Non-thermal processes in Young Supernova Remnants

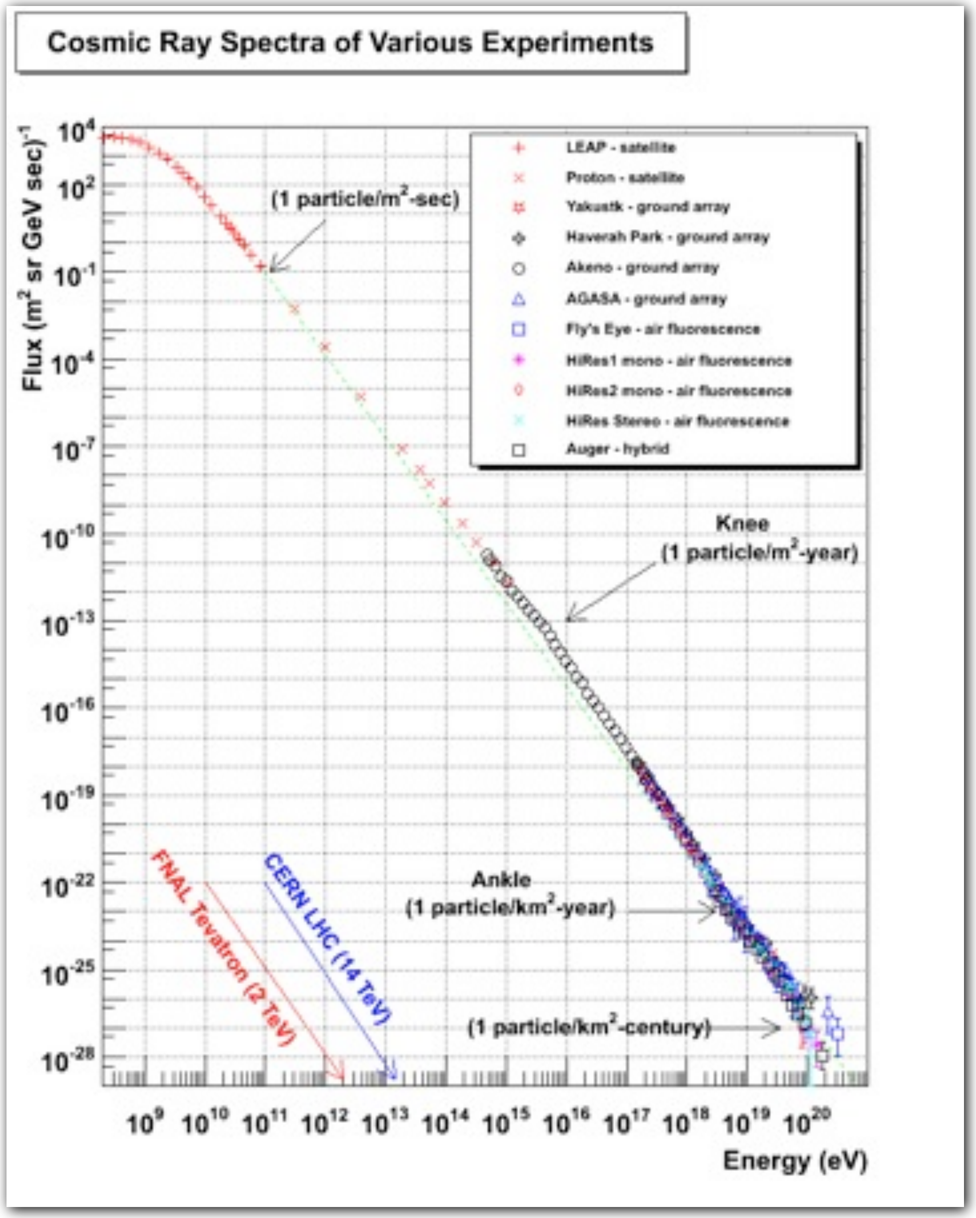
Jacco Vink

Outline

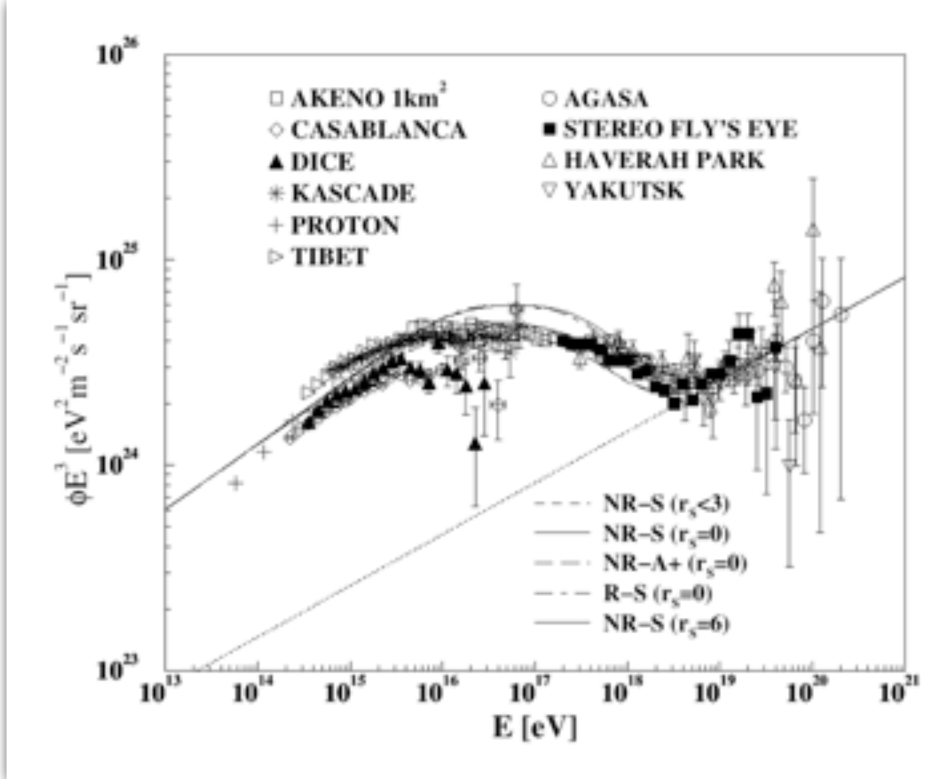
I. Supernovae & the origin of cosmic rays
II. Supernovae & their remnants
III. Thermal X-ray emission from supernova remnants
IV. Non-thermal radio emission from supernova remnants
V. Diffusive shock acceleration& the structure of cosmic-ray dominated shocks
VI. Non-thermal X-ray emission from SNRs
VII. Non-thermal bremsstrahlung & hard X-ray emission Gamma-ray emission from SNRs
VIII. Gamma-ray emission from SNRs
IX. Optical spectroscopy & cosmic-ray acceleration
X. Summary & Conclusions

I
Supernovae
&
the origin of cosmic rays

Cosmic Rays


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
10^4
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m^2-sec)
Knee
(1 particle/m^2-year)
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)

Cosmic Rays



- Up to ~10^{18}eV of Galactic origin
- Galactic CRs: likely powered by supernovae (Baade & Zwicky), as they provide sufficient power
- 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?
- Are particles mainly accelerated in supernova remnant phase?
- Alternatives:

  in SN phase, or <50 yr, or due to

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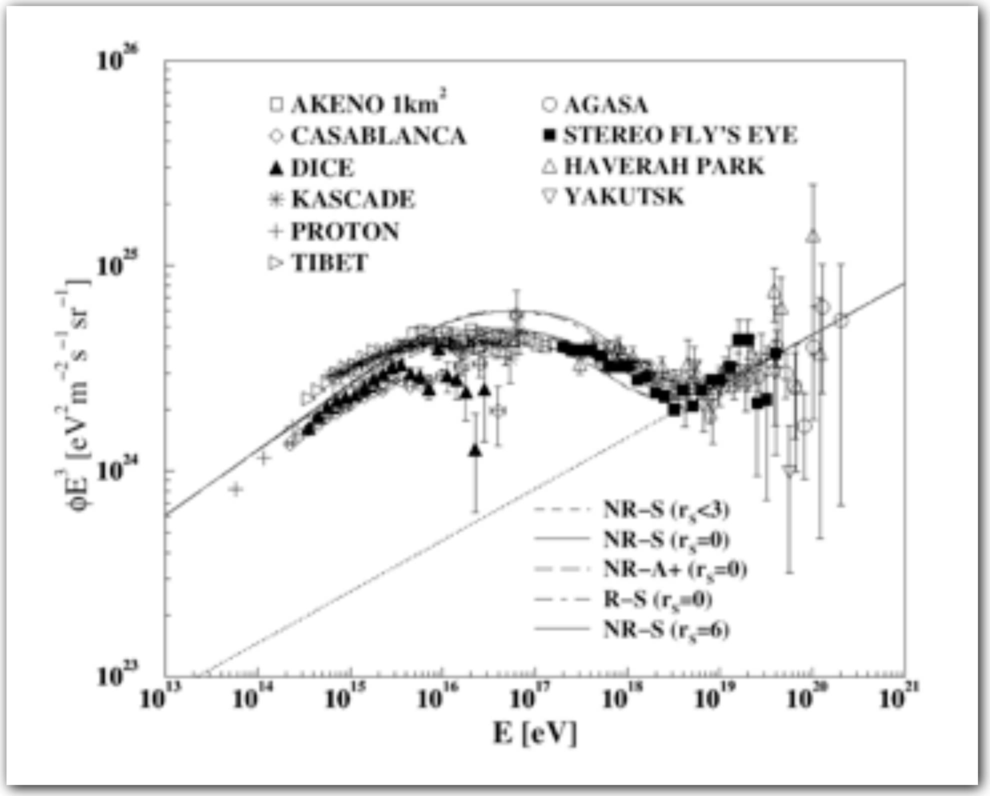

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See lecture on cosmic rays by Alan Watson

Why supernova (remnants) as sources?

- In normal spiral galaxies as the Milky Way: SNe most energetic sources
- What about rare, more energetic sources (GRBs, ULXs)?
  - Cosmic rays remain in Galaxy for $t_{cr} \sim 10^7$ yr
  - Steady state/homogeneity requires $t_{recur} << 10^7$ yr
  - SNe rate is 2-3 per century
  - SN explosion energy $E_{kin}=10^{51}$ erg
- SNe fulfil cosmic-ray energy requirements
  - Energy density CRs $u_{cr} \sim 1$ eV/cm^3
  - Volume Galaxy: $V_{gal}=\pi R_{disk}^2(2z) \sim 3\times10^{11}$ pc^3 $\sim 10^{67}$ cm^3
  - Power needed: $L=u_{cr}V_{gal}/t_{cr}=5\times10^{40}$ erg/s
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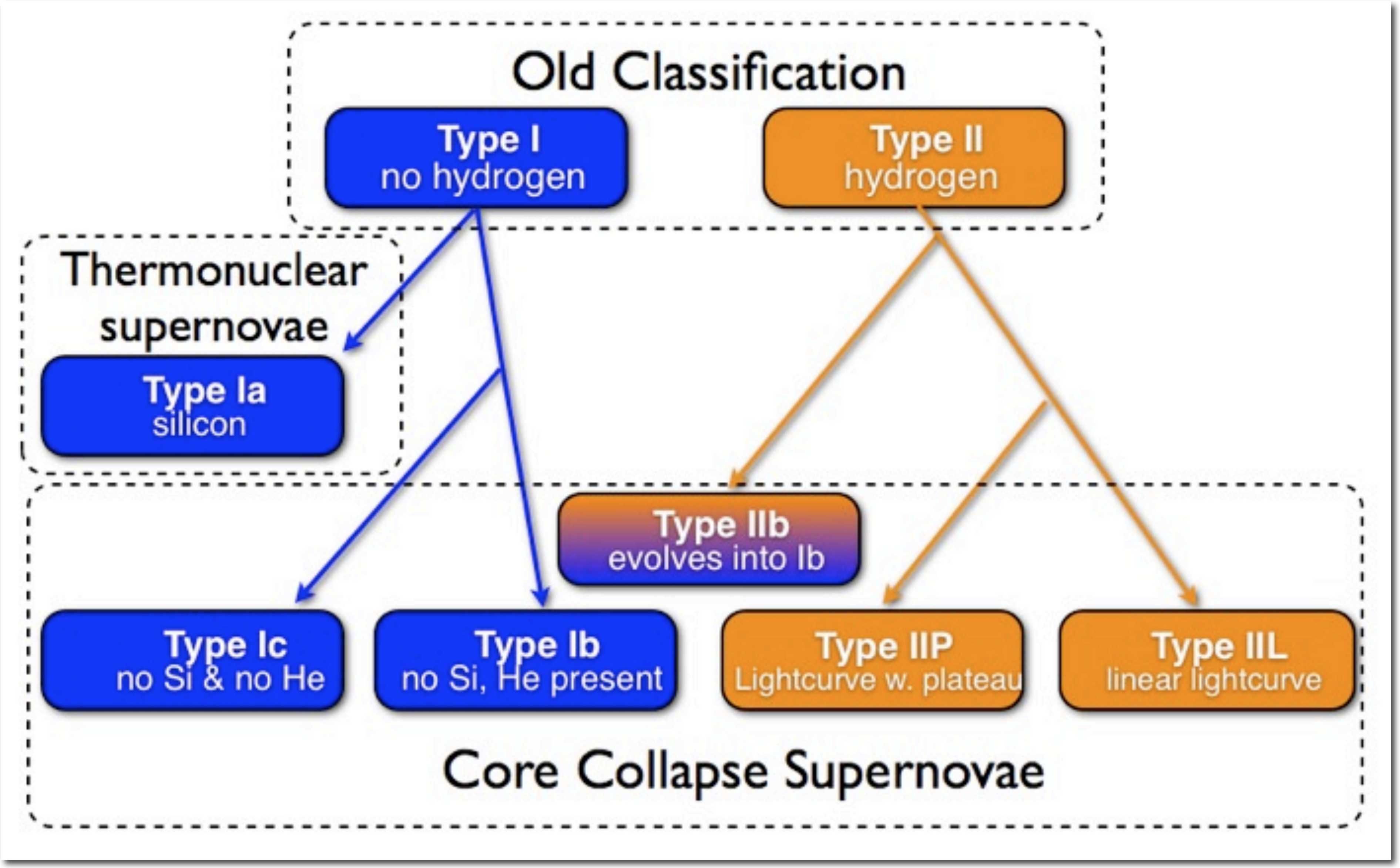
SNe provide enough power for cosmic rays if efficiency is ~10%

II
Introduction supernovae
&
their remnants

Supernova classification



Old Classification

Type I
no hydrogen

Type II
hydrogen

Thermonuclear supernovae

Type Ia
silicon

Type IIb
evolves into Ib

Type Ic
no Si & no He

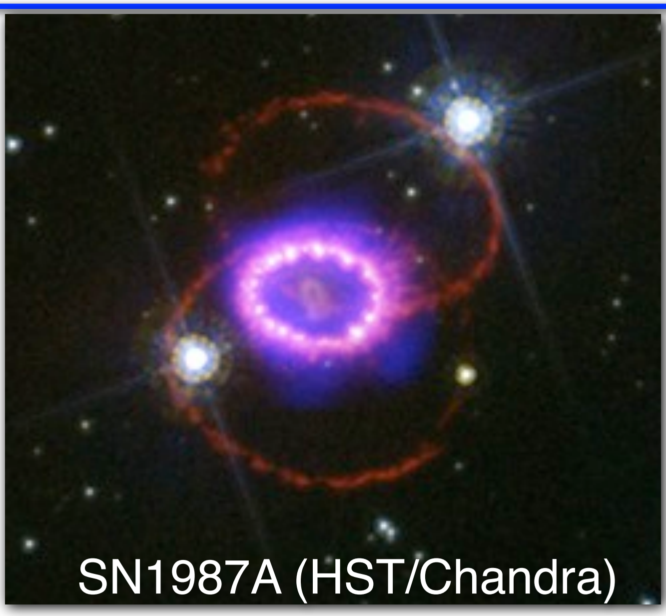
Type Ib
no Si, He present

Type IIP
Lightcurve w. plateau

Type IIL
linear lightcurve

Core Collapse Supernovae

From supernovae to supernova remnants

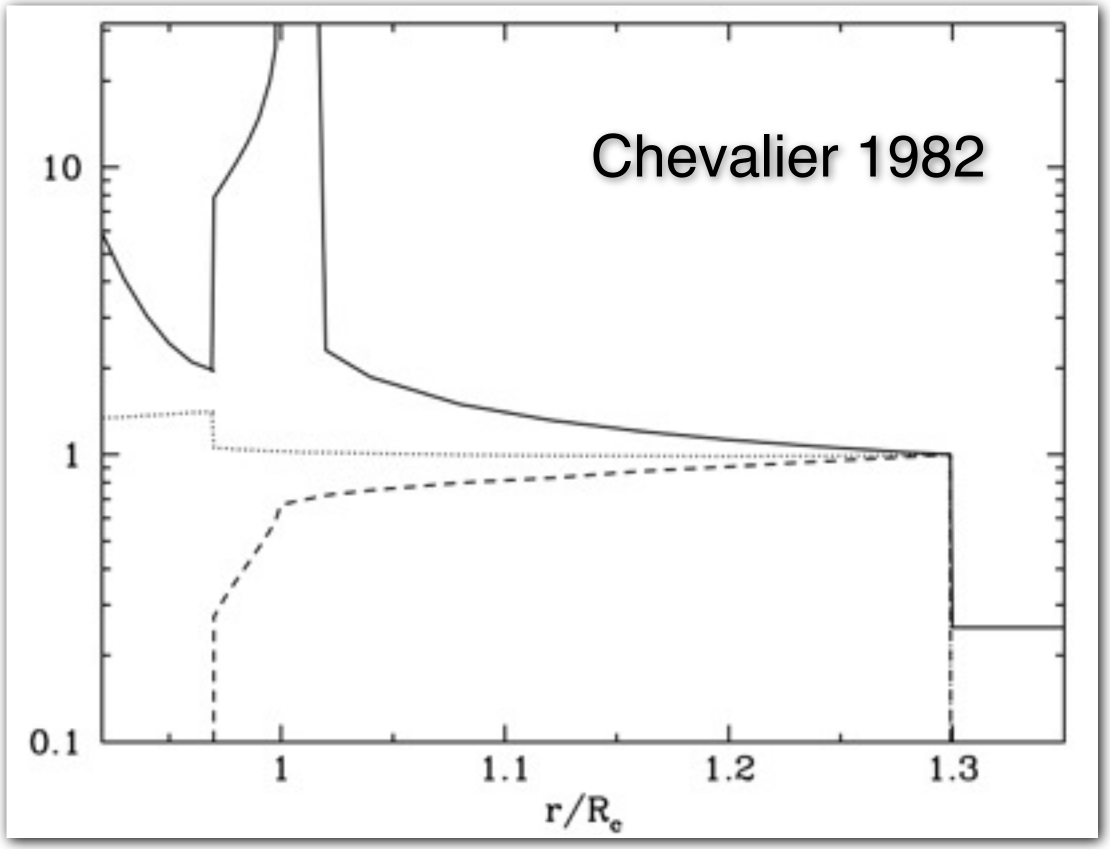


SN1987A (HST/Chandra)

- SNRs are hot shells created by a SN explosion ($E\sim10^{51}$ erg)
- The shells consist of a mixture of SN ejecta and shocked CSM
- Initial velocities are >~10000 km/s
- Young SNRs (~500 yr) have ~2000-5000 km/s
- SN ejecta shocked by reverse shock
- In “mature SNRs” reverse shock has reached center

- As long as Vs> 100 km/s: X-ray emission from hot plasma
- For V_s< 200 km/s ($kT<10^6$ K): rapid cooling -> energy loss important

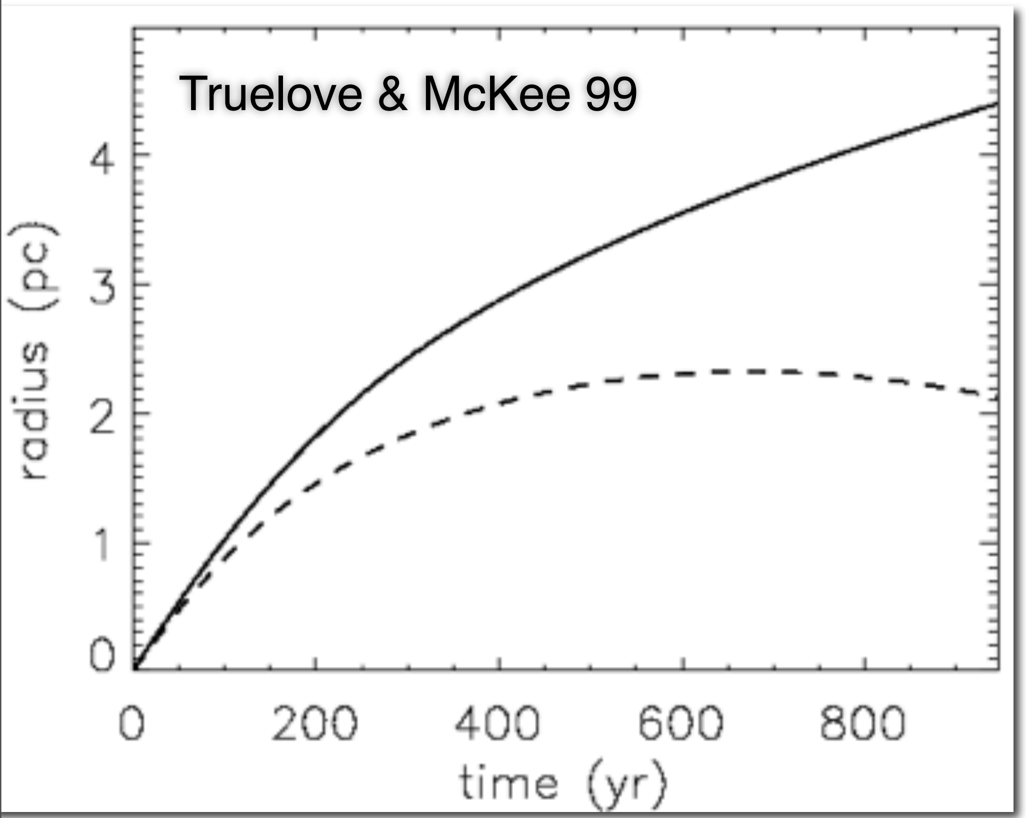
Young SNRs: structure

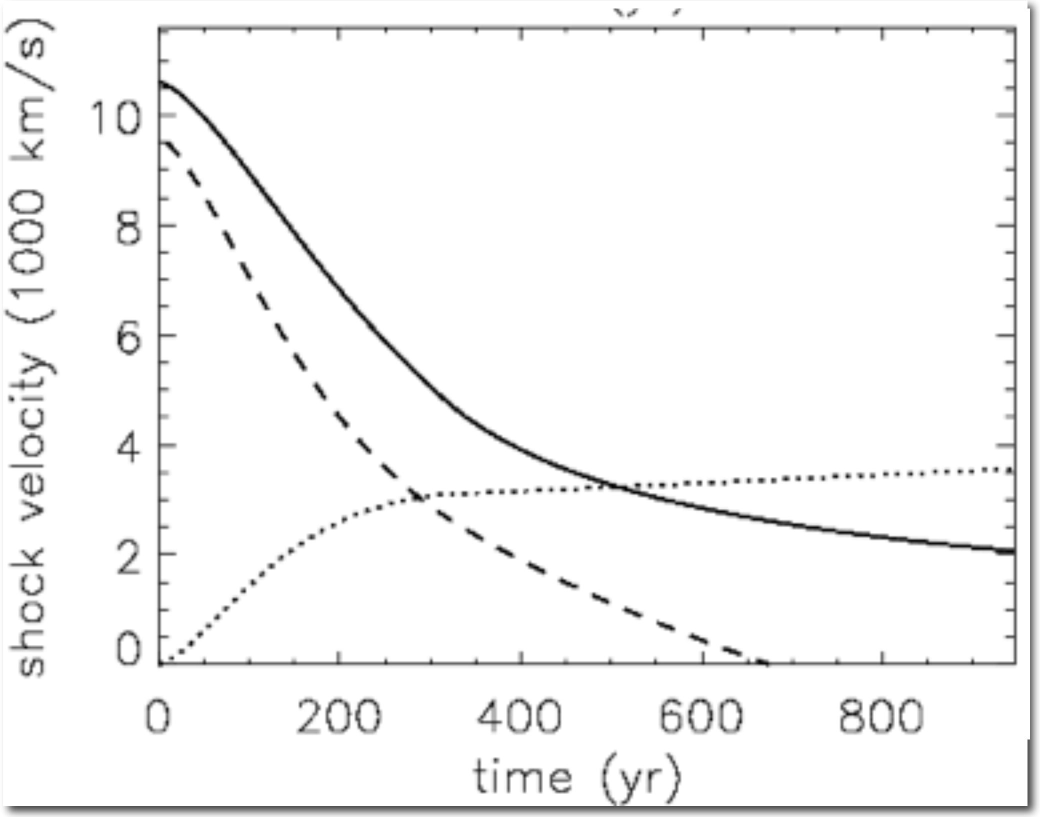


- Solid: density
- Dotted: velocity
- Dashed: pressure

- The shock wave leads to creation of hot shell (T> 10^7 K)
- Pressure in shell drives a shock wave back into expanding (cold) ejecta

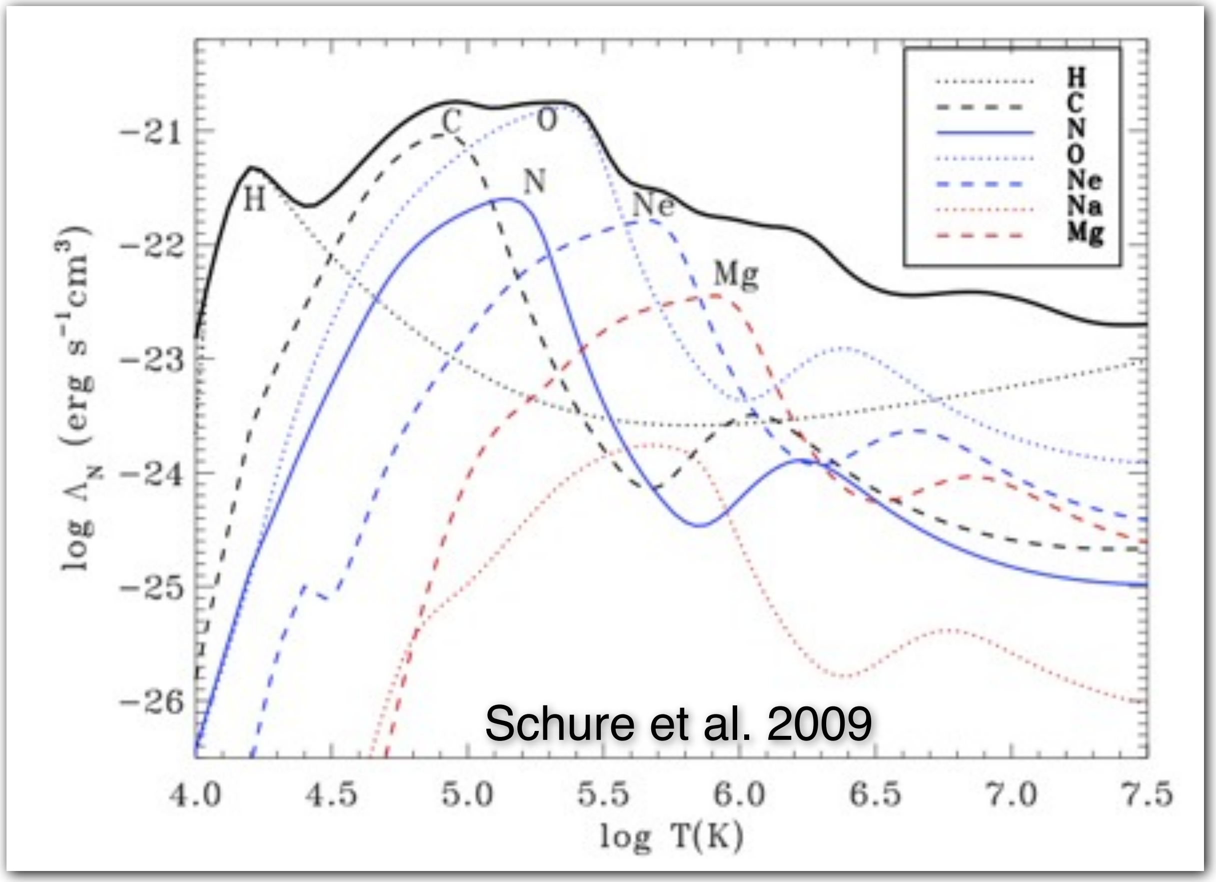
SNR evolution


Truelove & McKee 99



- Reverse shocks move first outward than inward, eventually heating all ejecta
- Asymptotically in adiabatic phase: $R=Kt^{2/5}$ ($R=Kt^{2/3}$ for density~$1/r^2$)

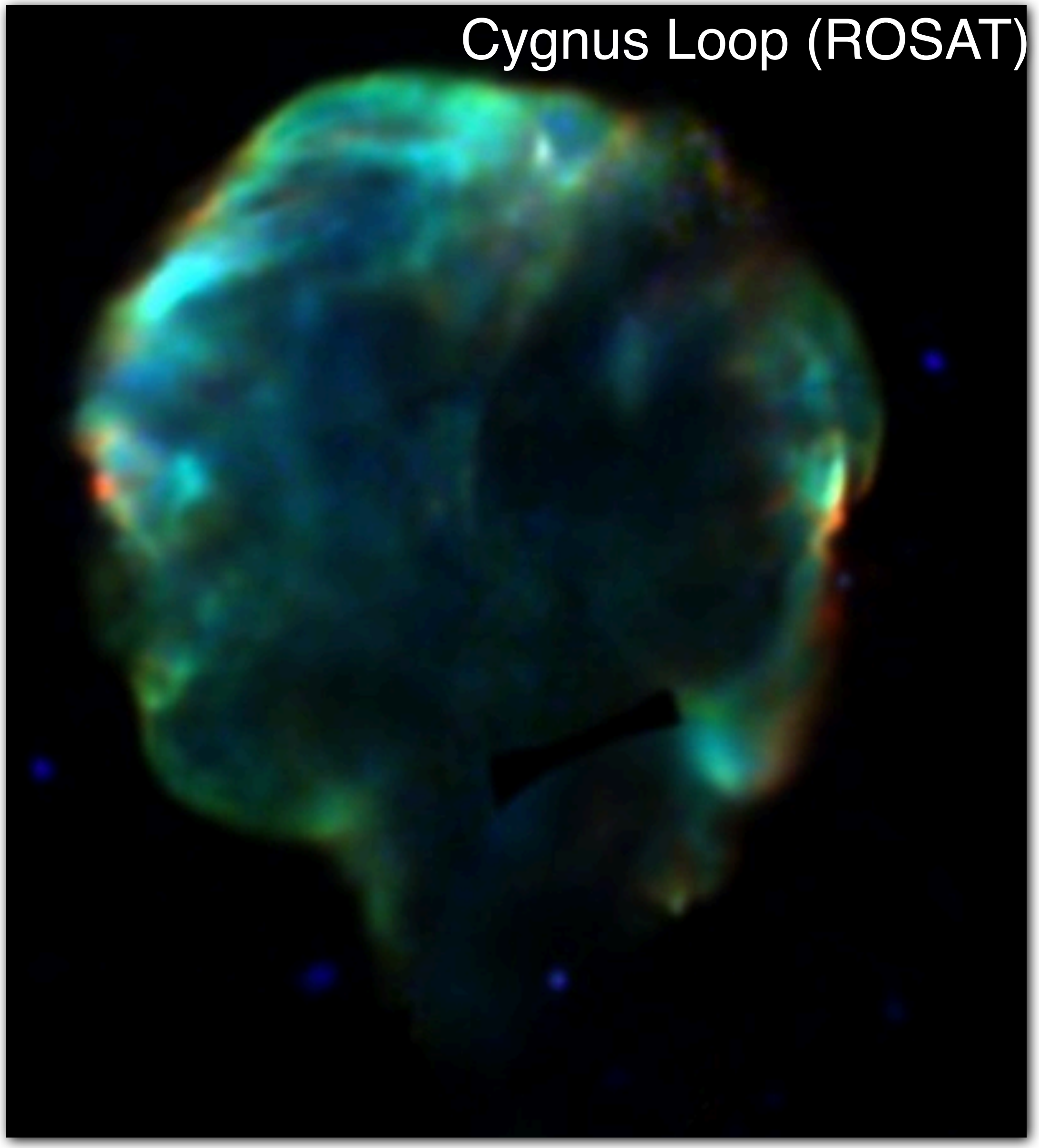
“Mature SNRs”



Schure et al. 2009

- For T<5x10^5 K: cooling becomes very strong (oxygen line emission)
- SNR no longer adiabatic: R~$t^{0.25}$ (momentum conservation)

SNR Types: shell-type



SNR Types: Plerion


Crab nebula


3C58 (Chandra)

- Plerions are dominated by synchrotron emission from pulsar wind nebula
- They can still be considered SNRs as they have some ejecta components (in Crab nebula only seen in the optical)

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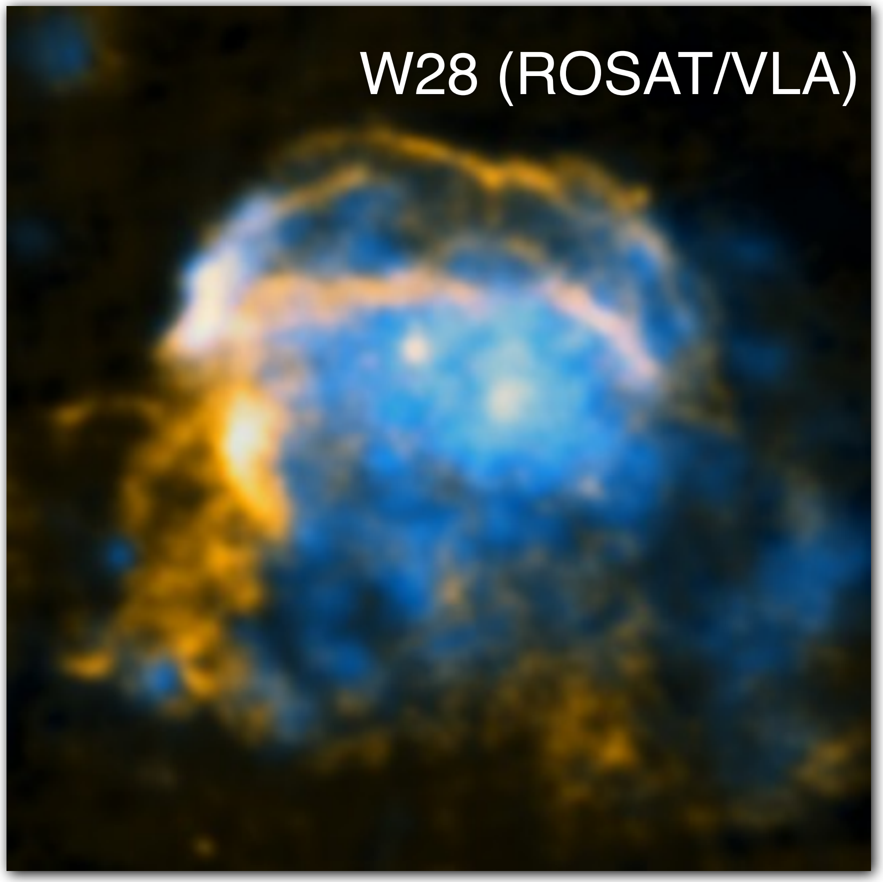
See lectures by Jon Arons, Emma de Ona Wilhelmi

SNR Types: Composite SNRs

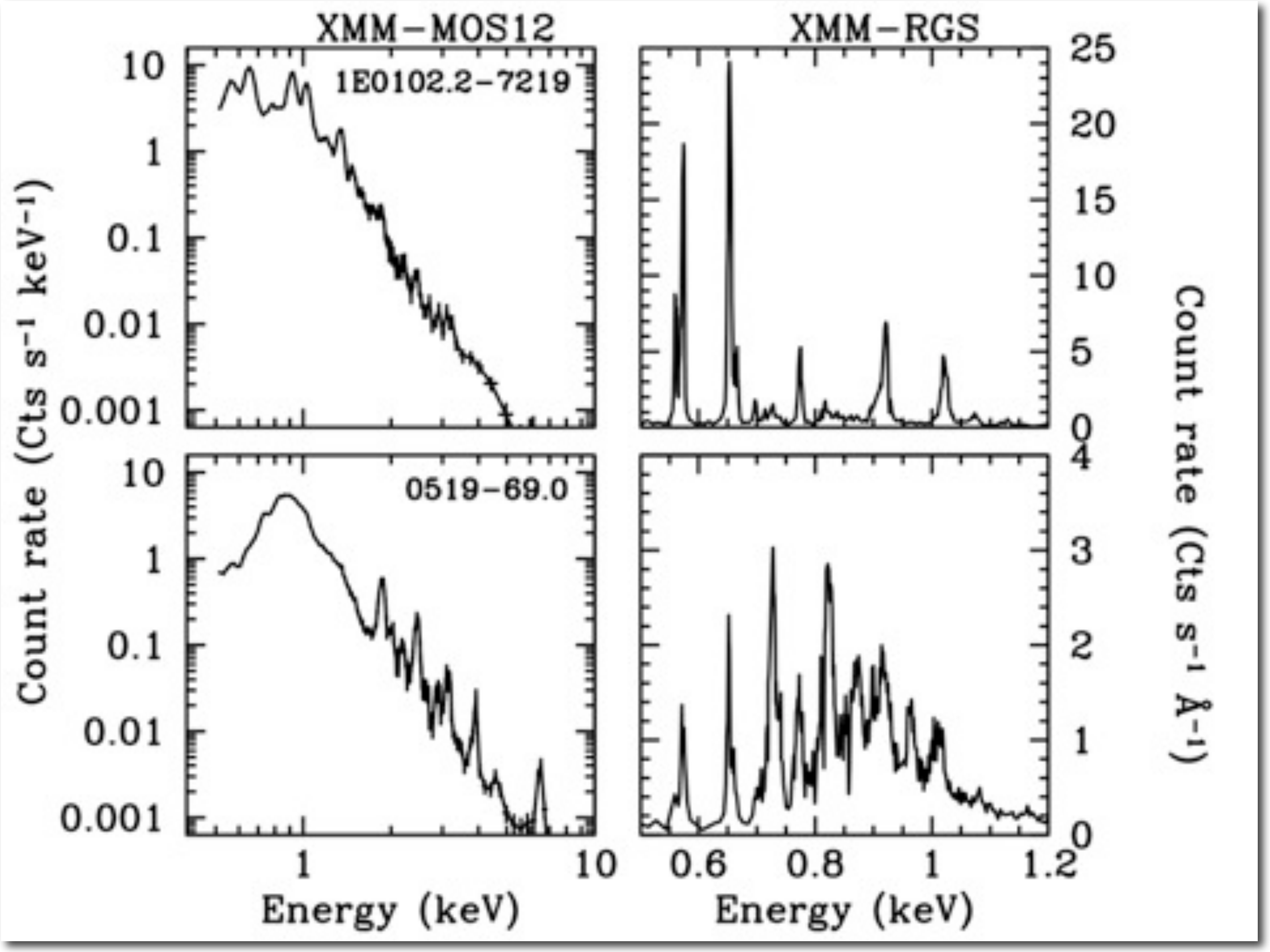
- Composite are a combination of a shell-type SNR and a pulsar wind nebula
- Not all core collapse SNRs are plerions/composites:
  neutron stars not always powerful pulsars!

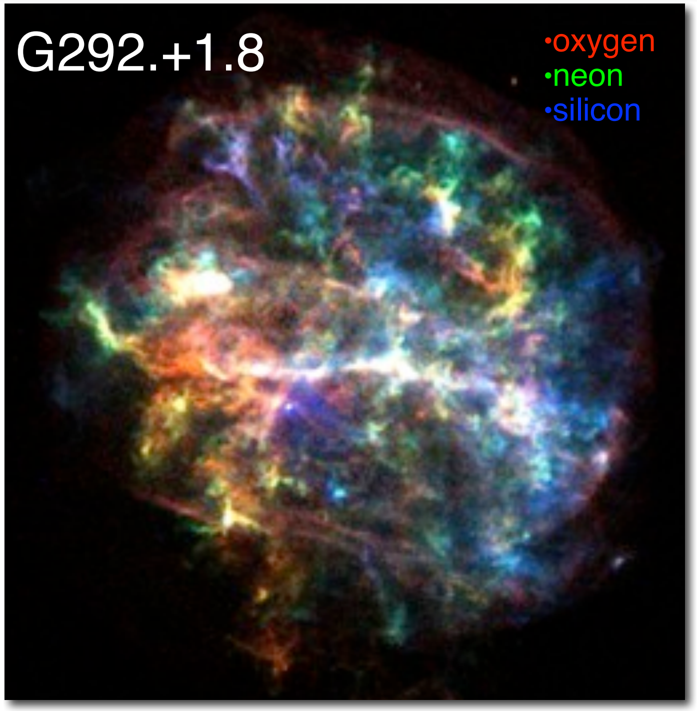
Mixed-morphology/Thermal composite SNRS

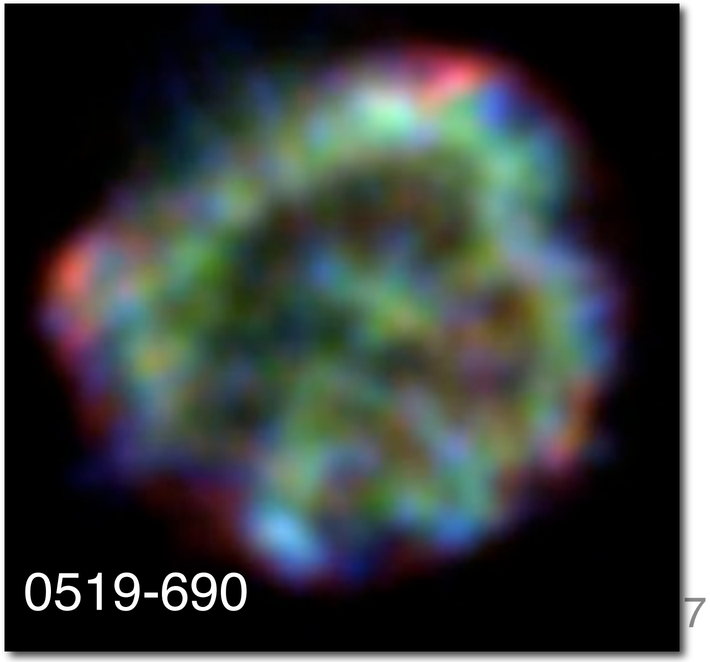


- Mixed-morphology SNRs are centrally bright
- X-ray emission is thermal
- Are older SNRs
- Idea: shell too cool for X-rays, but center hot enough for X-rays (Cox+ ’99)
- Many of the gamma-ray emitting old SNRs are MM!!

