X-ray & Optical Evidence for

Efficient Cosmic Ray Acceleration by Supernova Remnants

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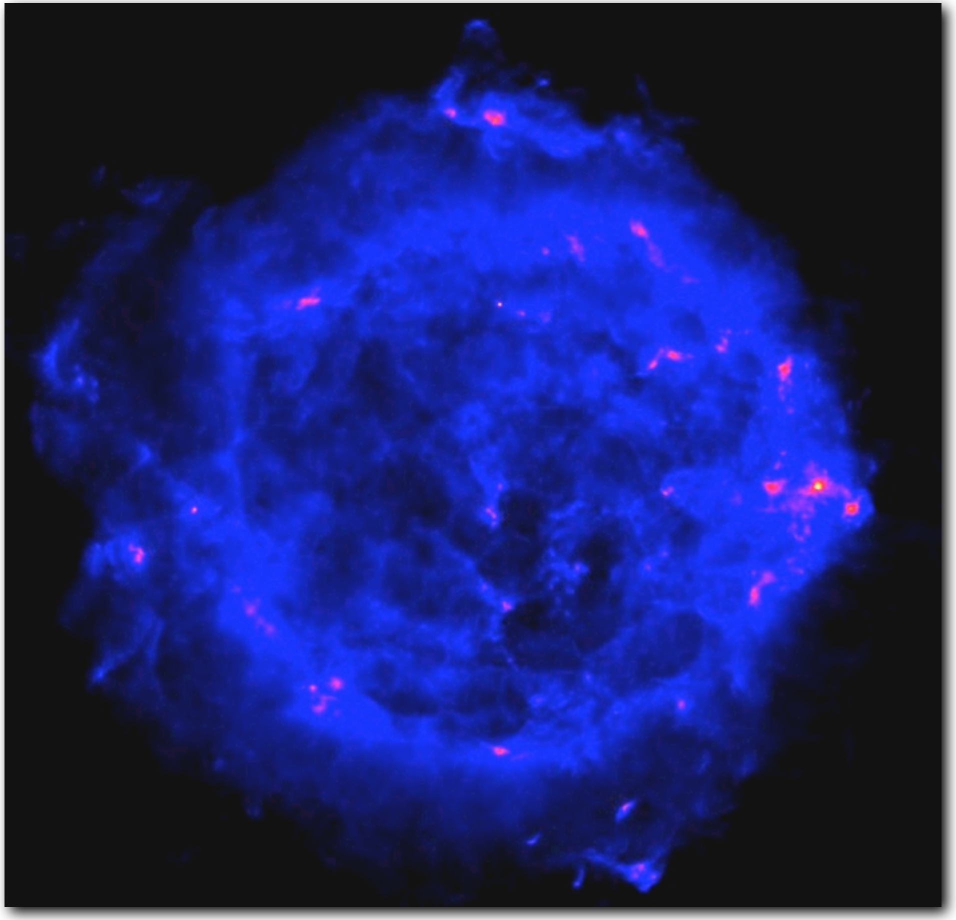
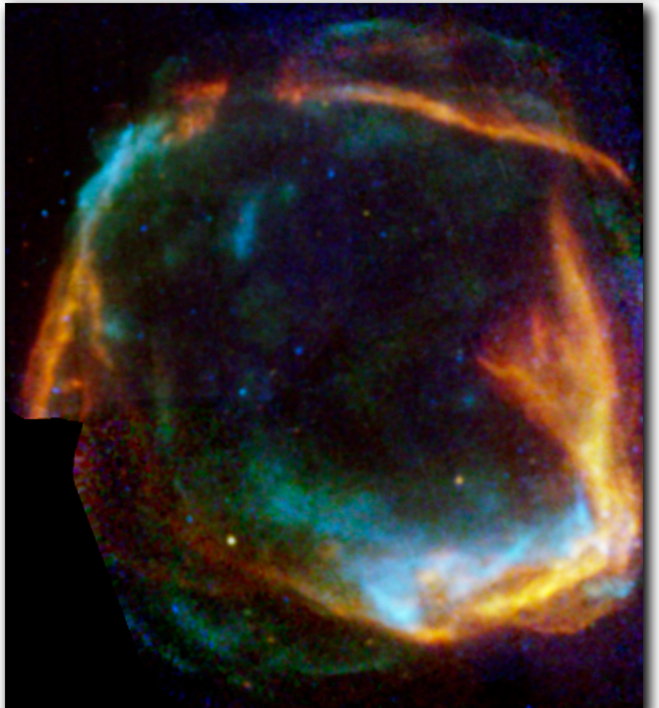
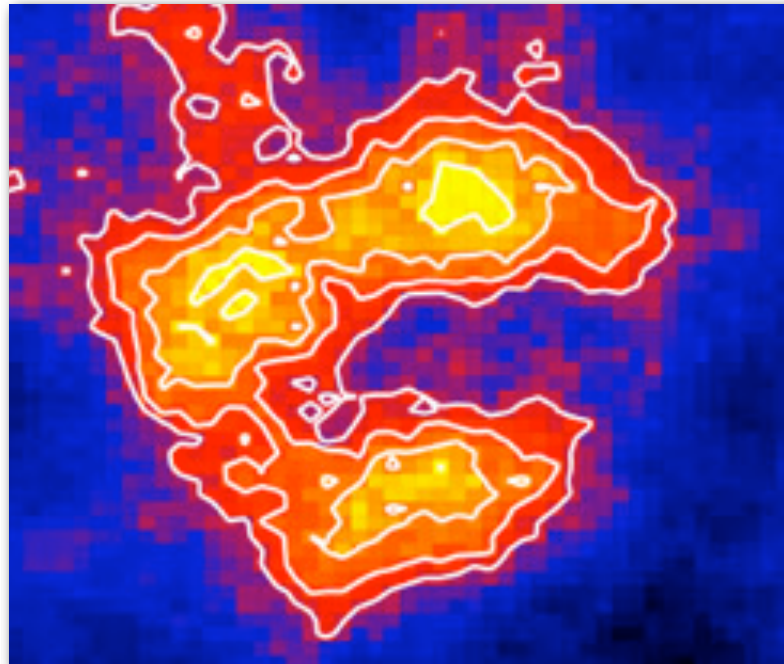
SNRs as particle accelerators

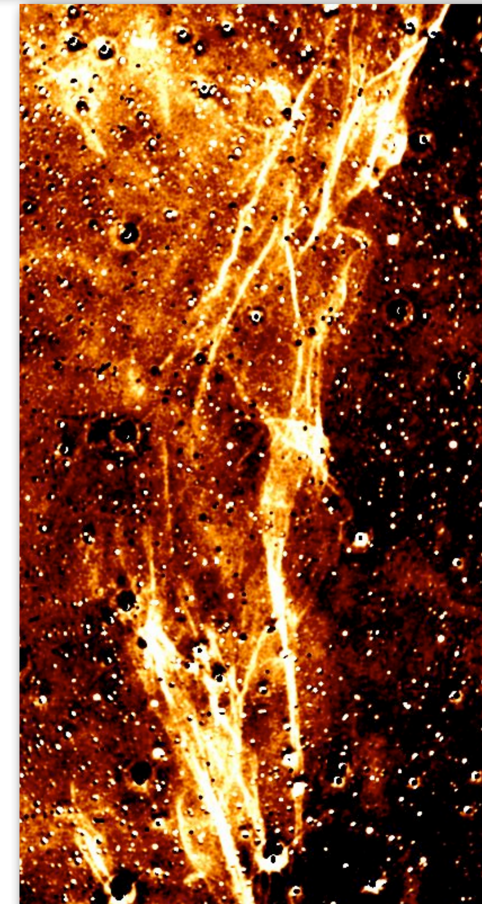
- Supernova energy as source for cosmic rays suspected since Baade & Zwicky
- Early evidence for particle acceleration in SNRs:
  Radio synchrotron emission
- Prime example: Cas A
  - young (~330 yr)
  - brightest radio source
  - radio flux decreases 1%/yr
  - explanation: adiabatic losses (Shklovksy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



Last 15 years







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

TeV gamma-ray astronomy

8 m class optical telescopes

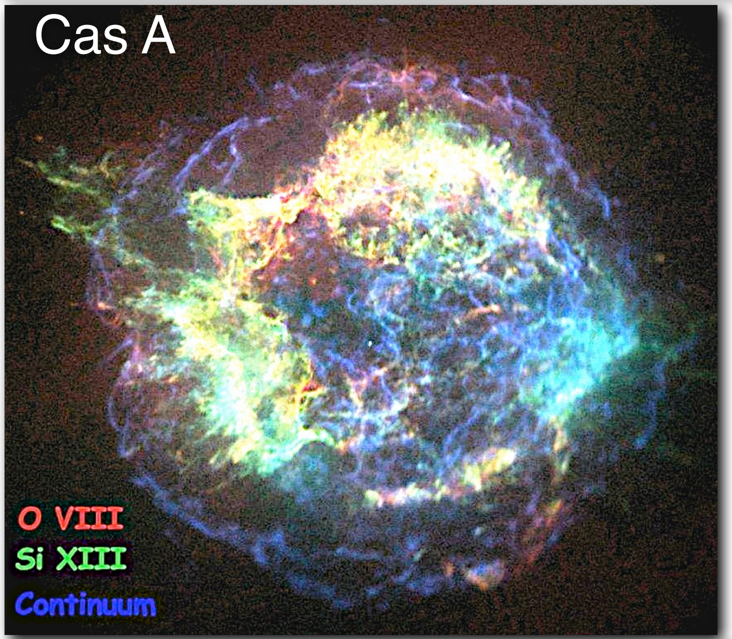
(Object: RCW 86, Vink+ '06, Aharonian+ '09, Helder+ '09)

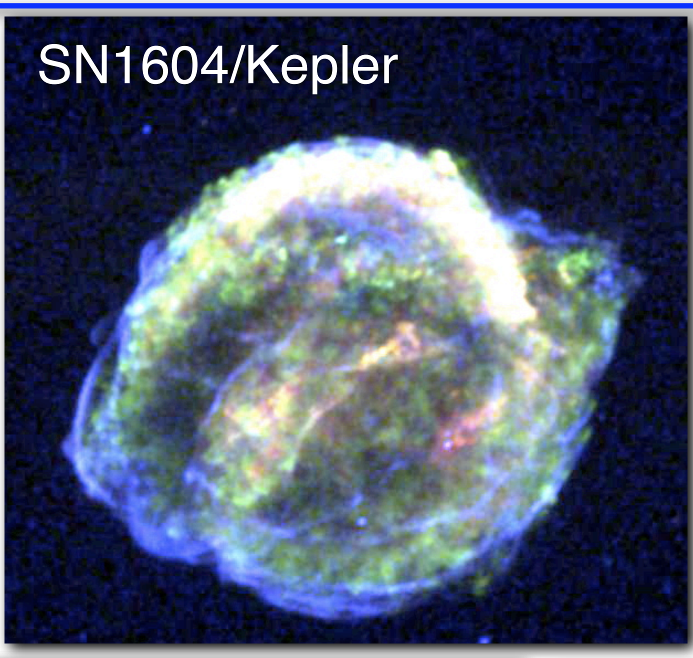
Evidence for efficient acceleration

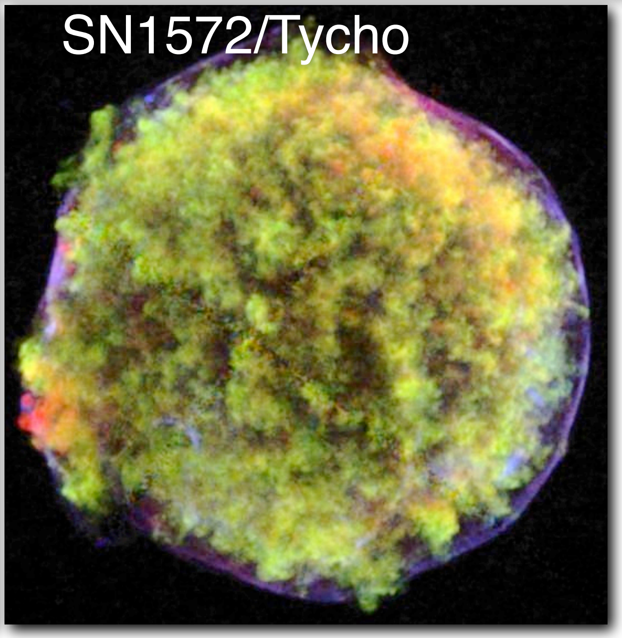
1. Direct observations of accelerated particles
   - Electrons:
     - synchrotron radiation (10^7Hz- 10^{18} Hz)
     - inverse Compton (IC) scattering (GeV/TeV γ-rays)
     - bremsstrahlung (keV- TeV)
   - Ions: pion-decay (GeV/TeV γ-rays)
   - Identification of pion decay or IC not always clear!

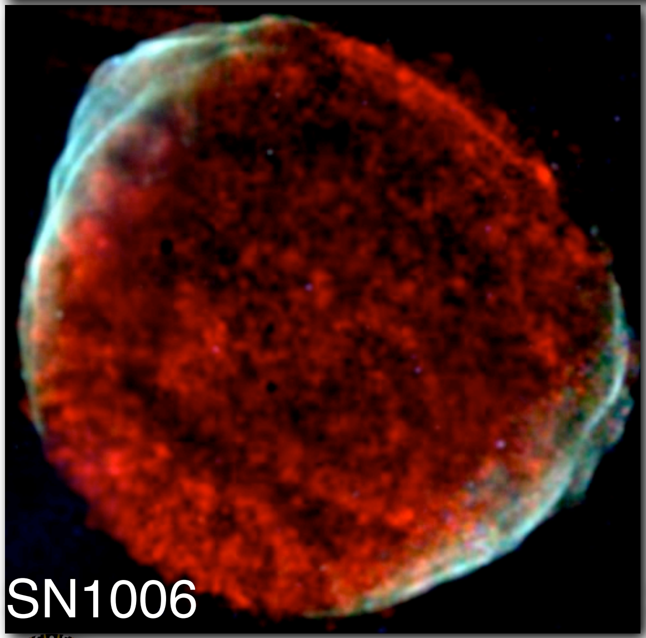
2. Indirect evidence:
   - Magnetic field amplification (20- 500μG)
   - High compression ratios (> 4)
   - Concave synchrotron spectra
   - Lower than expected plasma temperatures
   - Evidence for shock precursors (Hα)

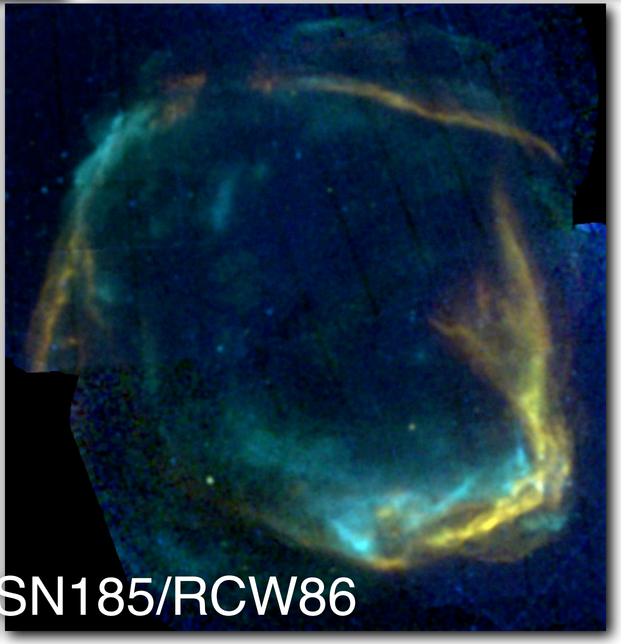
X-ray synchrotron & B-field amplification

