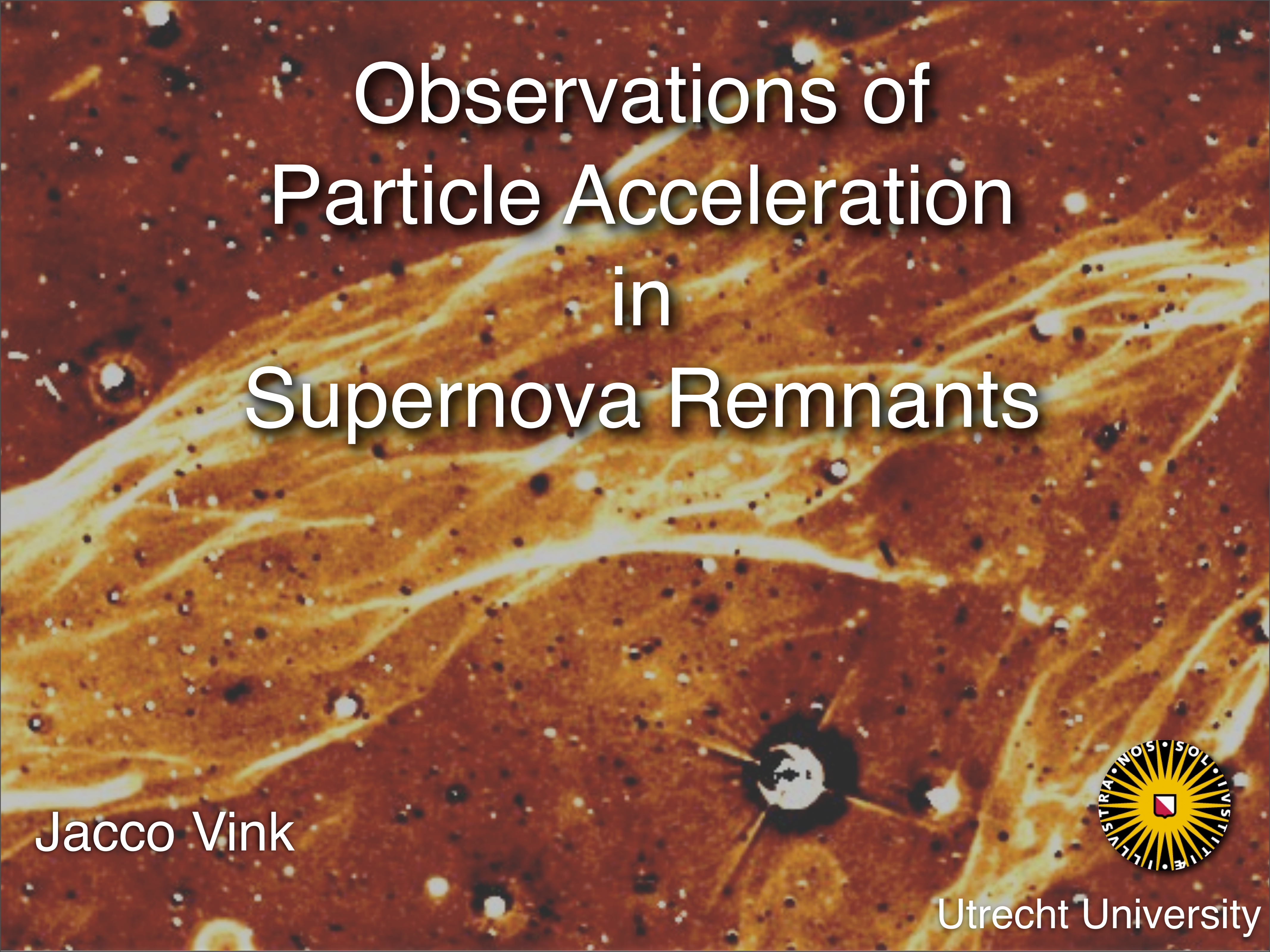
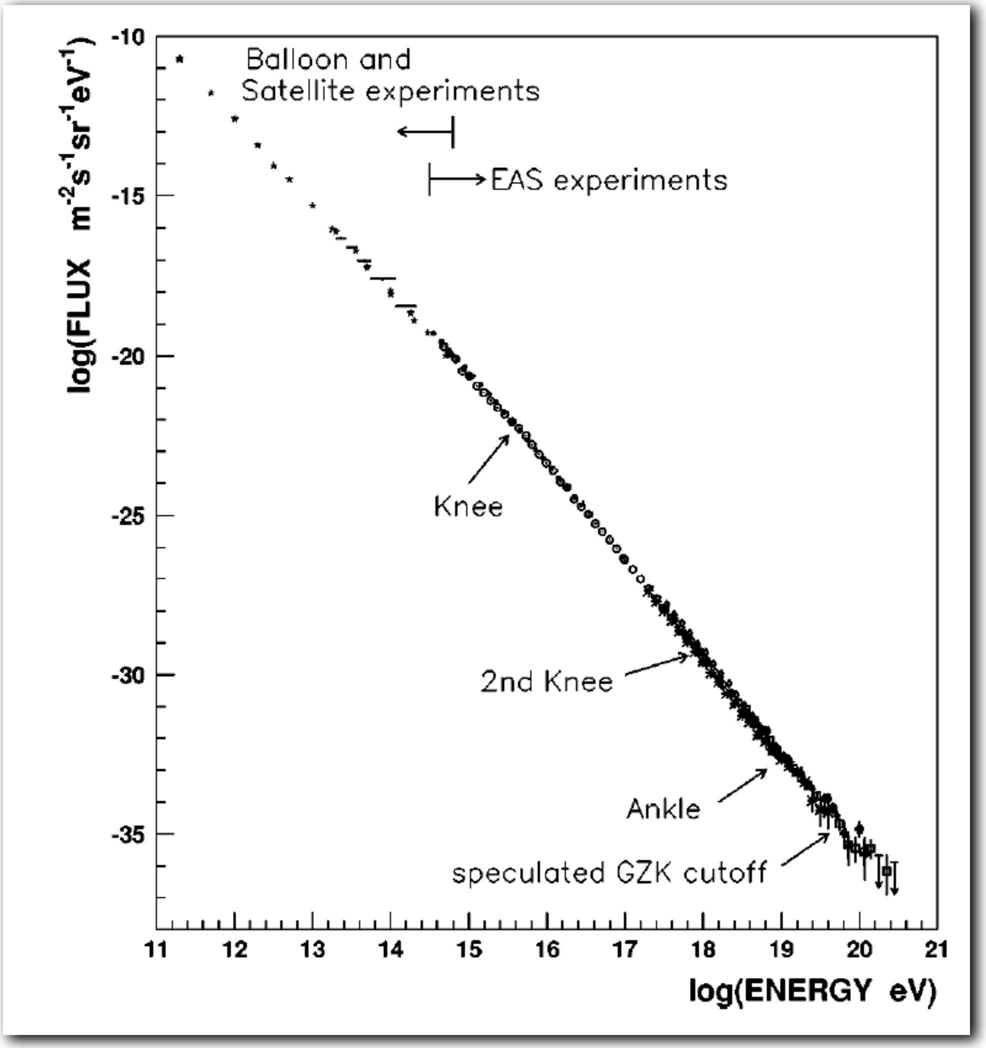


Observations of Particle Acceleration in Supernova Remnants

Jacco Vink

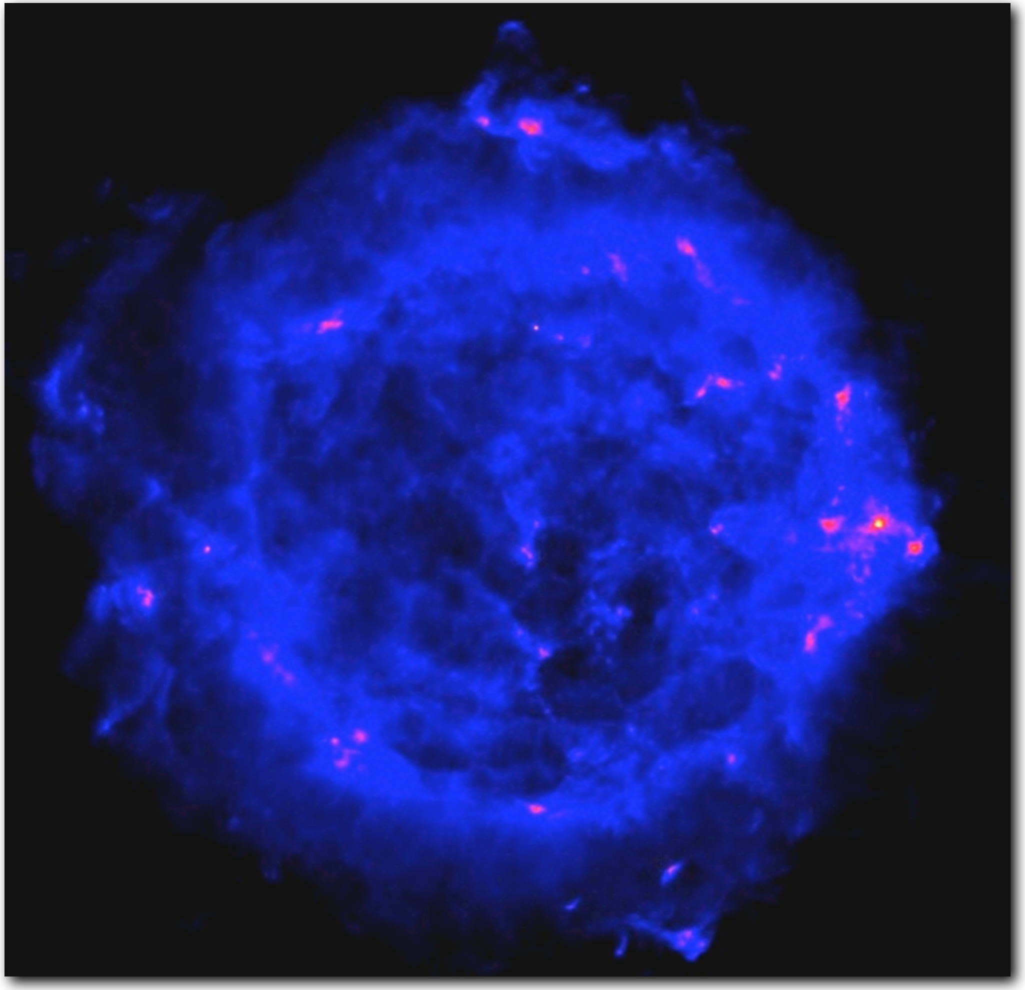
Utrecht University

Cosmic Rays



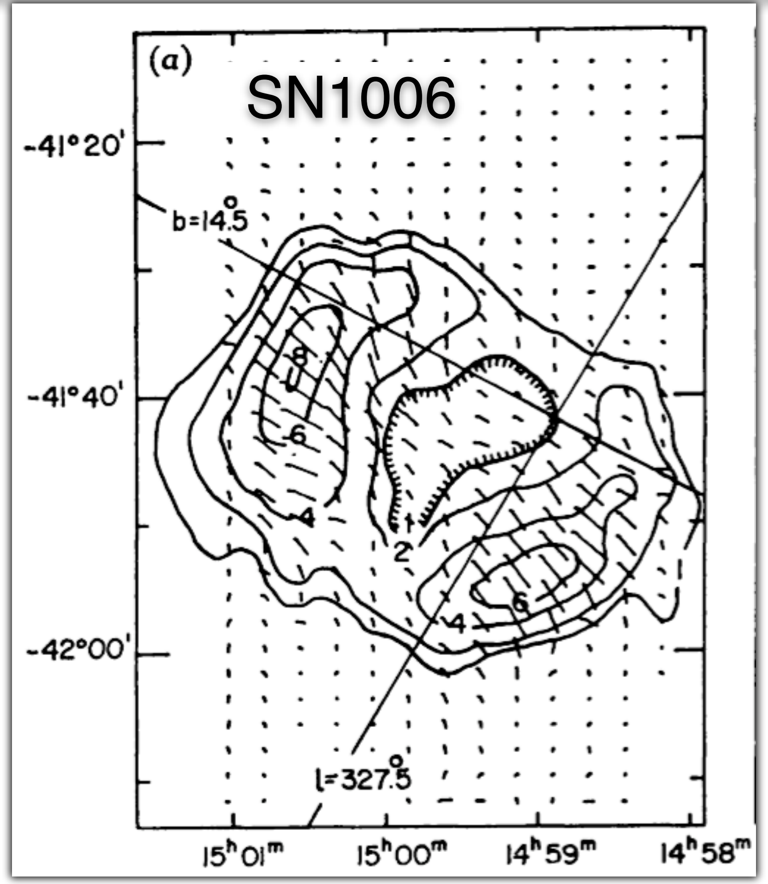
- Up to ~10^{18}eV of Galactic origin
- Galactic CRs: likely powered by supernovae (Baade & Zwicky)
- The “Knee” (10^{15}eV): must be linked to a common property among Galactic accelerators
- Evidence for composition change around “knee”: cut-off in rigidity?
- Important: accepting SNe as source of energy, are particles mainly accelerated in SNR phase?
- Alternatives:
  - in SN/very early SNR phase
  - collective effects in superbubbles