Linking SNRs with SN classes







- Core collapse SNRs are rich in O, Ne, Mg
- Type Ia SNRs are iron-rich

III
Thermal X-ray emission from SNRs

Heating by strong shocks

- For now ignore particle acceleration
- Mass conservation (v in frame of shock)

$$\rho_0 v_0 = \rho_2 v_2$$

- Compression factor

$$\chi \equiv \frac{\rho_2}{\rho_0} = \frac{v_0}{v_2}$$

- Momentum conservation ($v_0=V_s$)

$$P_0 + \rho_0 V_s^2 = P_2 + \rho_2 v_2^2$$

$$\Rightarrow P_2 = P_0 + \left(1 - \frac{1}{\chi}\right)\rho_0 V_s^2$$

- Using $P_2=n_2kT_2=\rho_2kT_2/\mu m_p$, $P_0 \ll P_2$

$$kT_2 = \frac{1}{\chi}\left(1 - \frac{1}{\chi}\right)\mu m_{\rm p} V_s^2$$

- Energy conservation

$$\left\{P_2 + u_2 + \frac{1}{2}\rho_2 V_s^2\right\} = \left\{P_0 + u_0 + \frac{1}{2}\rho_0 V_s^2\right\}$$

$$u + P = \frac{5}{2}P \ (\Gamma \equiv \frac{5}{2})$$

$$\chi = \Gamma + \sqrt{\Gamma^2 - (2\Gamma - 1)} = 4$$

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Expected temperatures

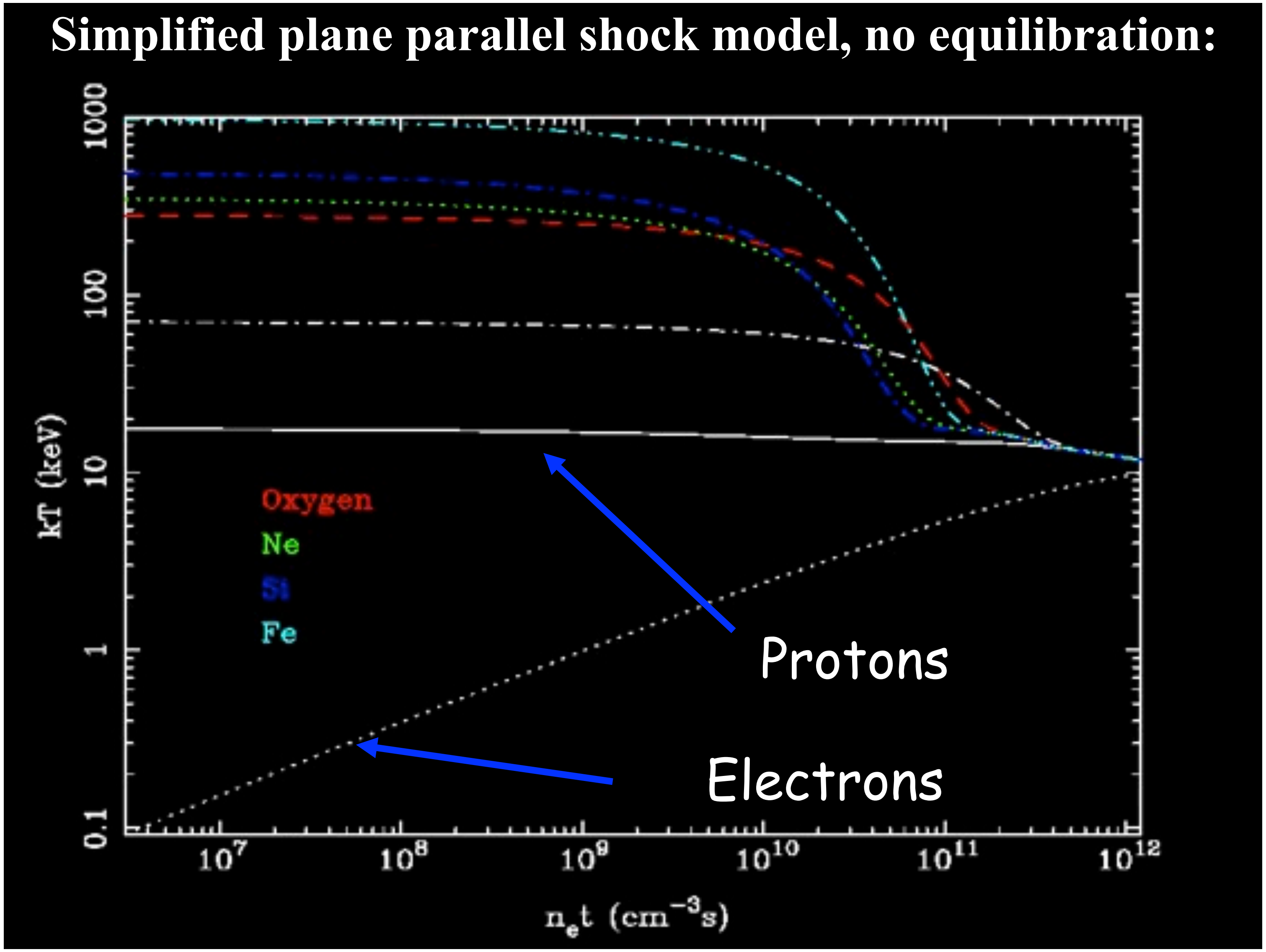
- For strong shocks ($P_0 << P_2$) we expect temperatures of:

$$kT_2 = \frac{1}{\chi}\left(1-\frac{1}{\chi}\right)\mu m_{\rm p} V_s^2 = \frac{3}{16}\mu_{\rm p} V_s^2 \approx 1.2\left(\frac{V_s}{1000\ {\rm kms}^{-1}}\right)^2\ {\rm keV}$$

- Young SNRs with V_s~5000 km/s should therefore have kT ~ 30 keV
- This is not observed! Typically $kT_e < 4$ keV!
- Possible reasons:
  - X-ray spectrum gives electron temperature and $kT_e < kT_p$
  - Efficient cosmic ray acceleration changes shock conditions!! (see later this lecture)

Temperature (Non-)Equilibration

Simplified plane parallel shock model, no equilibration:



Thermal X-ray emission

- SNRs are young (100-20,000 yr) and densities are low (n_e~1 cm^{-3})
- Result: atom-atom, or electron collisions are rare (mean free path ~ parsecs)
- How shock established is complicated (plasma waves, not atom-atom collisions)-> *collisionless shocks*
- Ionization proceeds slowly -> ionization distribution not in equilibrium
  -> *NEI* (non-equilibrium ionization)
  - relevant parameter: $\tau = n_e t$ (ionization age)
  - needed for equilibrium $n_e t > 10^{12}$ $cm^{-3}s$
  - young SNRs have $n_e t = 3 \times 10^9 cm^{-3}s$ (SN 1006) to 3×10^{11} $cm^{-3}s$ (Cas A)

- Thermal X-ray emission from hot plasmas:
  - Line emission (NEI)
  - Thermal bremsstrahlung continuum
  - Free-bound continuum + two photon continuum

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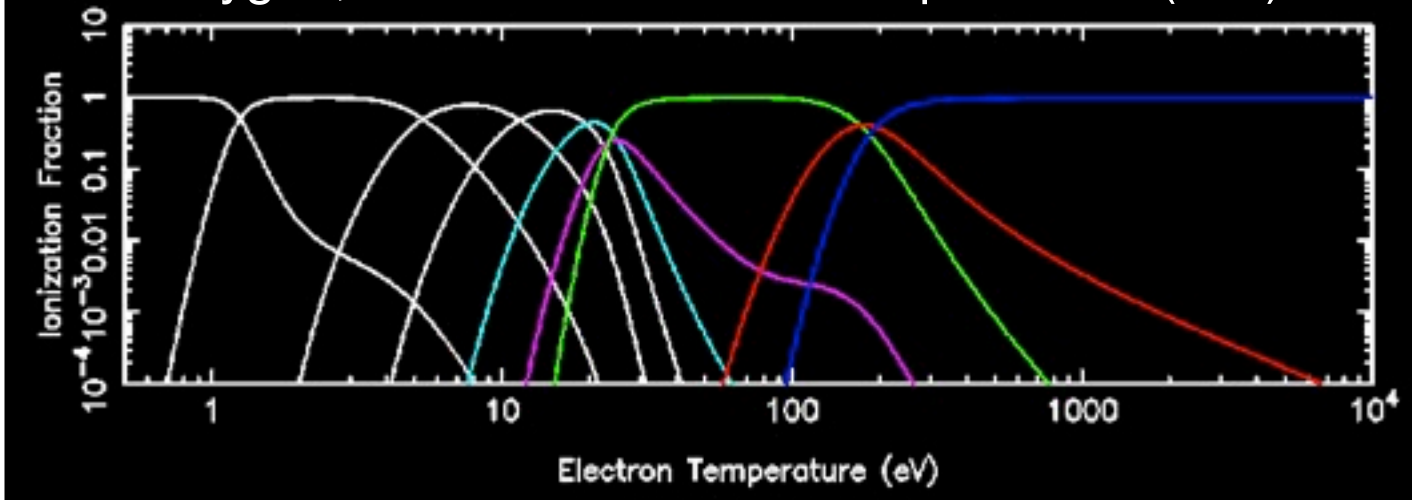
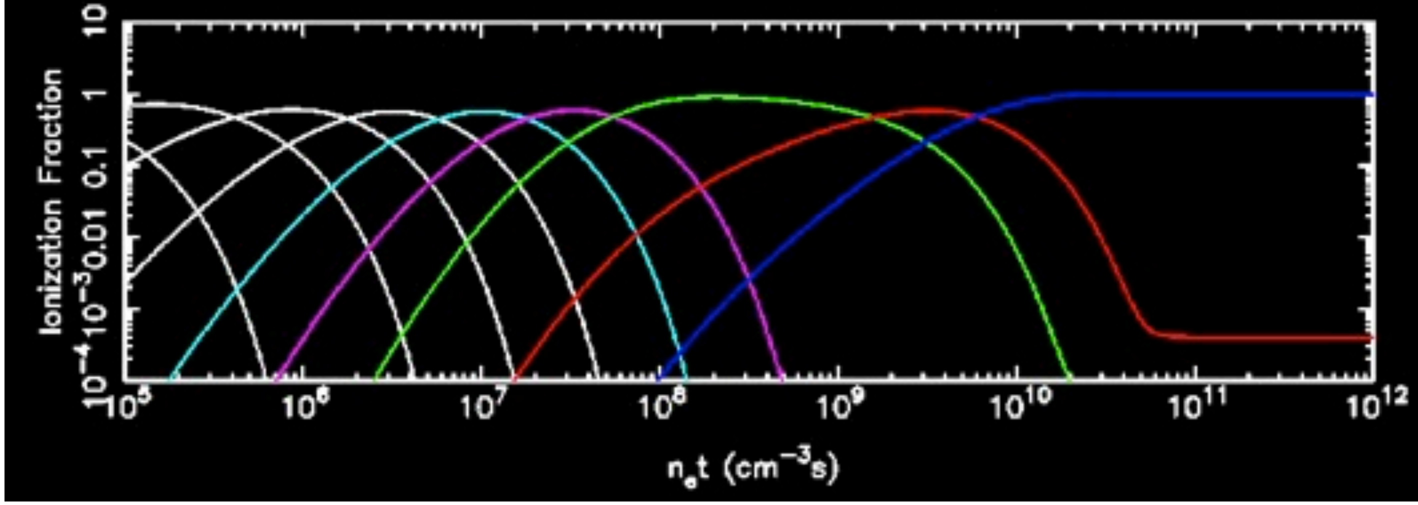
See lecture by Jelle Kaastra for more details

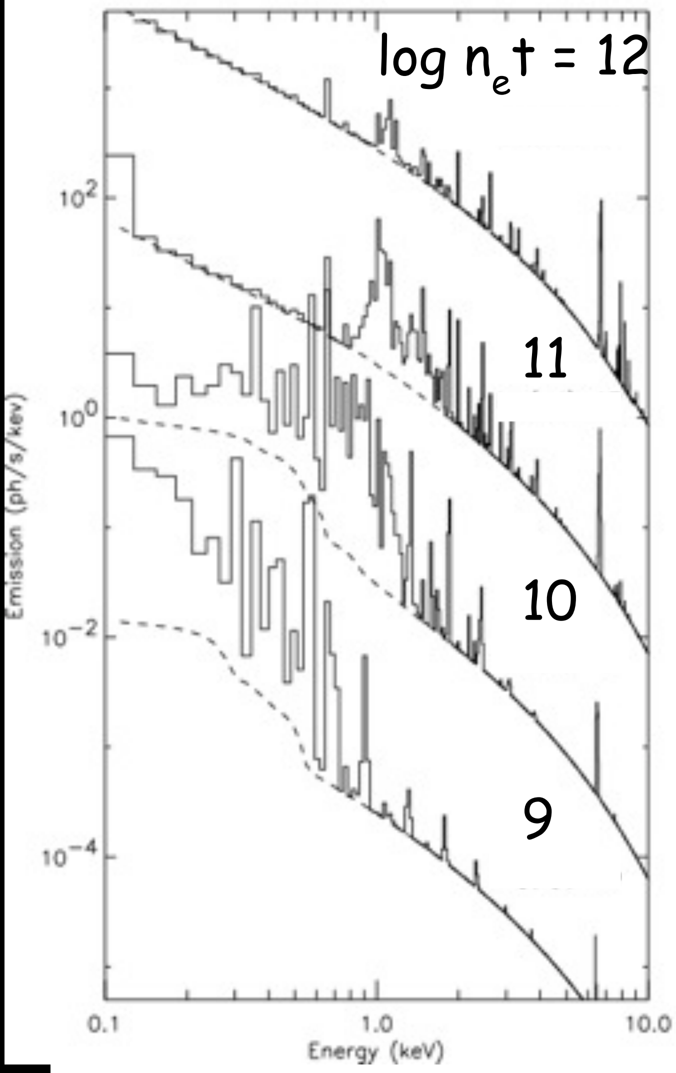
Non-equilibrium ionization

Oxygen, Collisional Ionization Equilibrium (CIE)



Oxygen, Non-equilibrium Equilibrium (NEI) (here kT fixed)





IV
Non-thermal radio emission from SNRs

First evidence for particle acceleration

- Since the 1950-ies SNRs associated with bright radio synchrotron sources
- Synchrotron emission: relativistic electrons deflected in magnetic fields
- Characteristic frequency

$$\nu_{\rm ch} = 46 \frac{B_\perp}{10\ \mu{\rm G}} \left(\frac{E}{1\,{\rm GeV}}\right)^2 {\rm MHz}$$

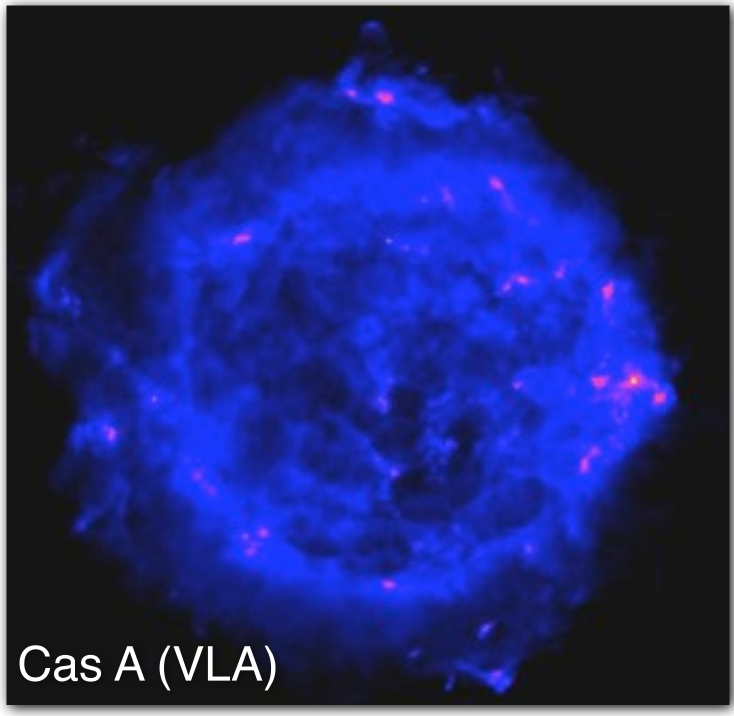
- Radio synchrotron ➔ electrons with GeV energies
- Brightness: number of rel. electrons + B-field
- For power law electron distribution

$$N_{\rm e} \propto KE^{-q},\ I_\nu \propto KB^{(q+1)/2}\nu^{-(q-1)/2}$$

- Relation electron and radio spectral index:

$$\alpha = (q-1)/2$$

- Typical young SNRs in Radio: α=0.6 ➔ q= 2.2



Cas A (VLA)

Consequences of radio synchrotron

- Brightness depends on magnetic field and number of electrons
- Minimum energy: minimize combined energy density of relativistic particles and magnetic fields
  - Gives for Cas A $E_{rel,\ electrons} \sim 10^{48}$ erg and B~0.5 mG
  - If protons are also present $E_{rel.\ part} \sim 10^{49}$ erg
- Radio emission from young SNRs: SNRs are capable of accelerating particles to very high energy
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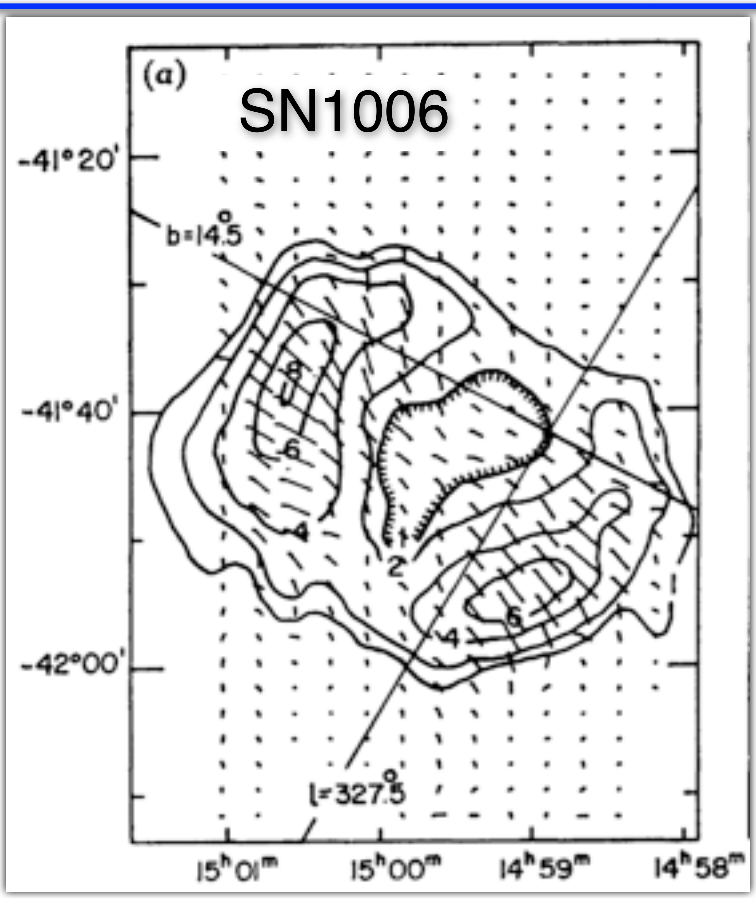
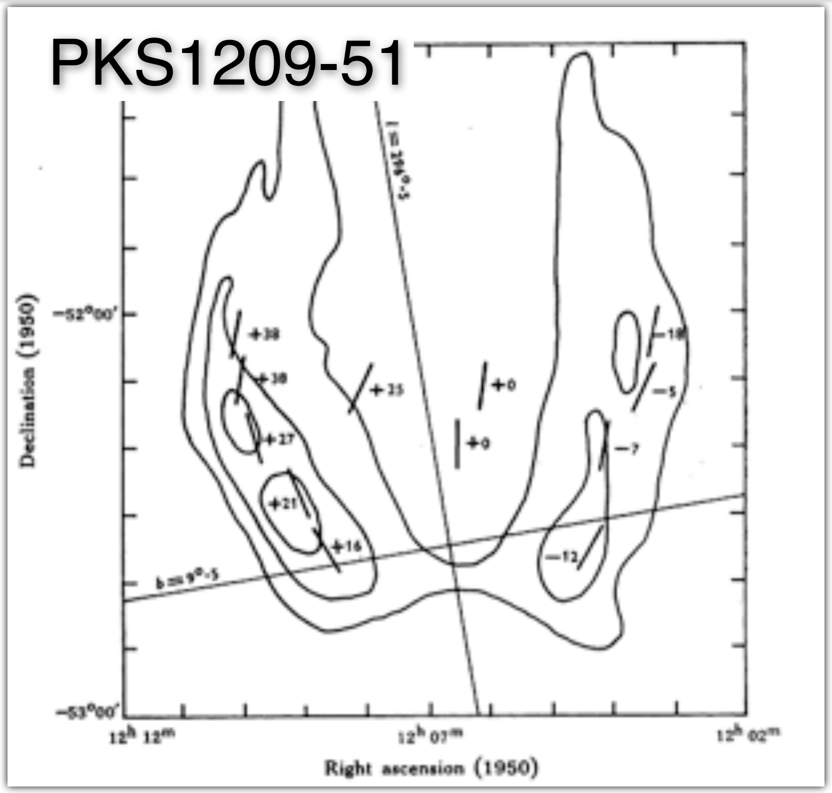
- Not for all SNRs it is clear that particles are accelerated in SNR:
  - In old SNRs compression of existing rel. electrons + B-field may enhance local synchrotron emission (van der Laan mechanism (1962))

Young versus Old SNRs





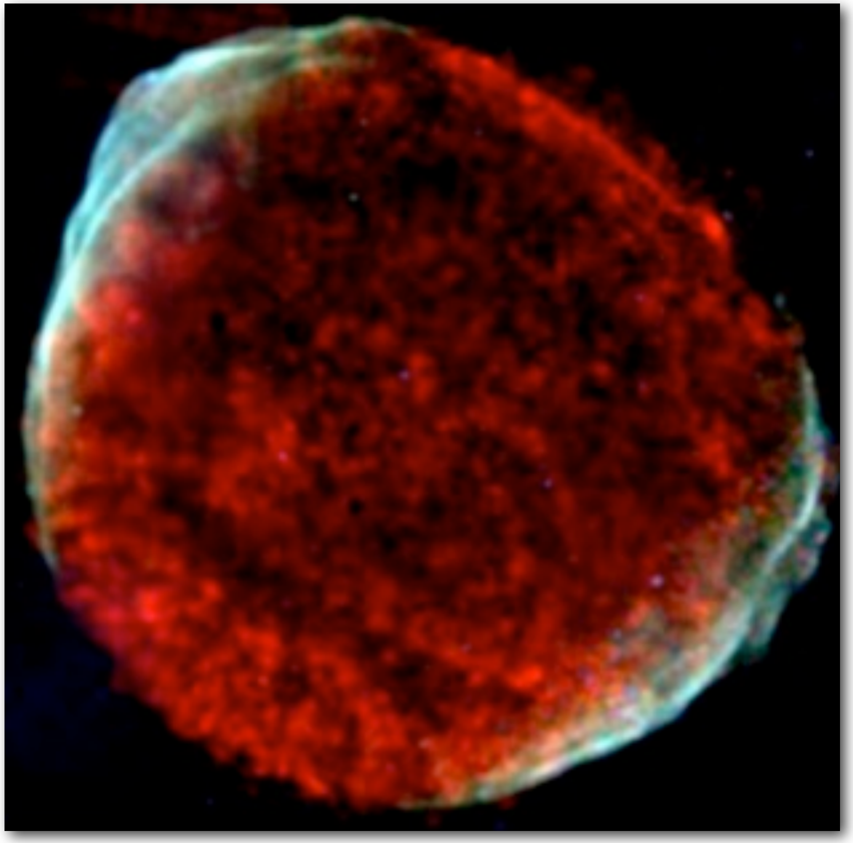
Dickel & Milne ‘96

- *Radial* magnetic fields
- Emission due to recently accelerated electrons

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

V
Diffusive shock acceleration
&
the structure of
cosmic-ray dominated shocks

Diffusive Shock Acceleration



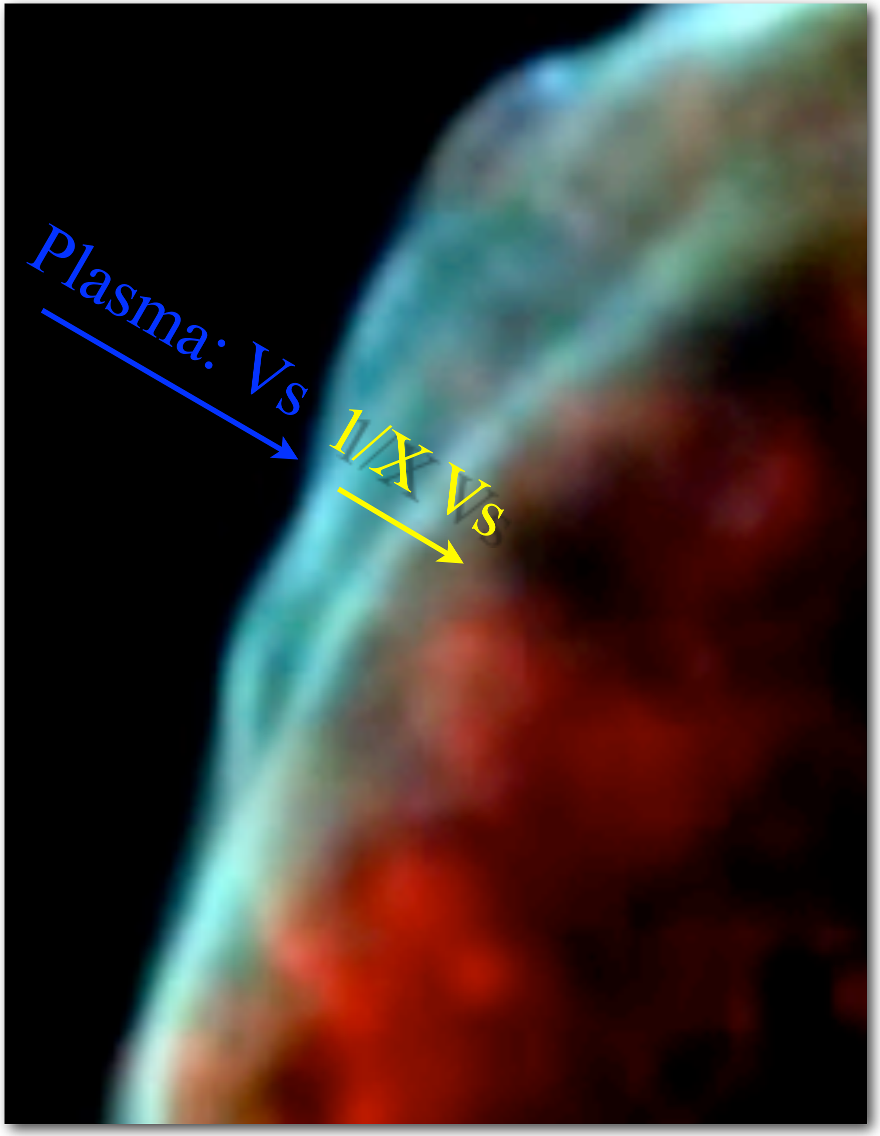
- Particles scatter elastically (B-field turbulence)
- Each shock crossing the particle increases its momentum with a fixed fraction ($\Delta p = \beta p$)
- *Net movement downstream* (particles taken away from shock)
- Resulting spectrum (e.g. Bell 1978):

$$dN/dE = C\ E^{-(1+3/(X-1))}$$

X shock compression ratio,
$X=4 \rightarrow dN/dE = C\ E^{-2}$

Axford et al. , Blanford & Ostriker, Krymsky, and Bell (all 1977-78)

Diffusive Shock Acceleration



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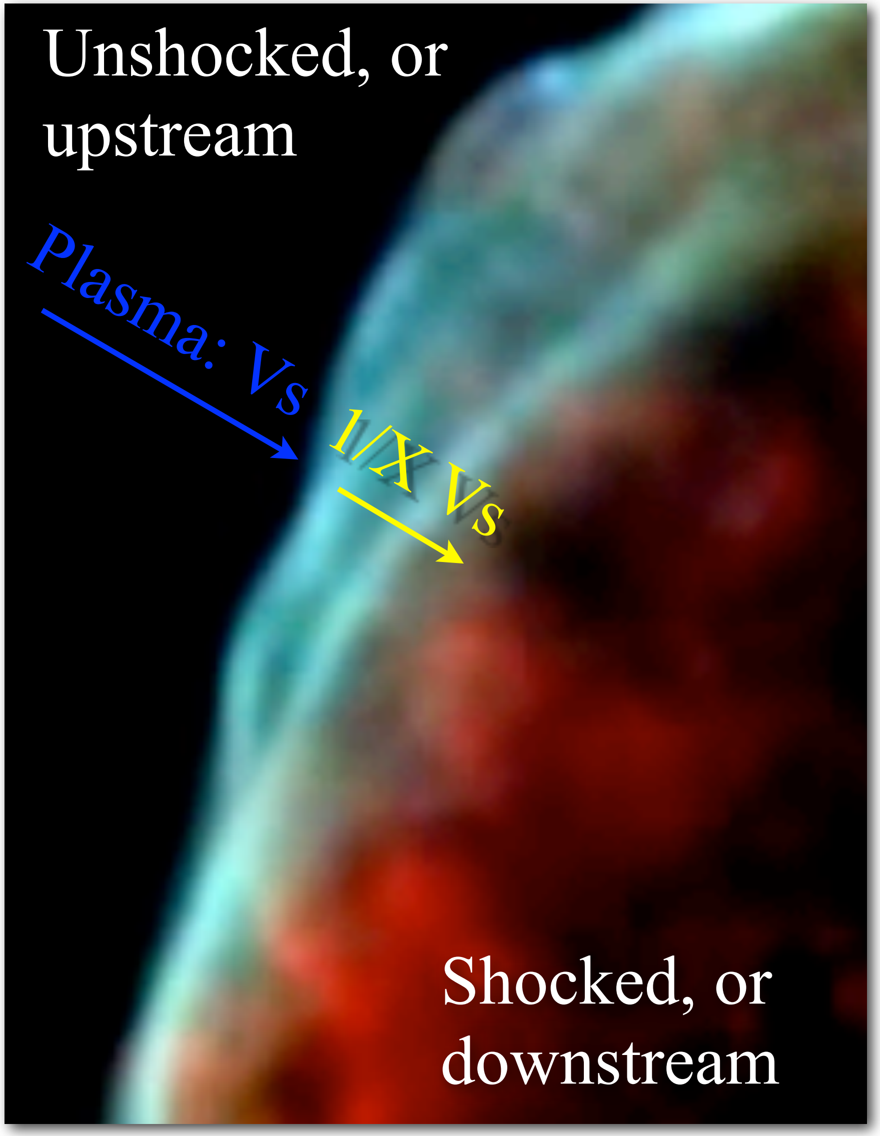

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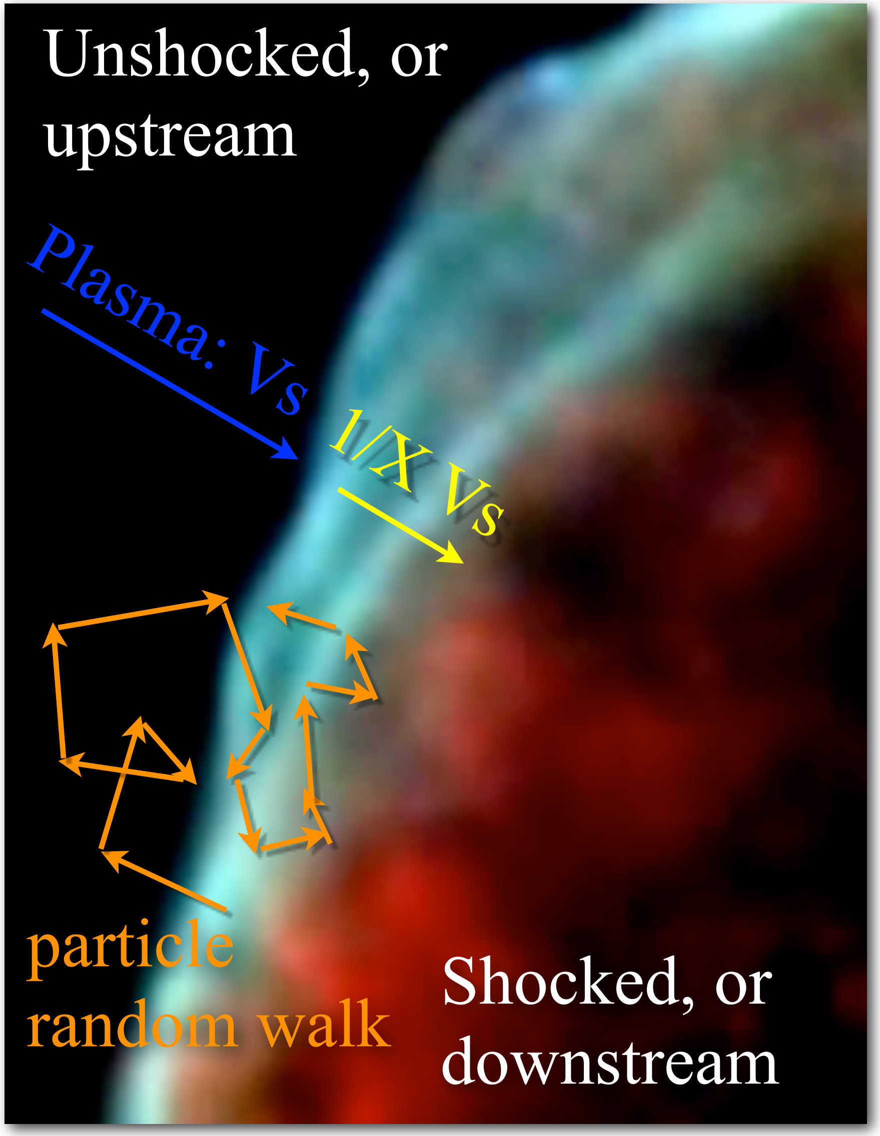

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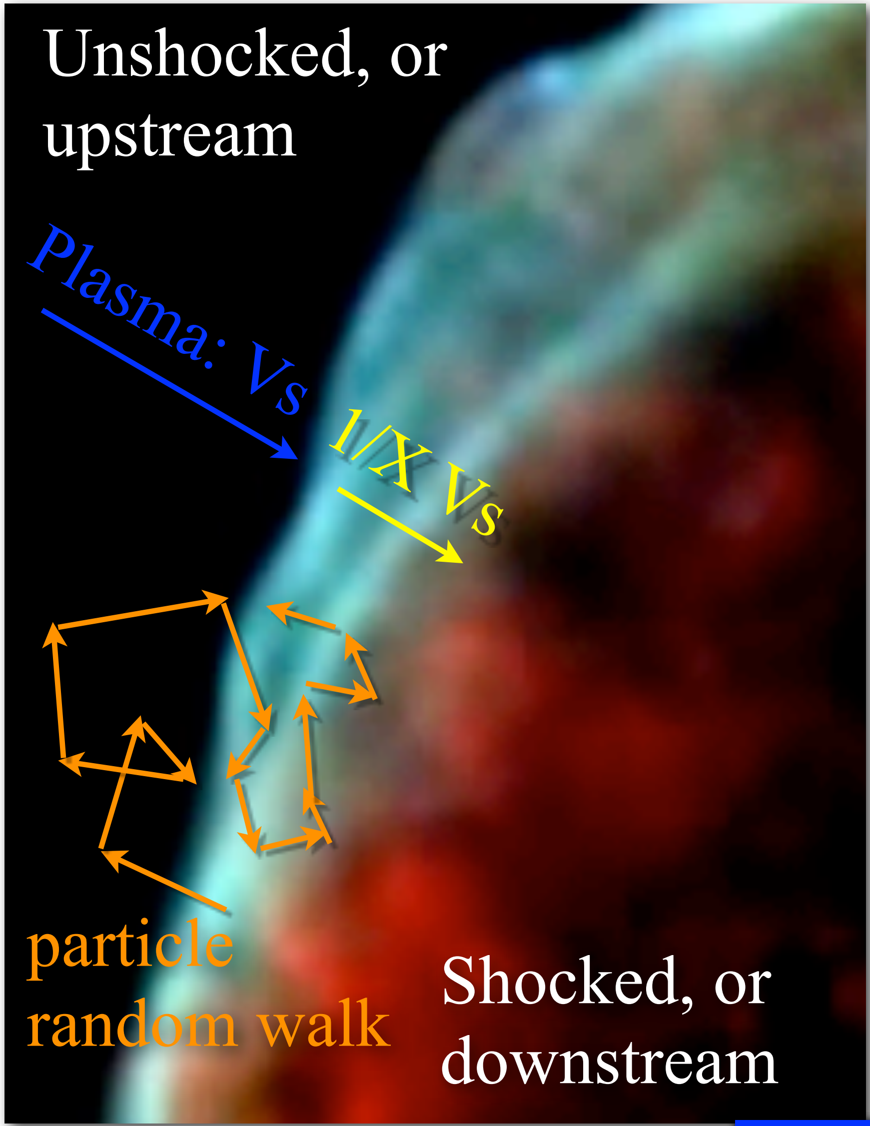

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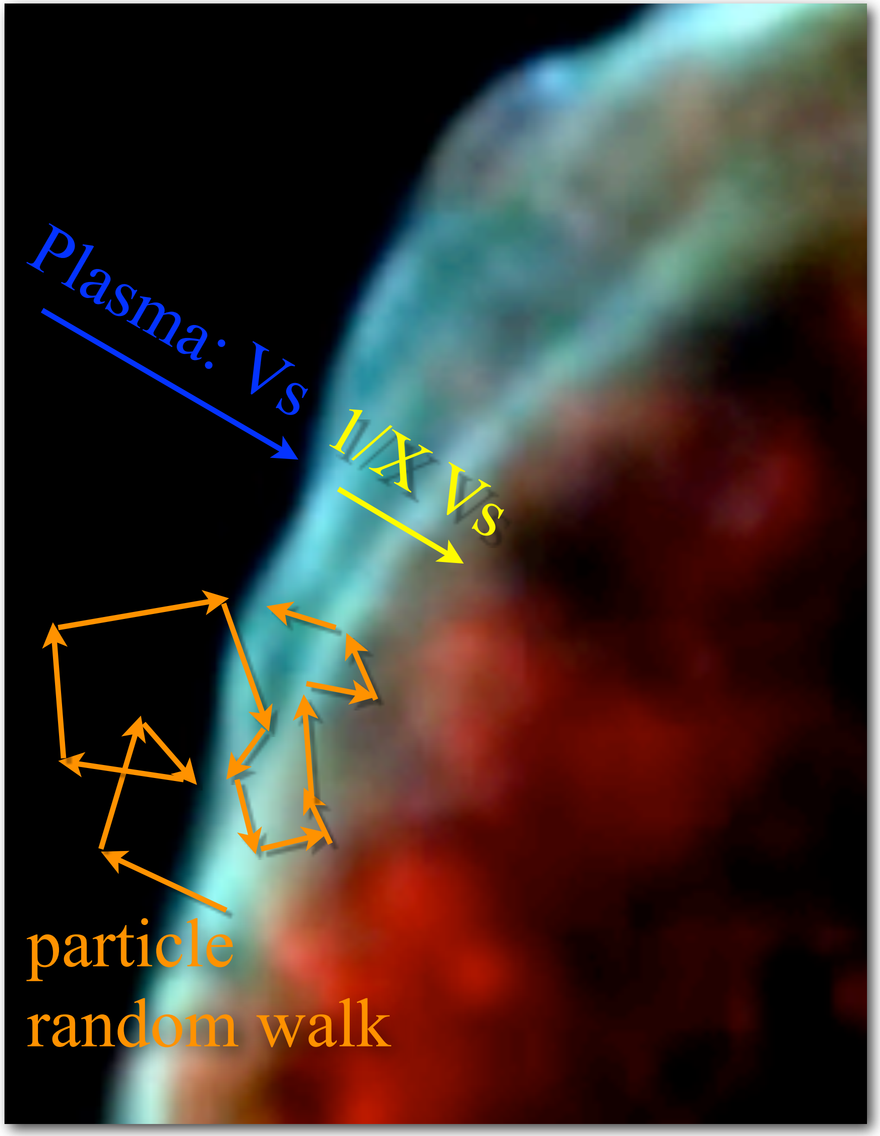
Axford et al. , Blanford & (

See lectures by Alex Lazarian and Tony Bell

Diffusive Shock Acceleration II



- Spectral shape determined by escape probability
- Length scale for which diffusion dominates over advection:

$$l_{\rm diff} = \sqrt{2Dt},\ \ l_{\rm adv} = vt$$

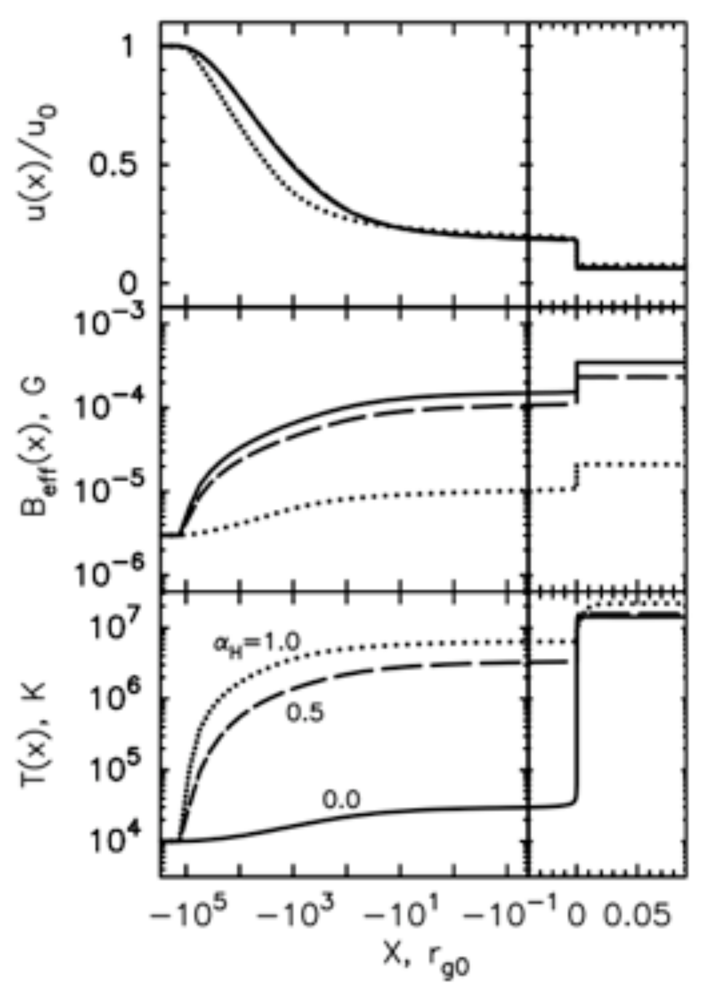
$$\Rightarrow l_{\rm diff} = \frac{2D}{v},\ \ t_{\rm diff} = \frac{2D}{v^2}$$

- $t_{\rm diff}$ is typical time for particle to cross shock again ($t_{\rm diff}$~$t_{\rm acc}$)
- Smaller mean free path, smaller D, faster acceleration
- Bohm diffusion: $\lambda_{\rm mfp} = r_{\rm gyro}$

$$D = \eta\lambda_{\rm mfp}\frac{1}{3}c = \frac{Ec}{3eB}$$

Non-linear acceleration

- If a large part of pressure is in cosmic rays:
  - simple DSA models doesn’t work
  - rel. particles change the shock structure
  - process is *non-linear*
- Presence of cosmic rays changes EOS ⇒ larger compression ratios
- Upstream escape of CRs: energy loss ⇒ larger compression ratios
- Compression ratio sampled depends on energy of particle ➔ curved spectra
- 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



Vladimirov, Bykov, & Ellison 08

Thermodynamics

- Non-linear cosmic ray acceleration studied theoretically using kinetic codes (Monte-Carlo, semi-analytic, Hybrid: Ellison c.s., Blasi c.s., Jones&Kang)
- Codes give self-consistent result: particle spectra ⇔ shock hydrodynamics
- Easy to include new processes, but outcome depends on assumptions made

- Thermodynamics approach:
  - Also named: two-fluid approach
  - Only assumptions: conservation laws
  - Drawback: no microphysics, no particle spectra (i.e. index γ assumed)
  - no-precursor heating yet included
- Outcome:
  - extension of standard Rankine-Hugoniot shock relations
  - post-shock compression and temperature as a function of V_s, Mach number, CR pressure, adiabatic index CRs γ

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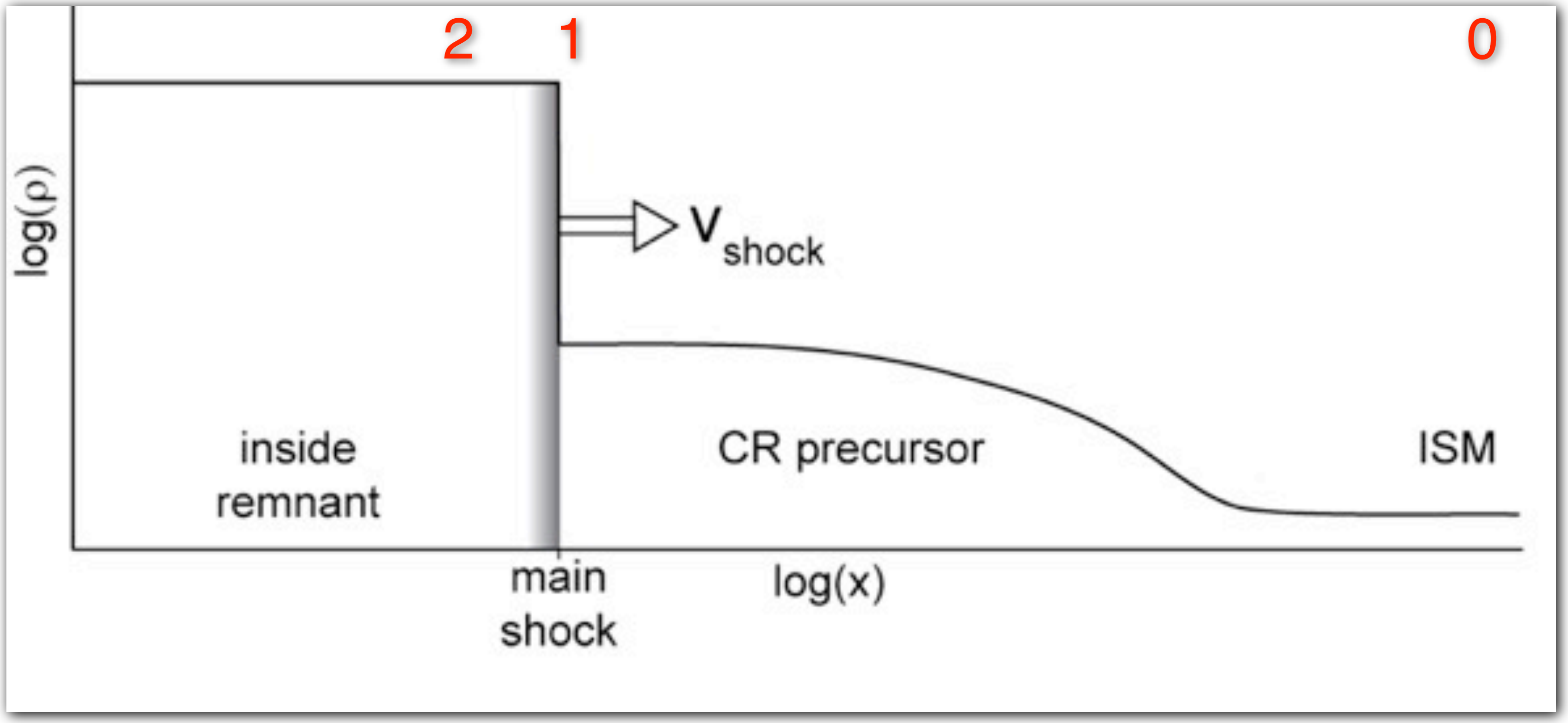
Vink, Yamazaki, Helder Schure, 2010

Two fluid approach

- Standard shock continuity relations with some modifications:
  - Three regions

    0: far upstream;1: precursor, just upstream of main shock; 3: shocked gas
  - cosmic ray pressure continuous from 2-3
  - cosmic rays can escape (no energy flux conservation!)



Conservation laws

Conservation laws

Mass conservation: $\rho_0 v_0 = \rho_1 v_1 = \rho_2 v_2$

Compression $\chi_1 \equiv \frac{\rho_1}{\rho_0}, \chi_2 \equiv \frac{\rho_2}{\rho_1}, \chi_{12} \equiv \chi_1 \chi_2 = \frac{\rho_2}{\rho_0}$

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(pressure equilibrium)
$$P_0 + \rho_0 V_s^2 = P_1 + \rho_1 v_1^2 = P_2 + \rho_2 v_2^2$$

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$$\epsilon_{esc} \equiv \frac{F_{cr}}{\frac{1}{2}\rho_0 V_s^3}$$

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Shocks with cosmic rays

- Expression for cosmic ray pressure fraction:

$$w \equiv \frac{P_{2,cr}}{P_{2,th} + P_{2,cr}}$$

- Pressure equilibrium between 0 and 2

$$\frac{P_2}{\rho_0 V_s^2} = \frac{P_{2,cr} + P_{2,th}}{\rho_0 V_s^2} = \frac{1}{\gamma_g M_0^2} + \left(1 - \frac{1}{\chi_{12}}\right)$$

- Pressure equilibrium between 1 and 2 and continuity of CR pressure

$$\frac{P_{2,th}}{\rho_1 v_1^2} = (1-w)\frac{P_2}{\rho_1 v_1^2} = \frac{\chi_1^{\gamma_g+1}}{\gamma_g M_0^2} + \left(1 - \frac{1}{\chi_2}\right)$$

- Relation between post-shock CR pressure and compressions

$$w = \frac{(1-\chi_1^{\gamma_g}) + \gamma_g M_0^2\left(1 - \frac{1}{\chi_1}\right)}{1 + \gamma_g M_0^2\left(1 - \frac{1}{\chi_{12}}\right)} \approx \frac{1 - \frac{1}{\chi_1}}{1 - \frac{1}{\chi_{12}}}$$

Shocks with cosmic rays II

- Relations take χ_1 as primary variable, from which one creates a set of solutions
- For example: $$\chi_{12} = \frac{(\gamma_g+1)M_1^2\chi_1}{(\gamma_g-1)M_1^2+2} = \frac{(\gamma_g+1)M_0^2\chi_1^{-\gamma_g}}{(\gamma_g-1)M_0^2\chi_1^{-(\gamma_g+1)}+2}$$
- Escape $$\epsilon_{esc} = 1 + \frac{2G_0}{\gamma_g M_0^2} - \frac{2G_2}{\gamma_g M_0^2 \chi_{12}} - \frac{2G_2}{\chi_{12}}\Big(1 - \frac{1}{\chi_{12}}\Big) - \frac{1}{\chi_{12}^2}$$

$$G_2 \equiv w\frac{\gamma_{cr}}{\gamma_{cr}-1} + (1-w)\frac{\gamma_g}{\gamma_g-1}$$

- Interesting: standard shocks have $\chi_{12}=\chi_2=4$, for CR dominated shocks $\chi_{12}>4$, and $\chi_2\leq 4$
- Reason: CR dominated shocks have a low Mach number main shock!

Shocks with cosmic rays II

- Relations take X1 as primary variable, from which one creates a set of solutions
- For example:

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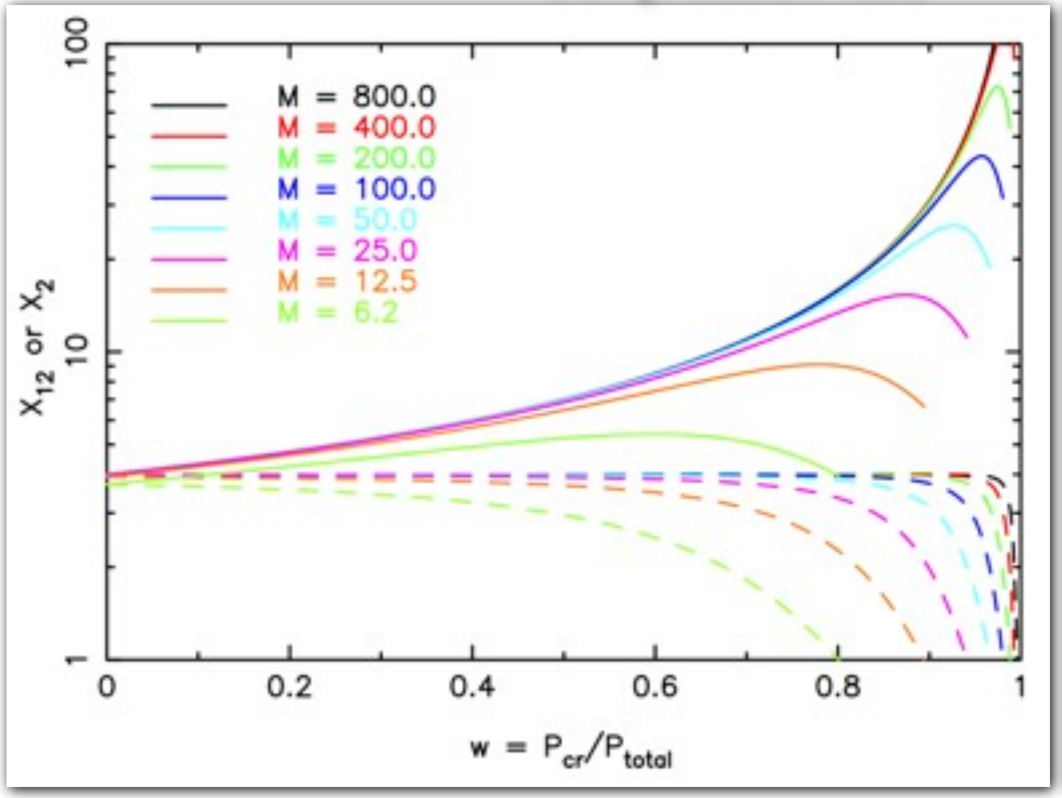
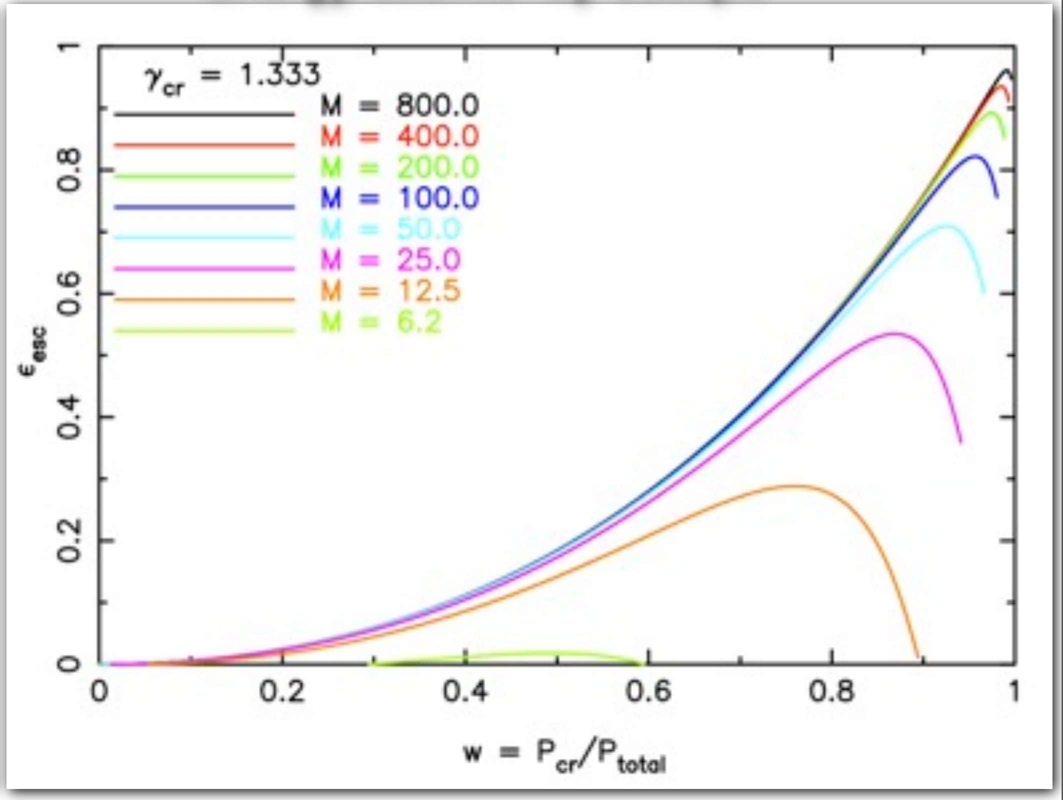
Together all these relations determine the compression ratios and downstream temperature (thermal pressure) as a function of fractional downstream cosmic ray pressure w!