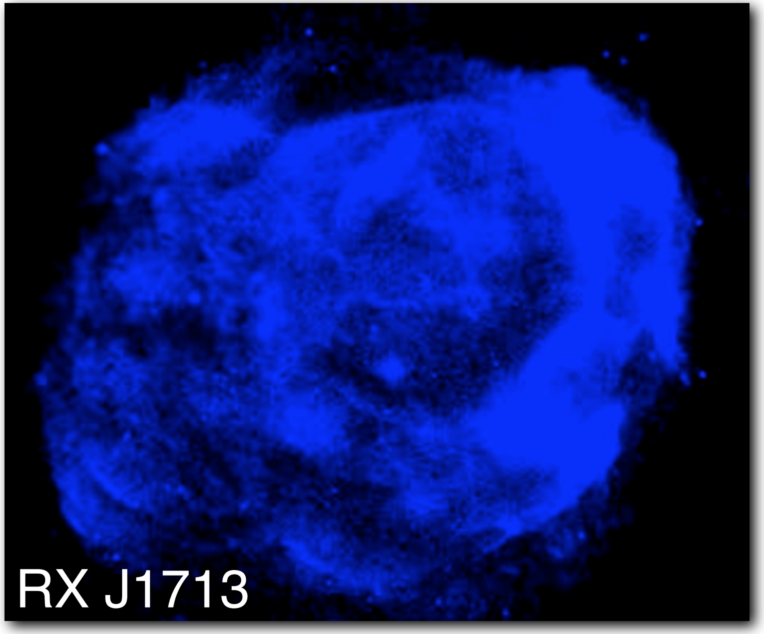












X-ray synchrotron radiation

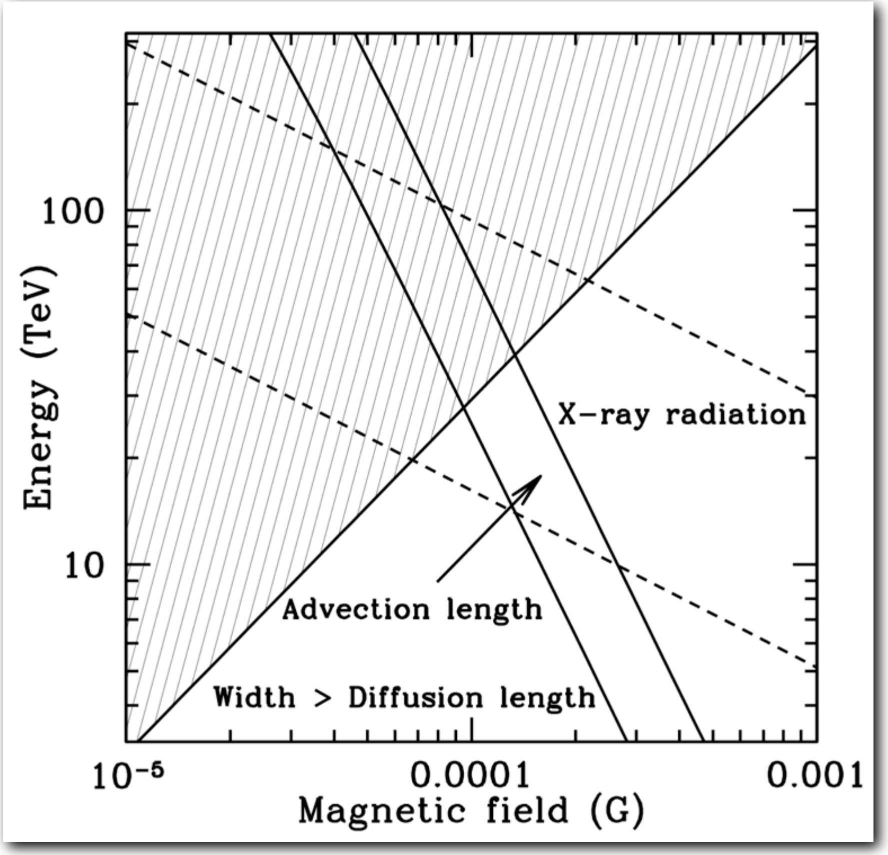
- One expects X-ray synchrotron emission only from young sources (i.e. high shock velocities), for loss limited case:

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

(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
  (but may be the reverse for protons!)

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: $B \approx 110\ (L/10^{17}\mathrm{cm})^{-2/3}\ \mu\mathrm{G}$
- Cas A/Tycho/Kepler: ~100-500 μG
  (e.g. Vink&Laming 03, Berezhko&Voelk 03, Warren+ '05)
- High B-field ⇒fast acceleration

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

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

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

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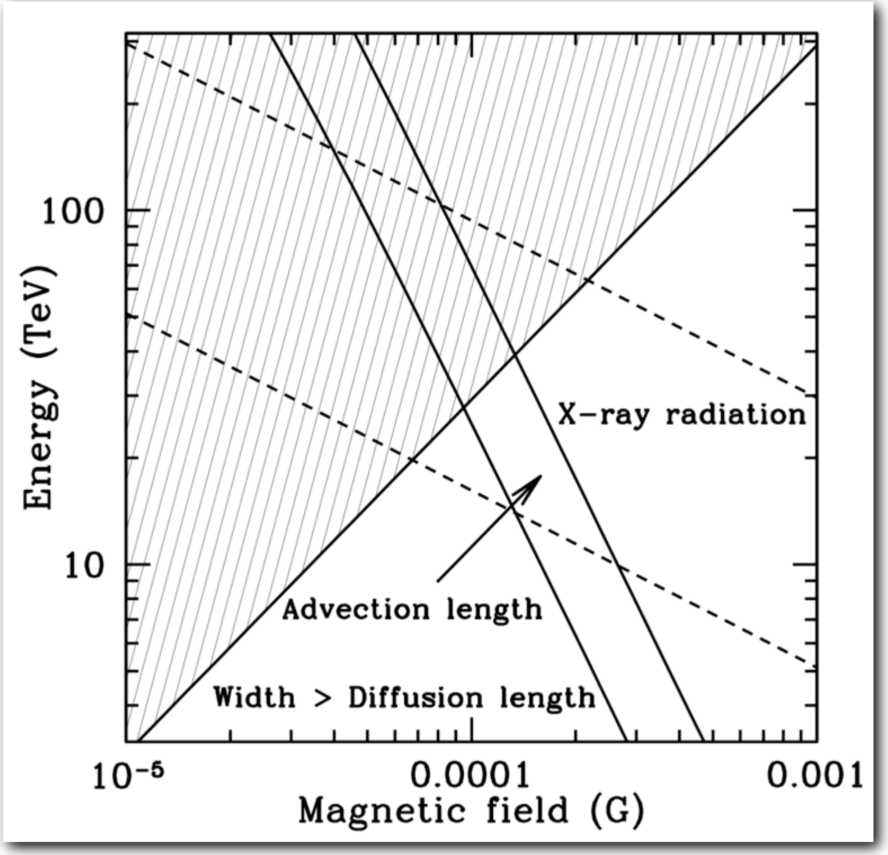

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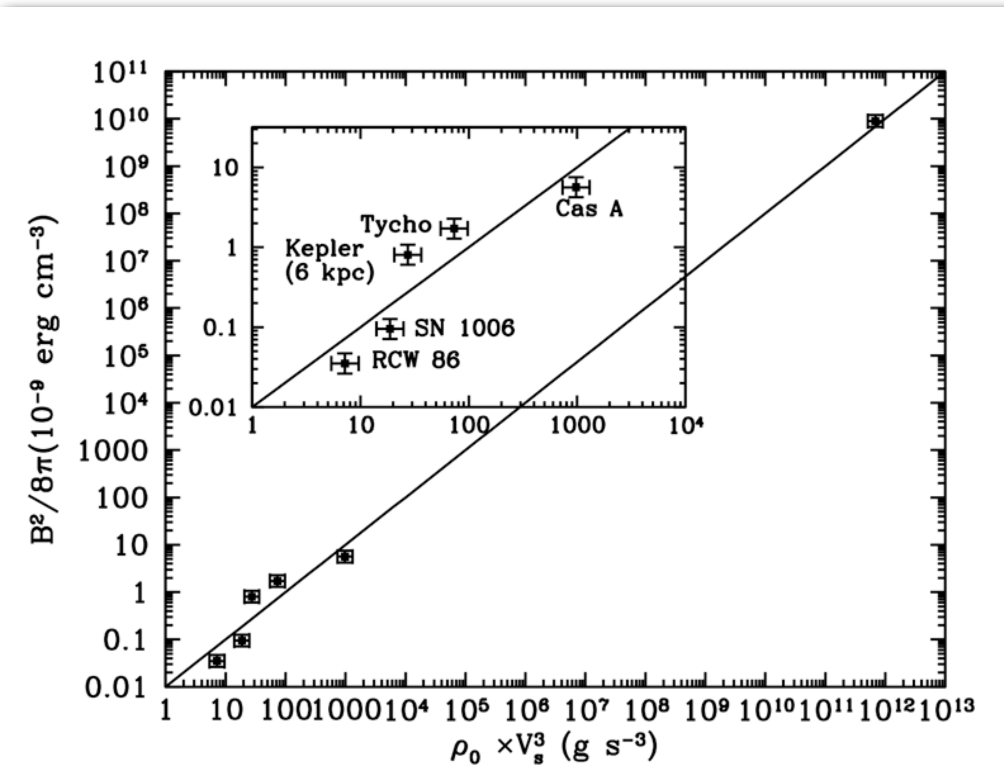
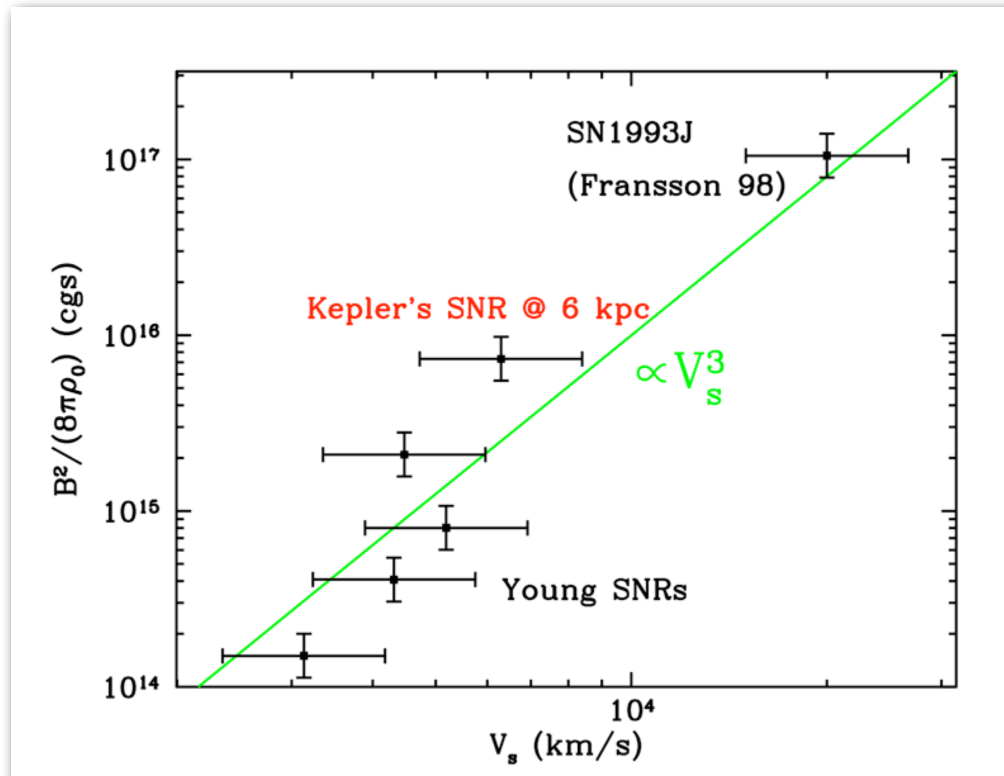
- High B-field likely induced by cosmic rays (e.g. Bell +04)
- High B-fields are a signature of ion cosmic rays

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)





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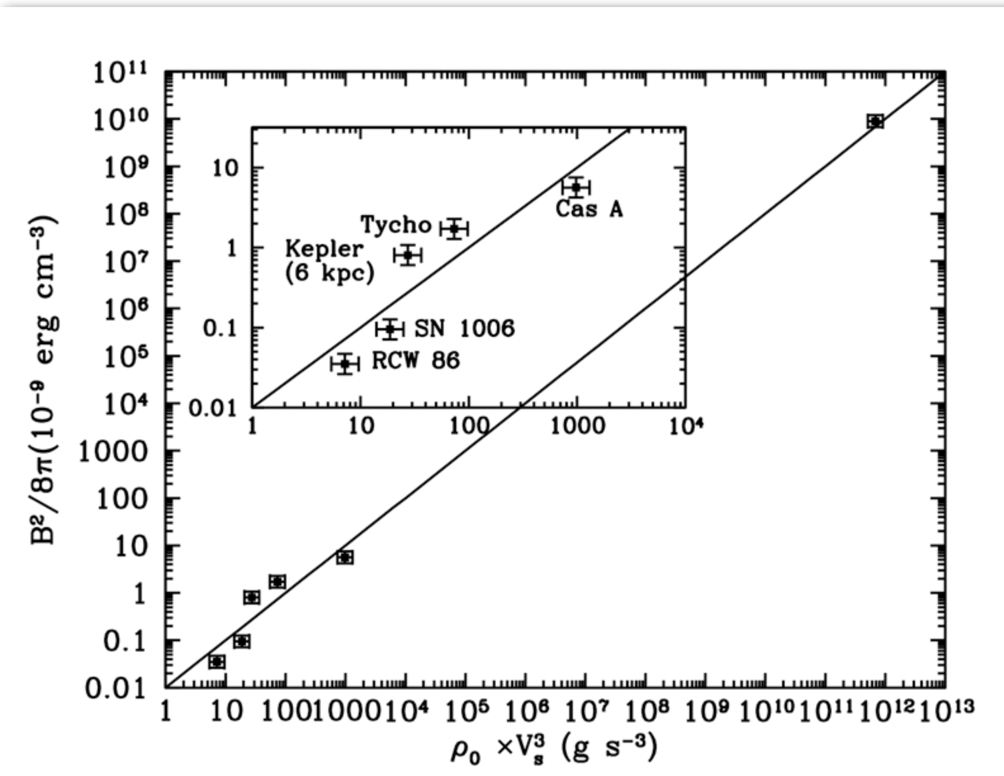
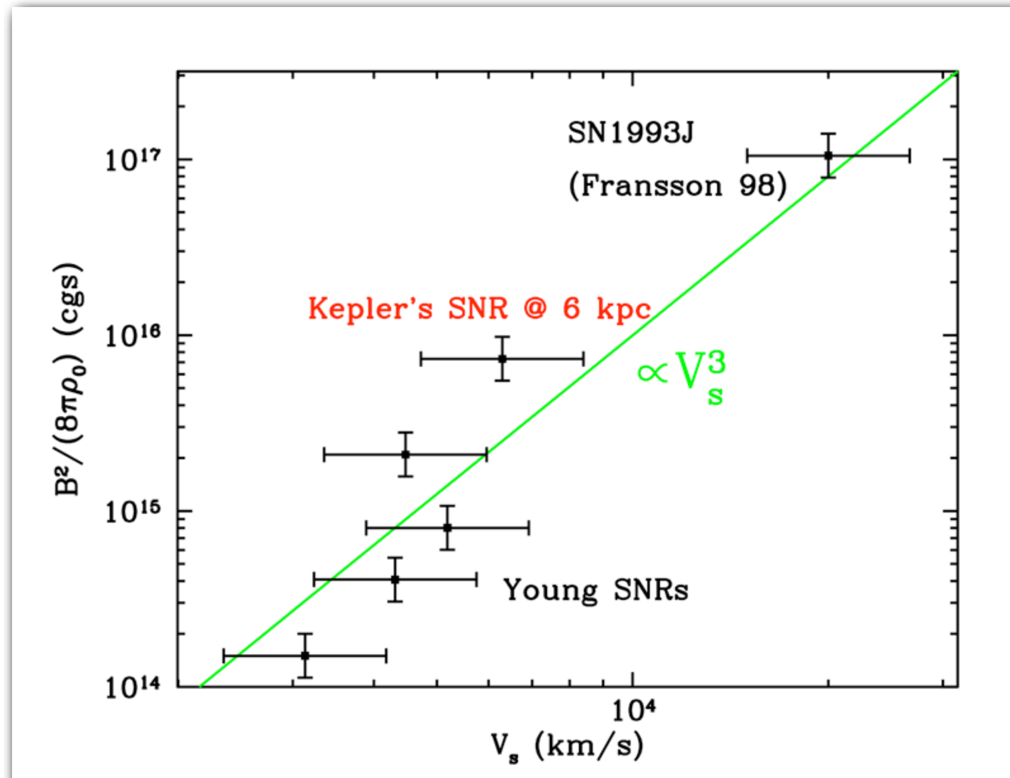
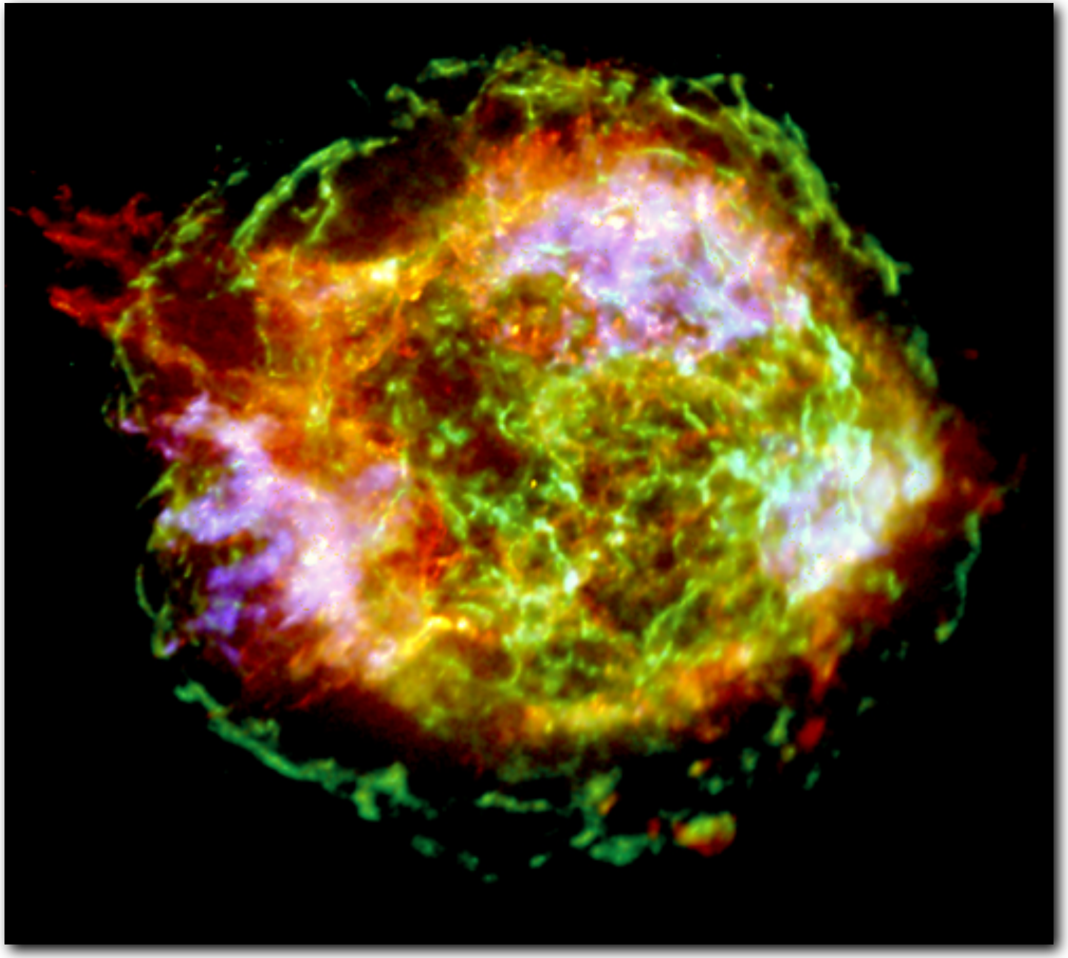




