Shock Physics in Supernova Remnants: an Observational Perspective

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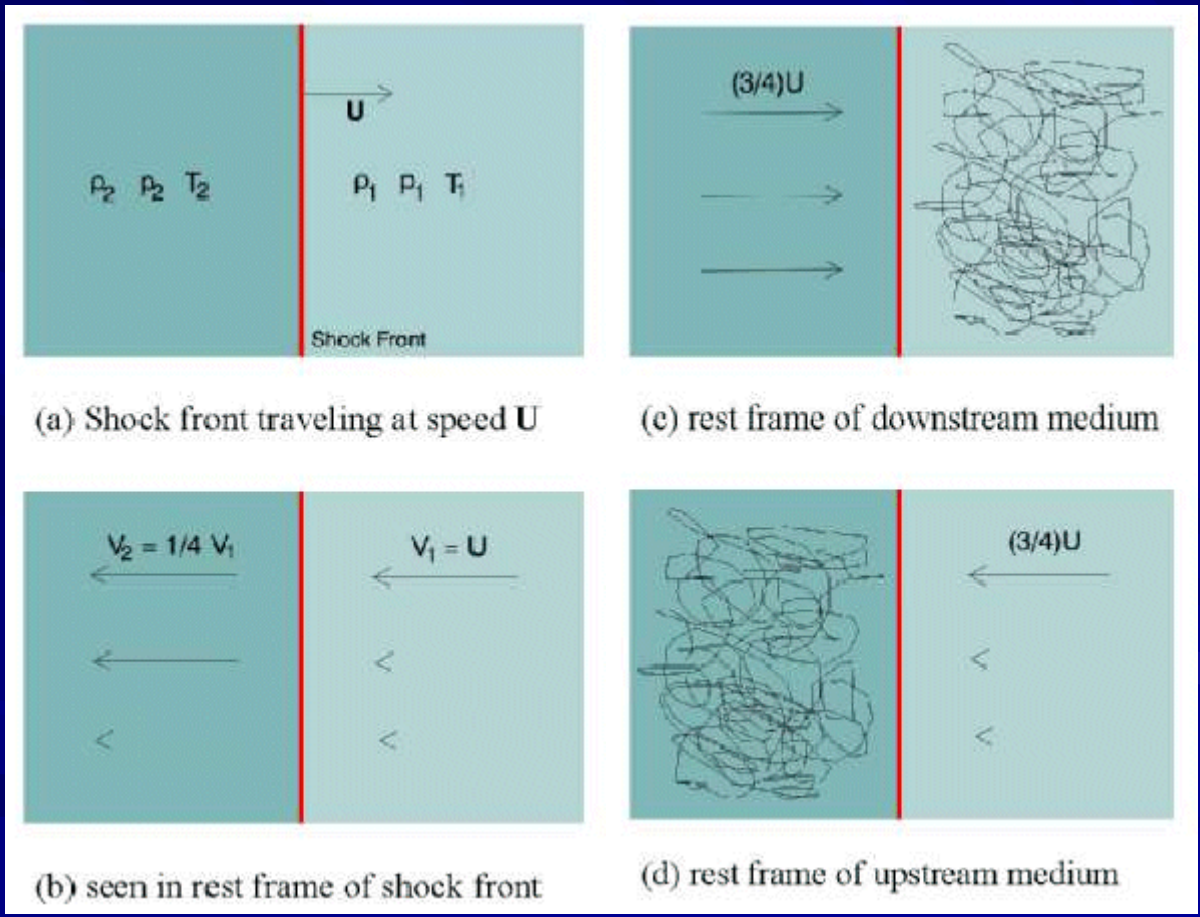
“collisionless shocks”



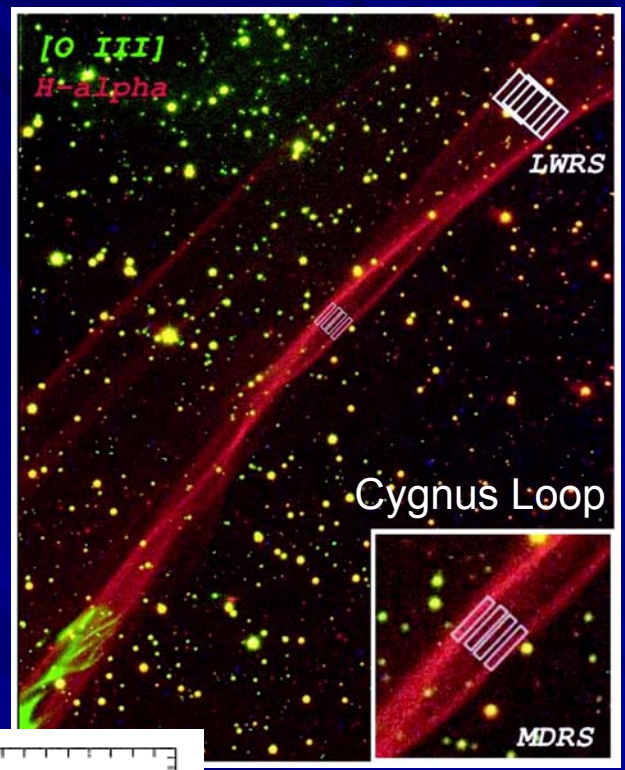
(a) Shock front traveling at speed **U**