Shock heating and compression

Compression ratio



Energy/cosmic ray escape



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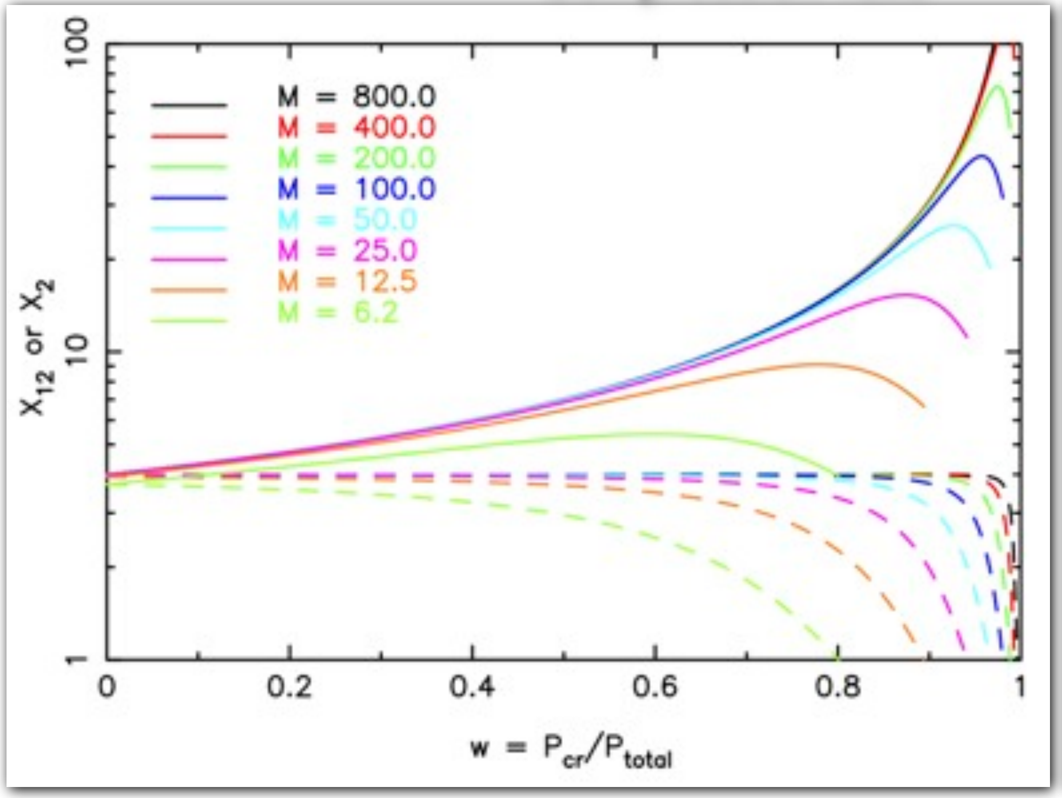

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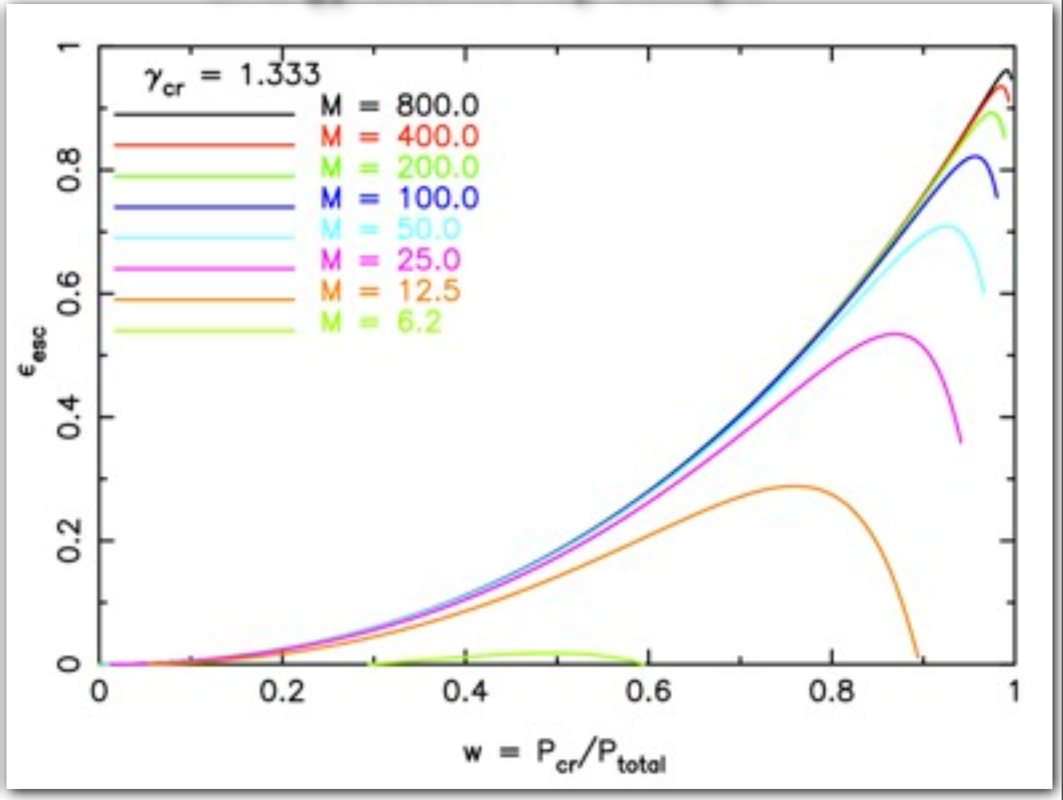

Escape is the price a shock has to pay for high cosmic ray pressures!

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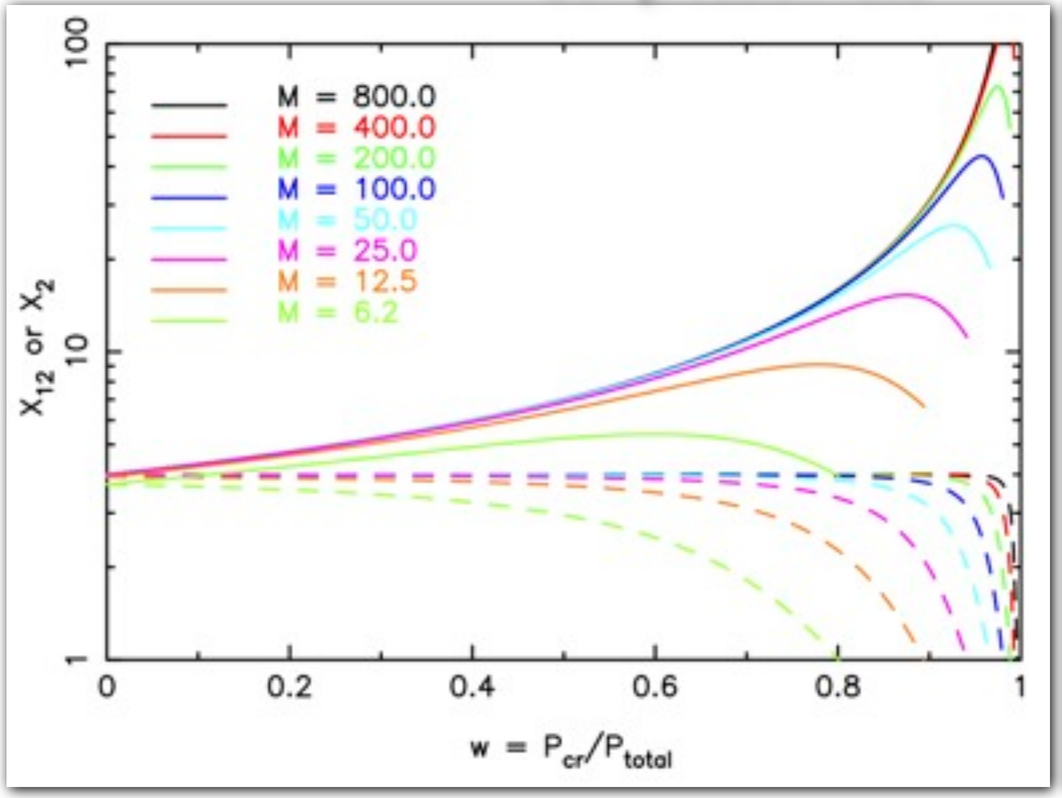

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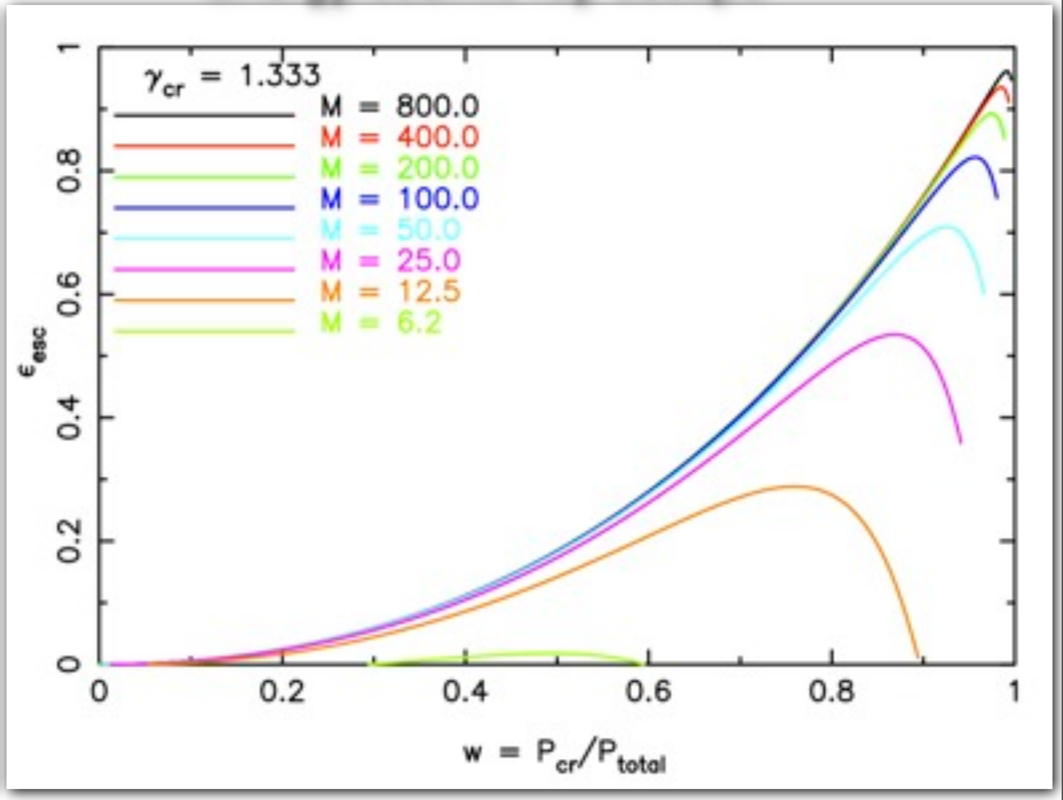


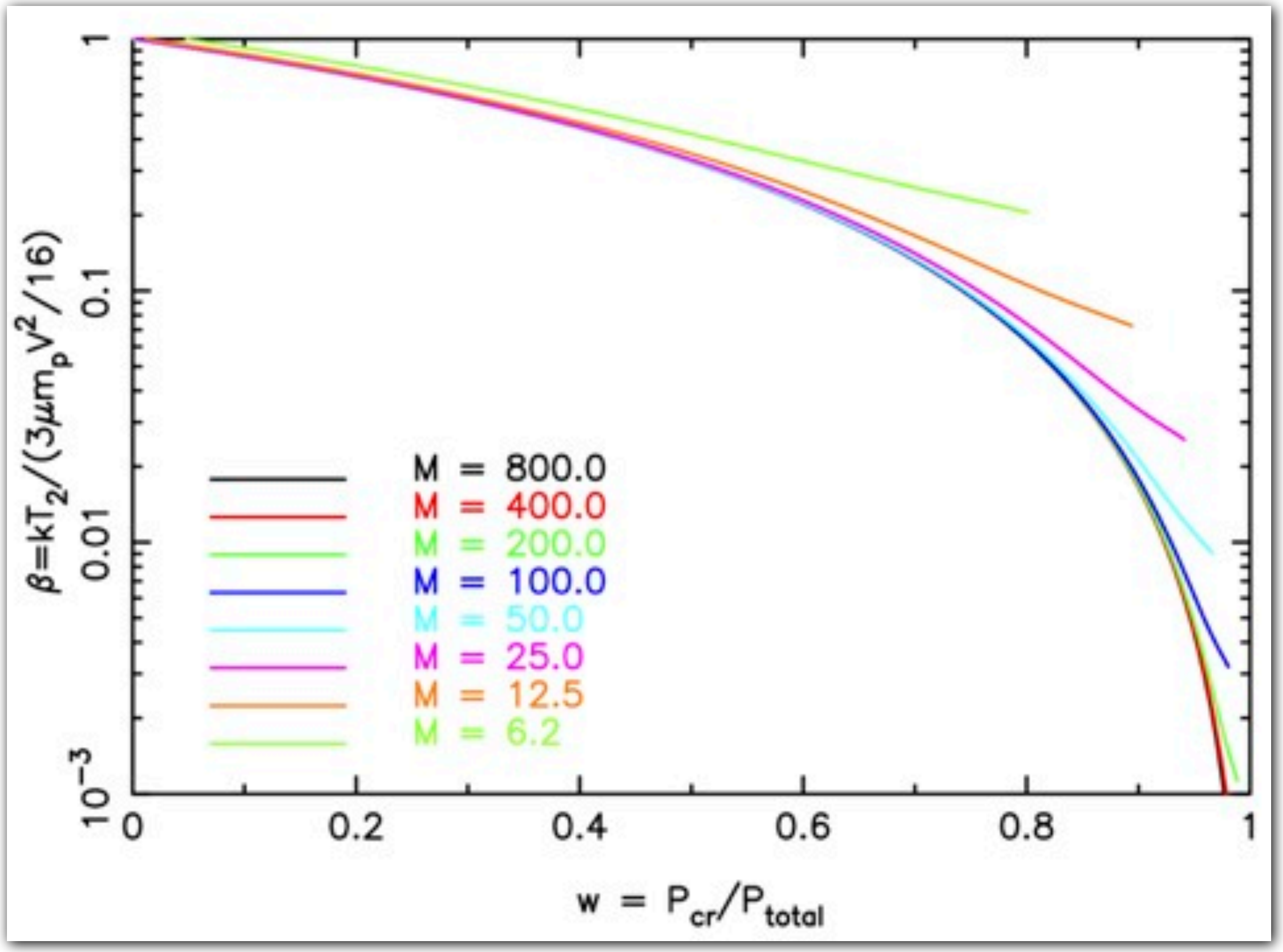
Escape is the price a shock has to pay for high cosmic ray pressures!

NB: low Mach number shocks cannot efficiently accelerate
Is important for intracluster shocks!

Temperatures

correction w.r.t. standard Hugoniot result

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



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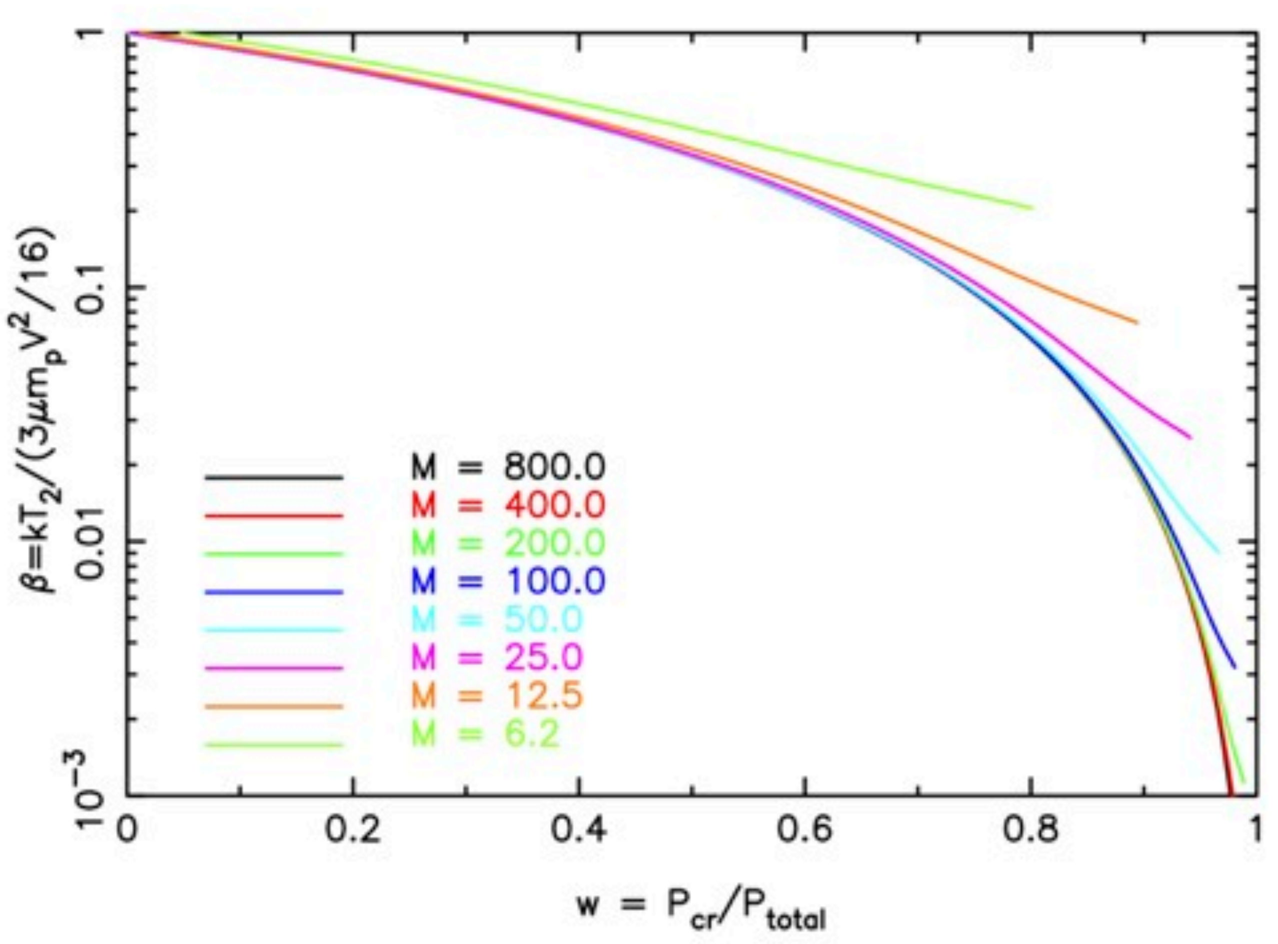
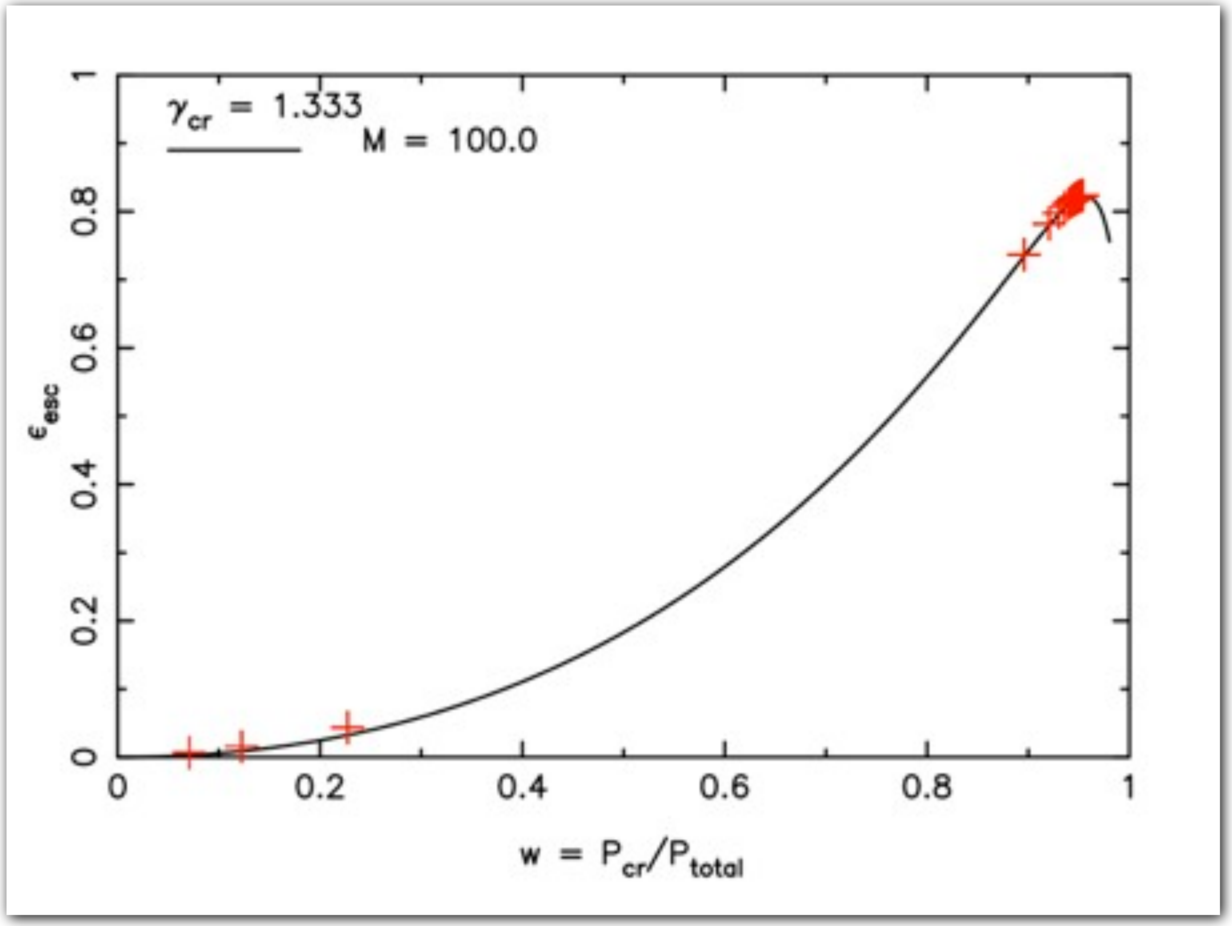


As to be expected: post-shock temperatures can be dramatically lower for cosmic ray dominated shocks!

Physics: main shock becomes low Mach number shock

Comparison with kinetic models

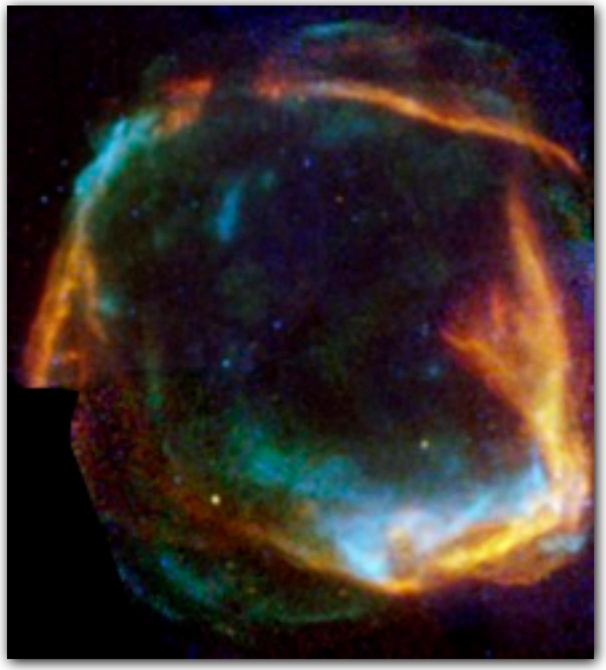


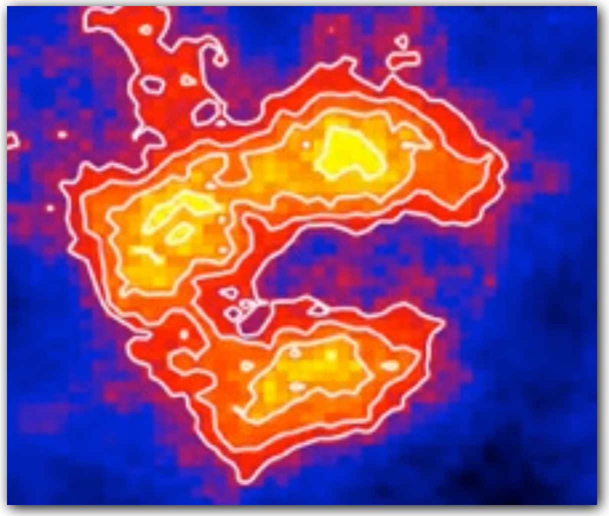
- Solid line: analytical, thermodynamic calculations using γ=4/3
- Crosses: semi-analytical kinetic model by Blasi et al. 2005
- Difference: thermodynamically more solutions are allowed

Break!!

VI
Non-thermal X-ray emission from SNRs

Advances over last 15 year





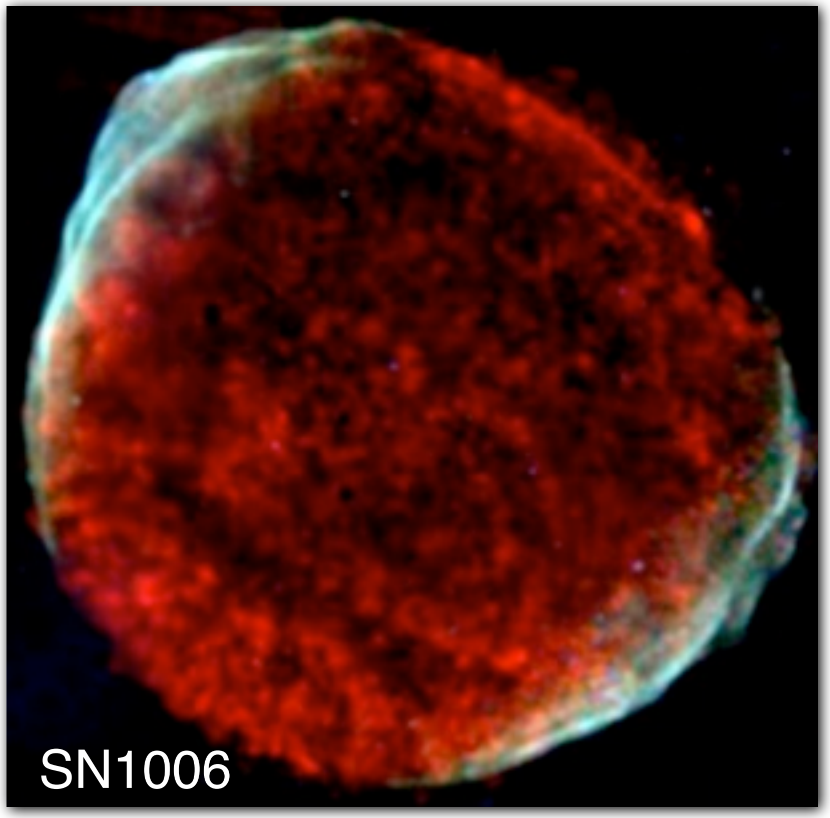
X-ray imaging/spectroscopy
(Chandra/XMM/Suzaku)

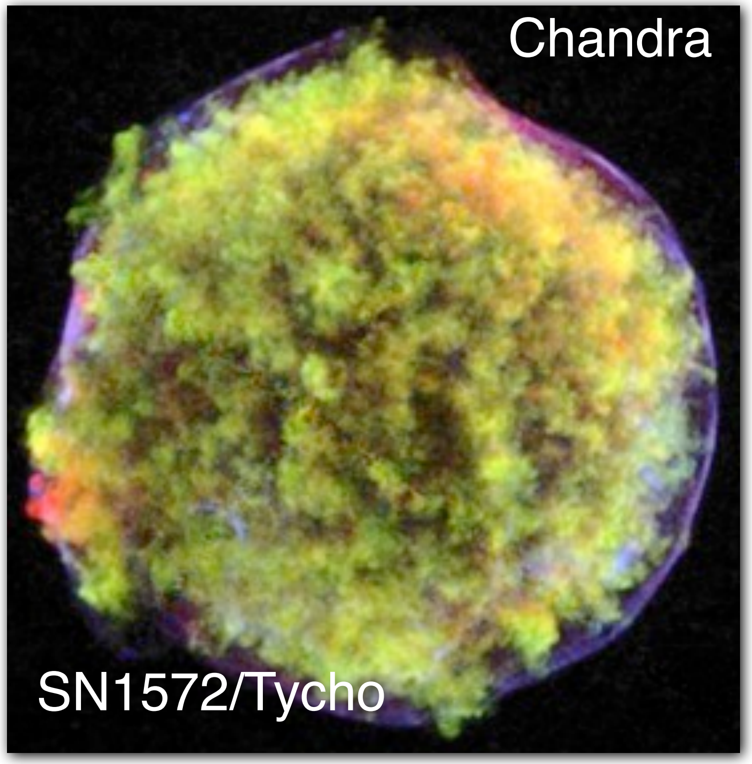
GeV/TeV γ-ray astronomy
(HESS, MAGIC, VERITAS, Fermi)

8 m class optical
telescopes

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

X-ray synchrotron emission





- In 1995 it was established that the X-ray emission from SN 1006 was a combination of thermal X-ray and synchrotron radiation (Koyama et al. 1995)
- X-ray synchrotron emission implies presence of 10-100 TeV electrons!!

$$h\nu_{\rm ch} = 13.9\left(\frac{B_\perp}{100\,\mu{\rm G}}\right)\left(\frac{E}{100\,{\rm TeV}}\right)^2\ {\rm keV}$$

Los limited versus age limited

- The maximum photon energy (or exponential break) is determined either by
  1) how much time was there to accelerate electrons?: *age limited*
  2) at what energies do acceleration gains=radiation losses?: *loss limited*
- Most young SNRs seem to have loss limited spectra (but discussion ongoing)
- For loss limited case: characteristic cut-off frequency independent of B!!

Further reading: Reynolds 1998, Aharonian& Atoyan 1999, Zirakashvili & Aharonian 2007

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- Taking account of all constants etc.:

$$h\nu_{\rm max} = 1.4\eta^{-1}\Big(\frac{\chi_4 - \frac{1}{4}}{\chi_4^2}\Big)\Big(\frac{V_s}{5000\ {\rm km\,s^{-1}}}\Big)^2\ {\rm keV}$$

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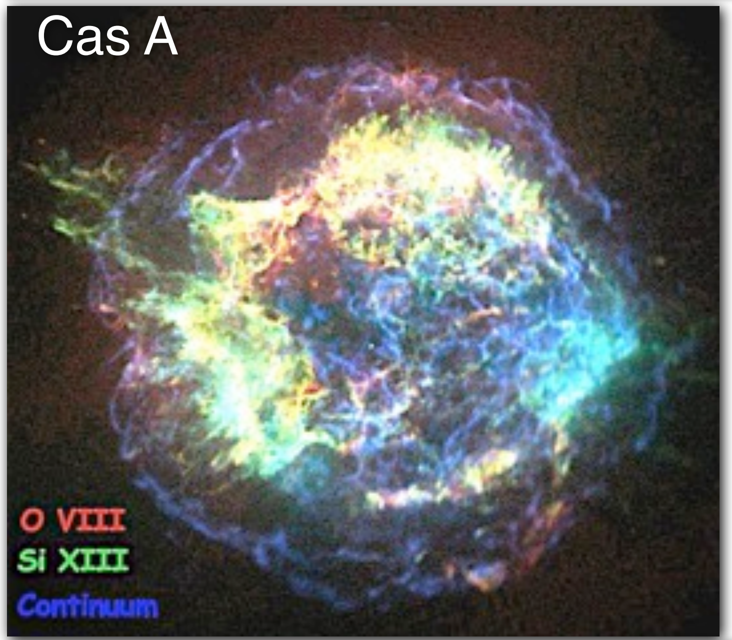
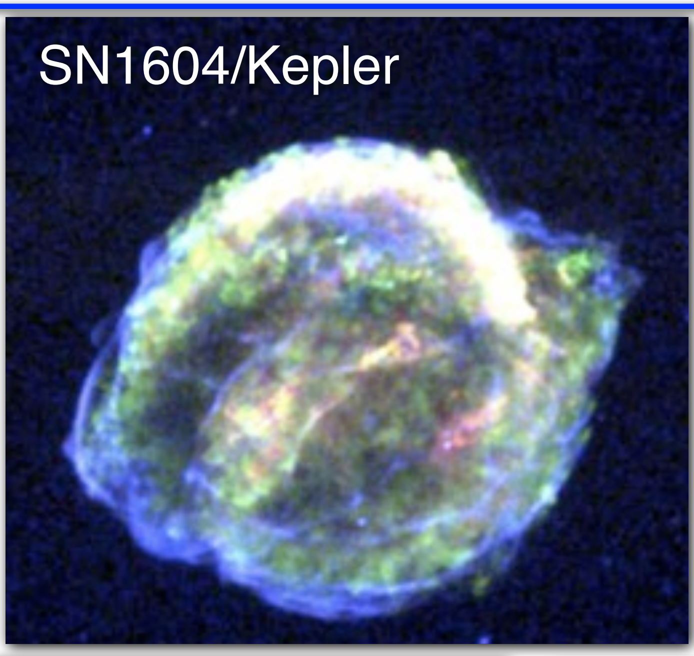
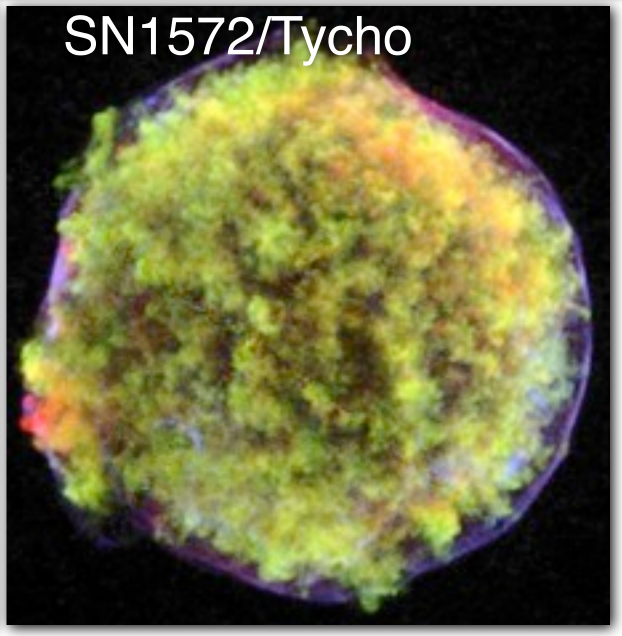
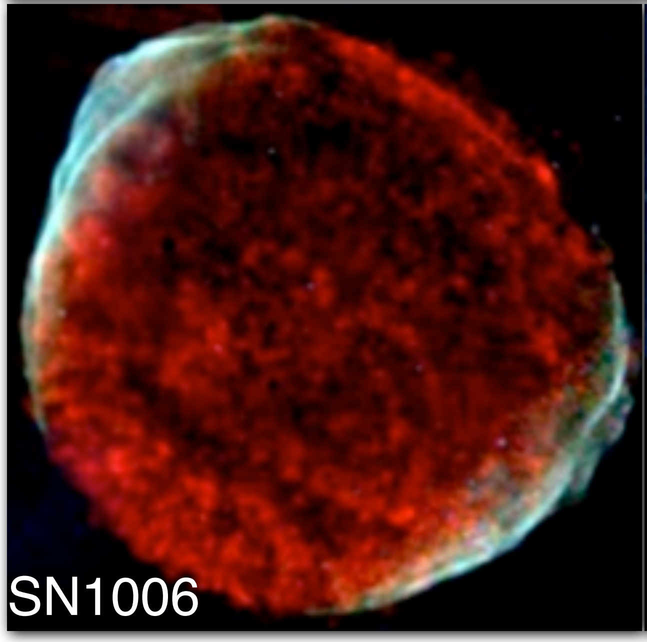
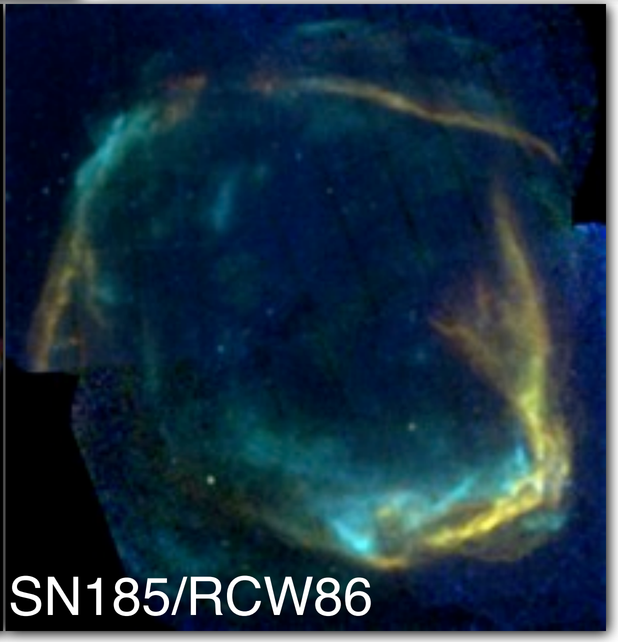
X-ray synchrotron from young SNRs

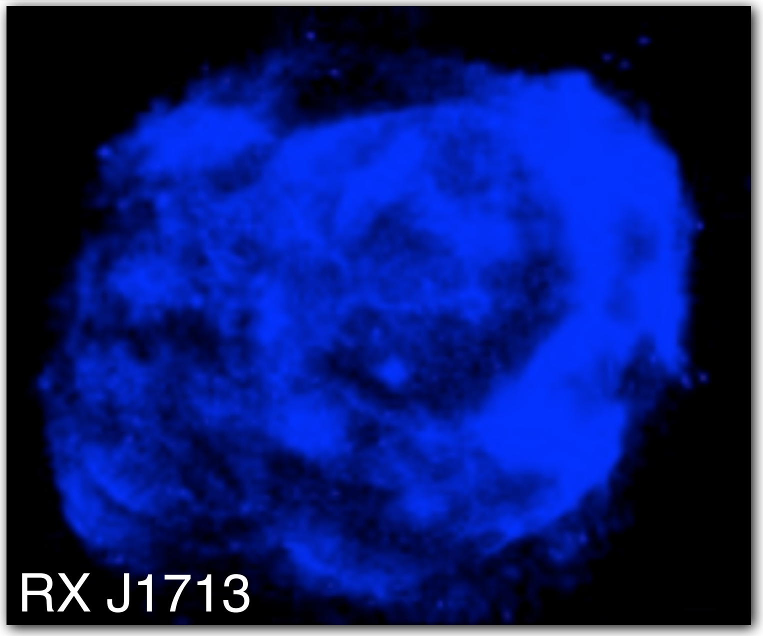

Cas A


SN1604/Kepler


SN1572/Tycho


SN1006


SN185/RCW86


RX J1713

Implications

- Synchrotron emissivity profile broad: gradual steepening beyond break
- Fact that young SNRs are synchrotron emitters: acceleration must proceed close to Bohm-diffusion limit!

$$\eta \lesssim 20$$

- The higher the B-field -> faster acceleration, but $E_{\rm max}$ lower!
- For B=10-100 μG: presence of 10^{13}-10^{14} eV electrons
- Loss times are:

$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2} {\rm yr.}$$

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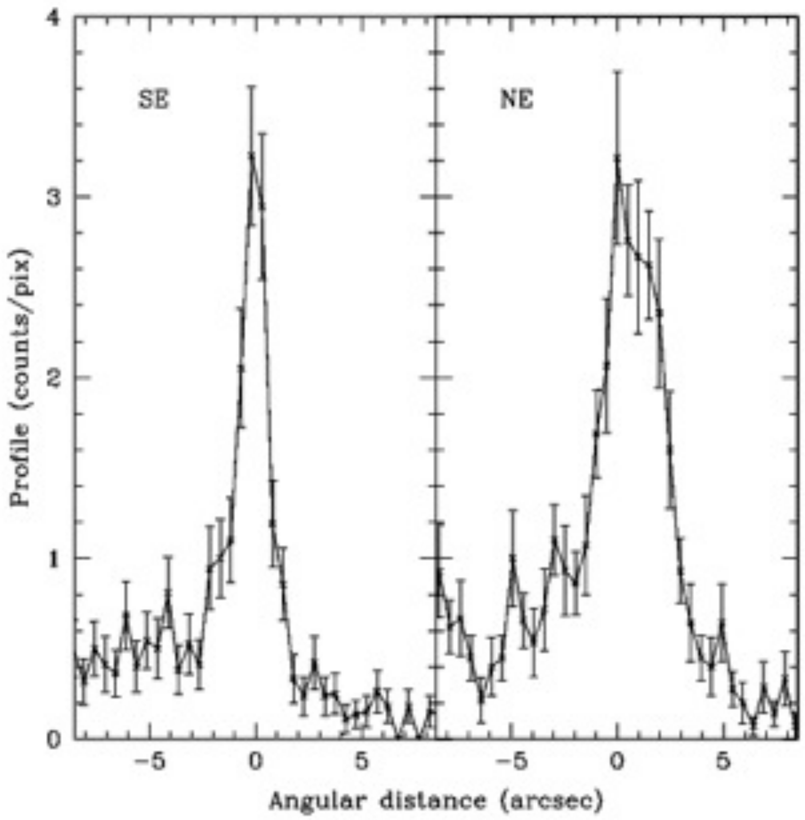
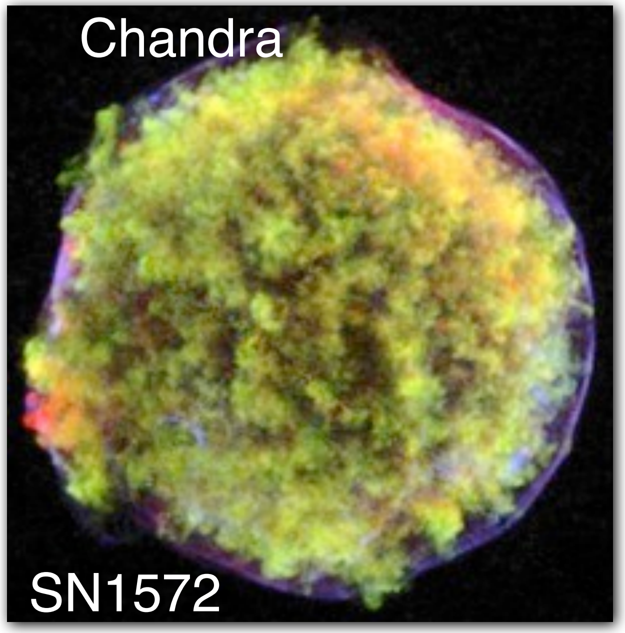
X-ray synchrotron emission tells us that

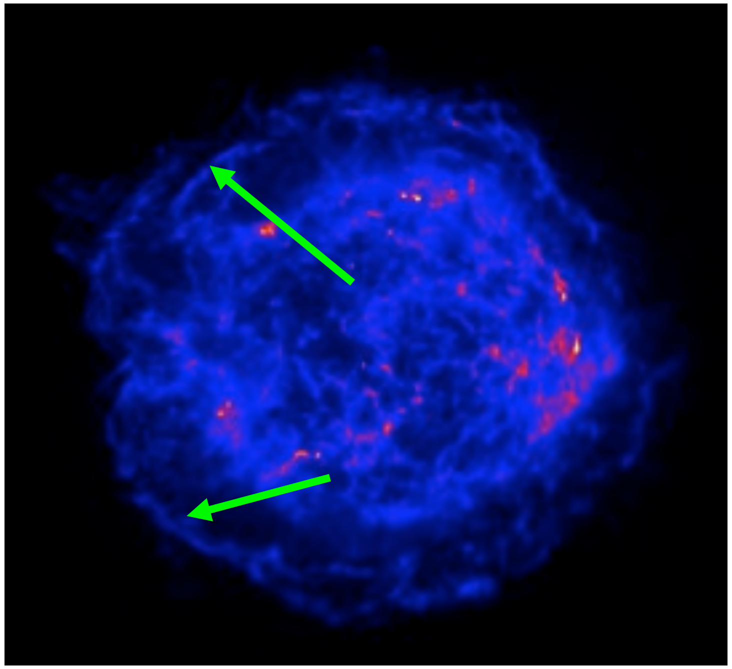
- electrons can be accelerated fast
- that acceleration is still ongoing (loss times ~years)
- that particles can be accelerated at least up to 10^{14} eV

Narrow X-ray synchrotron filaments

- In many cases X-ray synchrotron filaments appear very narrow (1-4”)
- Including deprojections impliess l≈10^{17}cm







Explanation narrow synchrotron rims

- Two explanations possible:
  - length scale associated with synchrotron loss time & advections:

$$l_{\rm adv} = \tau_{\rm syn}\Delta v = \tau_{\rm syn}\frac{V_s}{\chi}$$

  - length scale corresponds to diffusion length scale of 10-100 TeV electrons:

$$l_{\rm diff} = \frac{2D}{\Delta v} = \frac{2Ec\chi}{3eBV_s}$$

- Turns out the two are more or less equivalent

$$\tau_{\rm acc} = \frac{2D}{\Delta v^2} = \frac{l_{\rm diff}}{\Delta v} \qquad \tau_{\rm syn} = \frac{l_{\rm adv}}{\Delta v}$$

- So near break frequency: $\tau_{\rm syn} = \tau_{\rm acc} \Leftrightarrow l_{\rm adv} = l_{\rm adv}$
- So we can use either system provided we are near the break
- In reality the width is combination from advection and diffusion: broadening

Interpreting narrow X-ray rims

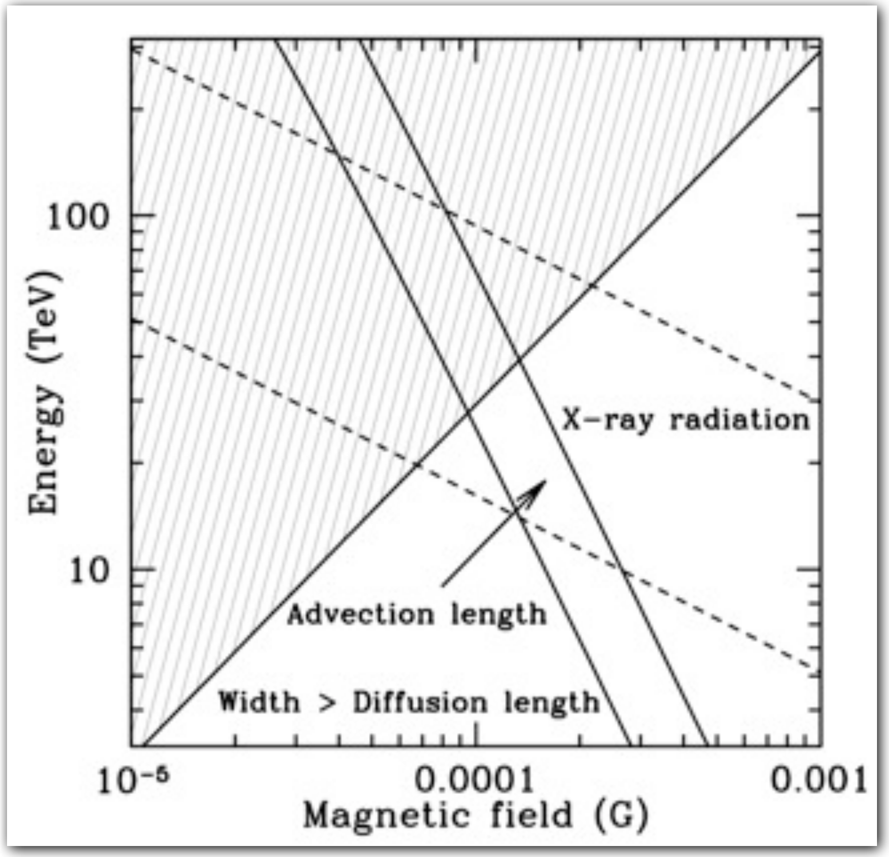
- Synchrotron loss time depends on B and E ($1/B^2E$)
- Emitted frequency depends on E^2B
- Two can be combined to determine magnetic field:

$$B_2 \approx \left(\frac{c}{3e}\right)^{1/3} l_{adv}^{-2/3} = 24\left(\frac{l_{\rm adv}}{1.0\times 10^{18}{\rm cm}}\right)^{-2/3} \mu{\rm G}$$