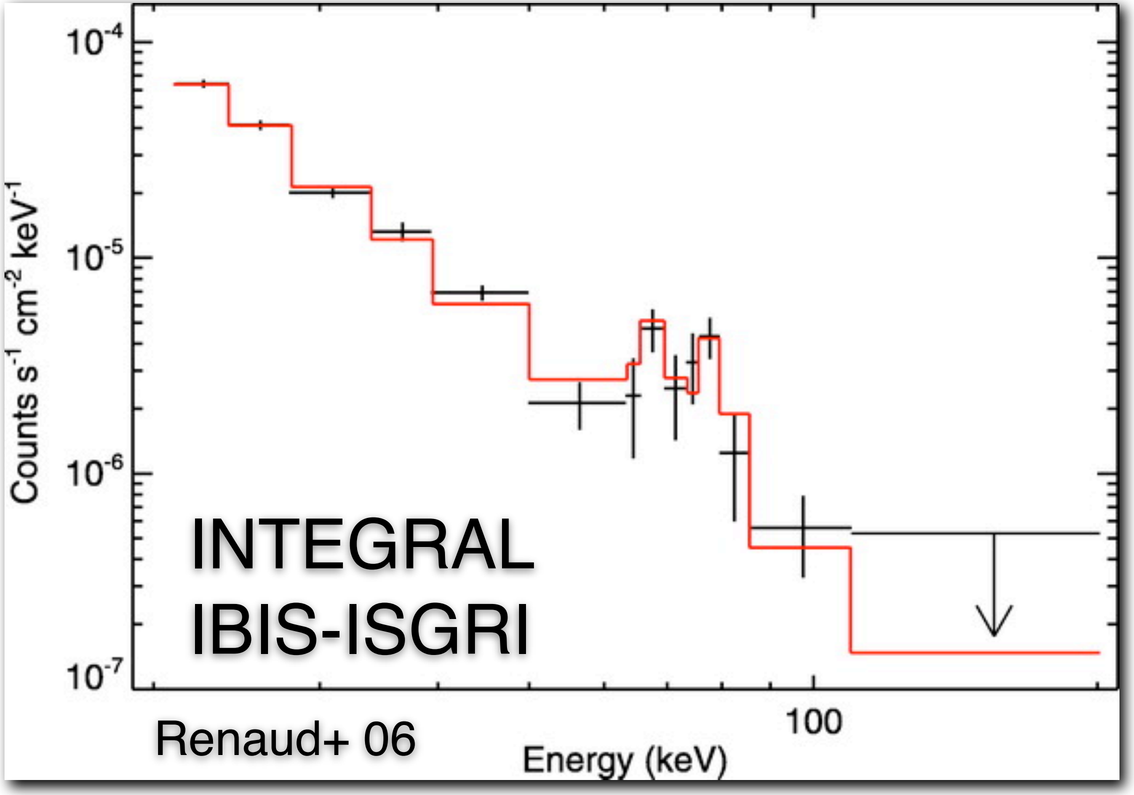
Cas A



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



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?

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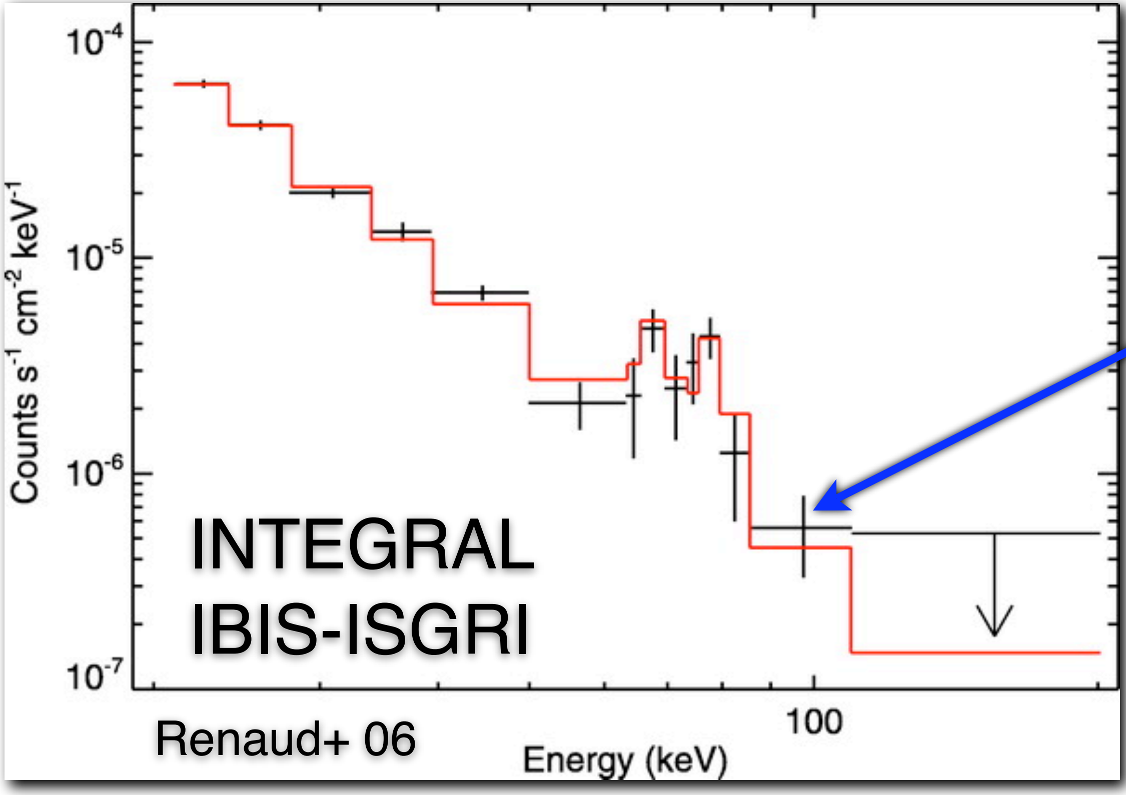

Synchrotron radiation?
Non-thermal bremsstrahlung?

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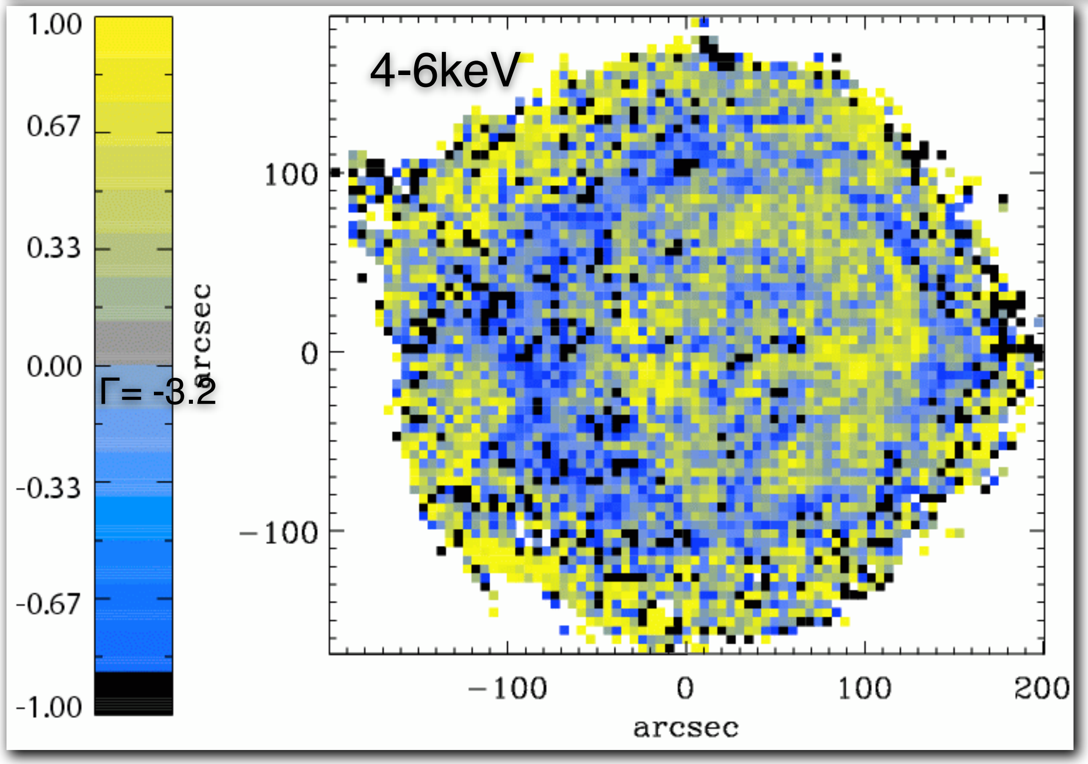
Acceleration @ Cas A reverse shock



- 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

Helder&Vink '08
Uchiyama+ '08

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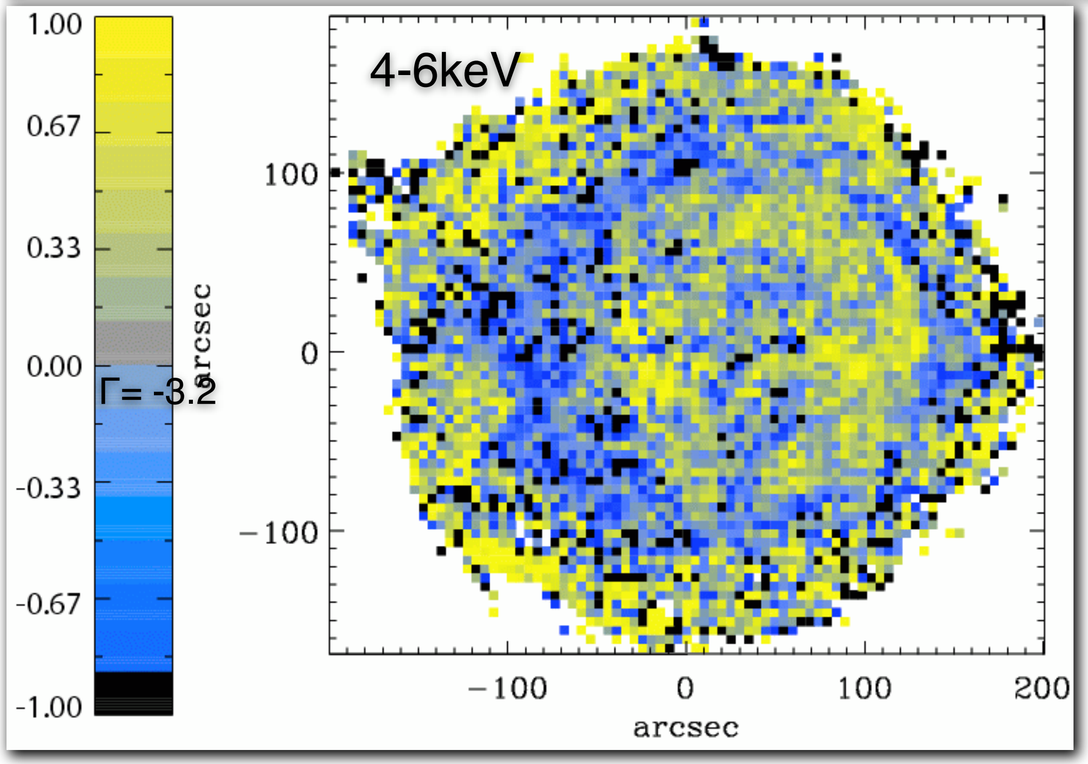

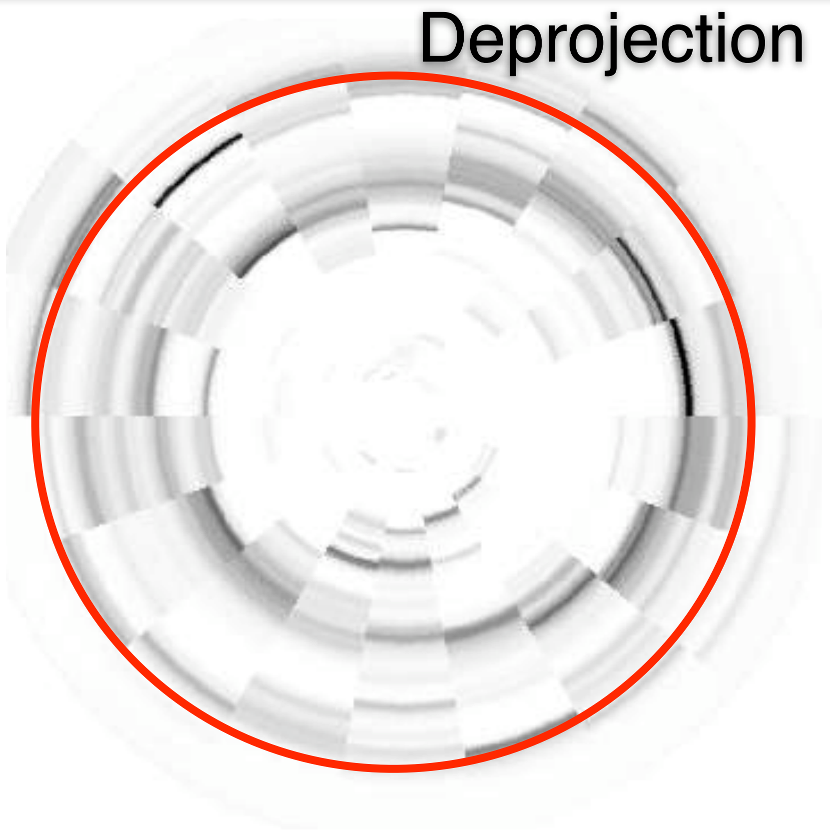

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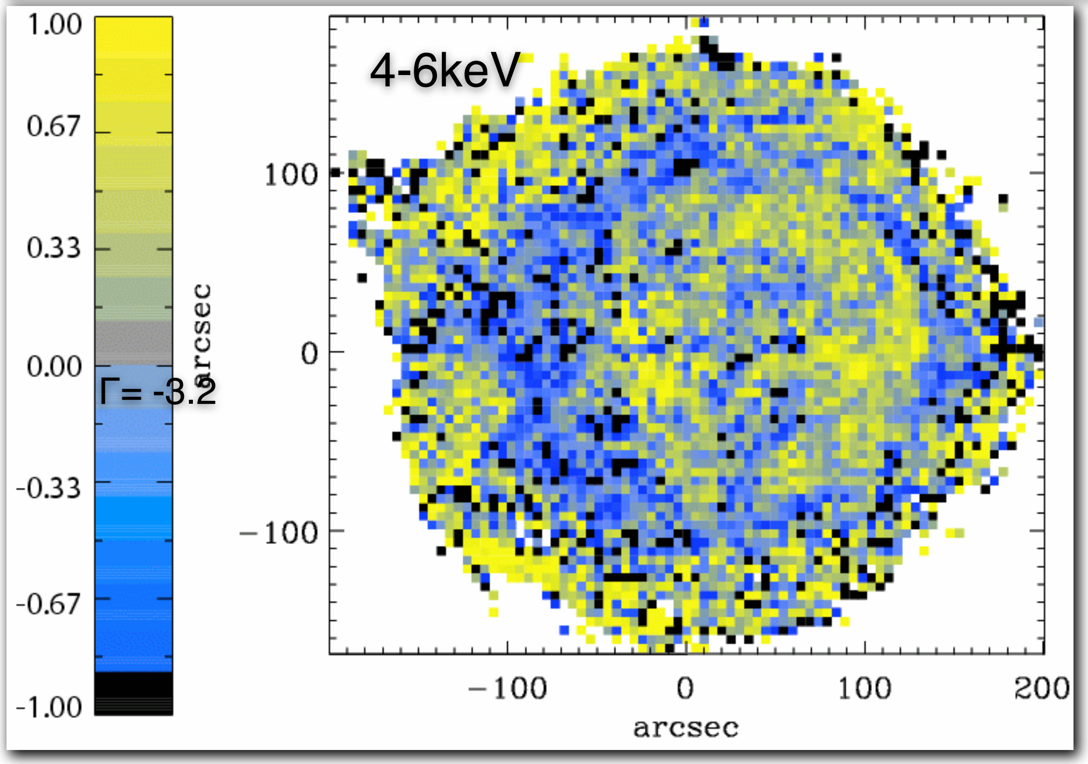