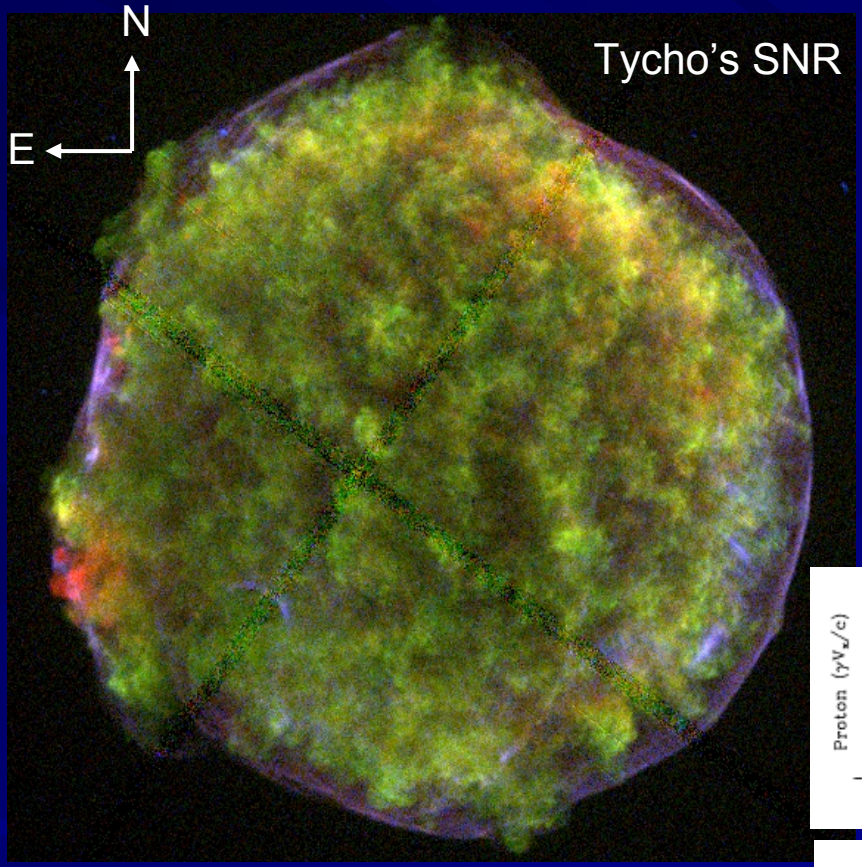
(e) rest frame of downstream medium

(b) seen in rest frame of shock front

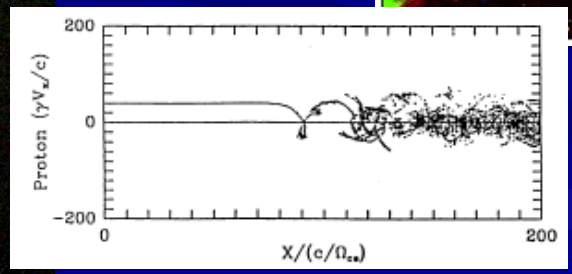
(d) rest frame of upstream medium

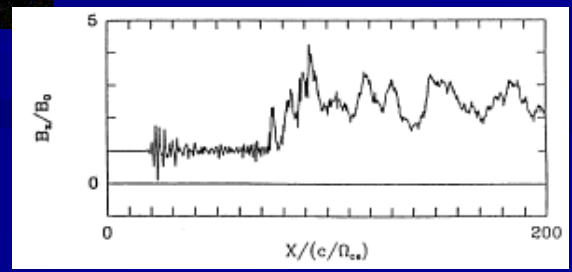
Raymond et al. 2003
ApJ 584, 770





Warren et al. 2005
ApJ 634, 376





Hoshino et al 1992
ApJ 390 454

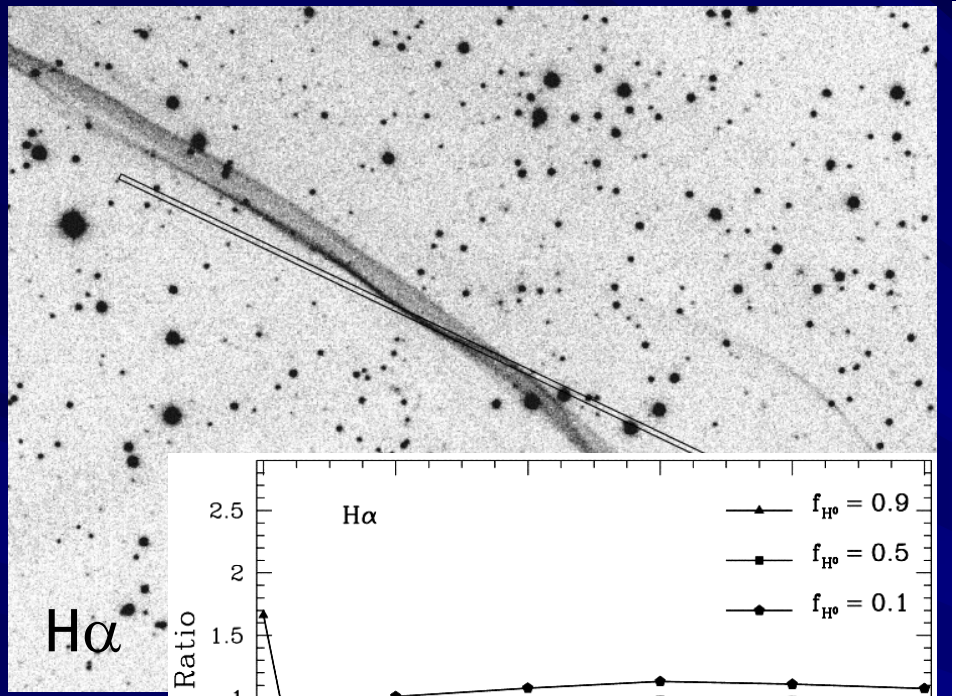
Ideally measure:

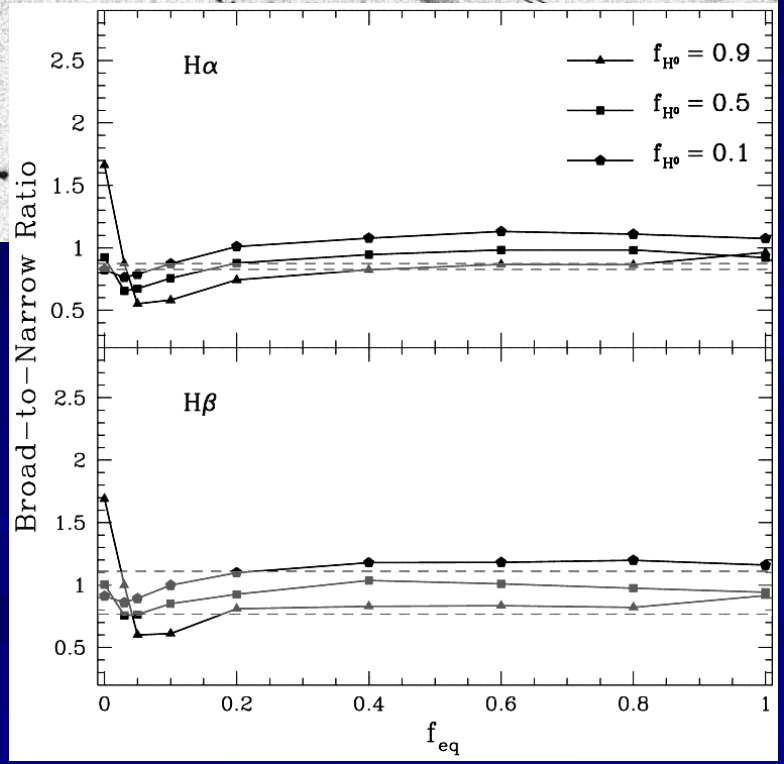
V_{Shock}, M_A, T_e, T_p, T_{He}, T_C, T_O, T_N, …

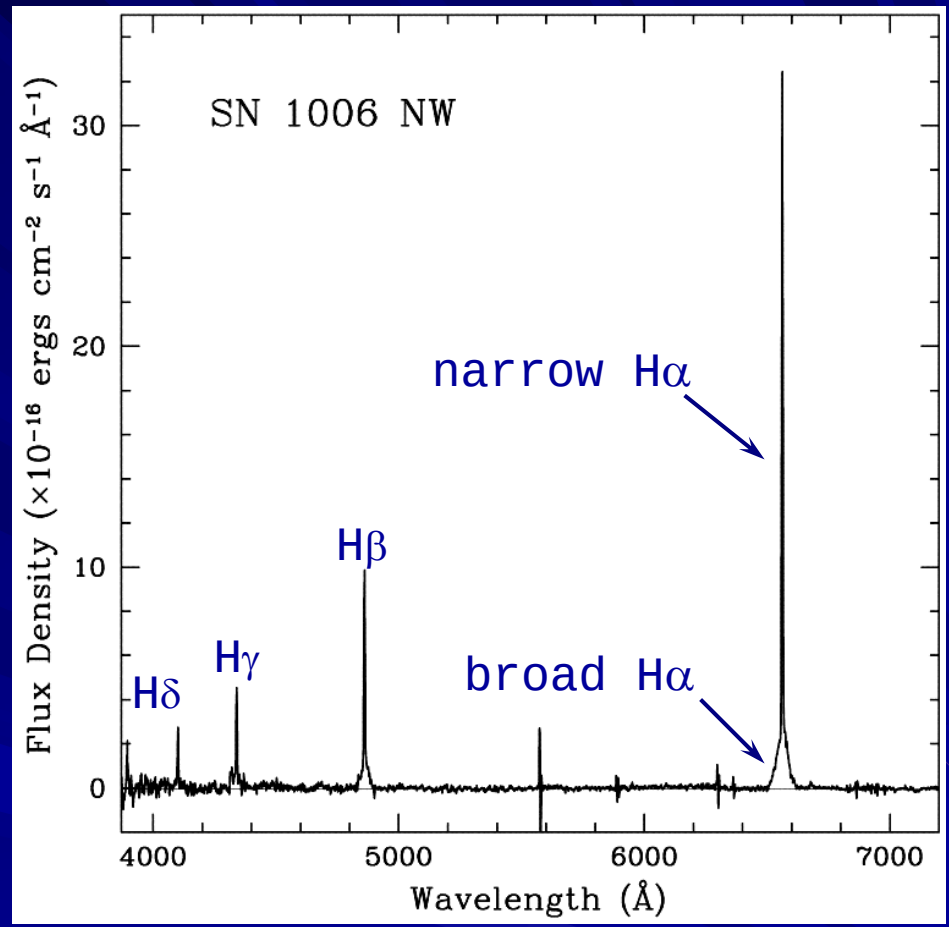
as well as cosmic-ray electrons and ions

Measuring "Temperature" UV, Optical, X-rays…

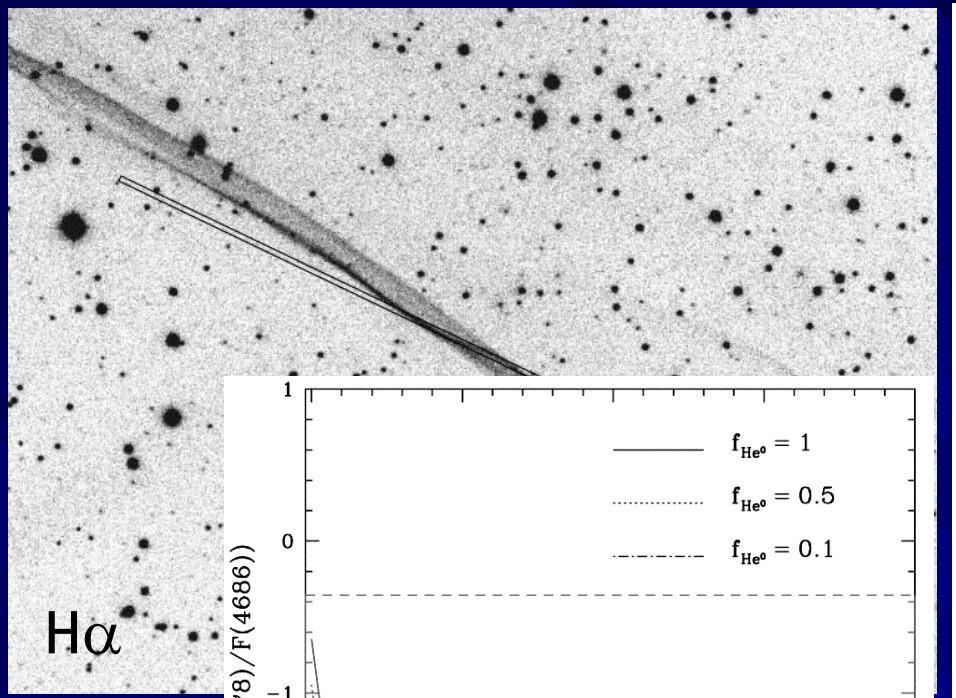
- Thermal broadening of line width
- Temperature dependence of emission line ratios
  - Best: single element, single ion
  - Ion fractions (*solar wind*)
  - Different elements, known abundances
- Thermal bremsstrahlung continuum

