Waves at Oblique Shocks and the Highest Cosmic Ray Energies in Tycho's SNR

Work supported by
Basic Research Funds
of CNR

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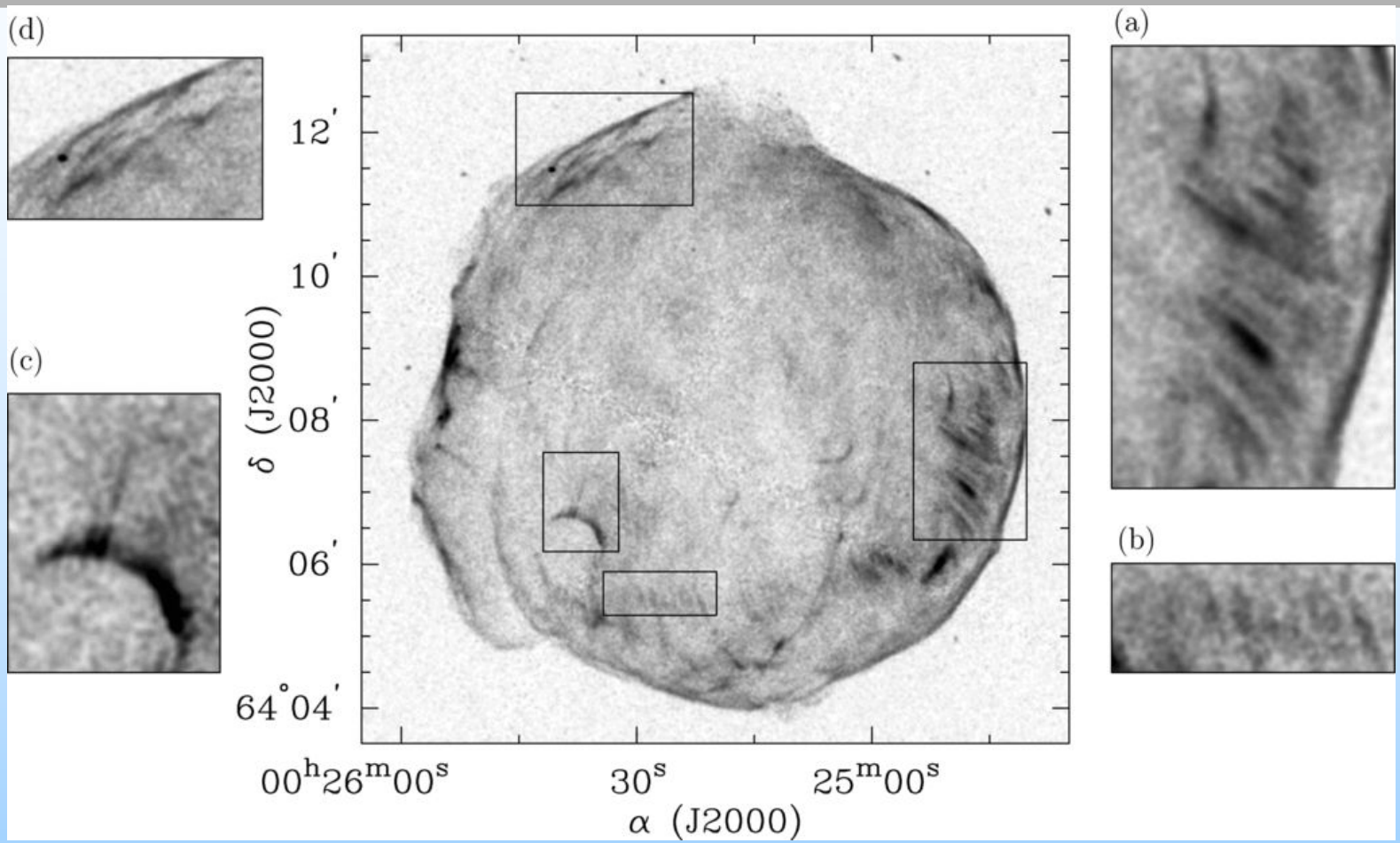
Eriksen et al. (2011), ApJ, 728, L28

