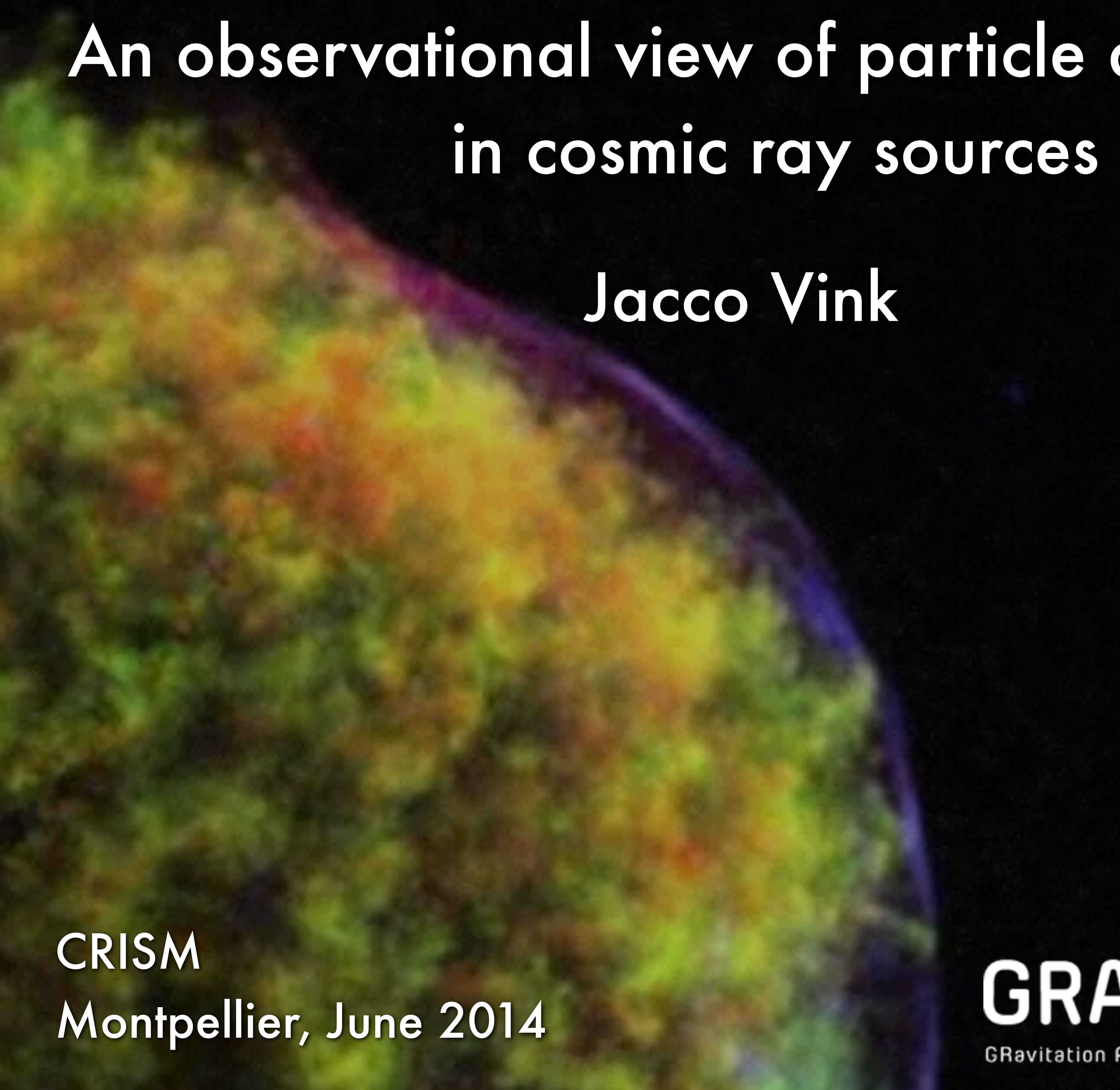
An observational view of particle acceleration in cosmic ray sources

Jacco Vink



CRISM
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GRAPPA
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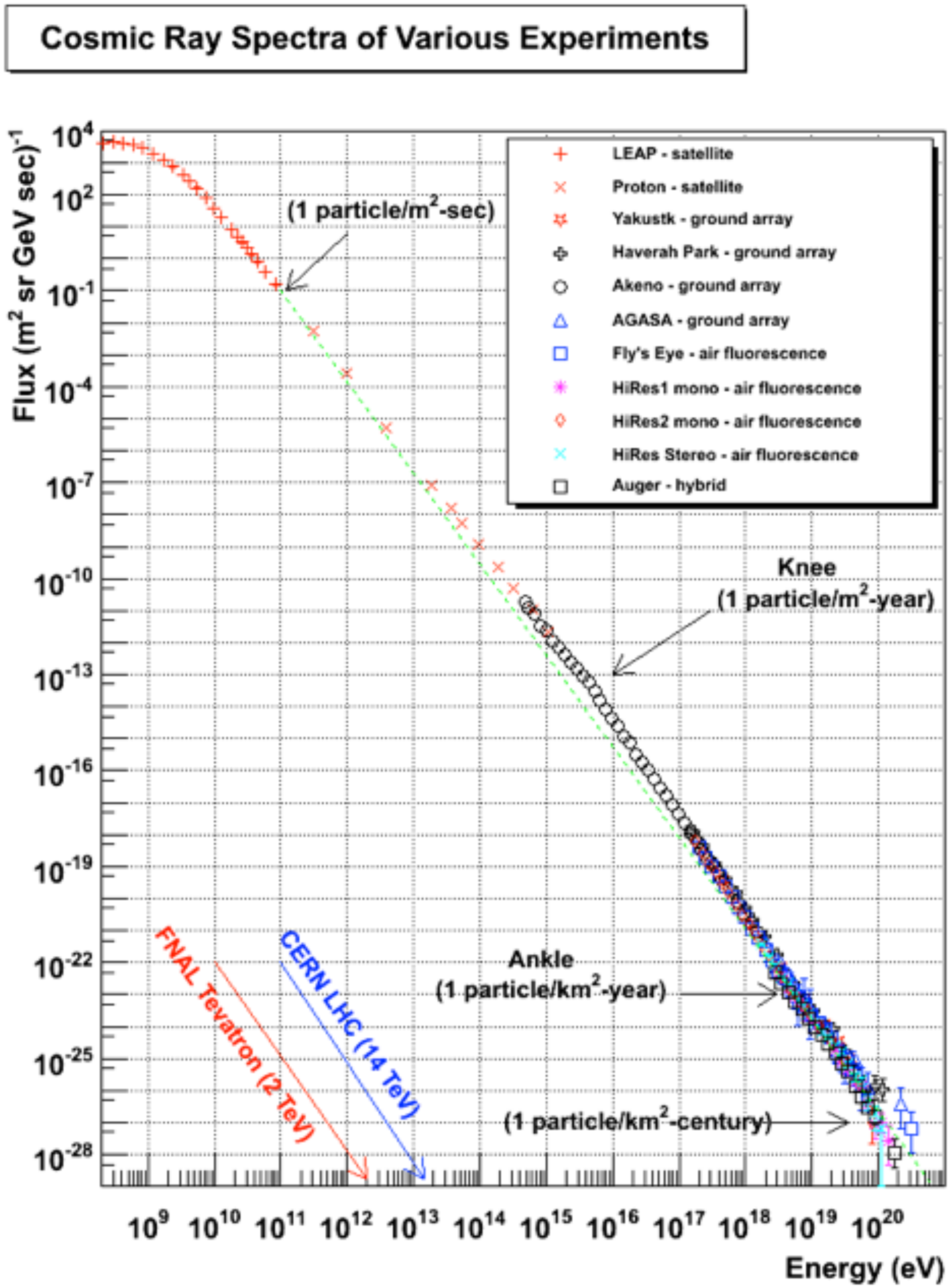
The Cosmic Ray Spectrum



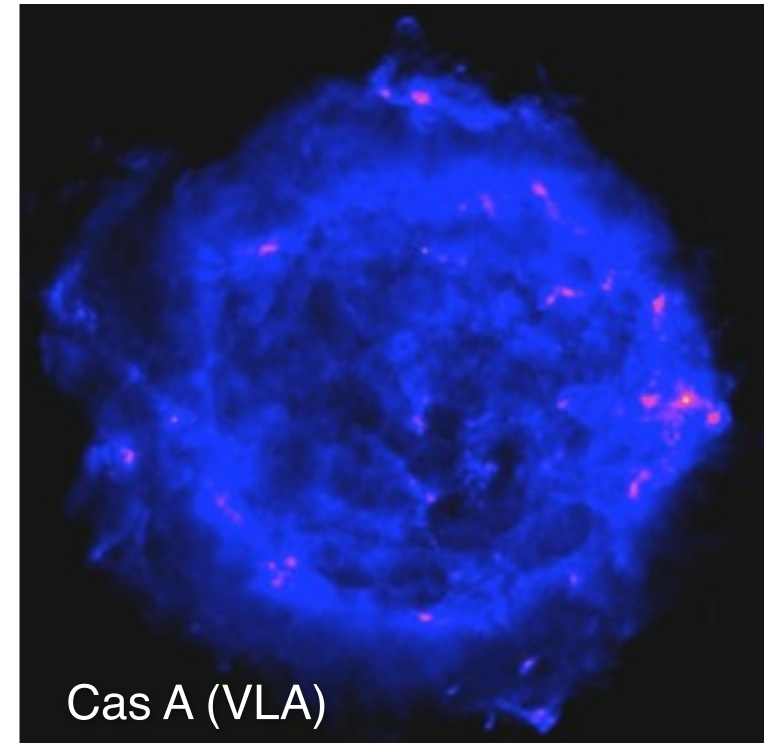
The origin of Galactic cosmic rays

In order for SNRs to be the source of Galactic cosmic rays, two criteria need to be satisfied:

1. SNRs should put 5-10% ($\simeq 10^{50}$ erg) of kinetic energy in cosmic rays
   ➜ *when do they do this, early, young, or Sedov stage?*
   ➜ *should collective effects be considered (super bubbles?→Bykov)*

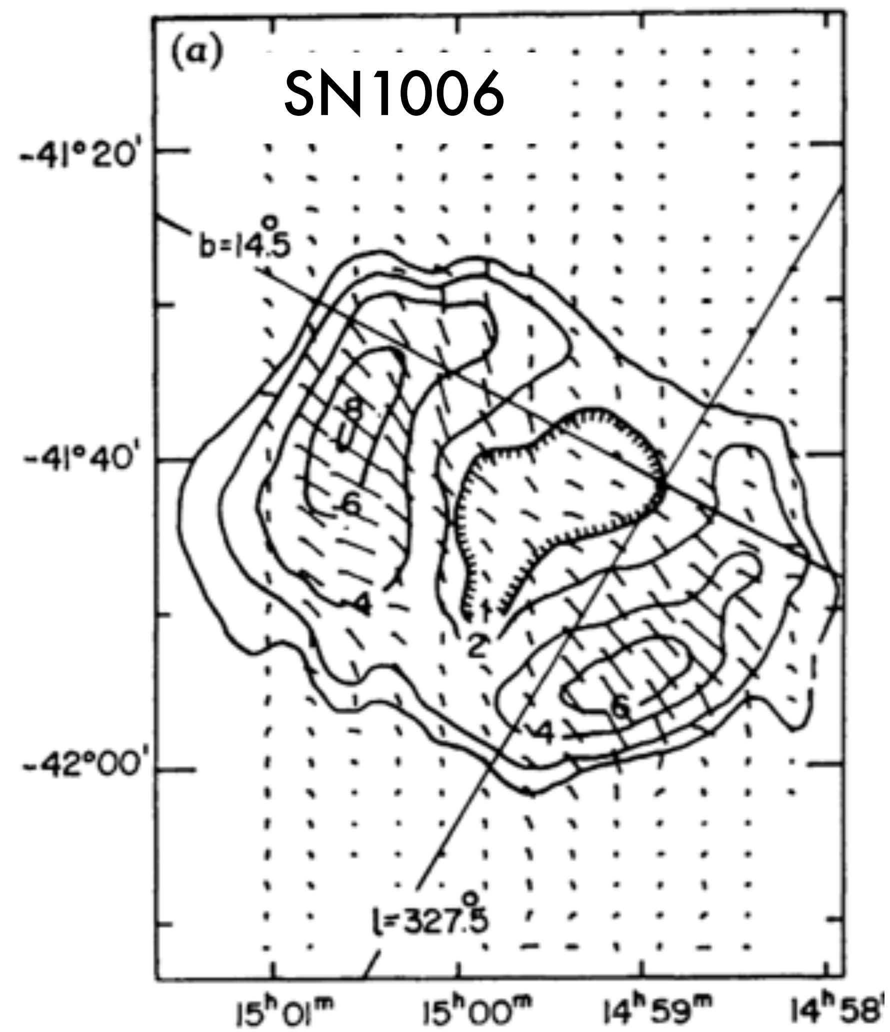
2. SNRs should be able to accelerate particles to $>3\times10^{15}$eV
   ➜ *where are the Galactic Pevatrons?*

Early evidence for particle acceleration by SNRs



- Supernovae associated with cosmic rays since Baade & Zwicky (1934)
- Development of radio astronomy (1950-1960): SNRs are radio synchrotron sources
- Since 1960ies: SNe sources of energy, but acceleration inSNR stage
- Important source: Cas A
  - Too strong a radio source to explain with compression pre-existing electrons (van der Laan mechanism)
  - Important: radio synchrotron radiation→ electrons of at least ≃1-10 GeV
    - *What about protons, and what about the cosmic ray knee?*