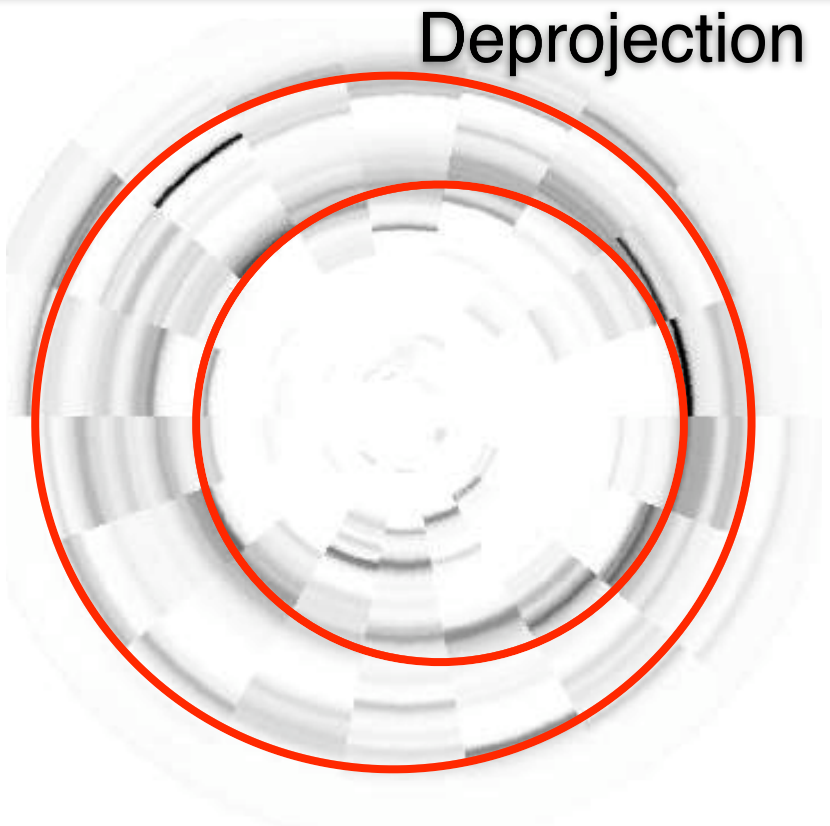

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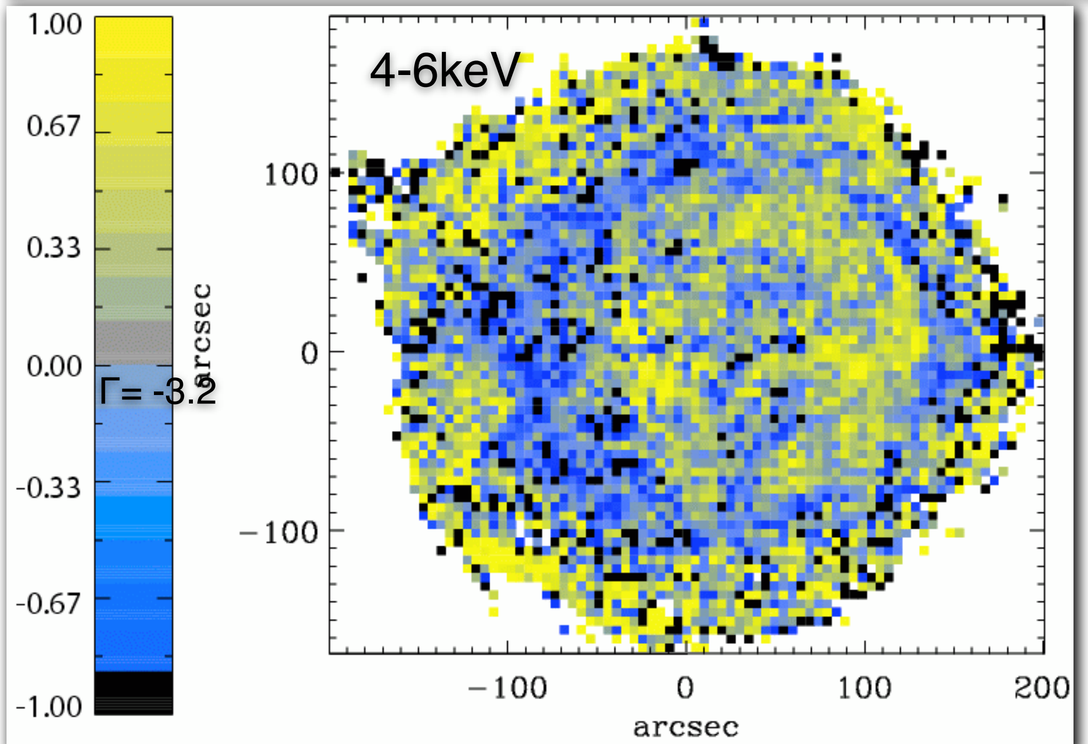

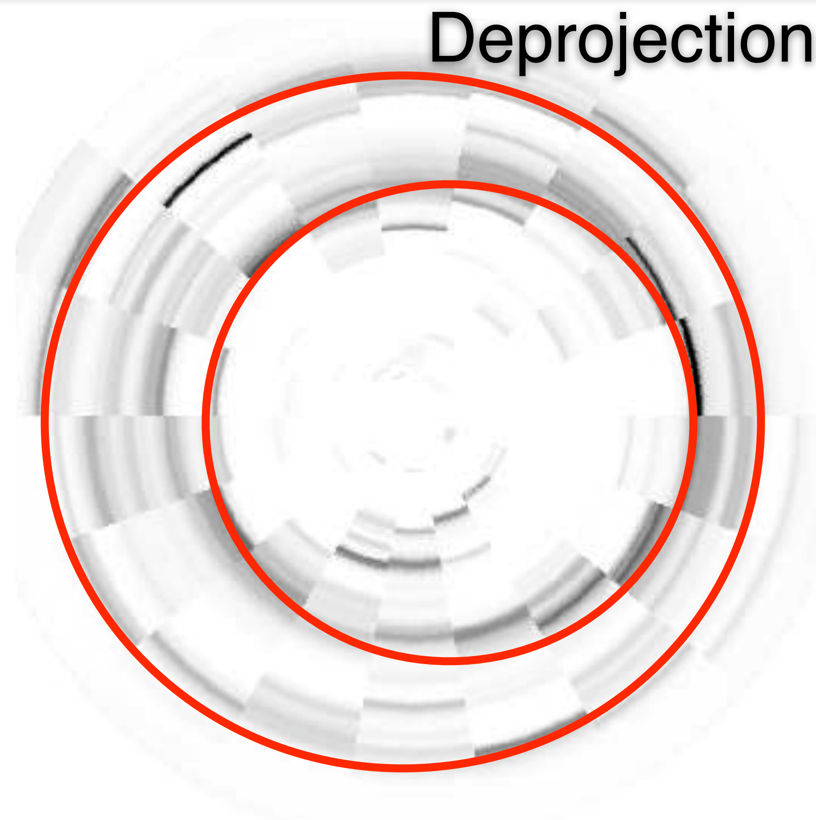

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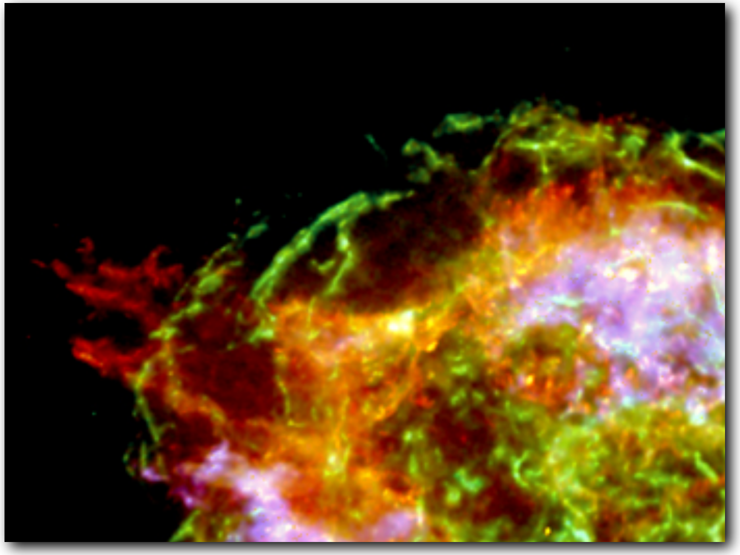
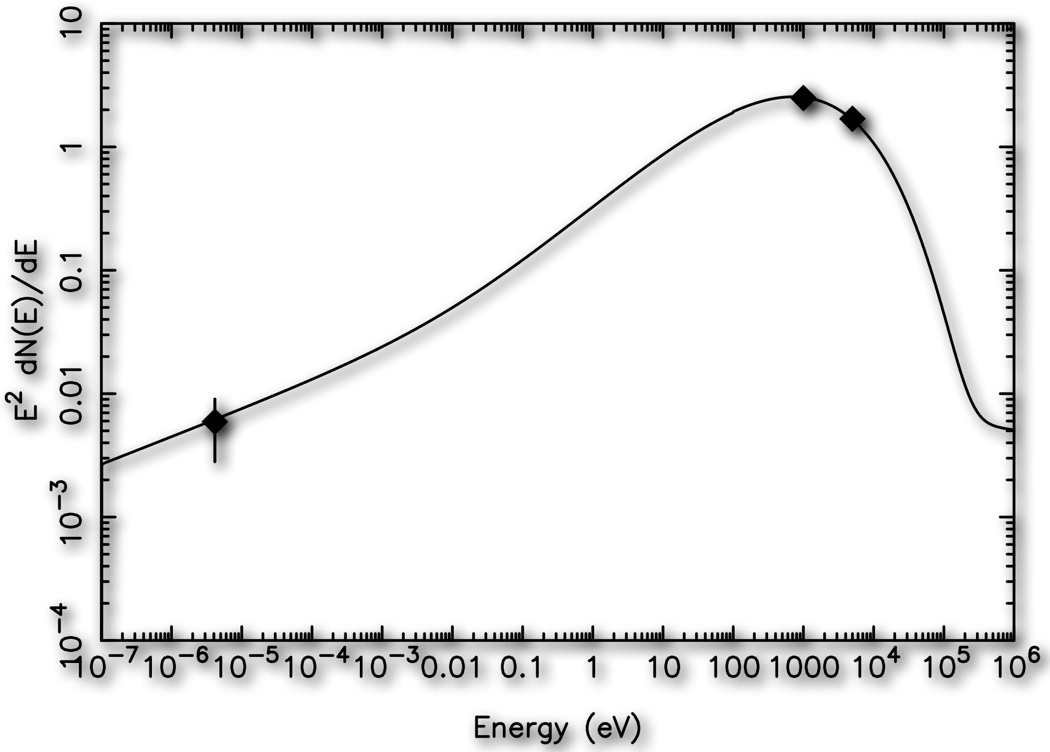
Final amplified B-field insensitive to initial field!?

Helder&Vink '08
Uchiyama+ '08

Curved spectra

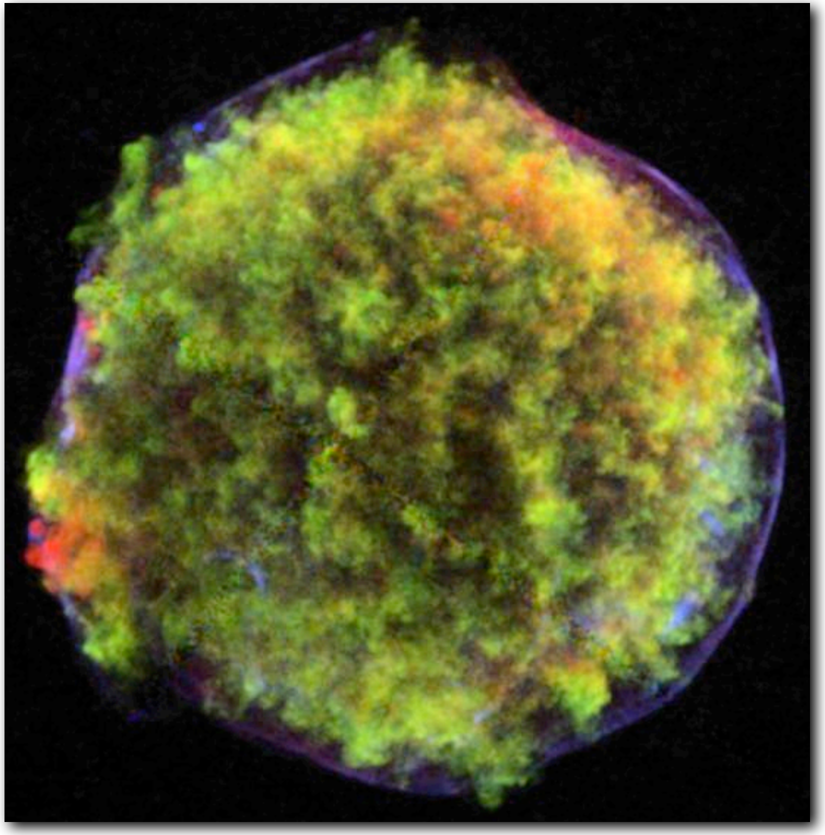
- Non-linear shock acceleration predicts curve spectra
- Curvature reported for radio spectra (Ellison+ 92), radio-infrared (Cas A, T.J. Jones+ 03), and radio to X-ray (Vink +06, Allen +08)
- Comparing radio to X-ray spectra: use a region near shock: otherwise sample old (cooled) and new electron populations
- Never published, radio / X-ray for NE of Cas A:





High Compression Ratios

- If acceleration is very efficient CRs dominate internal energy
- If Γ< 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)