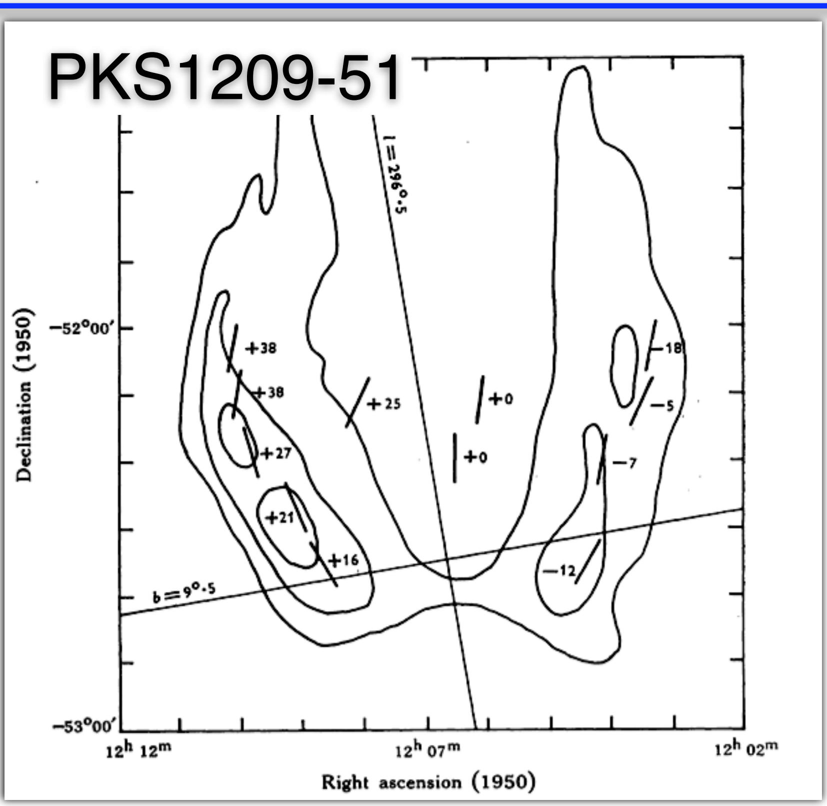
SNRs as particle accelerators



- Early evidence for particle acceleration in SNRs:
  Radio synchrotron emission
- Prime example: Cas A
  - young (~330 yr)
  - brightest radio source
  - radio flux decreases 1%/yr
  - explanation: adiabatic losses (Shklovksy '66)
  - suggests acceleration stronger in the past

Young versus Old SNRs



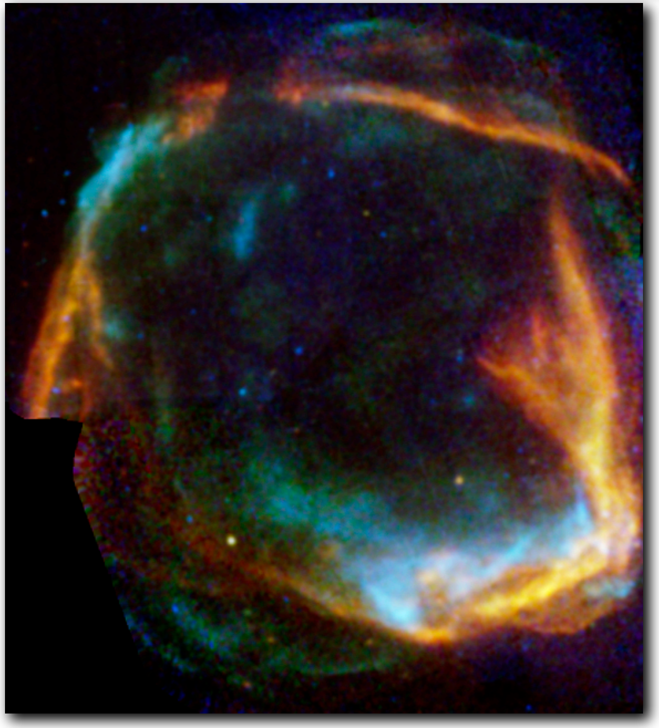


Dickel & Milne ‘96

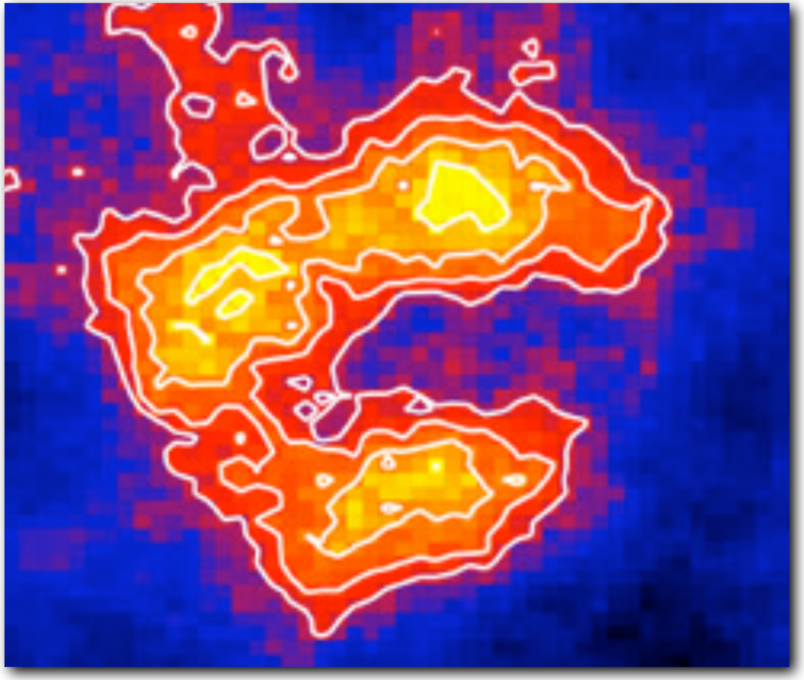
- Radial magnetic fields
- Emission due to recently accelerated electron

- Tangential magnetic fields
- Flux can be explained by Van der Laan mechanism (compression of pre-existing electron cosmic rays)

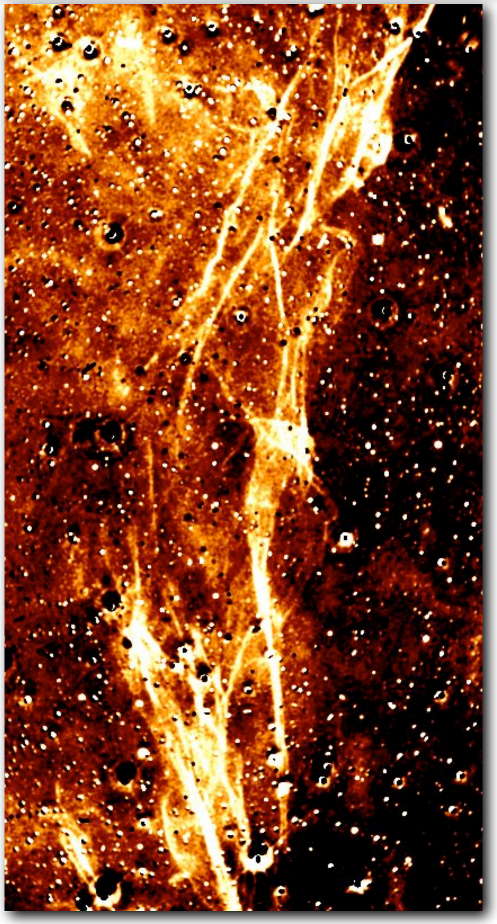
Today



X-ray imaging/spectroscopy
(Chandra/XMM/Suzaku)



TeV gamma-ray astronomy



8 m class optical telescopes

(Object: RCW 86, Vink+ ’06, Aharonian+ ’09, Helder+ ’09)

Evidence for efficient acceleration

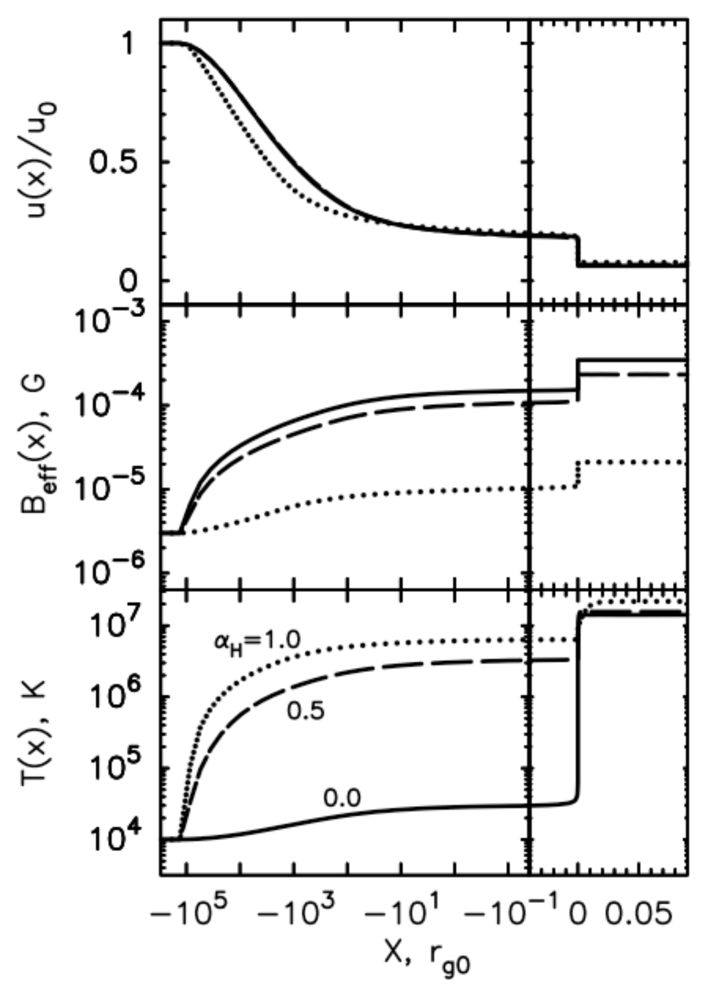
1. Direct observations of accelerated particles
    - Electrons:
        - synchrotron radiation (10^7Hz- 10^{18} Hz)
        - inverse Compton (IC) scattering (GeV/TeV γ-rays)
        - bremsstrahlung (keV- TeV)
    - Ions: pion-decay (GeV/TeV γ-rays)
    - Identification of pion decay or IC not always clear!
2. Indirect evidence:
    - Magnetic field amplification (20- 500μG)
    - High compression ratios (> 4)
    - Concave synchrotron spectra
    - Lower than expected plasma temperatures
    - Evidence for shock precursors (Hα)

Efficiently accelerating shocks

- Transform large fraction of shock energy in energy of accelerated particles
- Presence of relativistic particles changes EOS ⇒ larger compression ratios