Radio polarization of young vs mature SNRs



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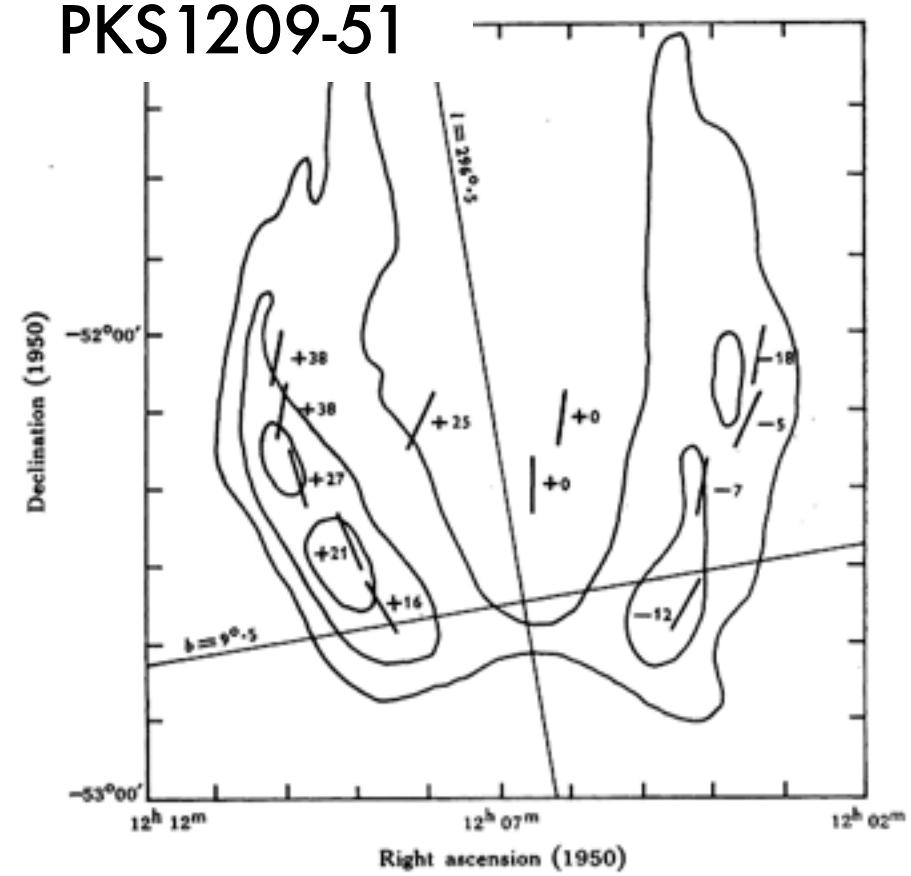


Dickel & Milne '96

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

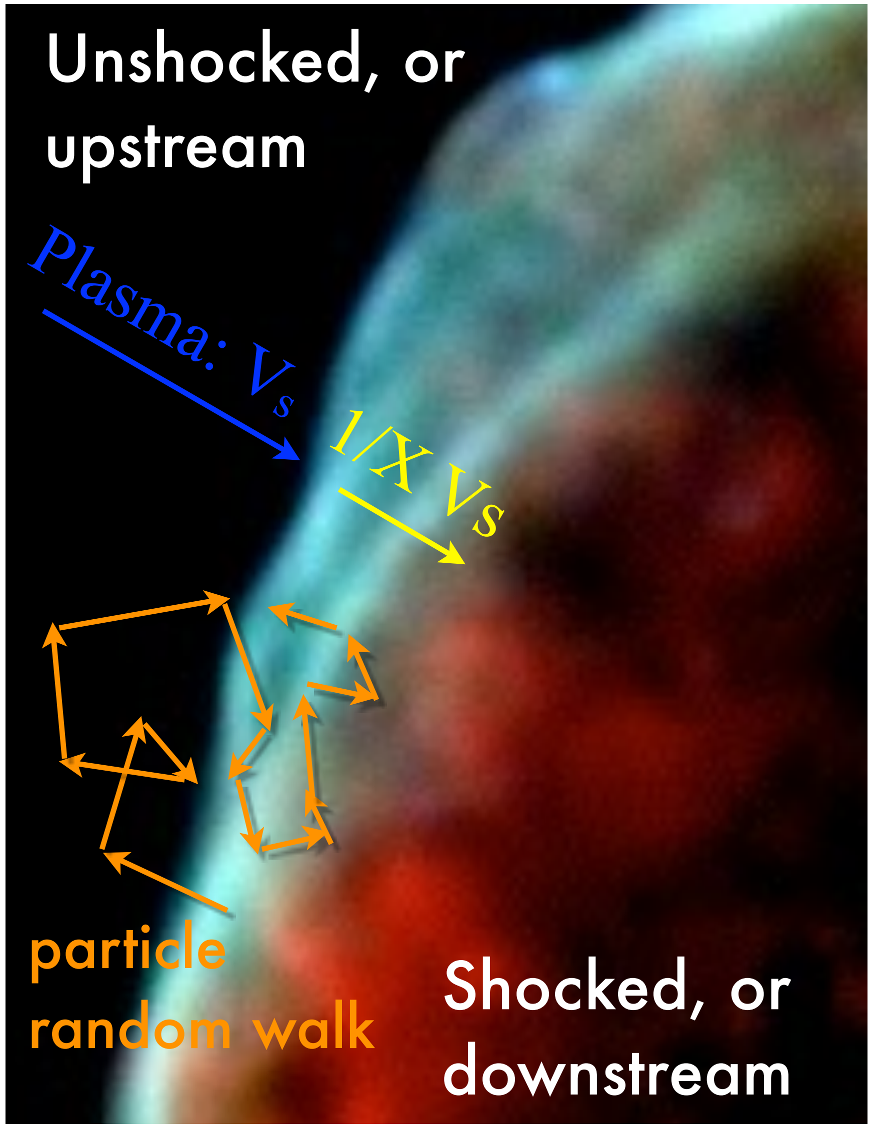
- *Tangential* magnetic fields
- Flux can be explained by *Van der Laan mechanism* (compression of pre-existing electron cosmic rays)

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 swept away from shock)
- Resulting spectrum:

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

with 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

- Length scale for which diffusion dominates over advection:

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

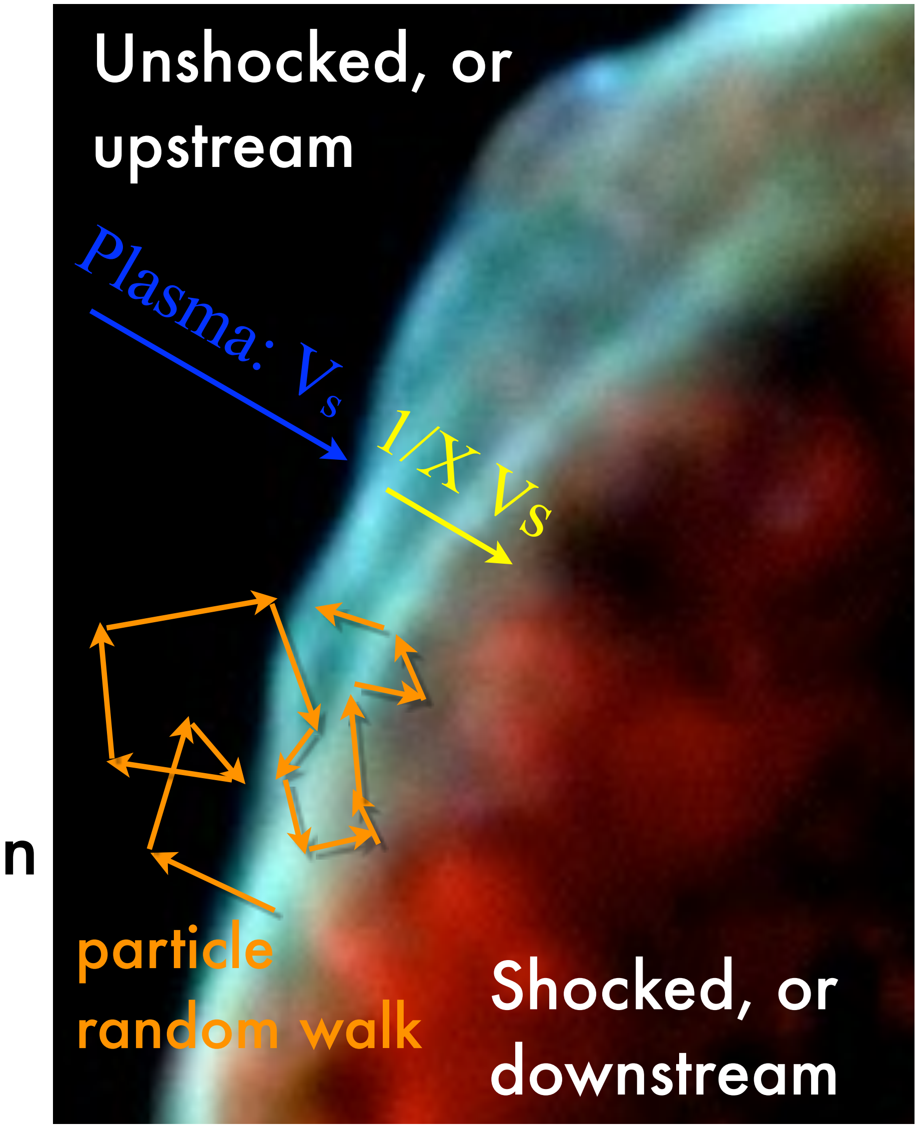
$$\Rightarrow l_{\text{diff}} = \frac{2D}{v},\ \ t_{\text{diff}} = \frac{2D}{v^2}$$

- t_{diff} is typical time scale for particle to cross shock
- Smaller mean free path, smaller D, faster acceleration
- Bohm diffusion (η=1):

$$\lambda_{\text{mfp}} = r_{\text{gyro}}$$

$$D = \eta \lambda_{\text{mfp}} \frac{1}{3} c = \eta \frac{cE}{3eB}$$

- Typical magnetic field in the Galaxy 10μG
- *Fast acceleration need strong, turbulent magnetic field!*



Can SNRs accelerate up to the knee?

The maximum energy of cosmic rays accelerated by supernova shocks

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Summary. The aim of this paper is
E_{max} that particles subjected to
acceleration can acquire during
remnant. The rate of acceleration
coefficient, which is determined by
energy present at a scale comparat
We study the variations of the diffusion coefficient as a function of momentum, space, and time.

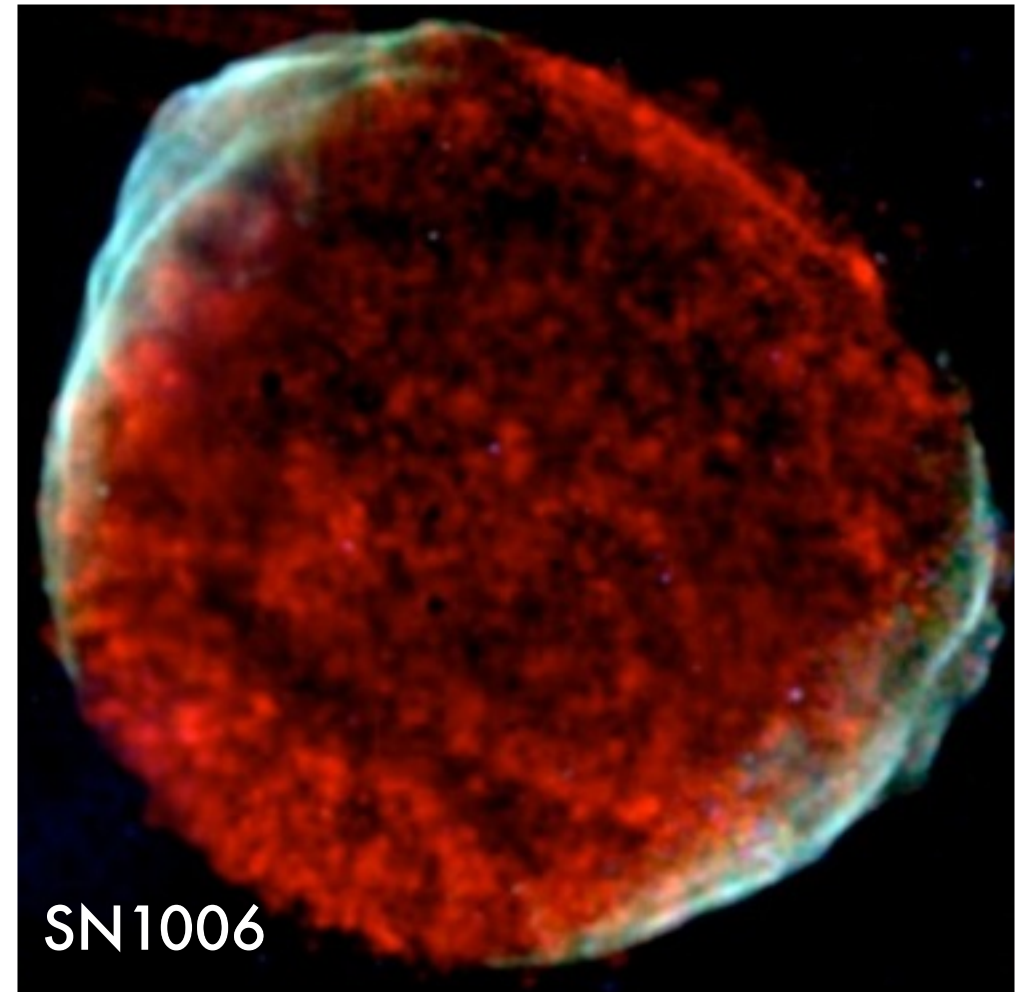
In the most optimistic case, the diffusion mean free path is everywhere comparable to the particle Larmor radius; then $E_{max} \sim 10^5$ GeV/n. Considering a more realistic behaviour of the diffusion coefficient, we obtain $E_{max} \lesssim 10^4$ GeV/n. Thus, supernova shock acceleration cannot account for the observed spectrum of galactic cosmic rays in the whole energy range 1–10^6 GeV/n.