Charge X-change/Hα emission

X-ray synchrotron

Compression/pre-heating

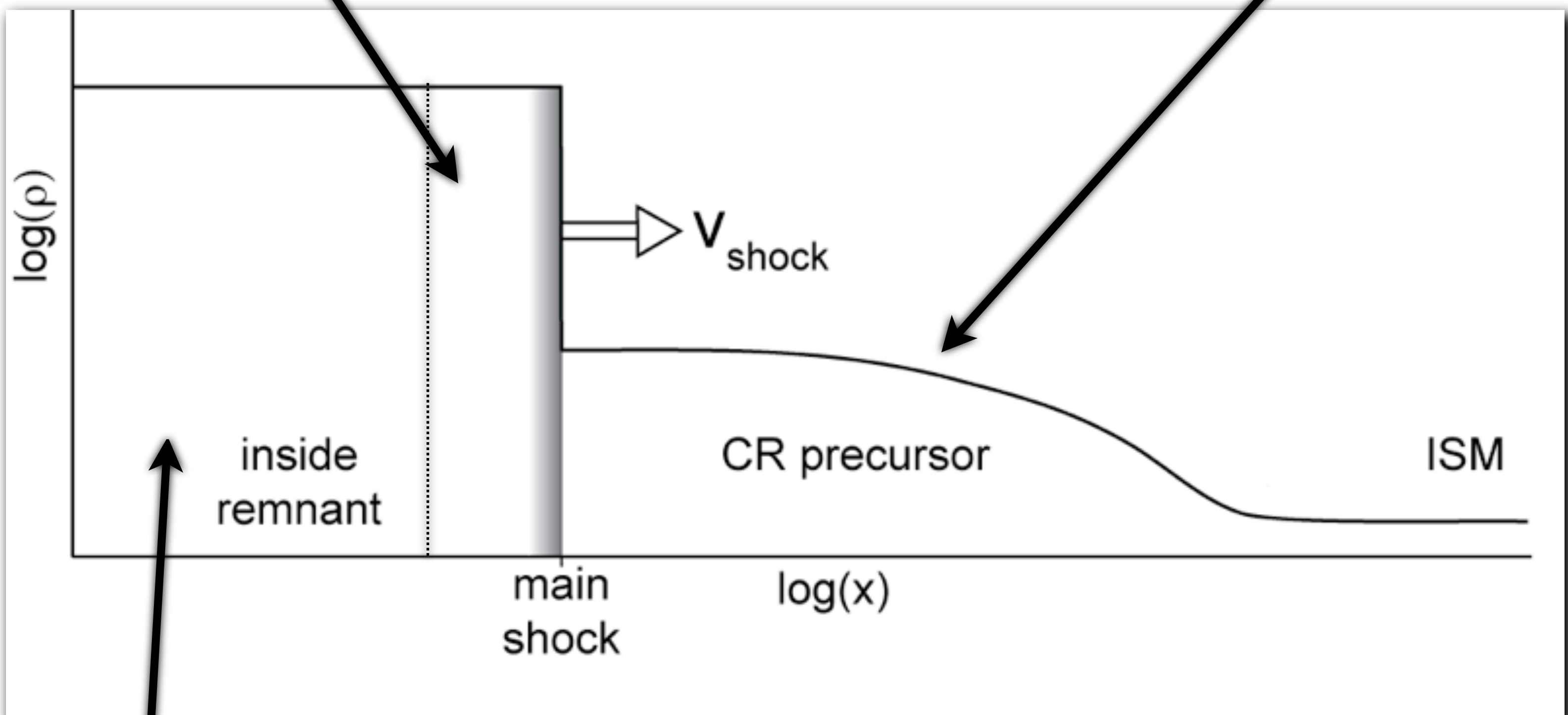


Fig: Eveline Helder

Thermal X-ray

Charge X-change/Hα emission

X-ray synchrotron

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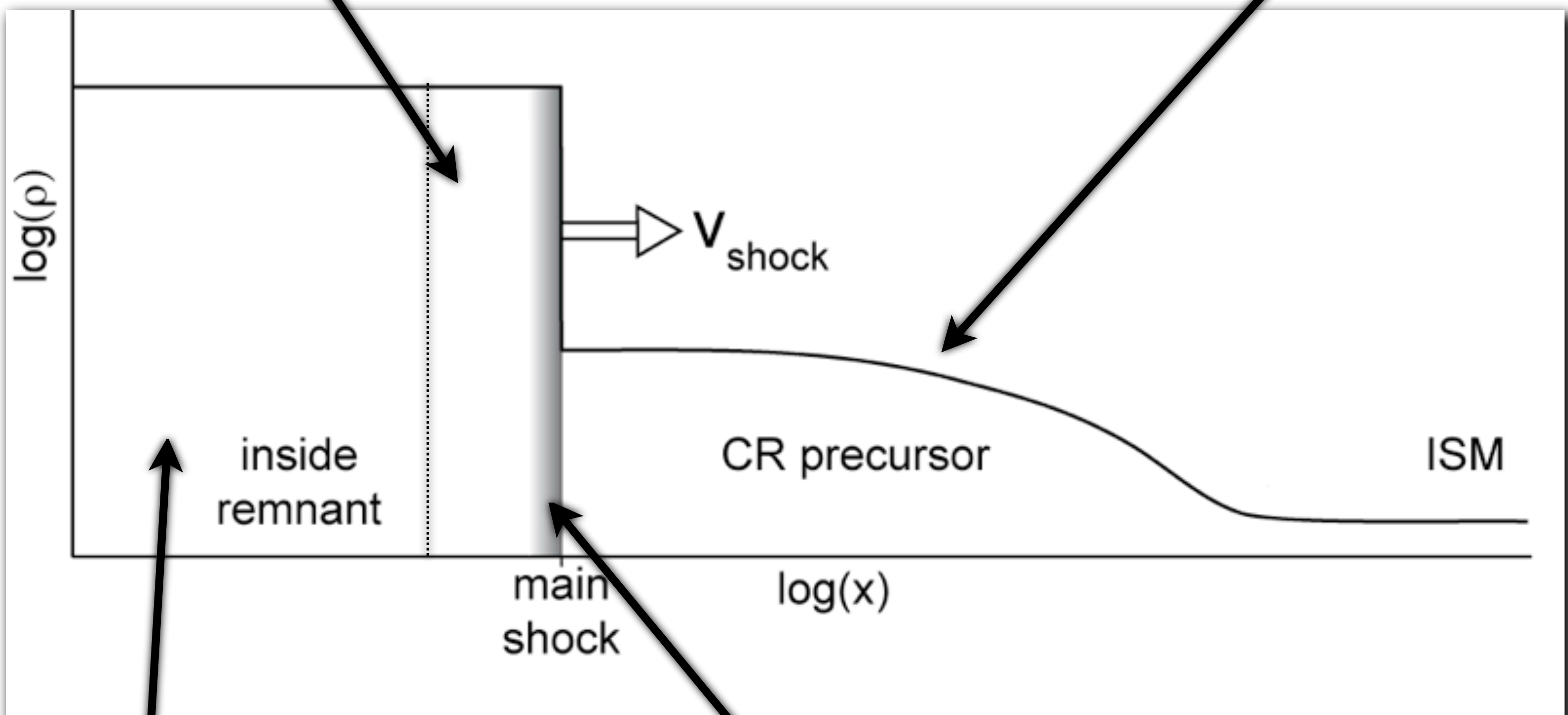
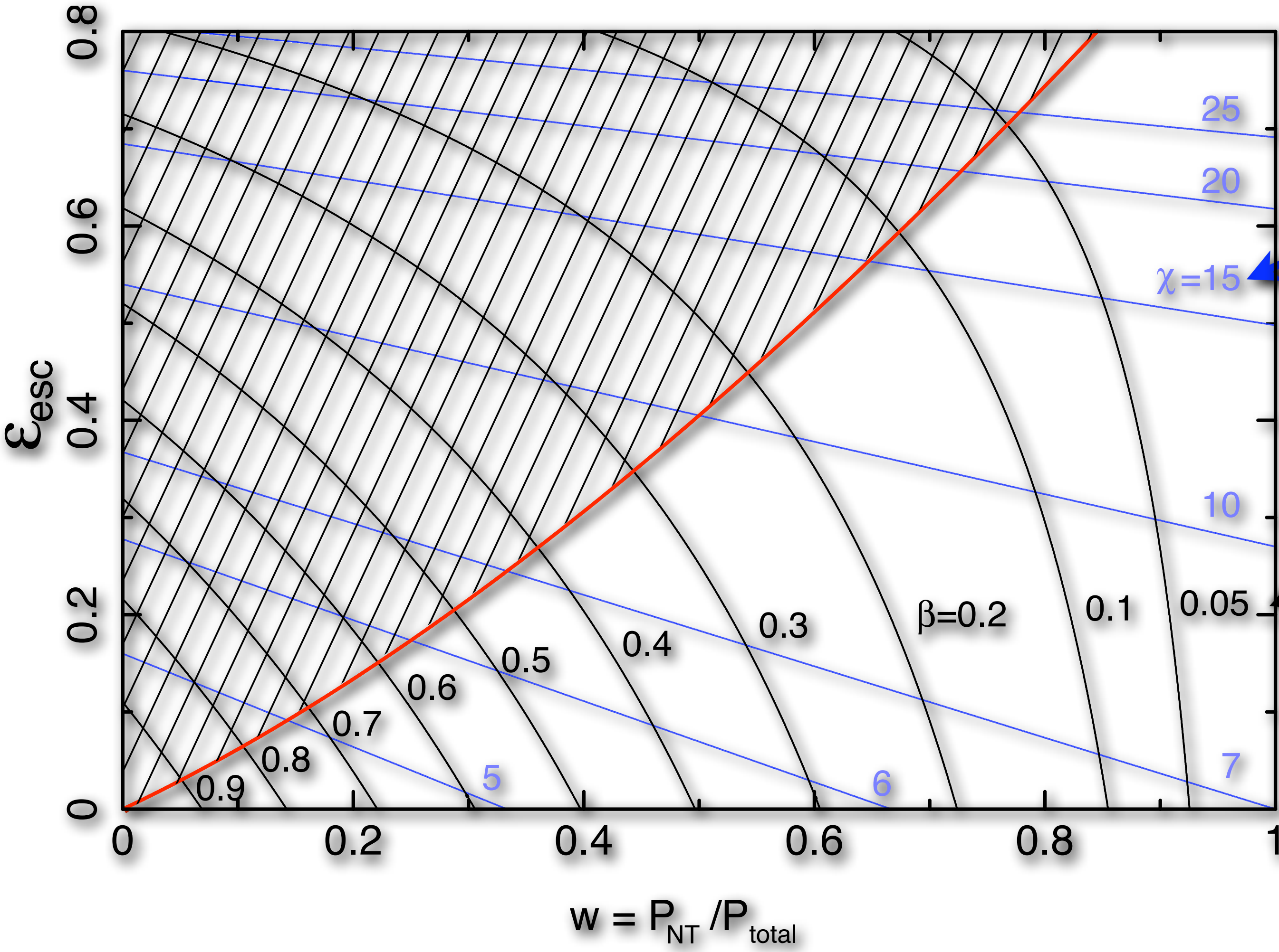


Fig: Eveline Helder

Thermal X-ray

Thin layer (~10^{15} /n_p cm):
neutrals excite, charge X-change, ionize

Shock heating and compression



Compression ratio

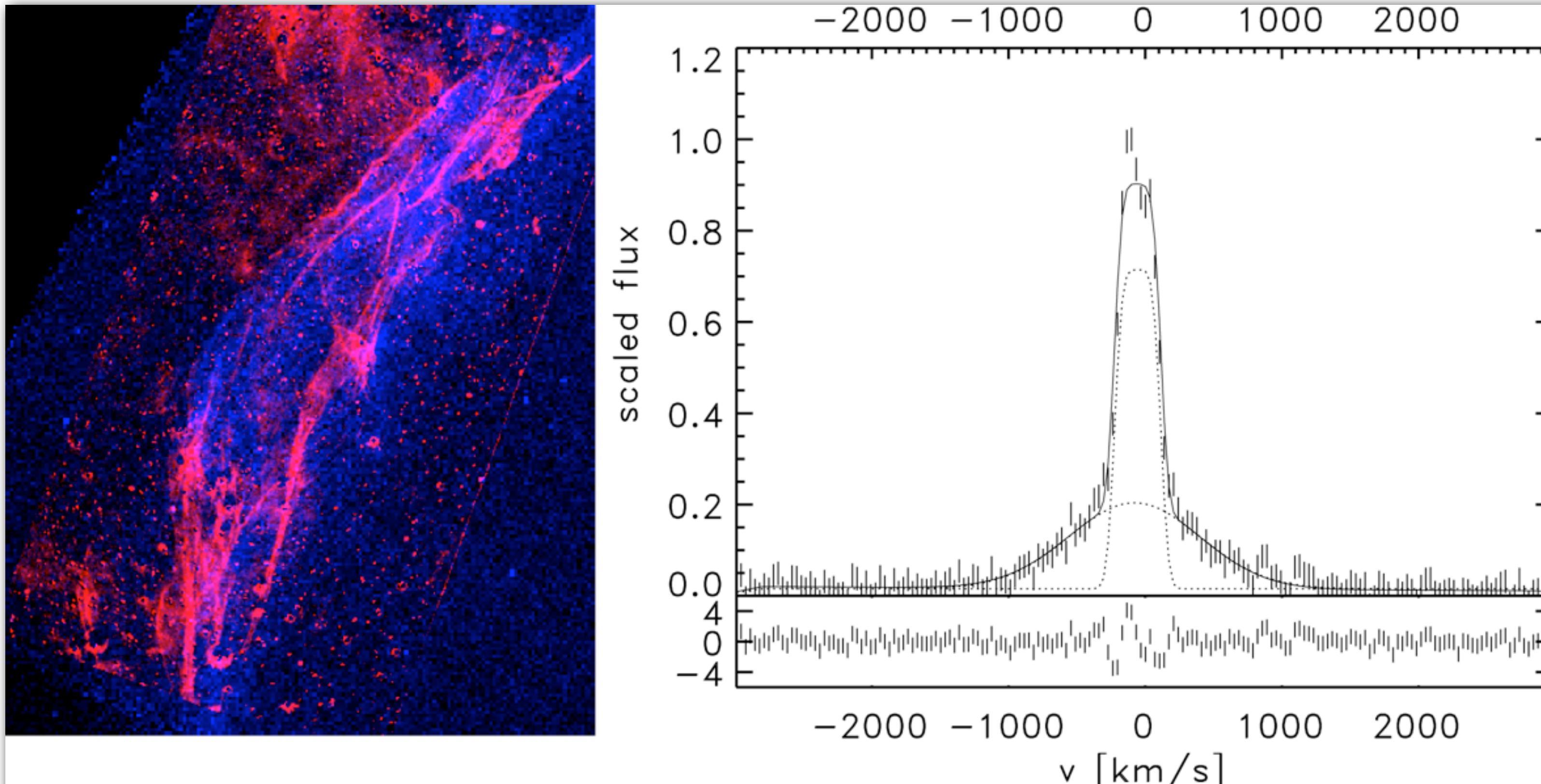
correction w.r.t.