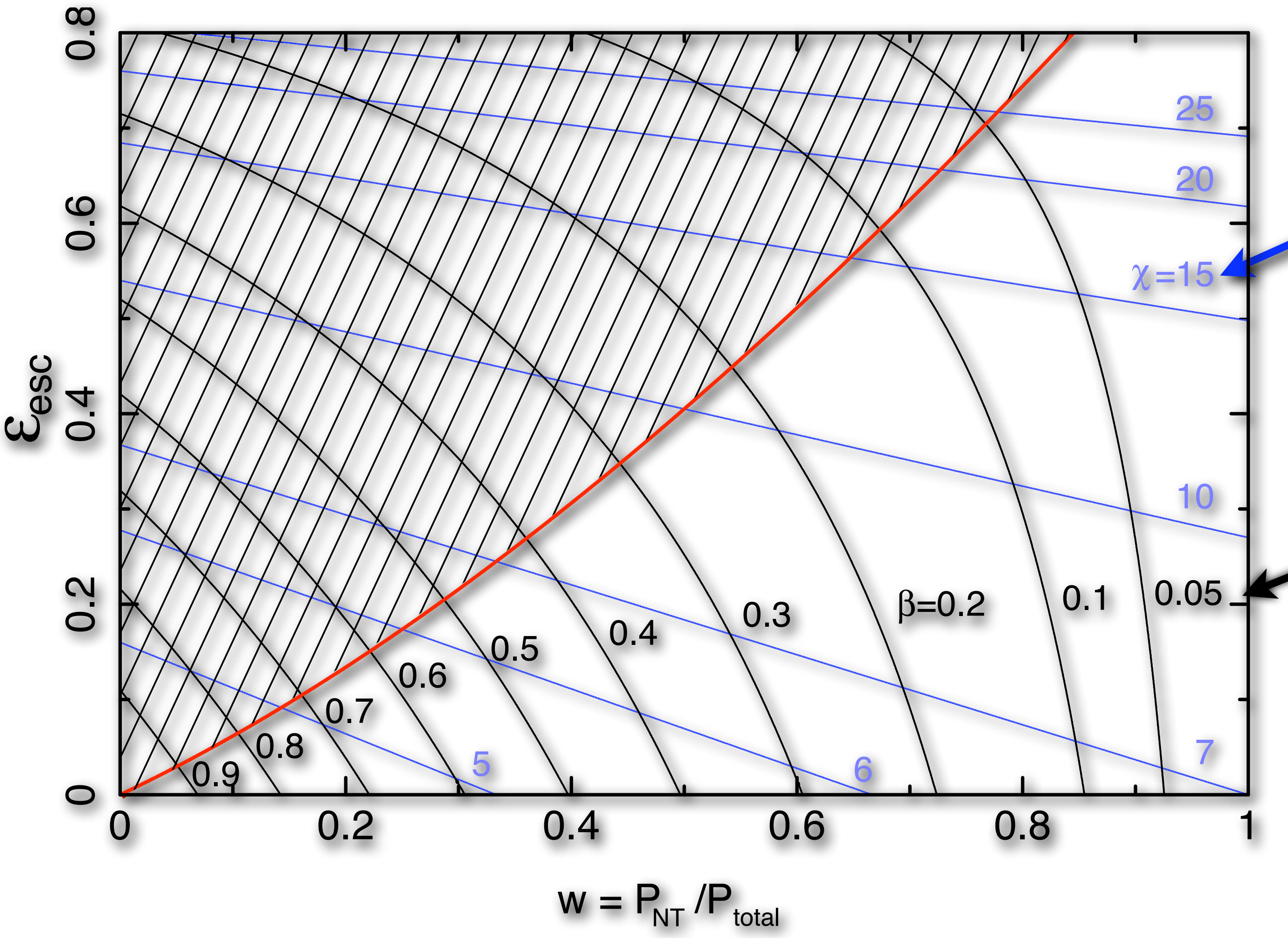
- Upstream escape of CRs: energy loss ⇒

  larger compression ratios
- Upstream particles provide pressure:
  - formation of shock pre-cursor (~10^{17} cm)
  - amplify magnetic fields
  - alters flow into shock
  - pre-heats ISM/CSM?
  - alters shock conditions at main shock (lower post-shock temperature for given V_s)



Vladimirov, Bykov, & Ellison 08

Shock heating and compression

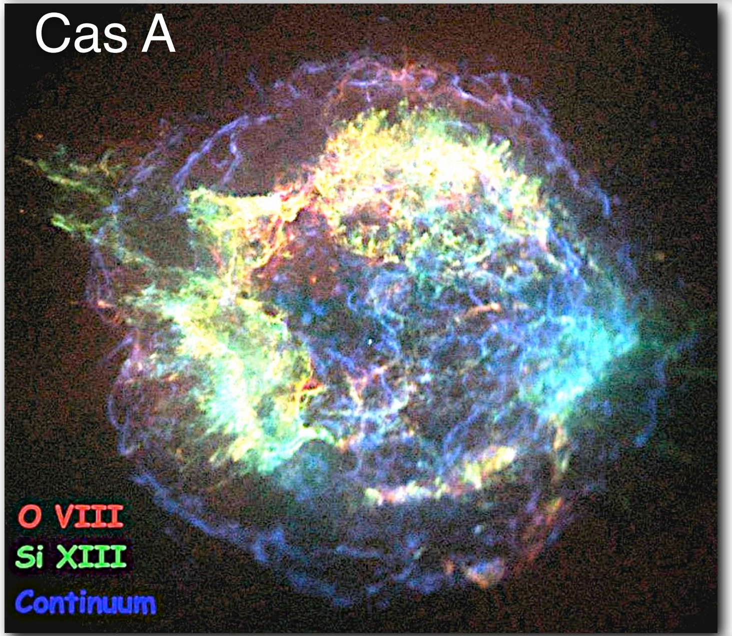


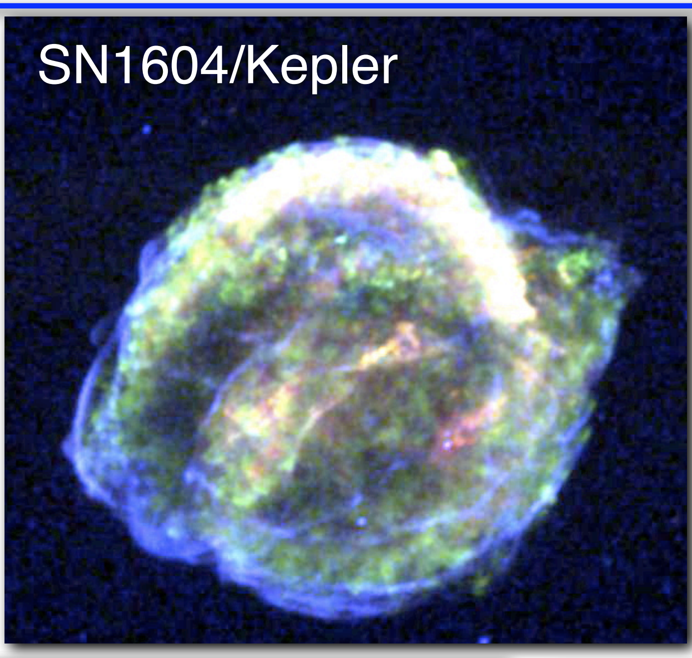
Compression ratio

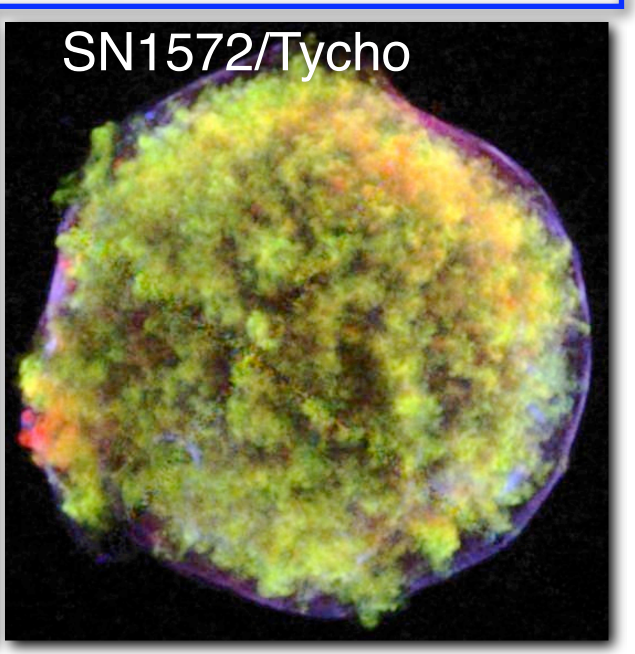
correction w.r.t.

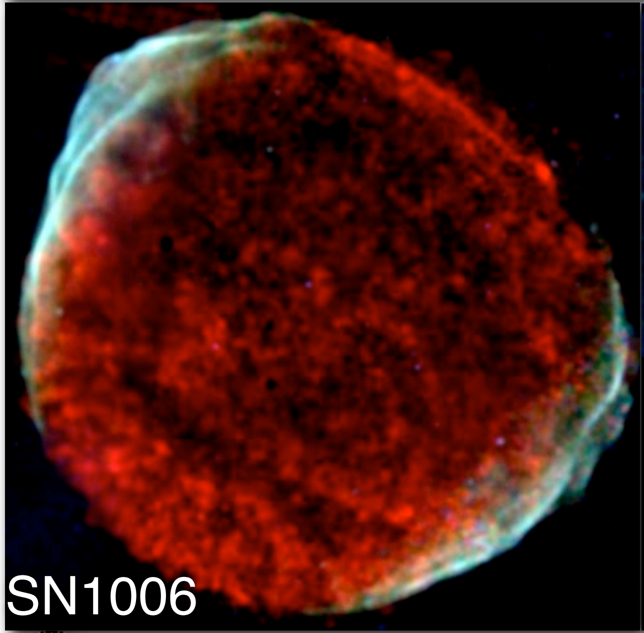
$$\overline{kT} = \frac{3}{16}\overline{m}V_s^2$$

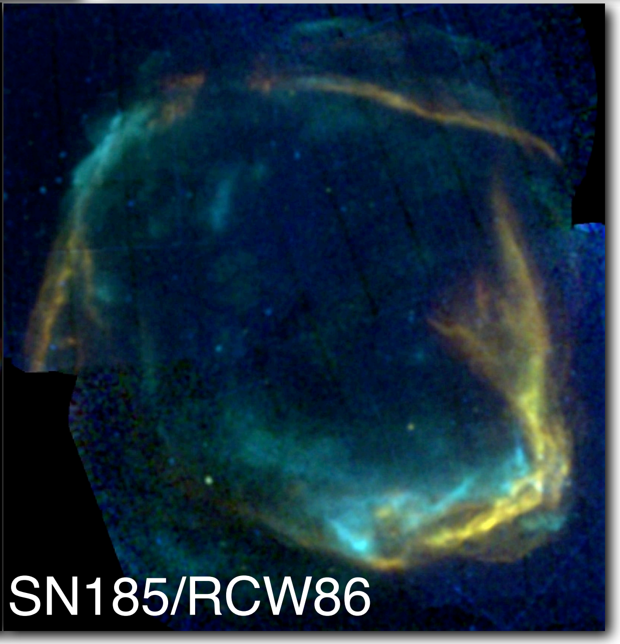
X-ray synchrotron & B-field amplification

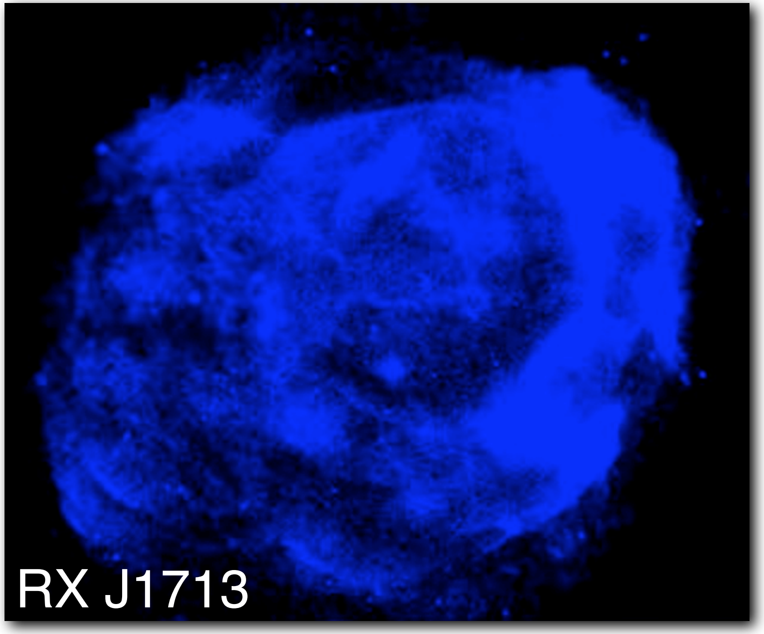

Cas A


SN1604/Kepler


SN1572/Tycho


SN1006


SN185/RCW86


RX J1713

X-ray synchrotron radiation

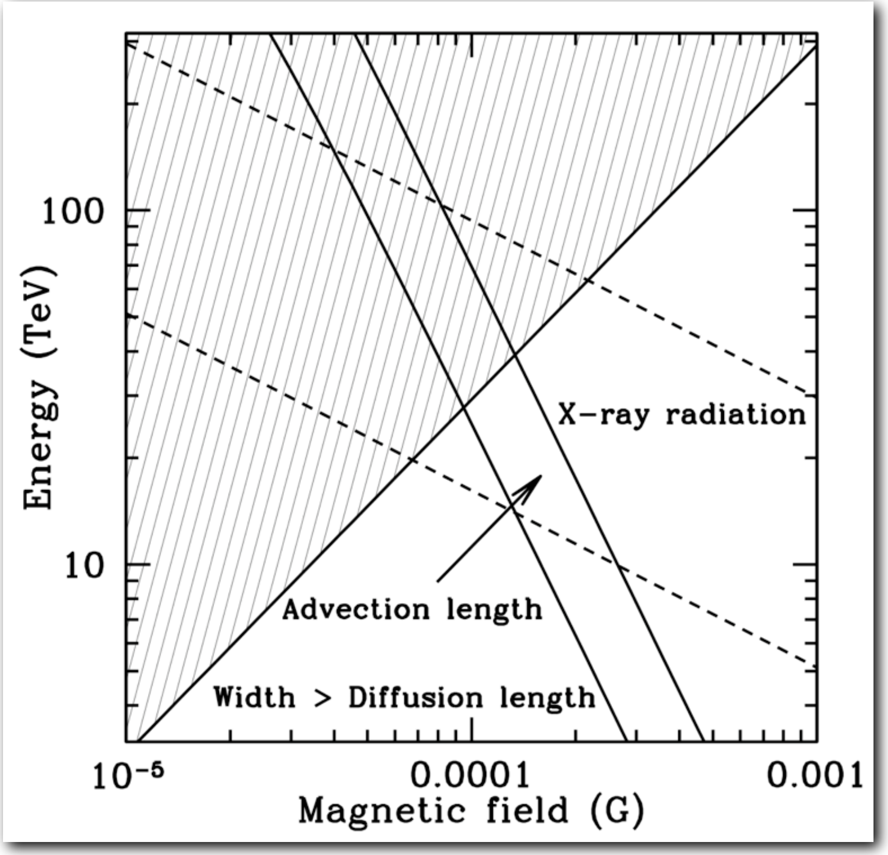
- One expects X-ray synchrotron emission only from young sources (i.e. high shock velocities), for loss limited case:

$$h\nu_{cutt\,of\,f} \approx 0.55\Big(\frac{V_s}{3000\,\mathrm{km\,s^{-1}}}\Big)^2 \eta^{-1}\ \mathrm{keV}$$