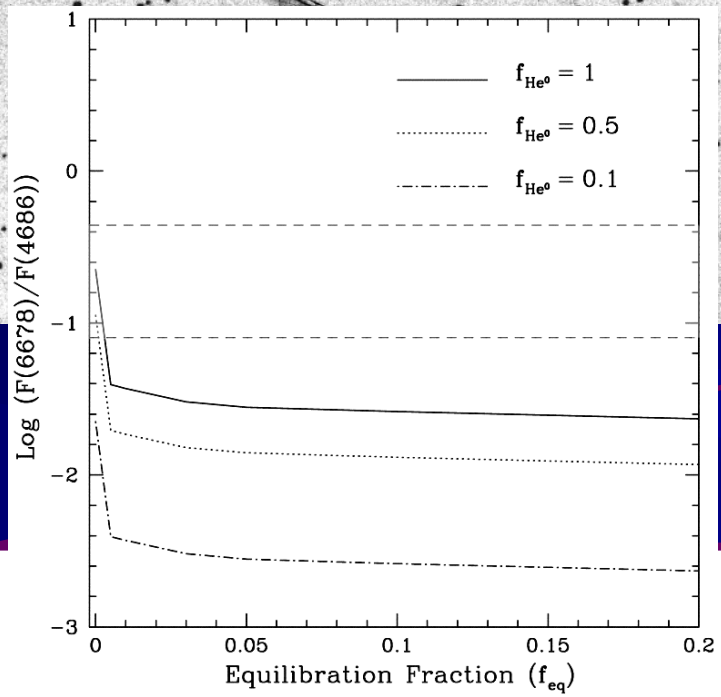


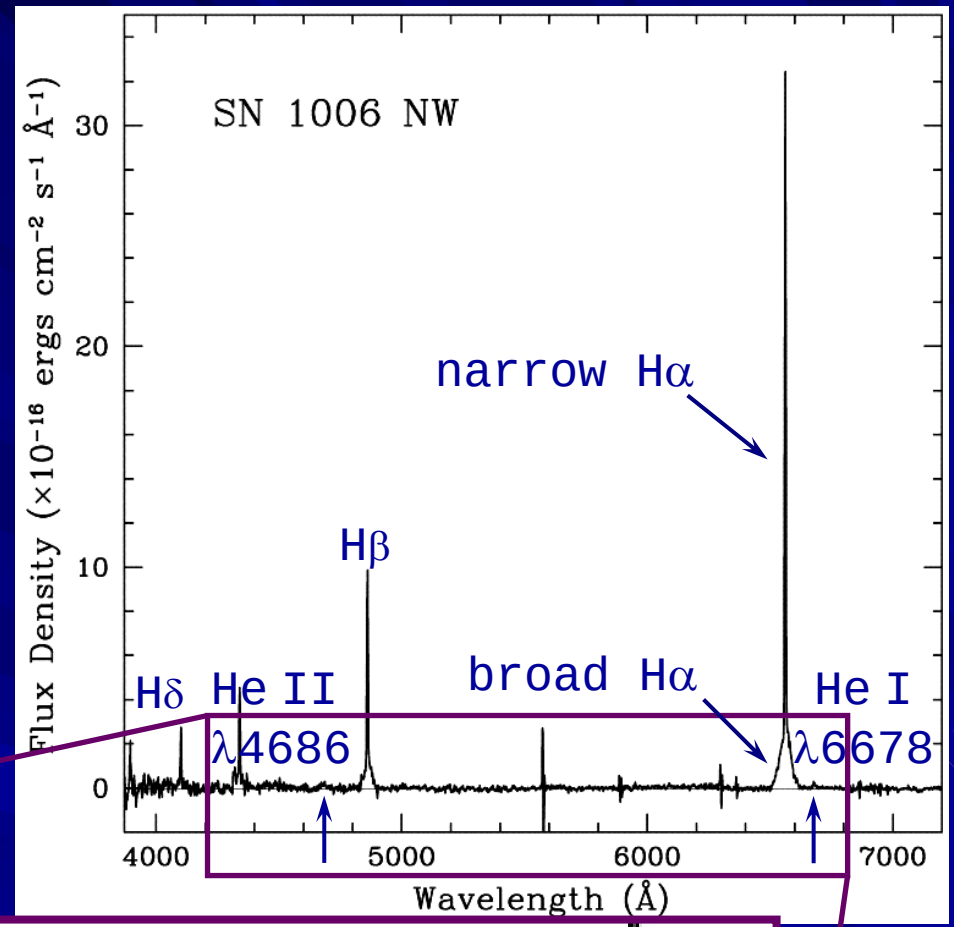


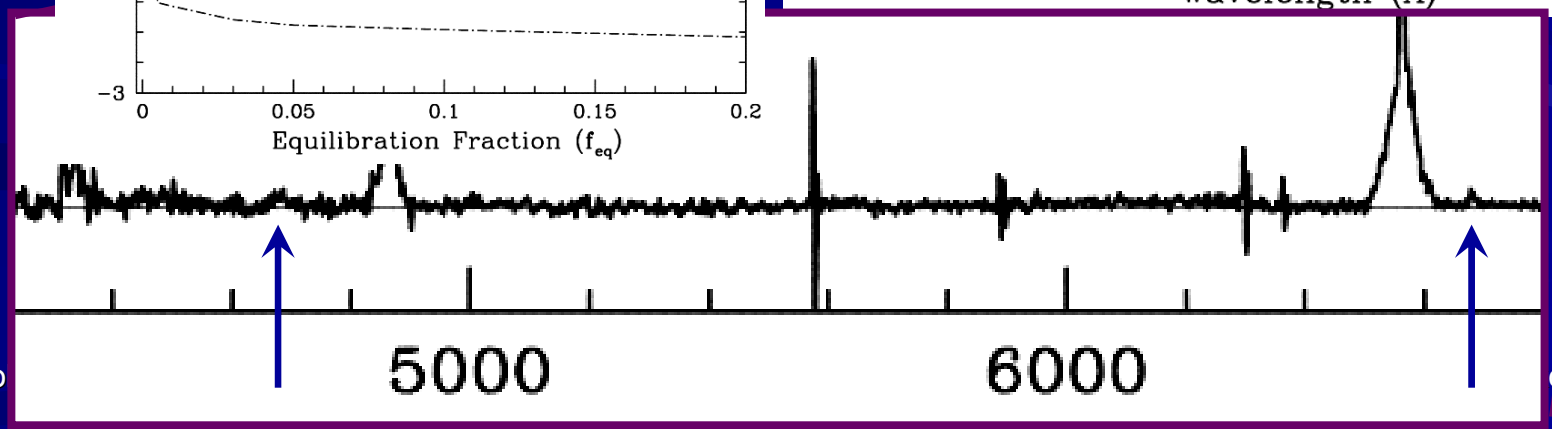


Ghavamian et al. 2002
ApJ 572, 888


Hα


Log (F(6678)/F(4686))
Equilibration Fraction (f_{eq})
f_{He^0} = 1
f_{He^0} = 0.5
f_{He^0} = 0.1


SN 1006 NW
Flux Density (×10⁻¹⁶ ergs cm⁻² s⁻¹ Å⁻¹)
Wavelength (Å)
narrow Hα
Hβ
Hδ
He II λ4686
broad Hα
He I λ6678