- Cas A/Tycho/Kepler: ~100-500 µG

  (e.g. Vink&Laming '03, Voelk et al. 03, Bamba+ '04, Warren+ '05)

- High B-field ⇒fast acceleration



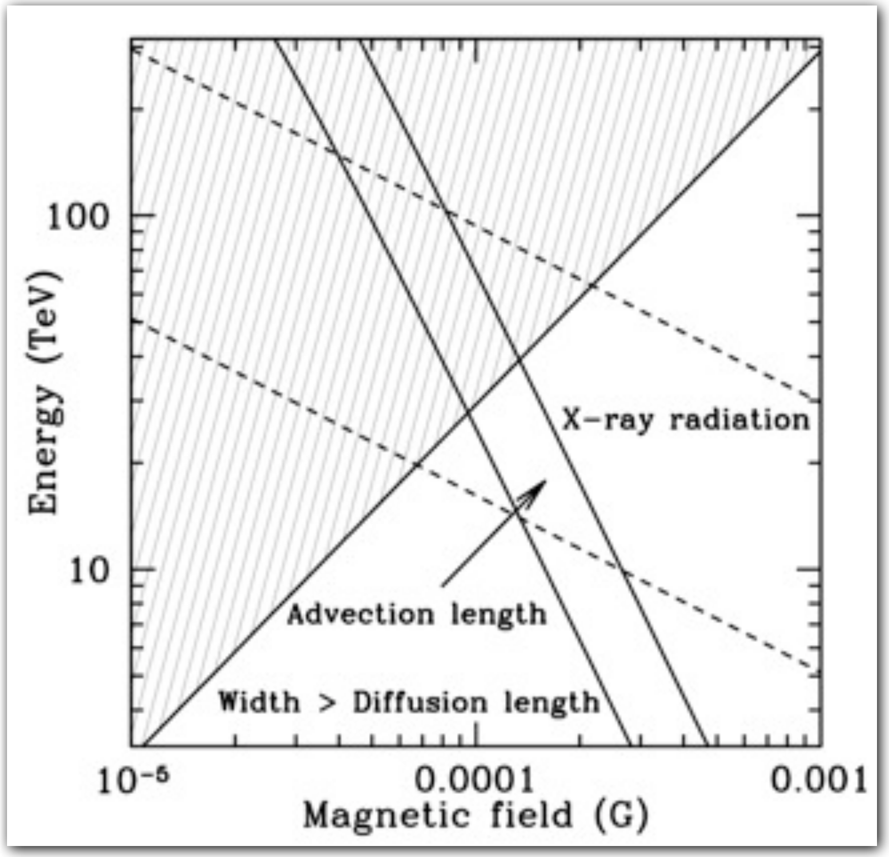
Interpreting narrow X-ray rims

- Synchrotron loss time depends on B and E ($1/B^2E$)
- Emitted frequency depends on E^2B
- Two can be combined to determine magnetic field:

$$B_2 \approx \left(\frac{c}{3e}\right)^{1/3} l_{adv}^{-2/3} = 24\left(\frac{l_{\rm adv}}{1.0\times10^{18}{\rm cm}}\right)^{-2/3} \mu{\rm G}$$

- Cas A/Tycho/Kepler: ~100-500 µG

  (e.g. Vink&Laming ‘03, Voelk et al. 03, Bamba+ ’04, Warren+ ‘05)
- High B-field ⇒fast acceleration

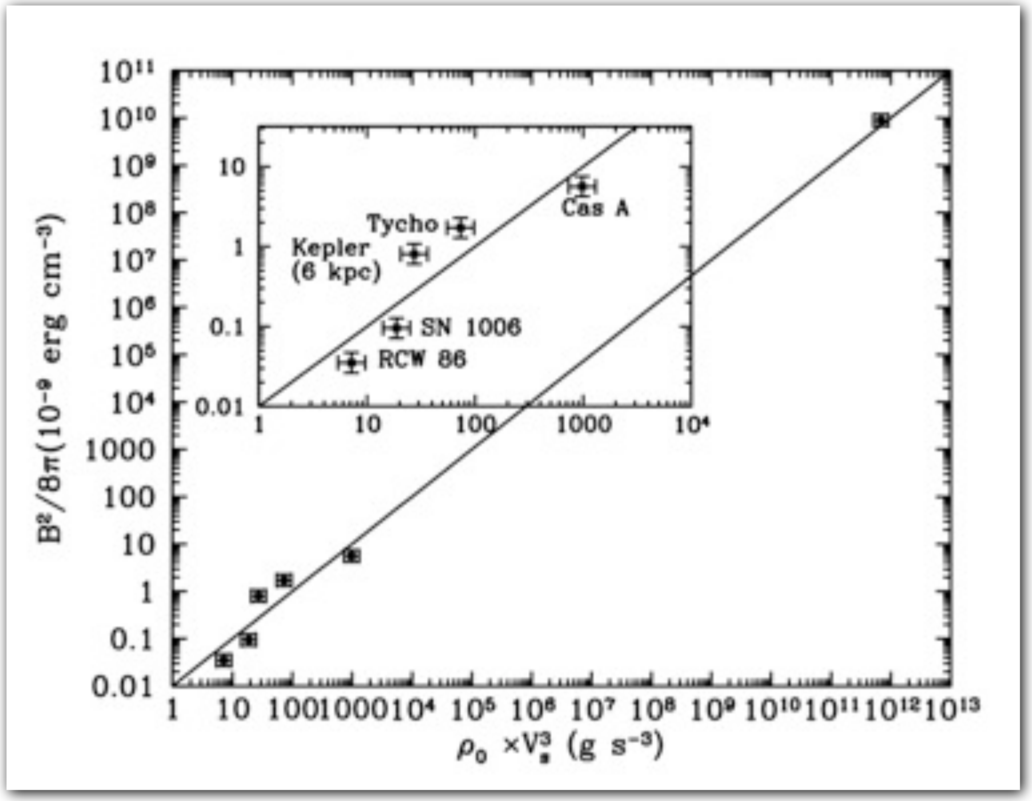


- High B-field likely induced by cosmic rays (e.g. Bell +04)
- High B-fields are a signature of ion cosmic rays

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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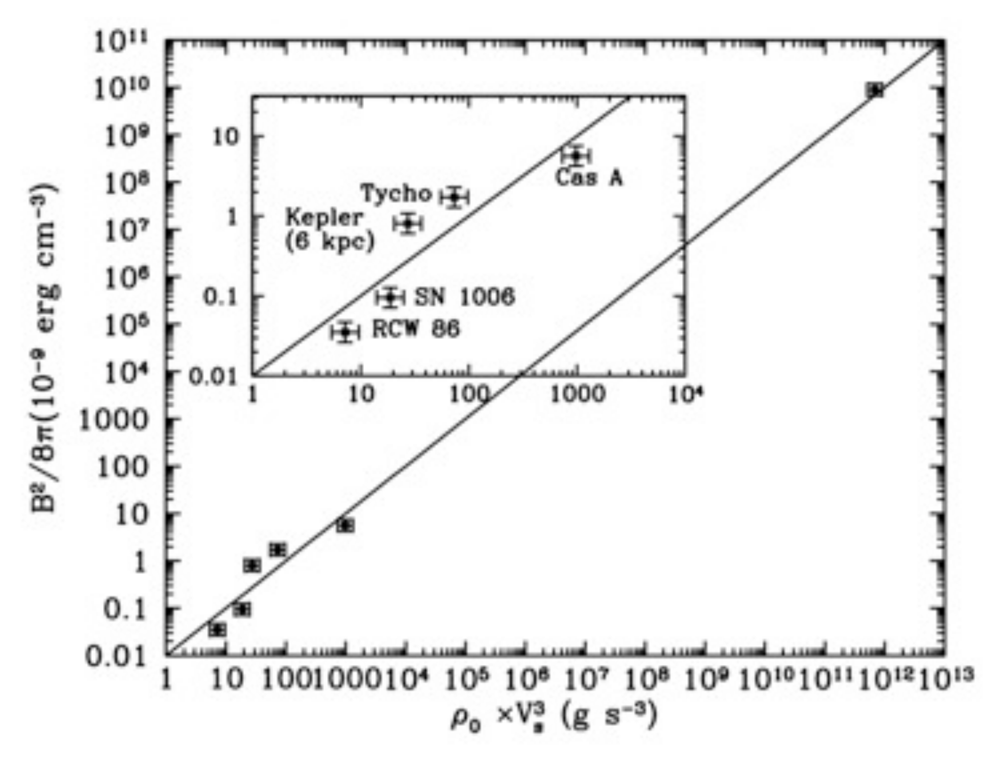

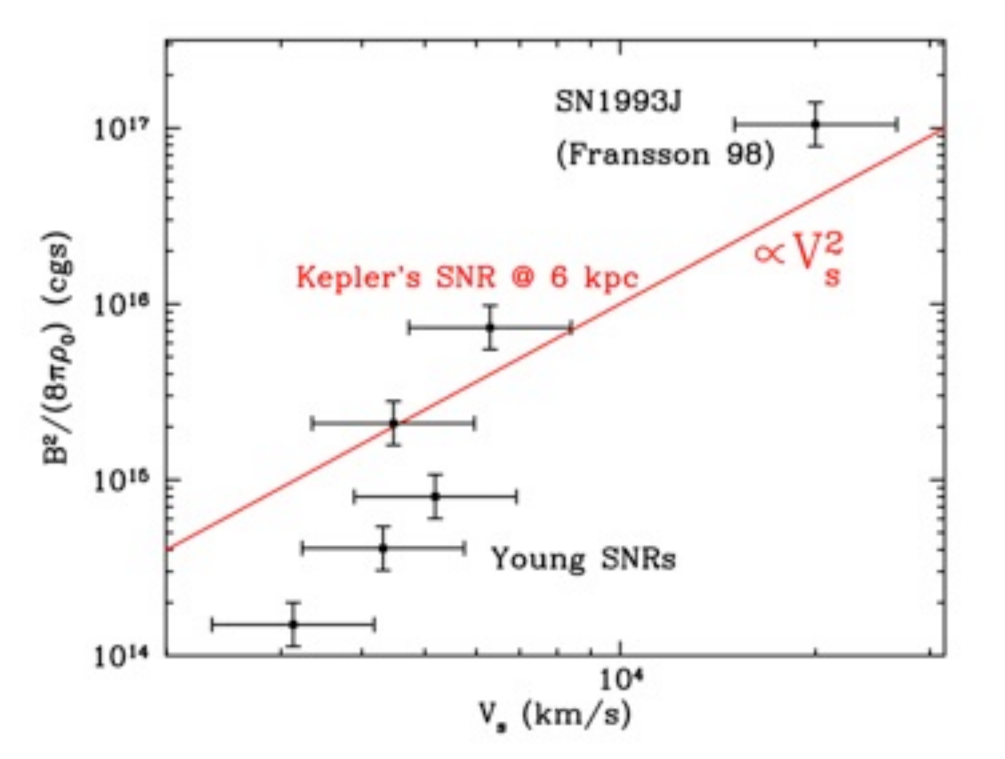

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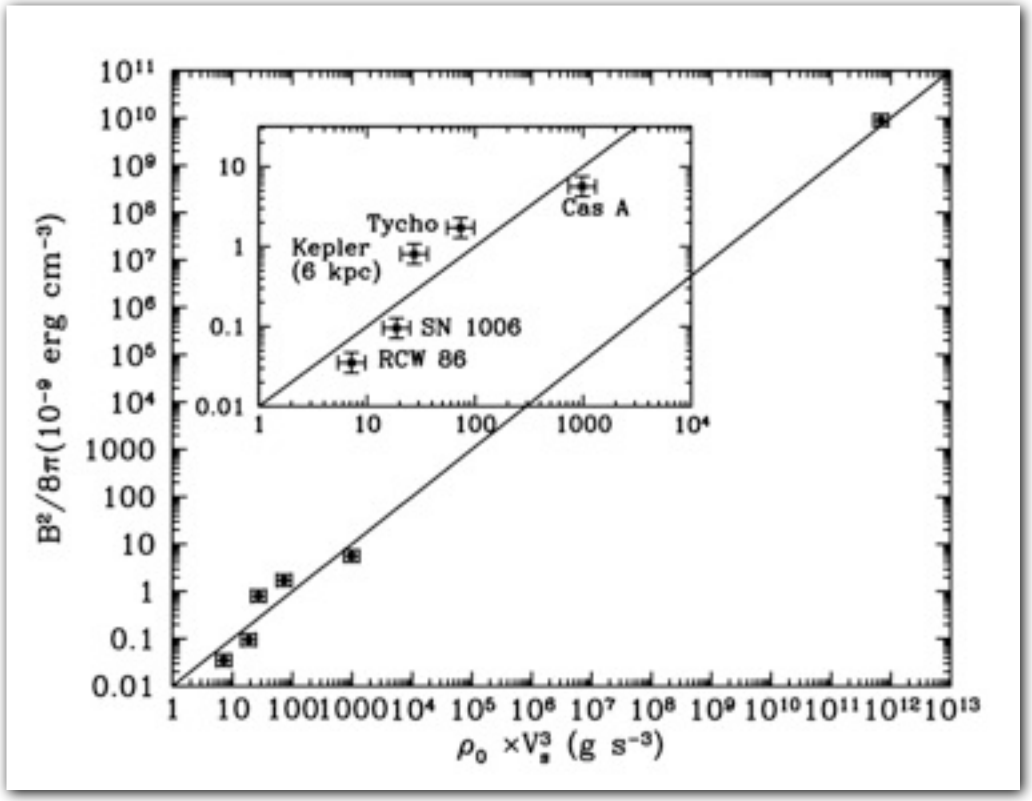

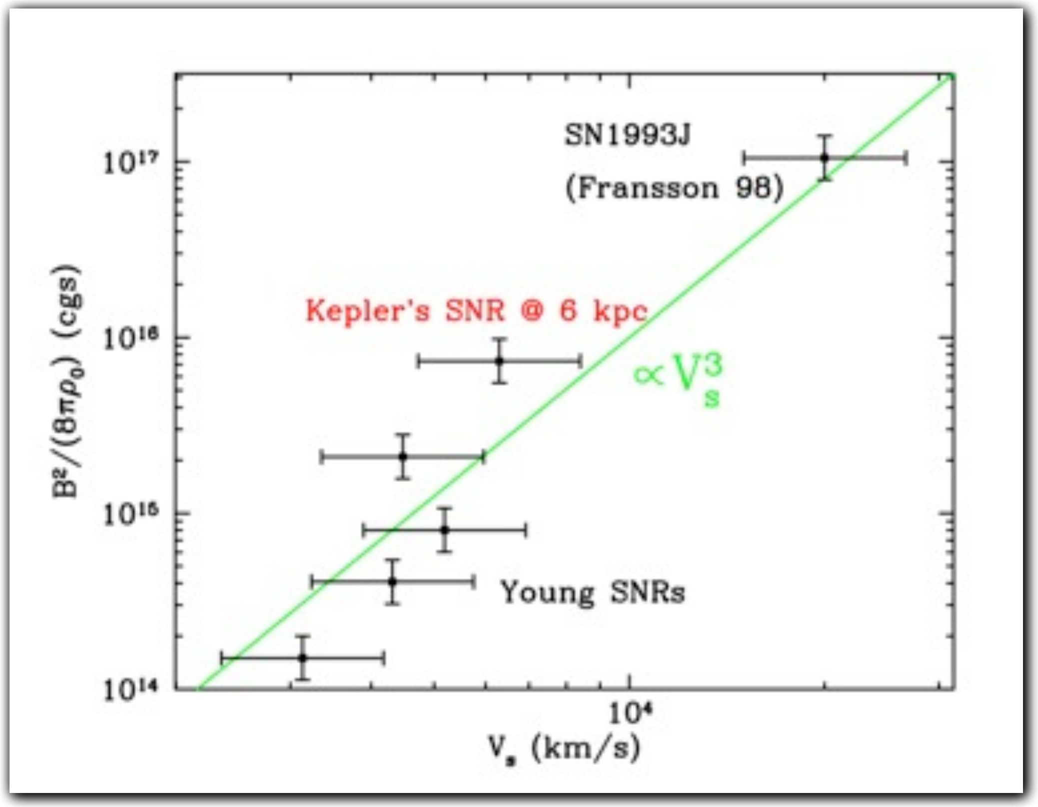

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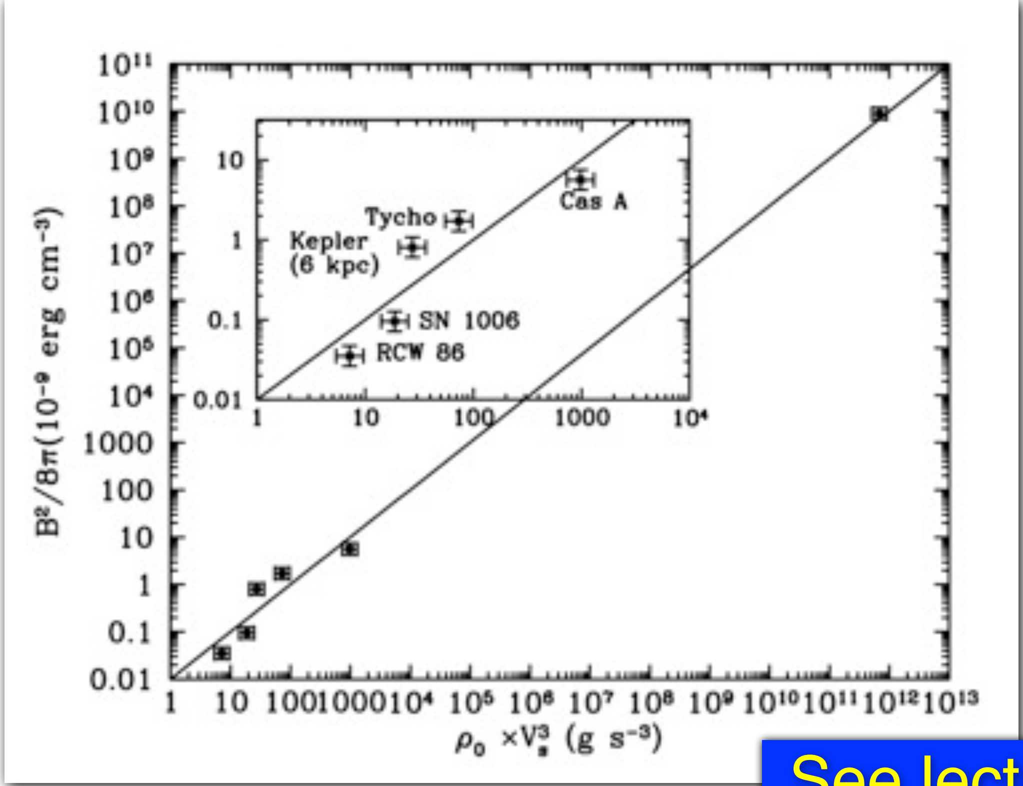
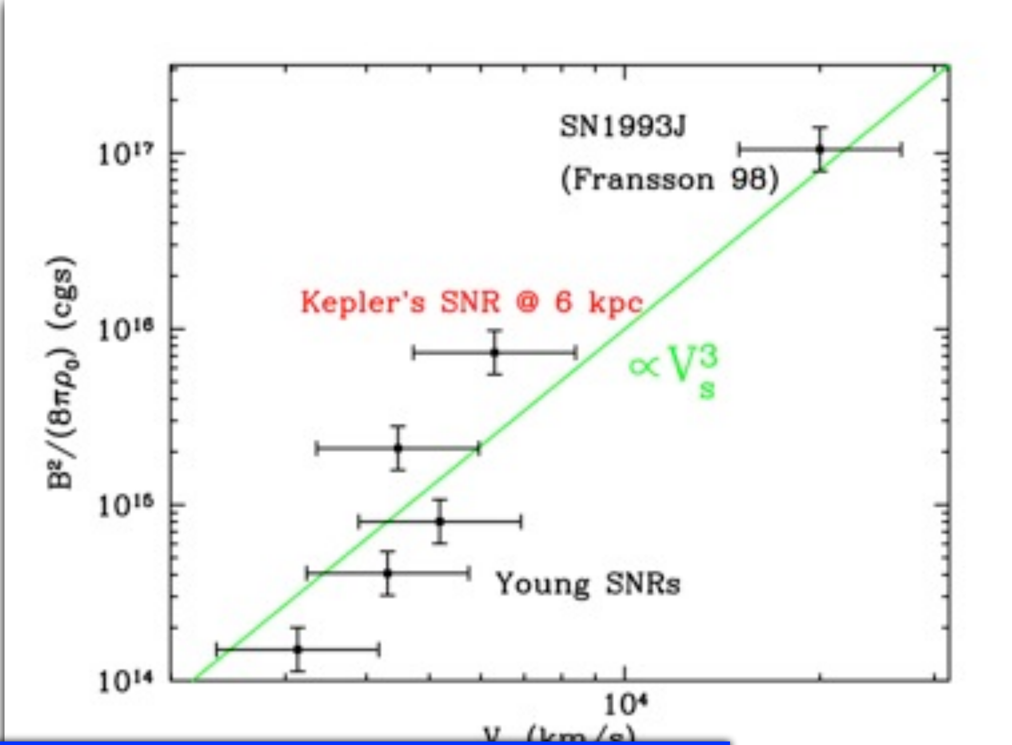
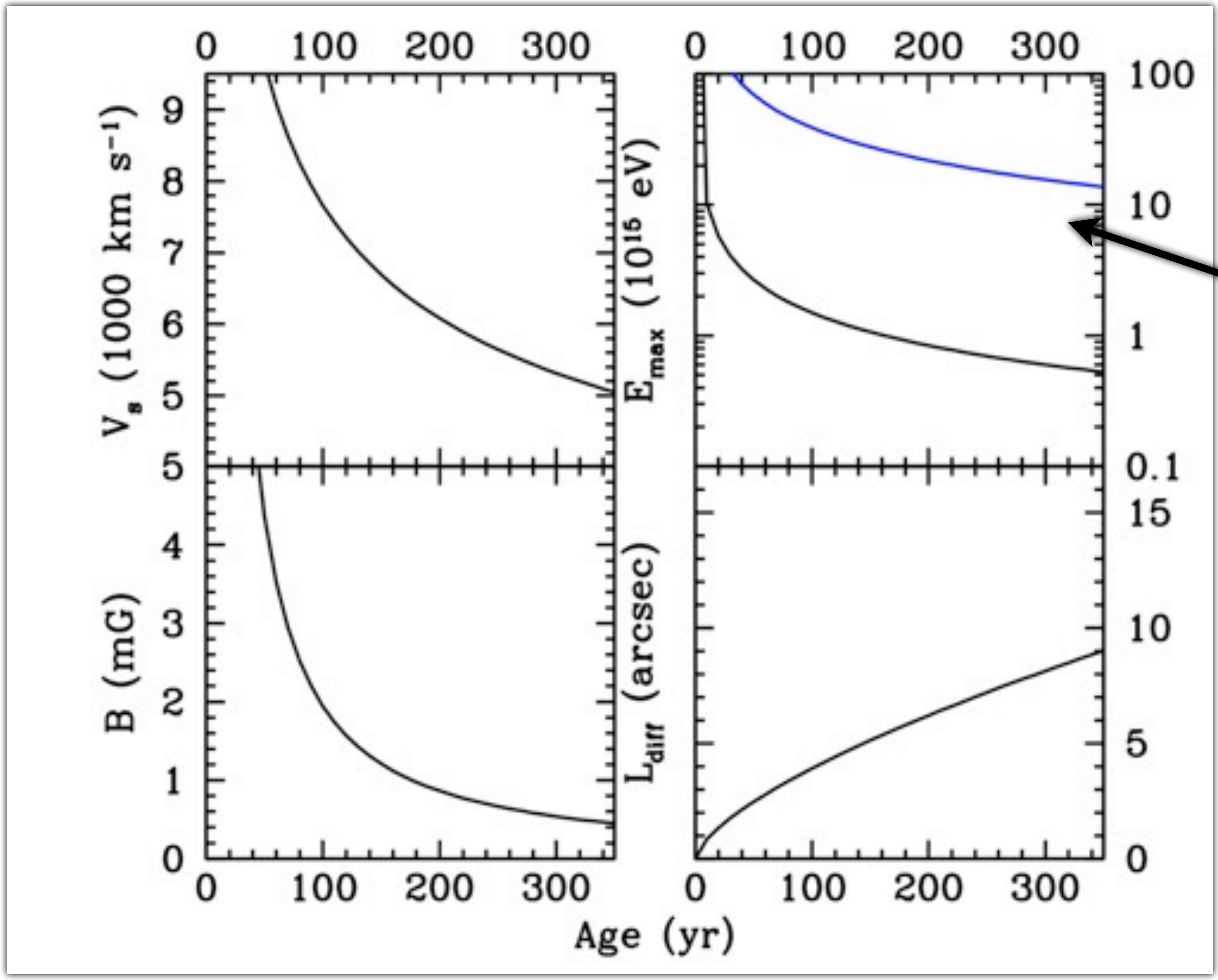




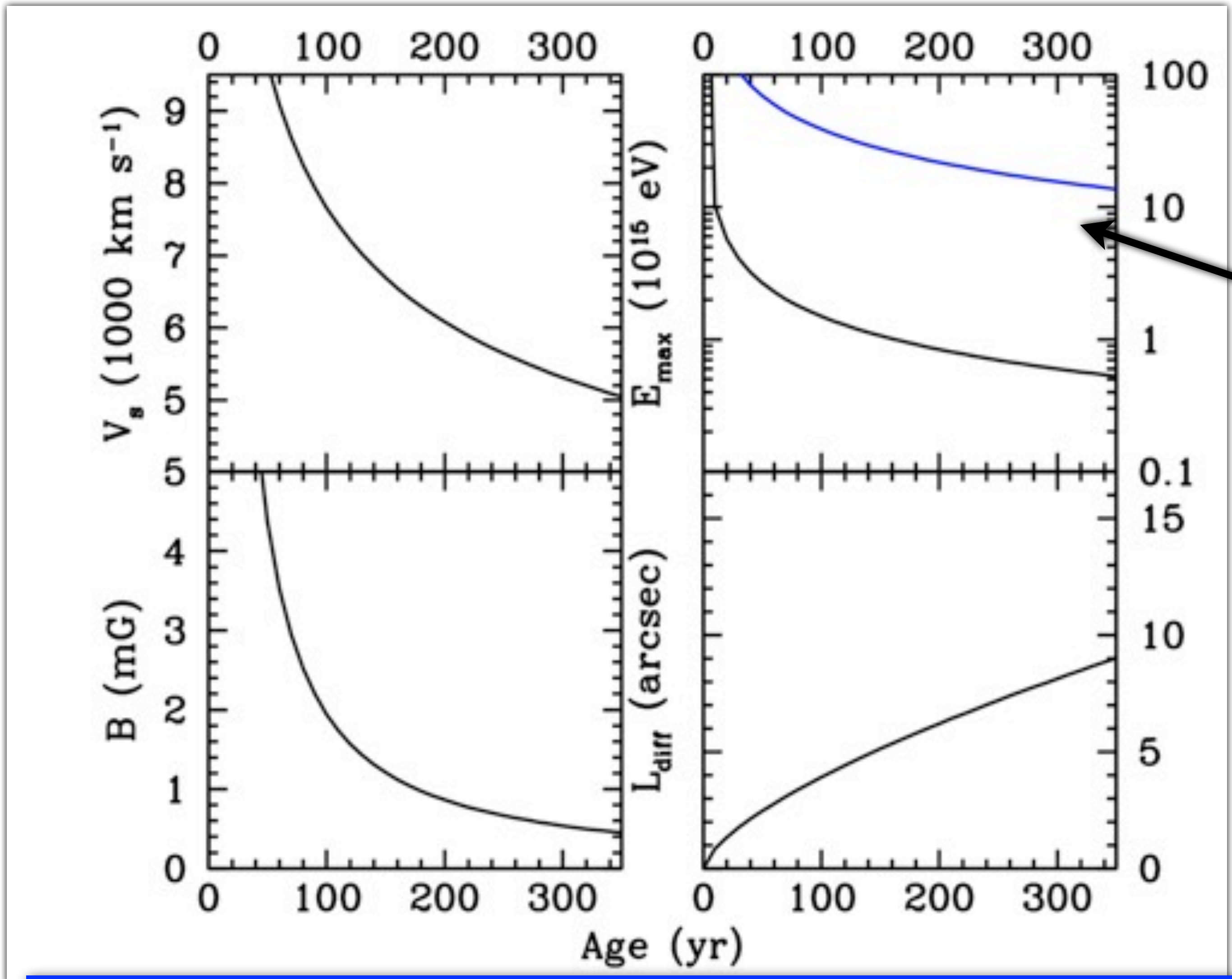
See lecture of Tony Bell for more on magnetic field amplification

A possible history for Cas A



Maximum energy for Fe

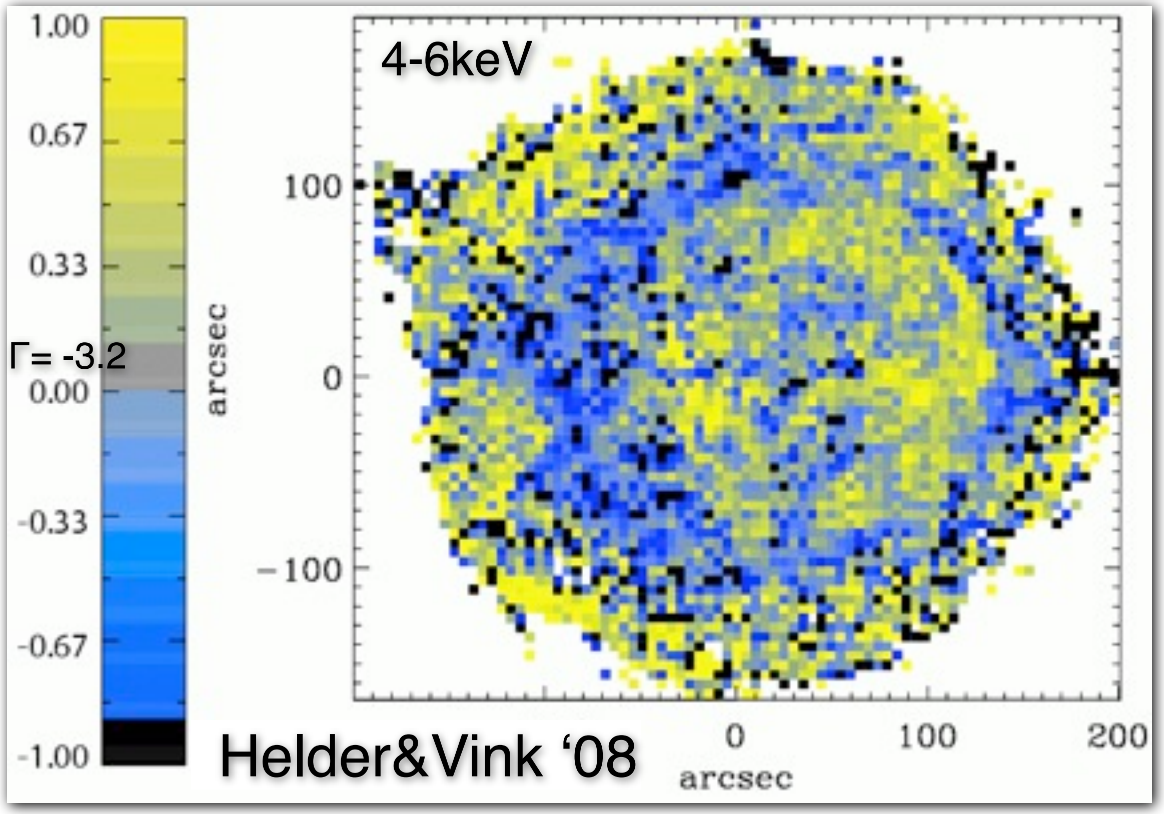
A possible history for Cas A



Maximum energy for Fe

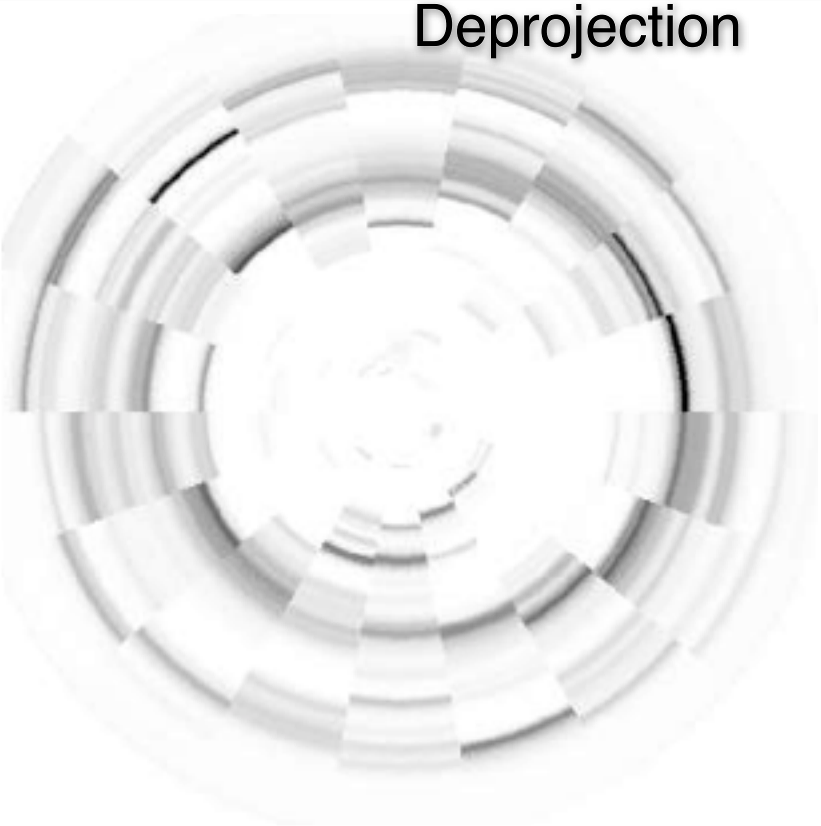
- Acceleration most efficient early on in supernovae in red supergiant winds (Type II/Type IIb) (e.g. Cas A, SN1993J)
- Highest energy CRs may escape first (Ptuskin & Zirakashvili '05)

Acceleration @ Cas A reverse shock



Helder&Vink '08

Deprojection



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- Deprojection: Most X-ray synchrotron from *reverse* shock!
- Prominence of West: No expansion ⇒ ejecta shocked with V>6000km/s

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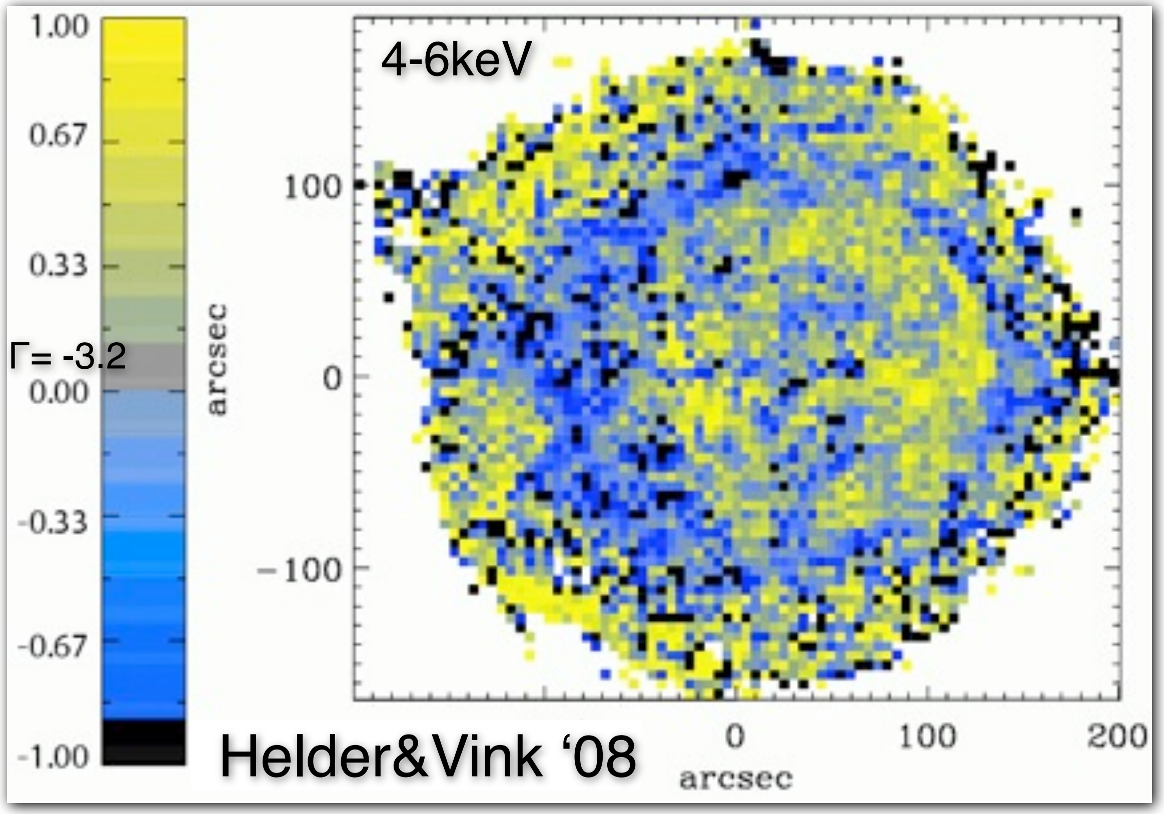

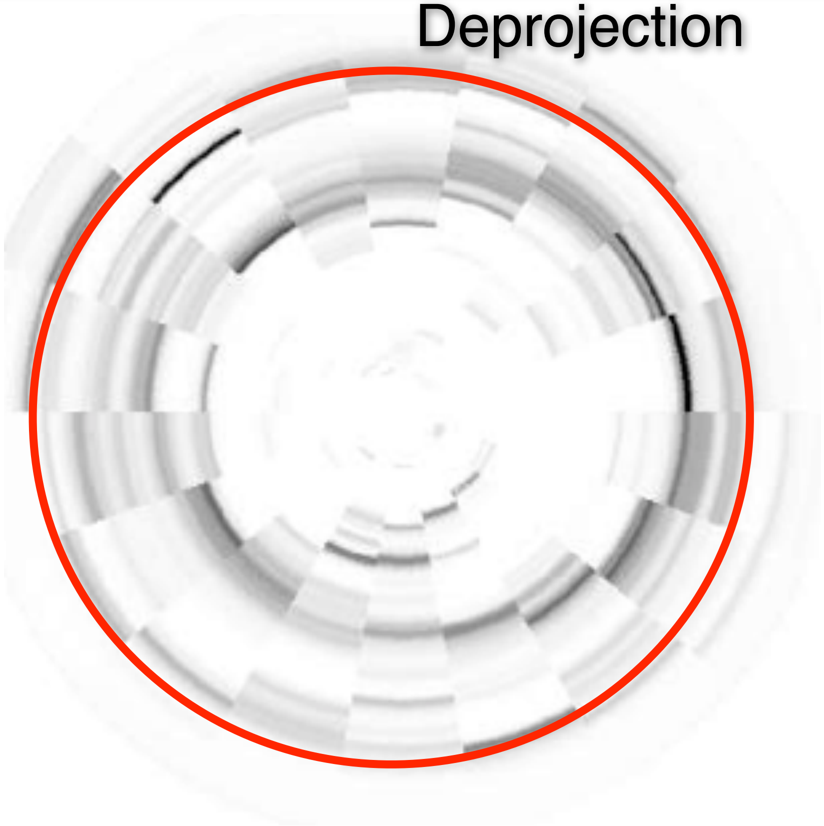

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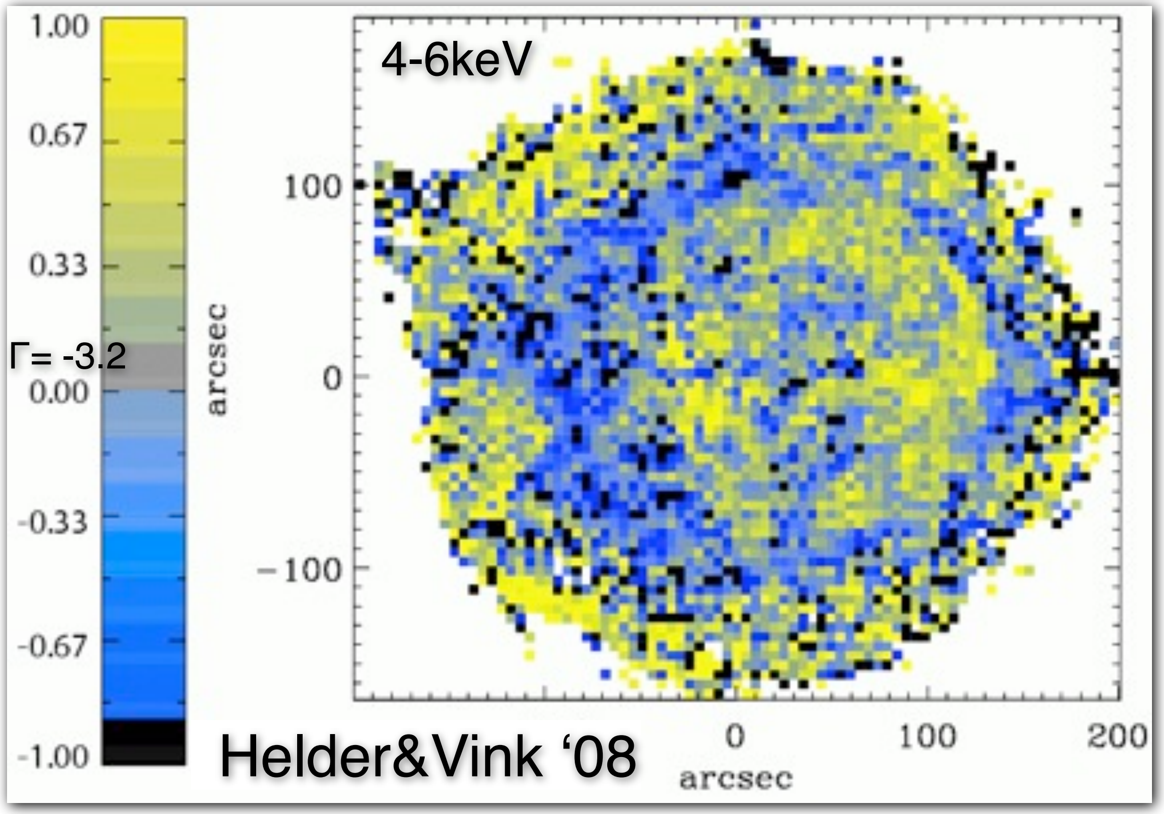

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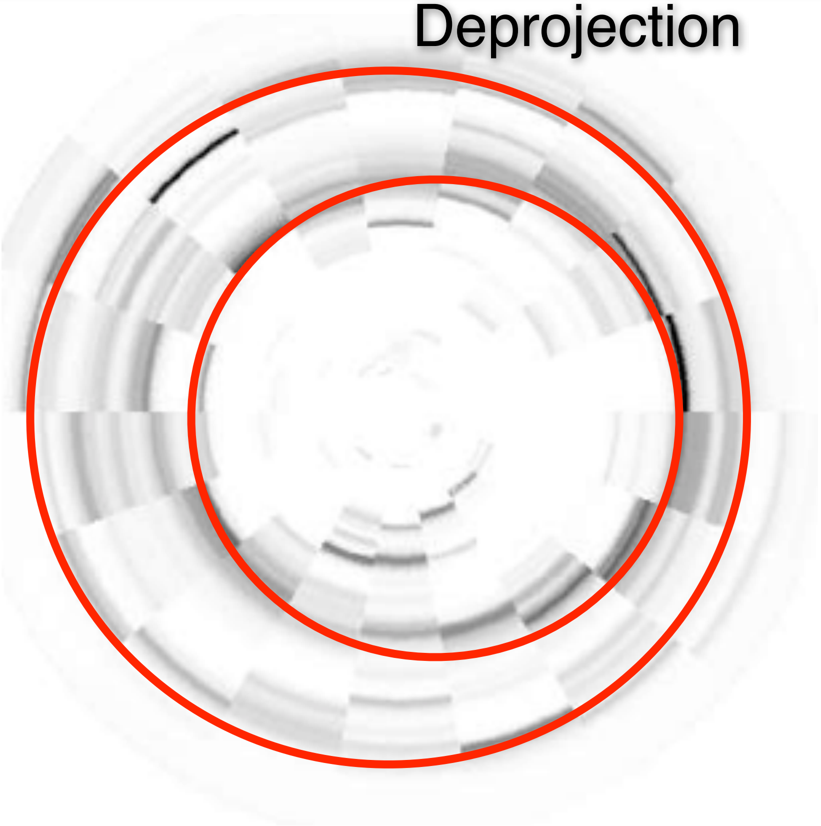

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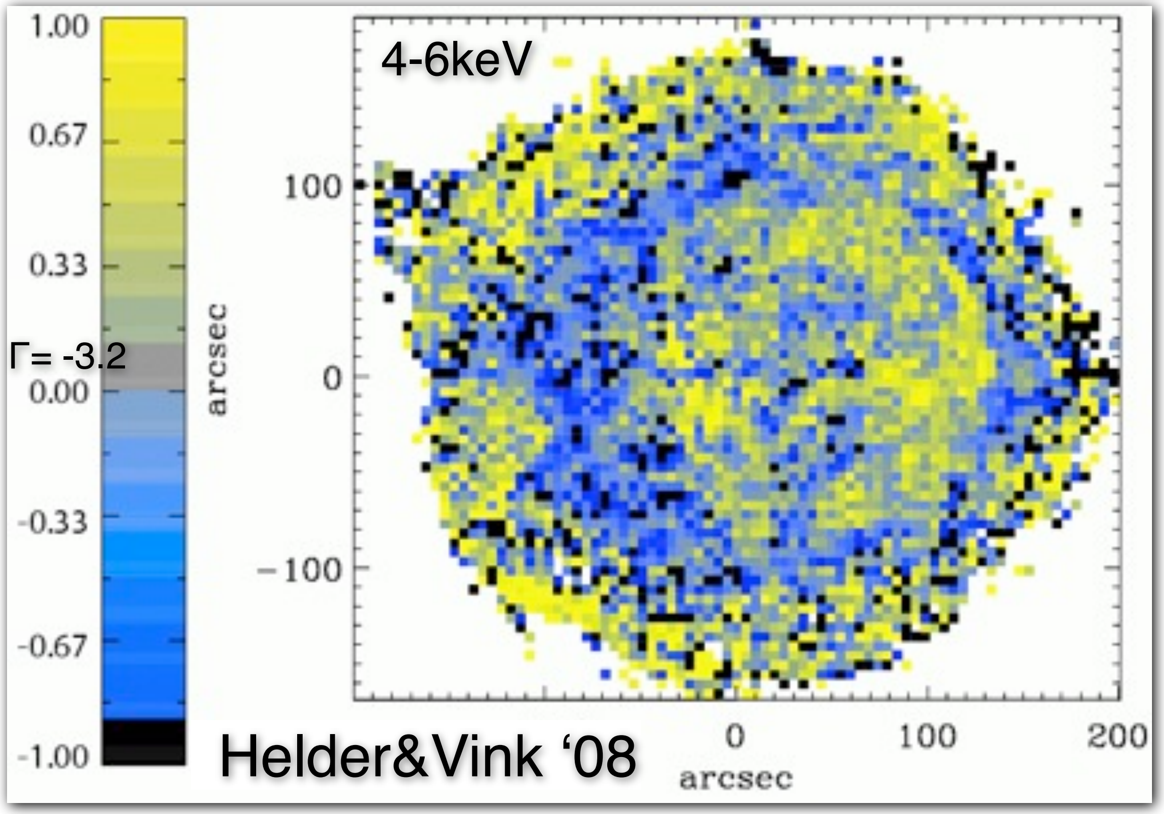

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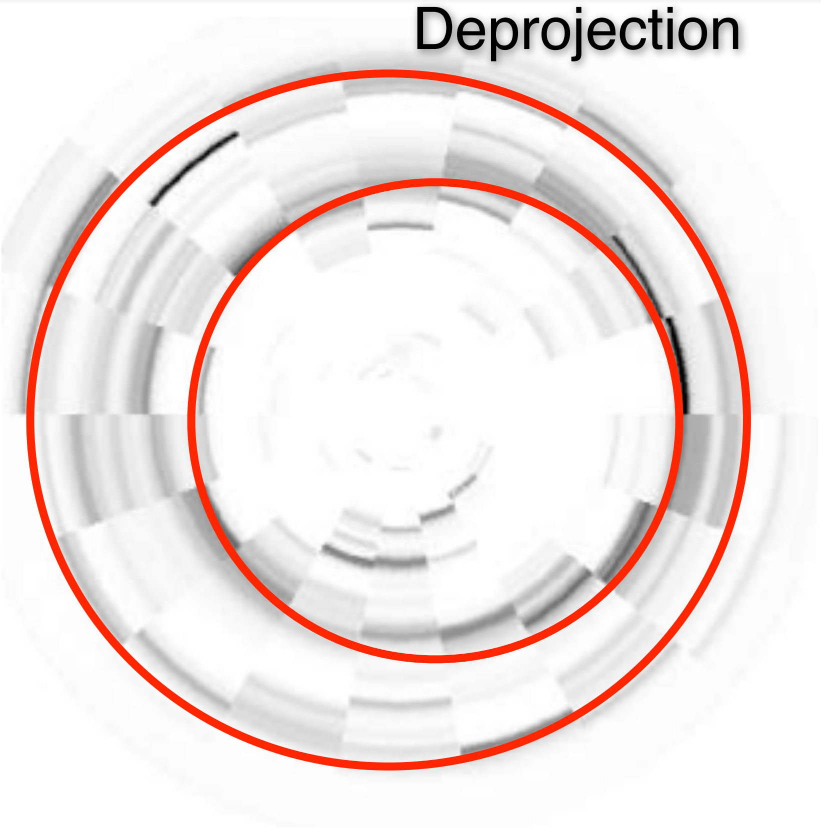

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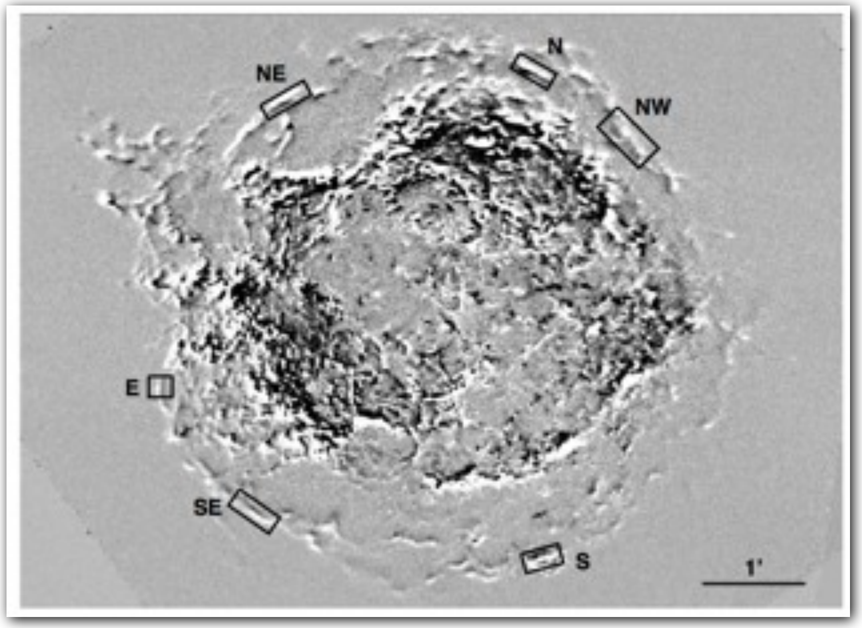
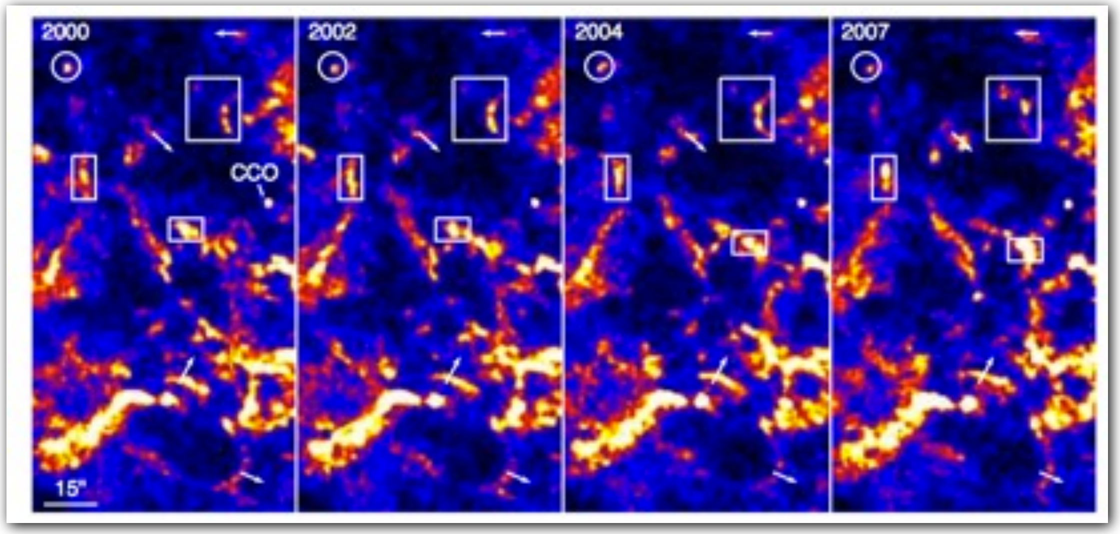
B-field amplification is not very sensitive to initial B-field!