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

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

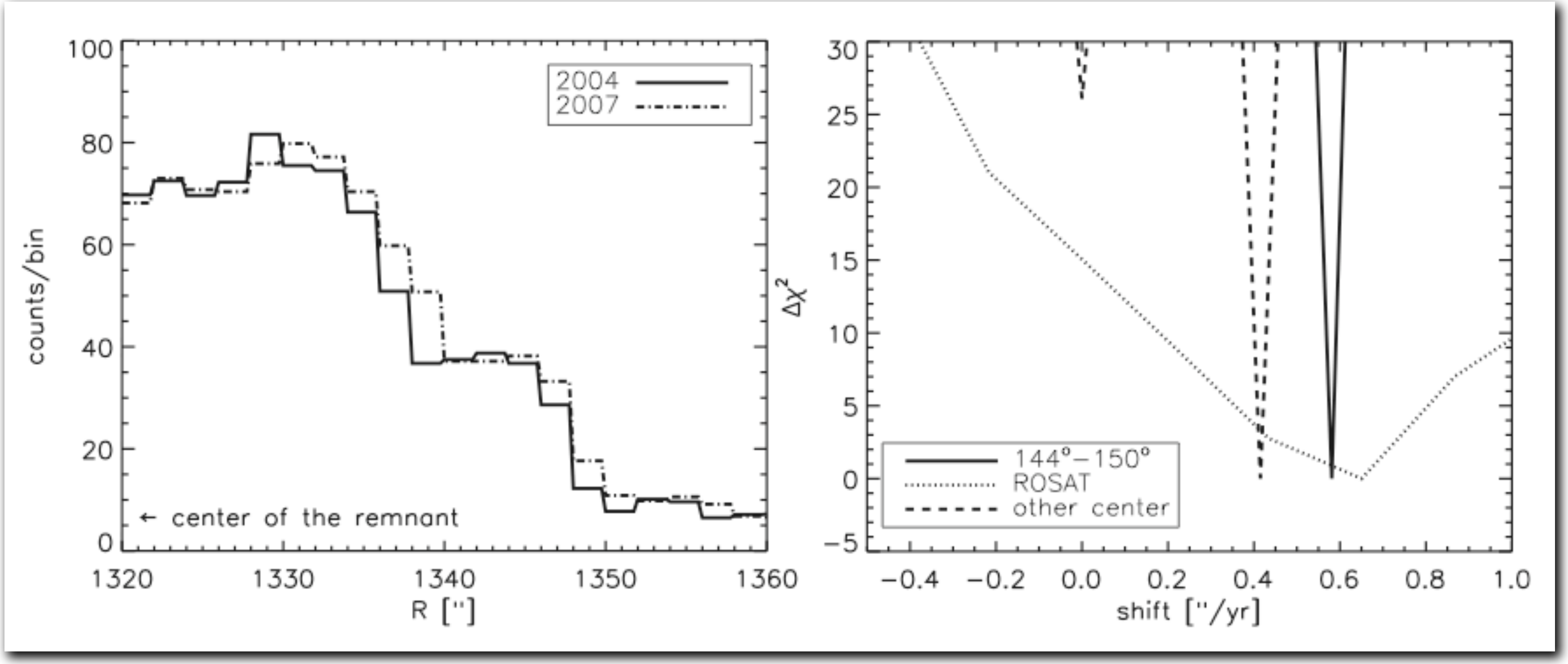
RCW 86 NE Hα measurements



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

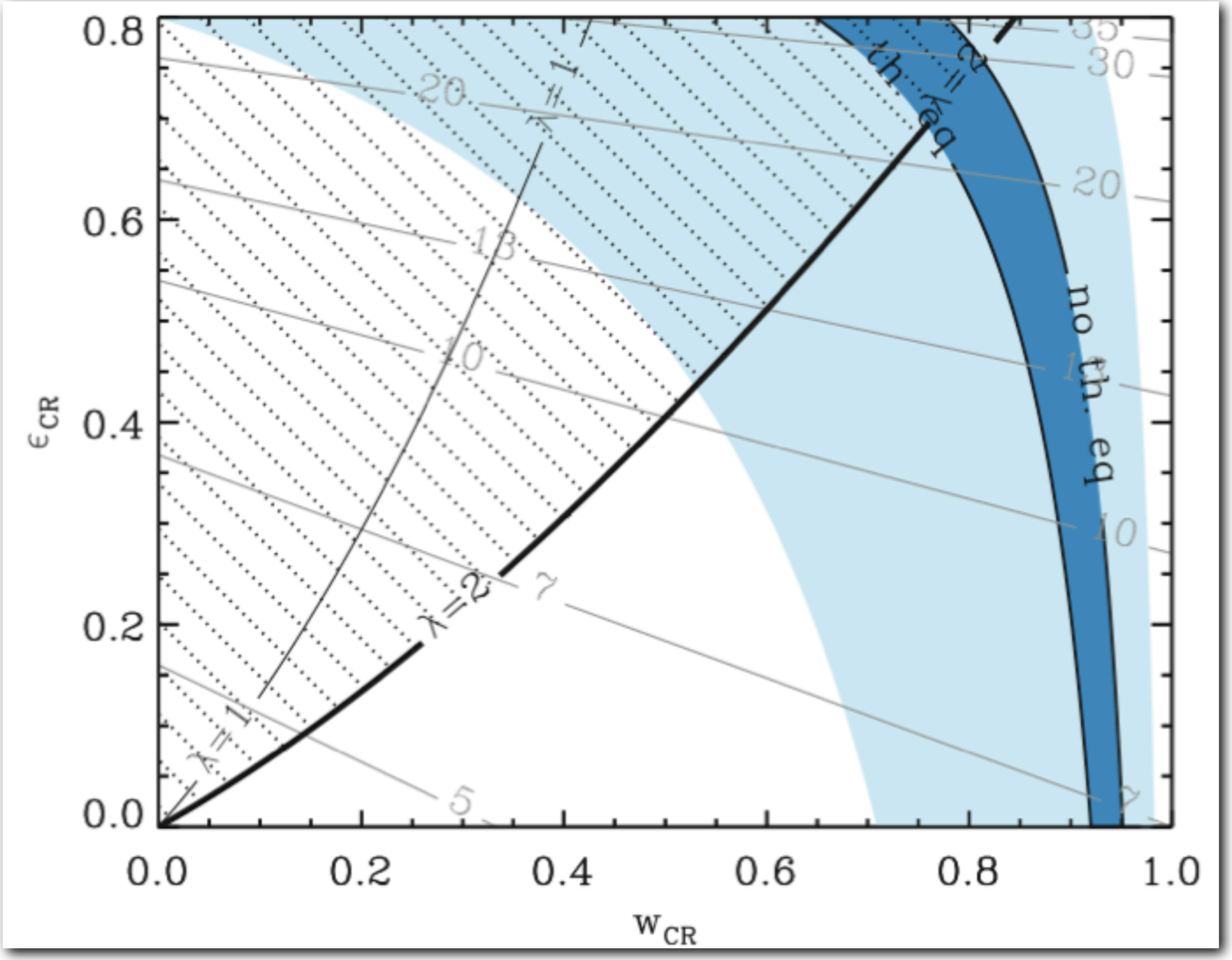
Helder+ 09

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



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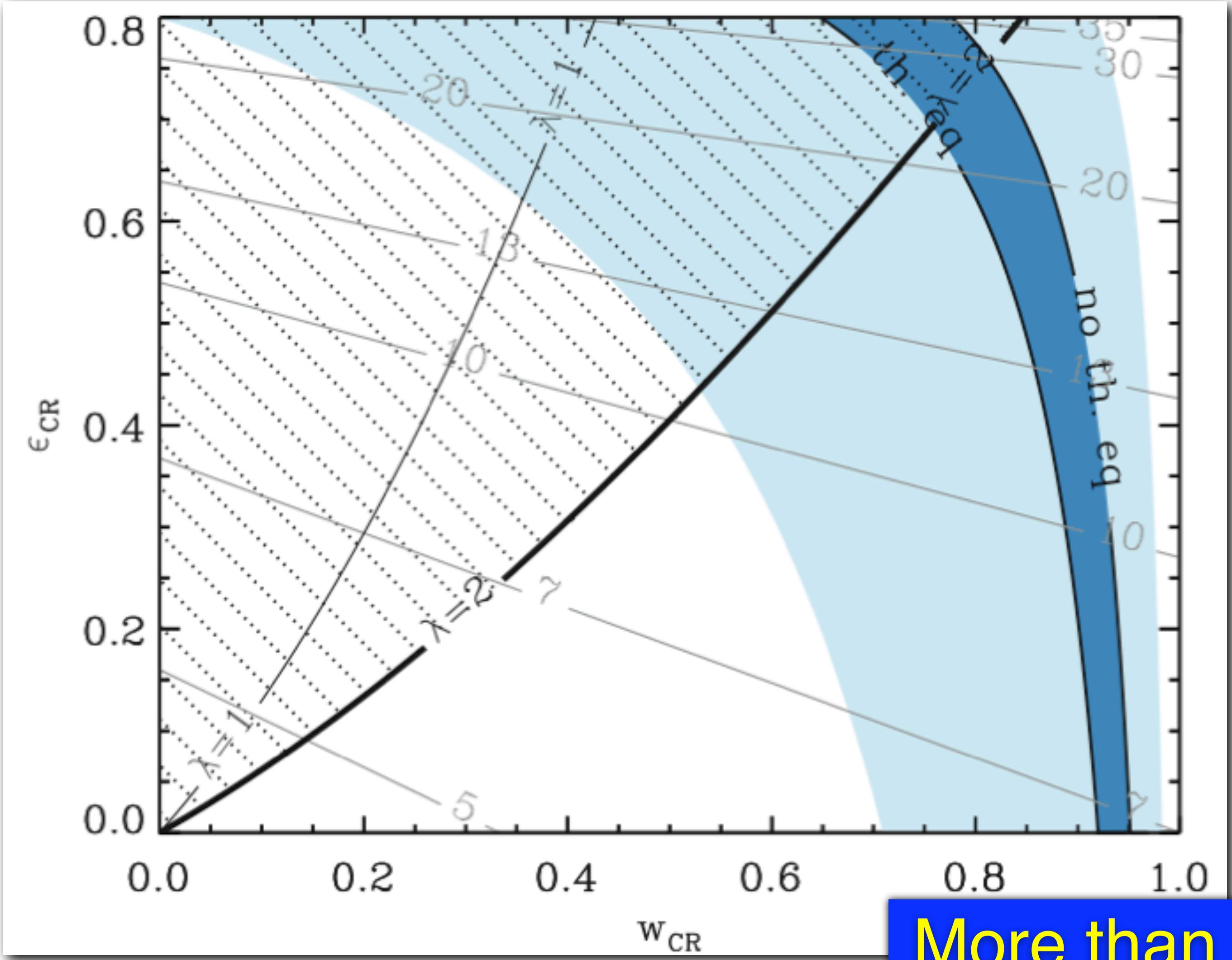
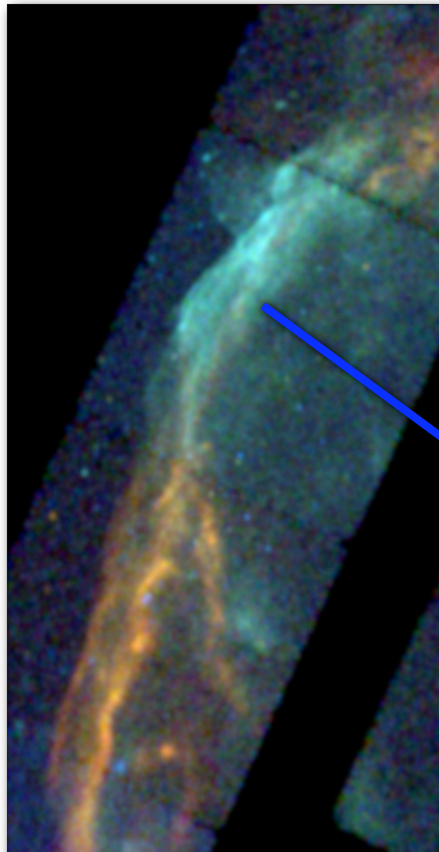
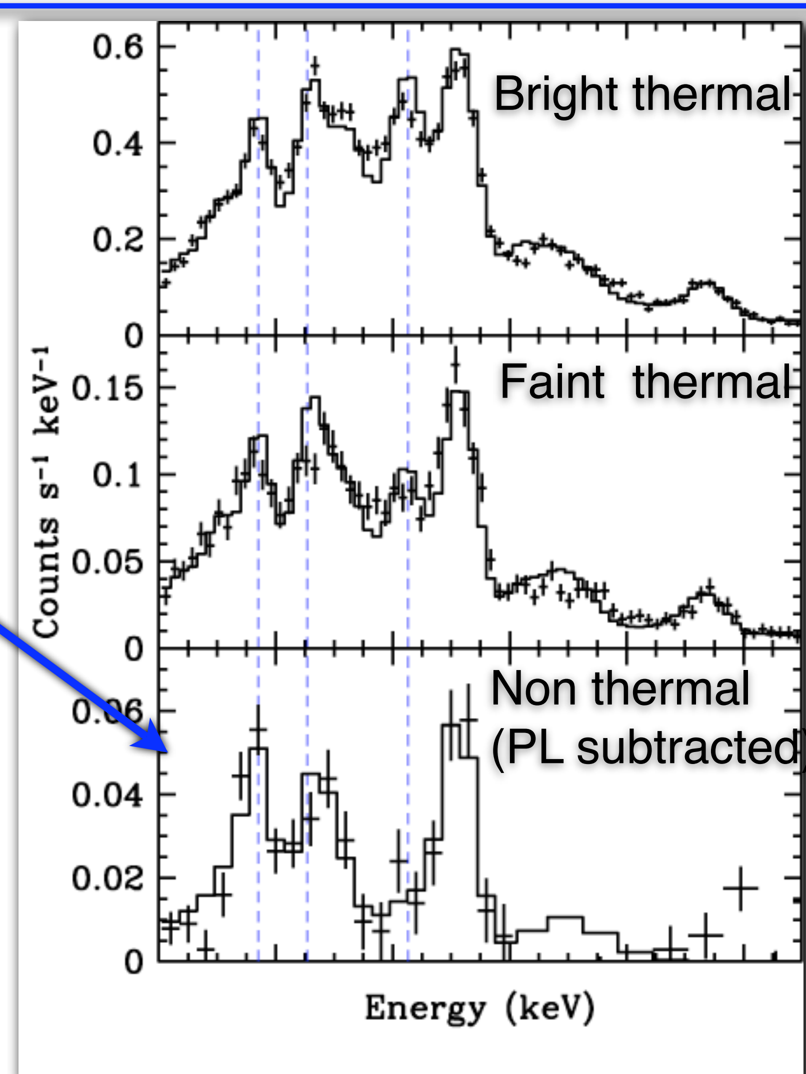


Helder+ 09

More than 50% of available energy in cosmic rays

Electron-Ion Equilibration RCW 86 NE

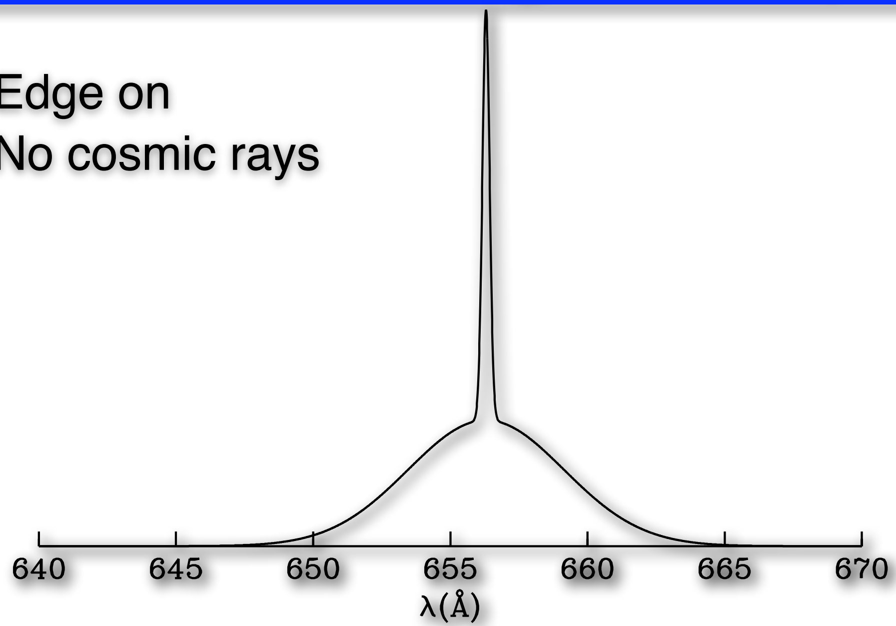




- From Hα kT_p = 2.2 keV
- XMM: kTe~1-5 keV (Vink+ '06)
- Close to equilibration!
- Low $n_e t$ -> low density
- Electron pre-heating in pre-cursor?

Probing the pre-cursor with Hα

Edge on
No cosmic rays



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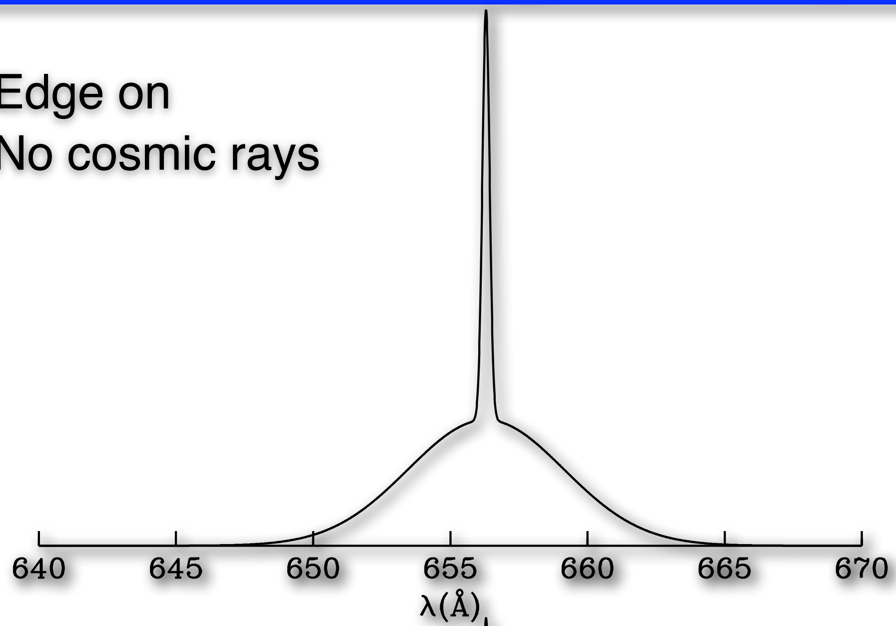
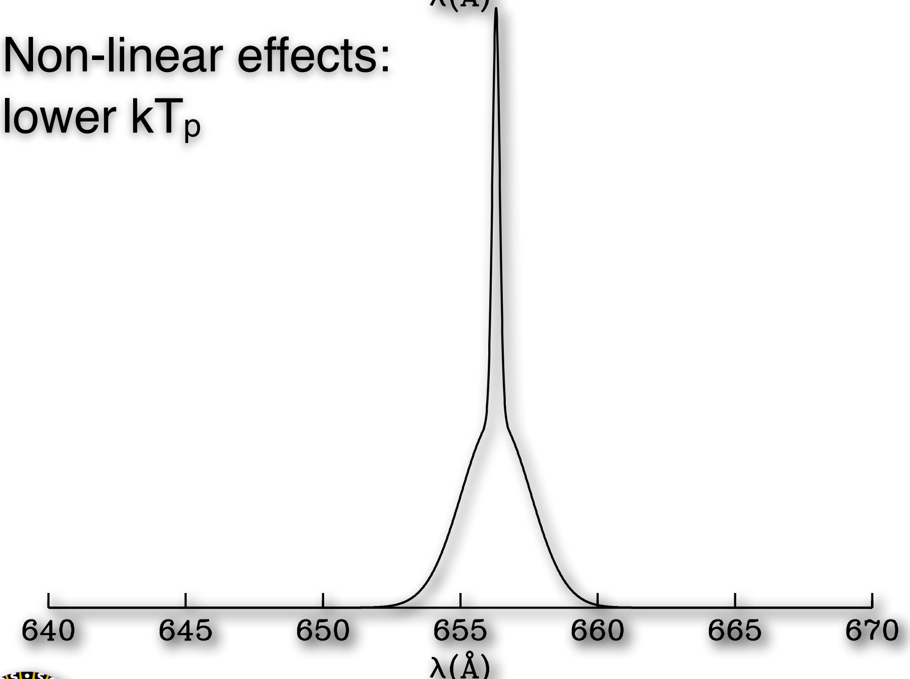