(Zirakashvili & Aharonian ‘07)

- $\eta > 1$ (=1 for Bohm-diffusion)
- Formula assumes loss limited maximum energy
- Note: maximum photon energy independent of magnetic field
- Hence: lower magnetic field larger electron energy

Interpreting narrow X-ray rims



- Rim widths determined by interplay of diffusion/advection and synchrotron losses
- Rim width can be used to measure B-field: B ≈ 110 $(L/10^{17}\mathrm{cm})^{-2/3}$ μG
- Cas A/Tycho/Kepler: ~100-500 μG
  (e.g. Vink&Laming 03, Berezhko&Voelk 03, Warren+ '05)
- High B-field ⇒fast acceleration

$$l_{diff} \propto \frac{1}{3}\frac{c}{v}\frac{E}{eB}$$

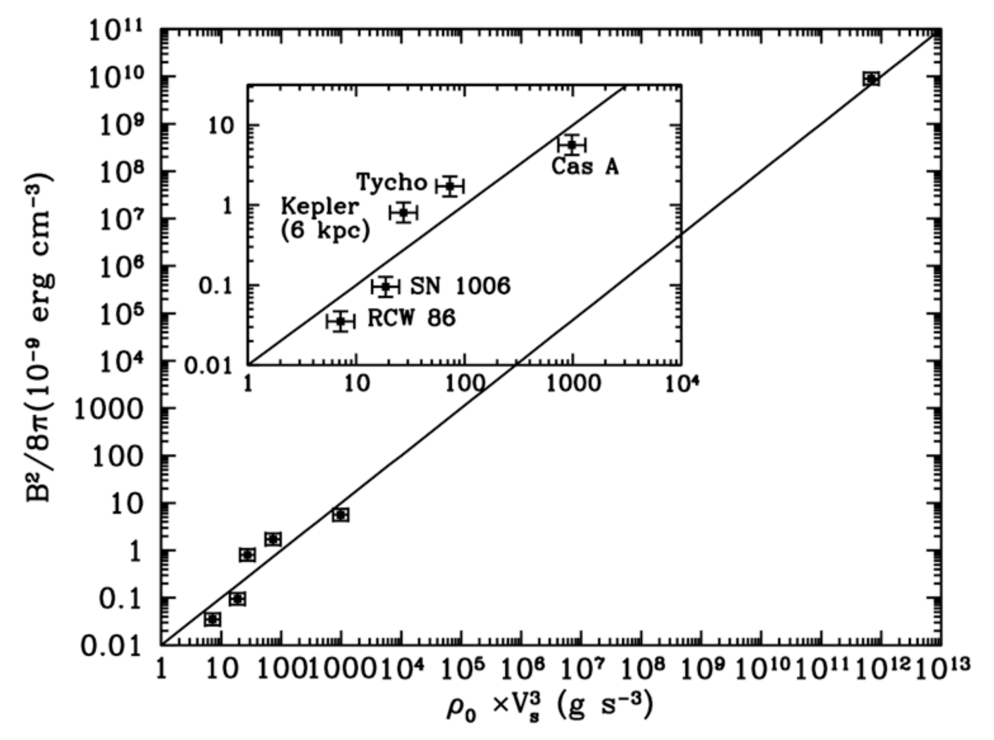
$$l_{adv} = v\tau_{loss} \propto \frac{v}{B^2E}$$

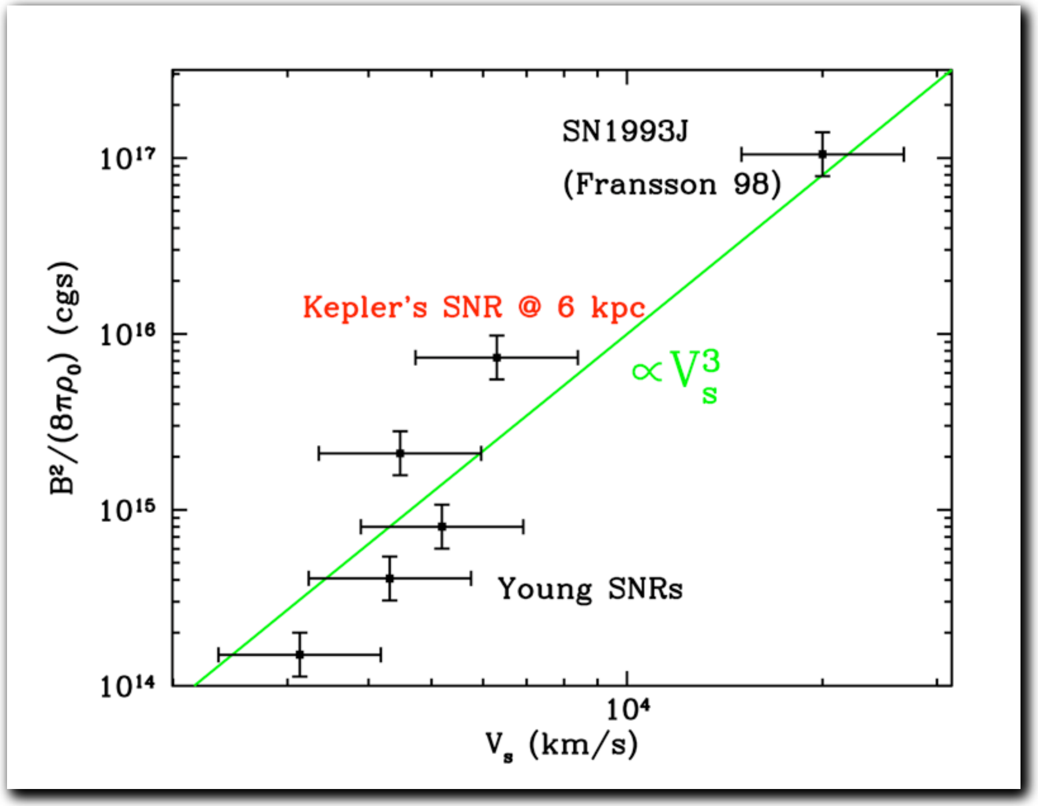
$$E_\gamma \propto E^2 B$$

- High B-field likely induced by cosmic rays (e.g. Bell +04)
- High B-fields are a signature of ion cosmic rays

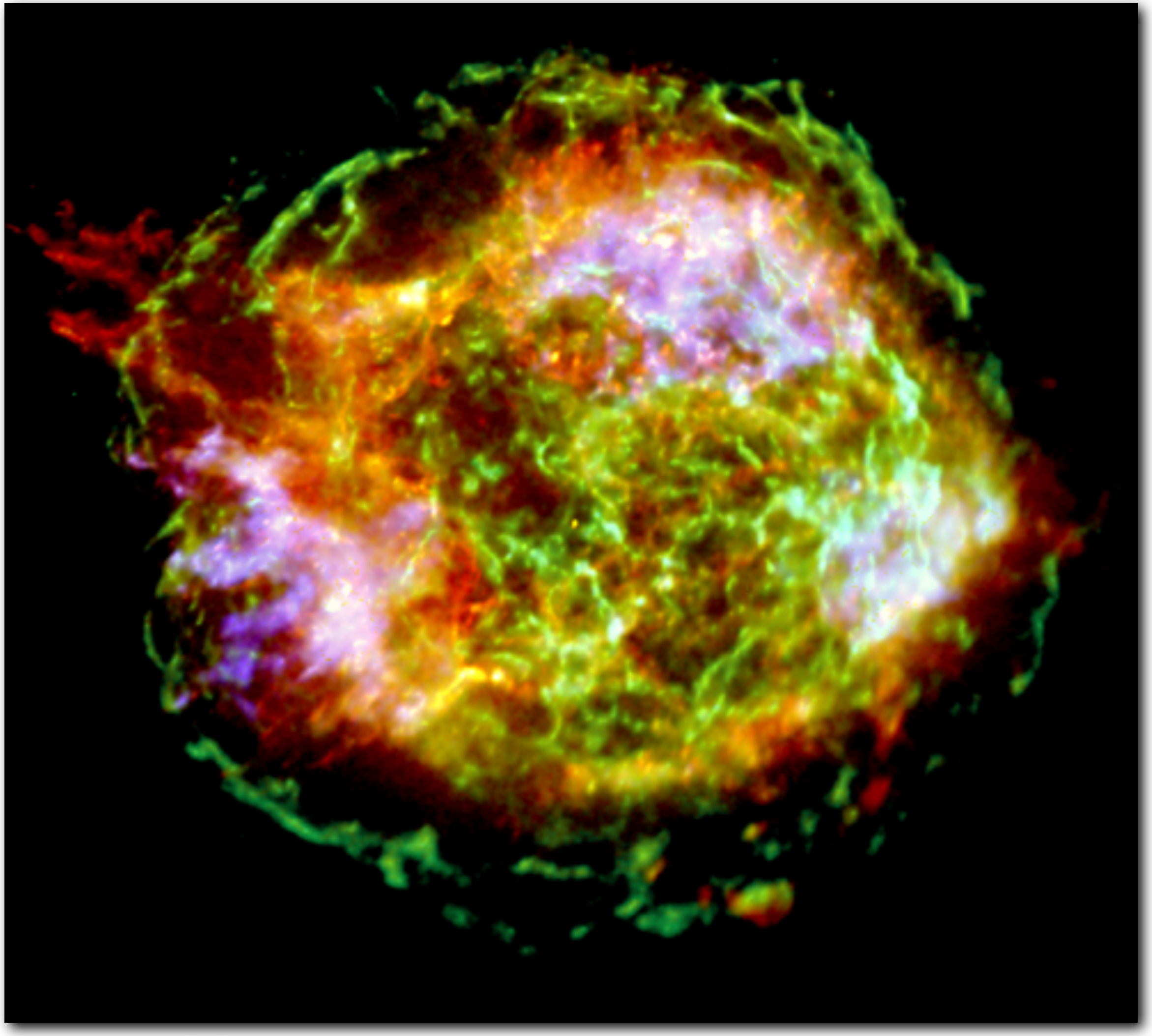
Magnetic Field Amplification

- There is a clear correlation between ρ, V and B, in rough agreement with theoretical predictions (e.g. Bell 2004)
- Relation may even extend to supernovae ($B^2 \propto \rho V_s^3$?) (Völk et al. ‘05, Vink ‘08)