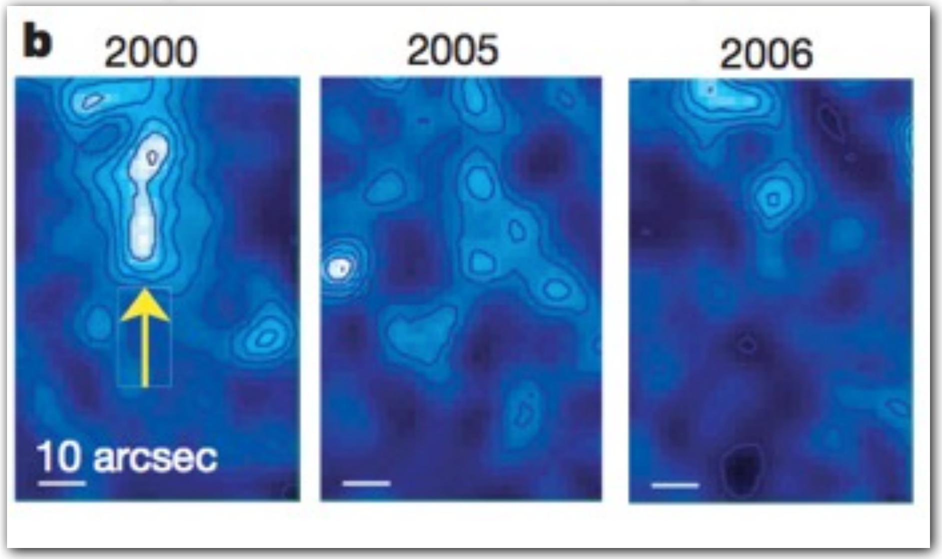
Temporal variations





Cas A (Patnaude+ 2007,09)

- Cas A & RX J1713 show X-ray synchrotron fluctuations
- Time scales ~ few years



RX J1713 (Uchiyama+ 2007 (Nat))

Explanations for variability

- Two possibilities suggested in the literature:
  1. Time scale corresponds with acceleration time=synchrotron loss time
     - Time scales of years imply B>100 μG (Uchiyama+ '07)

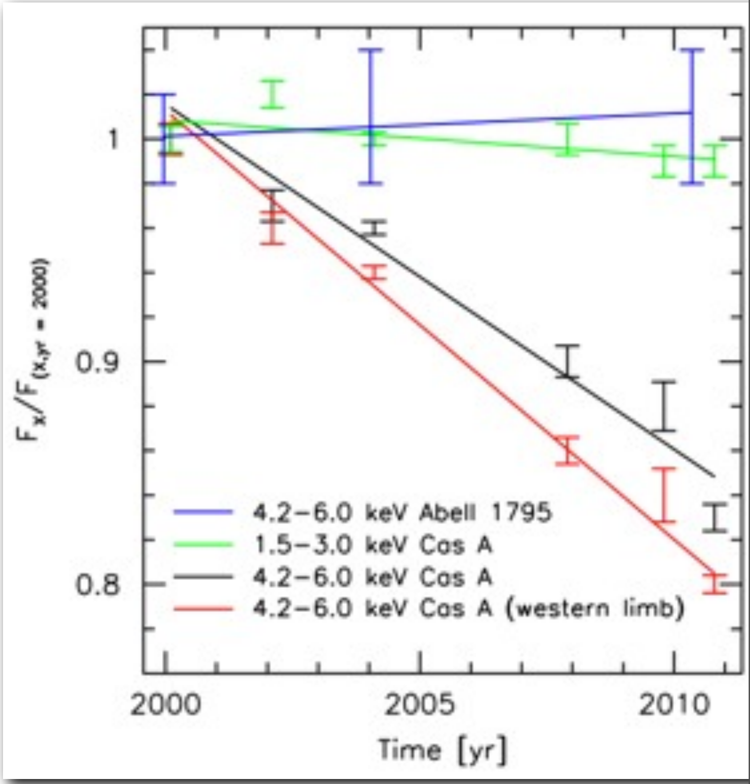
$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}\ {\rm yr.}$$

  2. Time scale corresponds with plasma wave passing by (Bykov+ '08)
     - Plasma waves are necessary for acceleration
     - Driven by cosmic-ray streaming (Bell '04)
     - There is a spectral distribution of waves (larger waves small amplitude)
     - Radio emission less sensitive to B-field fluctuations
     - X-ray synchrotron (beyond break) very sensitive

$$N_{\rm e} \propto KE^{-q},\ I_\nu \propto KB^{(q+1)/2}\nu^{-(q-1)/2}$$

The decline of Cas A

- X-ray synchrotron flux (4-6 keV) declines strongly:
  Whole SNR: –(1.5 ± 0.17)% yr–1
  Western part: –(1.9 ± 0.10)% yr–1
  Accompanied by *steepening* of spectral index Γ
- Critical check:
  no decline in line rich band (1.5-3 keV)
  no 4-6 keV decline cluster A1795



Patnaude, JV, Laming, Fesen, 2011

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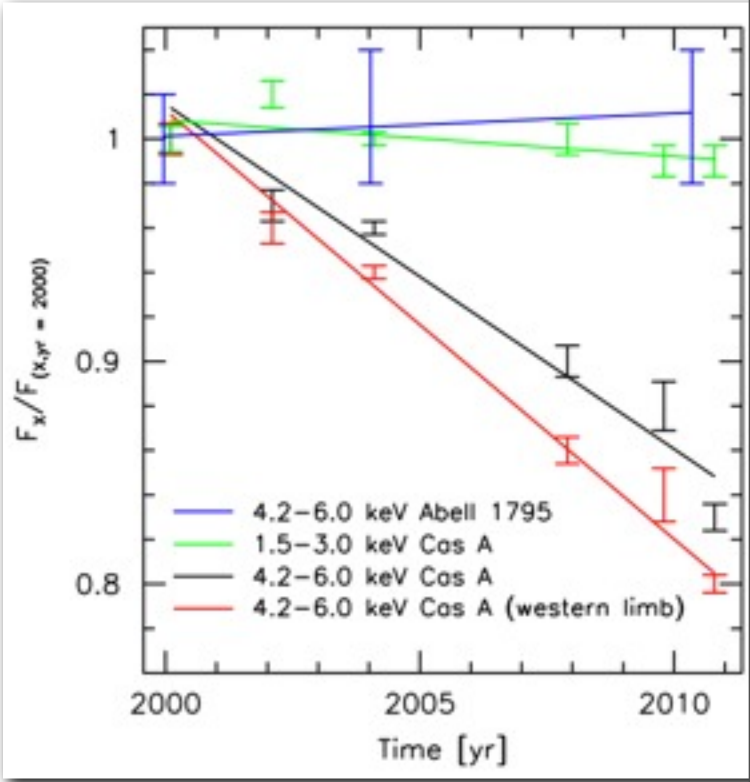


- Decline more than in radio: not adiabatic cooling
- Likely cause: shock deceleration

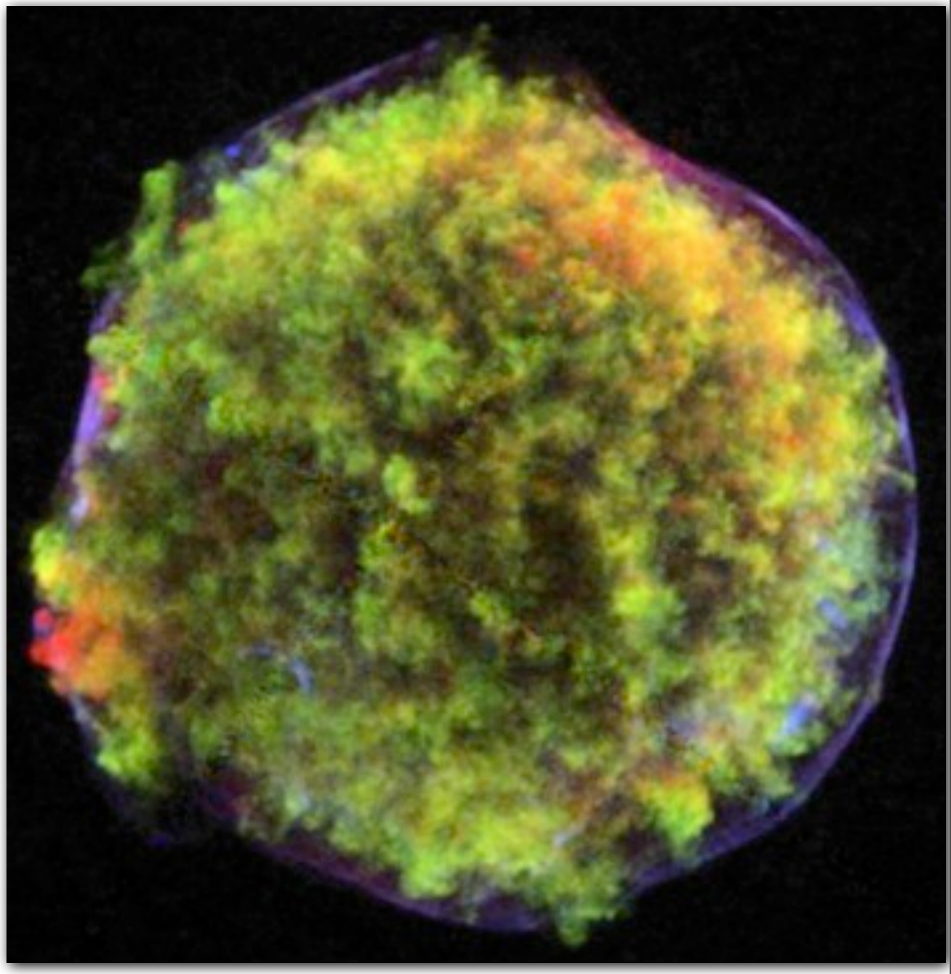
$$\frac{1}{F(\nu)}\frac{dF(\nu)}{dt} = -2\frac{d\Gamma}{dt} \qquad \frac{d\nu_c}{dt} = -4\sqrt{\frac{\nu_c}{\nu}}\nu_c\frac{d\Gamma}{dt}$$

- Confirms basic interpretation of synchrotron model
- Decline somewhat high, may imply small η, hence very fast acceleration
- Questions: spectral shape?

Patnaude, JV, Laming, Fesen, 2011

High Compression Ratios

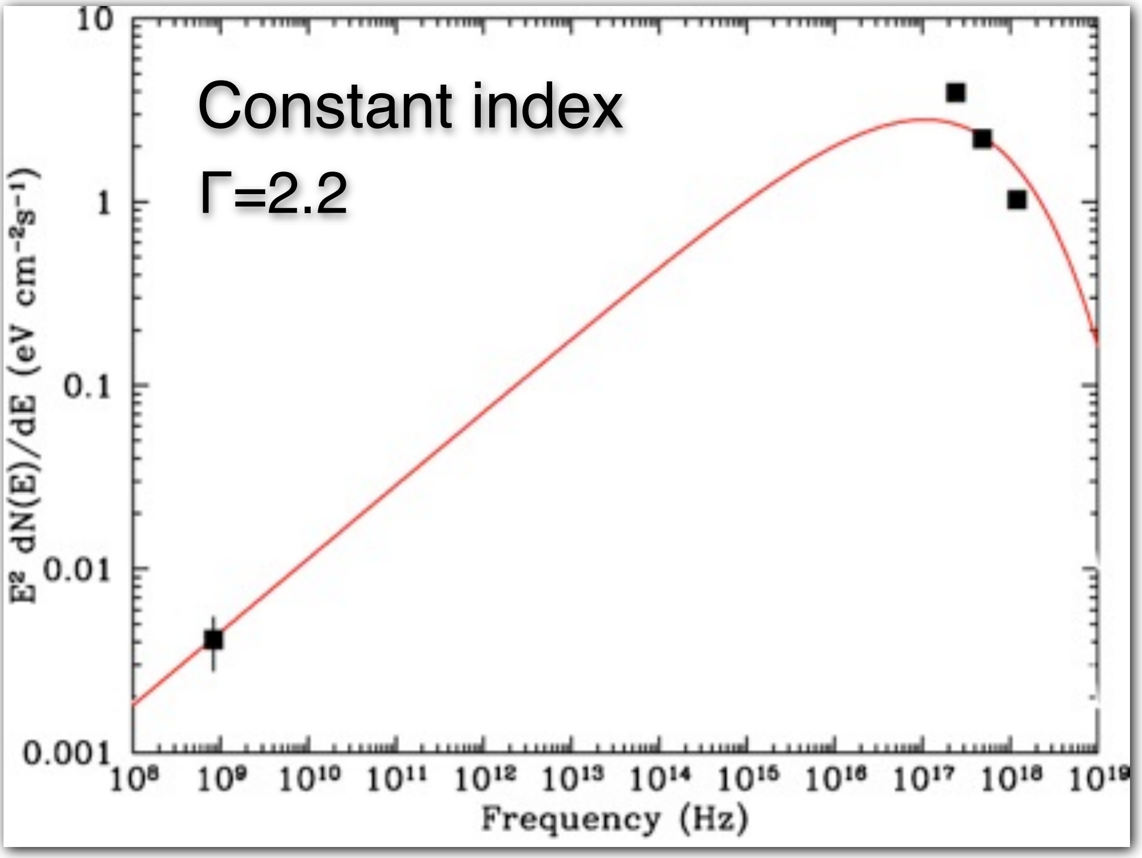
- X-ray evidence for Tycho's SNR:
  Ejecta too close to shock front
  →need high compression ratio!
- SN1006: effect seen as well
  (even outside X-ray synchrotron rims)



Decourchelle&Ellison '01, Warren+ '05,
SN 1006: Cassam-Chenai+ '08

A curved synchrotron spectrum

- Curved (non power law) spectra are a prediction of non-linear shock acceleration theory
- RCW 86 NE & SN 1006 shows evidence for it



Constant index

Γ=2.2

- Prediction of theory: Γ=1.5
- Data not conclusive:
  - steepening wrt radio Γ=2.2
  - either Γ=1.5 or 2.0 fit
- Lower maximum electron energy: e.g. ~28 TeV -> ~8TeV

Vink+ ’06, Allen, G.E.+ ’08

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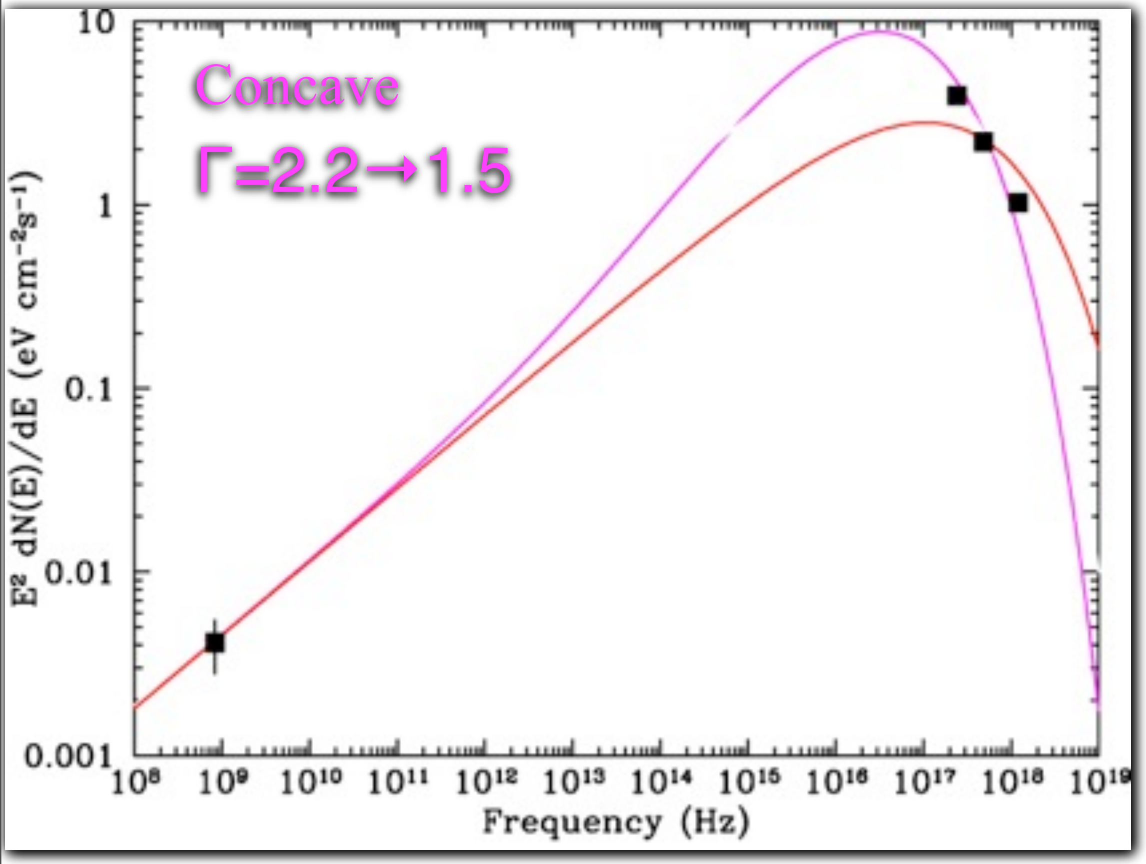

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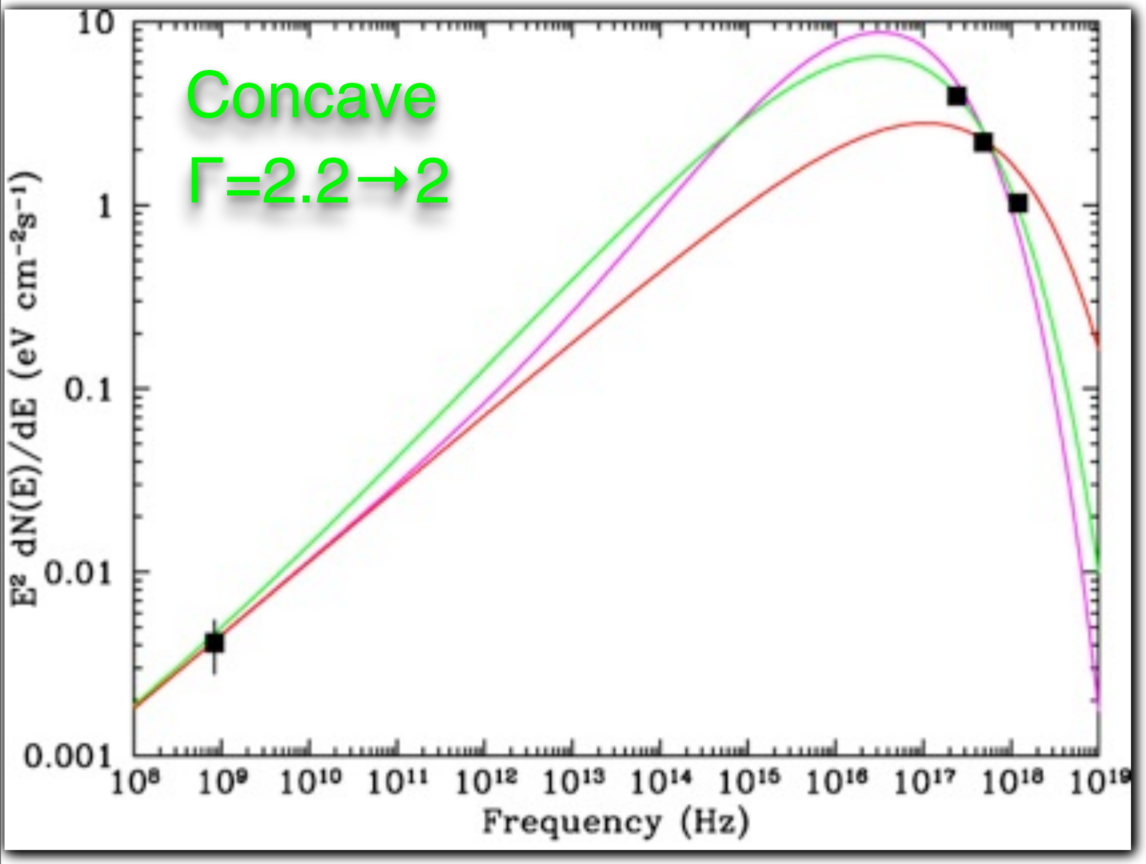

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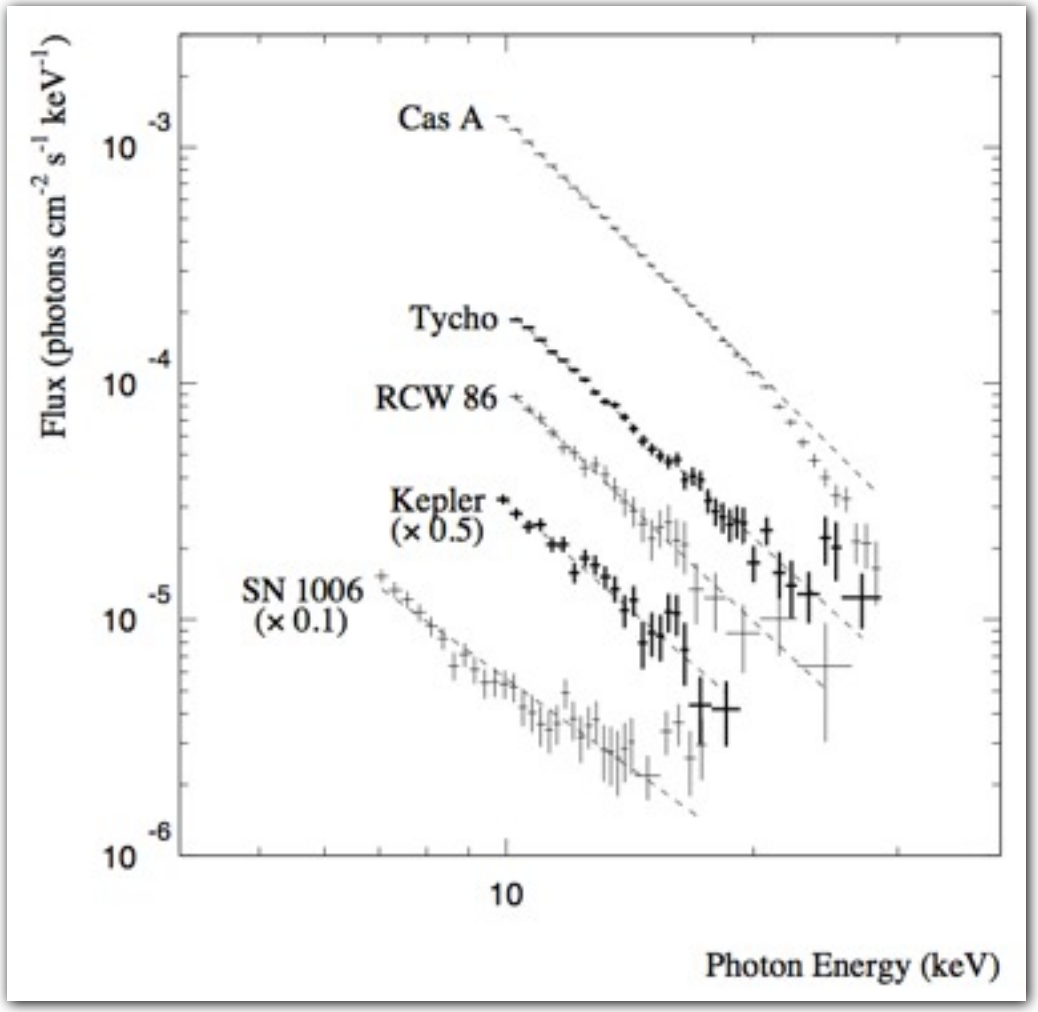
VII
Non-thermal bremsstrahlung & hard X-ray emission

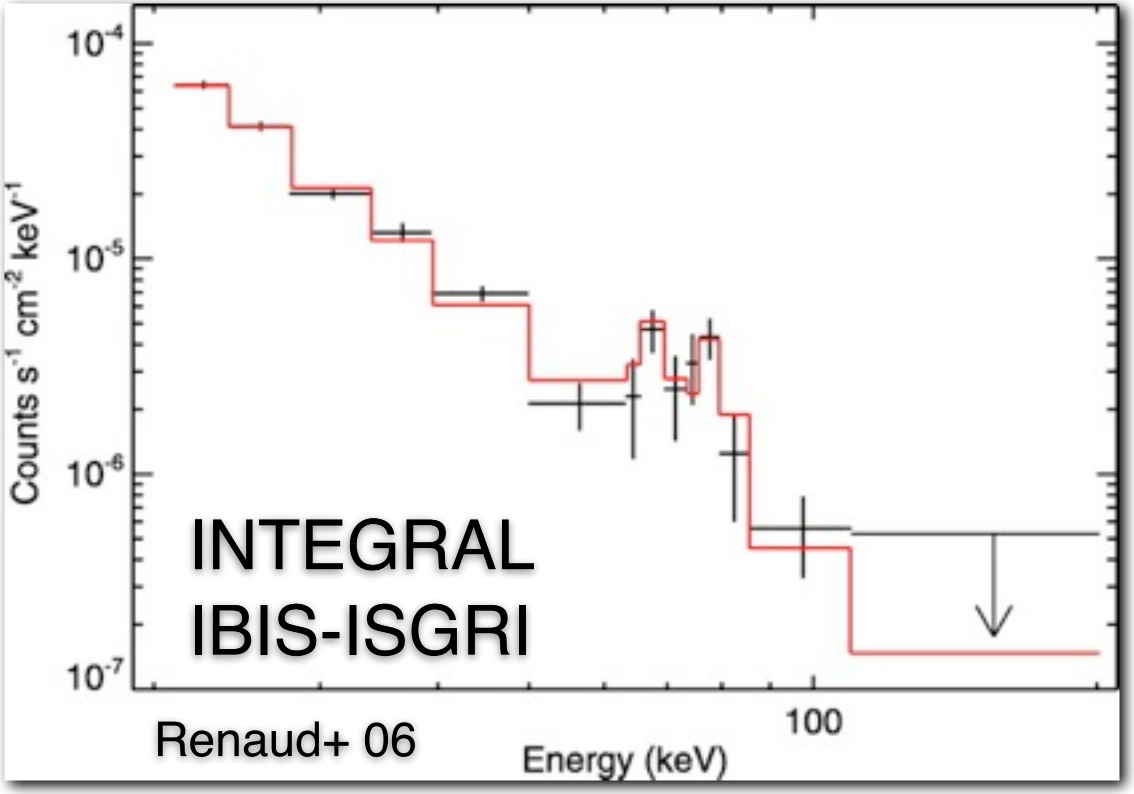
Hard X-ray emission



G.E. Allen 1999

(see also The et al. 96, Allen+ ’97, Favata+ ’97, Vink ’08

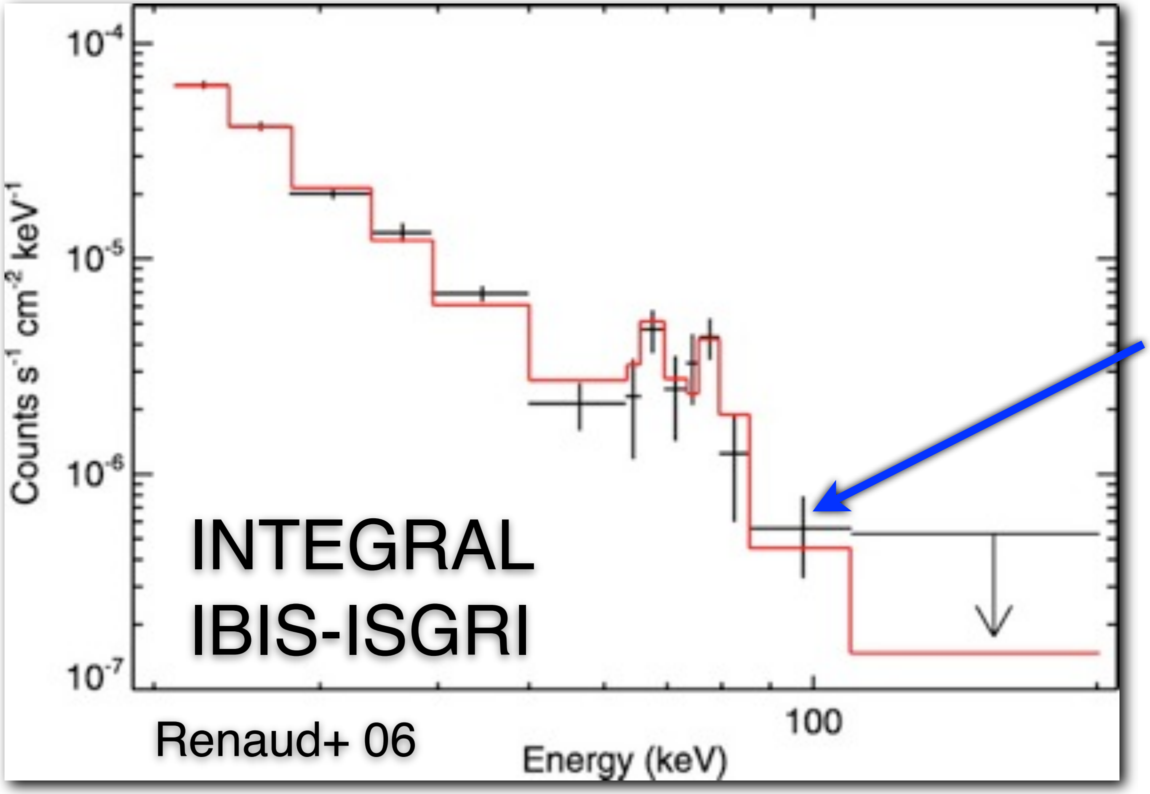
Hard X-ray emission Cas A



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

- Data best described by power law Γ=3.2
- Power law up to ~100 keV
- Expected synchrotron steepening not seen
- Speculation:
  - non-thermal bremsstrahlung?
  - B-field turbulence smoothing out cut-offs?

Hard X-ray emission Cas A



INTEGRAL
IBIS-ISGRI

Renaud+ 06

Synchrotron radiation?
Non-thermal bremsstrahlung?

The+ ’96, Allen+ ’97, Favata+ ’97,
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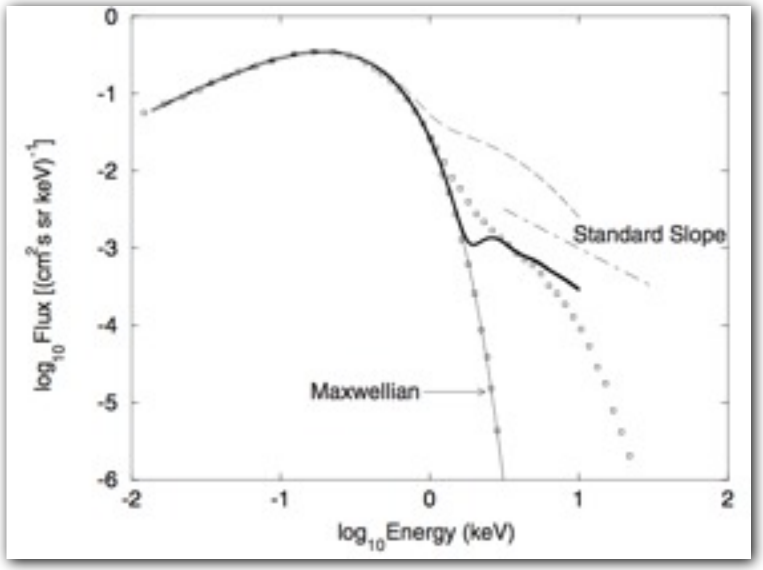
Non-thermal bremsstrahlung



- Thermal continuum SNRs: a.o. thermal-bremsstrahlung
- At the shock front: non-thermal tails to particle distribution
  - Could function as seed particles for Fermi acceleration
- Non-thermal tails: produce also bremsstrahlung
- Should non-thermal bremsstrahlung be considered?
  - Non-thermal bremsstrahlung in keV region should be accompanied by line emission (hence doesn’t work for featureless spectra)

Further reading: Asvarov+ ’90, Vink+ ’97, Laming ’01, Rho+ ’02, Vink ’08

The problem with NT bremsstrahlung

- Non-thermal electrons loser faster energy through collision than bremsstrahlung
- Energy losses proportional to $E^{-3/2}$
- Low energy electrons lose energy first
- Effect scales with $n_e t$ (like ionization!)
- Conclusions:
  - NT bremsstrahlung at low energies (<50 keV) unlikely
  - only very close to shock front expected
  - or $n_e t$ very low (low density)
  - around 100 keV only probably detectable (detected?) for Cas A (unless B-field is very low <- radio synchrotron normalization)

Vink 2008

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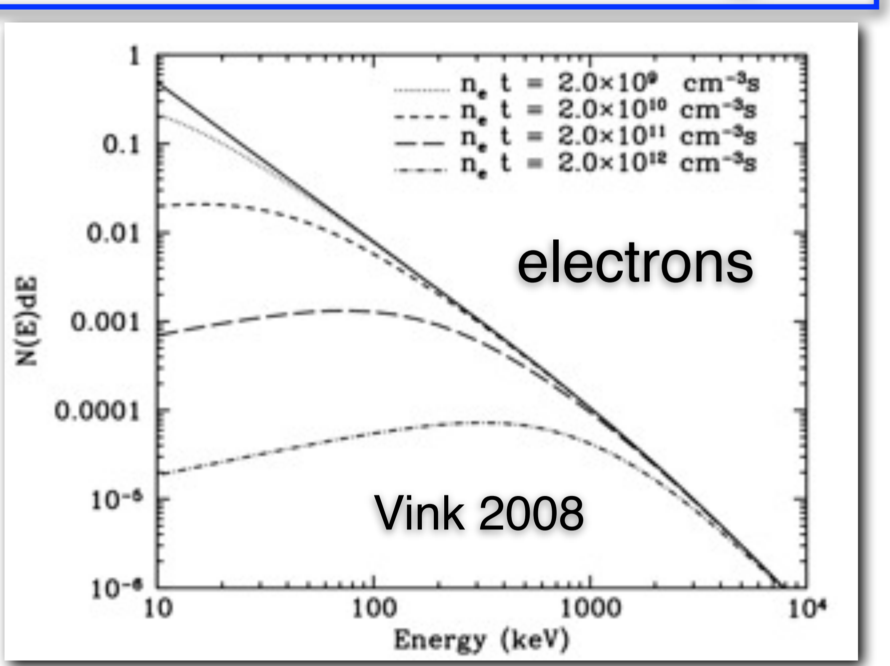
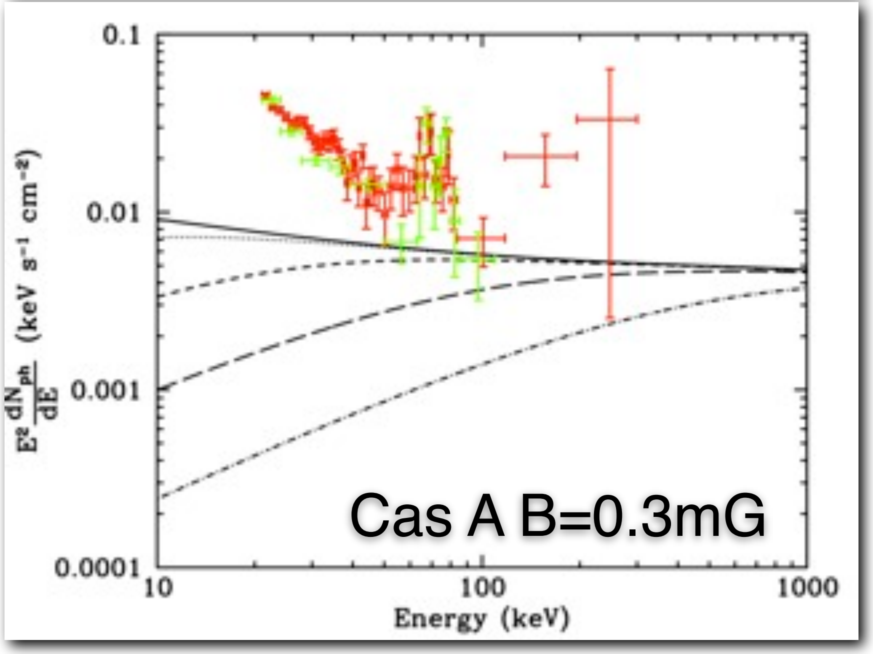


electrons

Vink 2008

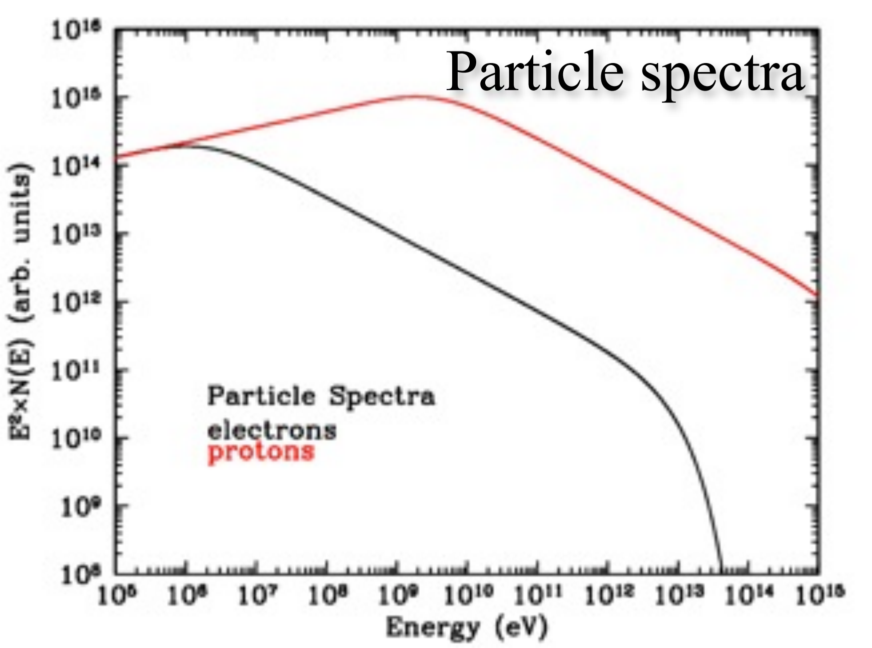


Cas A B=0.3mG

VIII

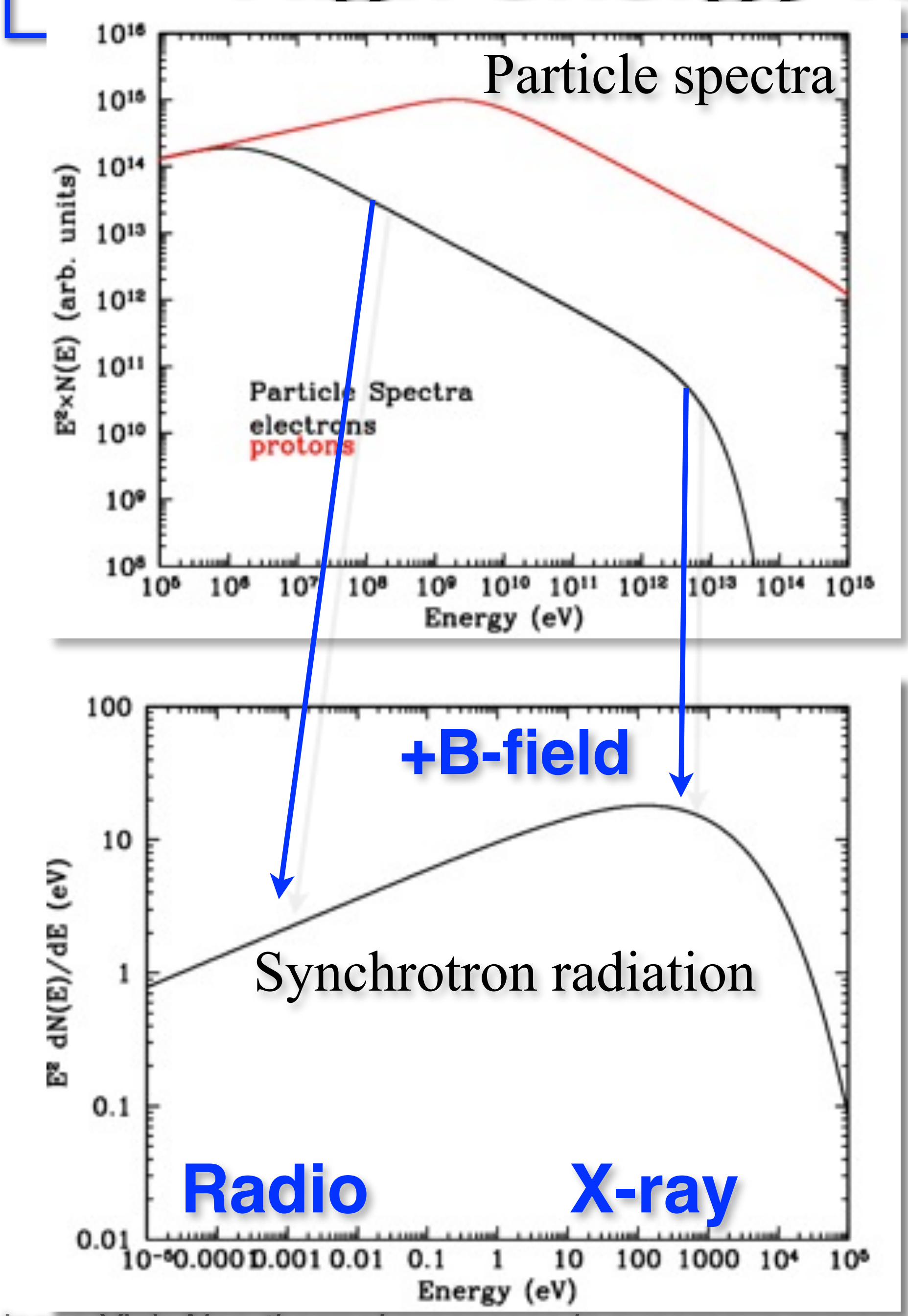
Gamma-ray emission from SNRs

High energy radiation processes



Particle spectra

High energy radiation processes



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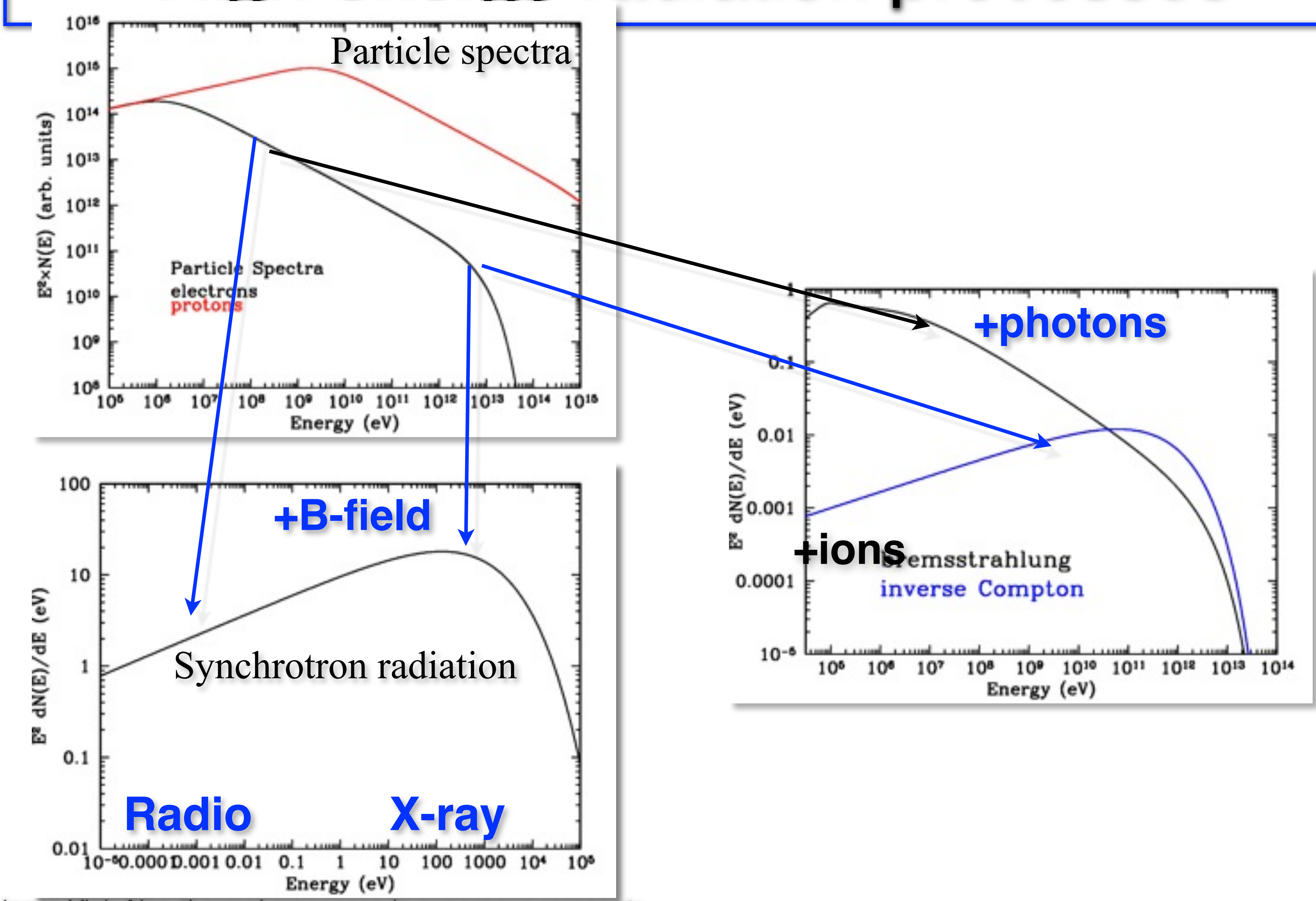