750 ks Chandra observation of Tycho's SNR,

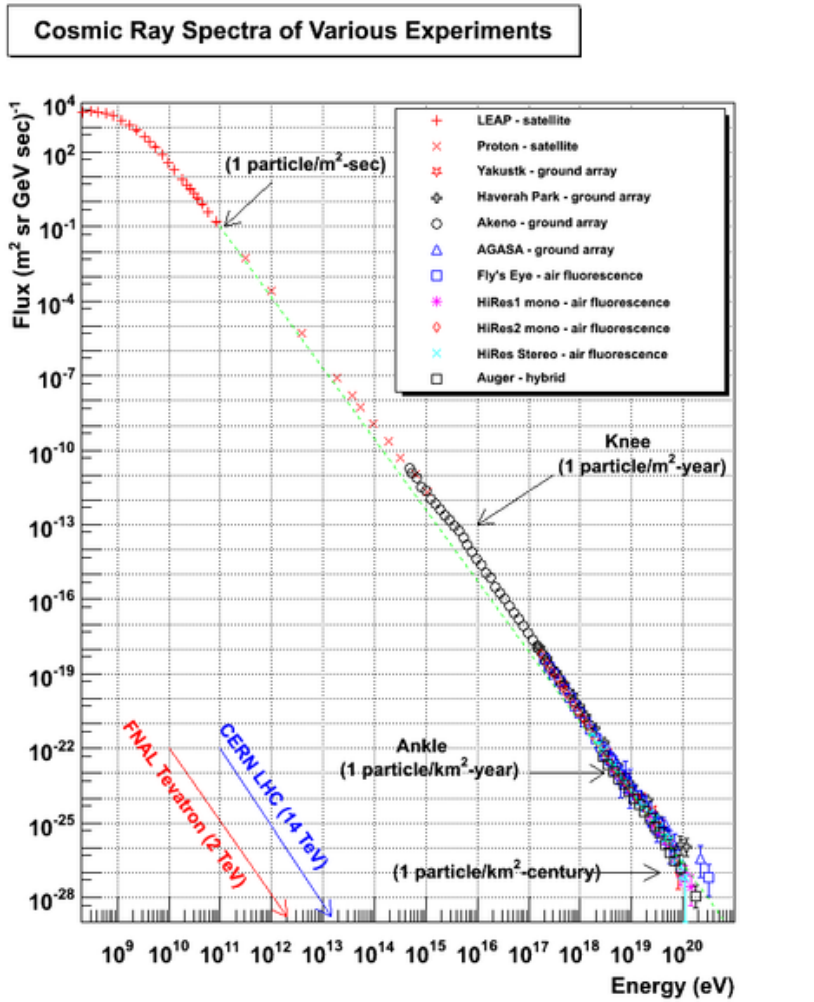
→ 4-6 keV bandpass dominated by electron synchrotron radiation

→ structures made by processes associated with cosmic ray ions?



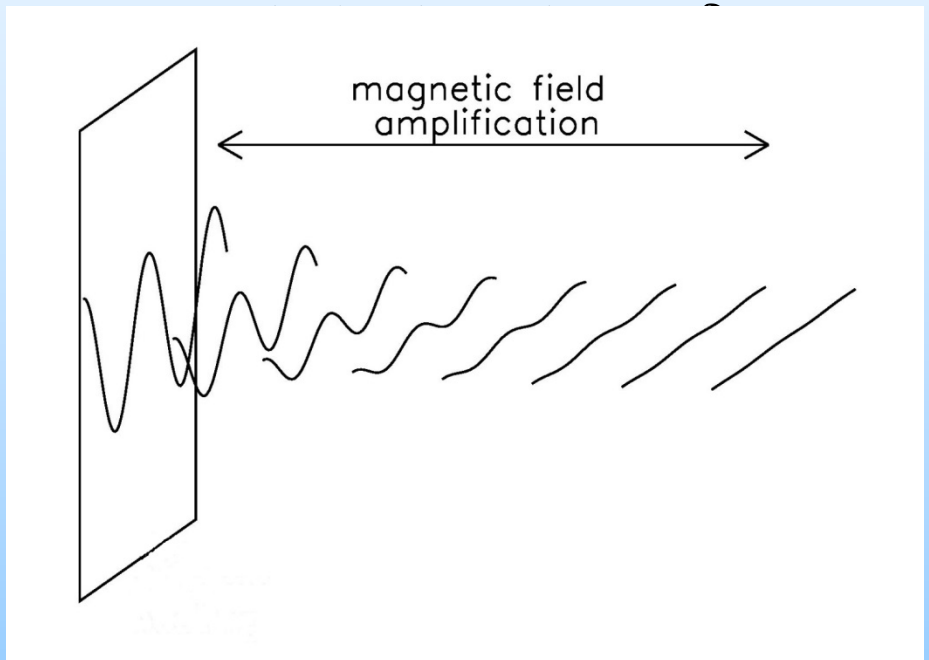
Bell (2004, 2005) Nonresonant Instability

