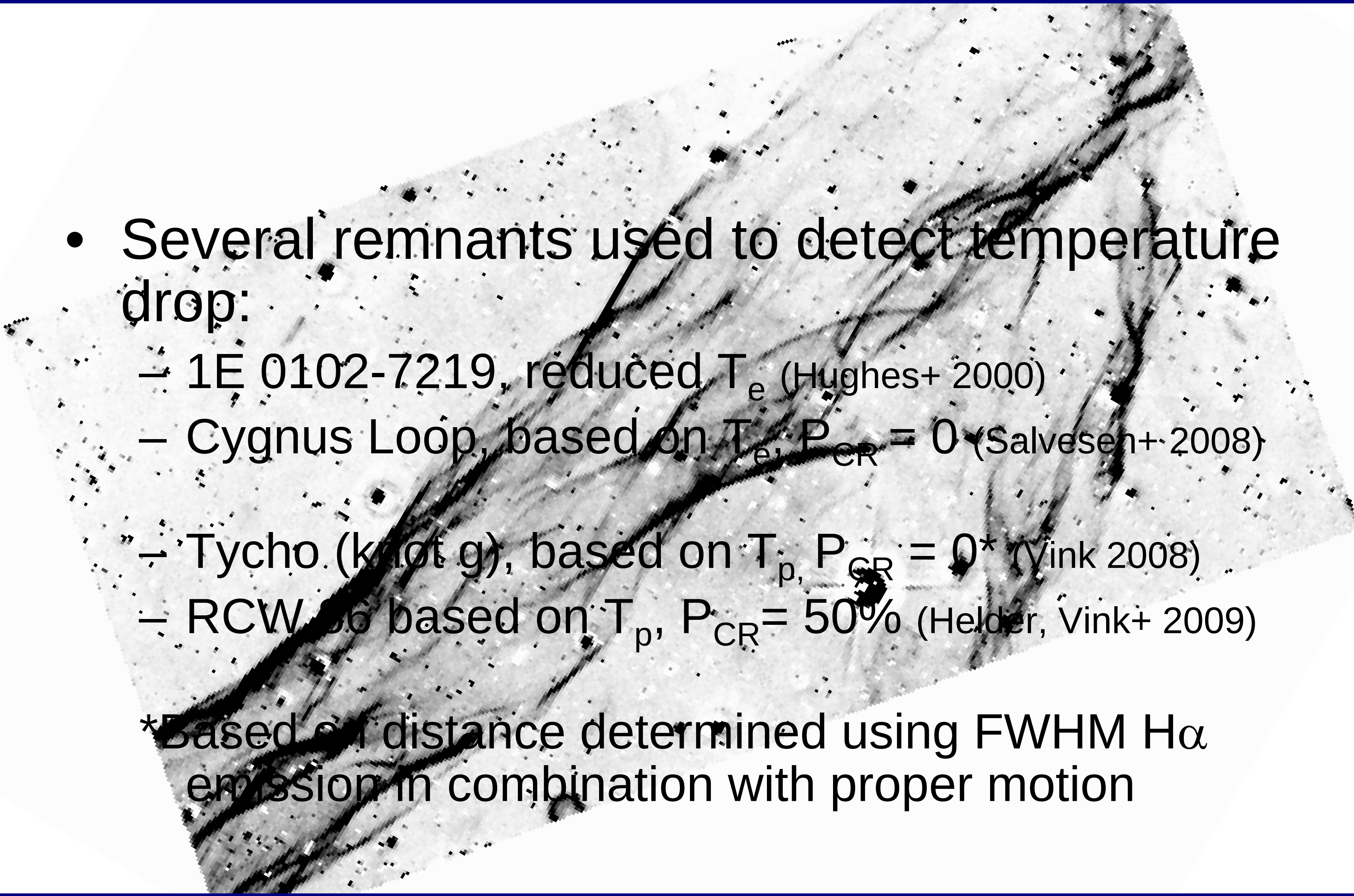
Hα emission of supernova remnants



- Diagnostic for particle acceleration efficiency:
  - Lower post-shock temperature
  - Jump conditions: conservation of
    - mass
    - momentum
    - and energy

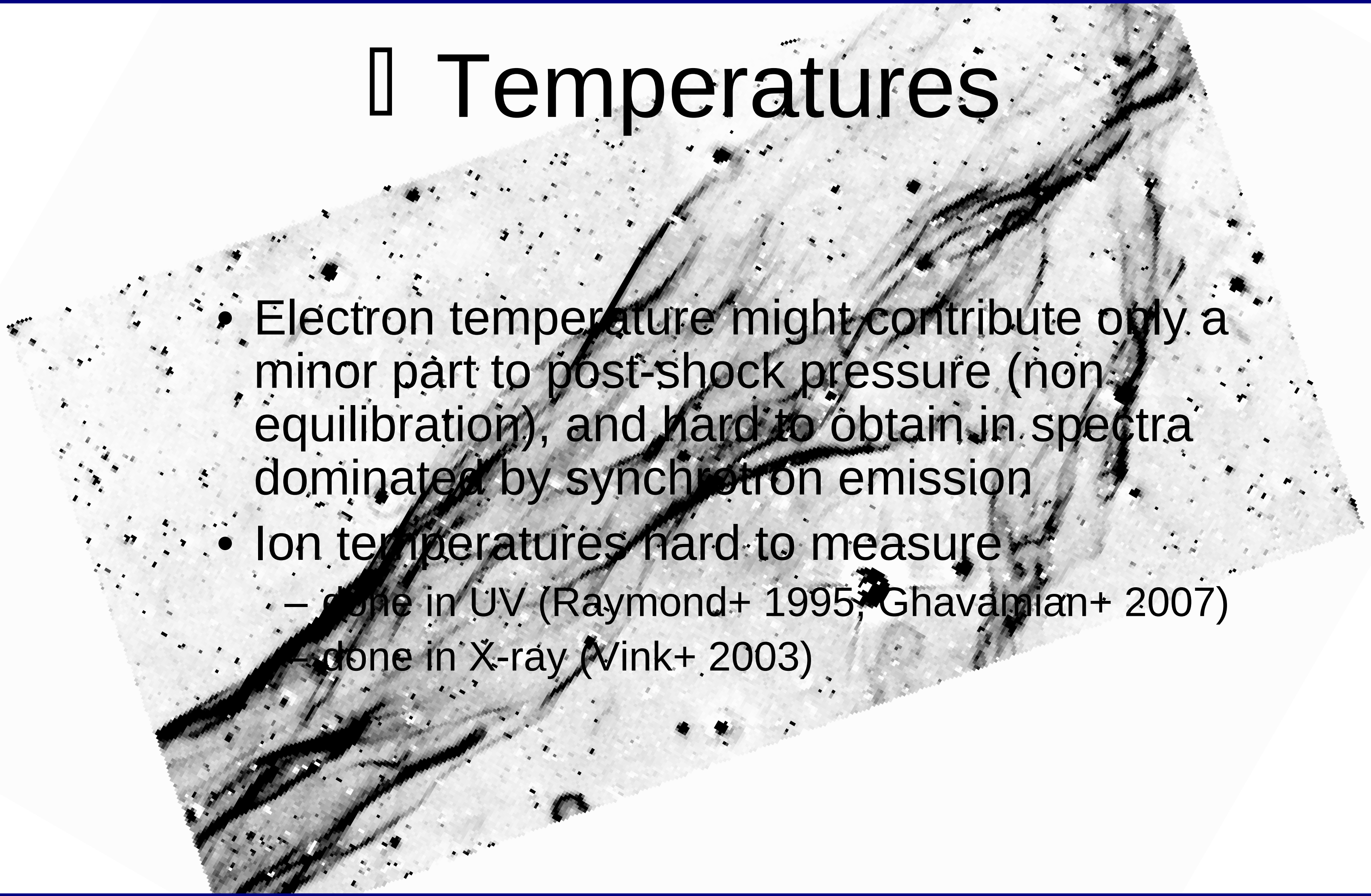
kT = (3/16) mV^2

$$\beta = \frac{kT_p}{3/16 m_p V^2}$$



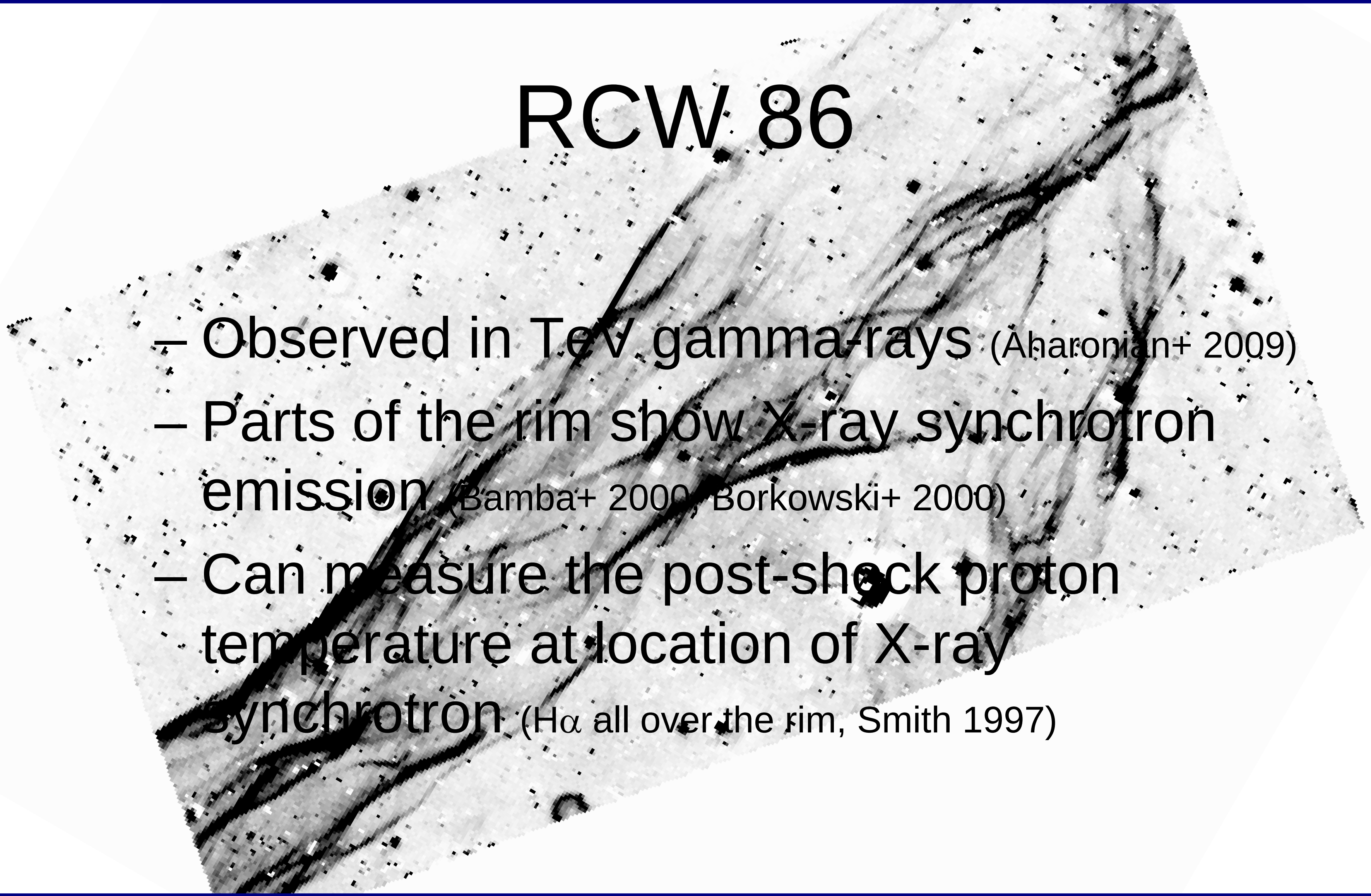
- Several remnants used to detect temperature drop:
  - 1E 0102-7219, reduced T_e (Hughes+ 2000)
  - Cygnus Loop, based on T_e, $P_{CR} = 0$ (Salvesen+ 2008)
  - Tycho (knot g), based on $T_{p,}$ $P_{CR} = 0$* (Vink 2008)
  - RCW 86 based on T_p, P_{CR}= 50% (Helder, Vink+ 2009)

*Based on distance determined using FWHM Hα emission in combination with proper motion