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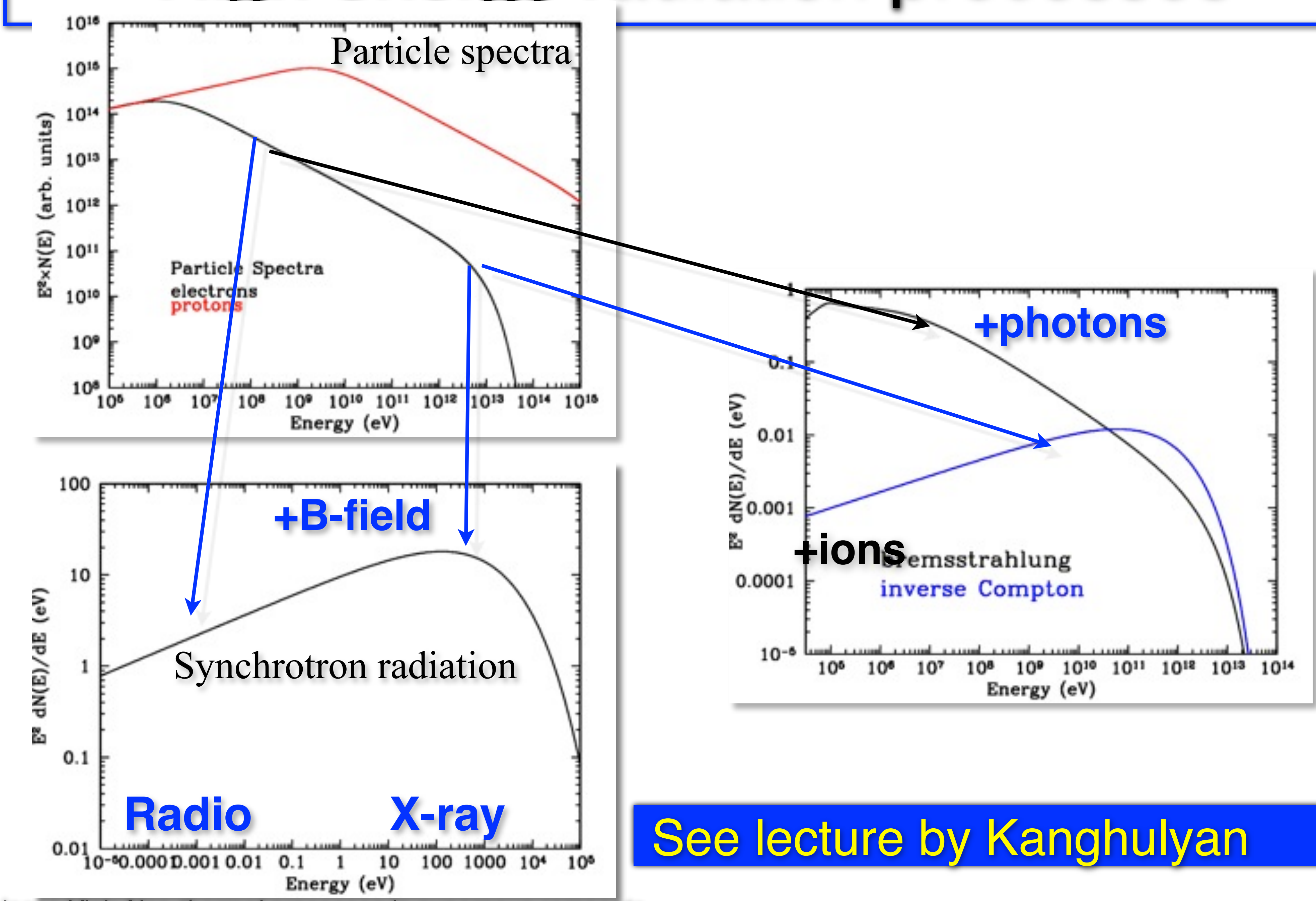
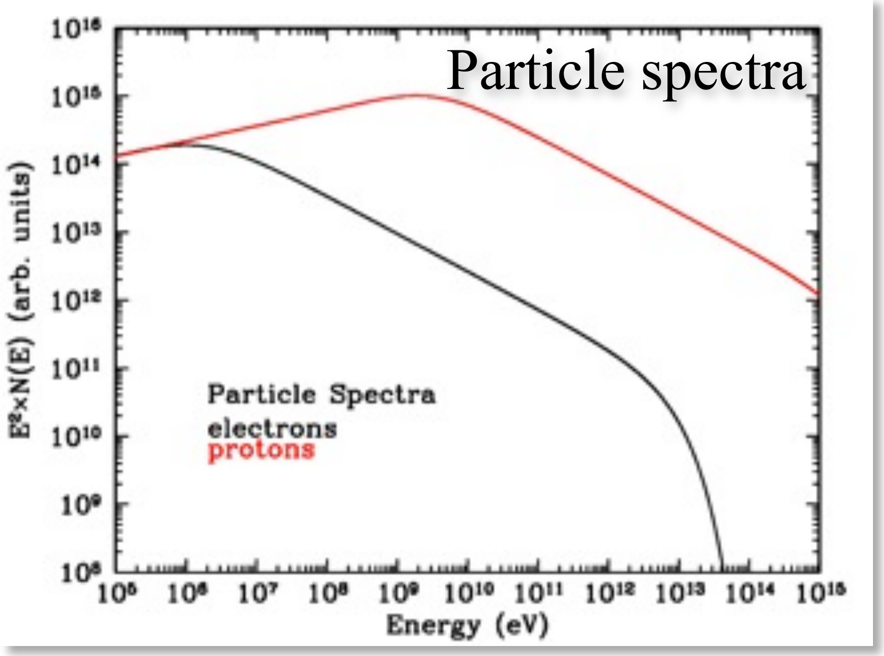


See lecture by Kanghulyan

Basic radiation processes



- Ion-ion collisions produce pions (π^0,π^+,π^-)
- Radiation: p+p → π^0 → 2γ

  (bump in GeV to TeV range)
- Detecting pion decay →

  direct evidence for ion acceleration
- Note: electron and ion Fermi acceleration similar accept:

  -at injection (low E)

  -electron radiation losses (high E break)

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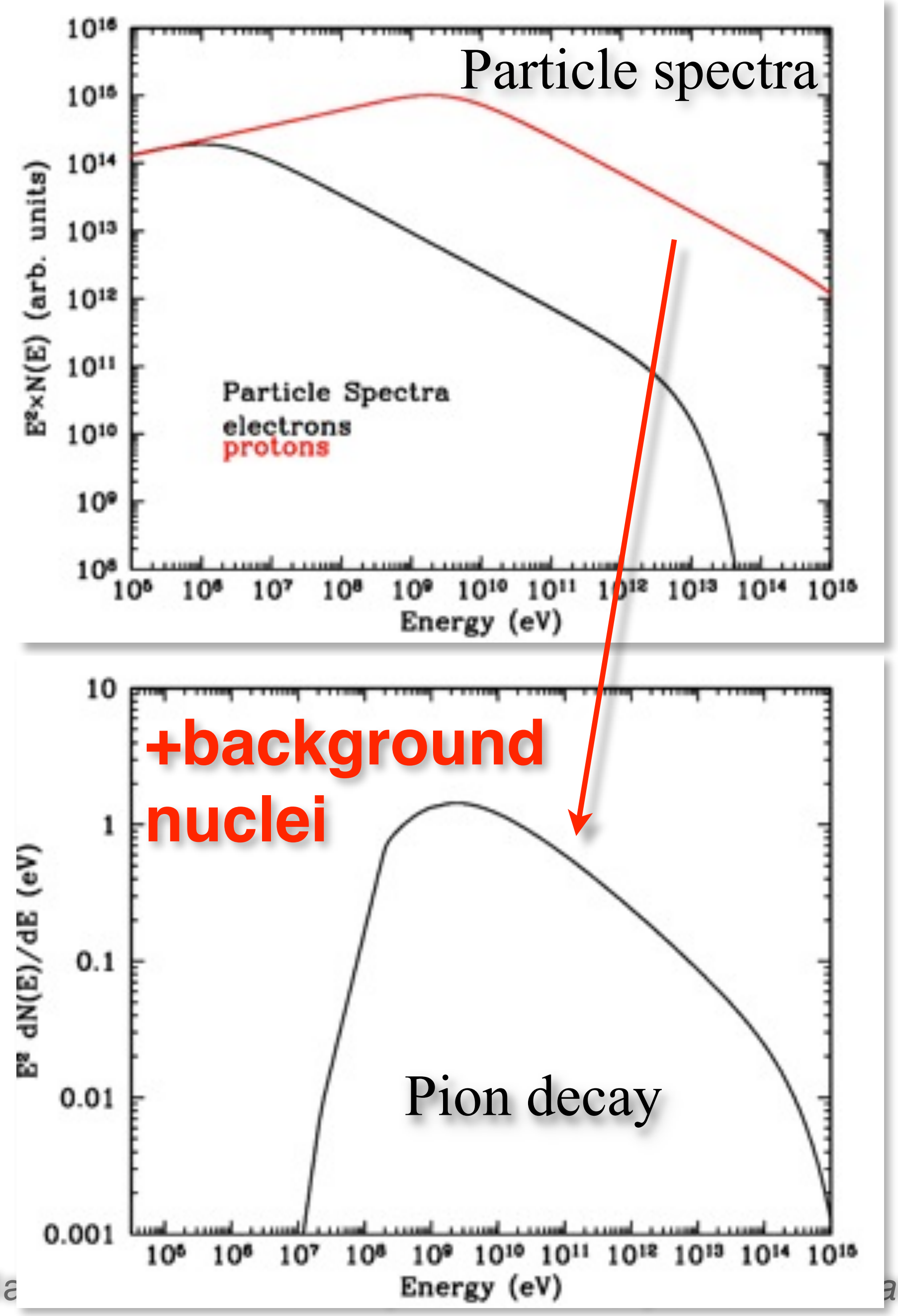

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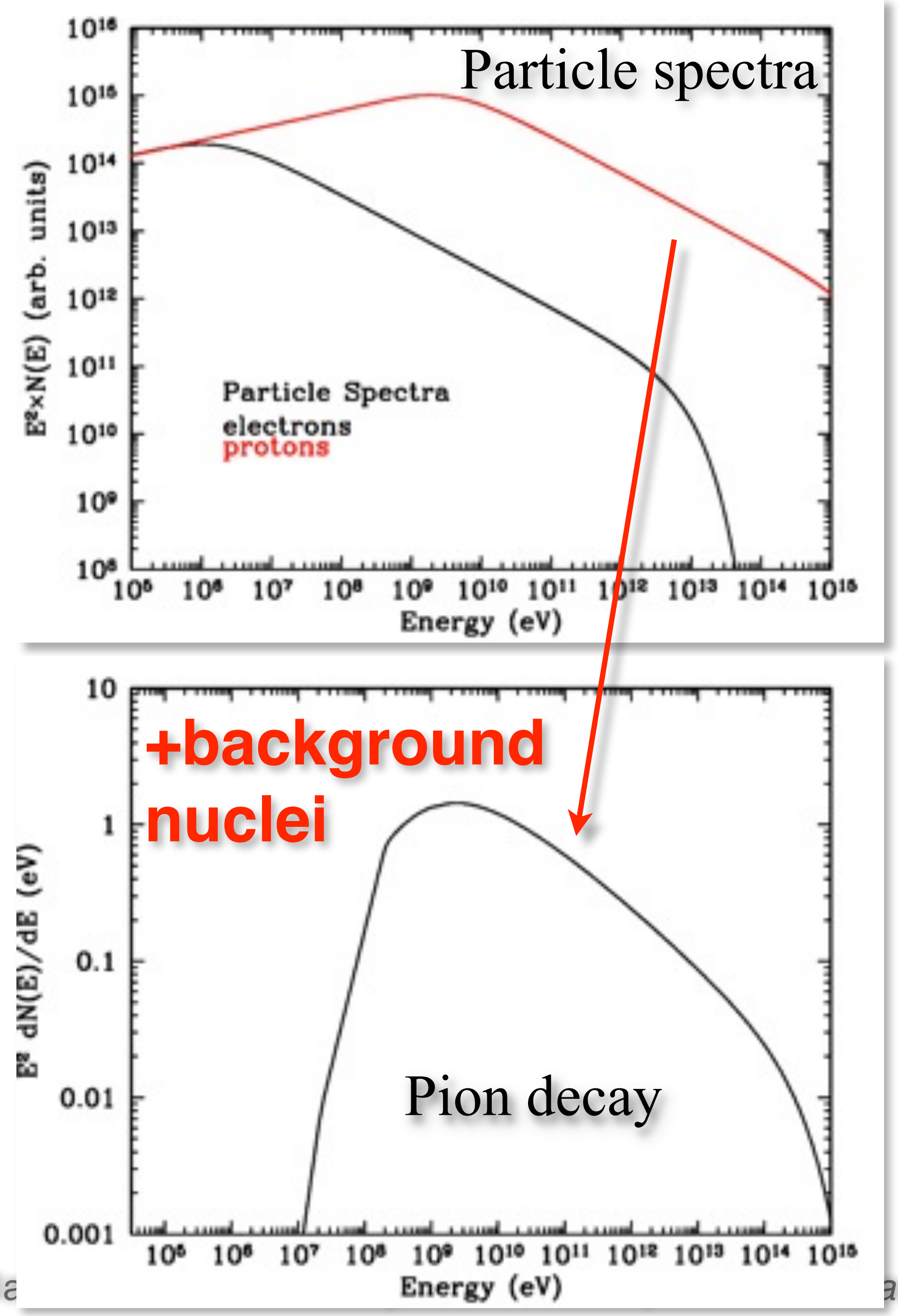

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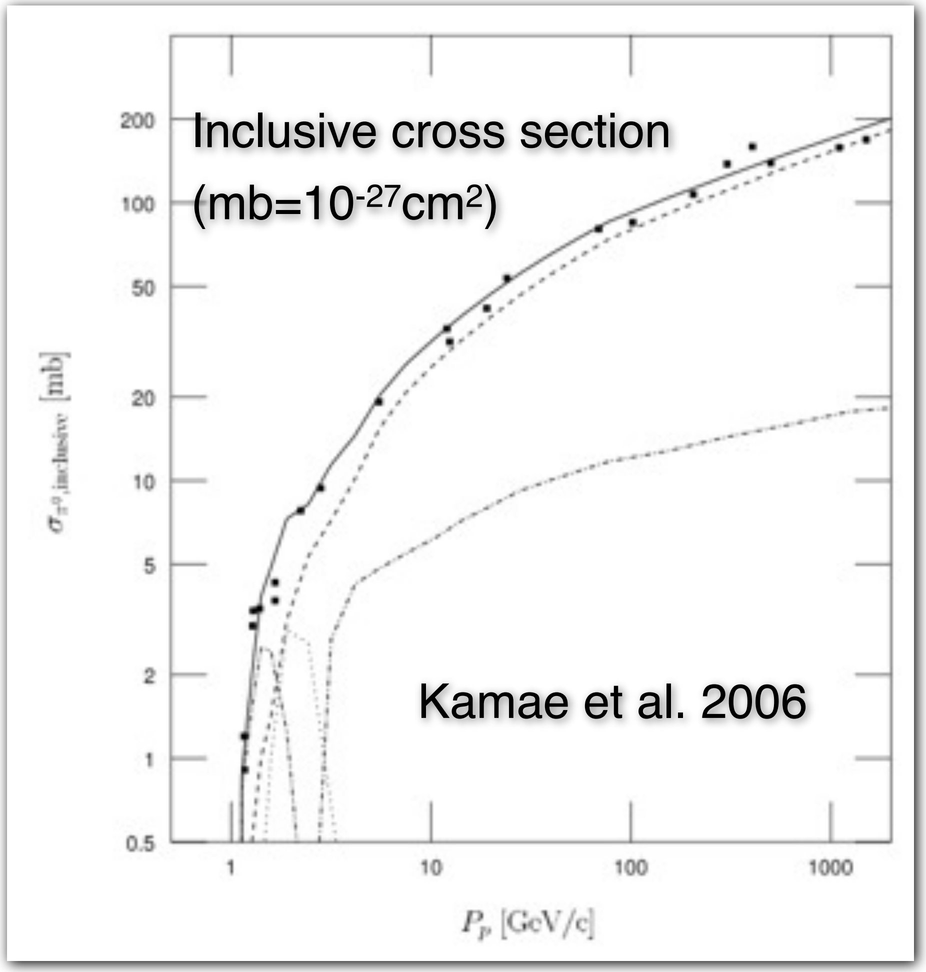
Interpreting detection radiation requires knowledge of:
1) B-field 2) photon field 3) densities

Pion-decay



Inclusive cross section (mb=10^{-27}cm^2)

Kamae et al. 2006

- Mass:
  m(π^0)=135 MeV/c^2
  m($\pi^{+/-}$)=139.6 MeV/c^2
- Pions only made when E> m(π)
- When E>> m(π) multiple pions, protons, neutrons, etc. can be made
- Number of particles created: multiplicity
- Inclusive cross section:
  inelastic cross section times number of π^0
- NB pion energy << energy of primaries (in TeV ~10%)

The gamma-ray blame game

- Gamma-ray spectra do not contain much directly interpretable physical data:
  - breaks difficult to see
  - determine only: spectral index + normalization
- Spectral index:
  - inverse Compton $\Gamma = (q-1)/2 - 1$
  - pion decay ($E \gg m_{\rm pion}c^2$) $\Gamma \approx q$

- Synchrotron vs inverse Compton scattering:
  - similar shapes, different energies
  - B-field up -> synchrotron normalization up, $E_{\rm max}$ the same
  - For a fixed synchrotron normalization:
    - B-field up -> IC normalization down, $E_{\rm break/IC}$ down
    - Hence: high B-fields -> more likely that pion decay contributes
- Pion decay: needs a high background density to work

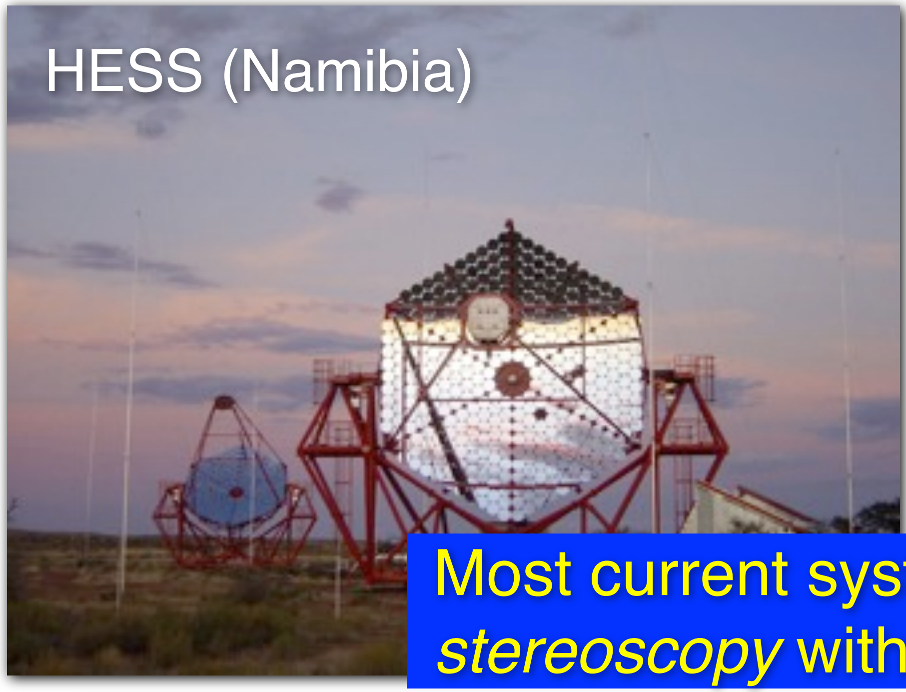
TeV Cherenkov Telescopes


HESS (Namibia)


MAGIC (La Palma)


VERITAS (Arizona)

TeV Cherenkov Telescopes

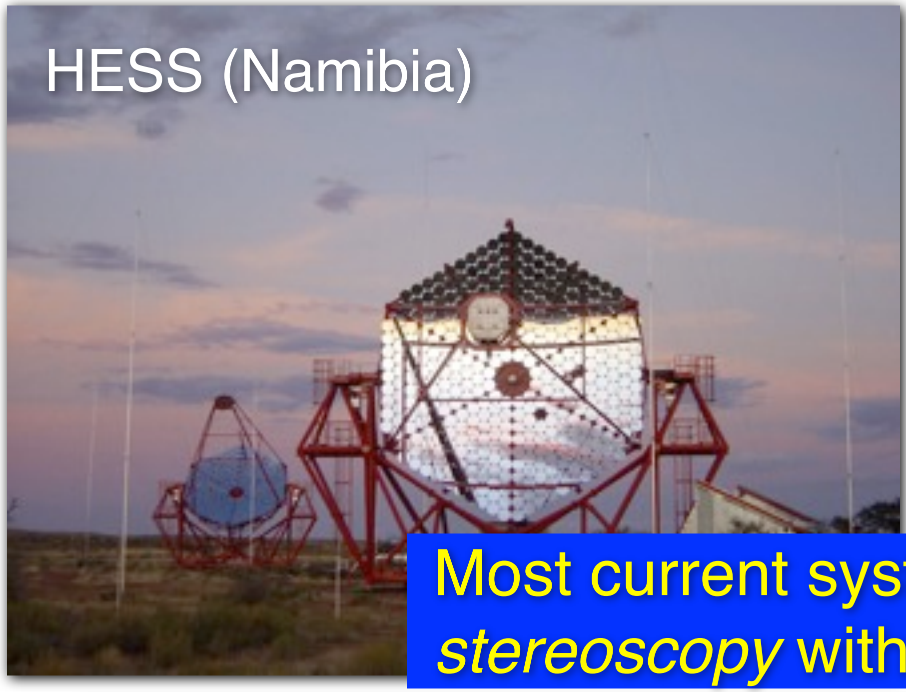

HESS (Namibia)


MAGIC (La Palma)

Most current systems use *stereoscopy* with up to 4 dishes


VERITAS (Arizona)

TeV Cherenkov Telescopes


HESS (Namibia)

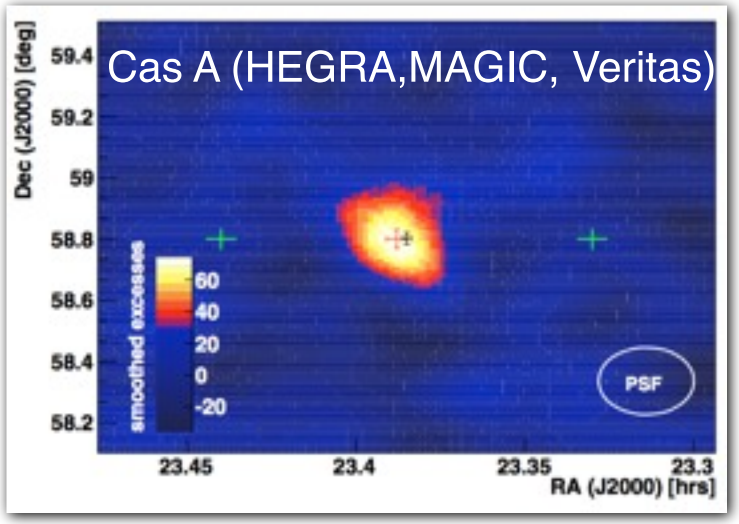

MAGIC (La Palma)

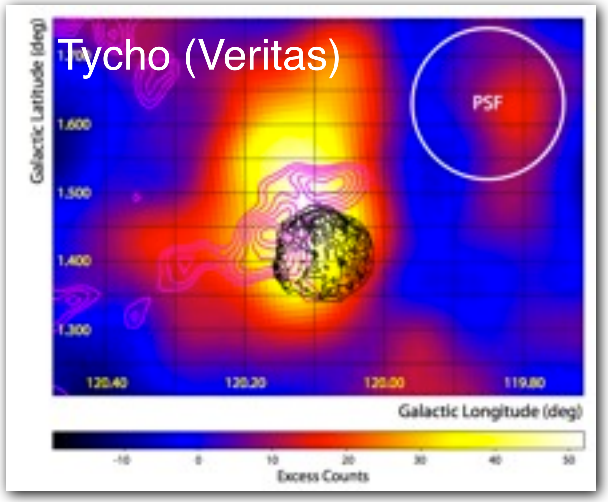
Most current systems use *stereoscopy* with up to 4 dishes

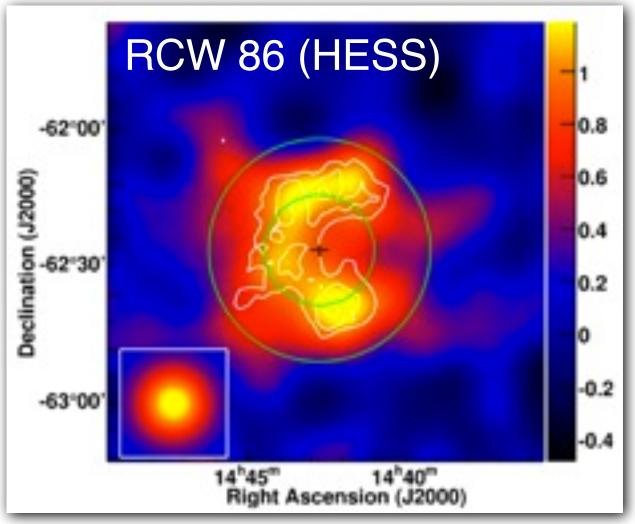

VERITAS (Arizona)

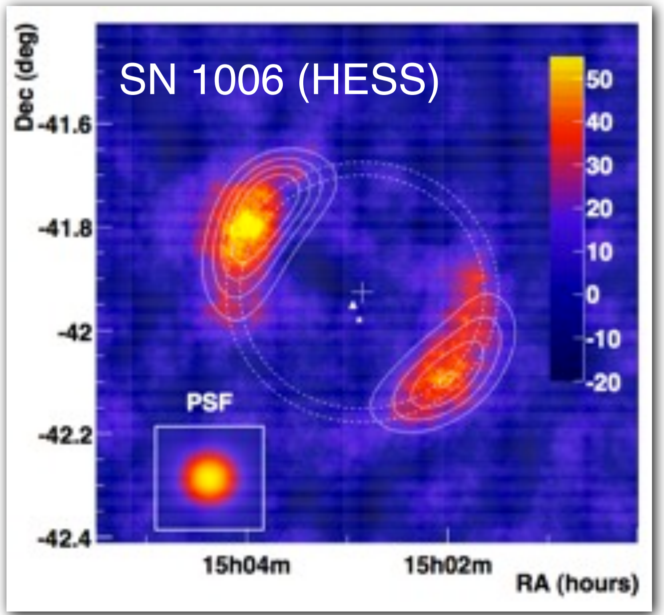
See lecture by Jim Hinton

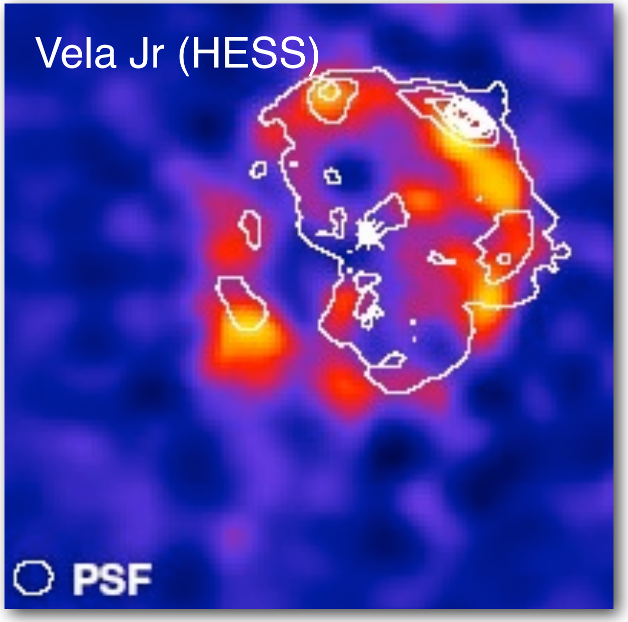
Young SNRs detect in TeV gamma-rays

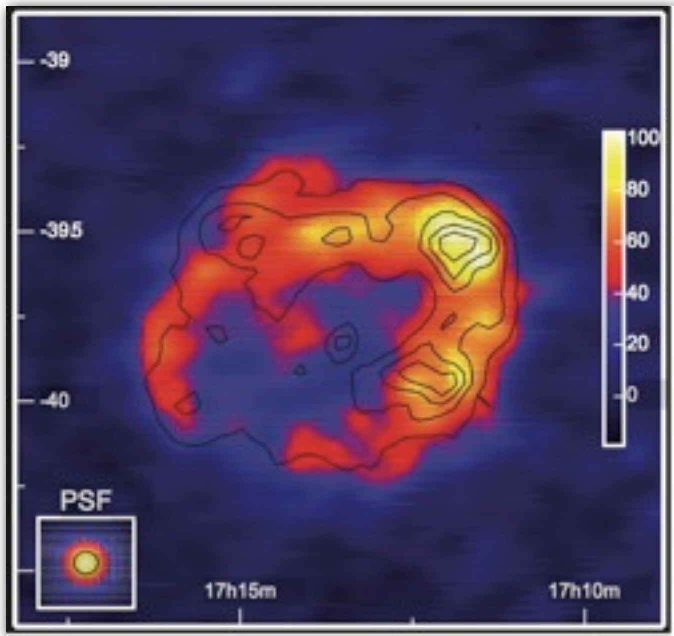




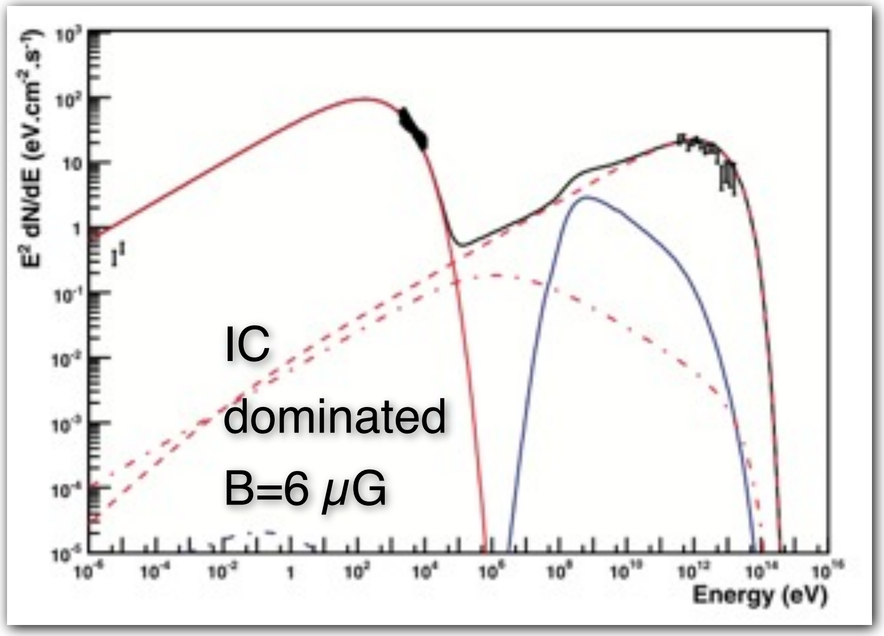


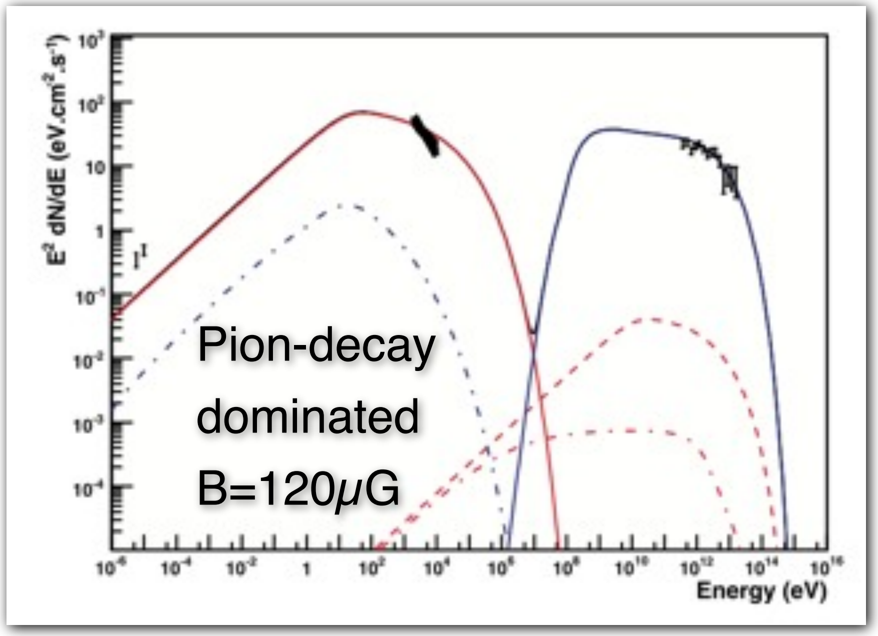


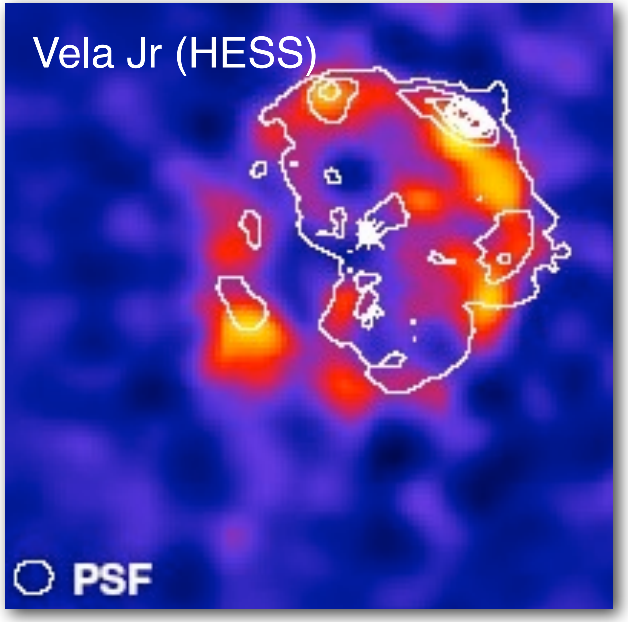




Gamma-ray blame-gaming in practise







The curious case of RX J1713.7-3946

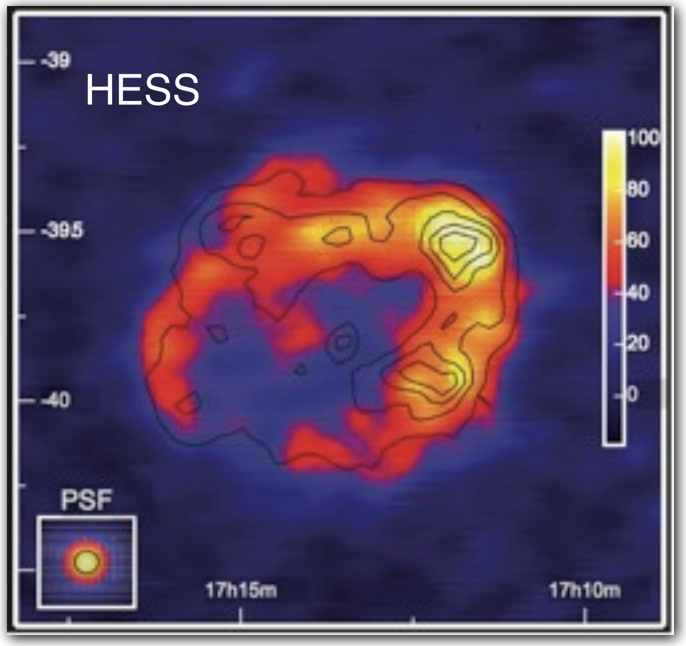
- RX J1713 is the brightest SNR in TeV and the first to be resolved
- SNR is very extended: ~1 degree
- In X-rays: only synchrotron radiation!!
  - Why? Two “schools”

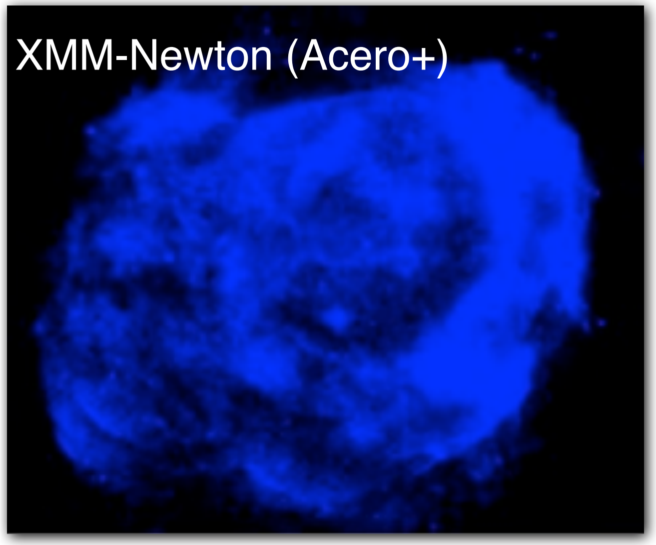
    1 Efficient acceleration -> $kT < 0.1$ keV

    (e.g. Drury+ 2009)

    2 Low density, thermal emission weak

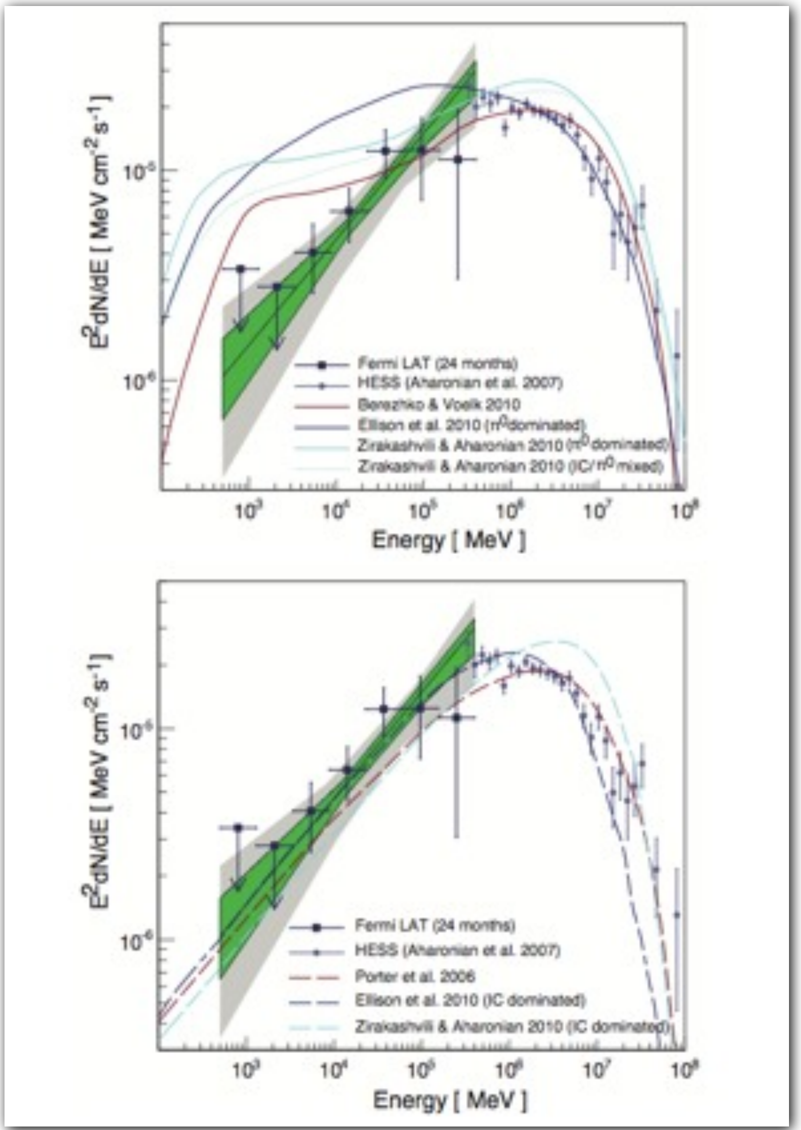
    EM~ n^2 (e.g. Katz & Waxman 08)
- If low density: pion decay unlikely
- If pion decay: high density + high B-field (gives low rel. electron density)
- High B-field evidence: flickering of X-ray knots (Uchiyama+ ’07)



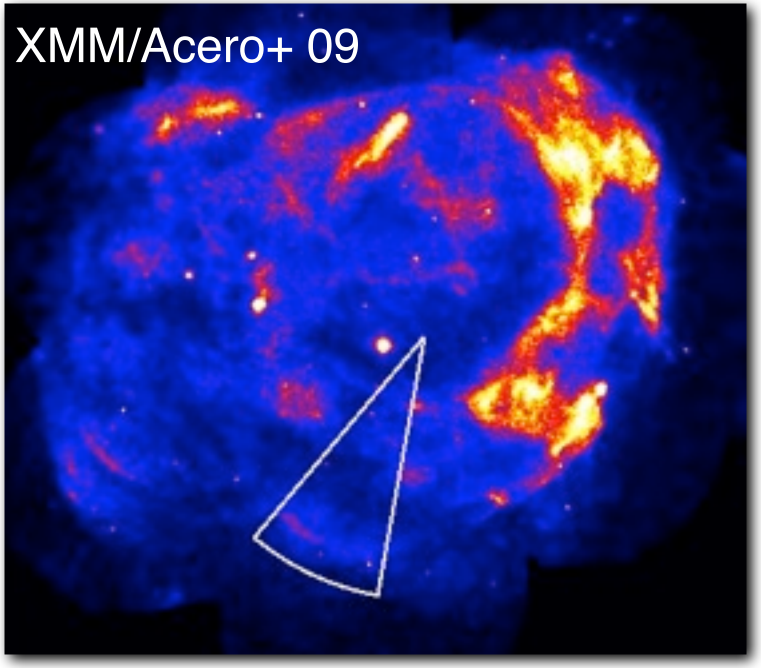


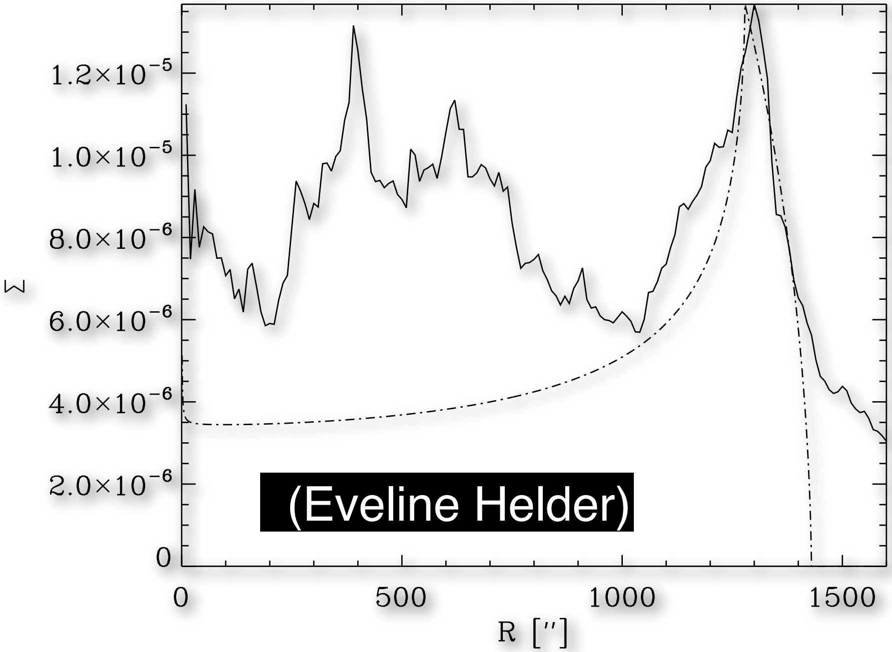
Fermi observations: Case solved?