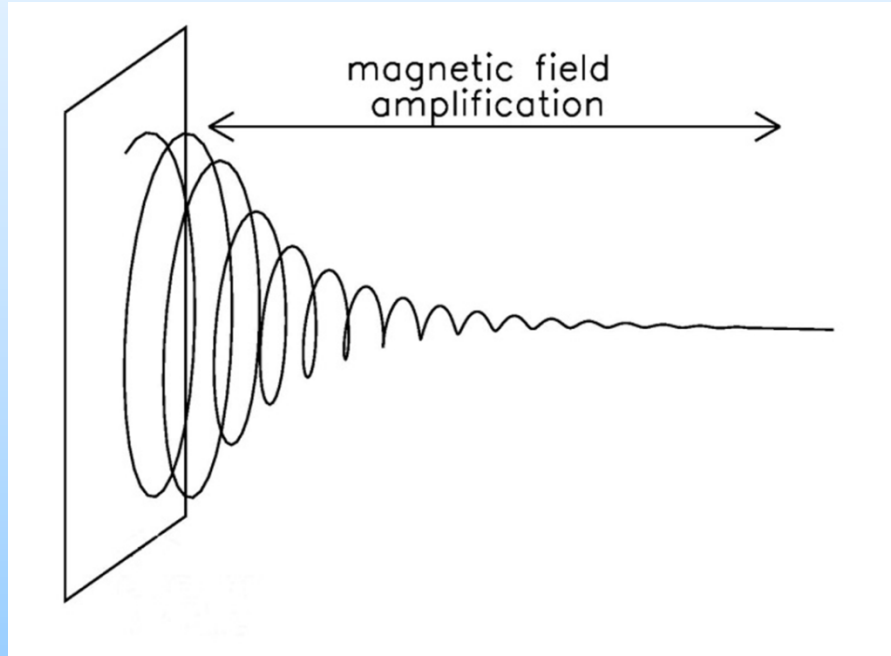
- Reactive instability where cosmic ray current generates modified Alfven waves, wave growth at zero frequency for $kr_g >> 1$
- Contrast with resonant wave growth $kr_g \sim 1$
- Max growth Γ at $k = J_{CR}B/2\rho c V_A^2 = \Gamma/\sqrt{2}\ V_A$
- Contrast with resonant wave growth → no max.
- At saturation, cosmic ray current and growth is driven by the few unmagnetized highest energy cosmic rays → wavelengths and spatial structures determined by **maximum cosmic ray energy**.
- Do SNRs accelerate cosmic rays up to the "knee"?



Earlier Ideas About the Stripes

- Bykov et al. 2011: quasi perpendicular shock, Bell instability generates linearly polarized structures leading to stripes?
- Caprioli & Spitkovsky 2013: forward shock protruding into cavities produced by Bell instability at saturation, also leading to stripes?
- Malkov et al. 2012: quasi parallel shock, Alfvénic solitons with