Temperatures

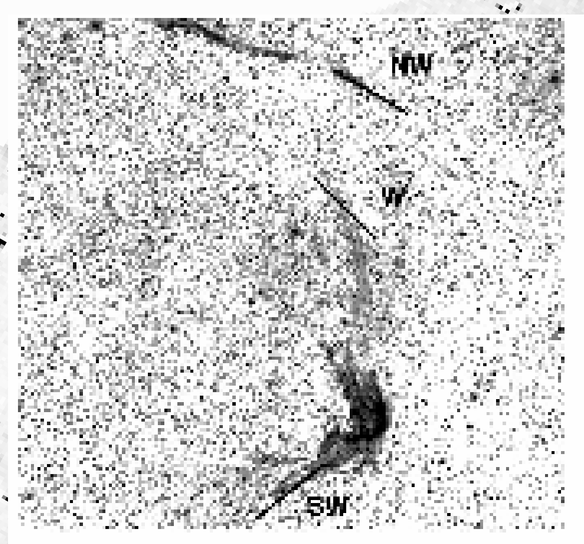
- Electron temperature might contribute only a minor part to post-shock pressure (non equilibration), and hard to obtain in spectra dominated by synchrotron emission
- Ion temperatures hard to measure
  - done in UV (Raymond+ 1995, Ghavamian+ 2007)
  - done in X-ray (Vink+ 2003)

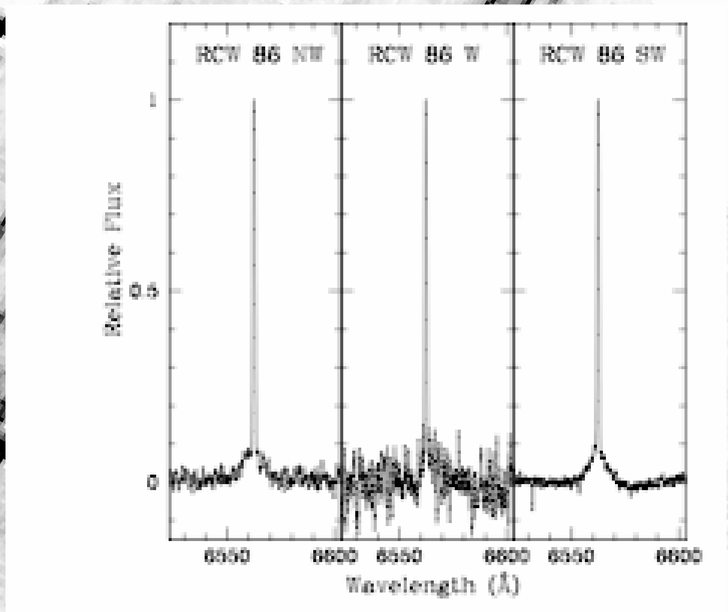


RCW 86

– Observed in TeV gamma-rays (Aharonian+ 2009)
– Parts of the rim show X-ray synchrotron emission (Bamba+ 2000, Borkowski+ 2000)
– Can measure the post-shock proton temperature at location of X-ray synchrotron (Hα all over the rim, Smith 1997)

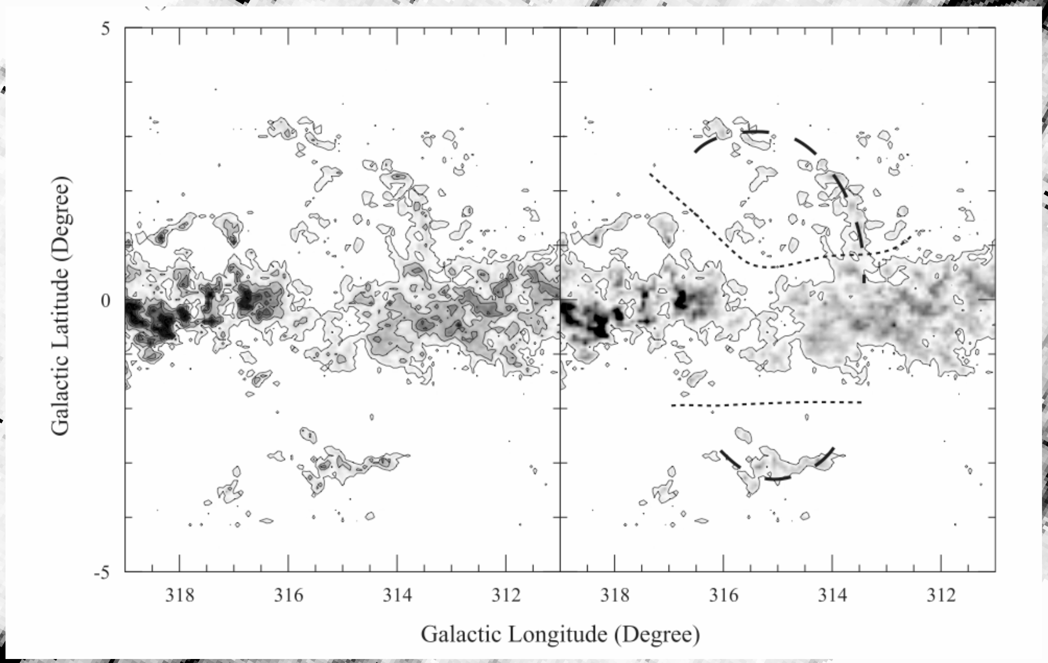
Distance towards RCW 86





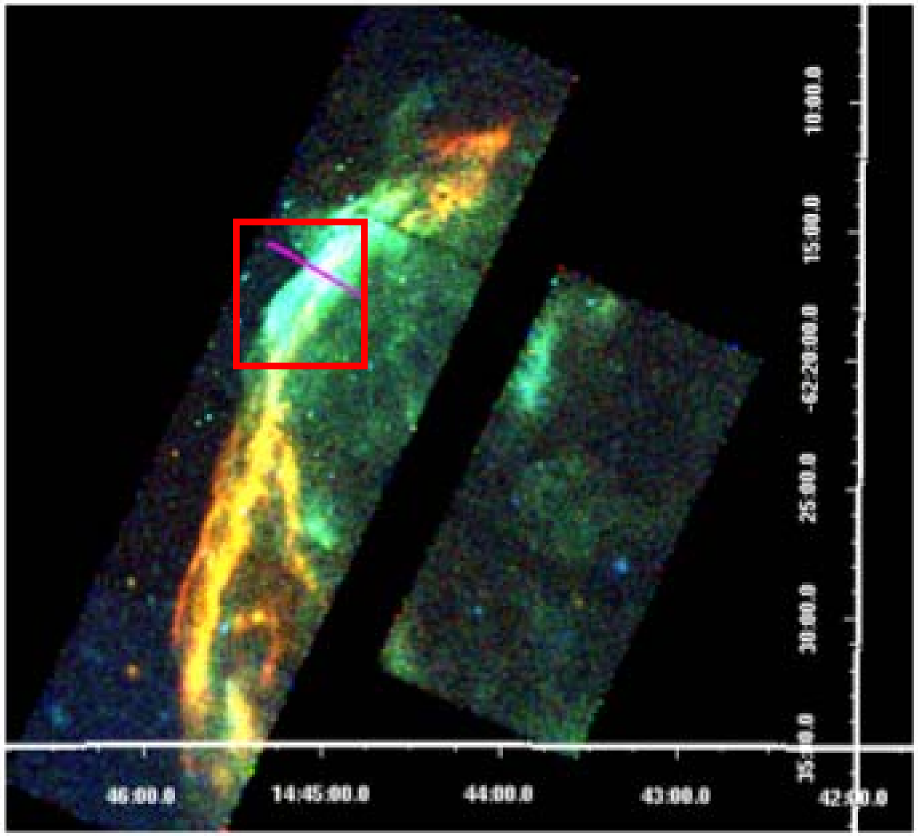
- OB association at 2.5 kpc (Westerlund 1969)
- Local V_{ISM} measured using narrow component Hα, combined with Galactic rotation curve gives ~2.5 kpc (Rosado+ 1996, Sollerman+ 2003)

Distance towards RCW 86

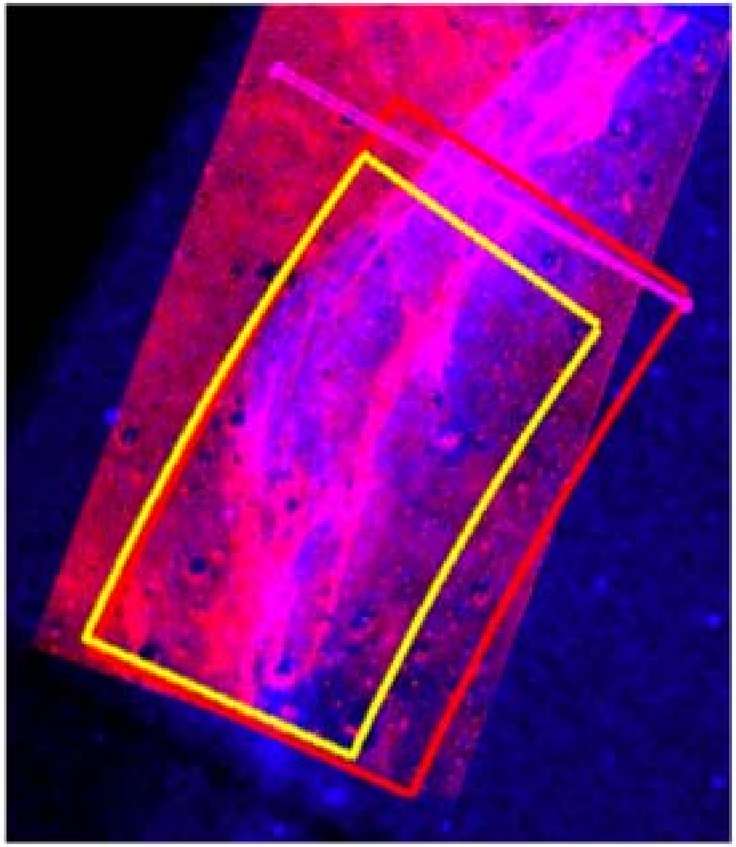


Blowout seen in CO with same l.o.s. velocity
(Matsunaga+ 2001)

RCW 86

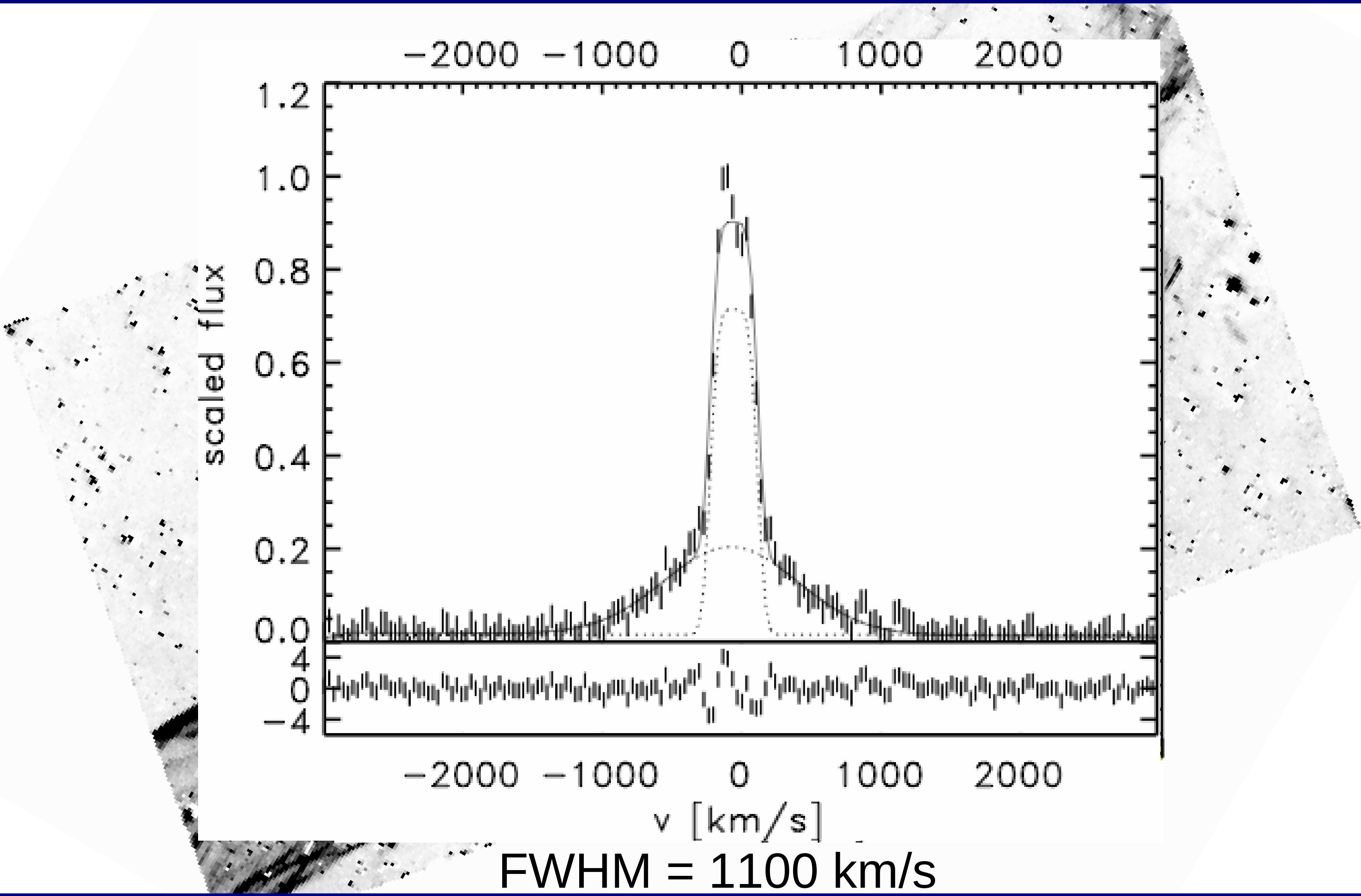


X-ray (Chandra)