- Fermi detected RX J1713 in GeV range (Abdo et al. 2011)
- Difficult: Galactic plane contamination
- Spectral shape suggests inverse Compton origin of GeV/TeV emission
- Has controversy ended?
  - Very difficult to defend pion decay scenario
  - More data/scrutinzation needed
  - IC models do not fit very well TeV end of spectrum



The B-field of RX J1713


XMM/Acero+ 09

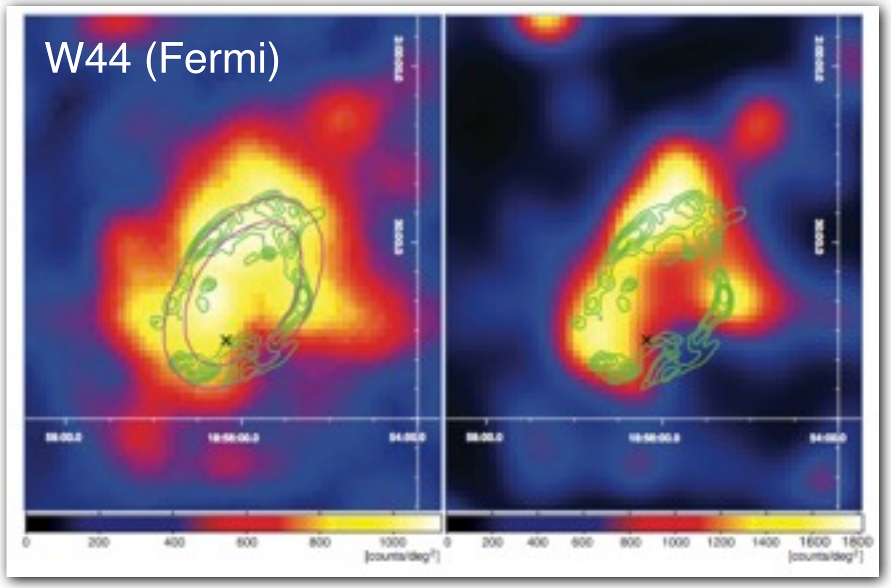


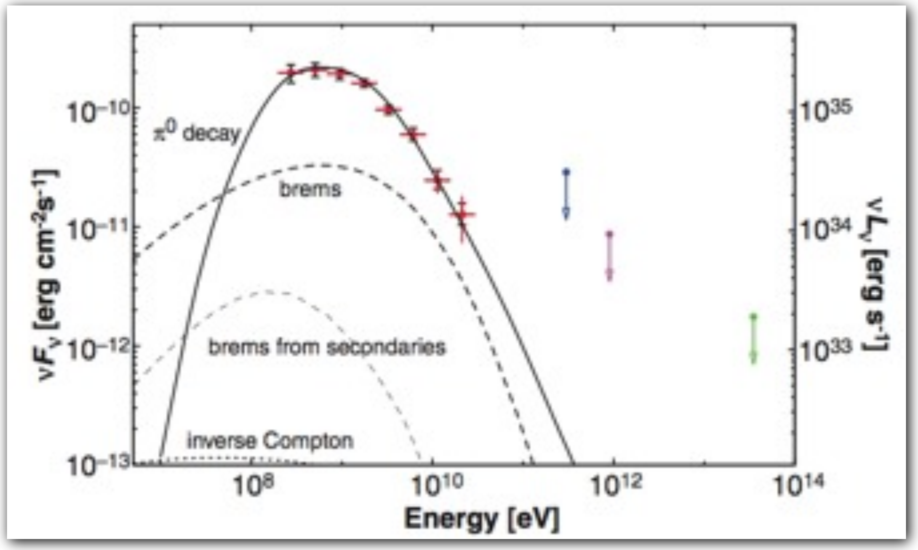
(Eveline Helder)

- 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

Slide taken from presentation 2009, KITP

Recent advances with Fermi



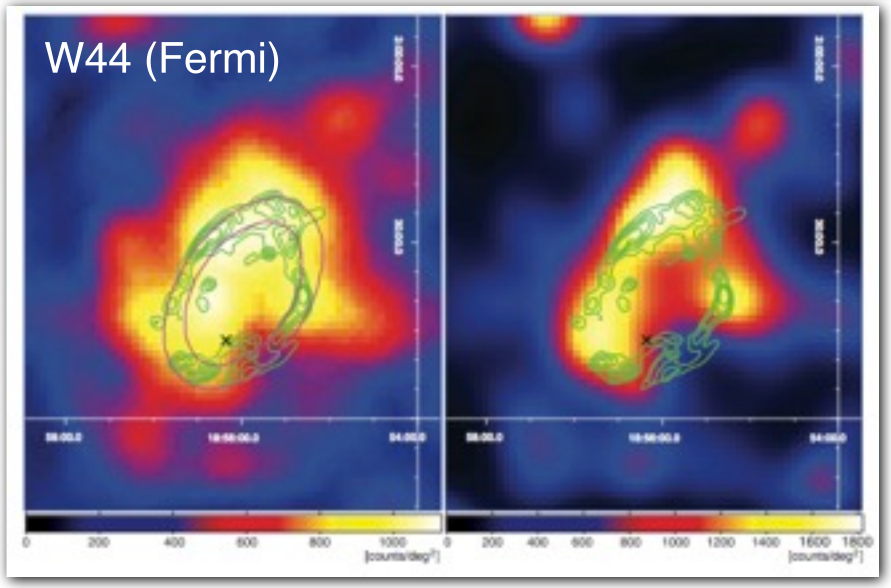


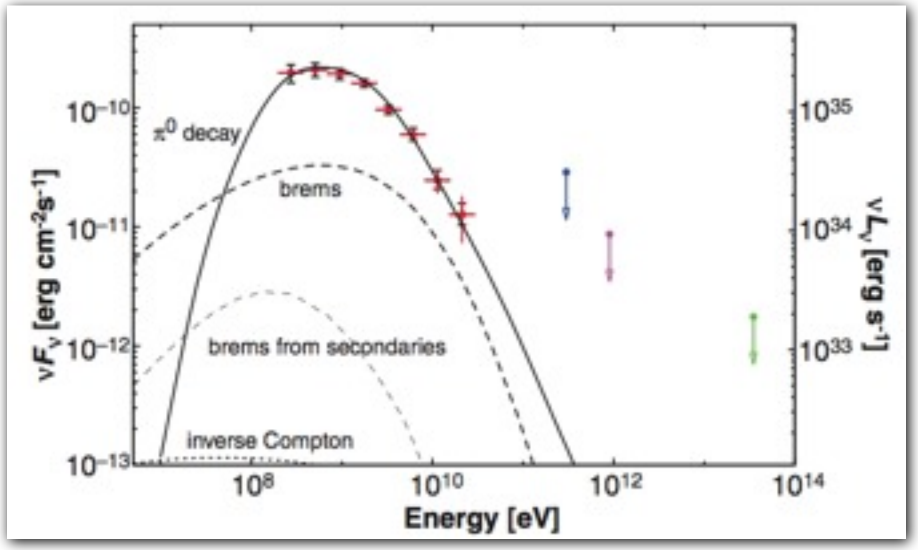
- CGRO-EGRET detected several GeV sources associated with old SNRs
- Fermi has confirmed these detections and added several more
- Old SNRs seem to have a break < TeV: escape of cosmic rays
- Old SNRs detected: many seem “mixed-morphology SNRs” & associated with molecular clouds -> suggest pion decay as source

- Some Fermi-detected SNRs also TeV associations, with TeV sources offset (IC 443, W28): other evidence for cosmic ray escape

e.g. Abdo et al 2010 (Science)

Recent advances with Fermi





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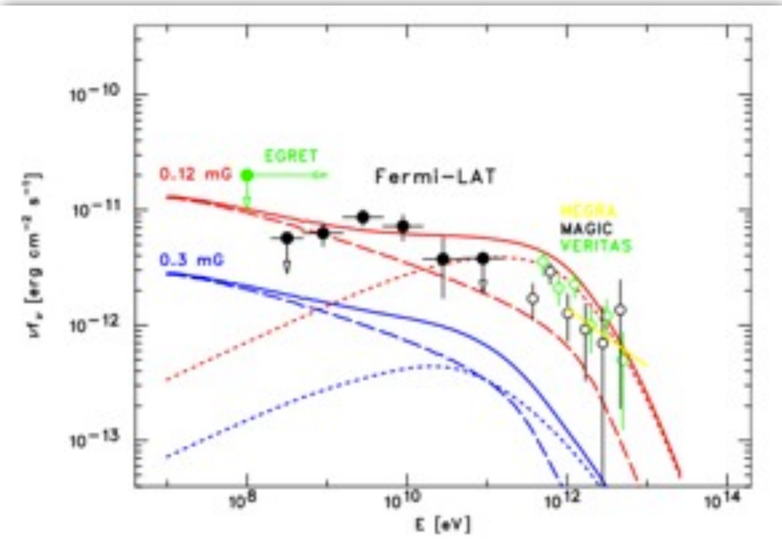
See lecture by Stefano Gabici

Fermi & Cas A

- Cas A has been regarded a protypical cosmic ray accelerator
- It is young (~330 yr)
- Bright in radio (many electrons accelerated)
- Bright in thermal X-rays (high density -> target for producing pions)
- Narrow X-ray synchrotron rim: CR induced magnetic field amplification

- Fermi detected Cas A (Abdo et al. 2010)
- Emission could be anything (pion decay, bremsstrahlung, IC or a combi)
- But surprise: whatever radiation nature $E_{\mathrm{rel.\ part}} < 4\% \ E_{\mathrm{expl}}$

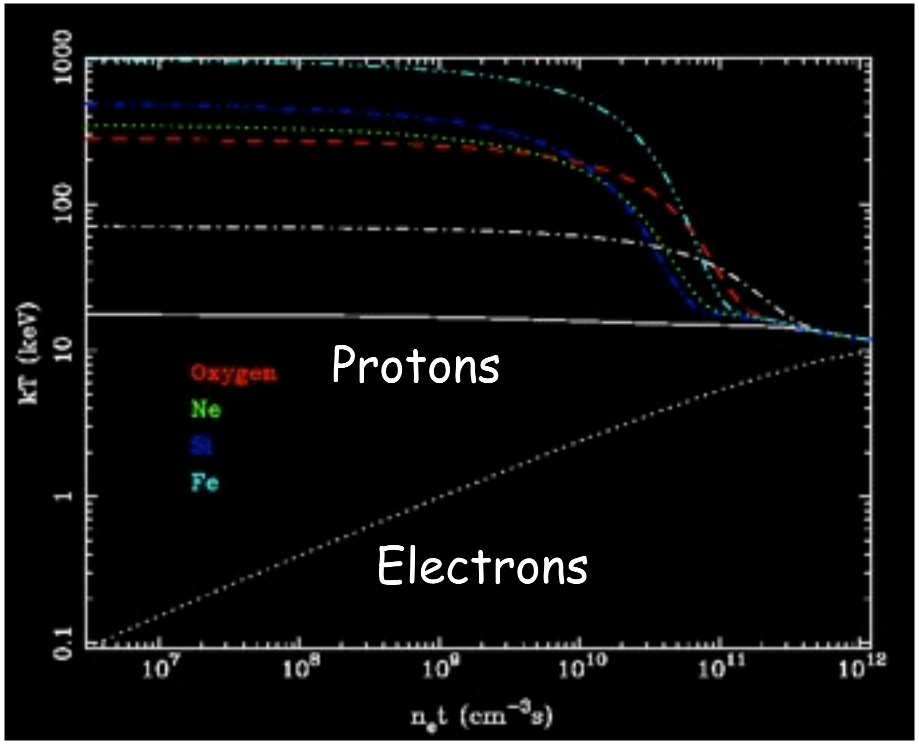


IX

Optical spectroscopy & cosmic-ray acceleration

Optical observations of shock heating

- Typical SNRs temperatures are 0.1-5 keV
- *Electron* temperatures routinely measured using X-ray telescopes
- Problem: *electron* temperature may be lower than plasma temperature!
- Electrons/ions only slowly equilibrate



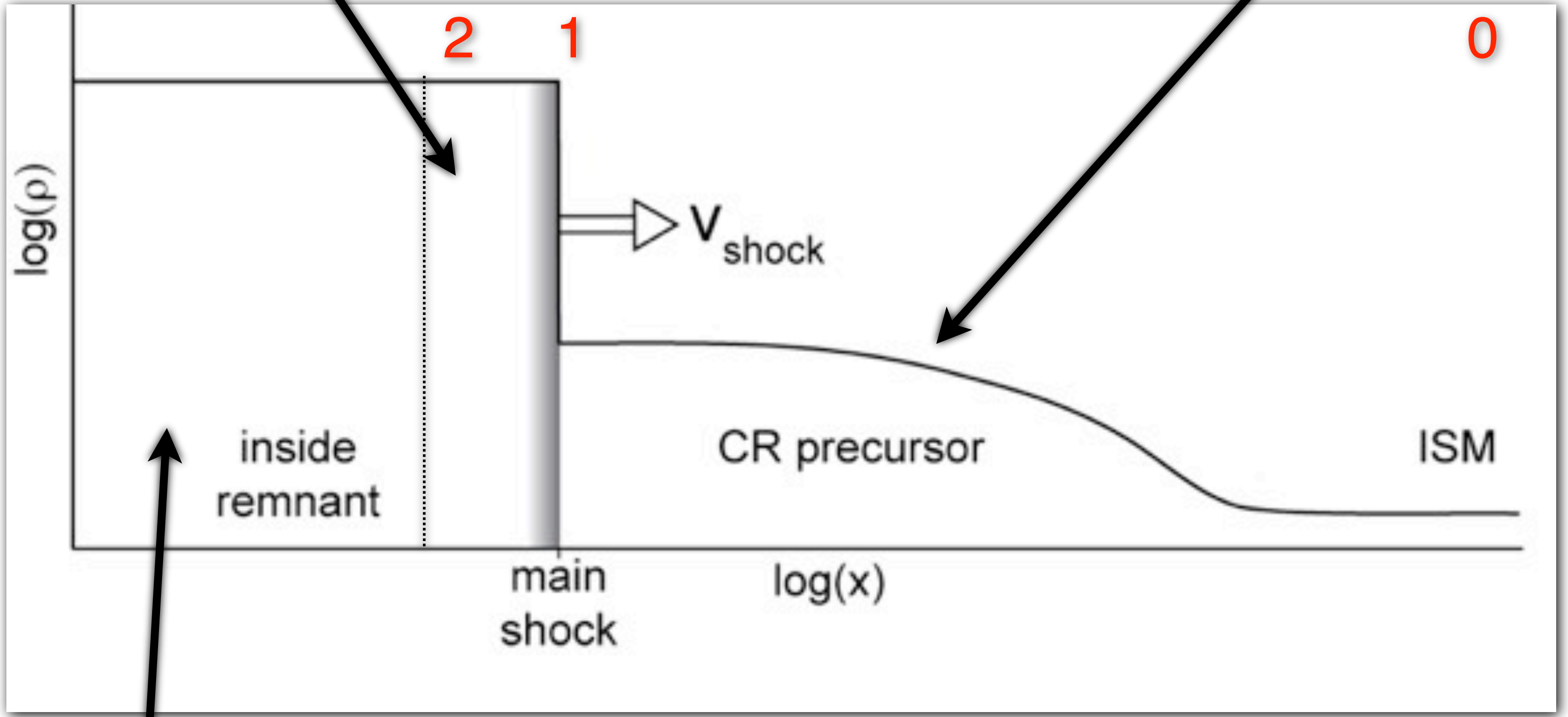
- Proton temperature close to thermodynamic temperature
- Proton temperature can be measured using Hα/Lyα thermal line broadening:
  - -Charge exchange reaction ensure that proton temperature is measured

    → broad component
  - -Direct excitation also gives narrow line
  - -Emission from close to shock ~10^{15}cm

Non-radiative H-alpha emissions

X-ray synchrotron

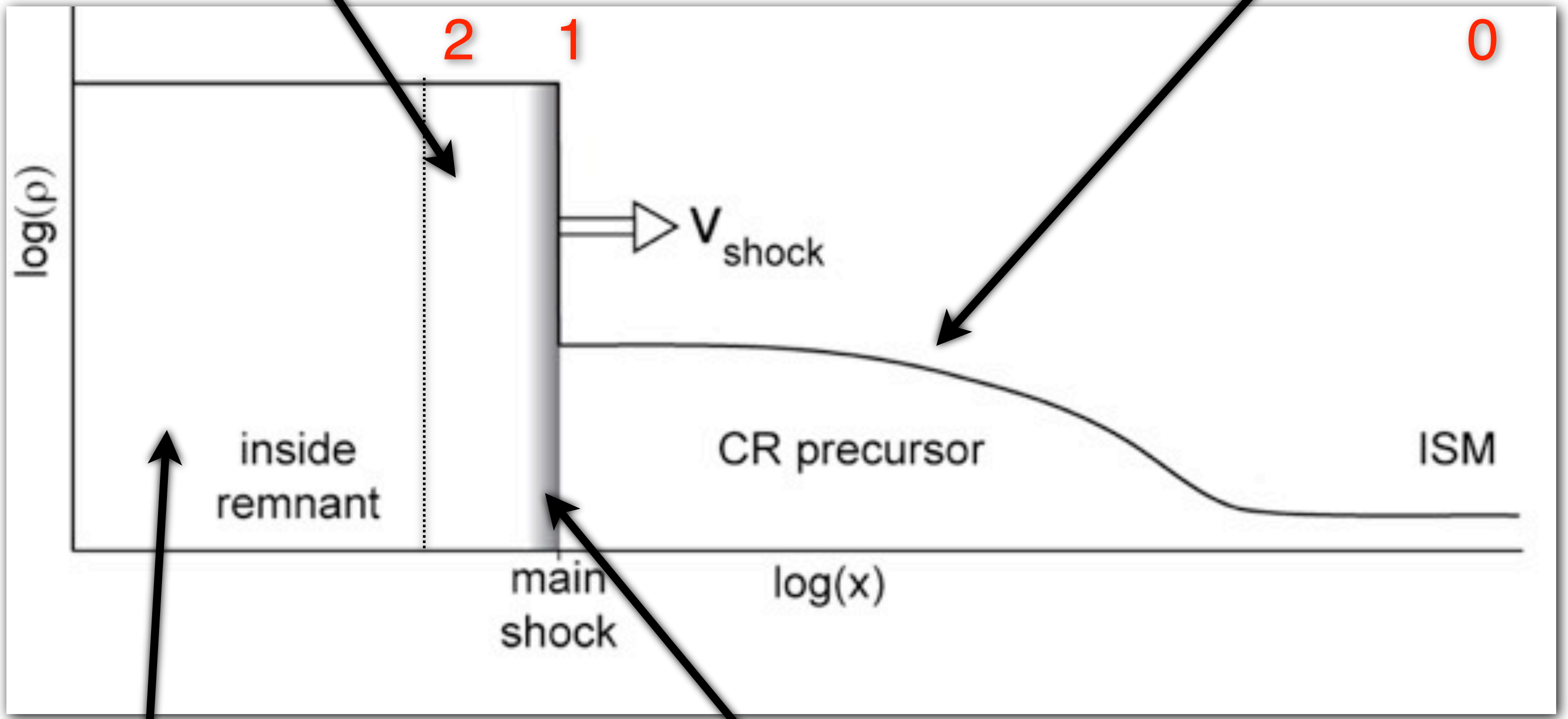
Compression/pre-heating



Thermal X-ray

Fig: Eveline Helder

Non-radiative H-alpha emissions



X-ray synchrotron

Compression/pre-heating

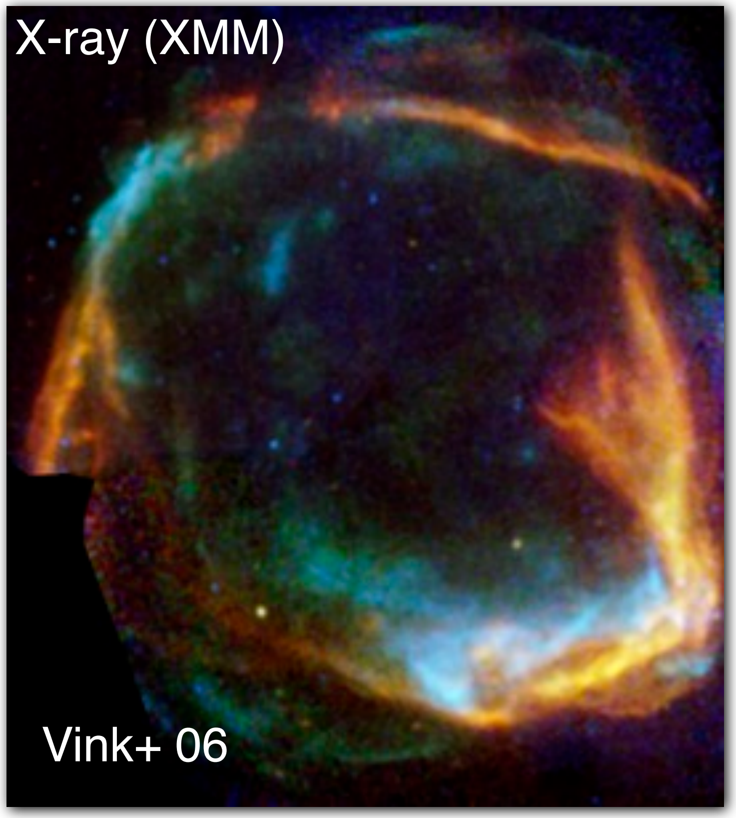
Thermal X-ray

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

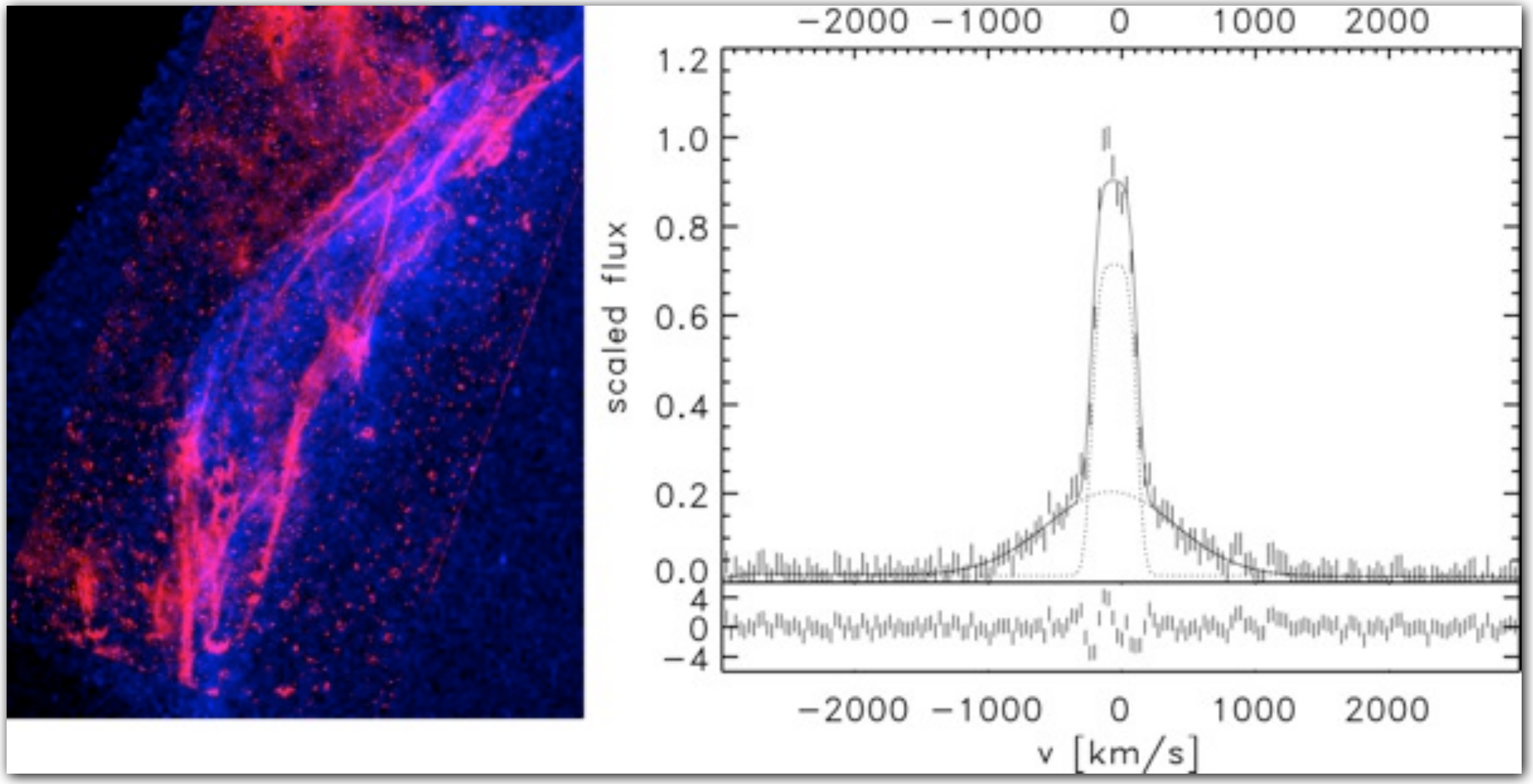
Fig: Eveline Helder

RCW86 NE X-ray synchrotron & Hα

- RCW 86 is ideal for measuring kT_p in presence of cosmic rays:
  - NE shows X-ray synchrotron emission
  - RCW 86 is a TeV source
  - Is a source of Hα emission from regions with X-ray synchrotron



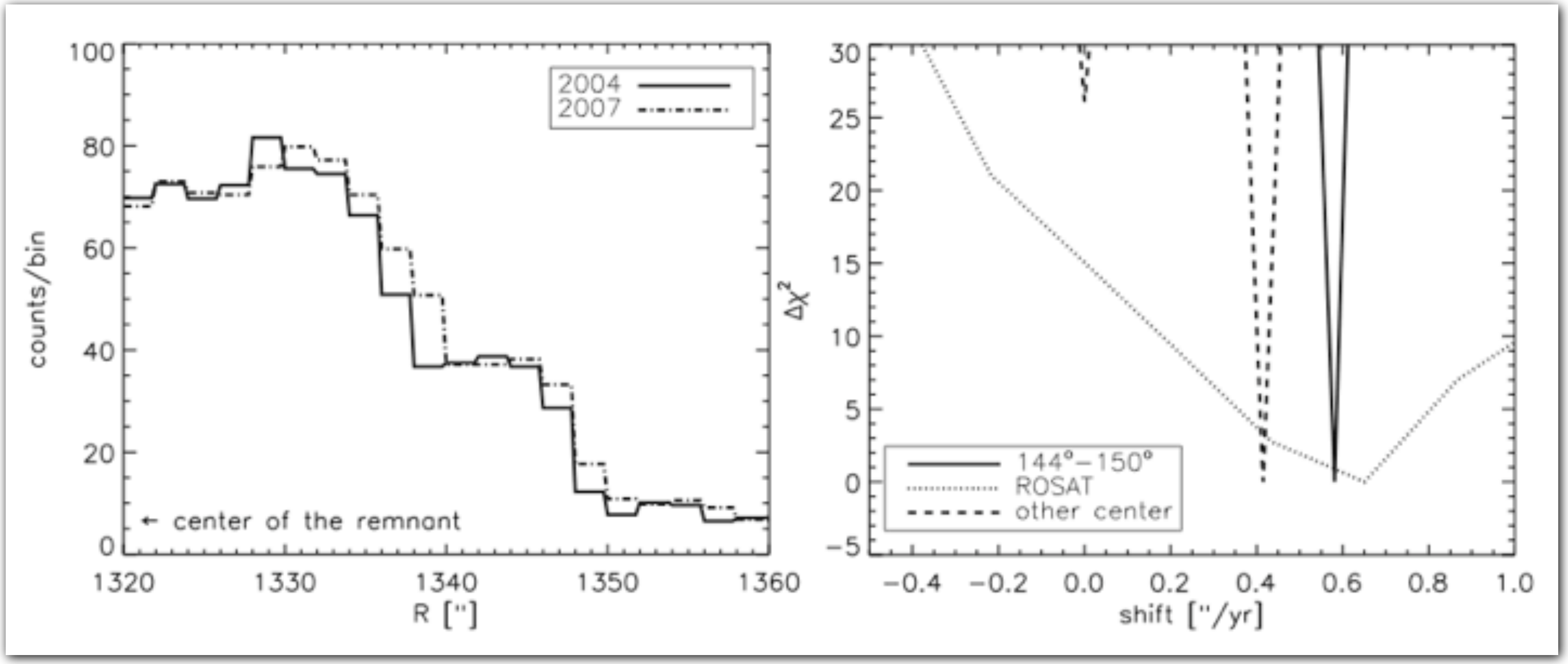
RCW 86 NE Hα measurements



- Broad line: charge exchange of neutrals with hot protons
- Narrow line: direct excitation of incoming neutrals
- Broad line width : 1100 ± 63 km/s ⇒ kT_p = 2.2 keV

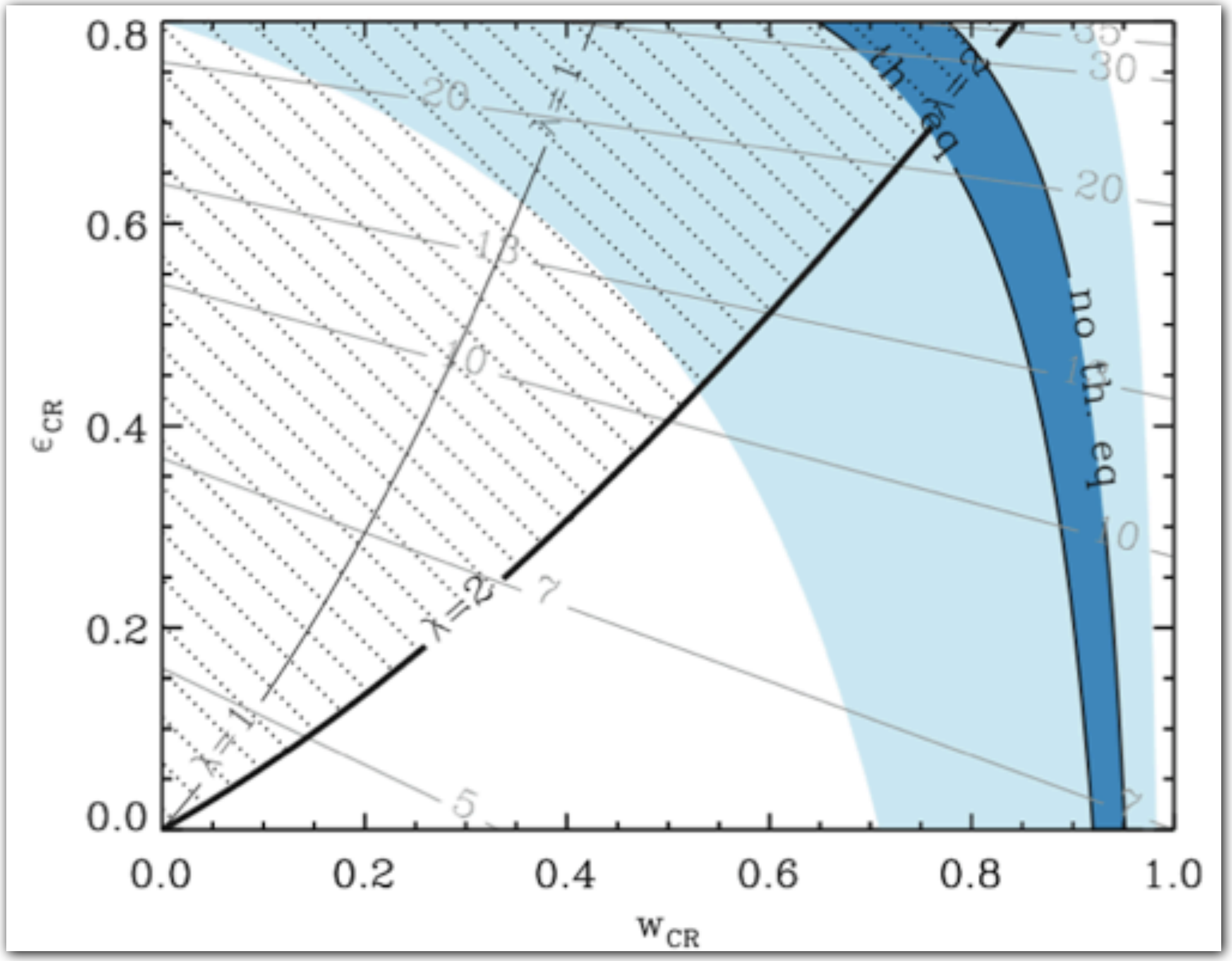
Helder+ 09

Shock proper motion (Chandra)



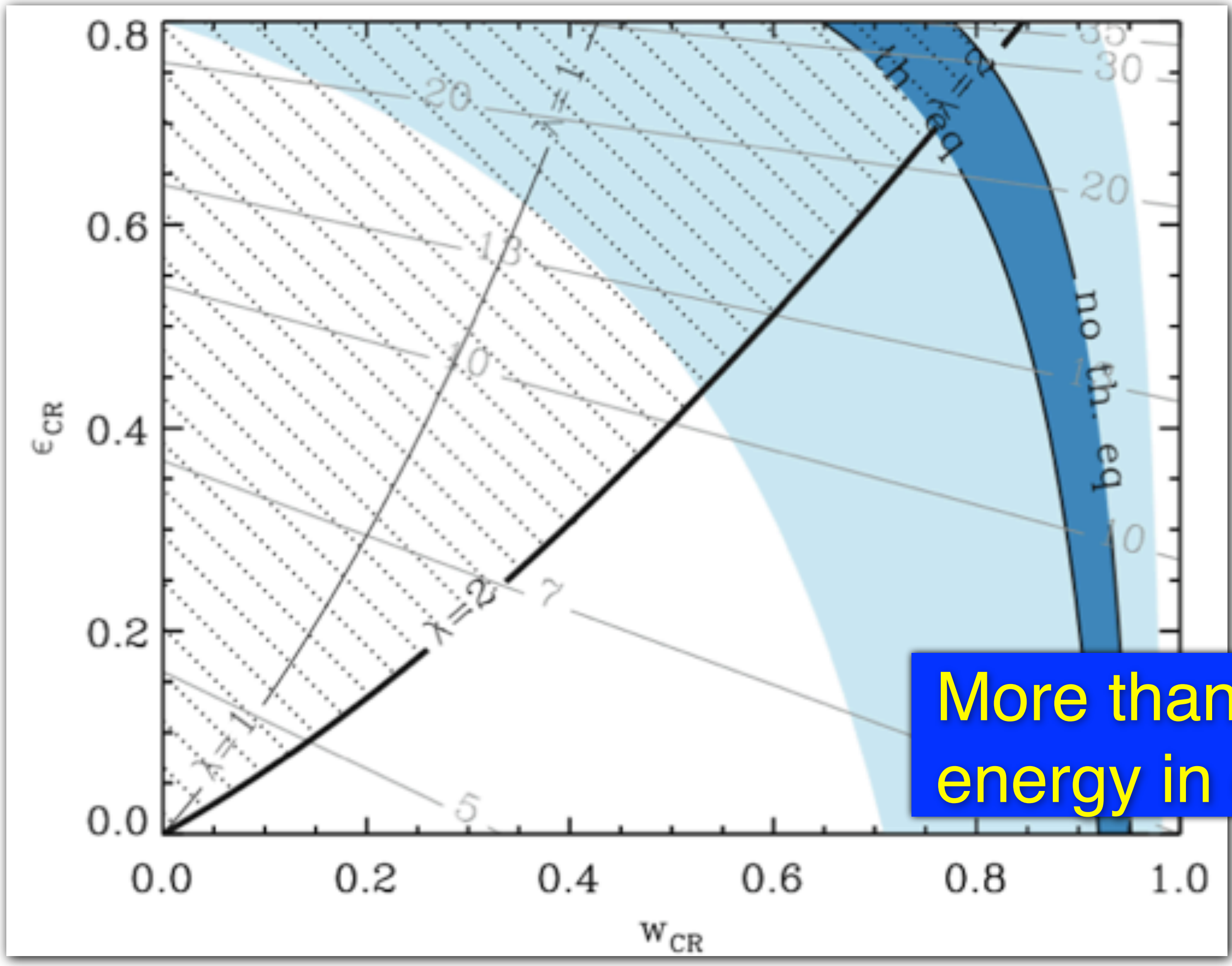
- Proper motion: (1.5±0.3)"/3yr (error largely systematic)
- $V_s = (5900\pm1200)\ d_{2.5}$ km/s
- Expected $kT_p = 43 - 98$ keV
- Ratio expected to observed temperature: 0.03 - 0.06

Cosmic Ray Acceleration Efficiency



Helder+ 09, Science (not part 2 relations)

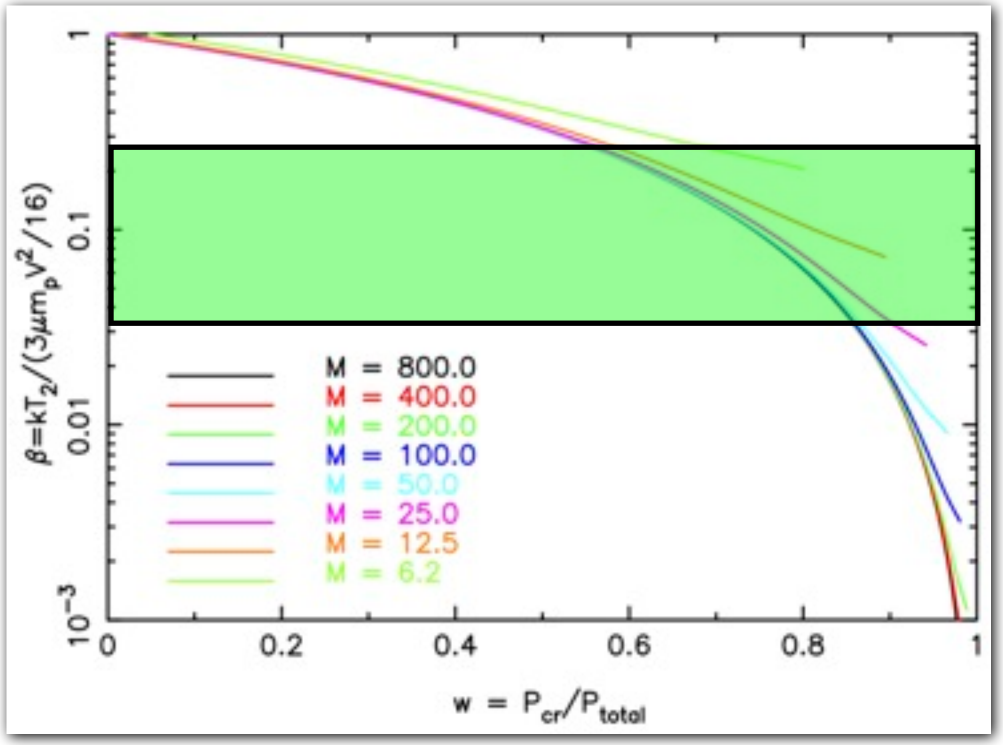
Cosmic Ray Acceleration Efficiency

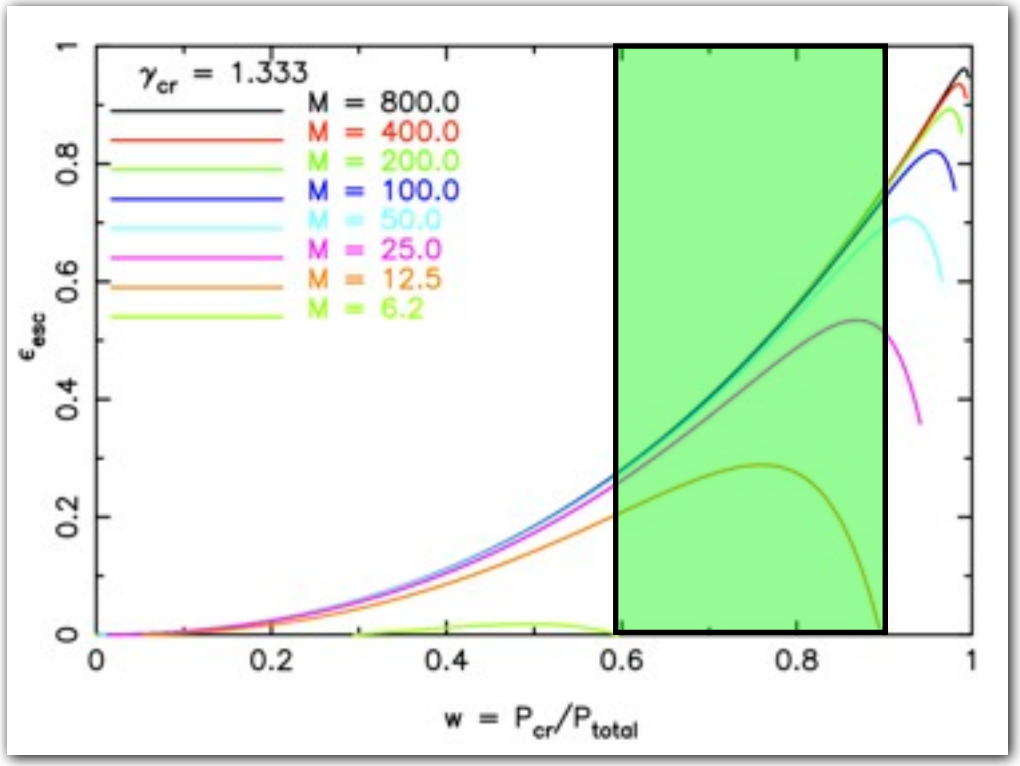


More than 50% of available energy in cosmic rays

Helder+ 09, Science (not part 2 relations)

Cosmic Ray Efficiency Revisited





- Includes all systematic uncertainties in shock velocity.
- NB X-ray synchrotron => V_S>2500 km/s
- Temperature quenching factor nominally 0.055,but may be as high as 0.3
- Confirms that result indicates w>50%
- Shows that escape must be > 20%

X
Summary & Conclusions

Conclusions

- Supernovae and SNRs for a long time linked to origin of Galactic cosmic rays
- Observations over last 16 years seems to confirm this link!!
  - X-ray synchrotron radiation
    - electrons accelerated up to 10^{14} eV
    - evidence for high B-fields: possibility that ions accelerated > 10^{15}eV
  - Gamma-ray observations
    - particles accelerated up to 10^{14} eV
    - nature of dominant emission unclear!!
    - evidence of escaping CRs from old SNRs
- Nevertheless some ambiguities:
  - No observational evidence for acceleration beyond 10^{15} eV
  - Scarce evidence that CR energy fraction in SNRs > 10%
    - Indirect evidence good (compression ratios, B-fields, temperatures)
    - Direct evidence lacking

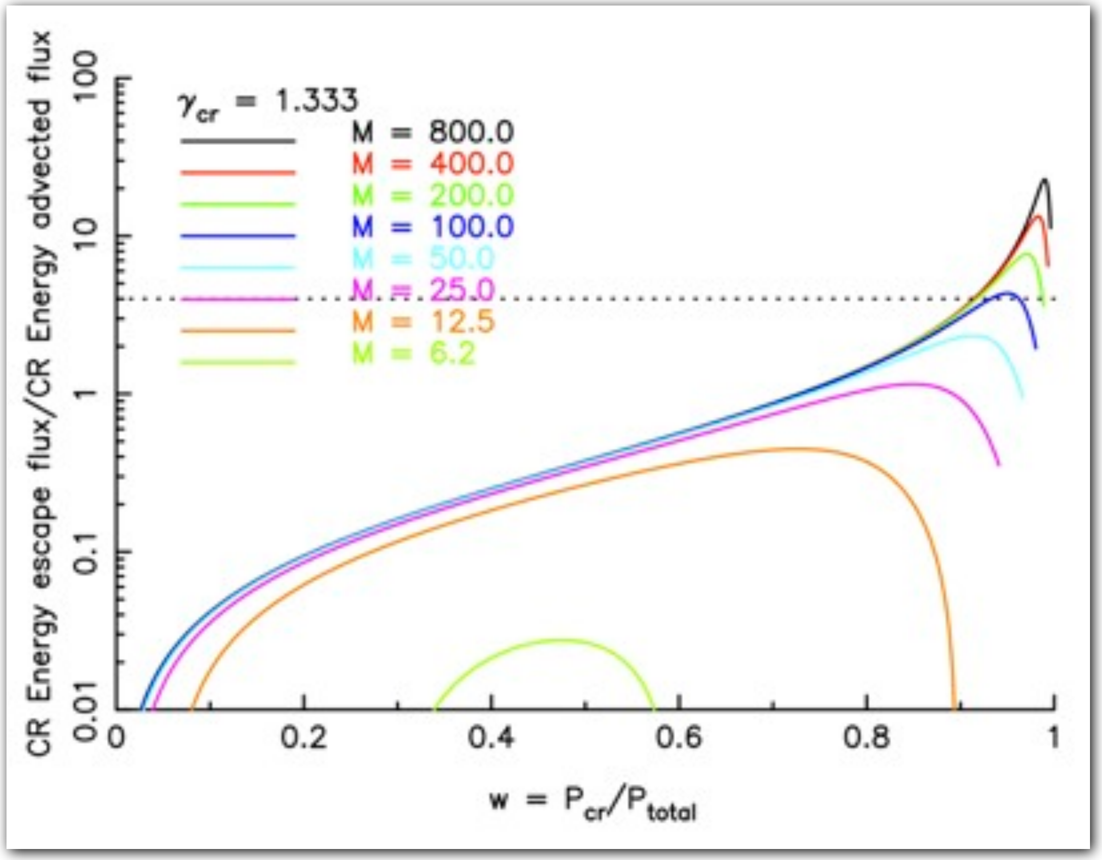
Outlooks

- Since ambiguities in linking SNRs to CRs remain:
  - more emphasis on escape of CRs (how long are CRs retained)
  - closer scrutiny of data (many results fresh, further testing needed)
  - Fermi/TeV telescopes are still producing new results:
    - completer image of acceleration
  - Thermal physics: more optical observations to measure kT_p
  - Further investigations on alternatives: SNOBs, magnetars,...
- Future relevant telescopes:
  - Cherenkov Telescope Array: wider spectral range and 10x more sensitive than HESS/MAGIC/VERITAS (in development):
    - Escaping cosmic rays, fainter sources, populations
  - Athena: future X-ray telescope (ESA):
    - high resolution spectroscopy: measure ion temperatures from Doppler broadening
  - Extremely Large Telescope: 38 m optical telescope
    - faint edge on H-alpha emission: measure shock speed, precursor heating, precursor speed at same time

Extra slides

What does thermodynamics say?