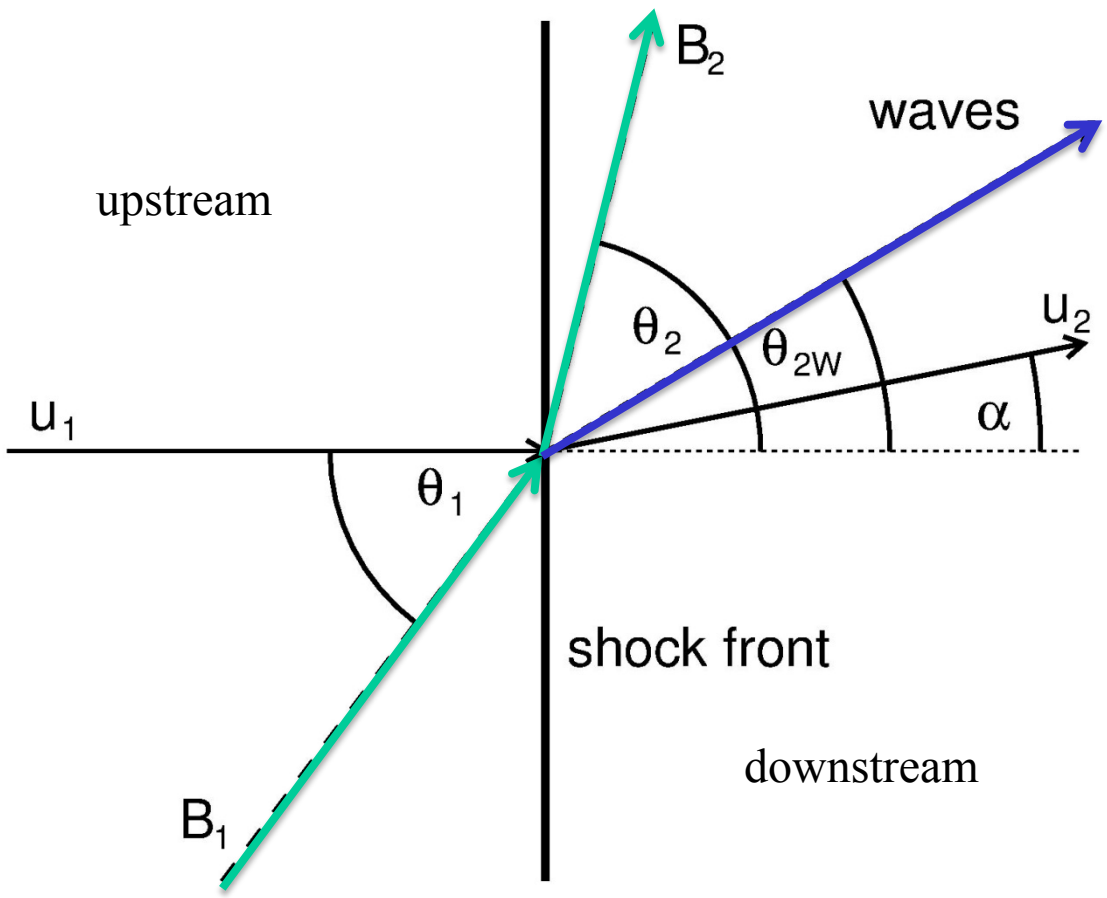




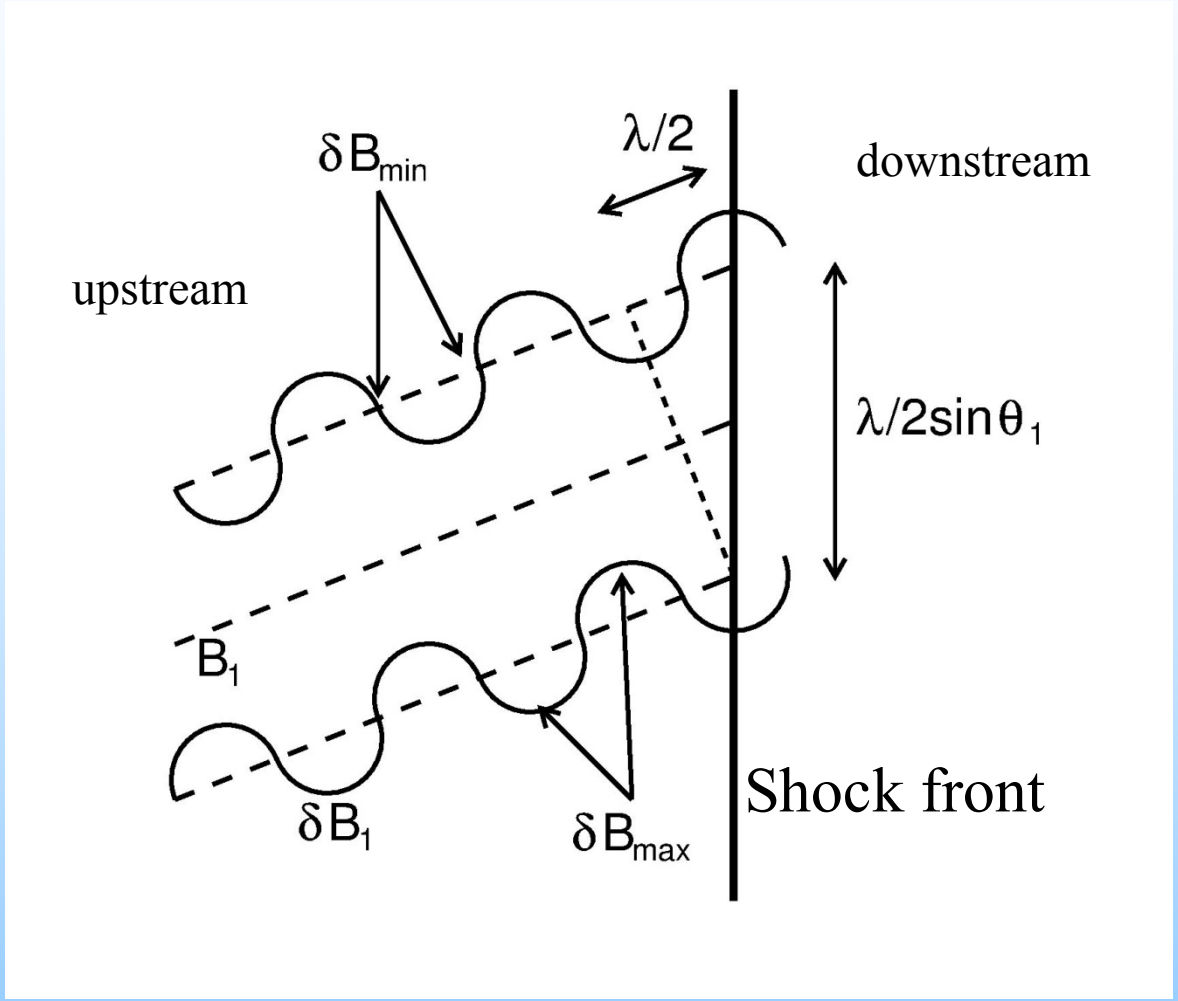
New Approach (Laming 2015)

- Parallel circularly polarized waves generated upstream by nonresonant Bell Instability at quasi-parallel shock
- With nonzero shock obliquity, upon shock passage waves become oblique propagating
- Magnetosonic polarization strongly damped by transit time damping
- Surviving Alfvén polarization gives rise to stripes