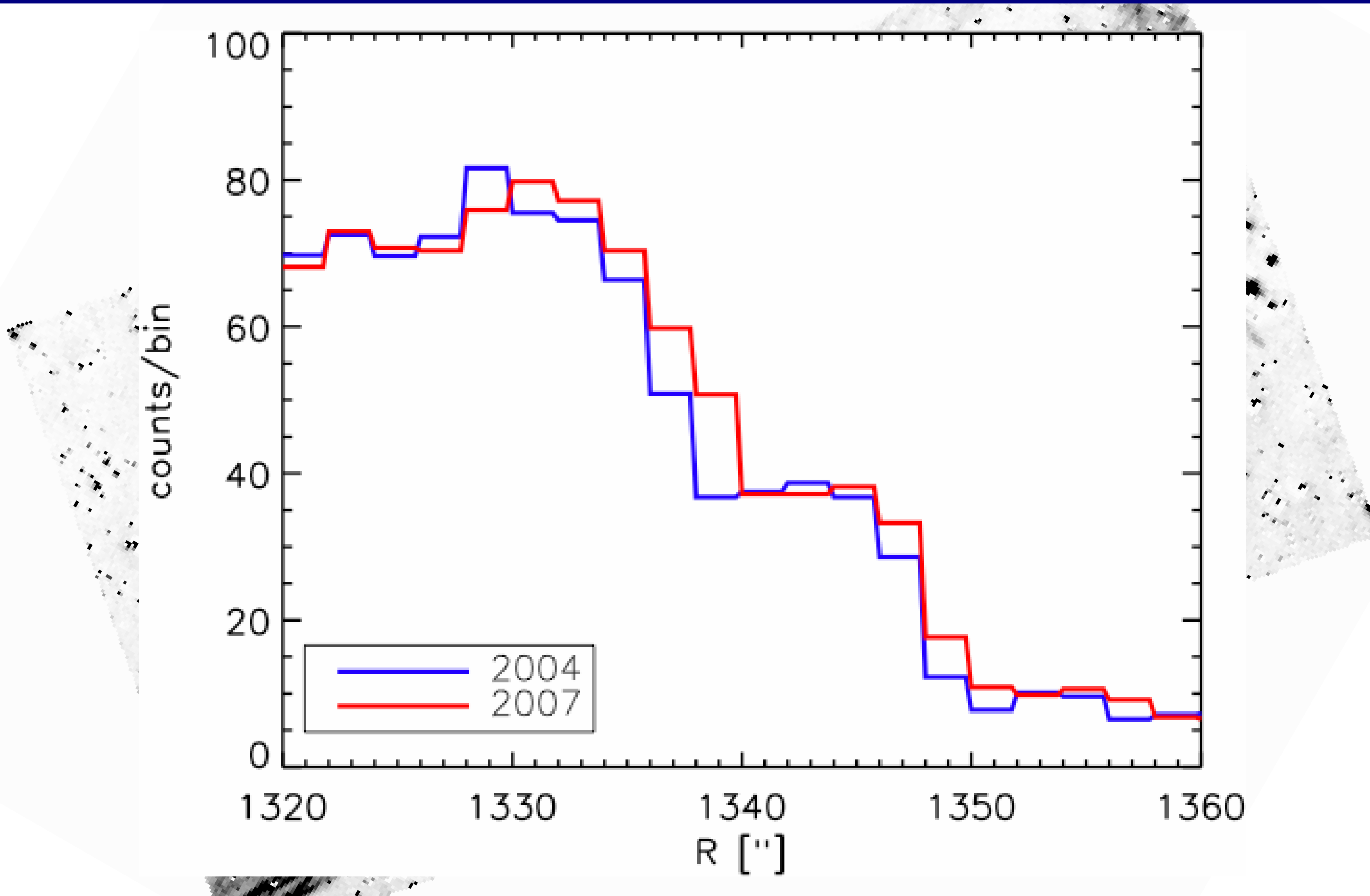
X-ray (blue) + Hα (red)