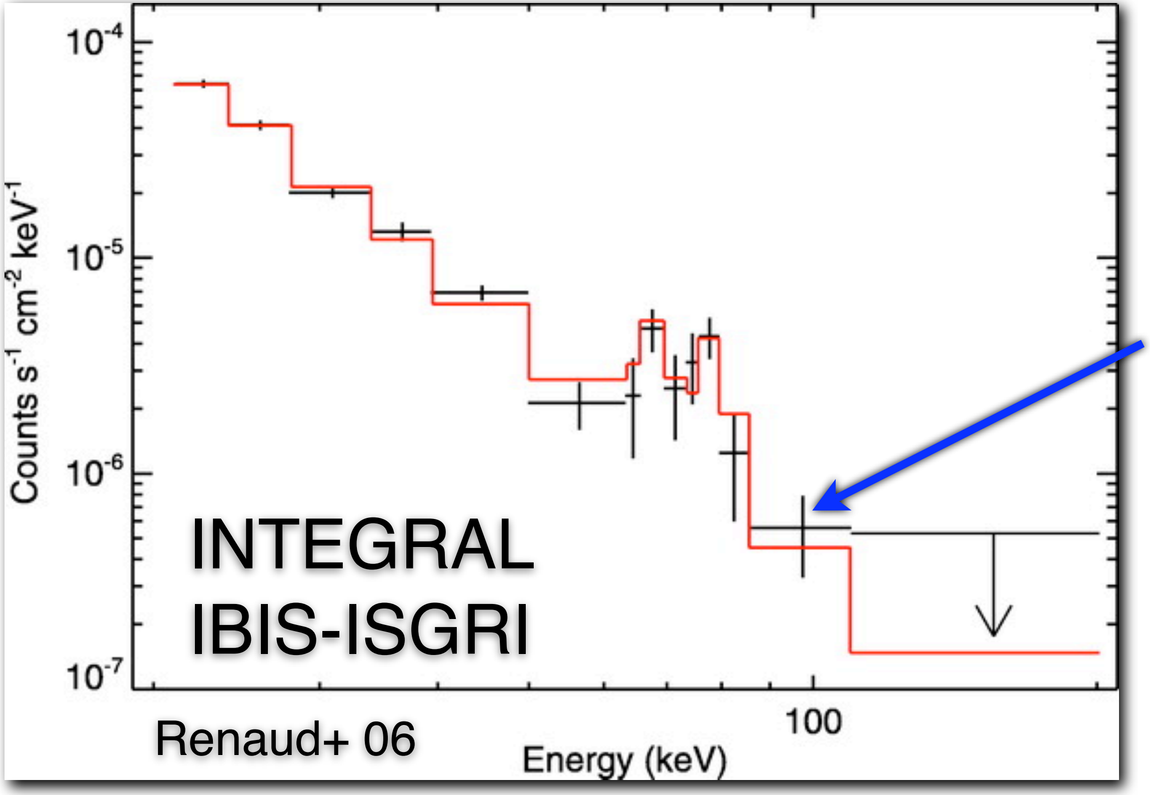
Cas A



Hwang+ 2004

- Strong continuum filaments (green) from inner region
- Temporal brightness fluctuations (t~few year)
  - acceleration/loss time? (Uchiyama+08, Patnaude+09)
  - B-field turbulence? (Bykov+ 08)

Hard X-ray Emission



INTEGRAL
IBIS-ISGRI

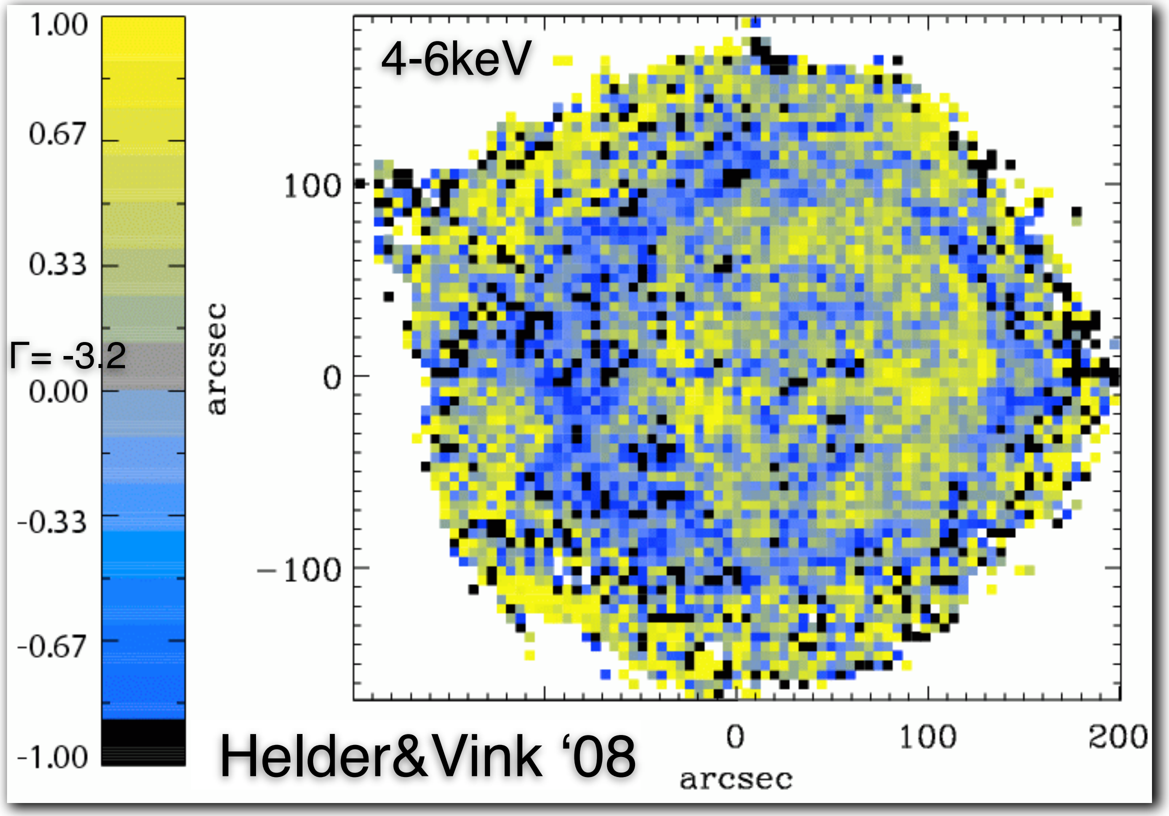
Renaud+ 06

Synchrotron radiation?
Non-thermal bremsstrahlung?

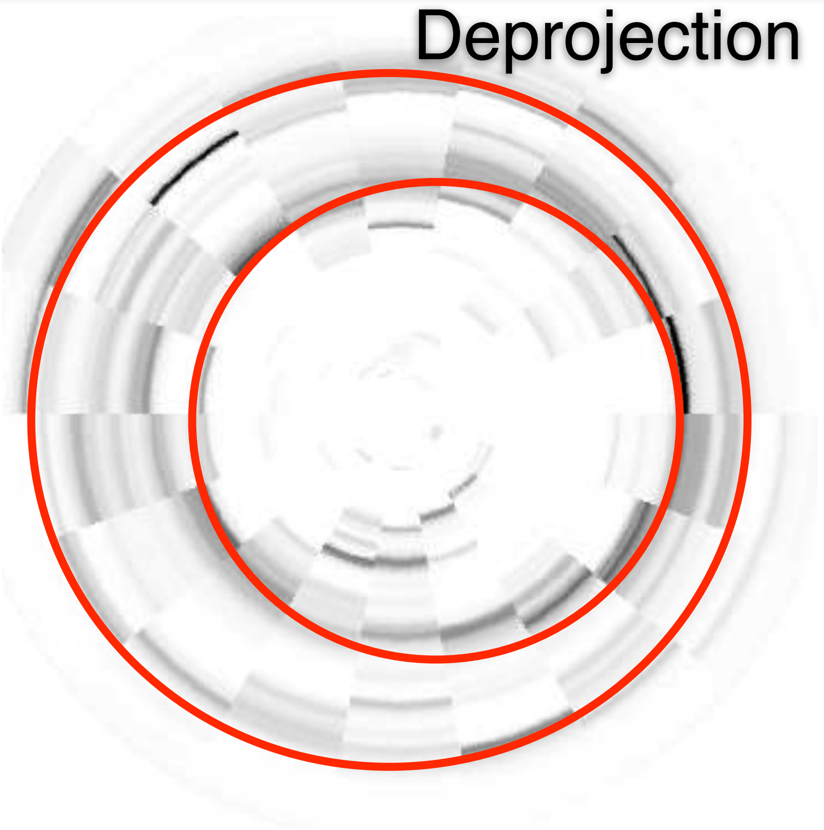
The+ ’96, Allen+ ’97, Favata+ ’97,
Vink+ ’01, Vink & Laming ’03

- Data best described by power law Γ=3.2
- Expected synchrotron steepening not seen
- Speculation:
  - non-thermal bremsstrahlung? (Vink ’08, see also Laming’s talk)
  - B-field turbulence smoothing out cut-offs?

Acceleration @ Cas A reverse shock



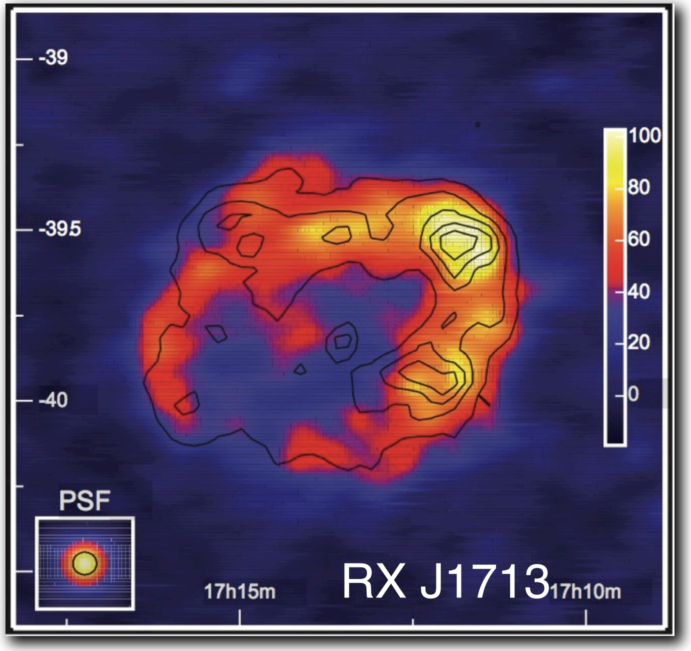
Helder&Vink ‘08

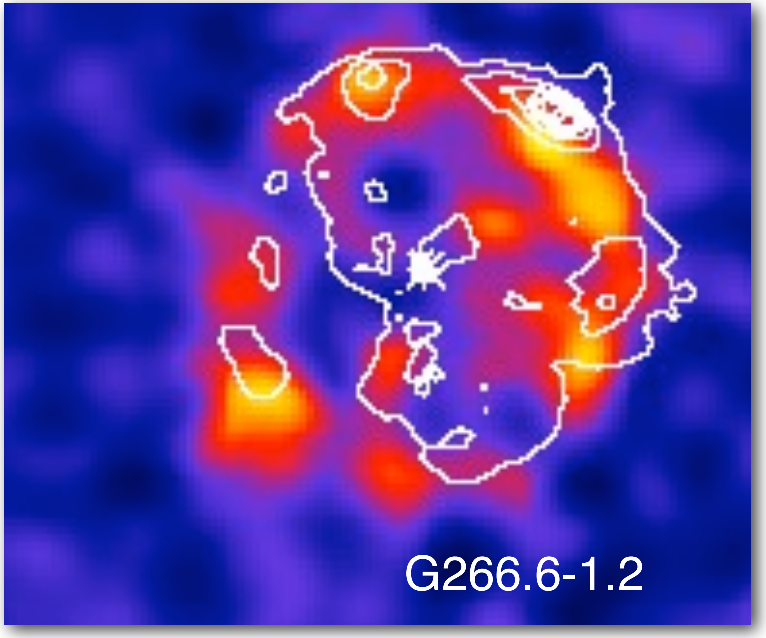


- Spectral index: 2 regions of hard emission: X-ray synchrotron emission
- Deprojection: Most X-ray synchrotron from reverse shock!
- Prominence of West: No expansion ⇒ ejecta shocked with V>6000km/s

B-field amplification is not very sensitive to initial B-field!