Key words: cosmic-ray acceleration – shock waves – hydromagnetic waves

1983:

Thus supernova shock acceleration cannot account for the observed spectrum of galactic cosmic rays in the whole energy range 1-10^6 GeV/n.

Discovery of X-ray synchrotron emission



- In 1995 ASCA X-ray satellite: X-ray synchrotron emission from SN 1006 (Koyama et al. 1995)
- What determines the maximum synchrotron photon energy?
  - time available for accelerating electrons → age limited spectrum
  - acceleration gains = synchrotron (+IC) losses → loss limited spectrum
  - electrons escape above certain energy → escape limited spectrum

Loss-limited X-ray synchrotron spectra

- Synchrotron loss-time

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

- Diffusive acceleration time (depends on diffusion coeff. D, compression X)

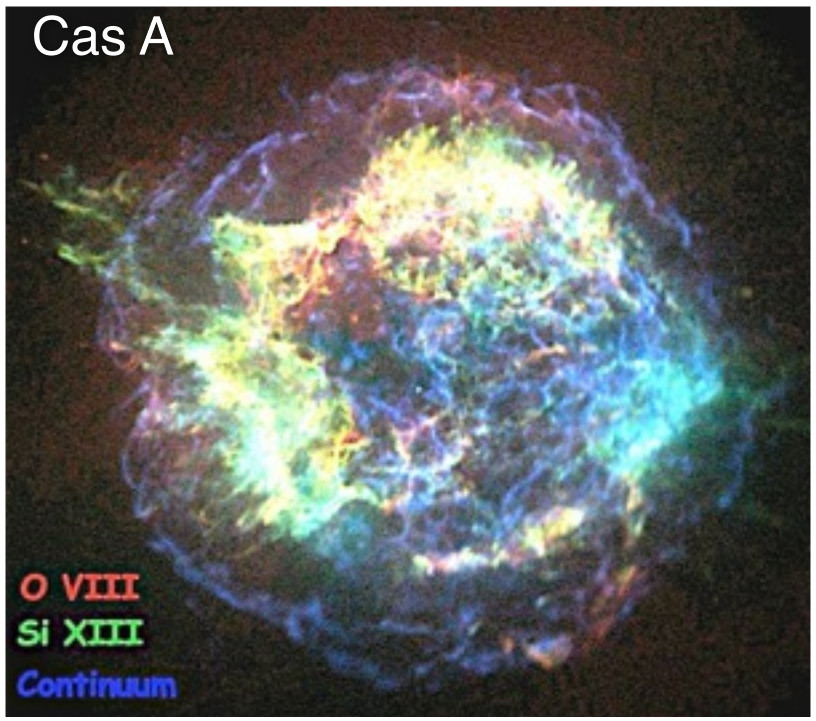
$$\tau_{\rm acc} \approx 1.83\frac{D_2}{V_{\rm s}^2}\frac{3\chi^2}{\chi-1} = 124\eta B_{-4}^{-1}\left(\frac{V_{\rm s}}{5000\ {\rm km\,s^{-1}}}\right)^{-2}\left(\frac{E}{100\,{\rm TeV}}\right)\frac{\chi_4^2}{\chi_4-\frac{1}{4}}\ {\rm yr.}$$

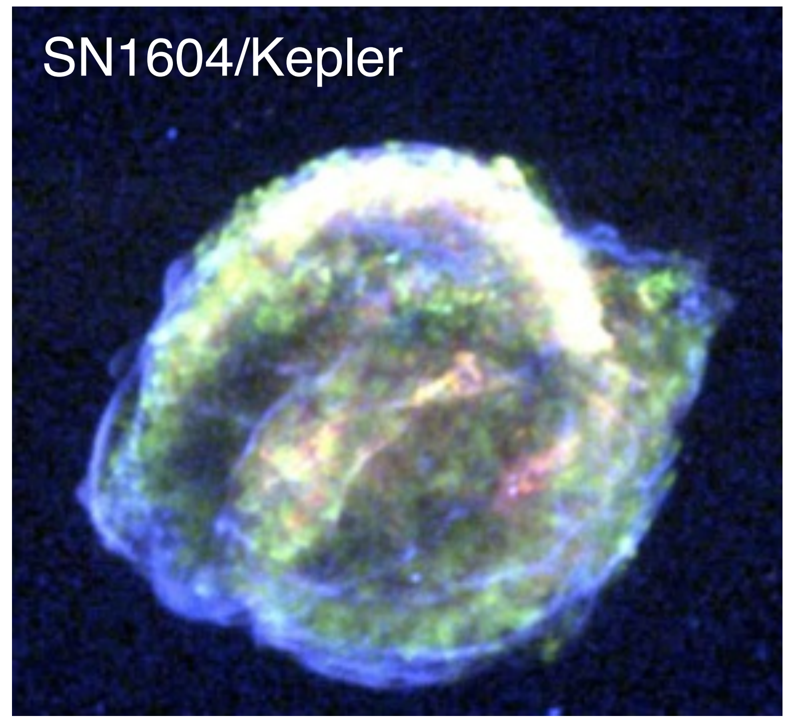
- Equating gives expected cut-off for loss-limited case (e.g. Aharonian&Atoyan '99)

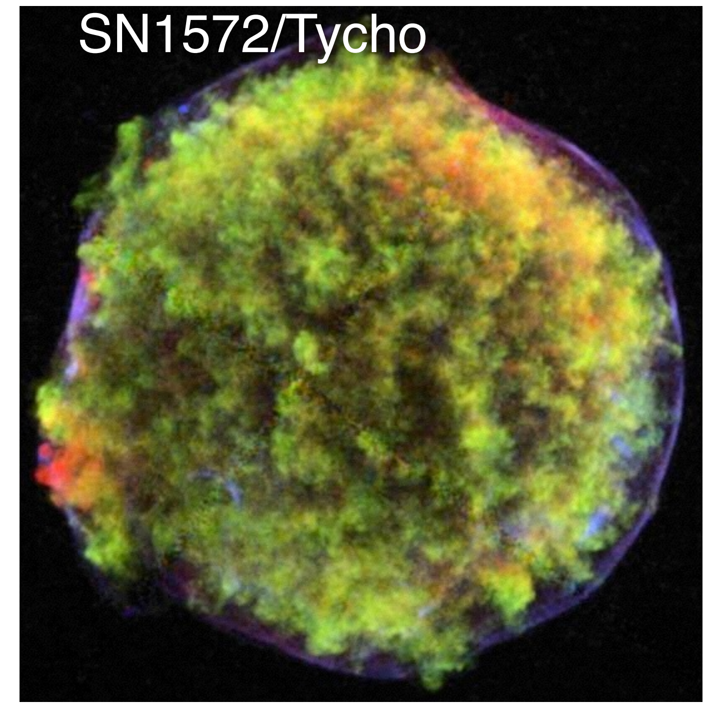
$$\boxed{h\nu_{\rm cut-off} = 1.4\eta^{-1}\left(\frac{\chi_4-\frac{1}{4}}{\chi_4^2}\right)\left(\frac{V_s}{5000\ {\rm km\,s^{-1}}}\right)^2\ {\rm keV}}$$

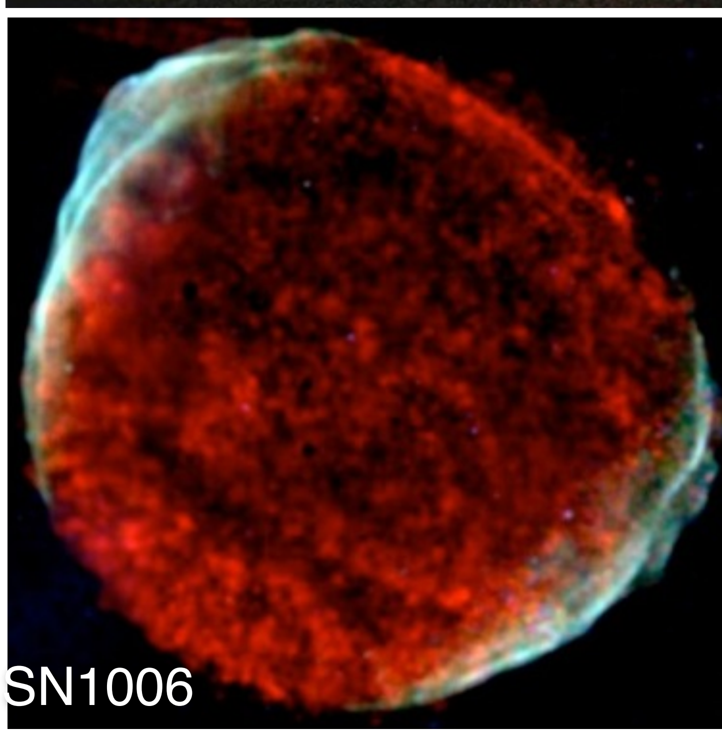
- NB loss limited case:
    - frequency cut-off independent of B!!
    - Strongly dependent on V_s

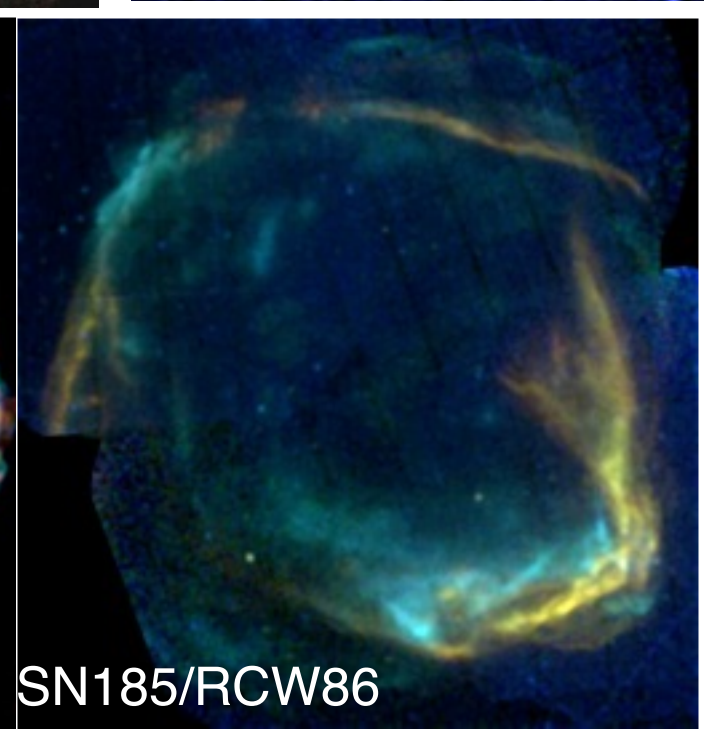
All young (100-1000 yr) SNRs show X-ray synchrotron radiation

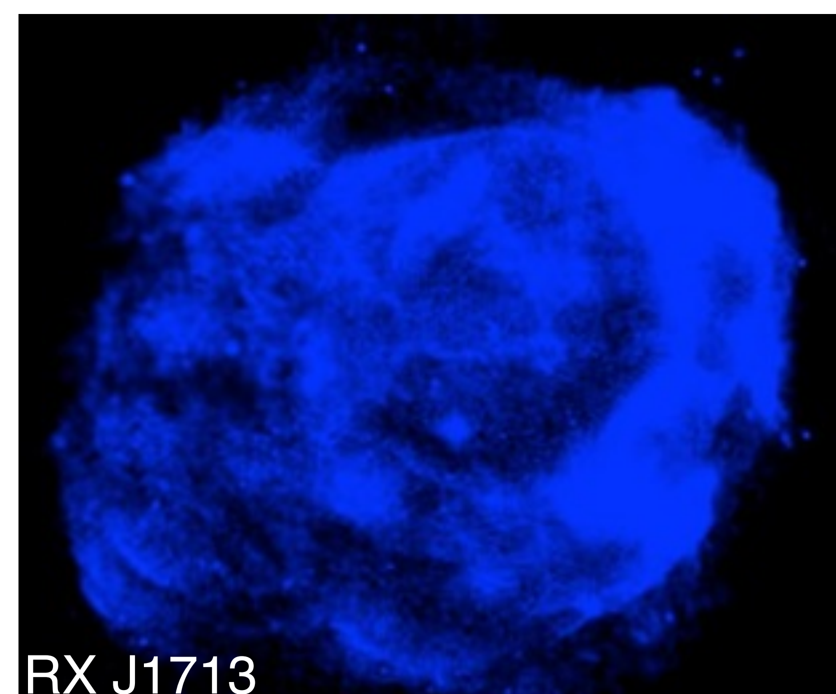












Implications of X-ray synchrotron emission

- Acceleration must proceed close to Bohm-diffusion limit!