Hα emission of supernova remnants

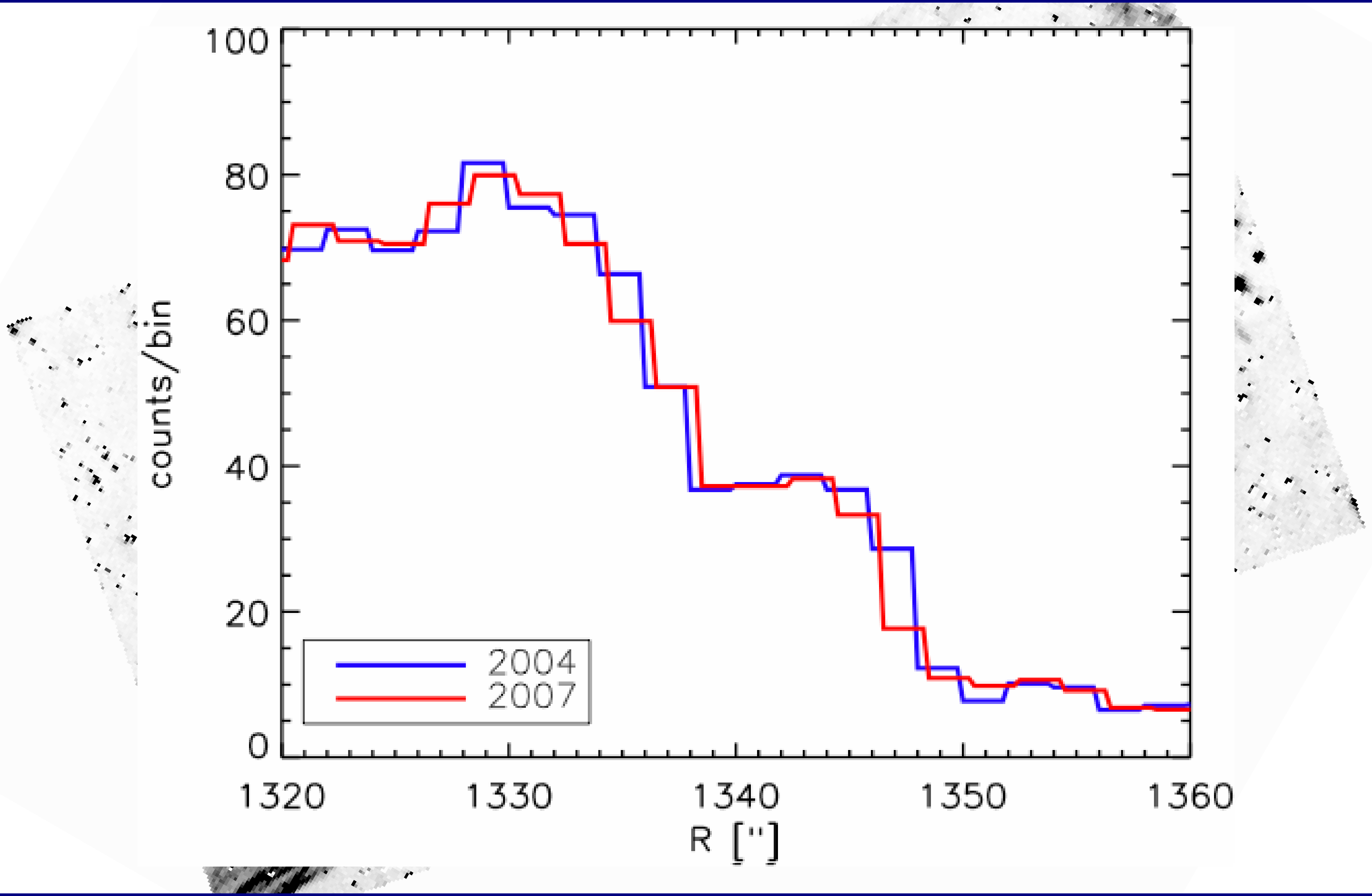


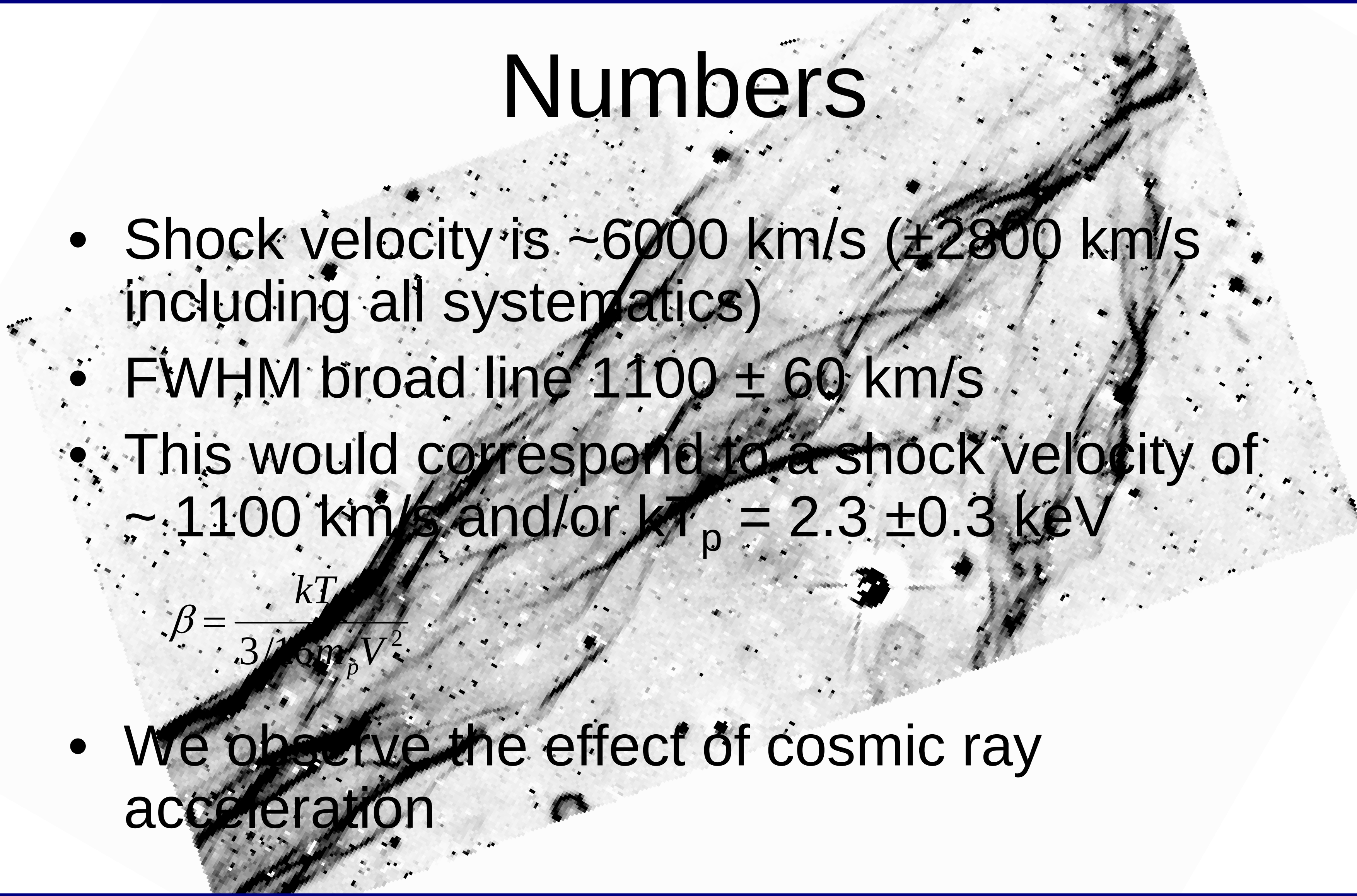
FWHM = 1100 km/s

Hα emission of supernova remnants



Hα emission of supernova remnants





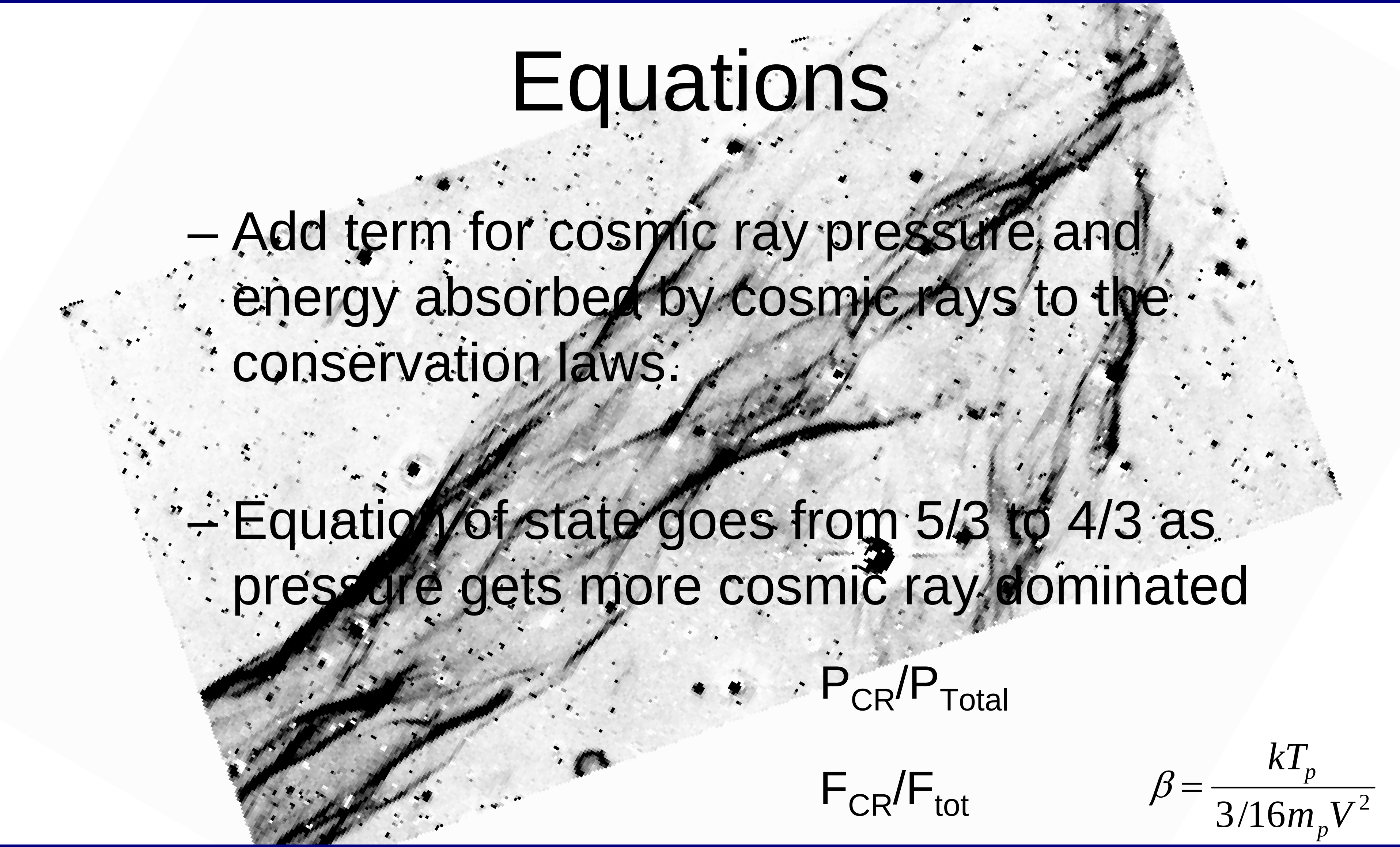
Numbers

- Shock velocity is ~6000 km/s (±2800 km/s including all systematics)
- FWHM broad line 1100 ± 60 km/s
- This would correspond to a shock velocity of ~ 1100 km/s and/or kT_p = 2.3 ±0.3 keV

$$\beta = \frac{kT}{3/16\, m_p V^2}$$

- We observe the effect of cosmic ray acceleration

Equations



– Add term for cosmic ray pressure and energy absorbed by cosmic rays to the conservation laws.

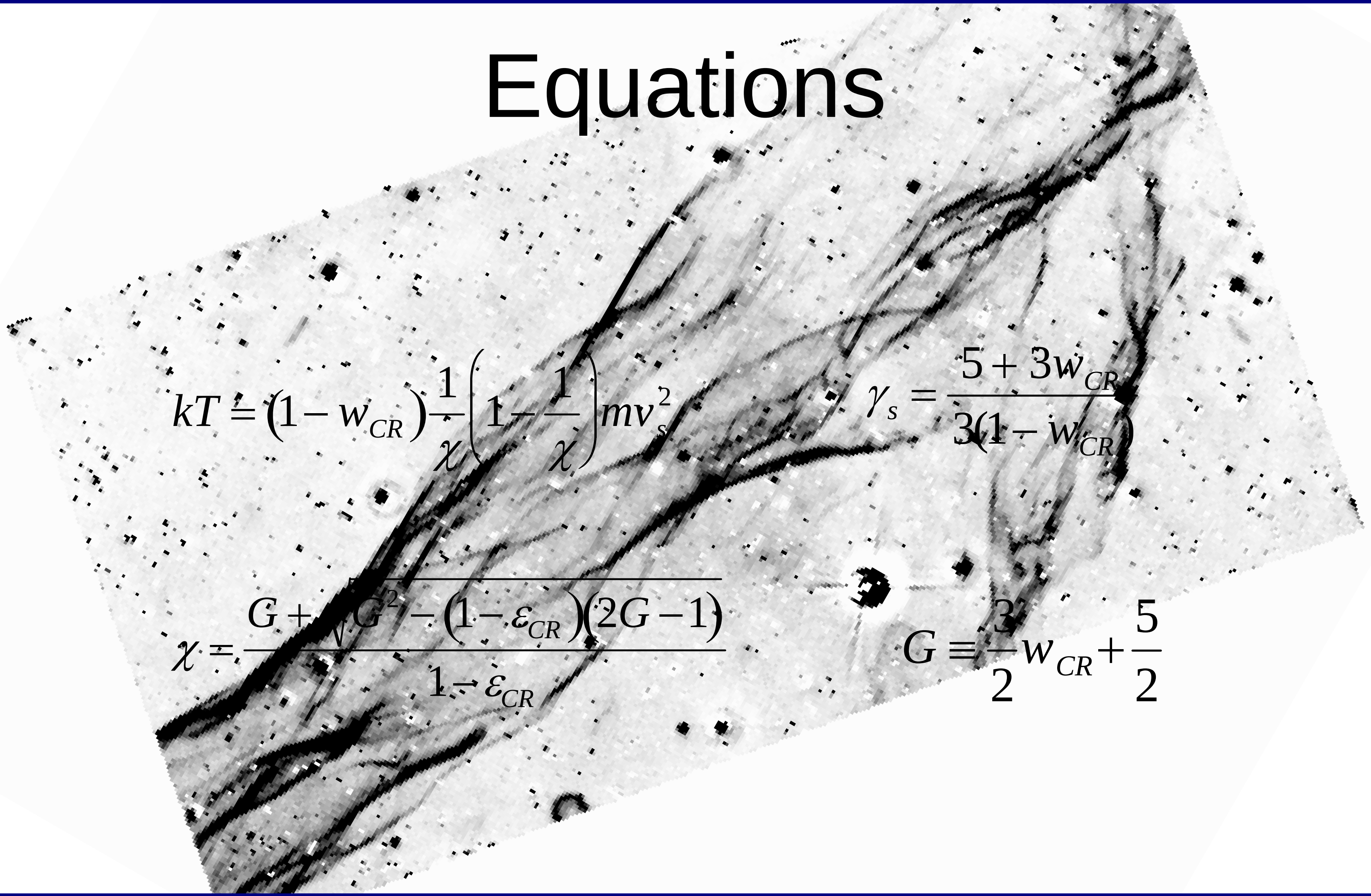
– Equation of state goes from 5/3 to 4/3 as pressure gets more cosmic ray dominated

P_{CR}/P_{Total}

F_{CR}/F_{tot}

$$\beta = \frac{kT_p}{3/16 m_p V^2}$$

Equations



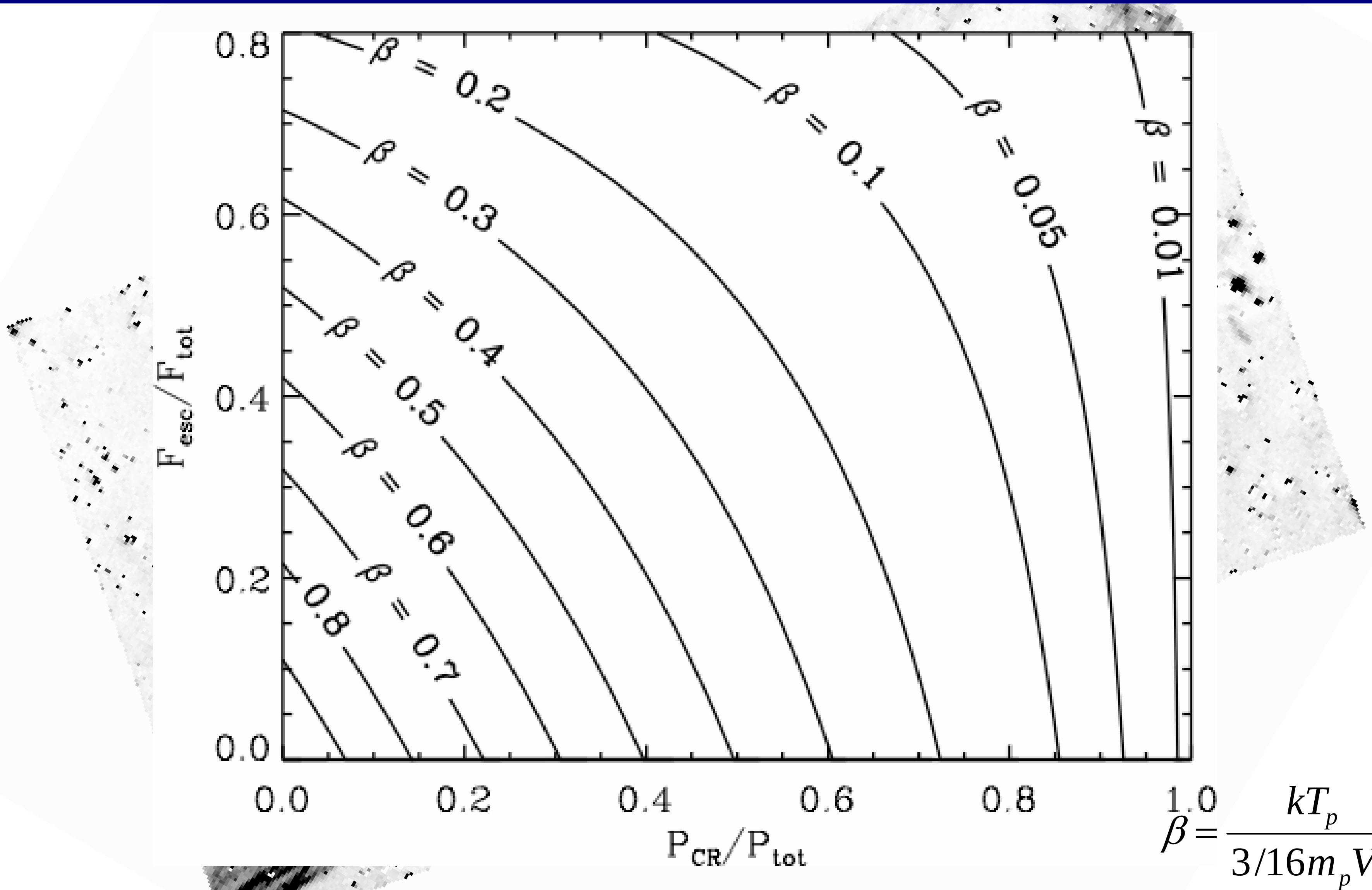
$$kT = (1 - w_{CR})\frac{1}{\chi}\left(1 - \frac{1}{\chi}\right) m v_s^2$$

$$\gamma_s = \frac{5 + 3w_{CR}}{3(1 - w_{CR})}$$

$$\chi = \frac{G + \sqrt{G^2 - (1 - \varepsilon_{CR})(2G - 1)}}{1 - \varepsilon_{CR}}$$