- Extended Hugoniot-relations allows calculation of downstream advected CR flux over escaping CR flux
- For w> ~0.8 escape flux exceeds advected flux!
- Requires very efficient shocks during part of SNR evolution



$$\frac{F_{adv}}{F_{esc}} = 2w\frac{\frac{\gamma_{cr}}{\gamma_{cr}-1}\left[\frac{\chi_1^{\gamma_g+1}}{\gamma_g M_0^2} + \left(1-\frac{1}{\chi_{12}}\right)\right]}{\chi_{12}\epsilon}$$

Probing the pre-cursor physics

- An important part of non-linear acceleration theory is precursor physics
- If CR heat precursor non-adiabatically, CRs are less efficiently heated

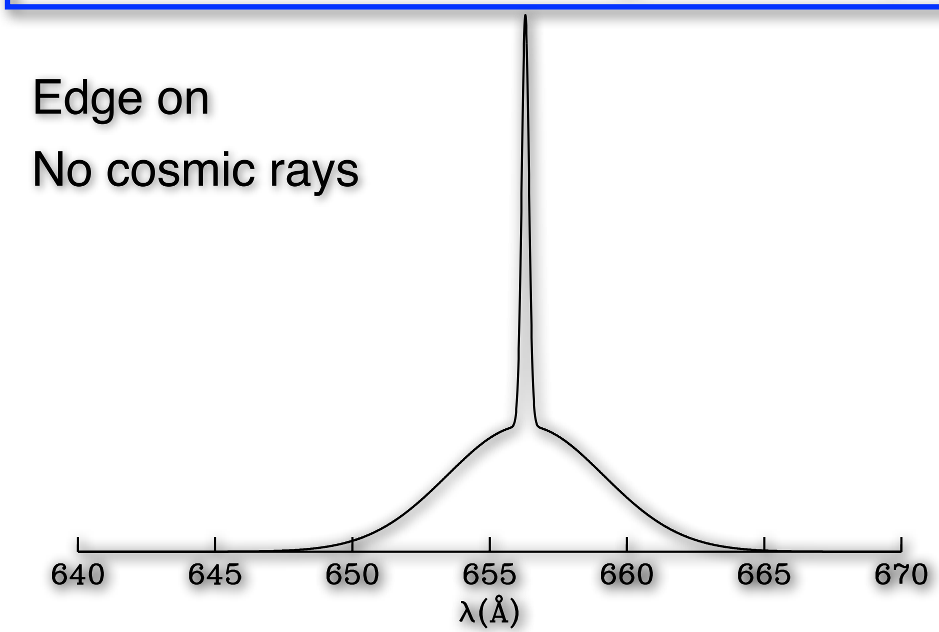
    -> basic reason is that entropy is increased, limits amount of free energy!
- Physics in the precursor may be probed through charge exchange reactions
  - The velocity difference in precursors between neutral and charge particles will lead to charge exchanges
  - Typical precursor lengths are 10^{16}-10^{17} cm, whereas the typical mean free path for charge exchange is ~$10^{15}/n_p$ cm
  - Charge exchange leads to ion-neutral friction -> non-adiabatic heating

      (described in a submitted paper by Raymond, Vink, Helder, De Laat)
  - Charge exchanges in precursor also affect post-shock charge-neutral interactions, as neutral enter shock with precursor velocity
  - Much could be learned from the (faint) Balmer-dominated shock edge on

Probing the pre-cursor with Hα

Edge on

No cosmic rays



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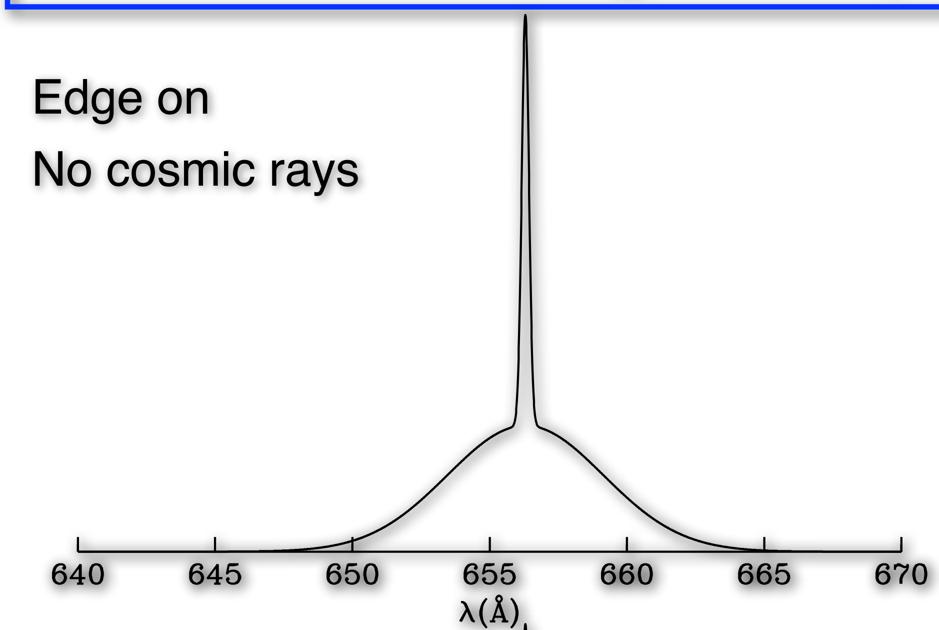
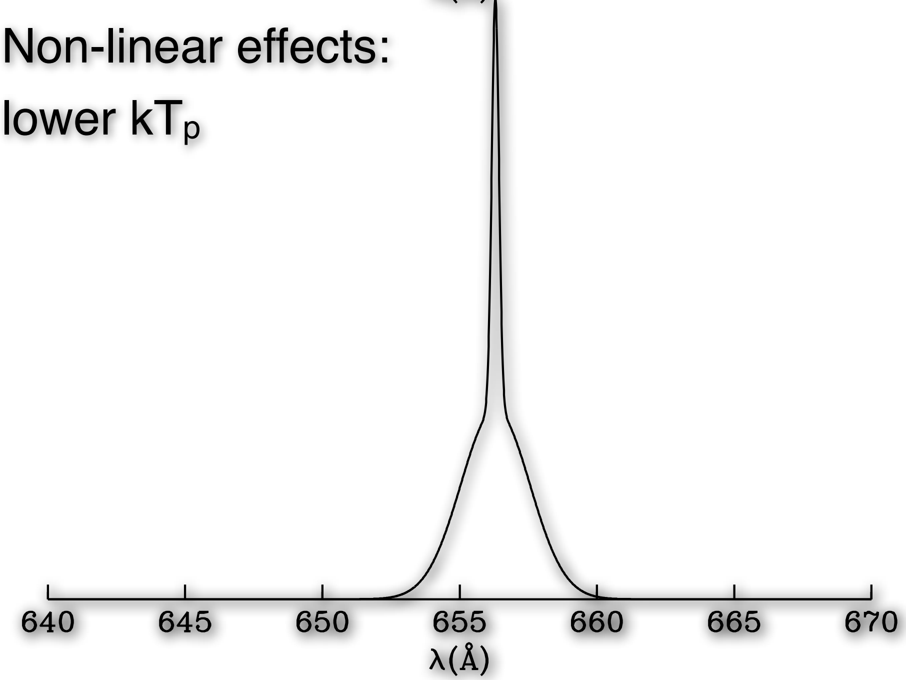


Non-linear effects:

lower kT_p



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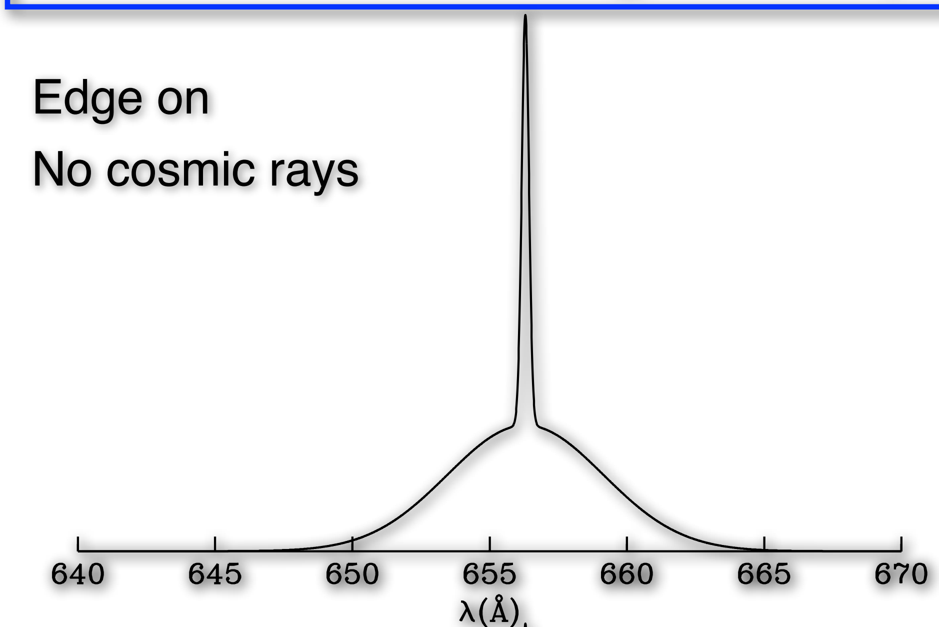
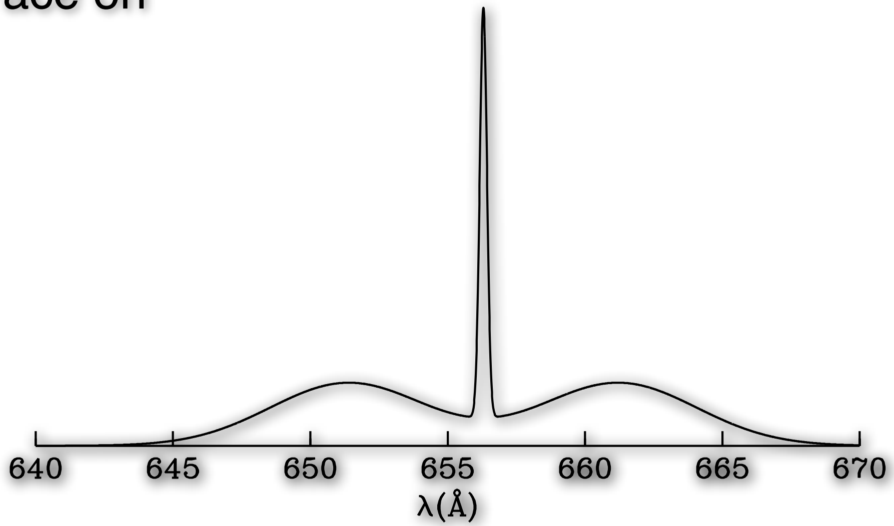


Face on



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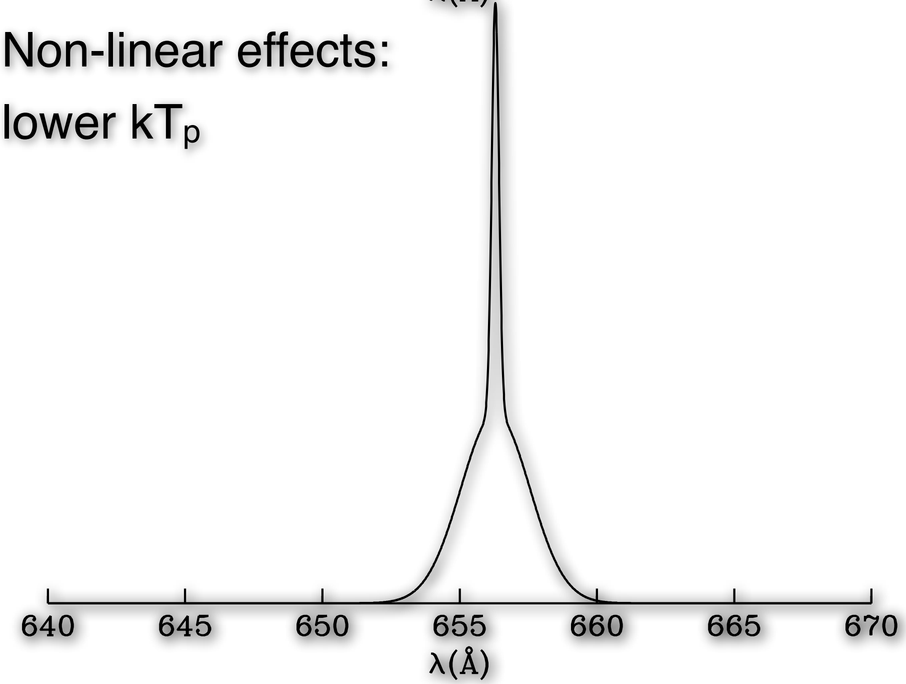

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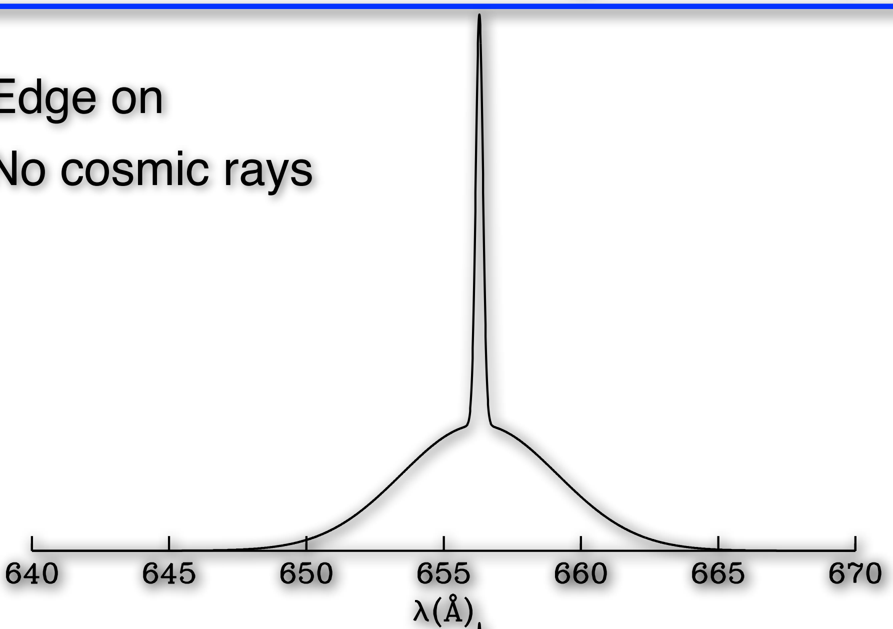

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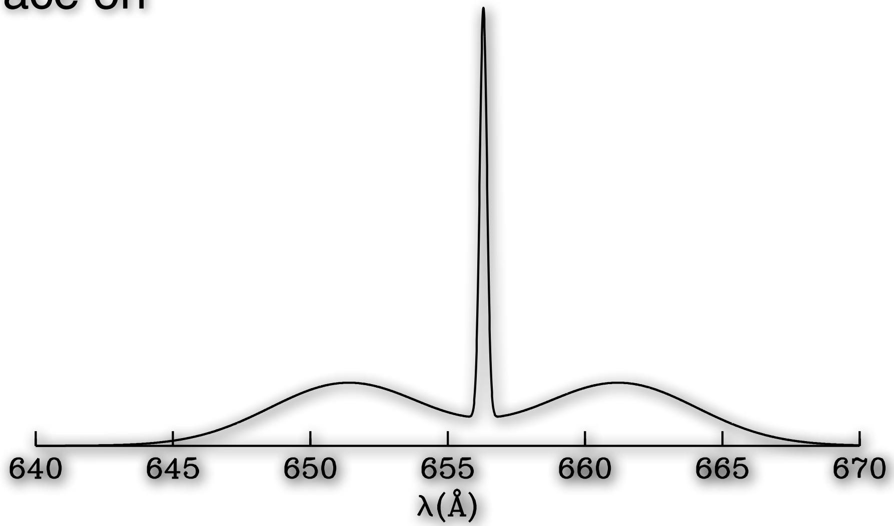

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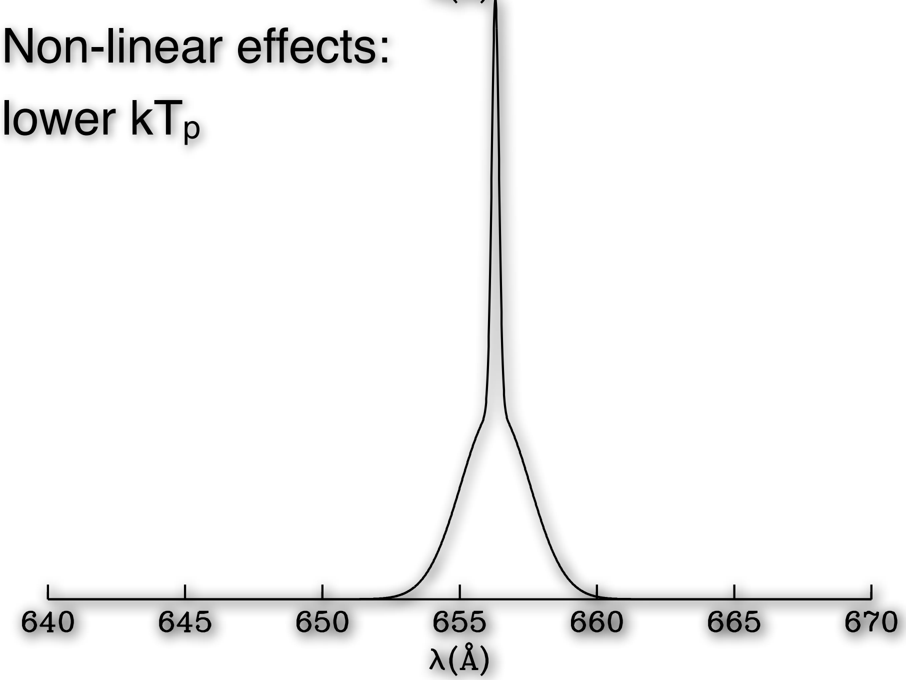
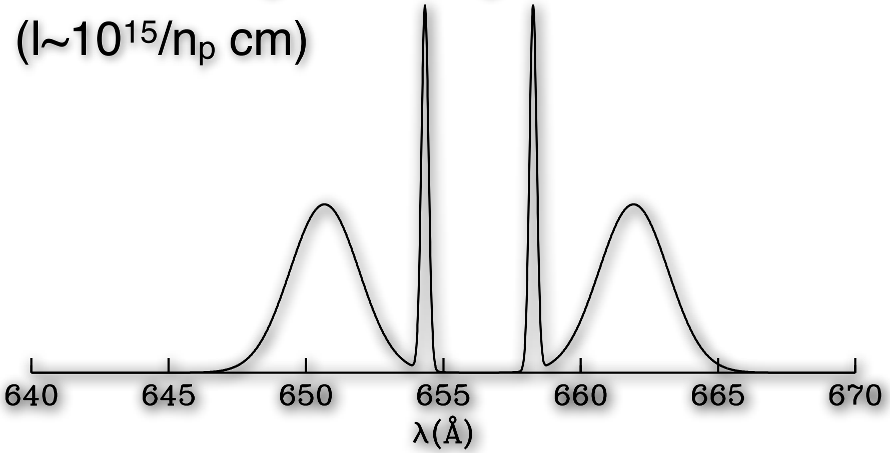


Non-linear effects: lower kT_p

narrow lines: precursor flow speed

@ last charge X-change

($l \sim 10^{15}/n_p$ cm)



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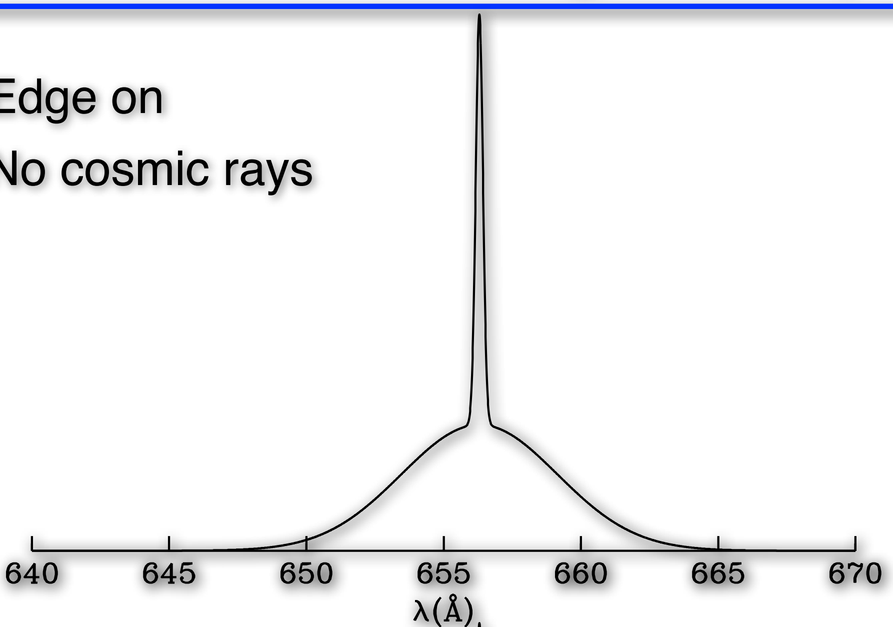
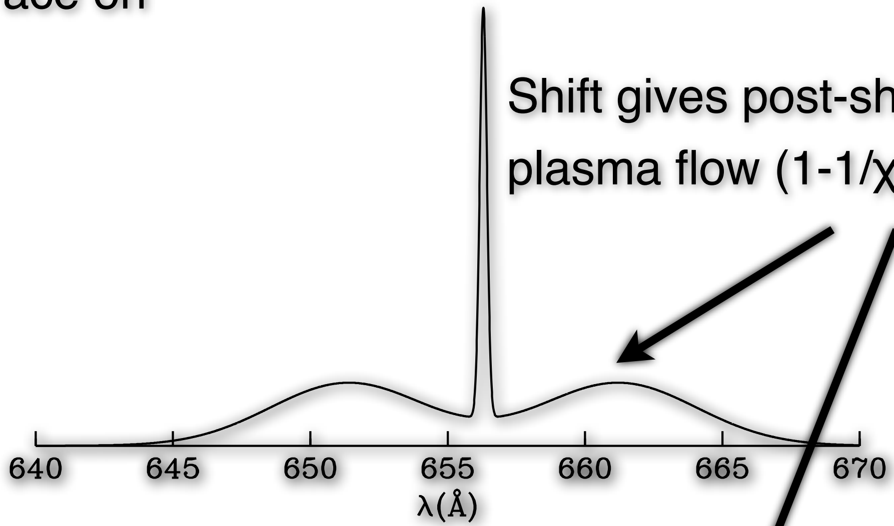


Face on

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



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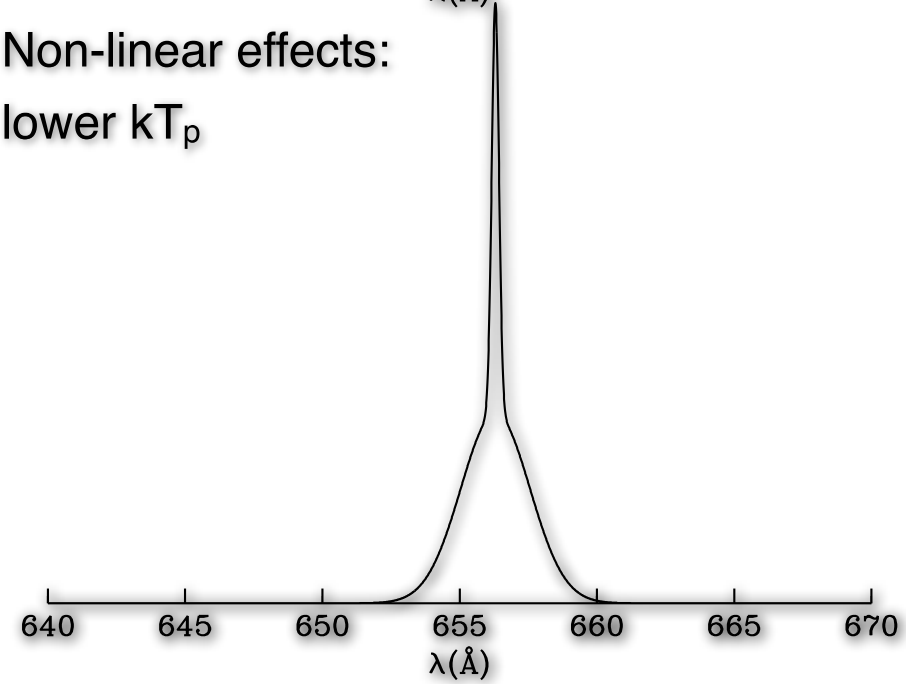

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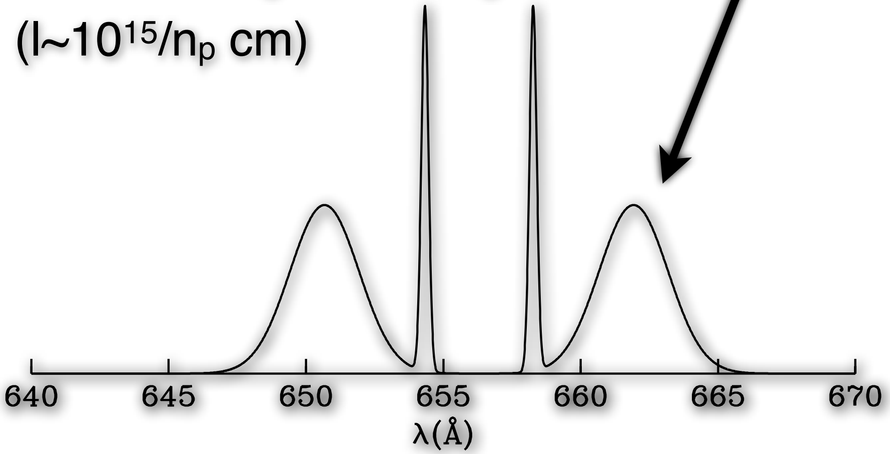
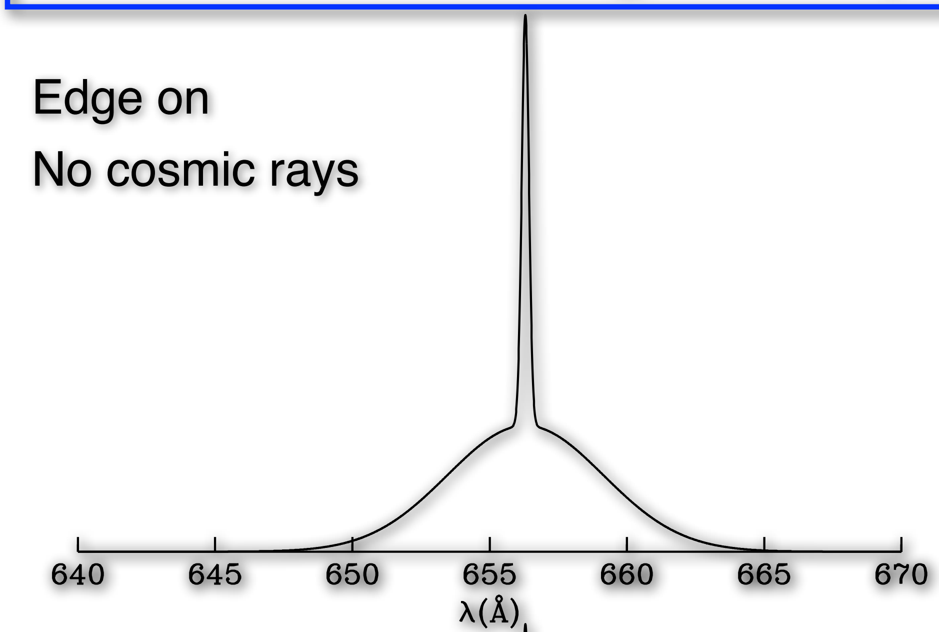


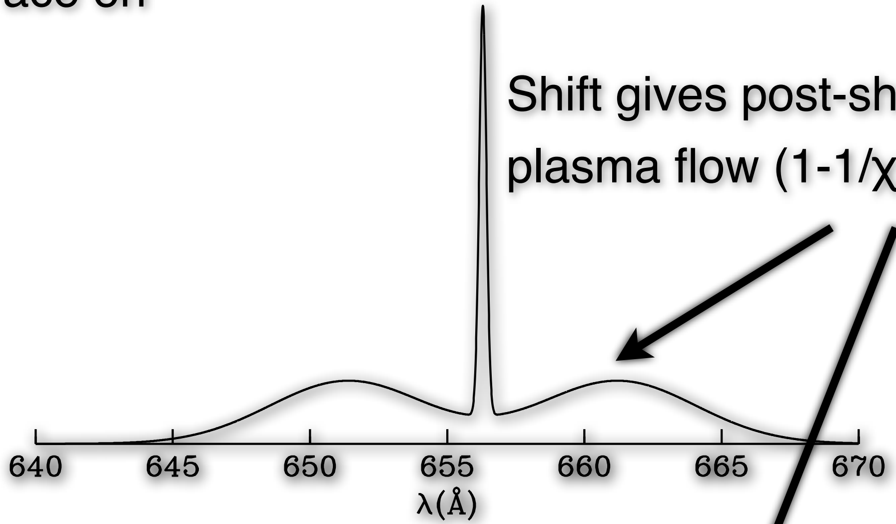
Probing the pre-cursor with Hα

Edge on

No cosmic rays



Face on



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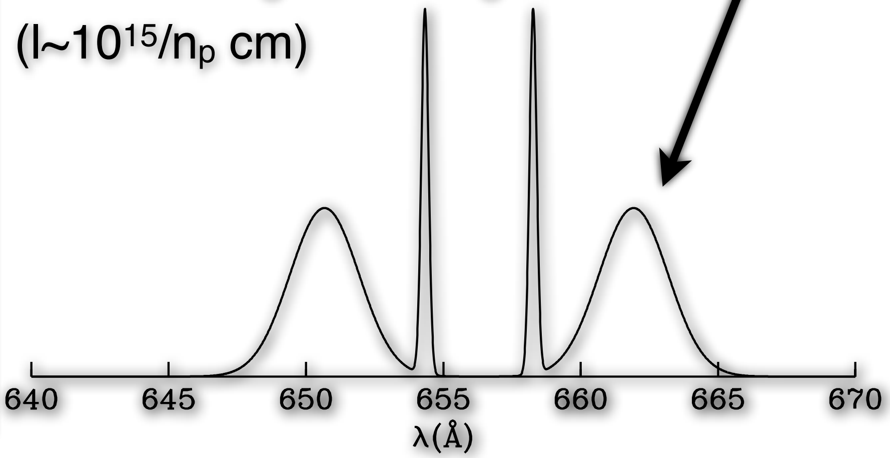
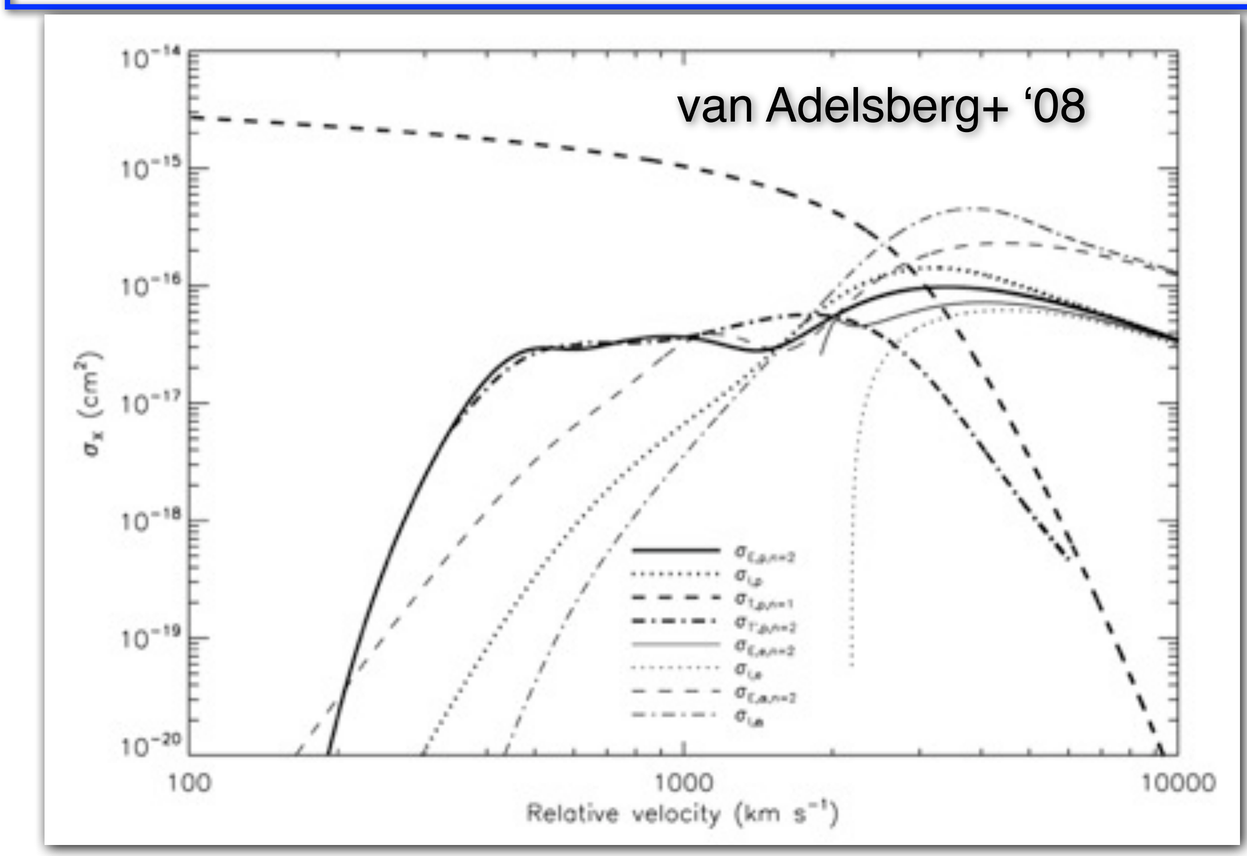


Dreaming on:

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

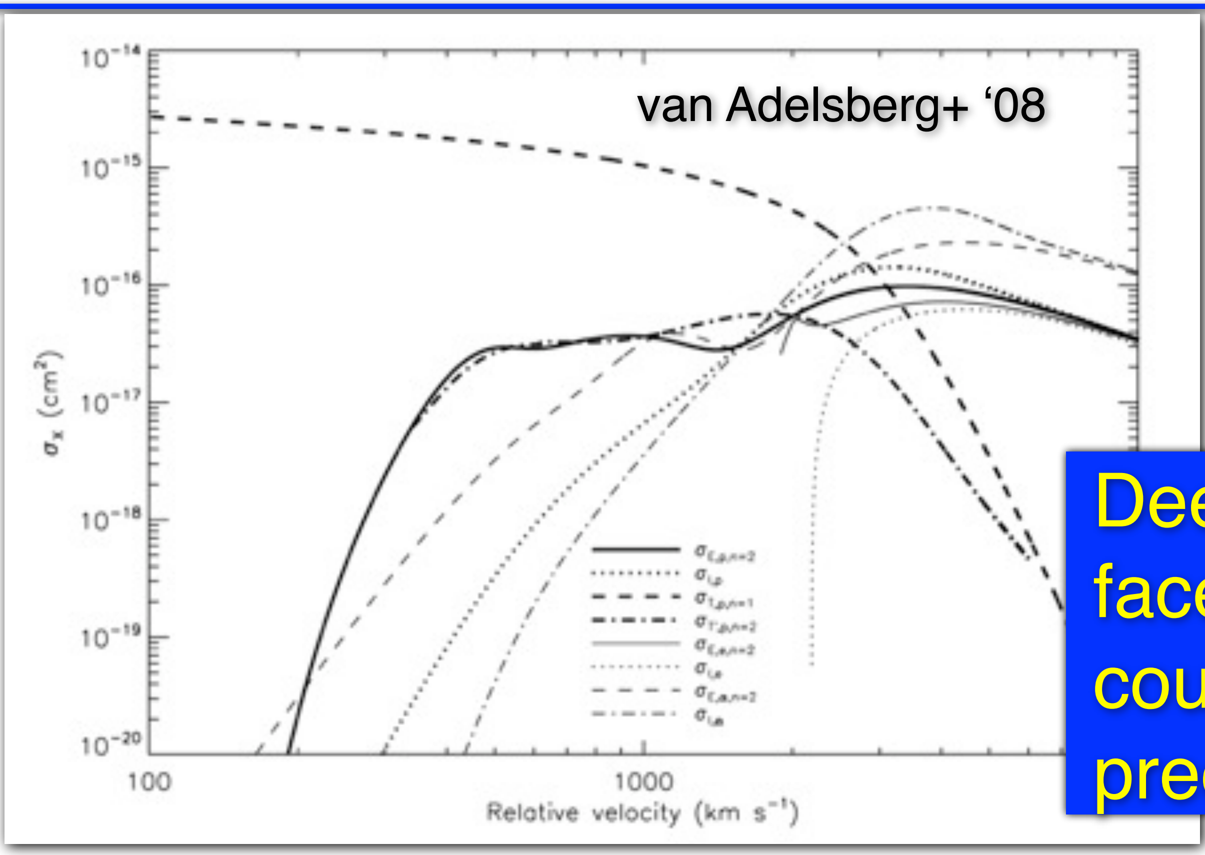
Extra slides

Probing the pre-cursor with Hα


van Adelsberg+ ‘08

- 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

Probing the pre-cursor with Hα



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

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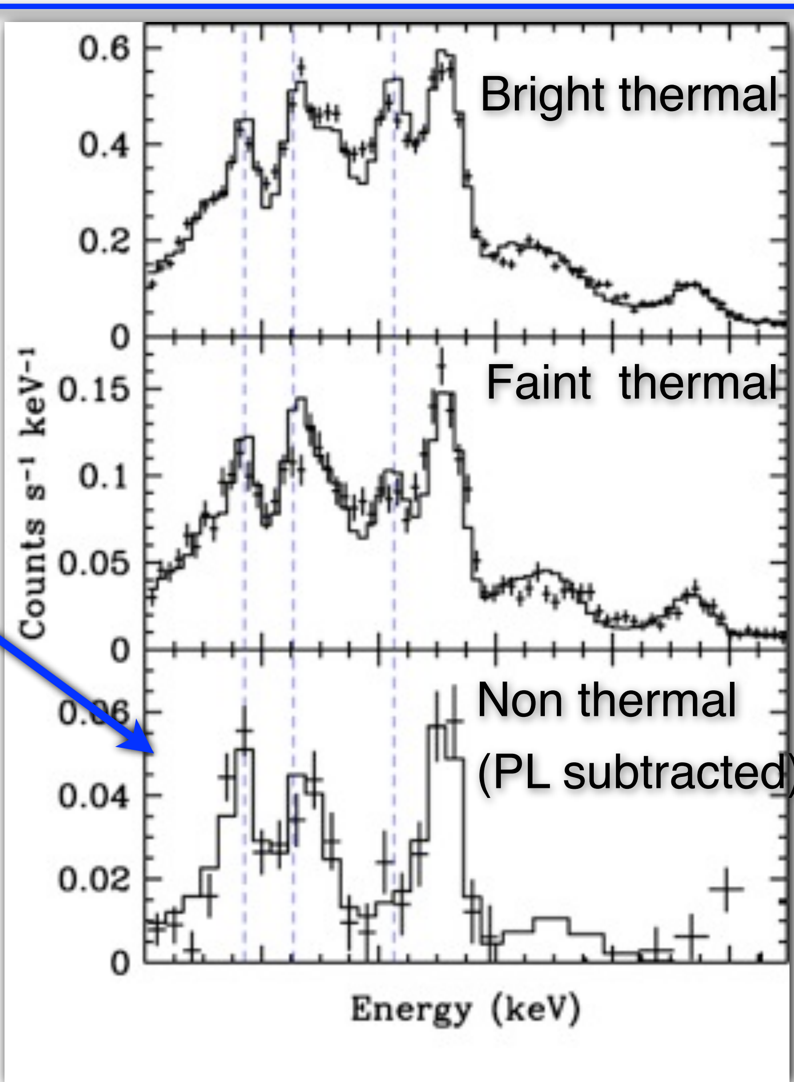
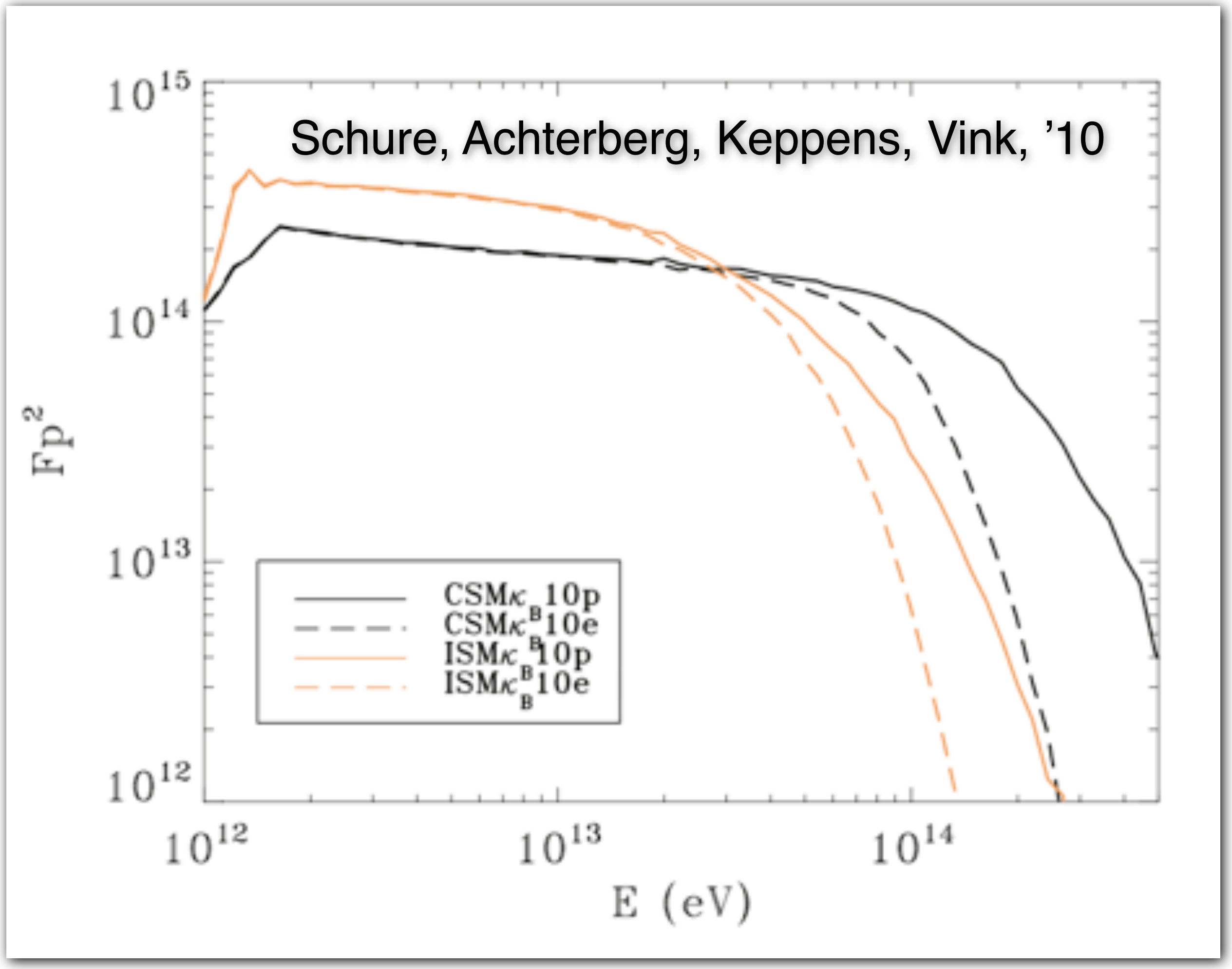
Electron-Ion Equilibration RCW 86 NE



- 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?

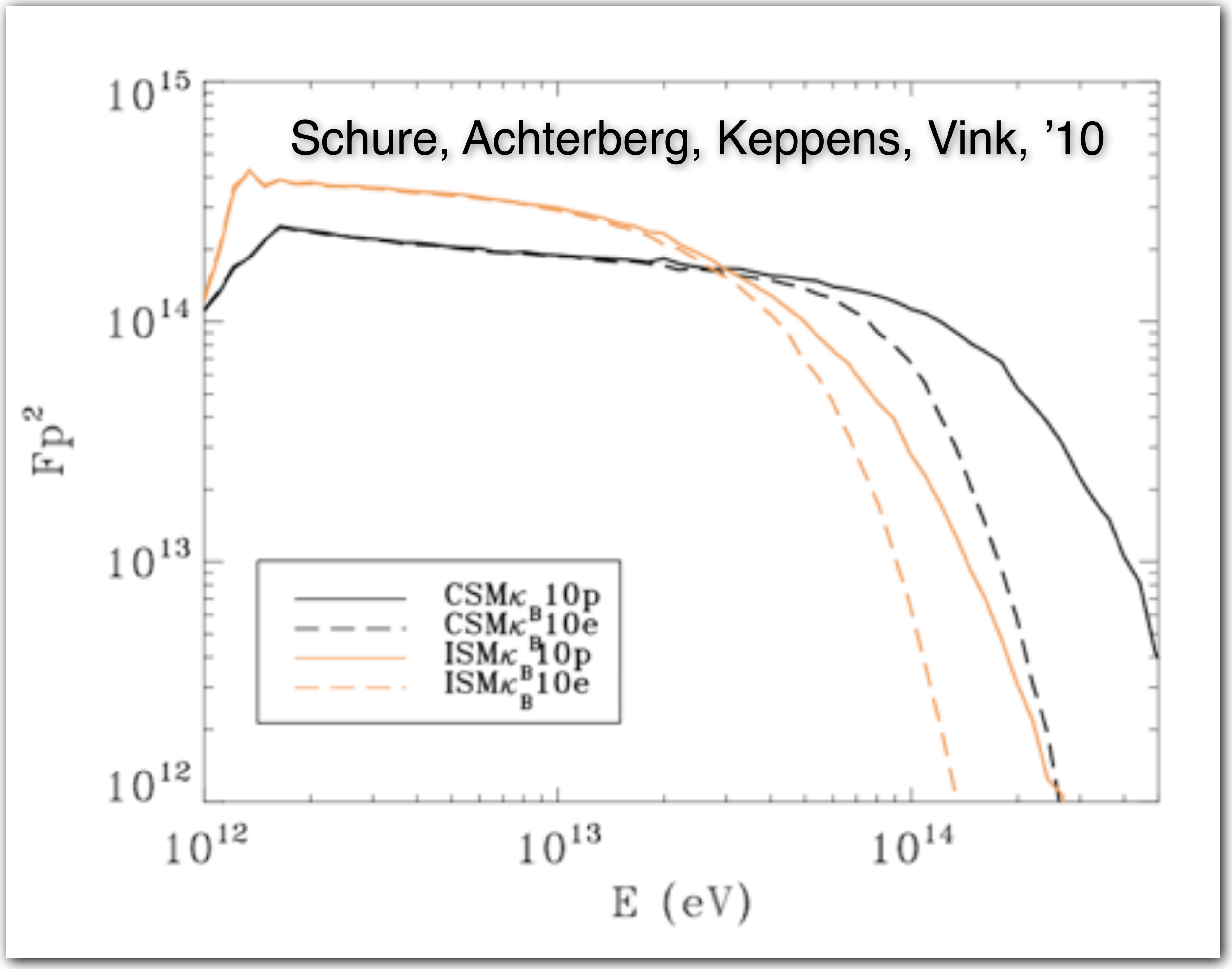
SNRs in wind



Schure, Achterberg, Keppens, Vink, ’10

Based on Monte Carlo code coupled to hydro-code

SNRs in wind

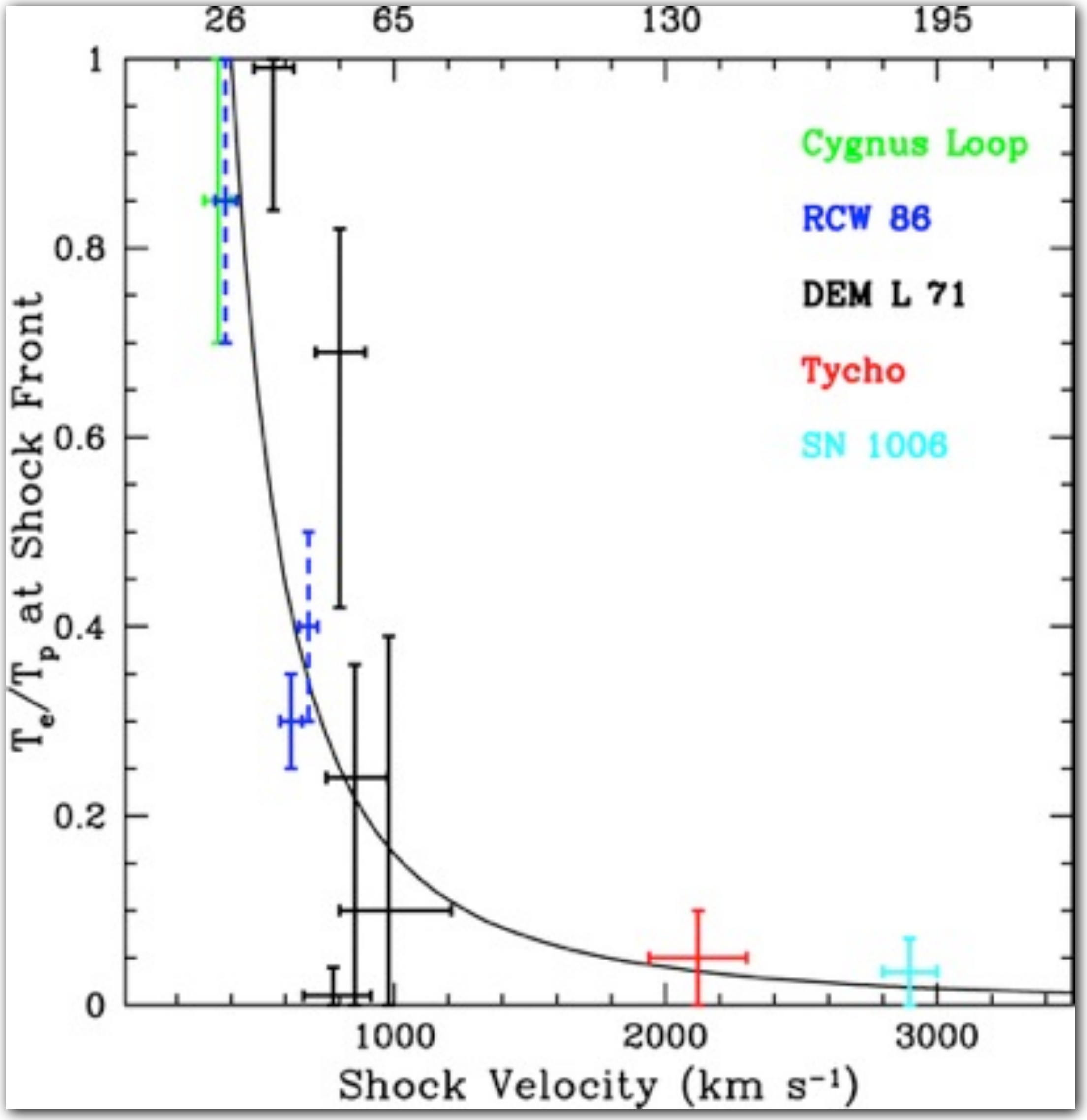


Schure, Achterberg, Keppens, Vink, ’10

Based on Monte Carlo code coupled to hydro-code

Even without amplification, SNRs inside strong winds are better accelerators

Proton temperatures



Comparing *electron* and *proton* temperatures

- Proton temperature:

  thermal Doppler broadening of Hα

- Electron temperature:

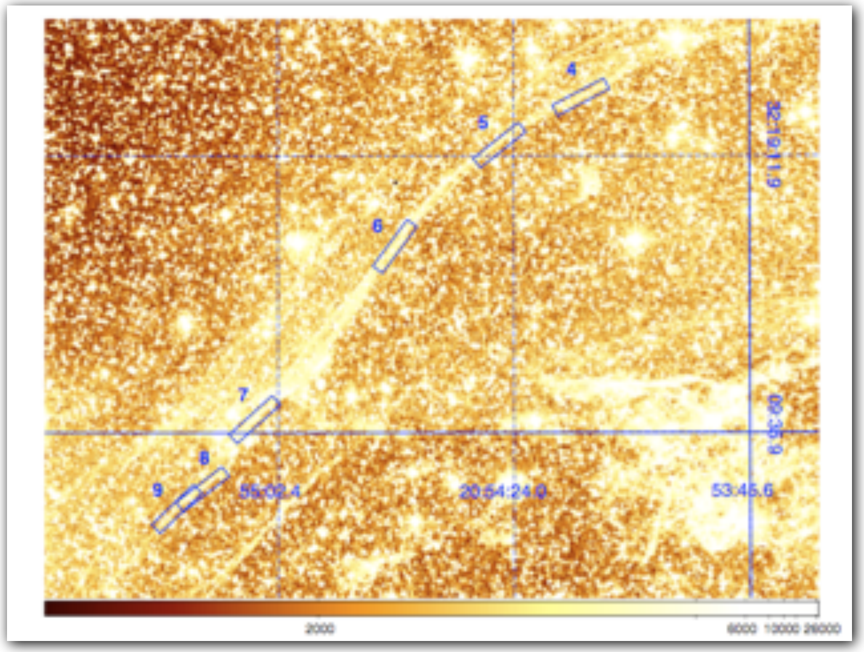
  X-ray spectra

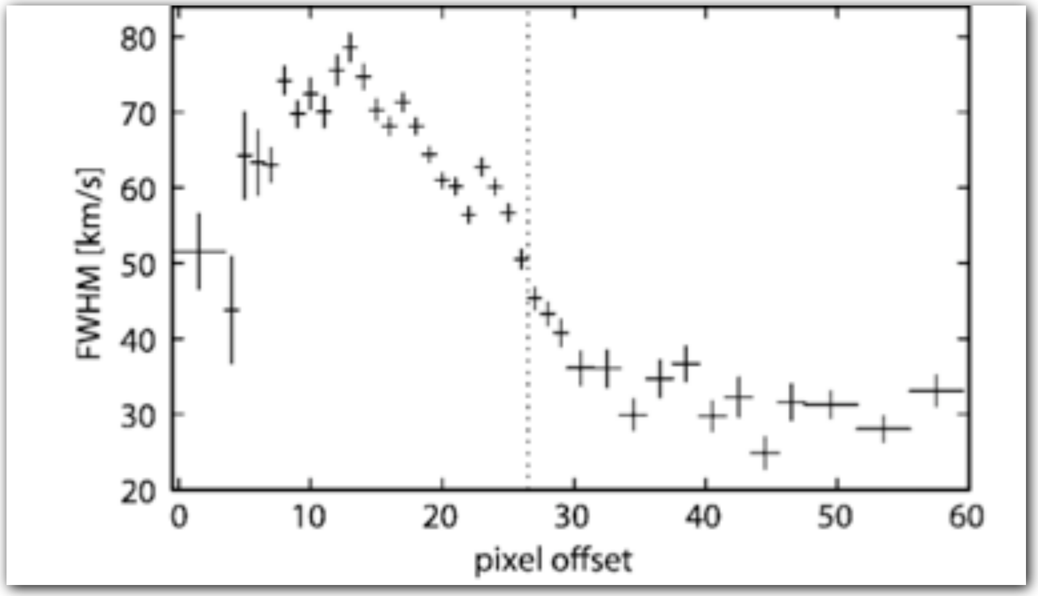
- $T_{\mathrm{protons}} > T_{\mathrm{electrons}}$ only for $V_s >$ 300 km/s

Ghavamian+ ‘07

van Adelsberg+ ‘08

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?