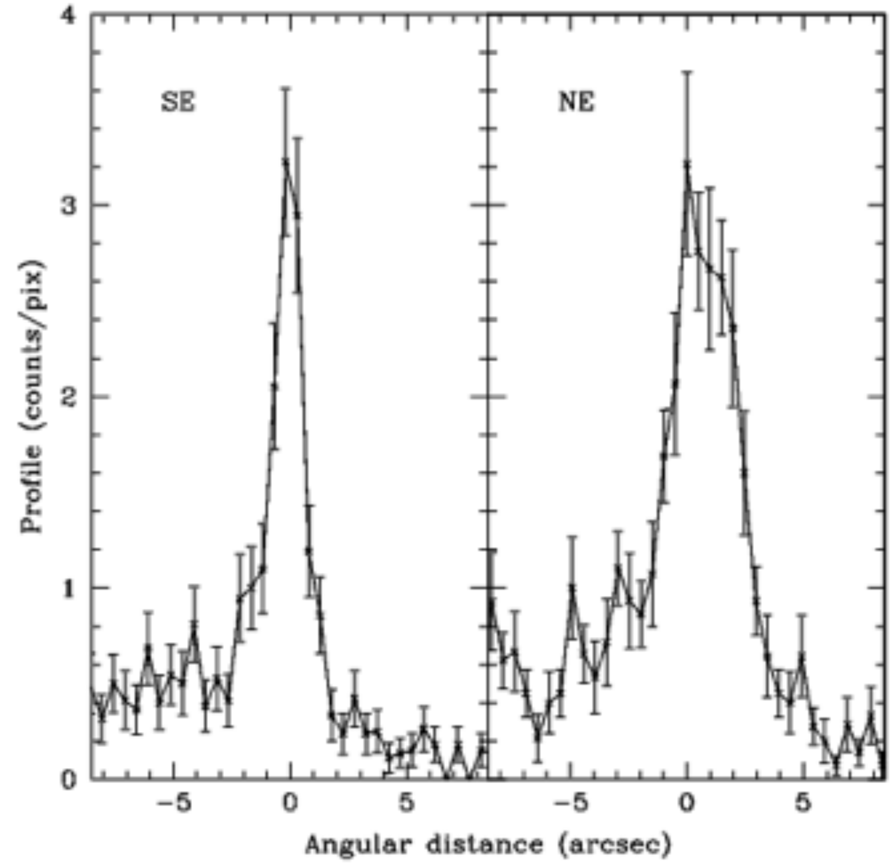
$$\eta \lesssim 10$$

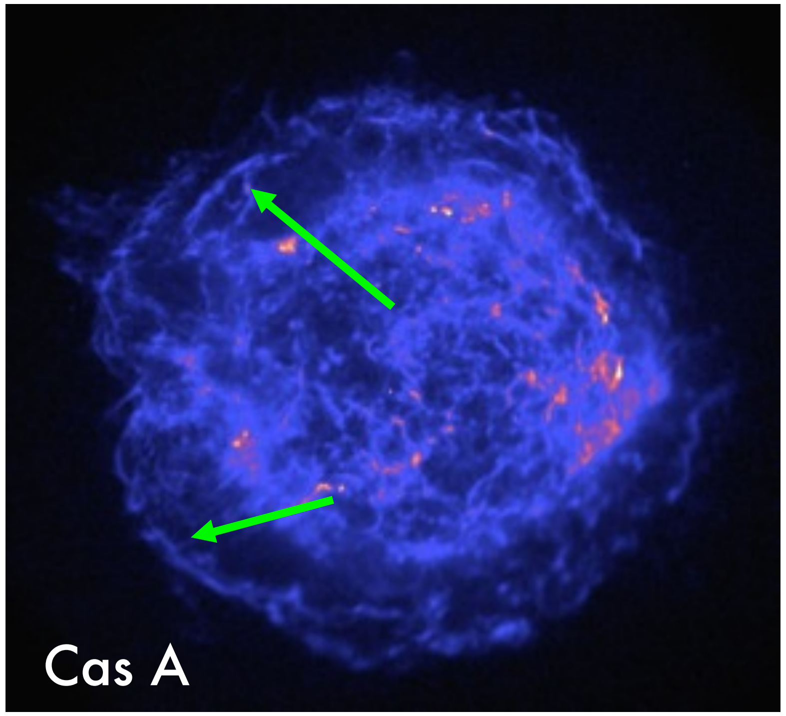
- The higher the B-field →faster acceleration, but for electrons: E_{max} lower!
- For B=10-100 μG: presence of 10^{13}-10^{14} eV electrons
- Loss times are:

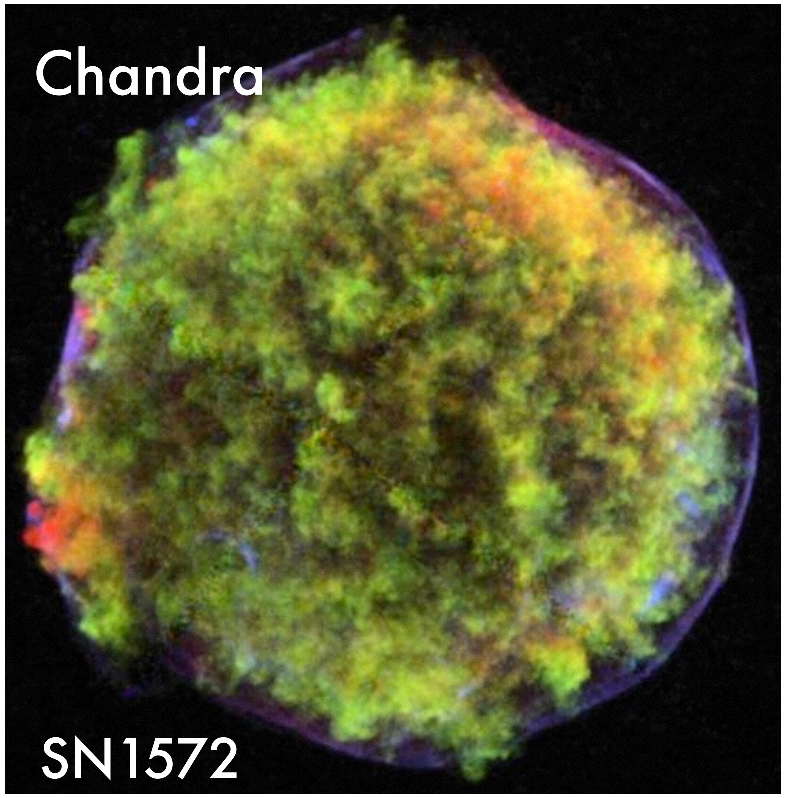
$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1}\left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}\ {\rm yr}.$$

X-ray synchrotron emission tells us that
- electrons can be accelerated fast
- that acceleration is still ongoing (loss times 10-100 yr)
- that particles can be accelerated at least up to 10^{14} eV

Narrowness of X-ray synchrotron filaments





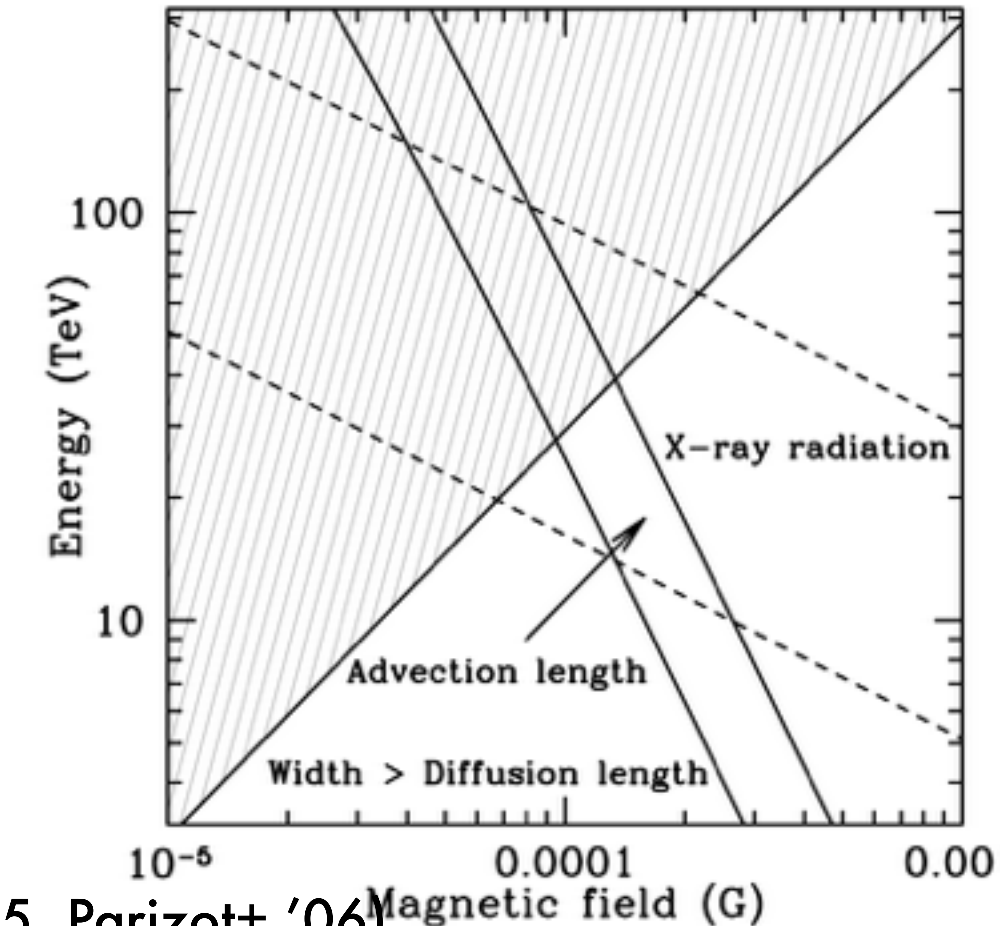


- In many cases X-ray synchrotron filaments appear very narrow (1-4″)
- Including deprojections implies $l \approx 10^{17}$cm

e.g. Vink&Laming ’03, Völk et al. 03, Bamba+ ’04, Ballet ’06,Warren+ ’05, Parizot+ ’06)

Narrowness X-ray synchrotron filaments: high B-fields

Vink&Laming '03



- Width≈diffusion length ≈ advection length:

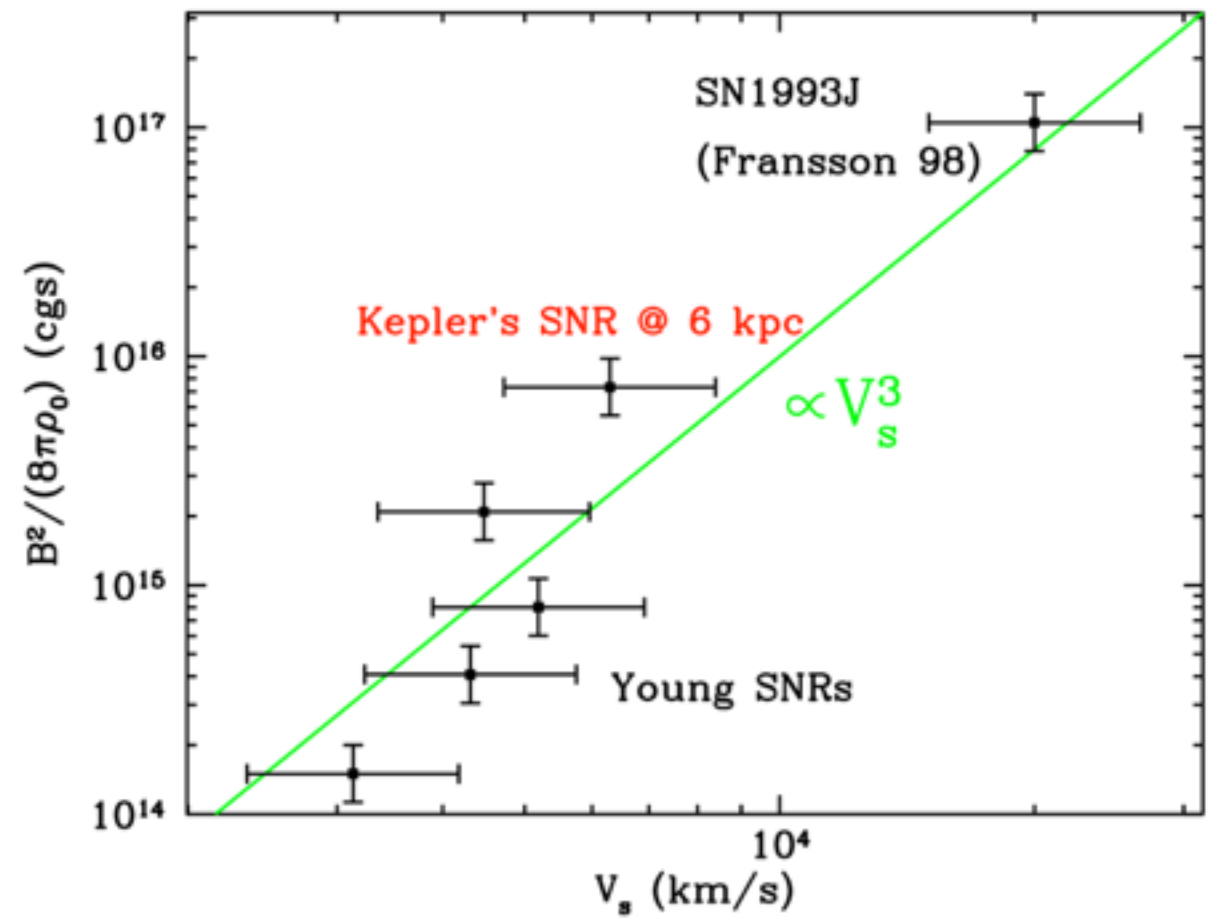
$$B_2 \approx 26 \left(\frac{l_{\rm adv}}{1.0 \times 10^{18} {\rm cm}} \right)^{-2/3} \eta^{1/3} \left(\chi_4 - \frac{1}{4} \right)^{-1/3} \ \mu{\rm G}$$

- Narrow rims → high B-field
- Cas A/Tycho/Kepler: 100-500 μG

  (e.g. Vink&Laming '03, Völk et al. 03, Bamba+ '04, Warren+ '05, Parizot+ '06)
- High B ⇒fast acceleration ⇒ protons beyond 10^{15}eV?