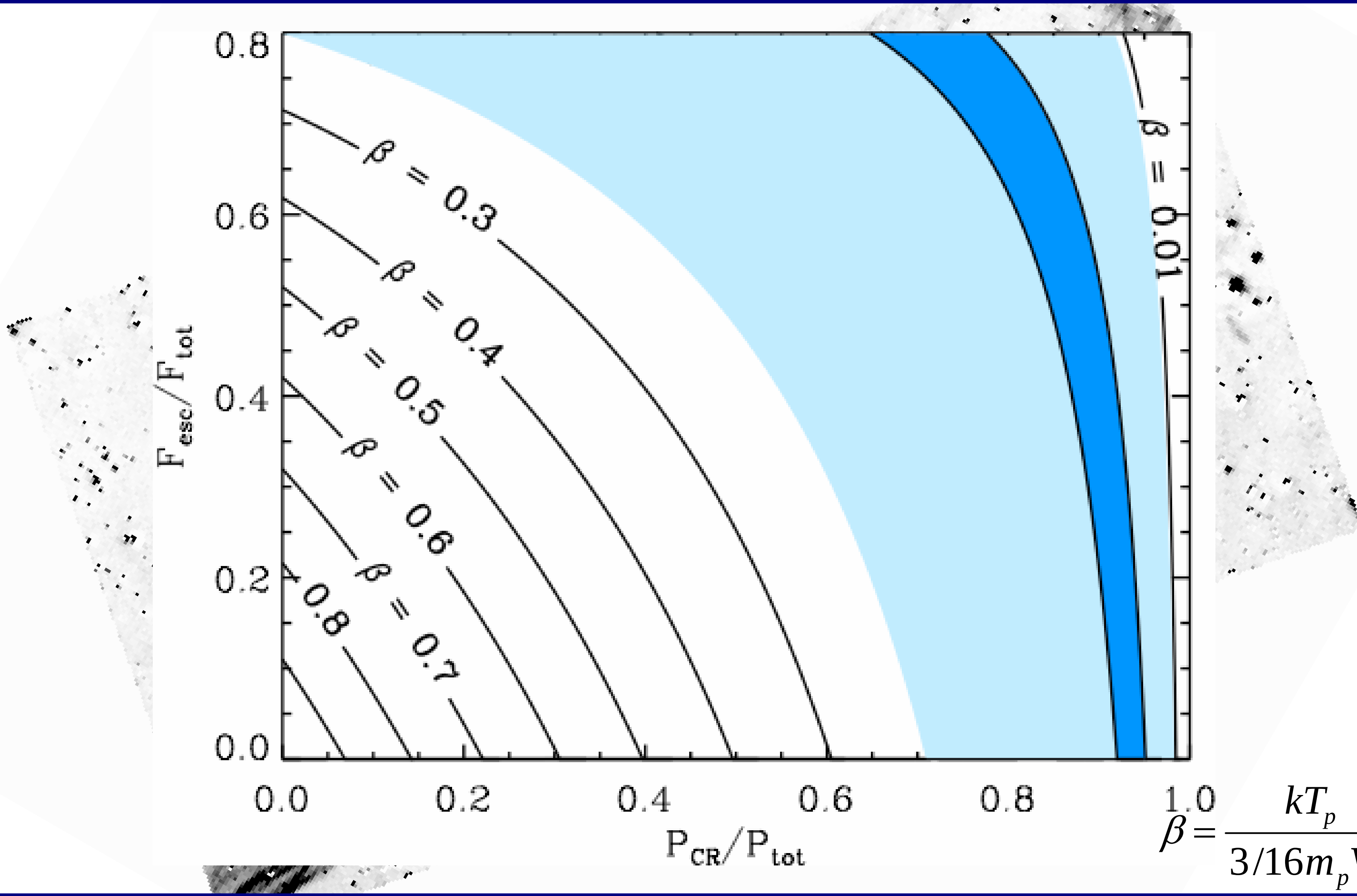
$$G \equiv \frac{3}{2} w_{CR} + \frac{5}{2}$$

Hα emission of supernova remnants



$$\beta = \frac{kT_p}{3/16 m_p V^2}$$

Hα emission of supernova remnants



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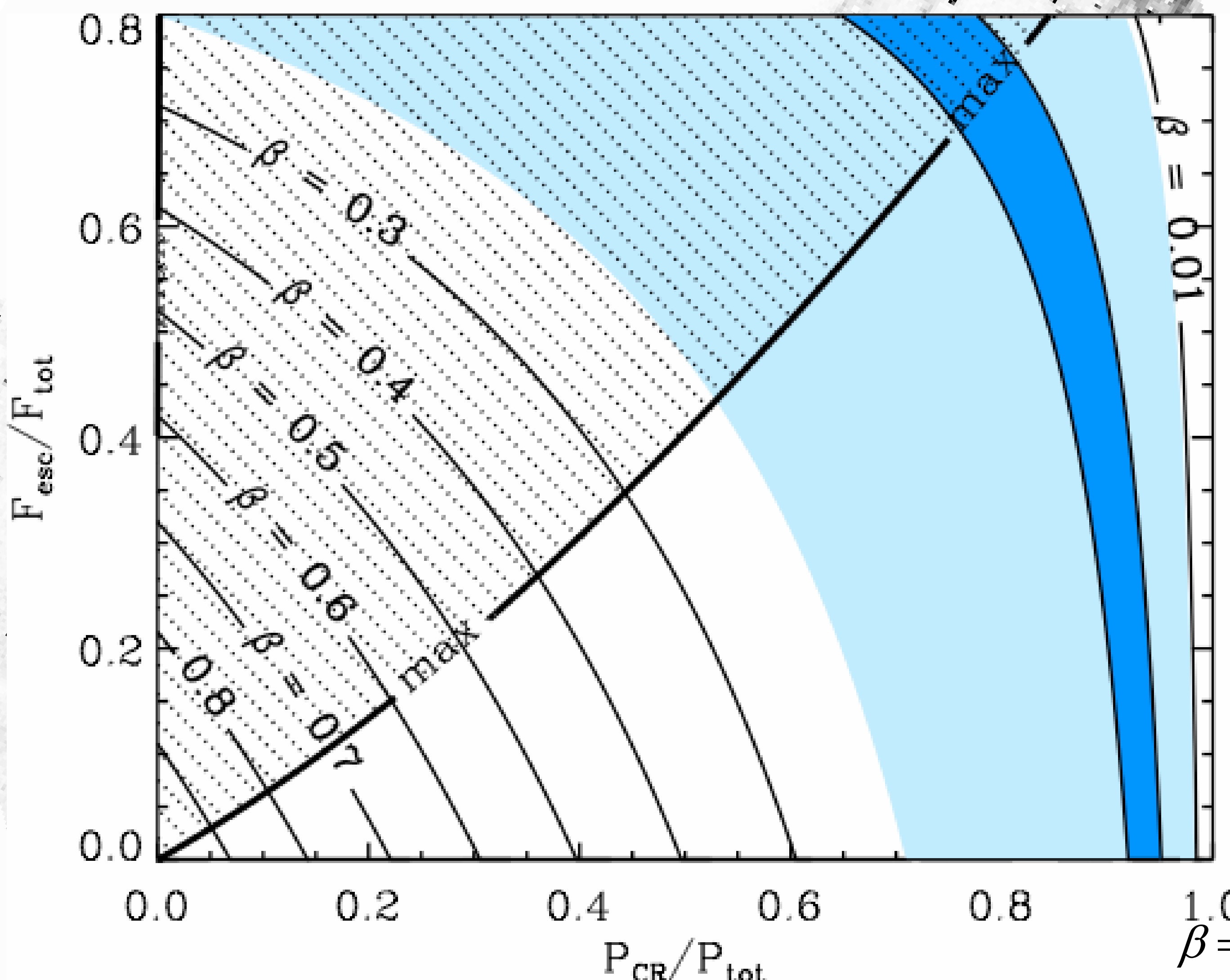
Hα emission of supernova remnants



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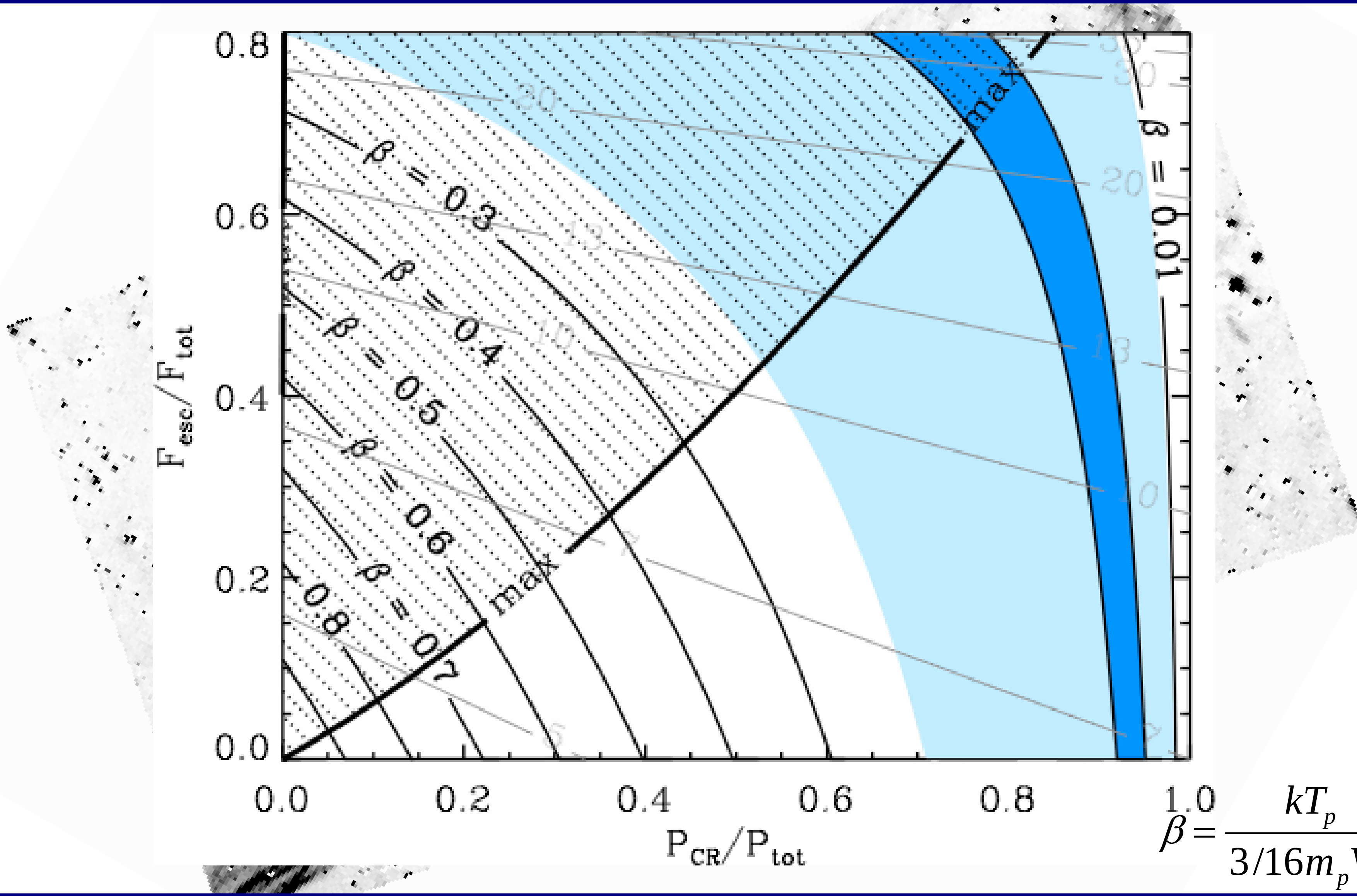
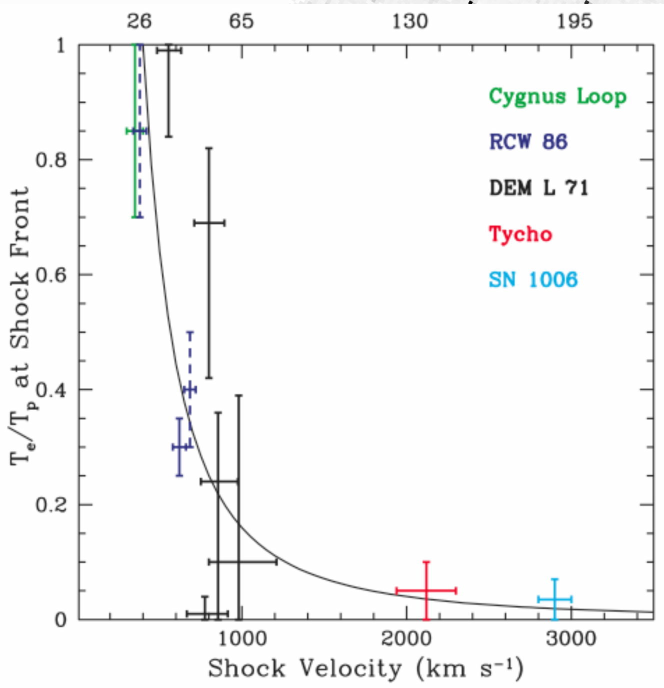
Hα emission of supernova remnants