RX J1713 & Vela Jr

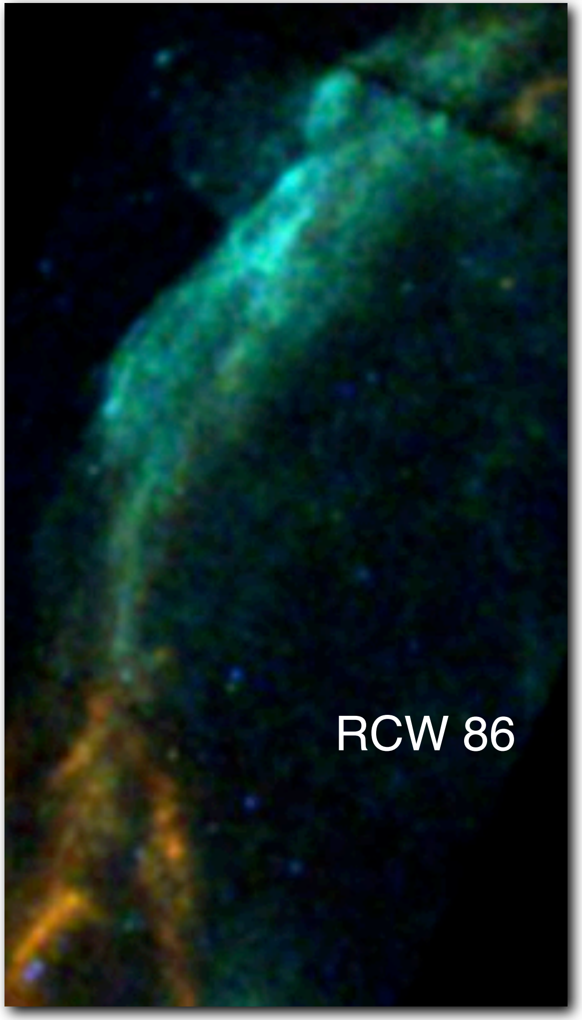




- Bright TeV sources, weak radio sources
- No thermal X-ray emission, only synchrotron!!!!
- TeV emission pion decay or inverse Compton? (←n_H, B?)
- Size, lack of X-rays: low density → IC
- TeV spectrum, low kT due to CR acc → pion decay

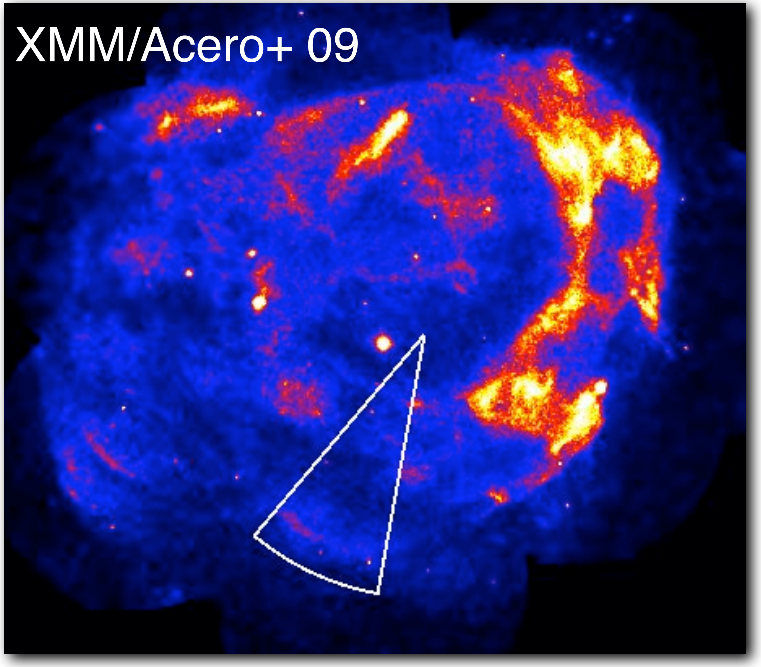
(Aharonian+ ’04,’05, ’07; Uchiyama+ ’07, Berezhko&Völk ’06, Katz&Waxman ’08, Drury+ ‘09)

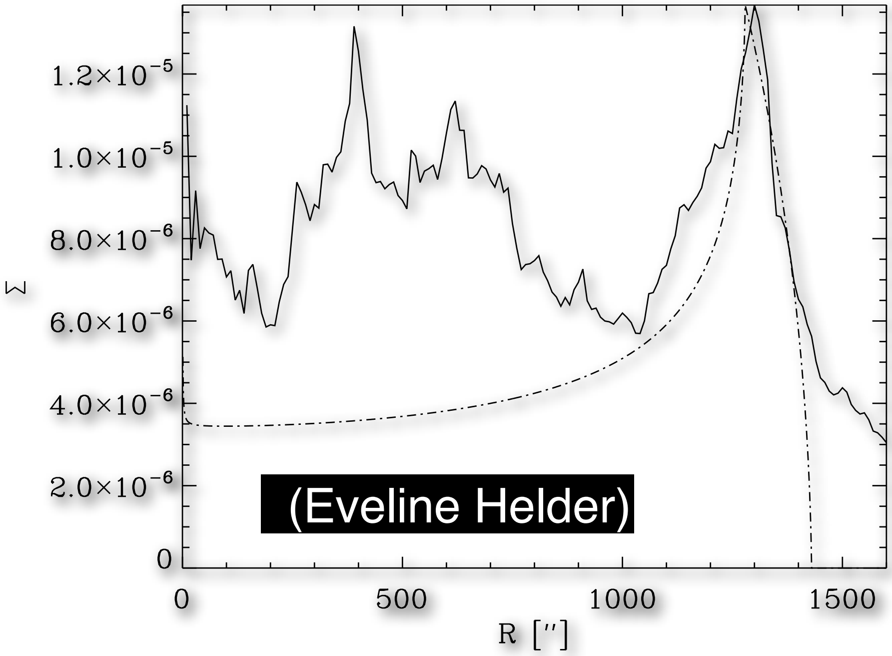
A problem with B-fields from X-ray filaments



- Narrow filaments (Cas A, Kepler, Tycho): too narrow to see substructure
- Wider filaments (SN 1006, RCW 86, RX J1713, Vela Jr):
  substructure visible
  analysis on substructure? → high B-field
  or on X-ray synchrotron shell? → low B-field

The case RX J1713



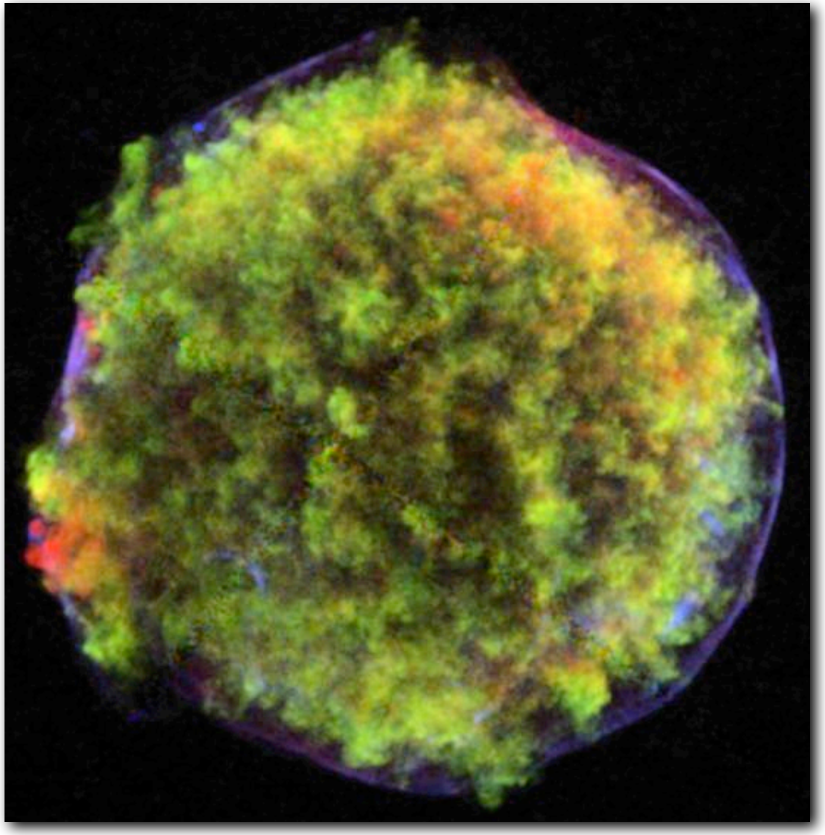


(Eveline Helder)

- High B-fields (>100μG) based on temporal fluctuations (Uchiyama+ '07) or on picking narrow 20" structures (Berezhko&Völk '06)
- Picking overall region gives a deprojected 150" ($2x10^{18}d_{kpc}$ cm)
- This gives: B~10-20 μG

High Compression Ratios

- If acceleration is very efficient CRs dominate internal energy
- If $\Gamma < 2$ cosmic ray energy losses become dynamically important
- Shock compression ratios become >4
- No losses: 4-7
- With losses > 7



- X-ray evidence in Tycho:
  Ejecta in Tycho's SNR too close
  to shock front
  → need high compression ratio!
- SN1006: effect seen as well
  (even outside X-ray synchrotron rims)

(Decourchelle&Ellison '01, Warren+ '05, Cassasm-Chenai+ '08)

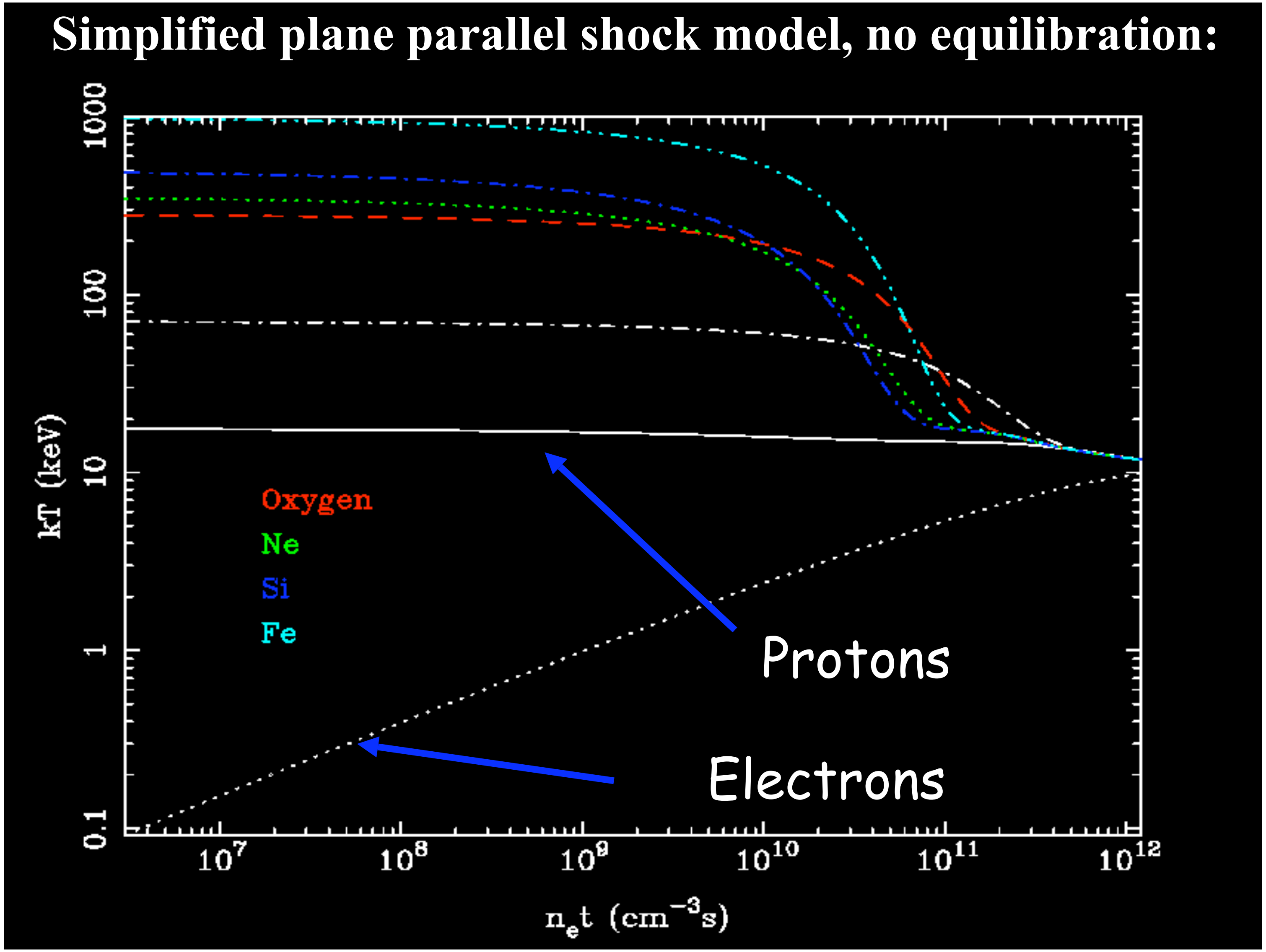
Efficient Acceleration & Shock Heating

- Collisionless shocks: temperature equilibration or not?
  - equilibration→implies direct particle-particle interaction
    →or, acceleration by electric field
  - non-equilibration →likely outcome of scattering (isotropization)
- Expected temperatures for non-equilibration/no heat sinks:

$$kT_i = \frac{2(\gamma-1)}{(\gamma+1)^2} m_i V_s^2 = \frac{3}{16} m_i V_s^2 = 2.0\left(\frac{m_i}{m_p}\right)\left(\frac{V_s}{1000\ \mathrm{km/s}}\right)^2\ \mathrm{keV}$$

- For young SNRs (V_s>3000 km/s) expect kT > 10 keV
- No SNR known with kT_e > 4 keV!!
- Possible solutions:
  - Measured is electron temperature: $kT_e < kT_p$
  - Cosmic ray acceleration