- High B-field likely induced by cosmic rays (e.g. Bell '04)
- High B-fields are a signature of efficient acceleration
- Optimistic scenario of Lagage & Cesarky seems to be realistic!

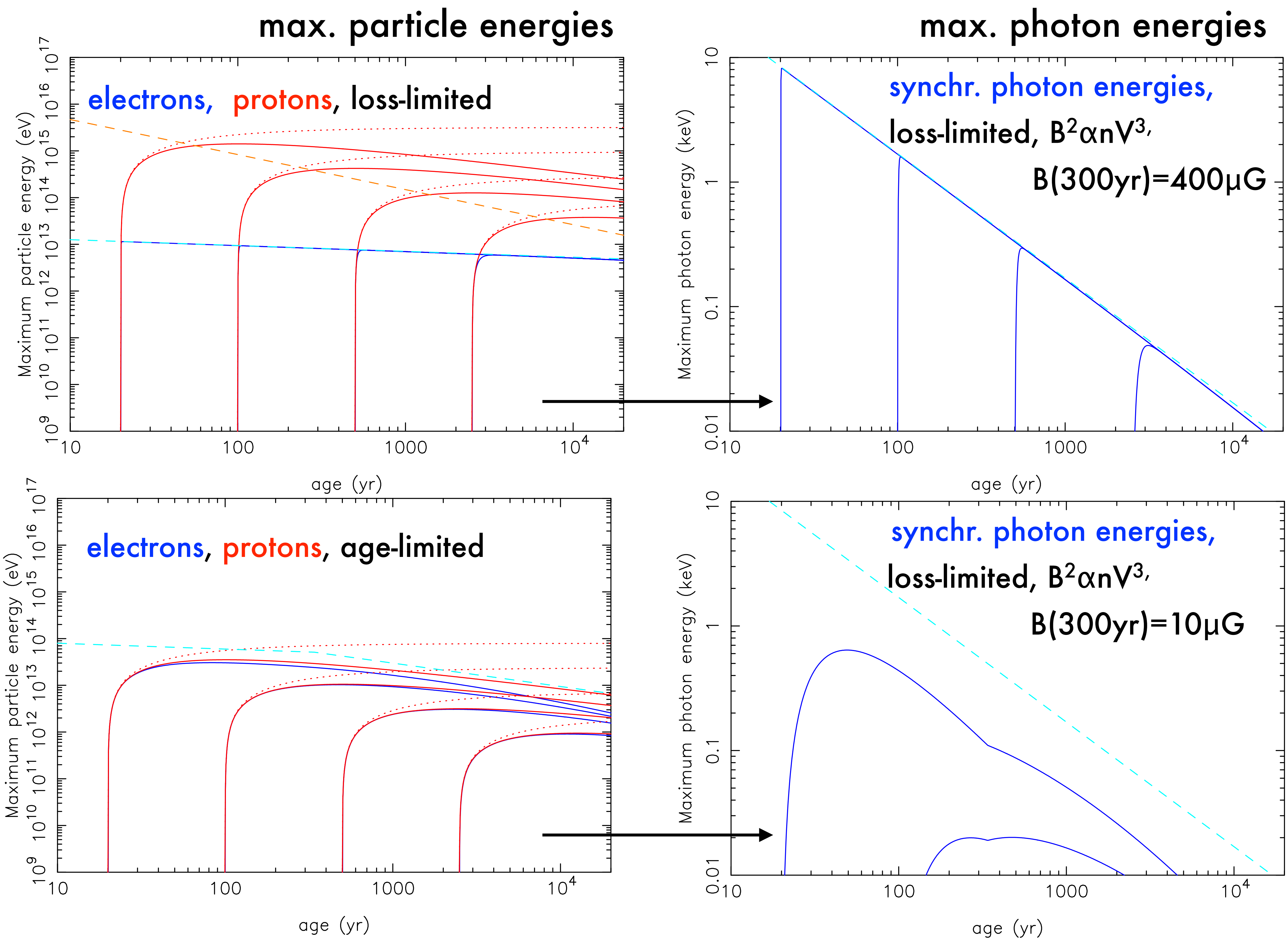
Magnetic field amplification



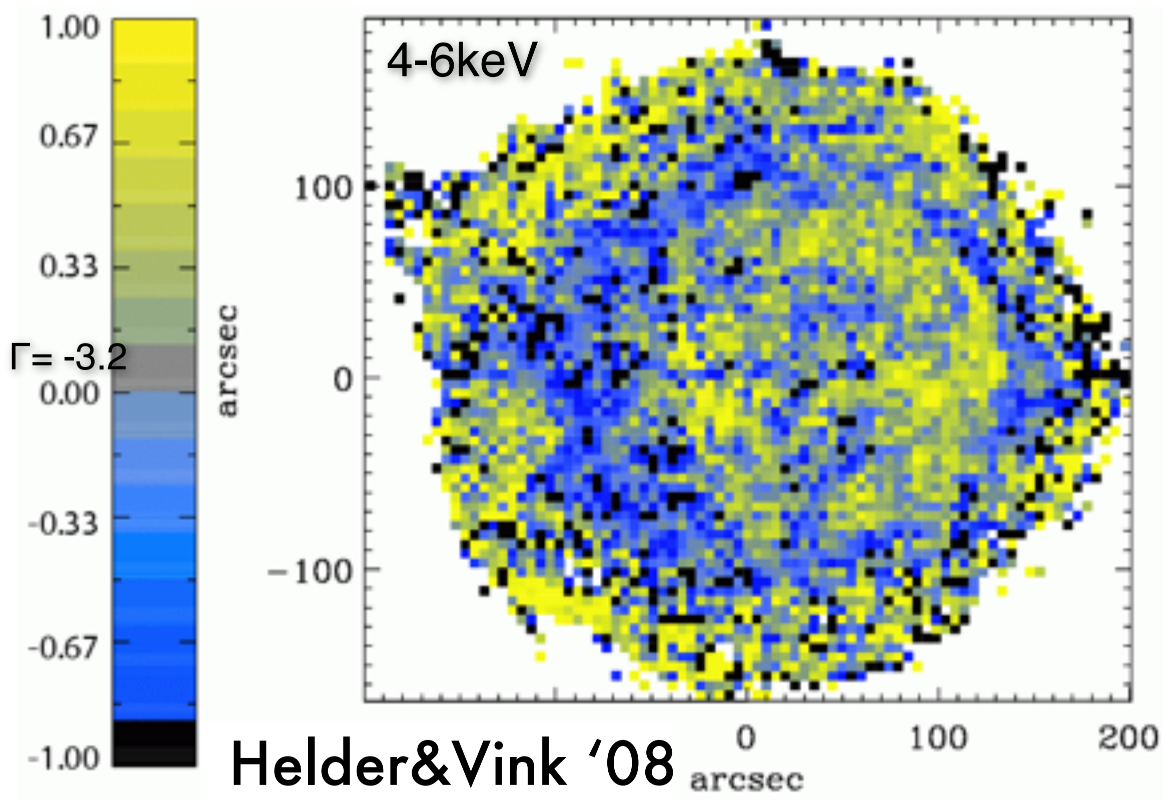
- Clear correlation between ρ, V and B
- In rough agreement with predictions (e.g. Bell 2004)
- Relation may even extend to supernovae ($B^2 \propto \rho V_s^3$?)

  (Völk et al. ’05, Vink ’08)
- SNRs: little dynamic range in V_s

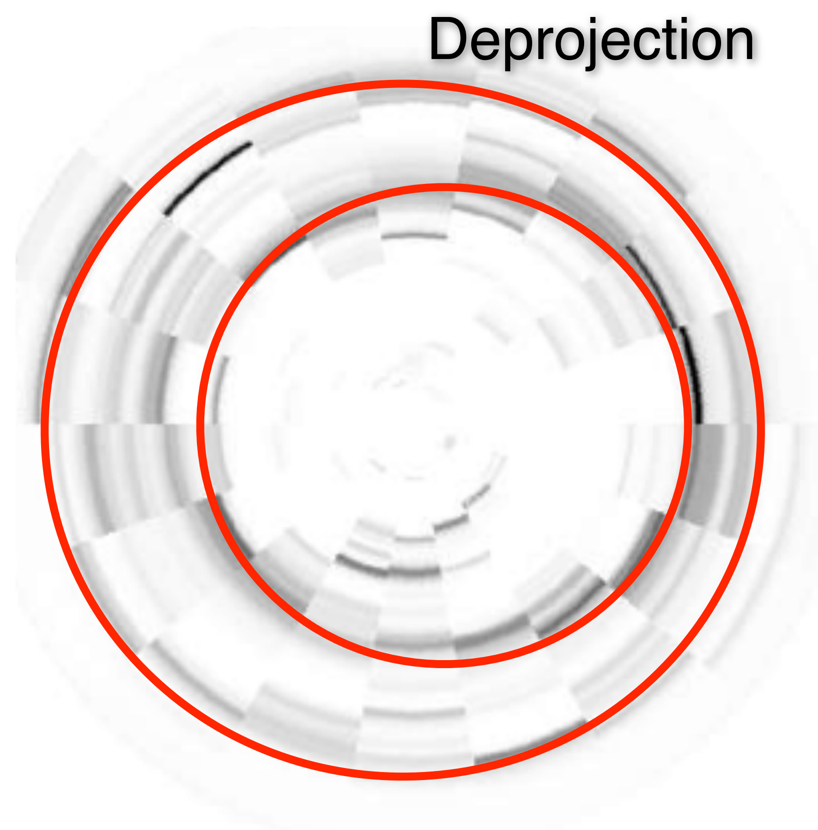
Age-limited vs Loss-limited electron/photon spectra



Acceleration @ Cas A reverse shock



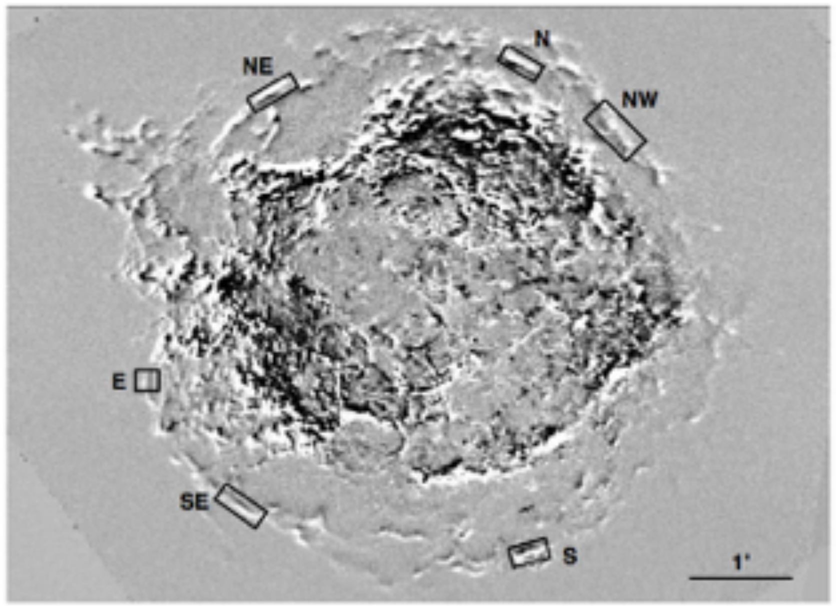
Helder&Vink '08

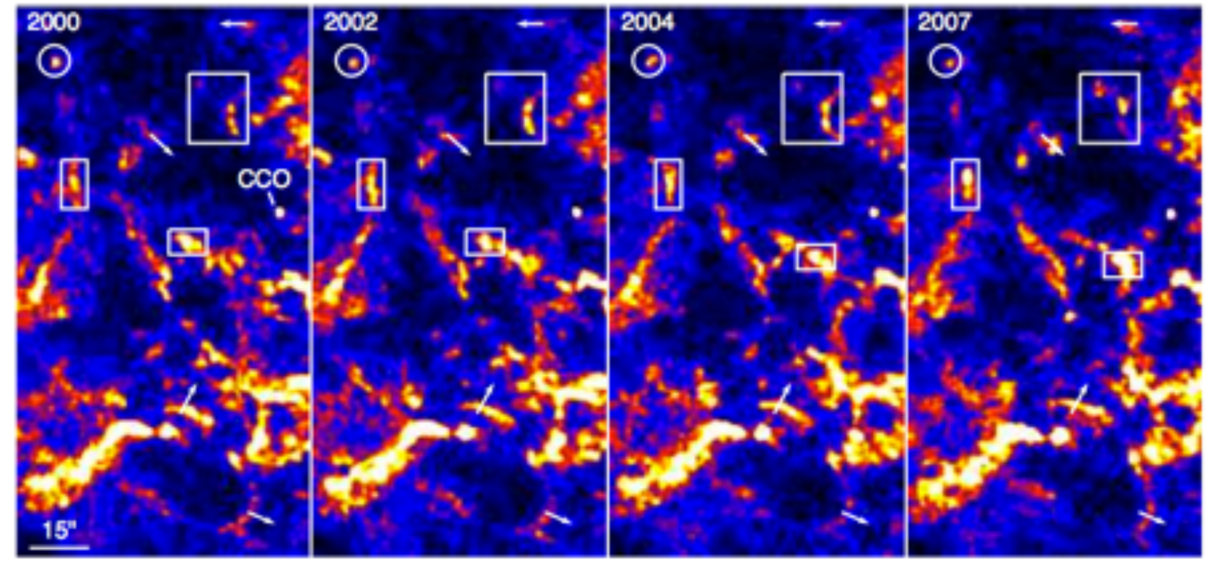


- Spectral index: 2 regions of hard emission: X-ray synchrotron emission
- Deprojection: Most X-ray synchrotron from reverse shock!
- Prominence of West: No expansion ⇒ ejecta shocked with V>6000 km/s
- Reverse shock: metal-rich → more electrons → bright radio