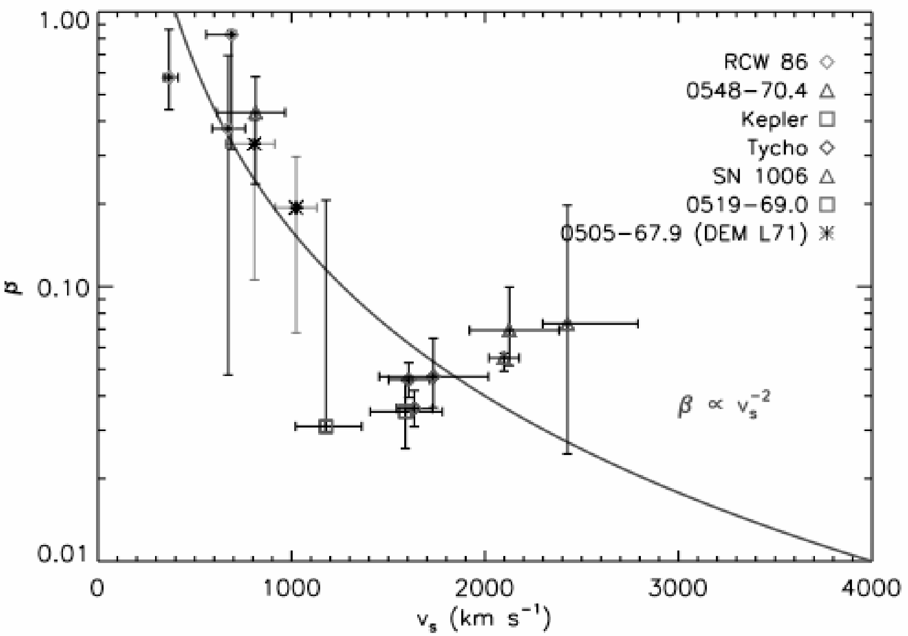
$$\beta = \frac{kT_p}{3/16 m_p V^2}$$

Hα emission of supernova remnants

T_e/T_p



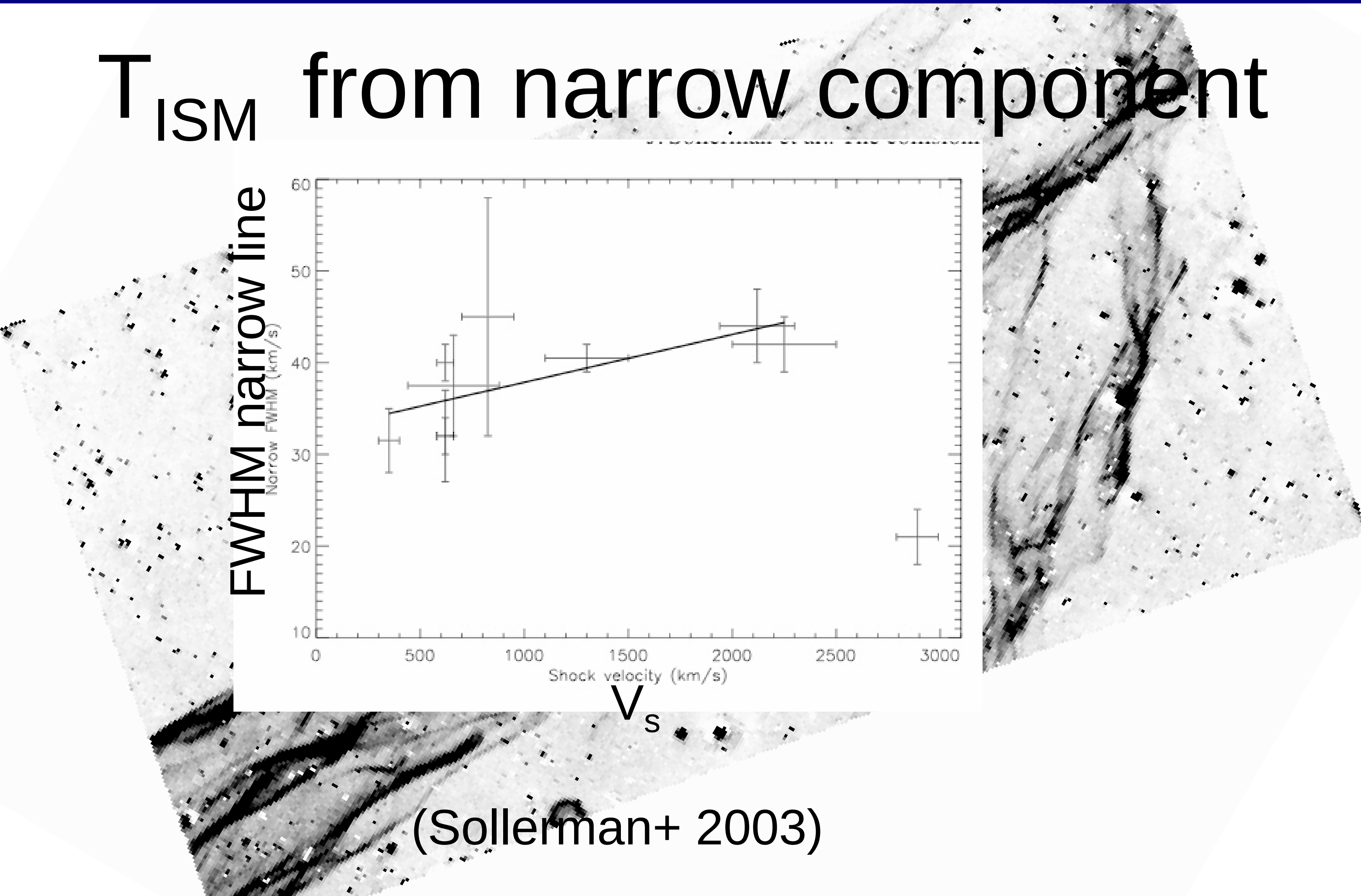
Ghavamian+ 2007



Van Adelsberg+ 2008

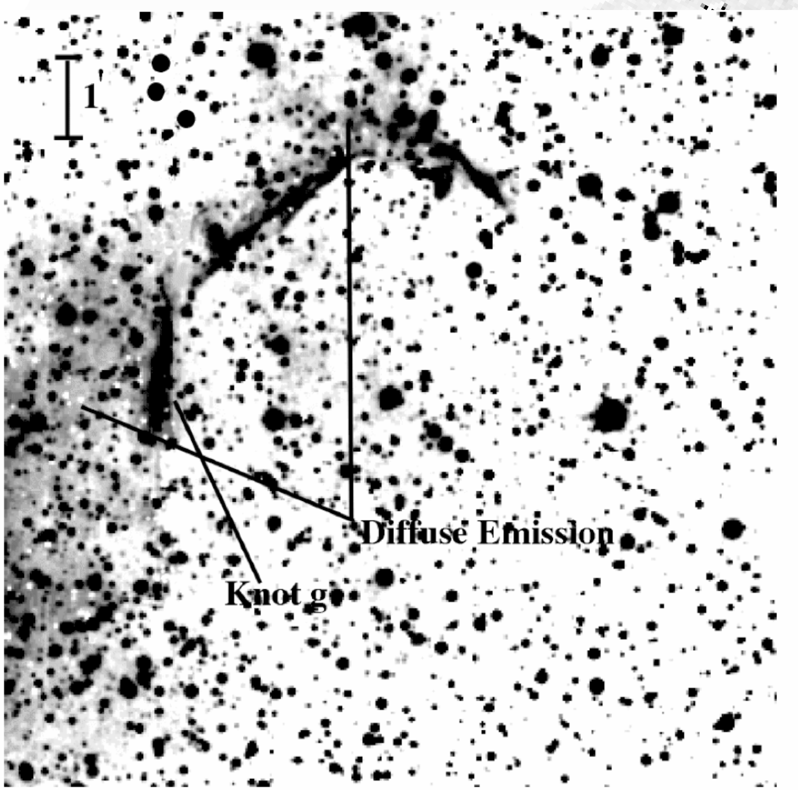
+

T_{ISM} from narrow component

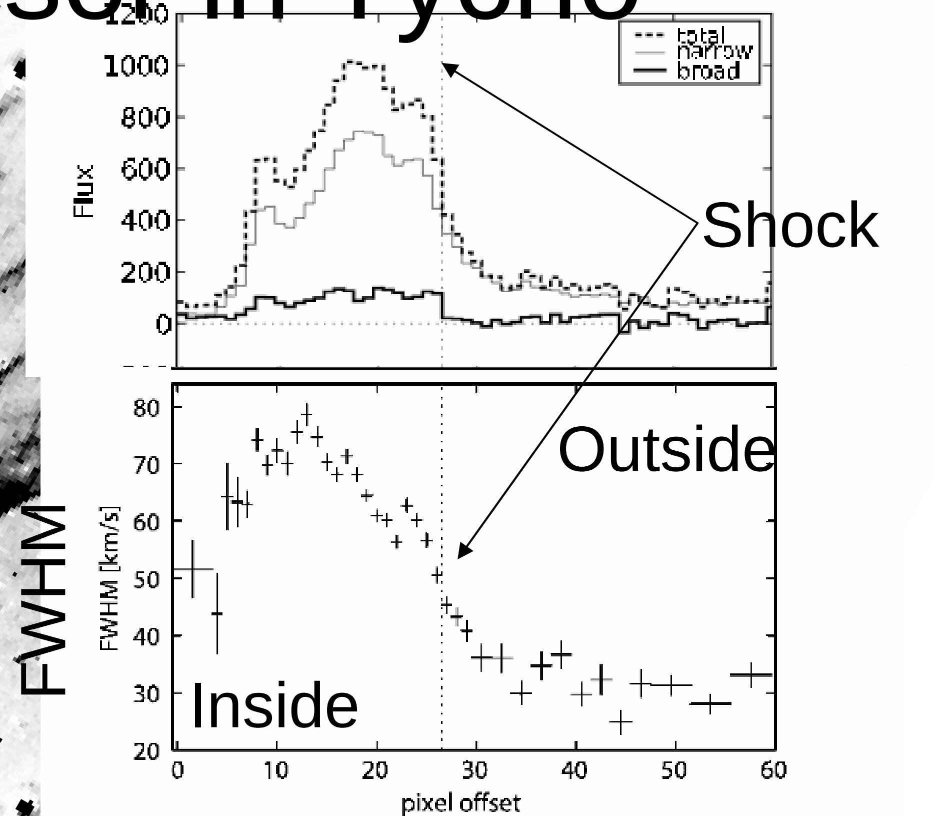


(Sollerman+ 2003)

Shock precursor in Tycho



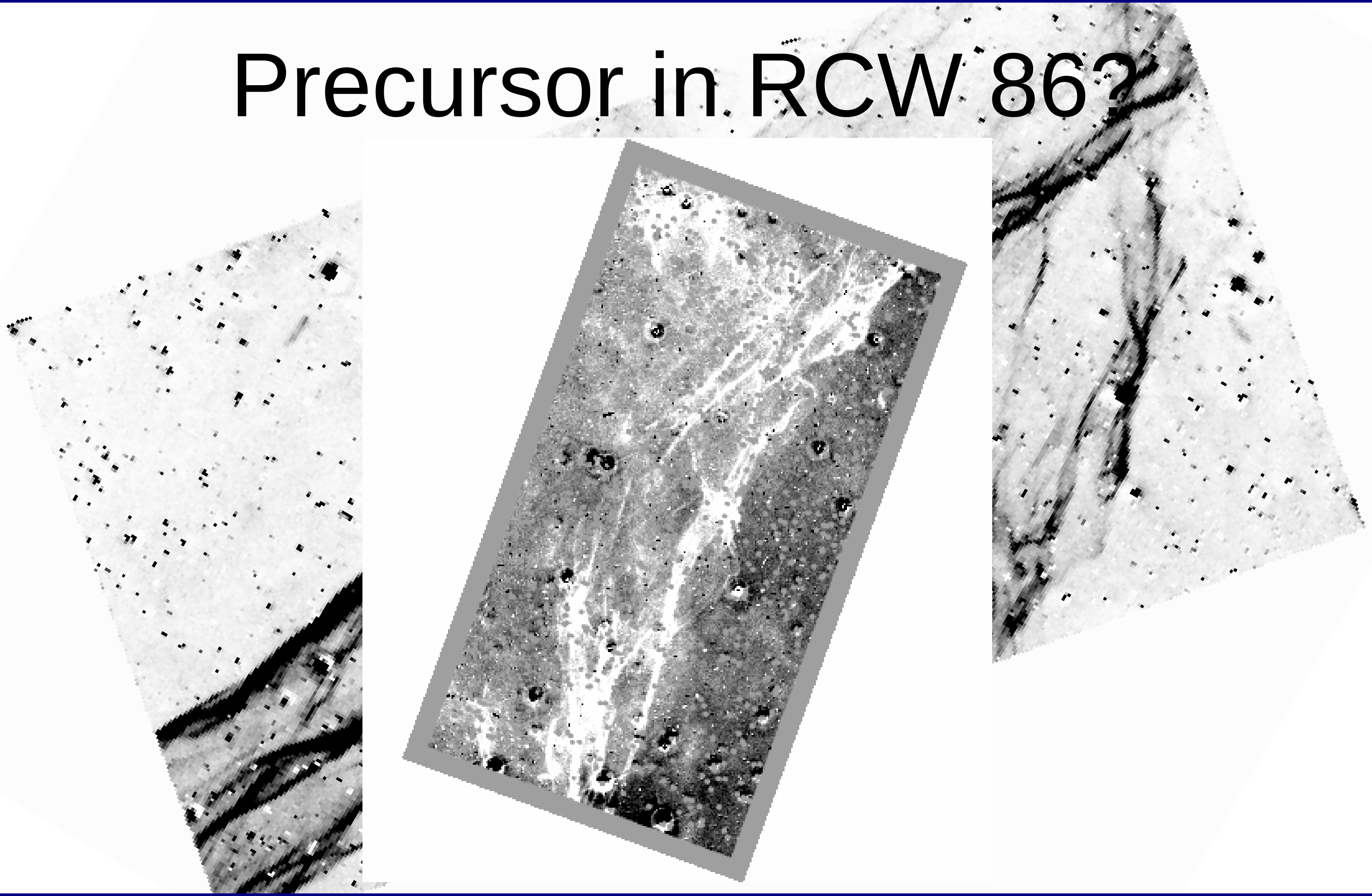
(Ghavamian+ 2000)