Non-linear effects:
lower kT_p



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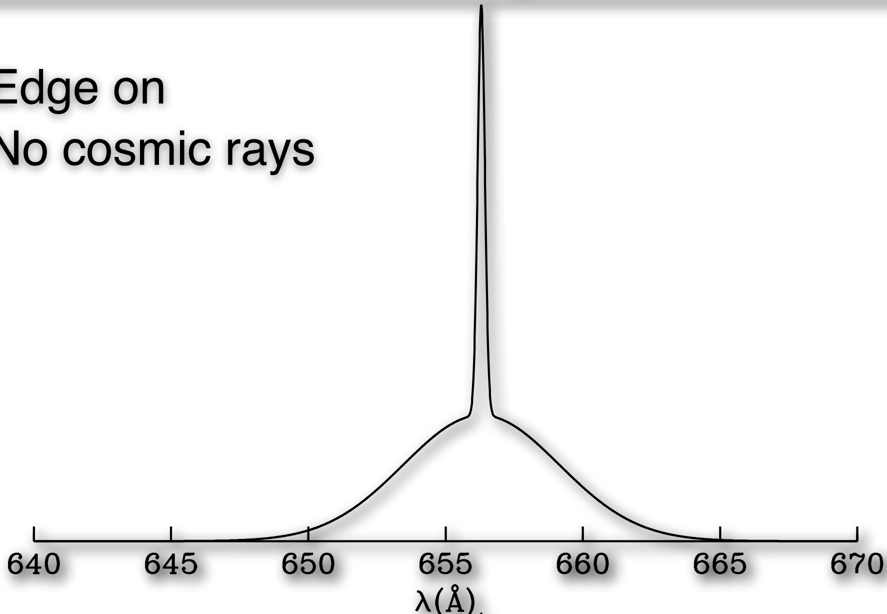
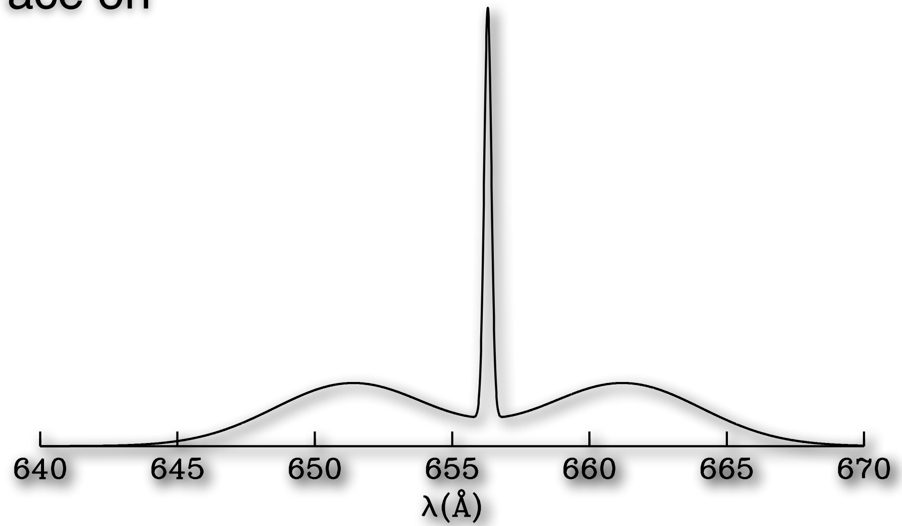


Face on



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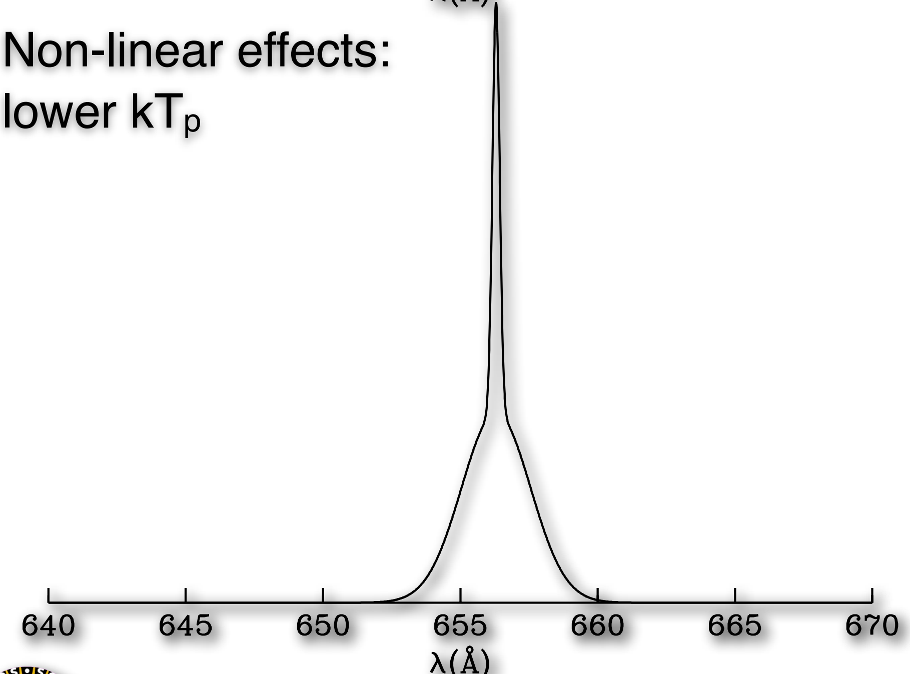

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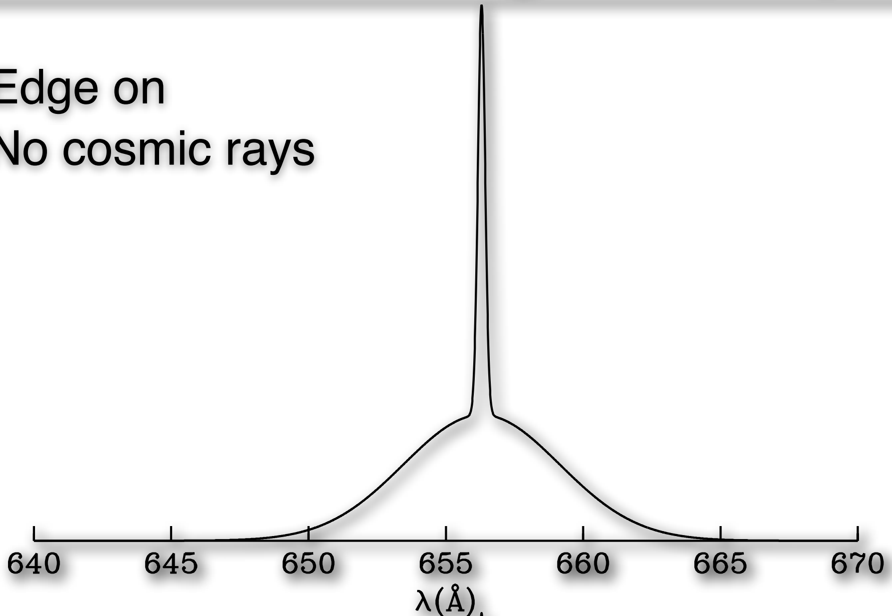

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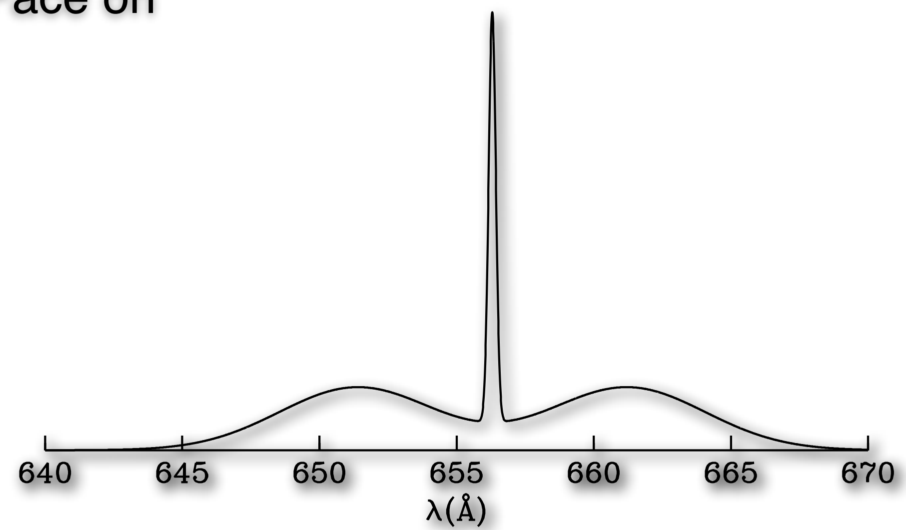

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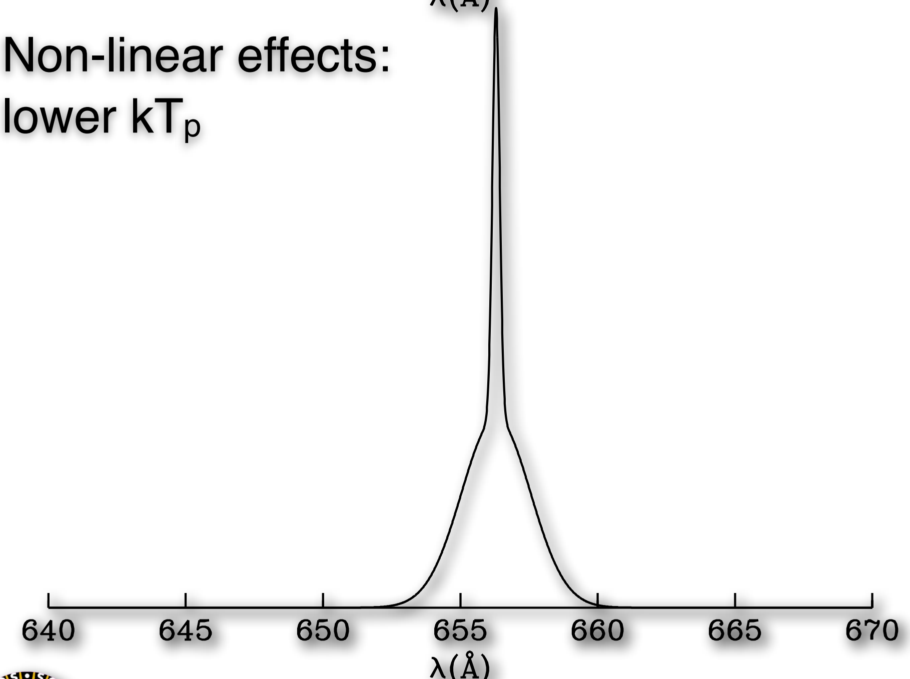
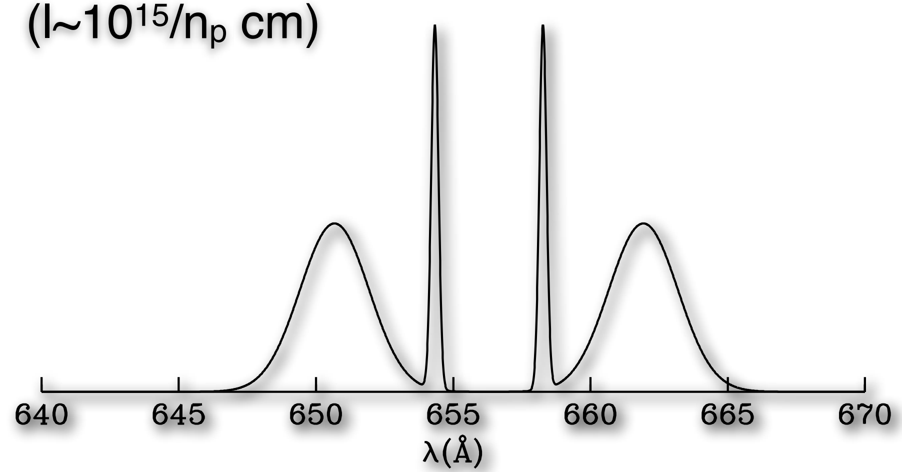


Non-linear effects: lower kT_p
narrow lines: precursor flow speed
@ last charge X-change
($l \sim 10^{15}/n_p$ cm)



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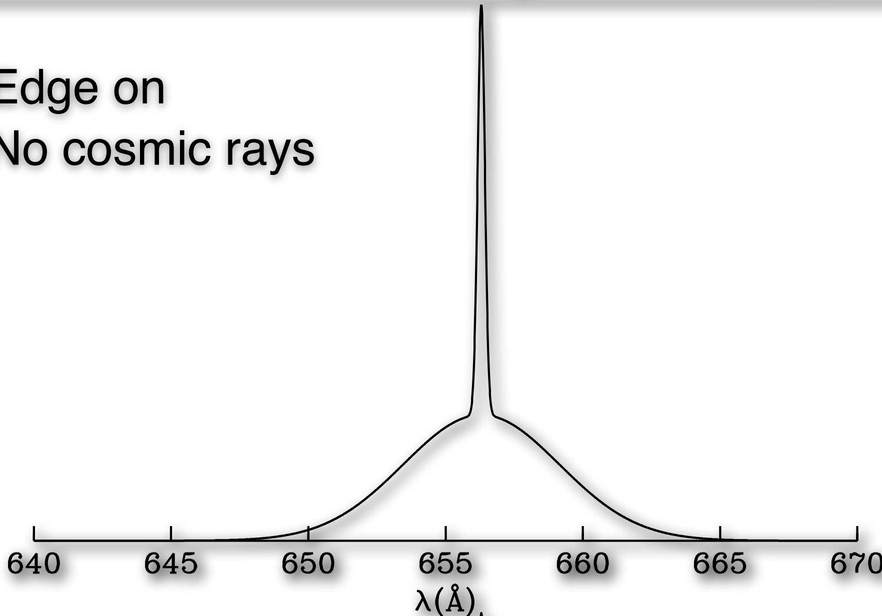
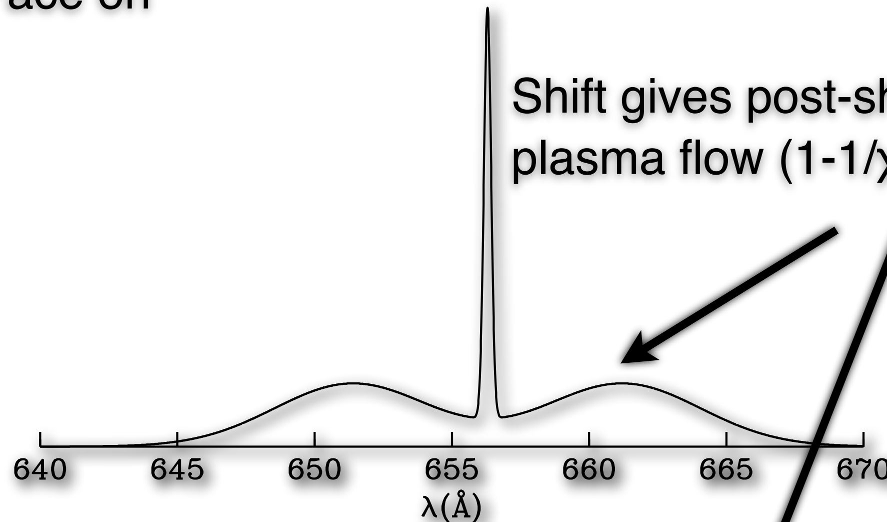