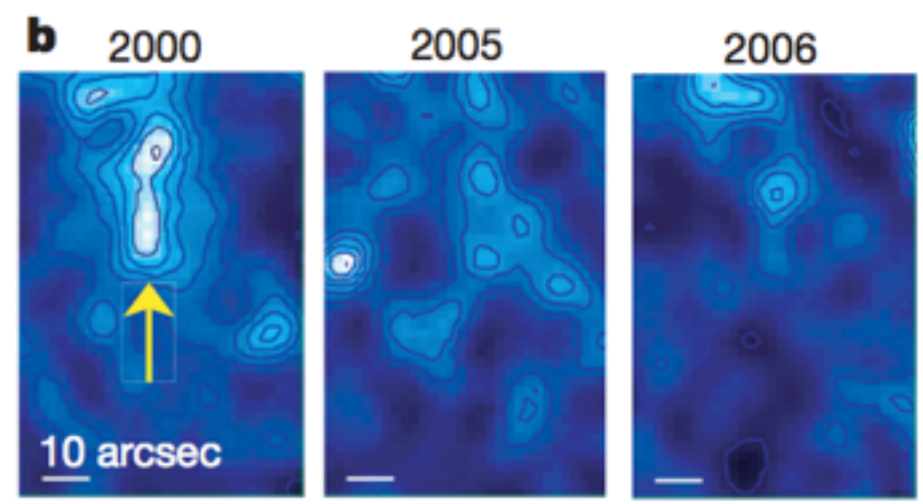
B-field amplification is not very sensitive to initial B-field!

Time varying X-ray synchrotron radiation





Cas A (Patnaude+ 2007,09)



RX J1713 (Uchiyama+ 2007)

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

Two possible explanations

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)

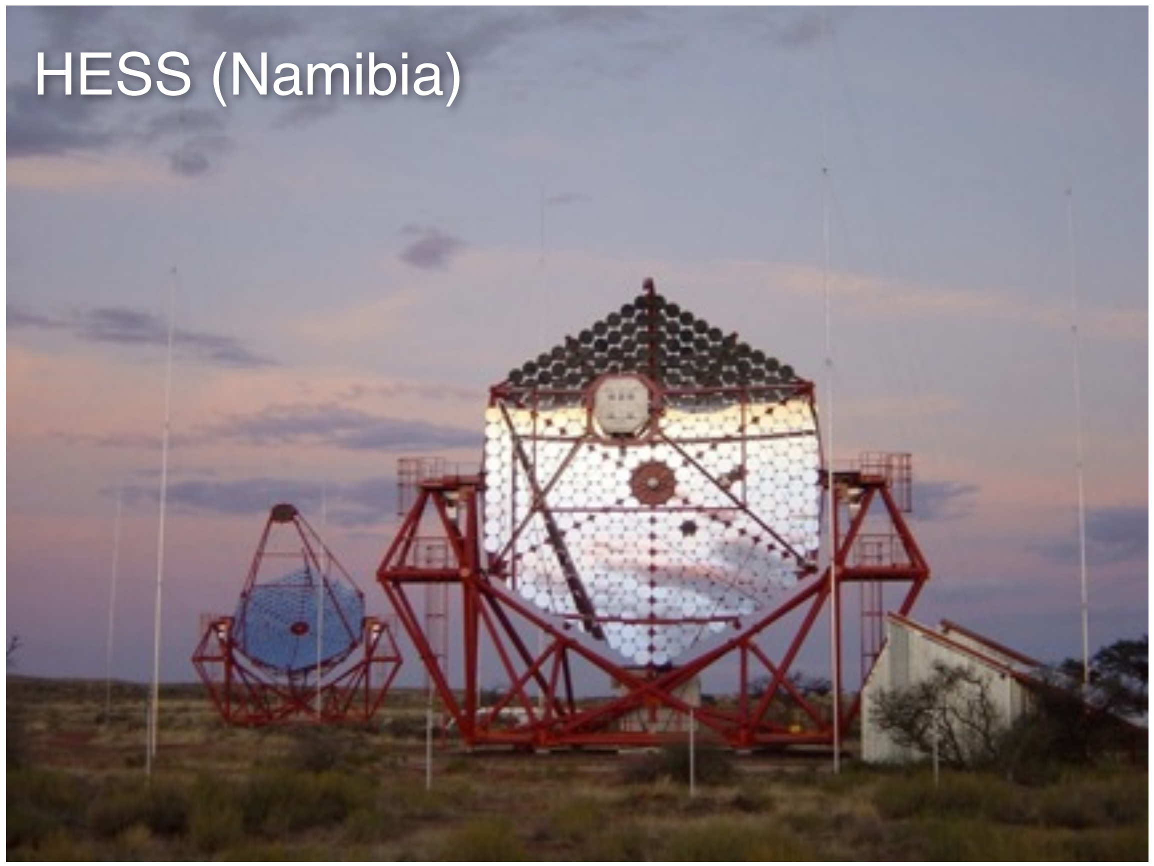
   -There is a spectral distribution of waves (larger waves small amplitude)

   -Radio emission less sensitive to B-field fluctuations

   - X-ray synchrotron (beyond break) very sensitive

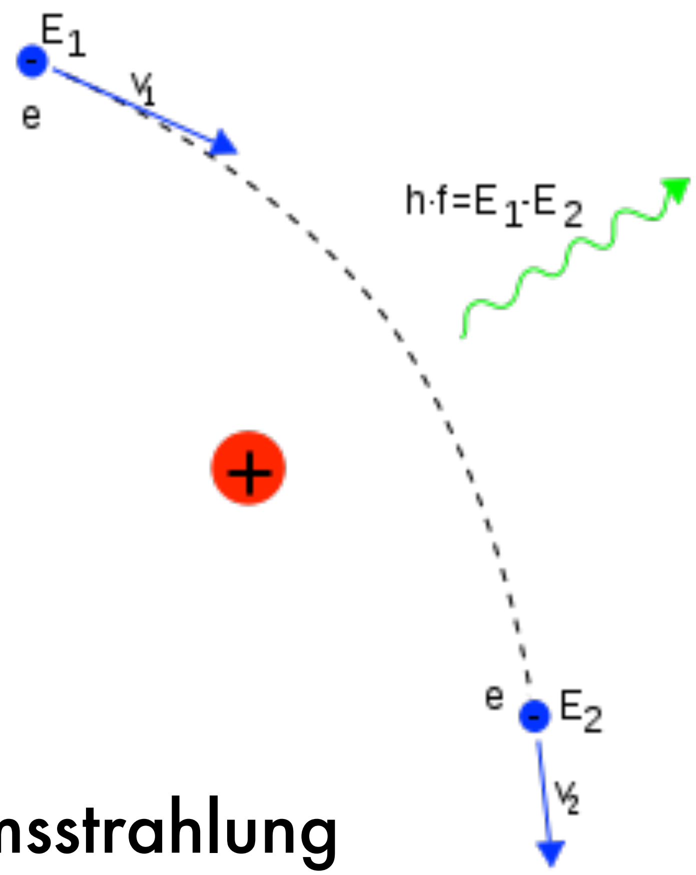
$$N_{\rm e} \propto K E^{-q},~ I_\nu \propto K B^{(q+1)/2} \nu^{-(q-1)/2}$$

The coming of age of Gamma-ray observatories: Cherenkov Telescope (TeV) and the Fermi and Agile satellites (GeV)

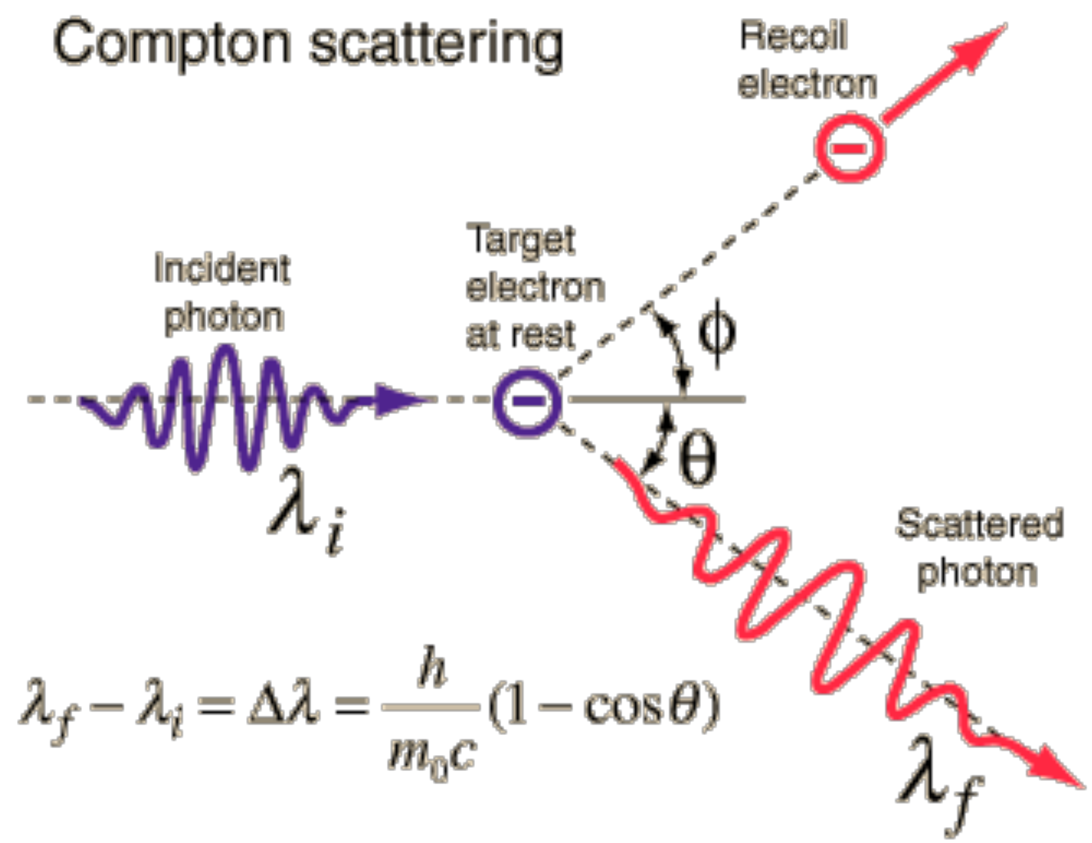


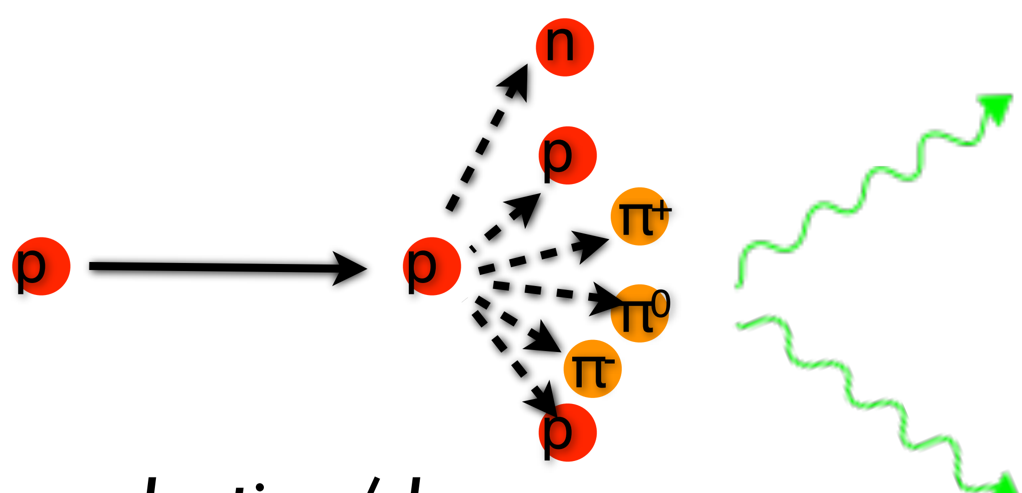
- Gamma-ray photons give more direct proof of high energy particles:
  - $E_{photons} \approx 10\% \, E_{particles}$
- Gamma-rays can provide direct proof for accelerated *ions* (hadronic cosmic rays)