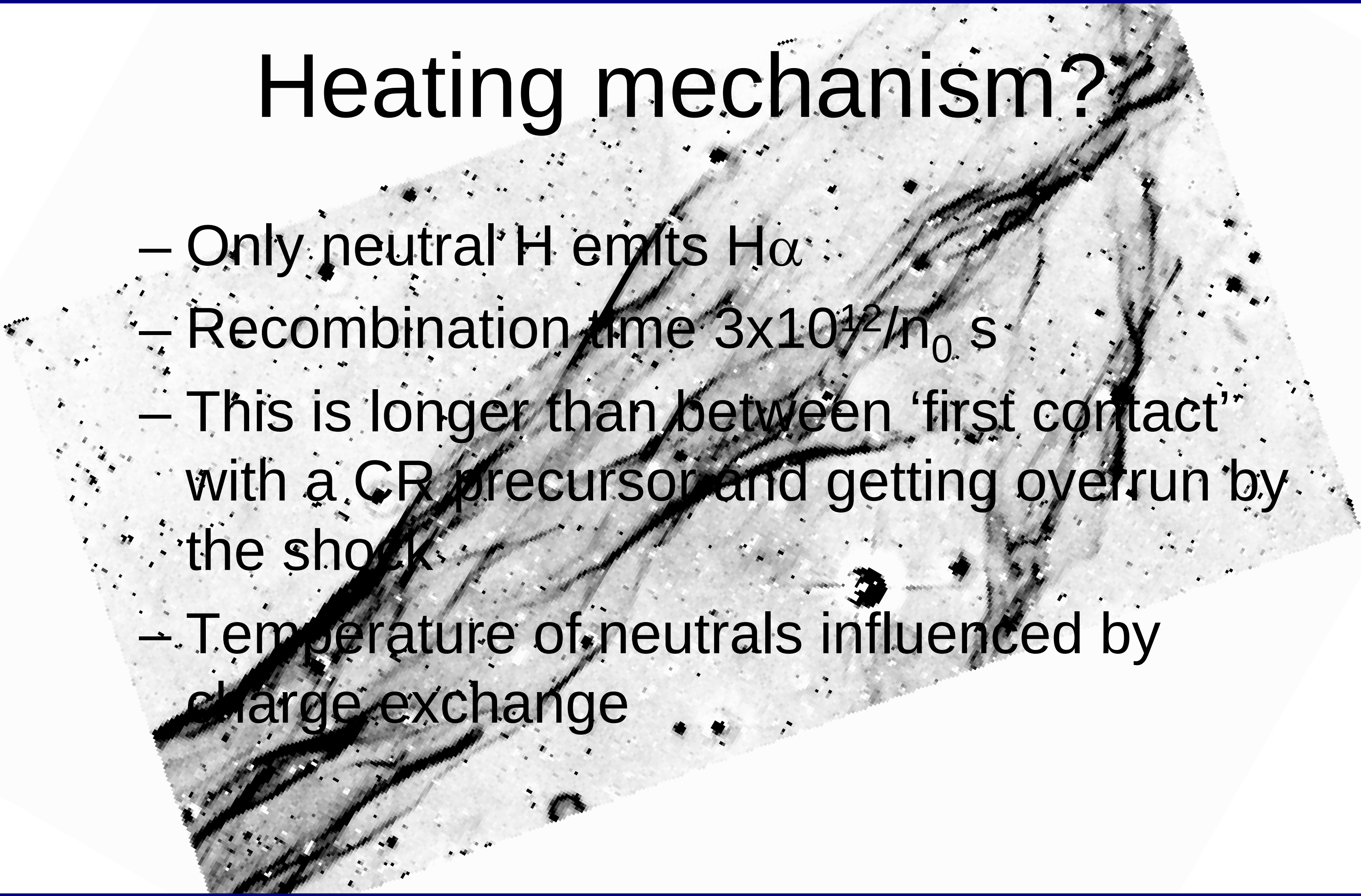
'X'

(Lee+ 2007, Wagner+ 2008)

Precursor in RCW 86?

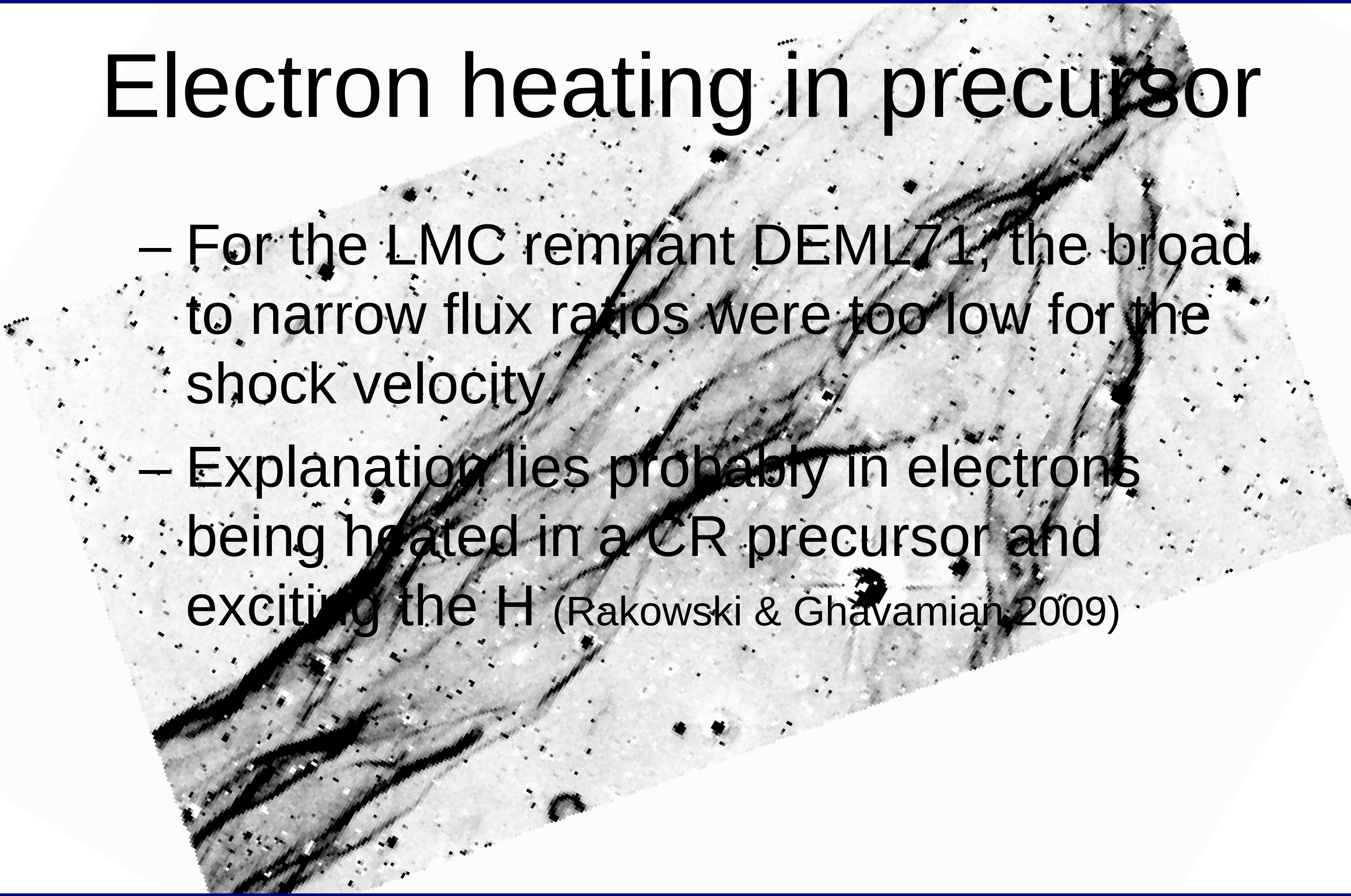


Heating mechanism?

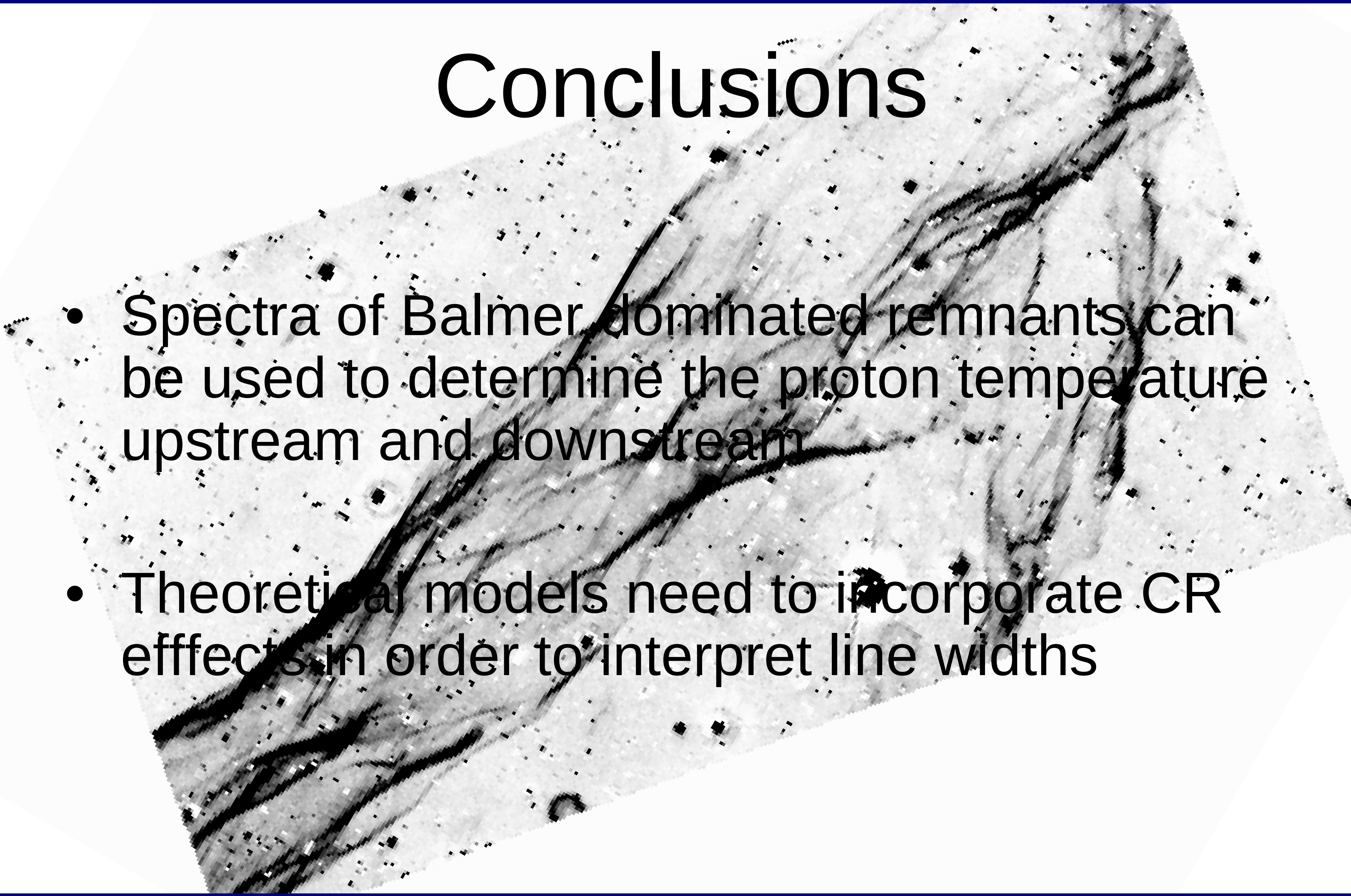


- Only neutral H emits Hα
- Recombination time $3\times10^{12}/n_0$ s
- This is longer than between ‘first contact’ with a CR precursor and getting overrun by the shock
- Temperature of neutrals influenced by charge exchange