5000
6000

Measuring "Temperature" UV, Optical, X-rays…

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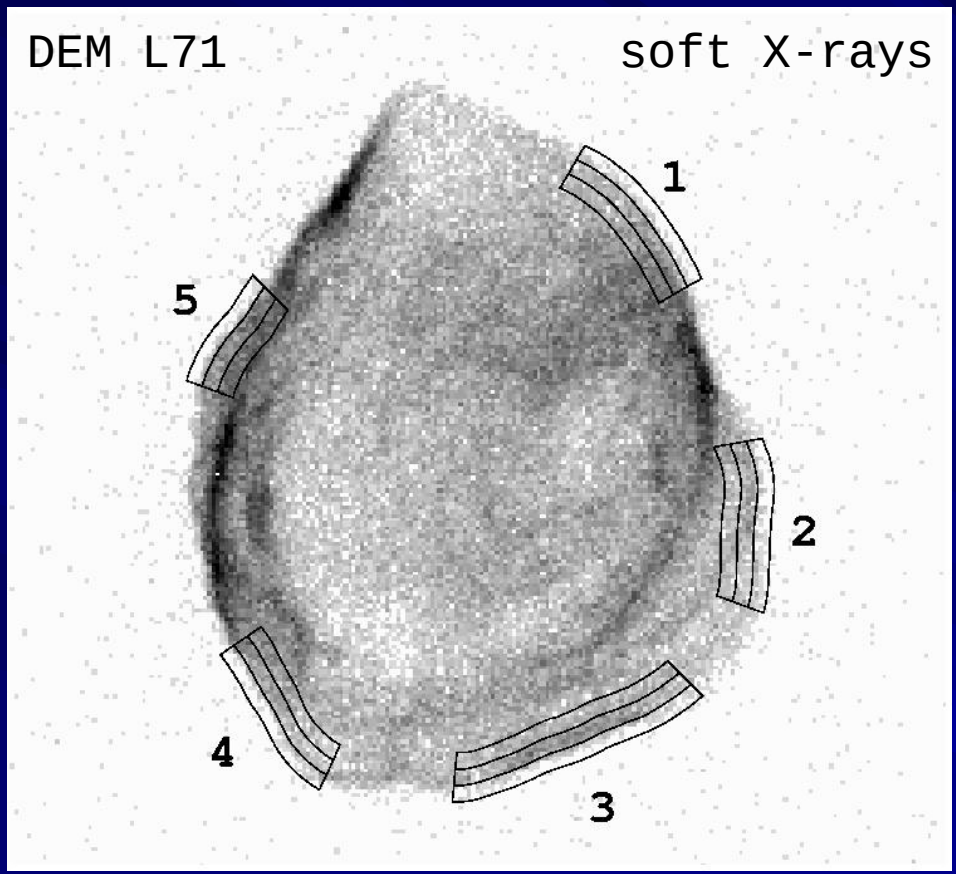
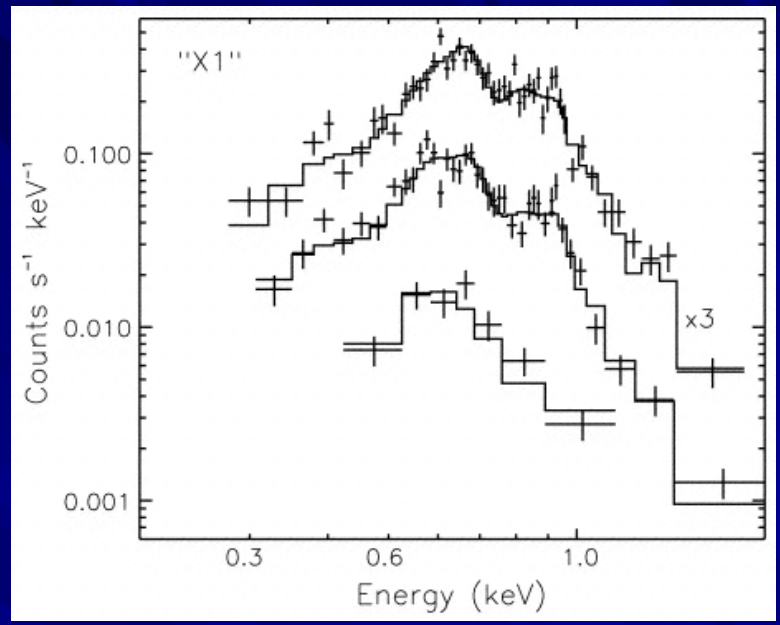
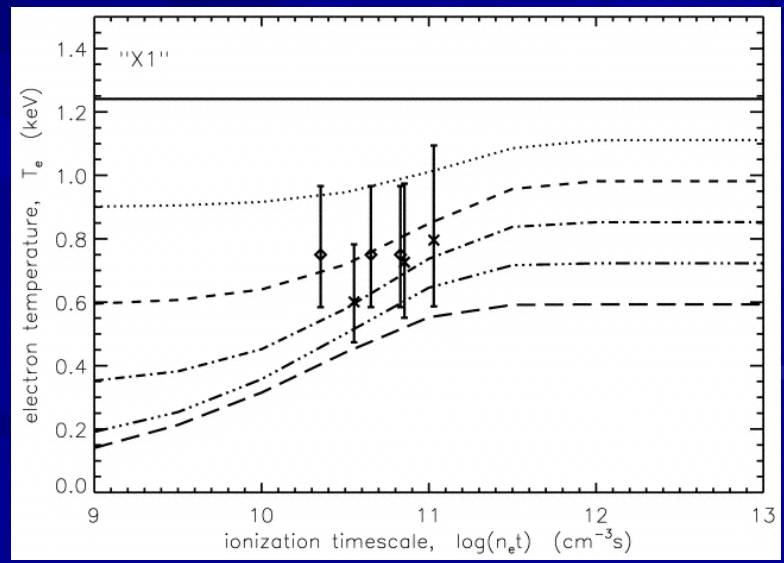
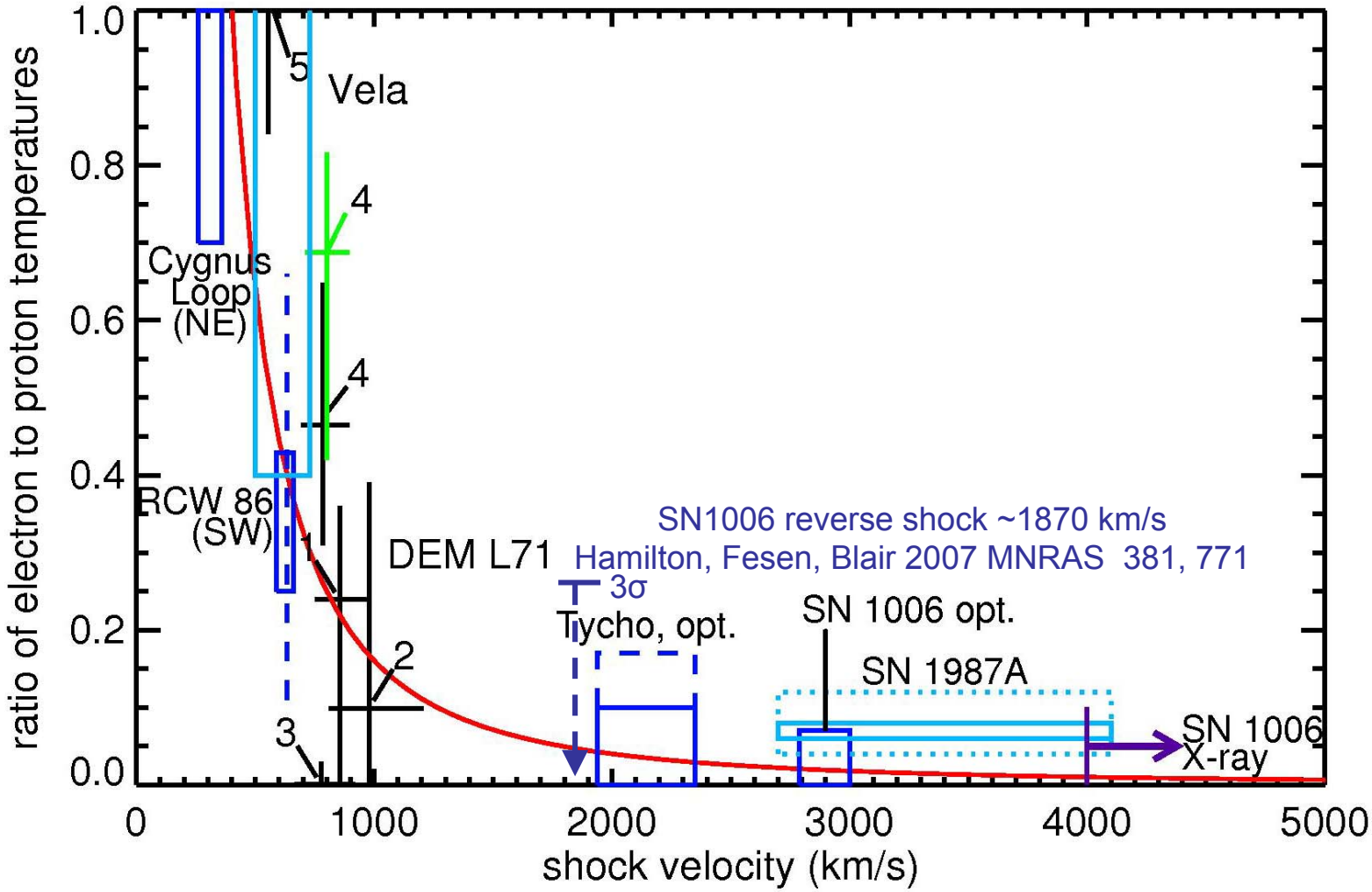