Face on

Shift gives post-shock plasma flow $(1-1/\chi)V_s$



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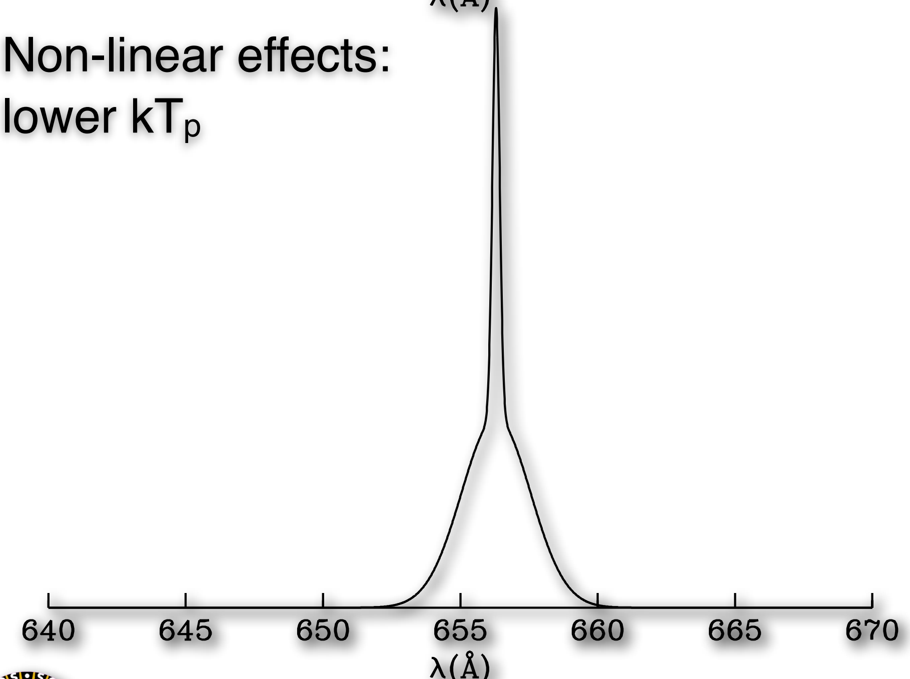

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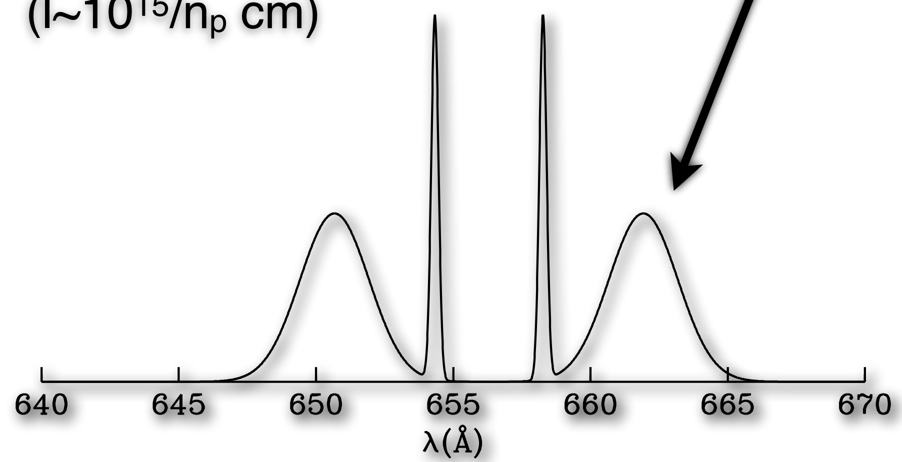
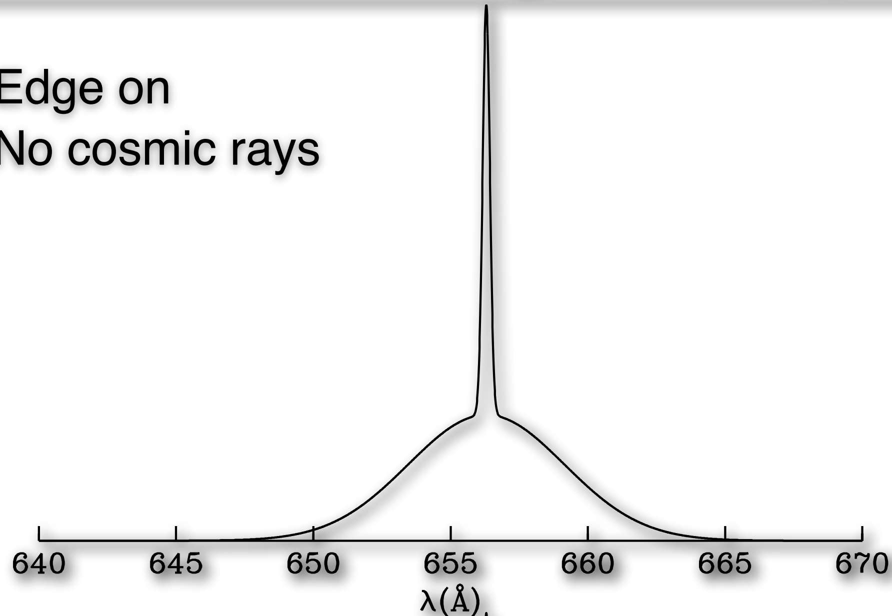


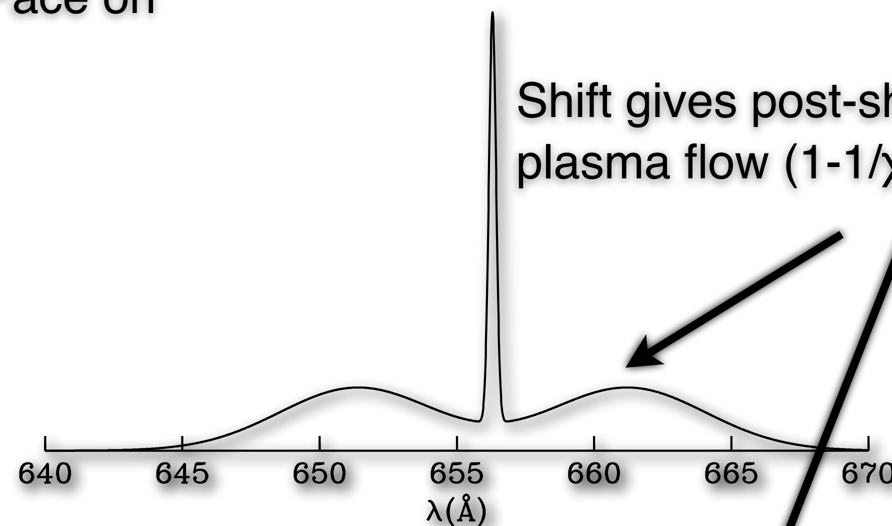
Probing the pre-cursor with Hα

Edge on
No cosmic rays

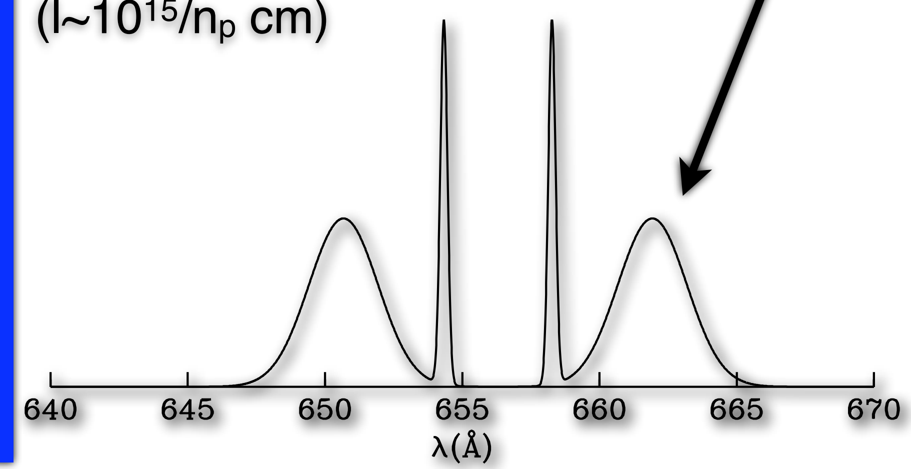


Face on

Shift gives post-shock plasma flow $(1-1/\chi)V_s$



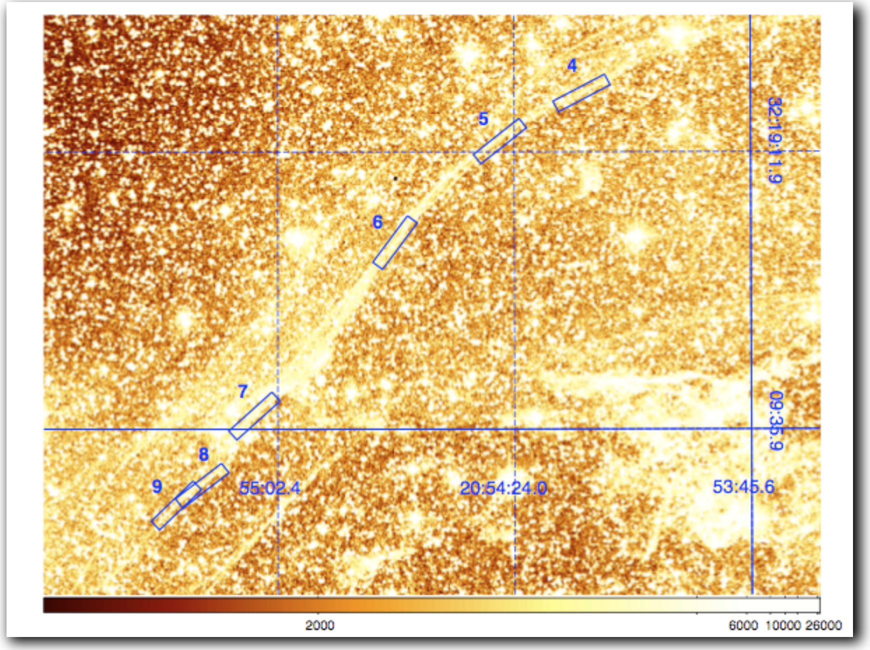
Non-linear effects: lower kT_p
narrow lines: precursor flow speed @ last charge X-change ($l \sim 10^{15}/n_p$ cm)

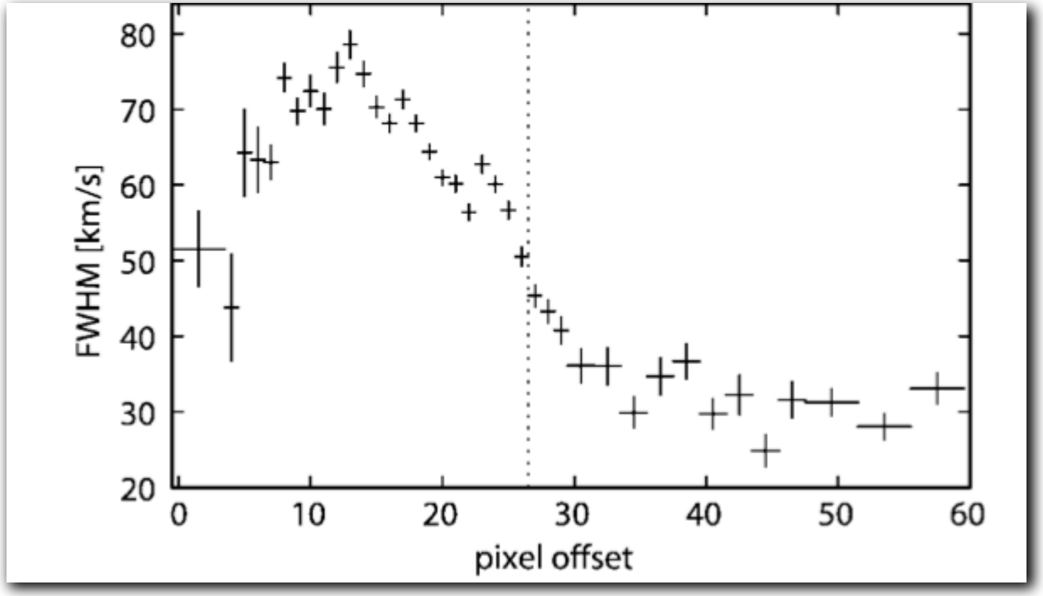


Dreaming on:

- Face on the Hα is very faint. Broad component hard to detect → Need EELT?
- No narrow line splitting seen in LMC remnants (Smith+ '96)
- Ideally need a large set of SNRs with different n_p, V_s, etc.

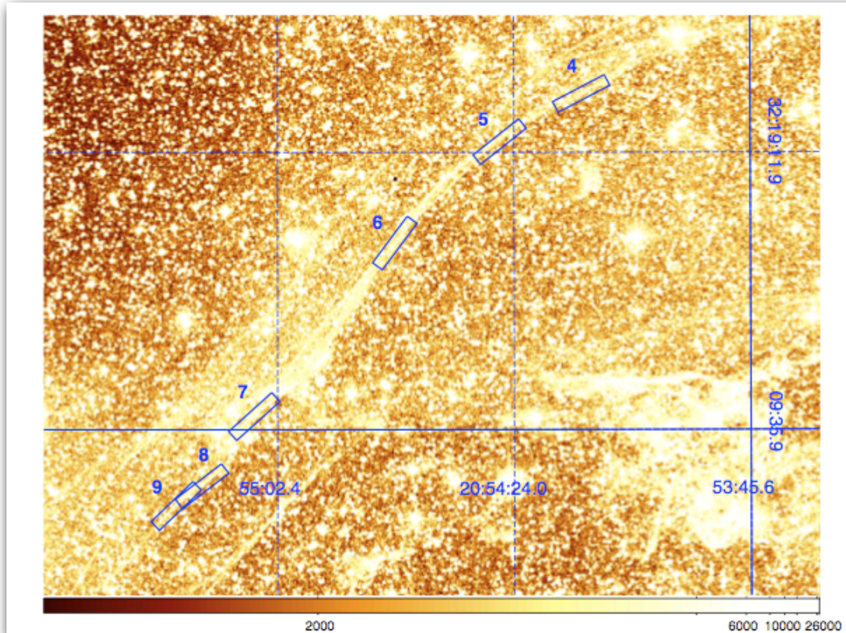
Some other Hα results

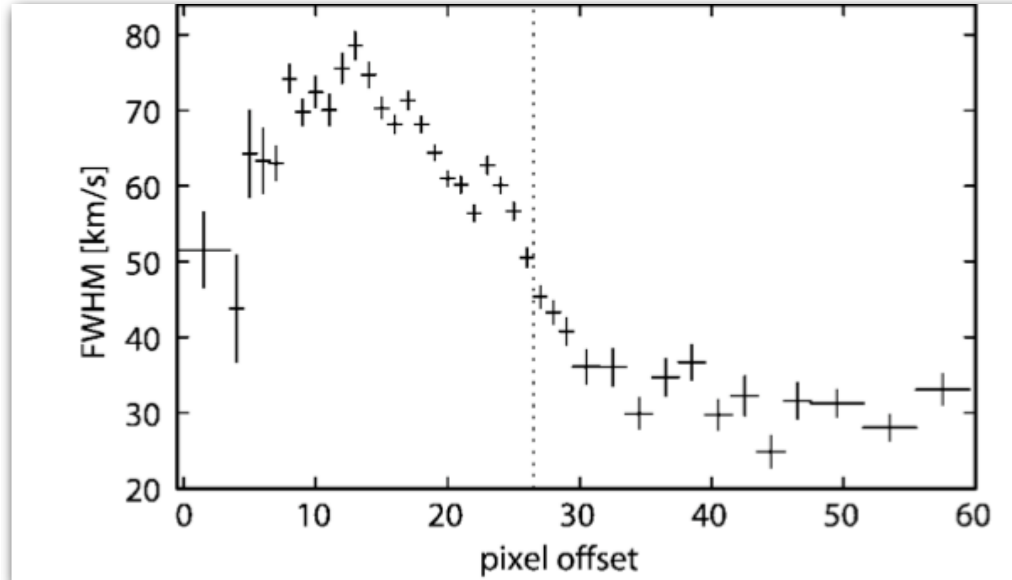




- Salvesen+ '09 observations of Cygnus Loop (Vs~200 km/s):
  - kT measurement consistent with no CR acceleration
- Lee+ '09 observations of Tycho knot g:
  - Narrow Hα emission ahead of shock front, seem hotter closer to shock
  - →shock precursor heating?

Some other Hα results





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See presentation by J. J. Lee

Conclusions

- A lot has been accomplished in last 10-15 yr:
  - X-ray synchrotron emission indicates E_e > 10 TeV
  - Narrow filaments X-ray filaments indicate B-fields up to 600μG
  - (TeV emission points to particle acceleration > 10 TeV)
- Indirect signs of presence of CRs:
  - B-field amplification
  - High shock compression ratios
  - Lower than expected plasma temperatures

- 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→η
  - probe cosmic ray precursor with Hα emission