Gamma-ray radiation processes



Bremsstrahlung

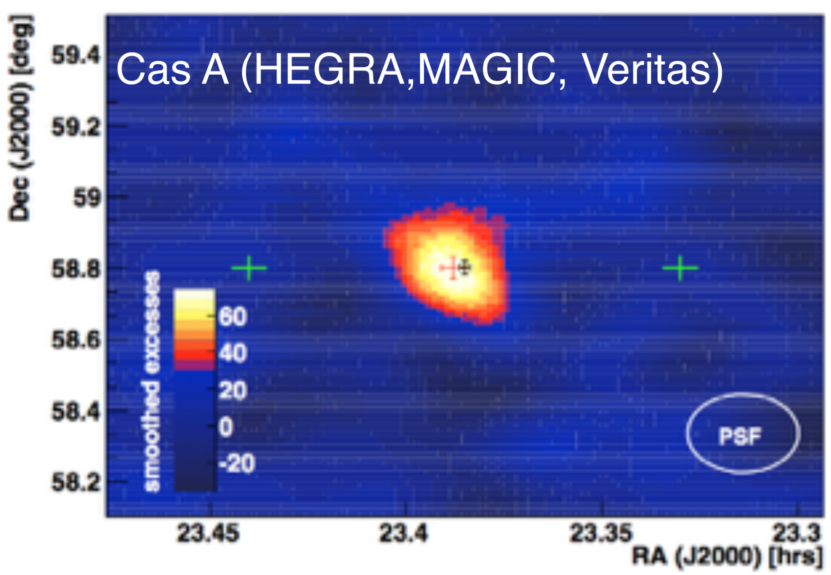


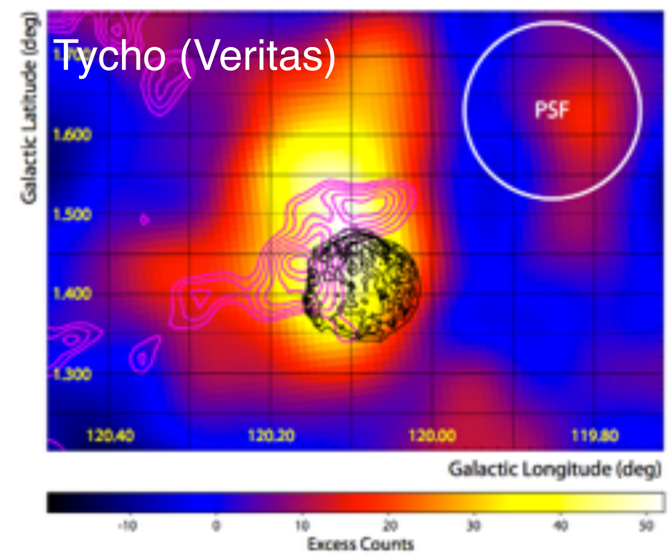


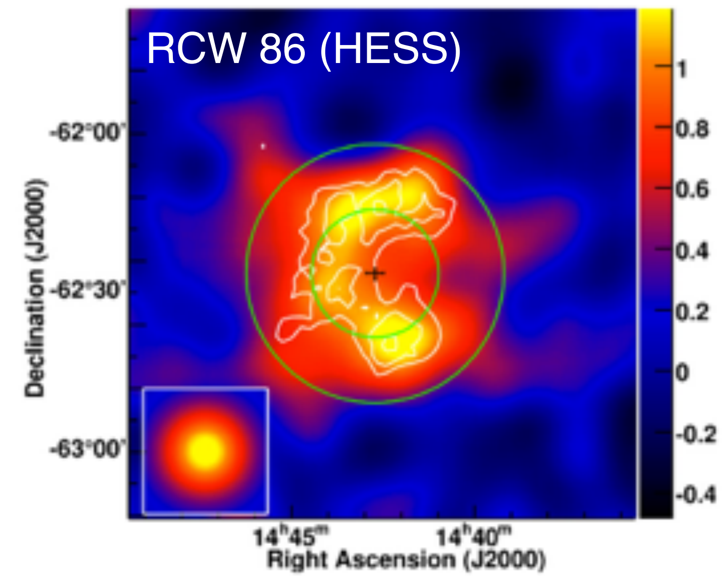
$$
\begin{aligned}
\pi^0 &\rightarrow 2\gamma \\
\pi^+ &\rightarrow \mu^+ + \nu_\mu \\
&\qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\
&\qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\end{aligned}
$$