Refraction at the Shock Front



Origin and Motion of the Stripes



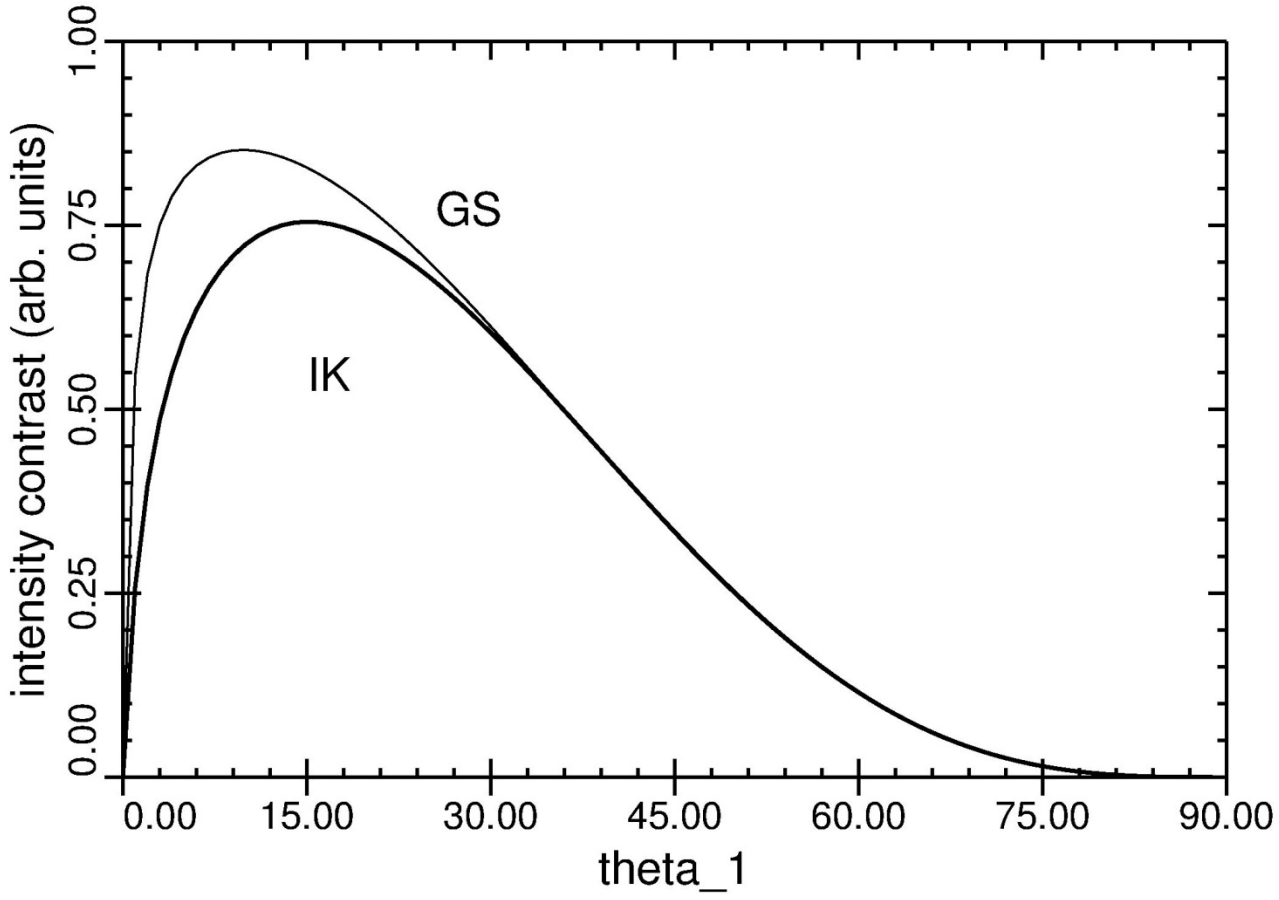
Recipe

following Webb et al. (1999), Achterberg & Blandford (1986), McKenzie & Westphal (1970)

- Calculate wave refraction at shock as function of obliquity
- Calculate wave reflection and transmission coefficients
- Calculate wave damping by turbulent cascade (Alfvén & magnetosonic) and by transit time damping (magnetosonic only)
- Calculate stripe contrast as function of obliquity for weak (Goldreich-Sridhar) and strong (Iroshnikov-Kraichnan) turbulence
- Find obliquity where contrast is maximum

Dependence of Stripe Contrast on Shock Obliquity

Goldreich-Sridhar or Iroshnikov-Kraichnan turbulence



Implications for Maximum CR Energy:

- Stripe separation 10” → 5e17 cm at Tycho
- Wavelength $\lambda/2\sin\theta=5e17$ cm
- Bell Instability at wavevector:

$k_{||}=1.5e\text{-}8\eta n_i(u/5000\ \mathrm{kms}^{-1})^3(3\mu G/B)/(4\gamma_{max}\ln\gamma_{max})=2\pi/\lambda$