Temperature (Non-)Equilibration



Shock heating

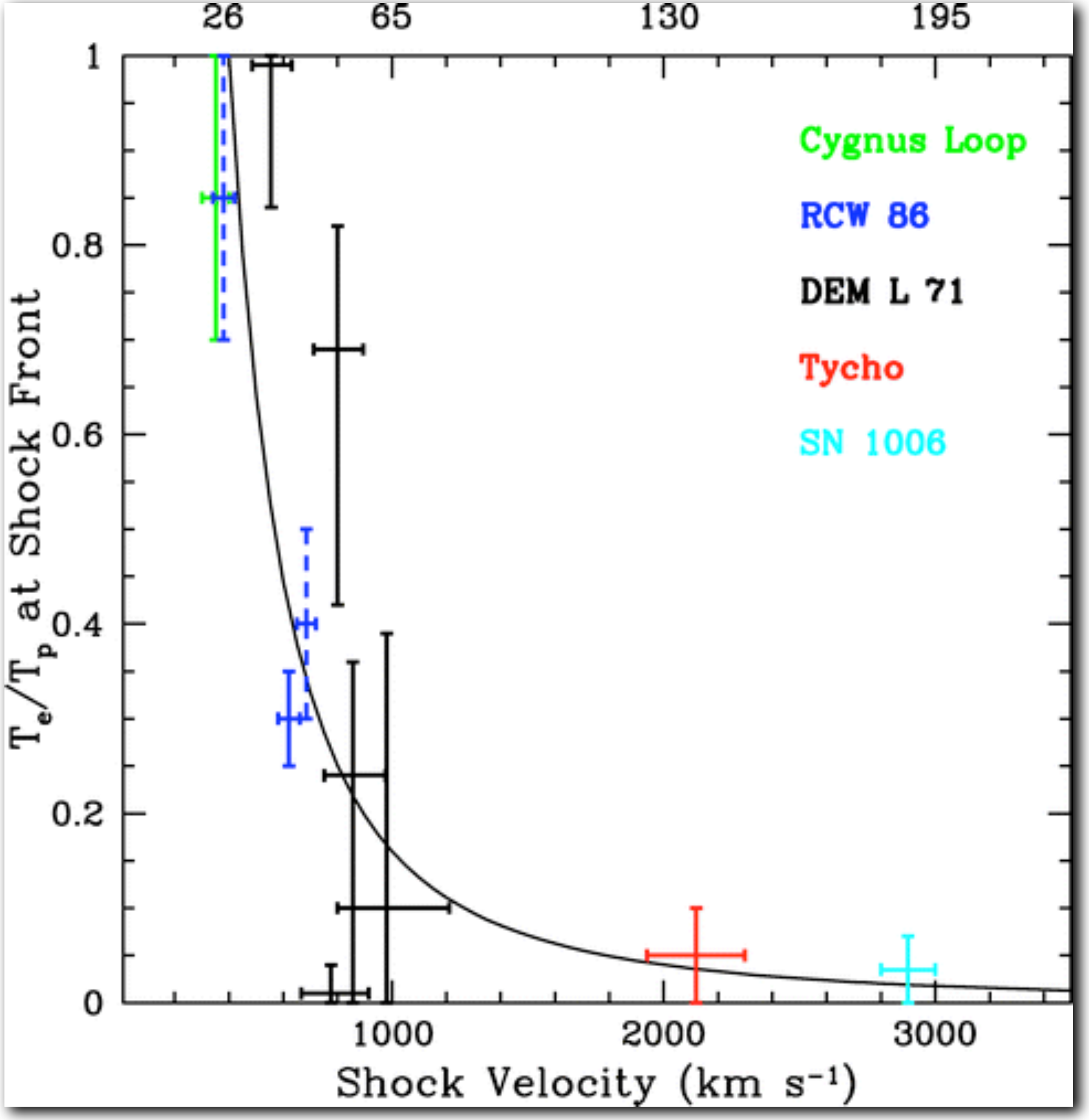
- A strong shock in a monatomic gas heats the plasma to (in absence of temperature equilibration)

$$kT_i = \frac{2(\gamma-1)}{(\gamma+1)^2} m_i V_s^2 = \frac{3}{16} m_i V_s^2 = 2.0 \Big(\frac{m_i}{m_p}\Big)\Big(\frac{V_s}{1000\ \mathrm{km/s}}\Big)^2\ \mathrm{keV}$$

- For young SNRs (V_s>3000 km/s) expect kT > 10 keV
- No SNR known with kT_e > 4 keV!!

- Possible solutions:
    - Measured is electron temperature: $kT_e < kT_p$
    - Large part of pressure comes from cosmic rays and/or energy taken away by CR escape

Proton temperatures



Comparing *electron* and *proton* temperatures

- Proton temperature: thermal Doppler broadening of Hα
- Electron temperature: X-ray spectra
- $T_{\text{protons}} > T_{\text{electrons}}$ only for V_s> 300 km/s

Ghavamian+ '07
van Adelsberg+ '08

Shock heating & Particle Acceleration

- Efficient cosmic ray acceleration & cosmic ray escape will give rise to lower post-shock temperatures
- X-ray temperatures not a good indicator: measure electron temperature (Hughes+ 2000)
- Needed: proton temperature
- Correlation with particle acceleration:
  proton temperature in X-ray synchrotron dominated shock

- Proton temperature can be obtained from broad Hα emission:
  neutrals entering shock will undergo
    - excitations → narrow line Hα (width → upstream kT_{HI})
    - charge exchange with shock heated protons
      → broad line Hα (width → down stream kT_p)

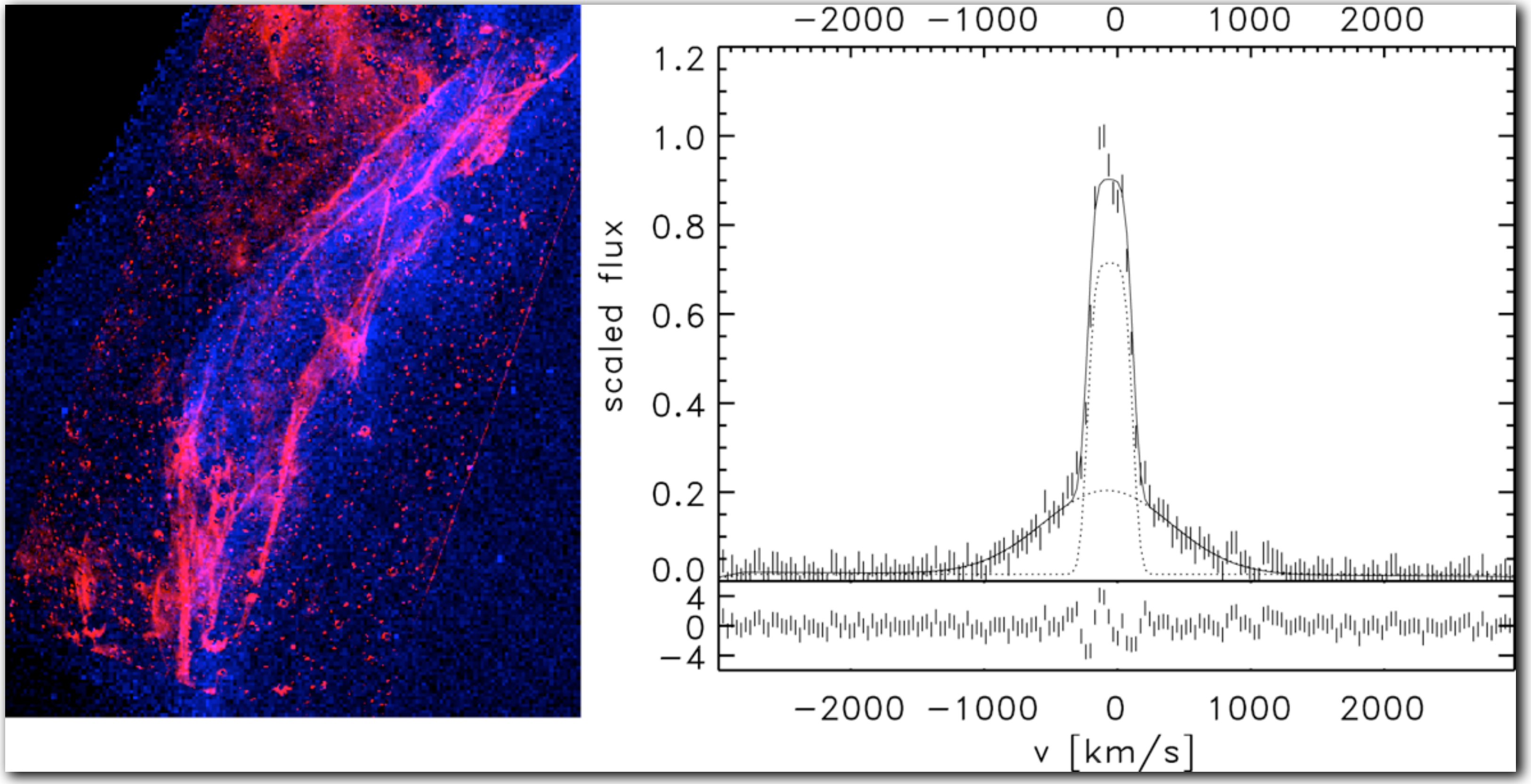
RCW86 NE X-ray synchrotron & Hα

- RCW 86 is ideal for measuring kT_p in presence of CRs:
  - NE shows X-ray synchrotron emission
  - RCW 86 is a TeV source
  - Is a source of Hα emission