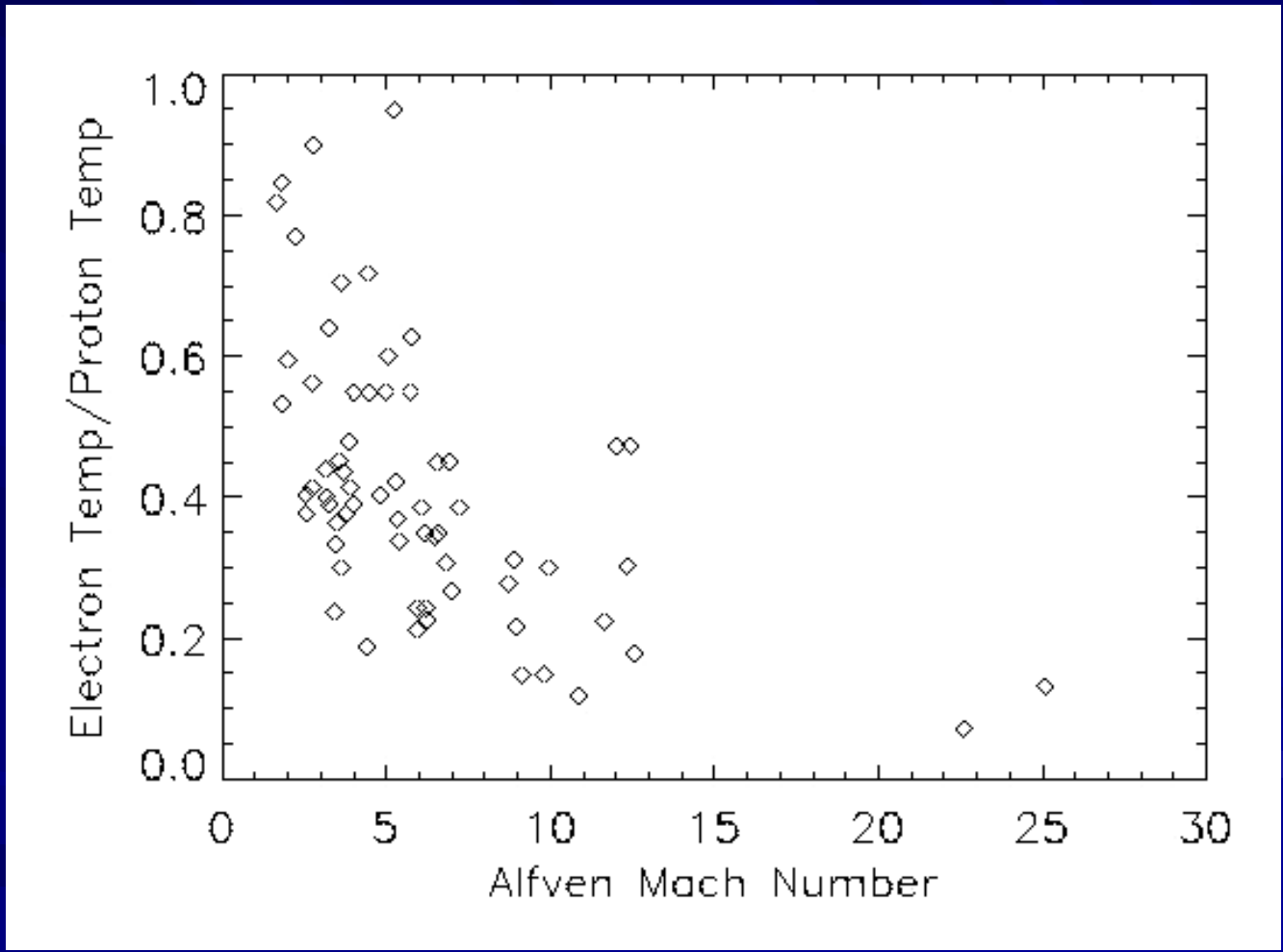


Rakowski et al 2003 ApJ 590, 846



Rakowski 2005 Adv. in Space Res. 35, 1017

Solar Wind Shocks



Recap:

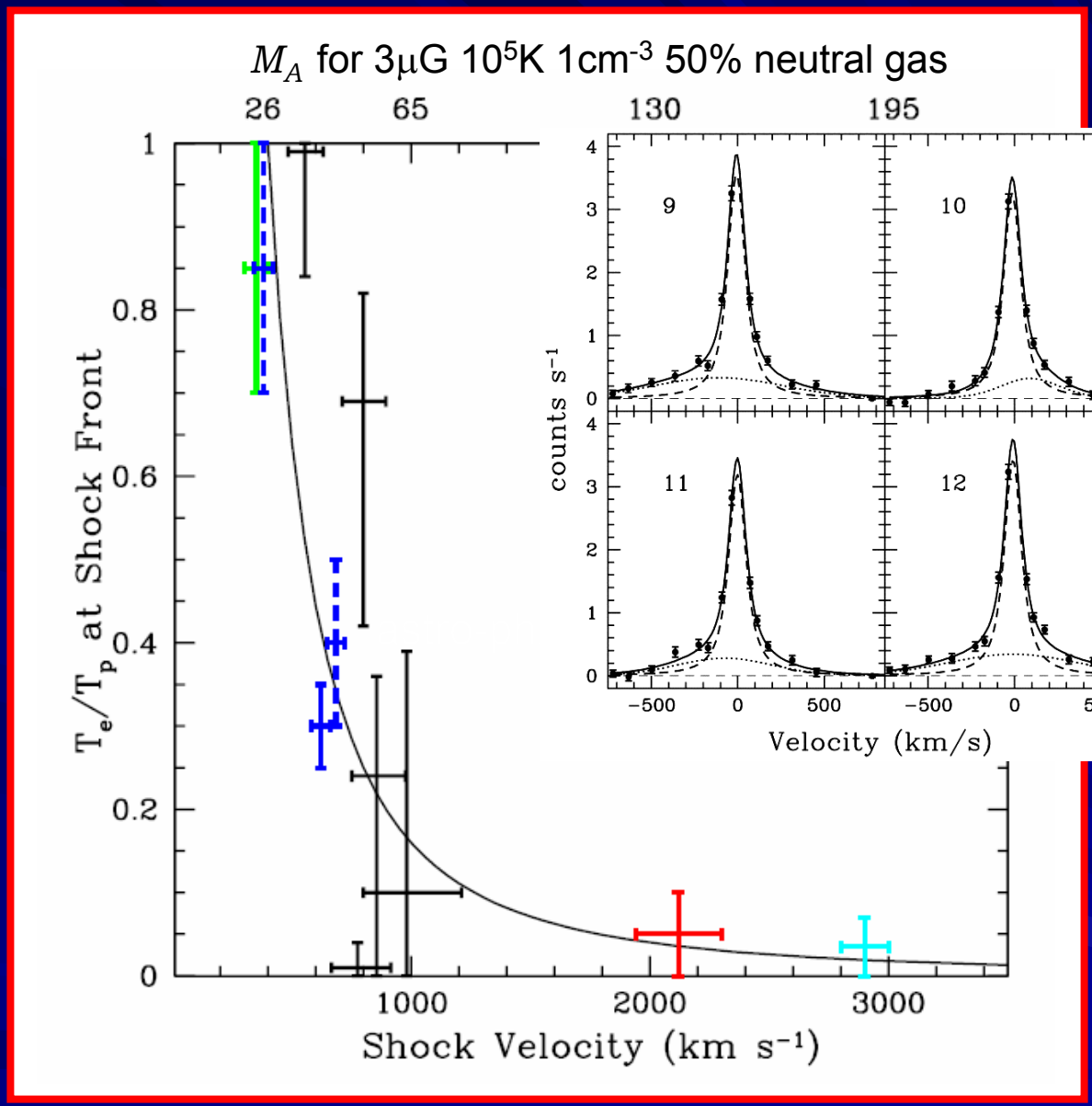
- SNR shocks are collisionless

$$d_{shock} << d_{mean\ free\ path}$$

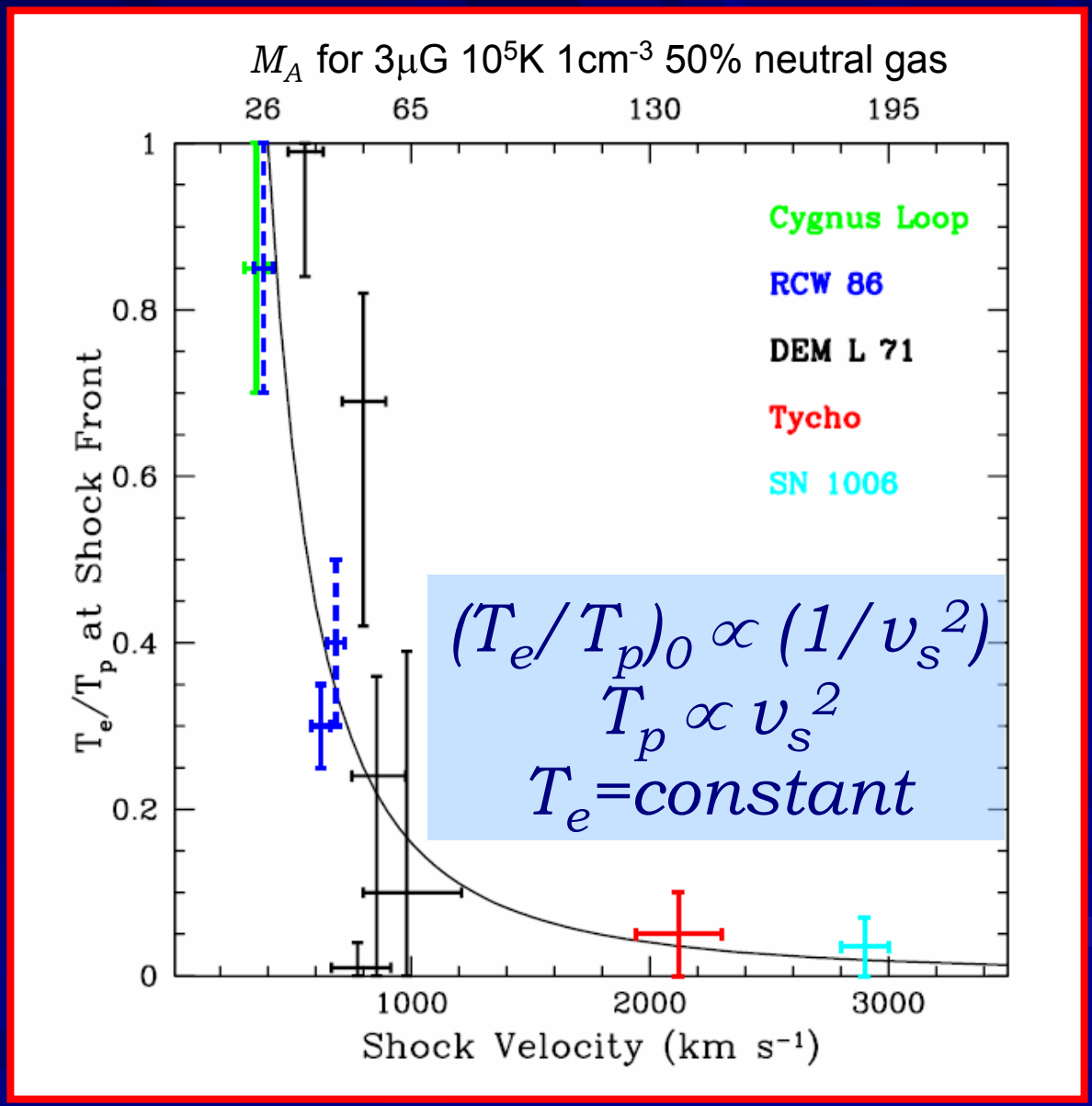
- UV, optical and X-ray spectral observations of line widths, ratios and continuum emission
- $(T_e / T_p)_0$ decreases with increasing v_s

initial electron-proton heating for shocks into partially neutral gas

Ghavamian, Laming & Rakowski, 2007 ApJ 654, L69

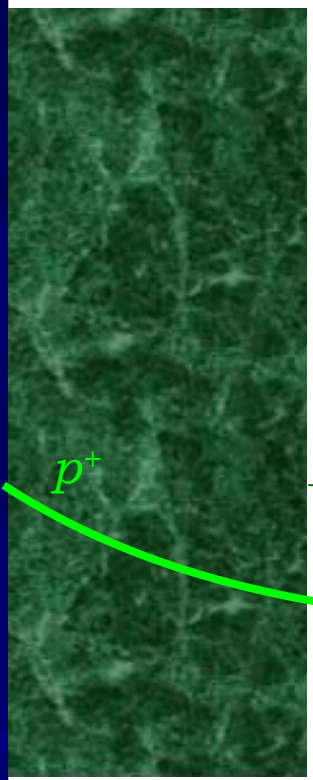


Ghavamian, Laming & Rakowski, 2007 ApJ 654, L69



Ghavamian, Laming & Rakowski, 2007 ApJ 654, L69

cosmic ray lower hybrid waves



upstream rest frame

$\omega^2 = \Omega_e \, \Omega_p$

$(\Omega_{e,p} \equiv eB/m_{e,p}c)$

$L \sim \kappa / v_s$

$t = \kappa / v_s^2$

$\frac{1}{2} m_e v_e^2 = \frac{1}{2} m_e D_{||} t$

$D_{||} \propto v_s^2 \quad (E^2)$

$\frac{1}{2} m_e v_e^2 \propto \Omega_e \kappa$

$\kappa \propto 1/B$

heating independent of both v_s and B!

cosmic ray lower hybrid waves

- reasonable values of κ
- need diffusive superthermals
- easy to excite
- age of the remnant to grow

Bottom Line

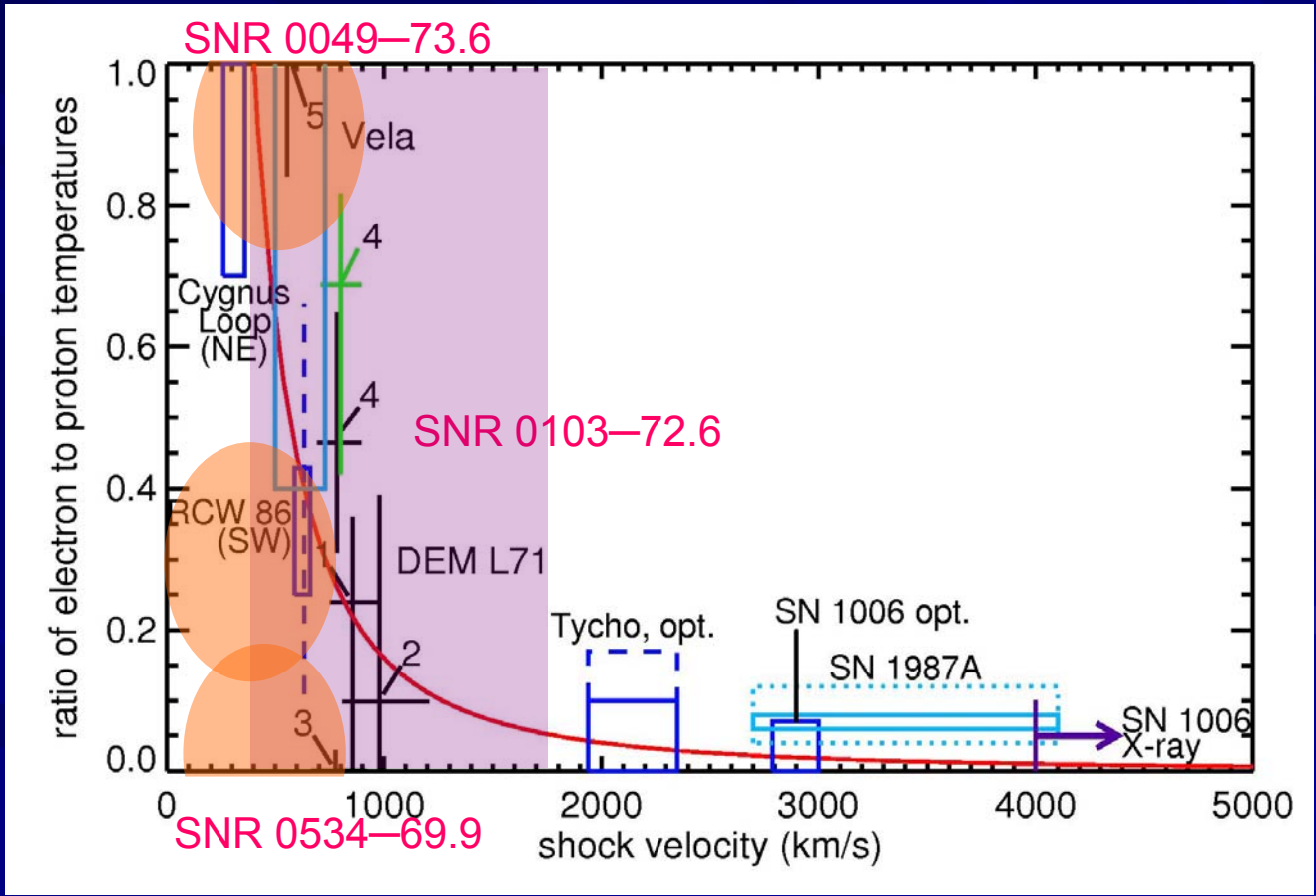
- Cosmic-rays are an integral part of collisionless shocks.
  - heating electrons
  - generating magnetic field