Electron heating in precursor



- For the LMC remnant DEML71, the broad to narrow flux ratios were too low for the shock velocity
- Explanation lies probably in electrons being heated in a CR precursor and exciting the H (Rakowski & Ghavamian 2009)



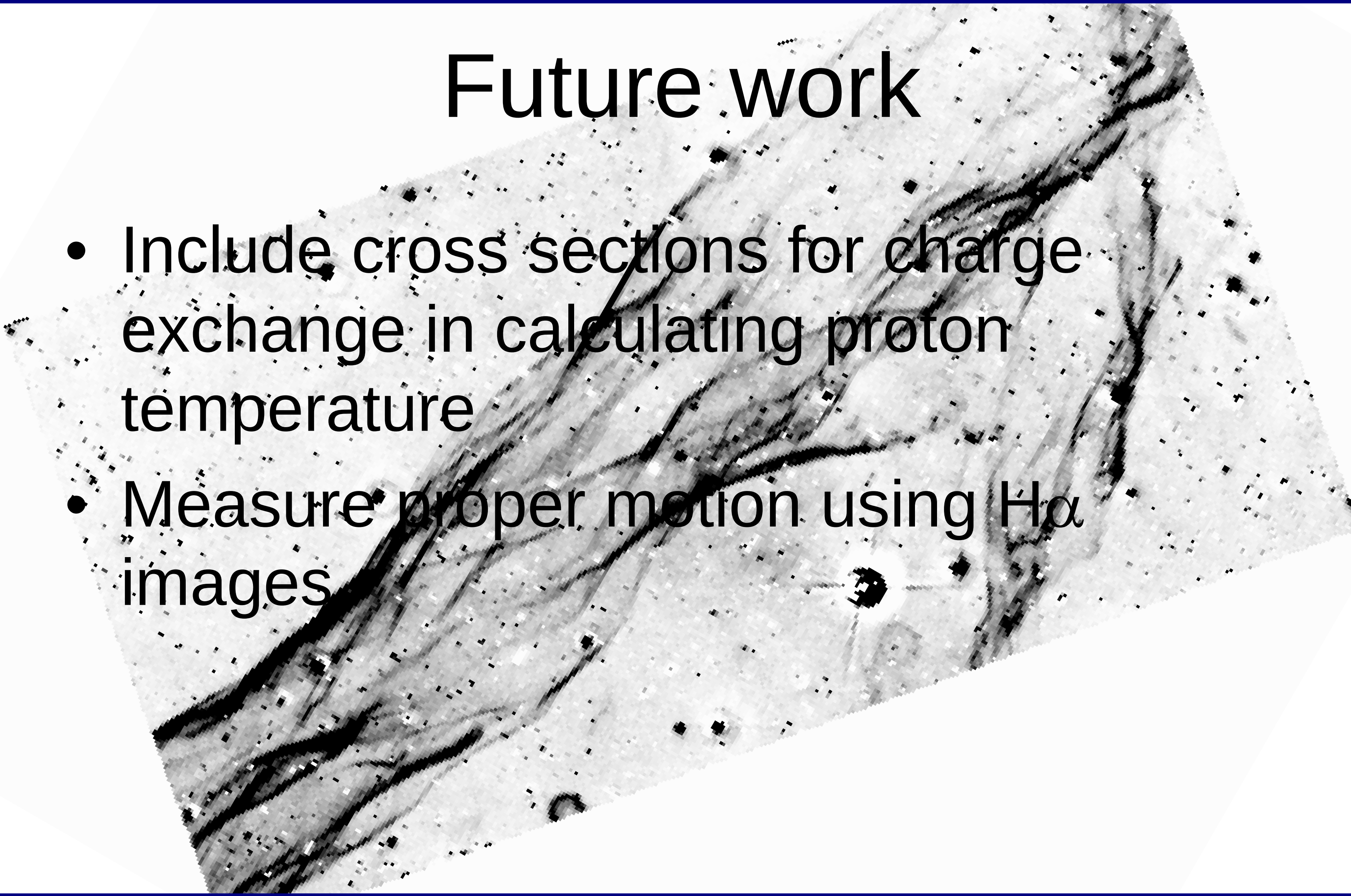
Conclusions

- Spectra of Balmer dominated remnants can be used to determine the proton temperature upstream and downstream
- Theoretical models need to incorporate CR efffects in order to interpret line widths

Hα emission of supernova remnants

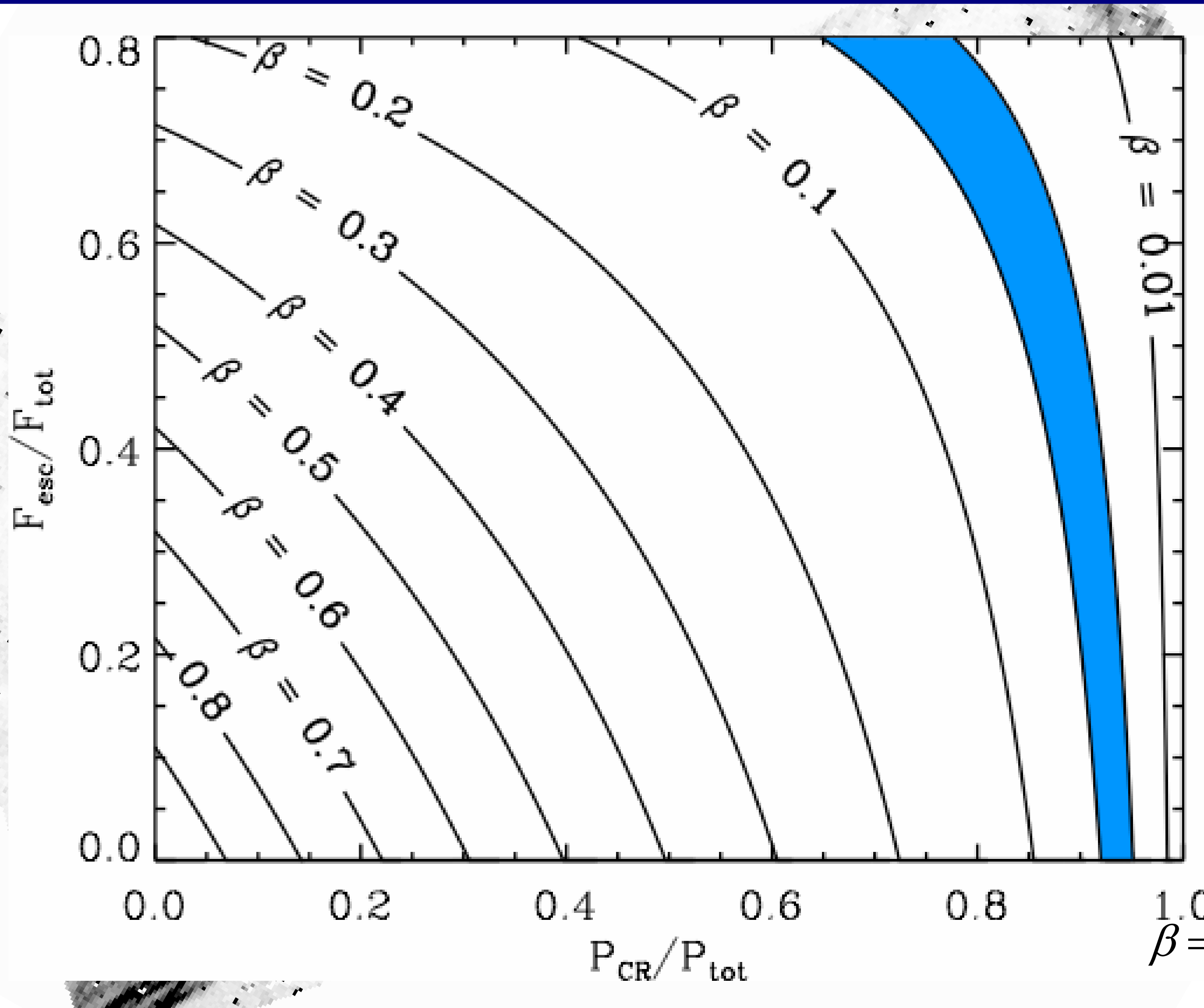
Thank you!

Future work



- Include cross sections for charge exchange in calculating proton temperature
- Measure proper motion using Hα images

Hα emission of supernova remnants



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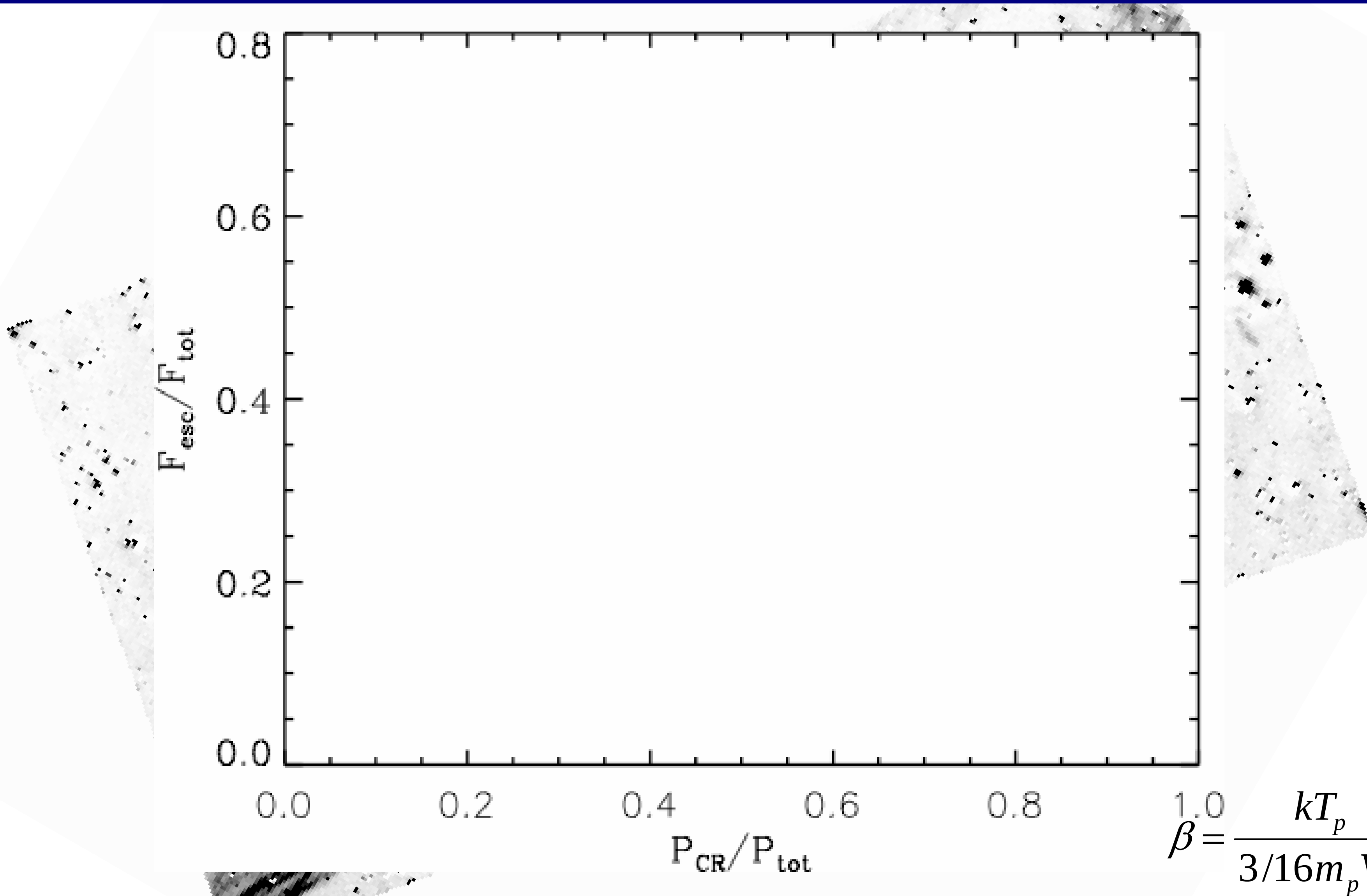
Hα emission of supernova remnants



$$\beta = \frac{kT_p}{3/16 m_p V^2}$$