Vink+ 06

Smith 1997

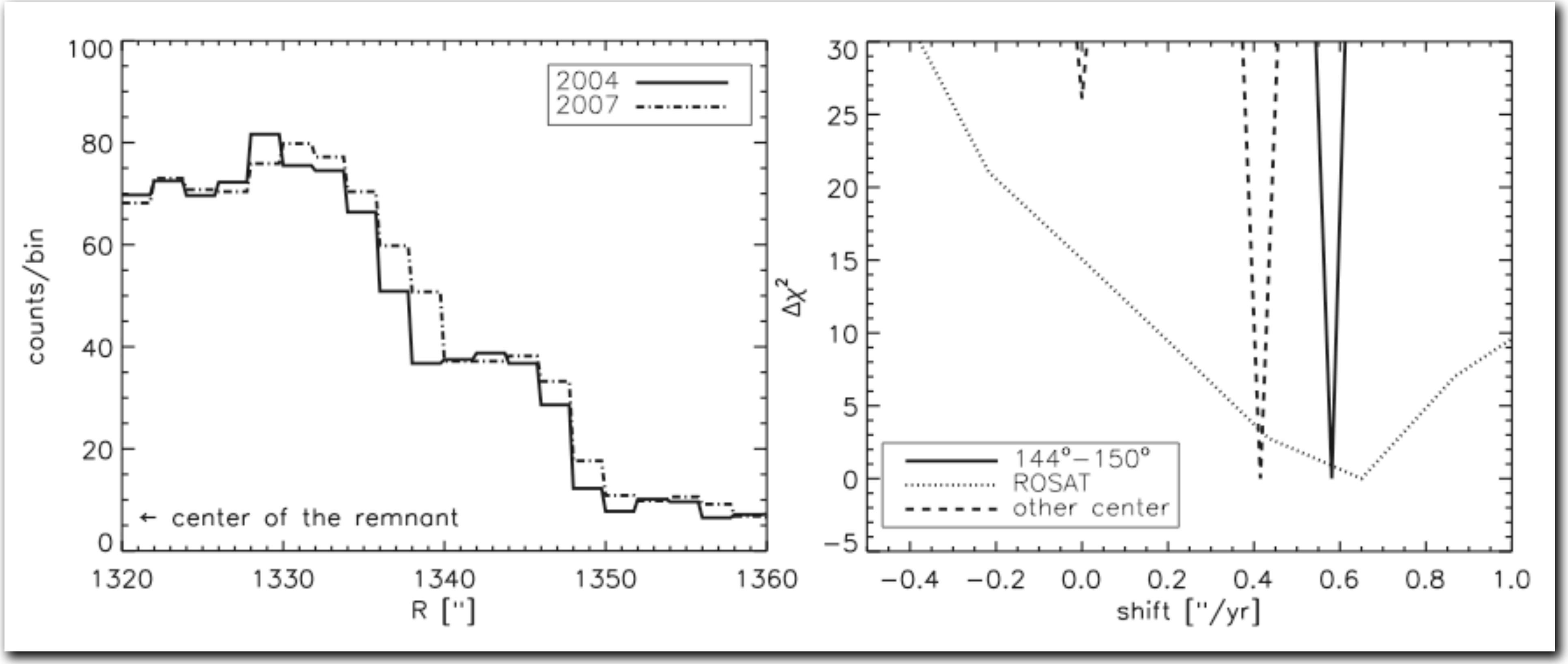
RCW 86 NE Hα measurements



- Broad line width : 1100 ± 63 km/s ⇒ $kT_p = 2.2$ keV

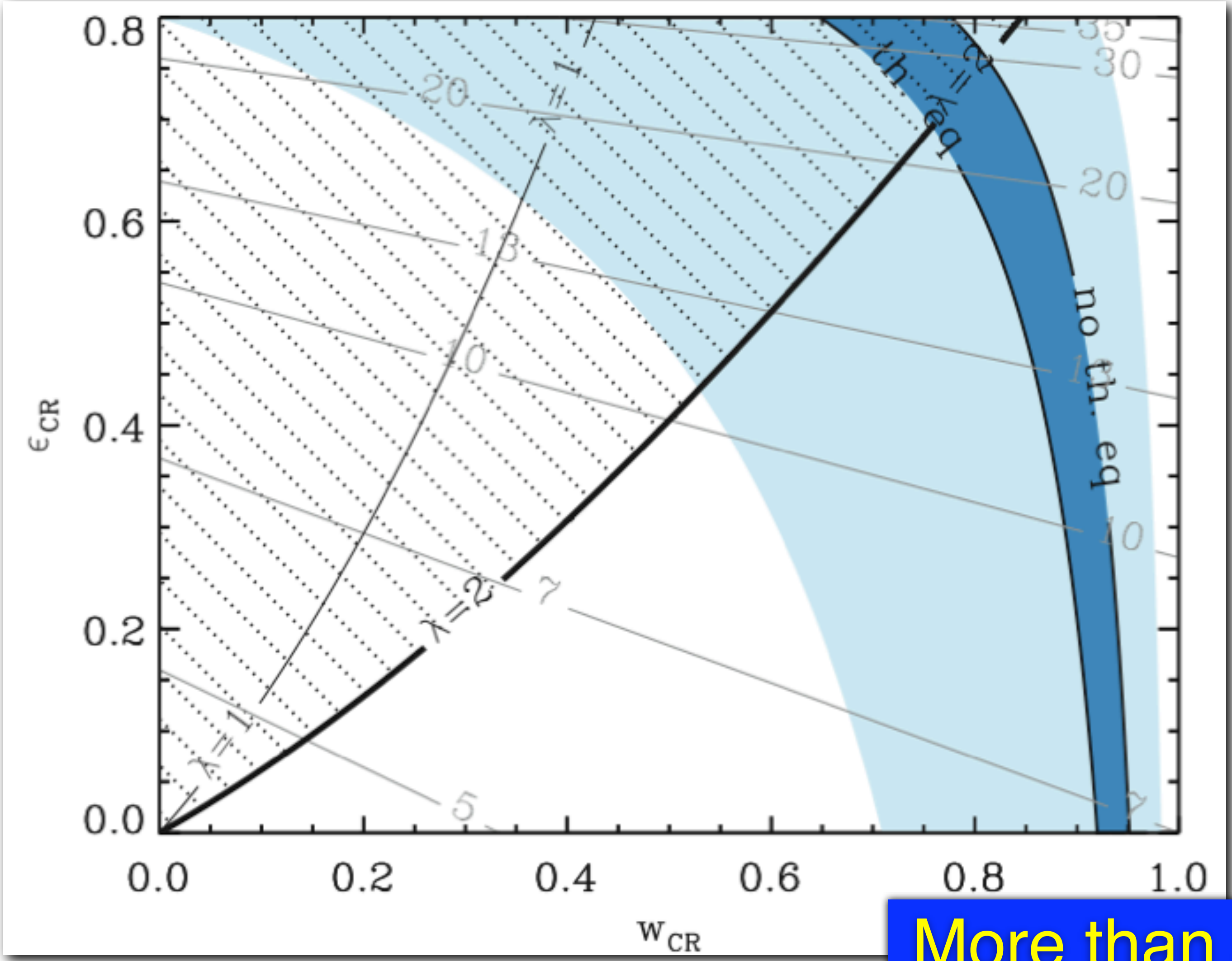
Helder+ 09

Shock proper motion



- Proper motion: (1.5±0.3)”/3yr (error largely systematic)
- V_s = (5900±1200) $d_{2.5}$ km/s
- Expected kT_p = 43 - 98 keV
- Ratio expected to observed temperature: 0.06 - 0.03

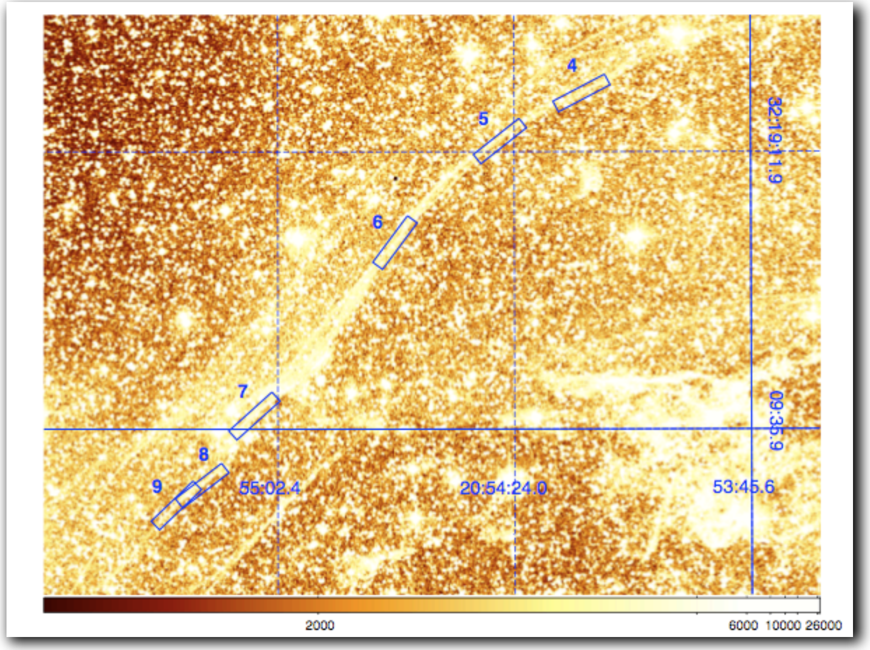
Cosmic Ray Acceleration Efficiency

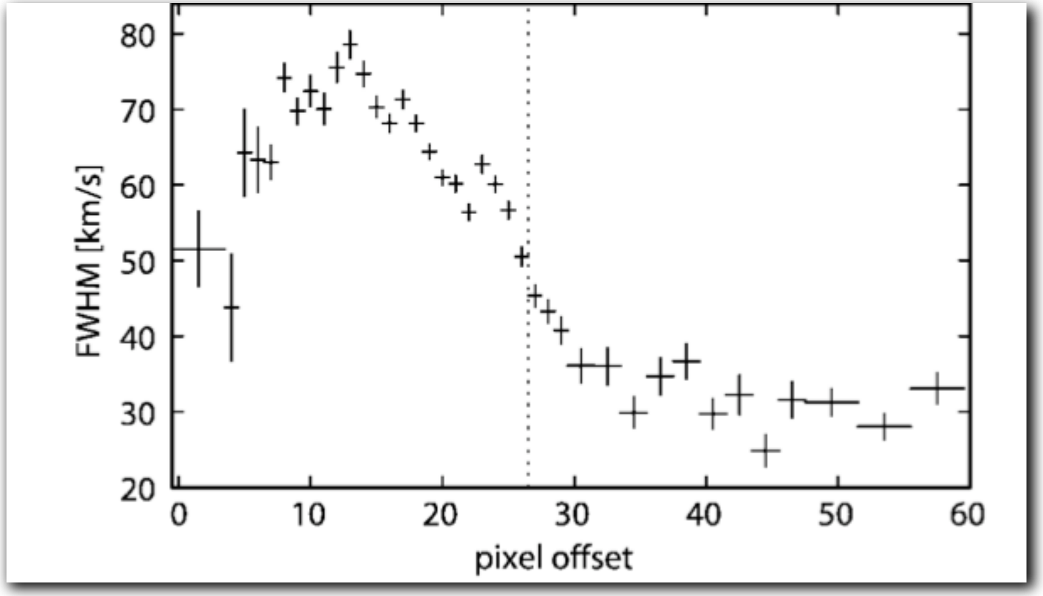


Helder+ 09

More than 50% of available energy in cosmic rays

Some other Hα results

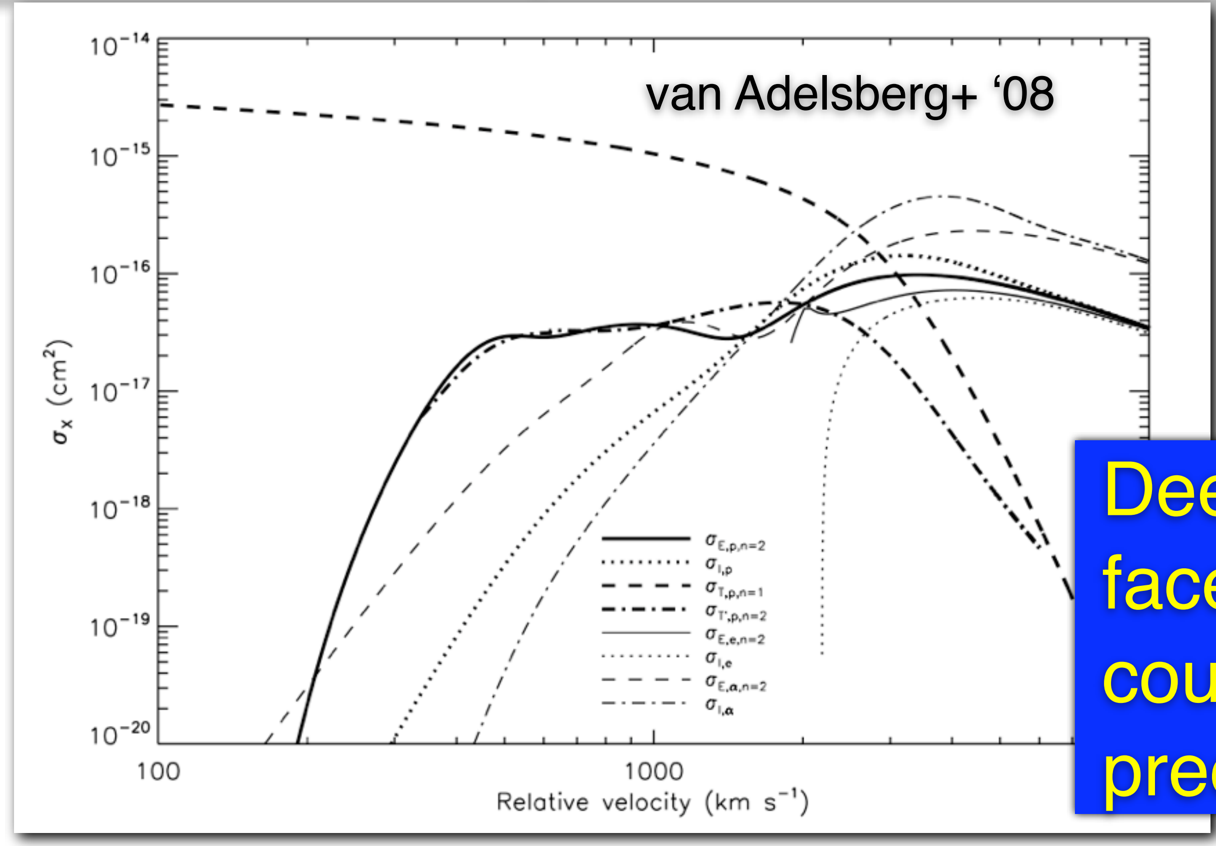




- Salvesen+ ’09 observations of Cygnus Loop (Vs:
  kT measurement consistent with no CR acceleration

- Lee+ ’09 observations of Tycho knot g:
  Narrow Hα emission ahead of shock front, seem hotter closer to shock
  →shock precursor heating?

Probing the pre-cursor with Hα



van Adelsberg+ ‘08

Deeper Hα spectroscopy of face on/edge on shocks could reveal details of CR precursor!!

- Charge exchange length scale $10^{15}/n_H$ cm
- Similar to CR pre-cursor length scale
- Charge exch. important in pre-cursor → neutrals heated & accelerated
- Face on: narrow line (pre-heated/acc. neutrals) should be shifted with plasma velocity at $l_{precursor} \sim 10^{15}/n_H$ cm

Conclusions

- A lot has been accomplished in last 10-15 yr:
  - TeV emission points to particle acceleration > 10 TeV
  - X-ray synchrotron emission indicates $E_e > 10$ TeV
  - Narrow filaments X-ray filaments indicate B-fields up to 600μG
- Indirect signs of presence of CRs:
  - B-field amplification
  - High shock compression ratios
  - Lower than expected plasma temperatures
- Still unclear: TeV emission: inverse Compton or pion decay?
- Much progress due to multiwavelength studies
- Many remaining questions:
  - when is CR acc. most important: <100 yr, Sedov, superbubbles?
  - related: in RCW 86 efficient acc. in Cygnus Loop not: what happens in between? (similar conclusion from radio polarization)
- Future work:
  - Accurate determination of V_s and X-ray synchrotron$\rightarrow\eta$
  - probe cosmic ray precursor with Hα emission