Work in Progress:

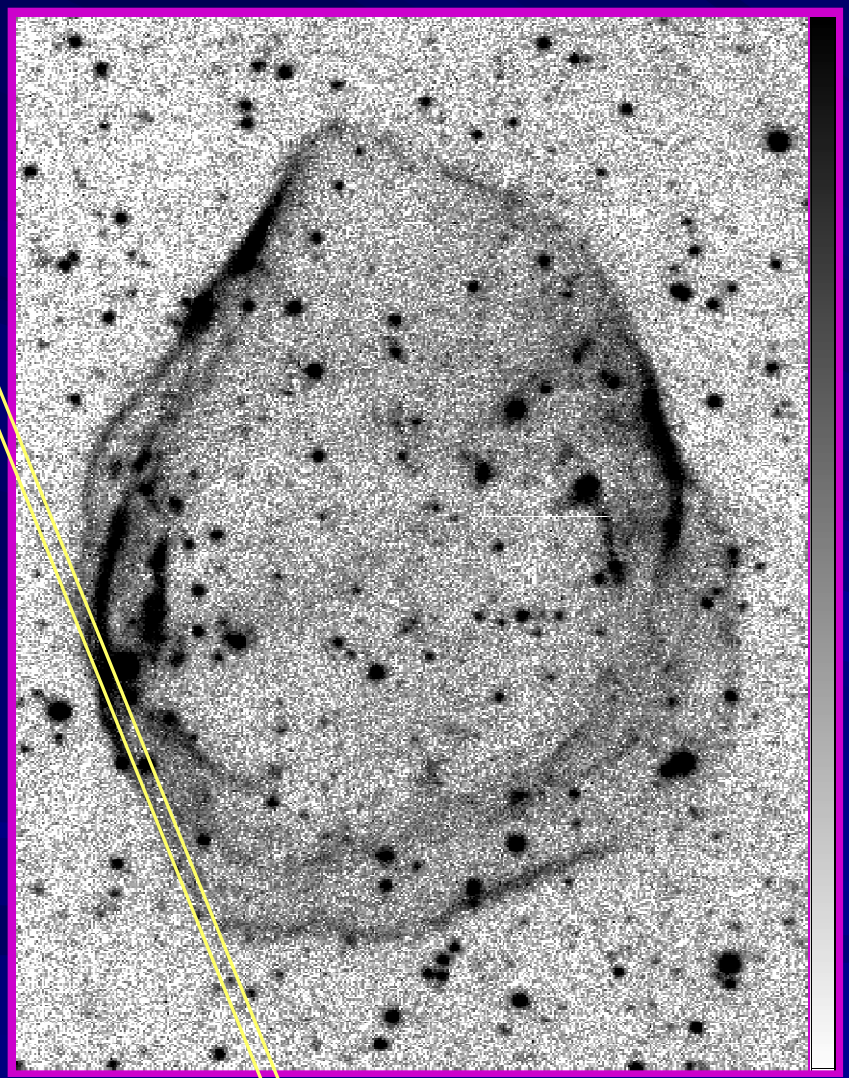
- Calculated kinetic (resonant) and reactive (nonresonant) growth rates for the instability
- $\gamma_{kinetic} \propto n_{CR} / n_{ion}$
- need seed particles to be diffusive (κ only weakly momentum dependent)
- no reactive instability yet found for isotropic CR distribution

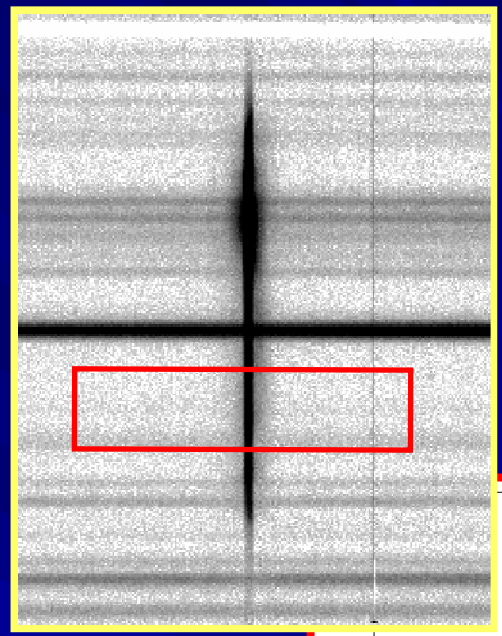
Next up:

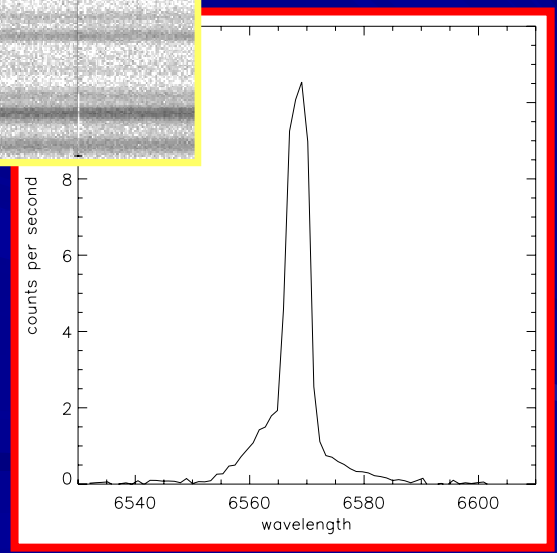
- Shocks into fully ionized gas
- Revisit DEM L71



DEM L71: new Hα spectra







Conclusions

- Lower hybrid waves of CR precursor can explain constant level of electron heating seen in SNR shocks into partially neutral gas.
- More work is needed to extend to other astrophysical situations in fully ionized gas.

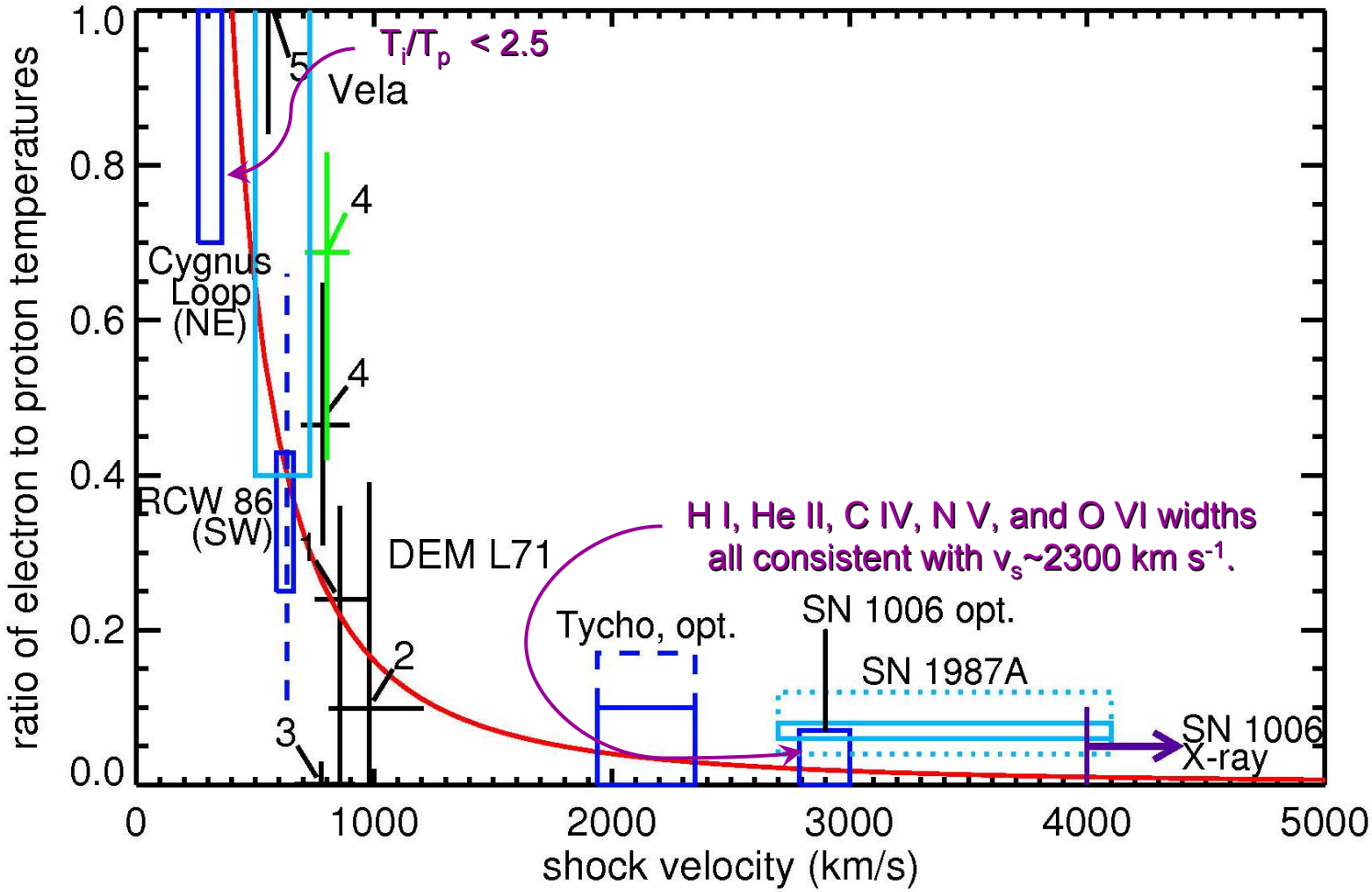
Collaborators:

- J. Martin Laming, NRL
- Parviz Ghavamian, Johns Hopkins
- John P. Hughes, Rutgers University
- Anne Decourchelle, CEA Saclay

the end

New Results

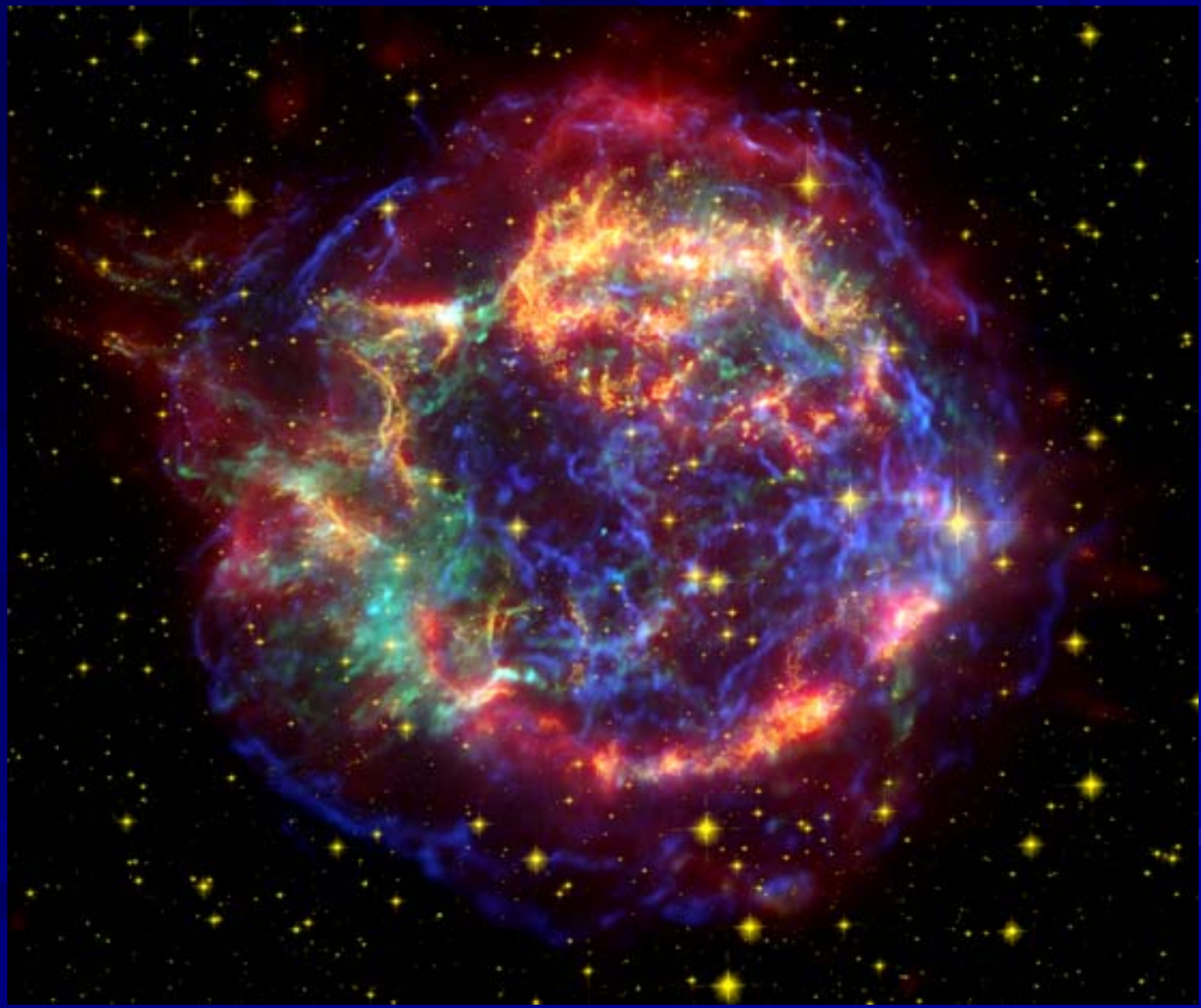
- Calculated kinetic (resonant) and reactive (nonresonant) growth rates for the instability
- $\gamma_{kinetic} \propto n_{CR}/n_{ion}$
- $\gamma_{reactive} \propto (n_{CR}/n_{ion})^{1/3}$
- assuming $n_{CR}/n_{ion} \sim 10^{-3}$ reactive growth rate needed to explain electron heating



Rakowski 2005 Adv. in Space Res. 35, 1017

maybe include:

probably skip:



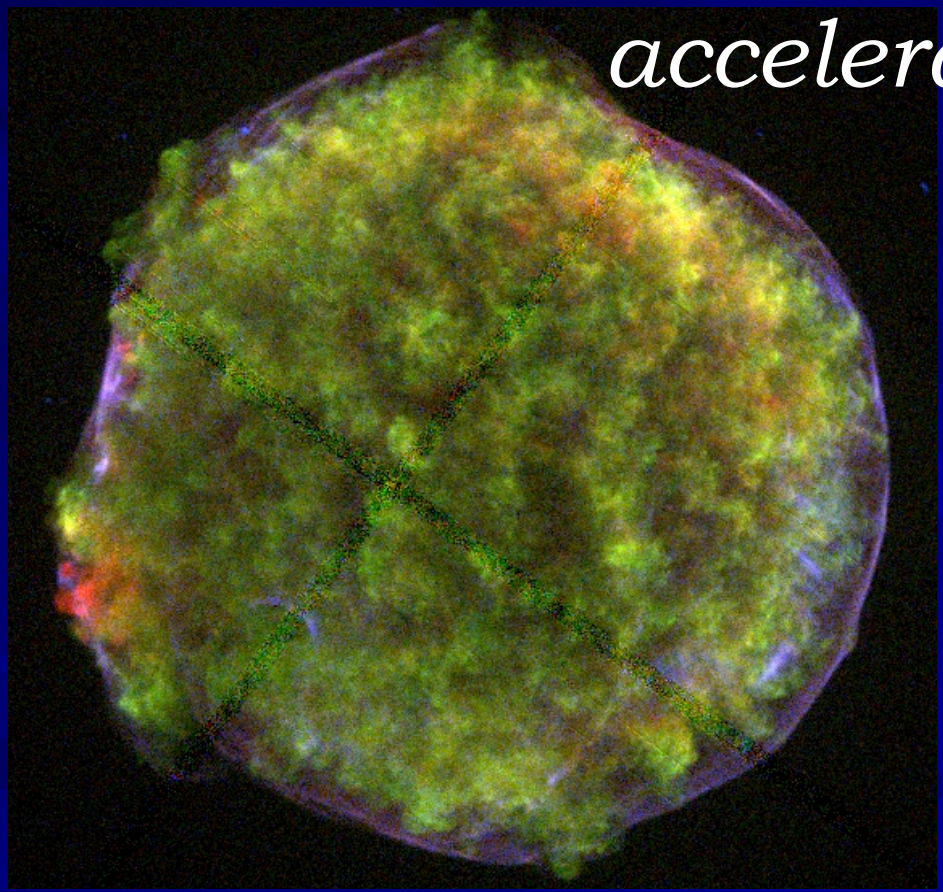
Chandra X-ray Center

Tycho's SNR

Warren et al. 2005

ApJ 634, 376

cosmic ray acceleration?



1E 0102-72

Hughes, Rakowski, & Decourchelle

2000 ApJ 543, L61

Recap:

- Cosmic Ray Acceleration inherent to collisionless shocks
- Indirect evidence for CRs
  - enhanced magnetic field
  - shock structure
  - reduced energy in thermal population

Influence electron heating? T_e / T_p ?