η=fraction of shock energy in cosmic rays

n_i=ambient plasma density

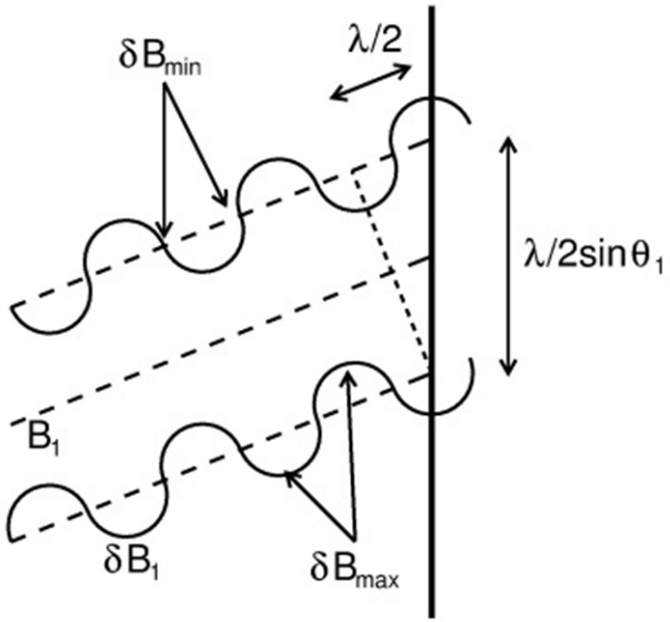
u=shock velocity

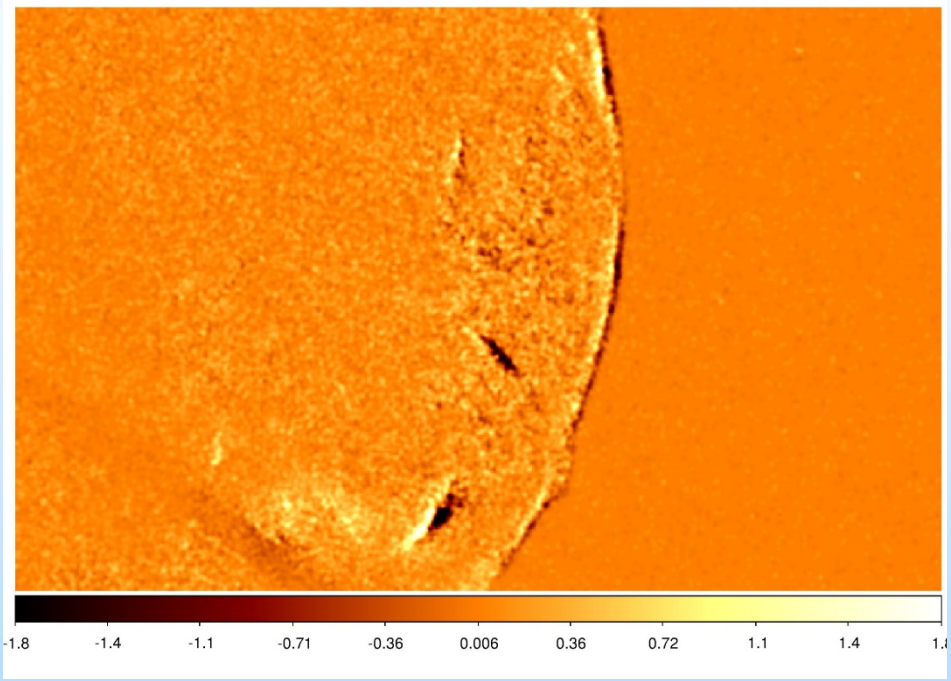
B=upstream magnetic field

→ $\gamma_{max} = 10^6$, $E_{max} = 10^{15}$ eV, taking $\eta=0.26$, $n_i=0.3\ \mathrm{cm}^{-3}$ (from Slane et al. 2014)

Apparent Motion 2003-2009

→Stripes cannot come from shock precursor





Courtesy Una Hwang, with approximate registration (to be improved, thanks to a Chandra Archive grant!)

For the X-Ray Surveyor…

- Curious that synchrotron “stripes” are not more ubiquitous.
- We think we can understand why some other SNRs (e.g. SN 1006, Cas A, Kepler) do not show them.
- Should be more to be discovered with X-Ray Surveyor
  - Evaluate maximum CR energy at more SNRs
  - Constrain shock obliquity at more SNRs, and at more locations within Tycho?
  - Move towards more complete models of diffusive shock acceleration at oblique shocks

Conclusions

- 10^{15} eV is close to the cosmic ray energy spectrum "knee", so the answer to our question is a definite "maybe"
- Entirely plausible that earlier in its history when it shocks were faster, Tycho did indeed accelerate cosmic ray ions to $> 5 \times 10^{15}$ eV.
- No stripes observed in other SNRs, which we think we can understand.
- Do we now have an observable to help us understand waves at oblique shocks?