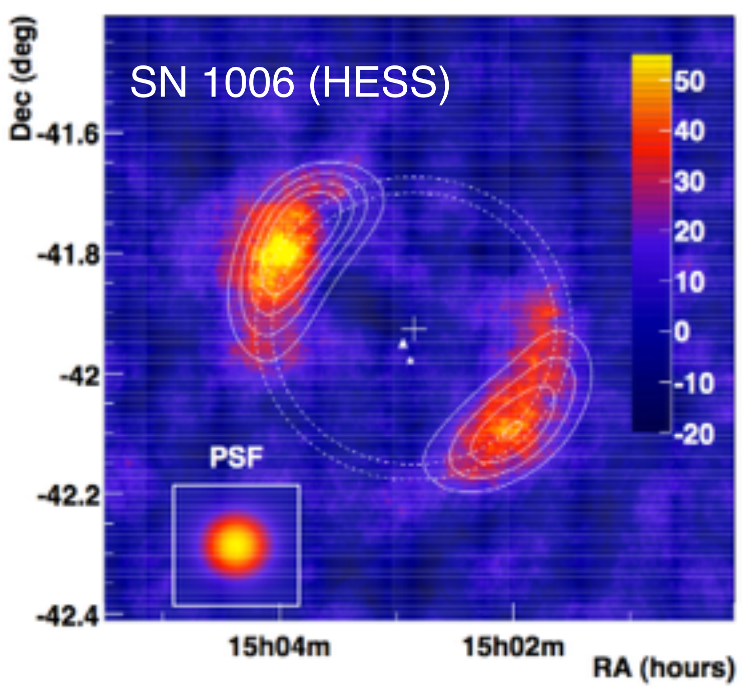
Neutral pion production/decay

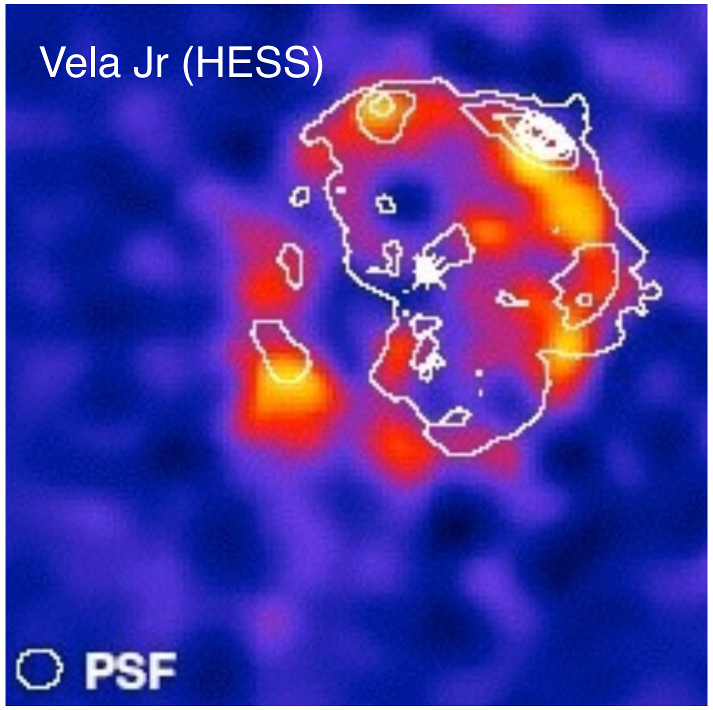
Some young SNRs in TeV gamma-rays

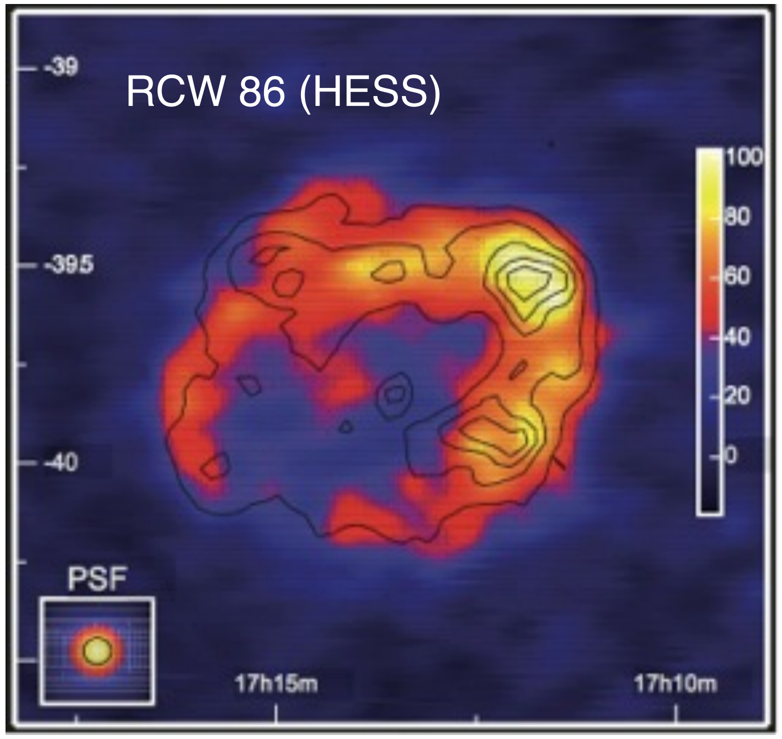






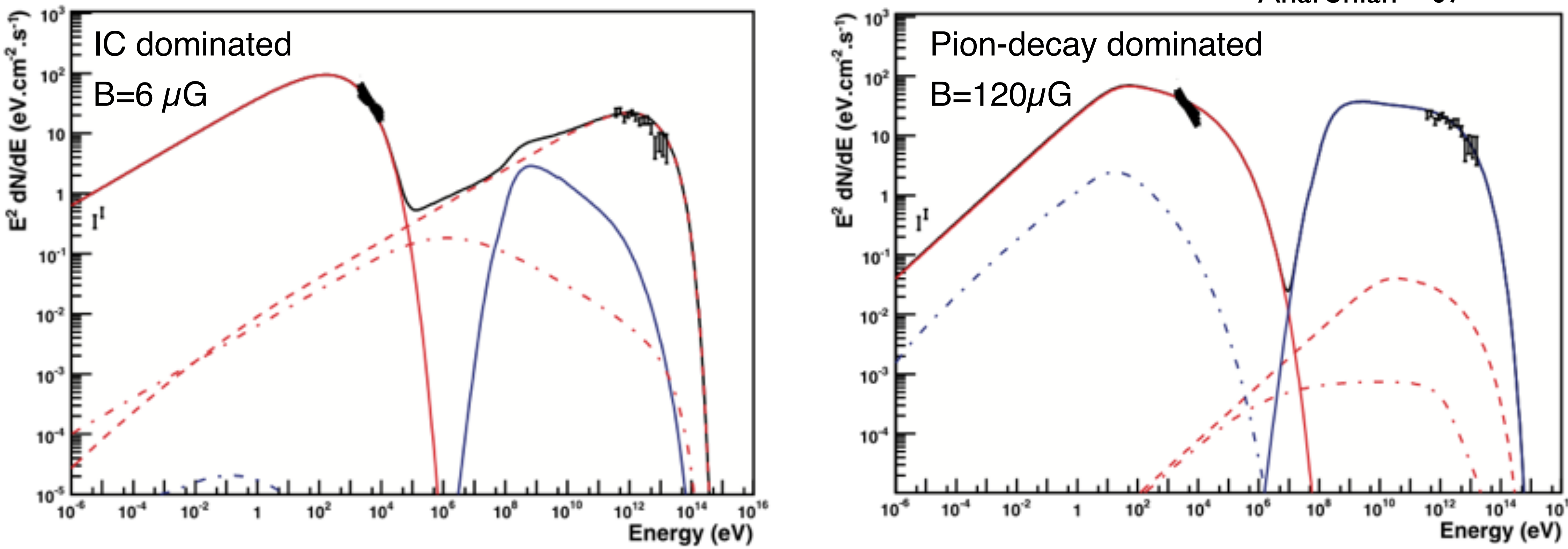




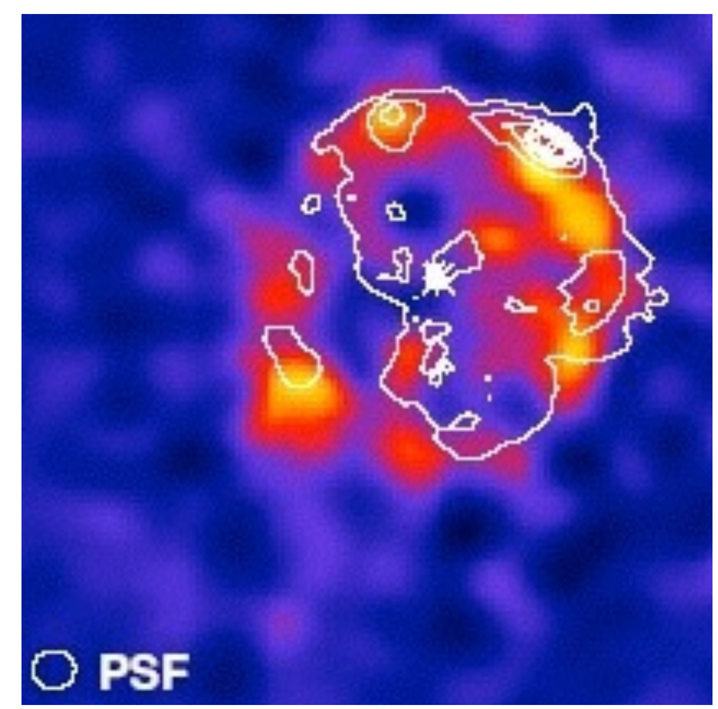


Interpretation problems in practice

Aharonian+ ‘07



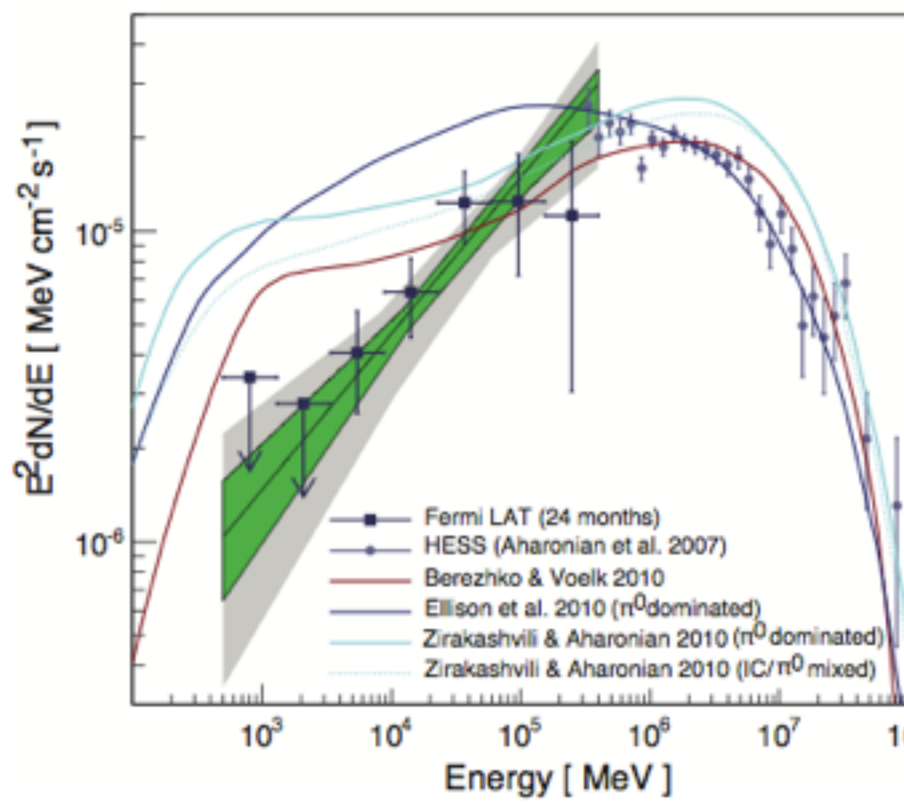
- Debates on the nature of most TeV SNRs
- Most heated: RXJ1713 and Vela Jr
- Heated debates on gamma-ray emission
  - pion decay:requires high densities/high B-fields

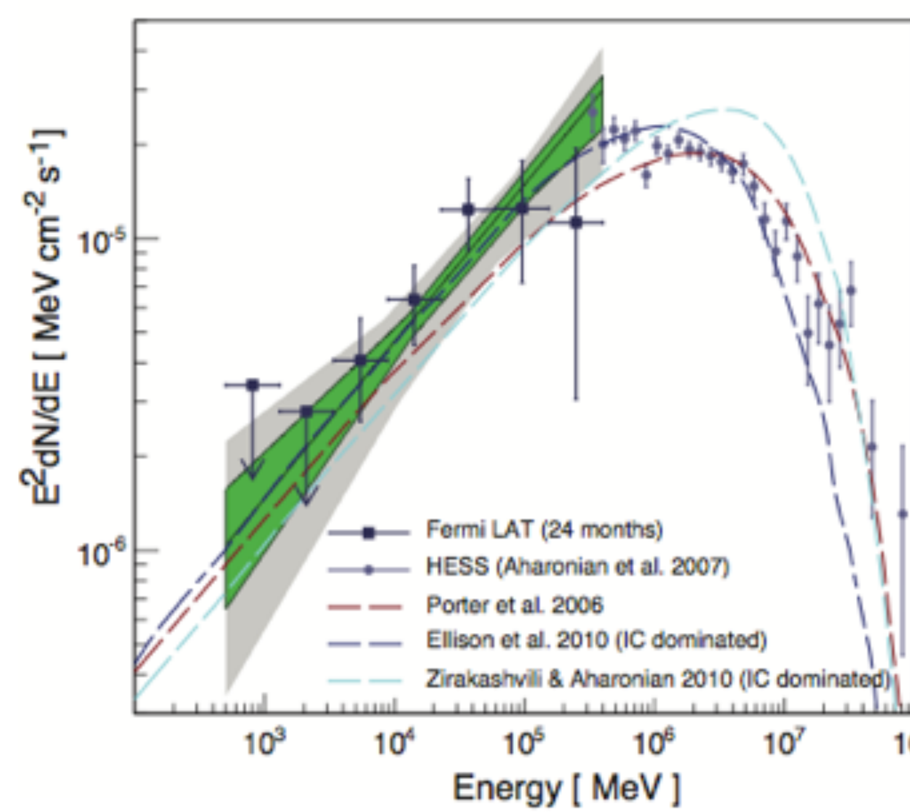


Adding Fermi: case solved?

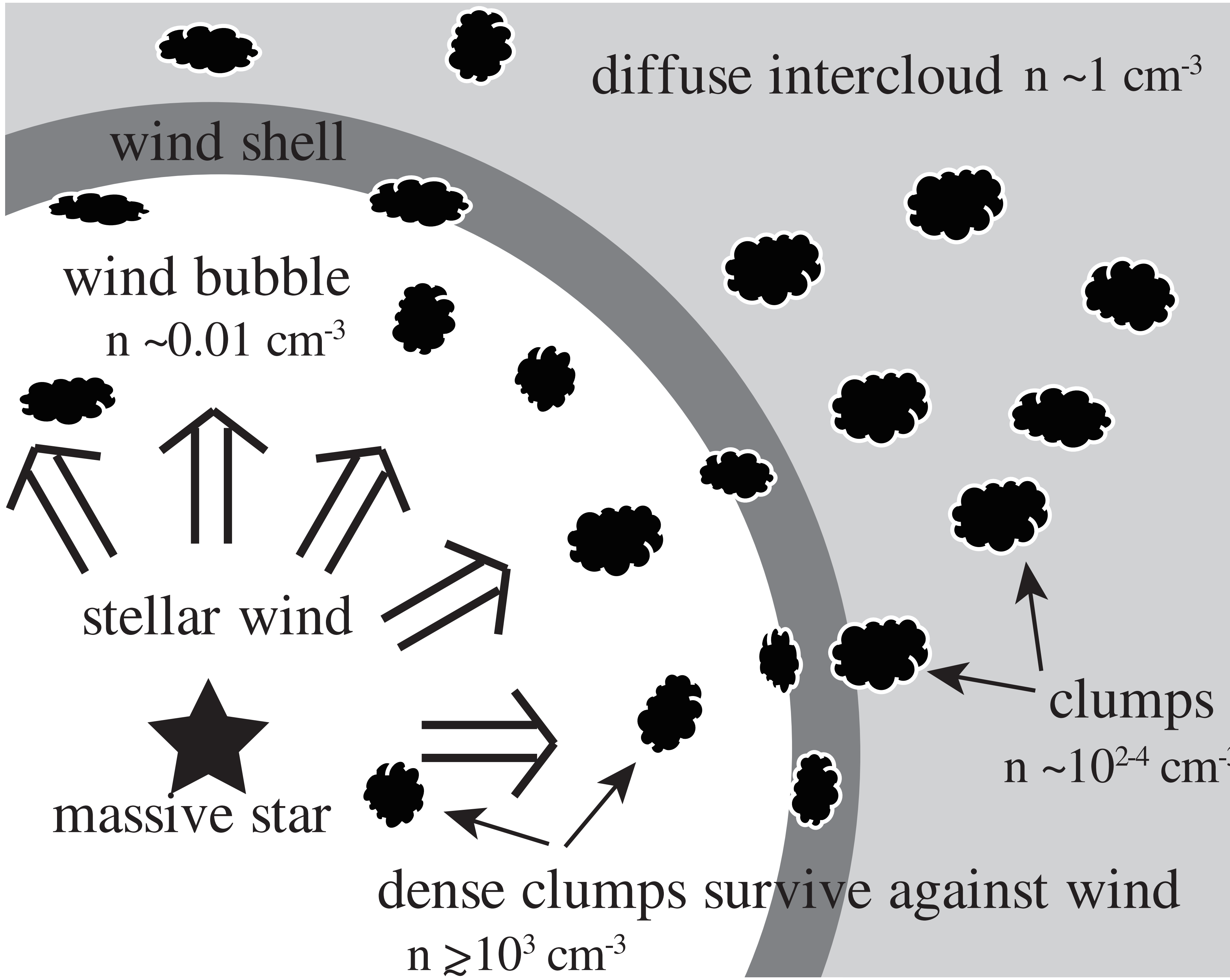
- Fermi detected RX J1713 in GeV range
- Caveat: Galactic plane contamination
- Spectral shape suggests inverse Compton origin of GeV/TeV emission
- Has controversy ended?
  - More data/scrutiny needed
  - IC models do not fit very well TeV-end of spectrum
  - Hadronic model does not follow initial predictions
  - Hadronic model may still be valid with more complicated scenarios: dense clumps in empty cavity (Inoue+ 2013, Gabici&Aharonian '14)

Abdo+ '11





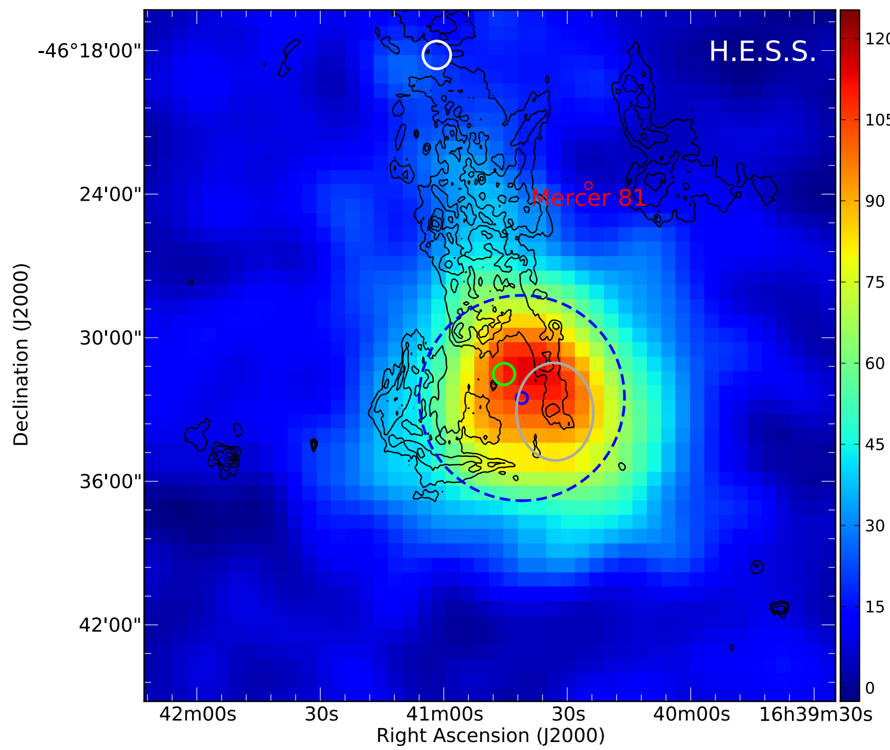
Clumpy medium

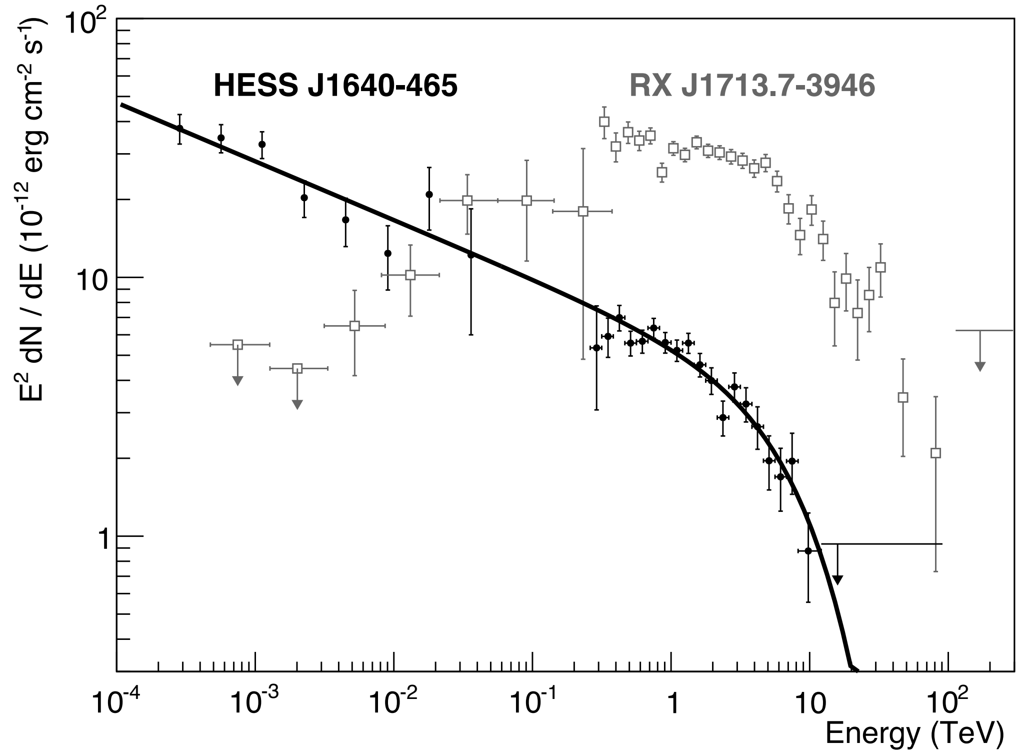


Inoue+ 2013, Gabici&Aharonian '14

HESS J1640-465: an exceptionally gamma-ray luminous SNR

Abramowski+ '11



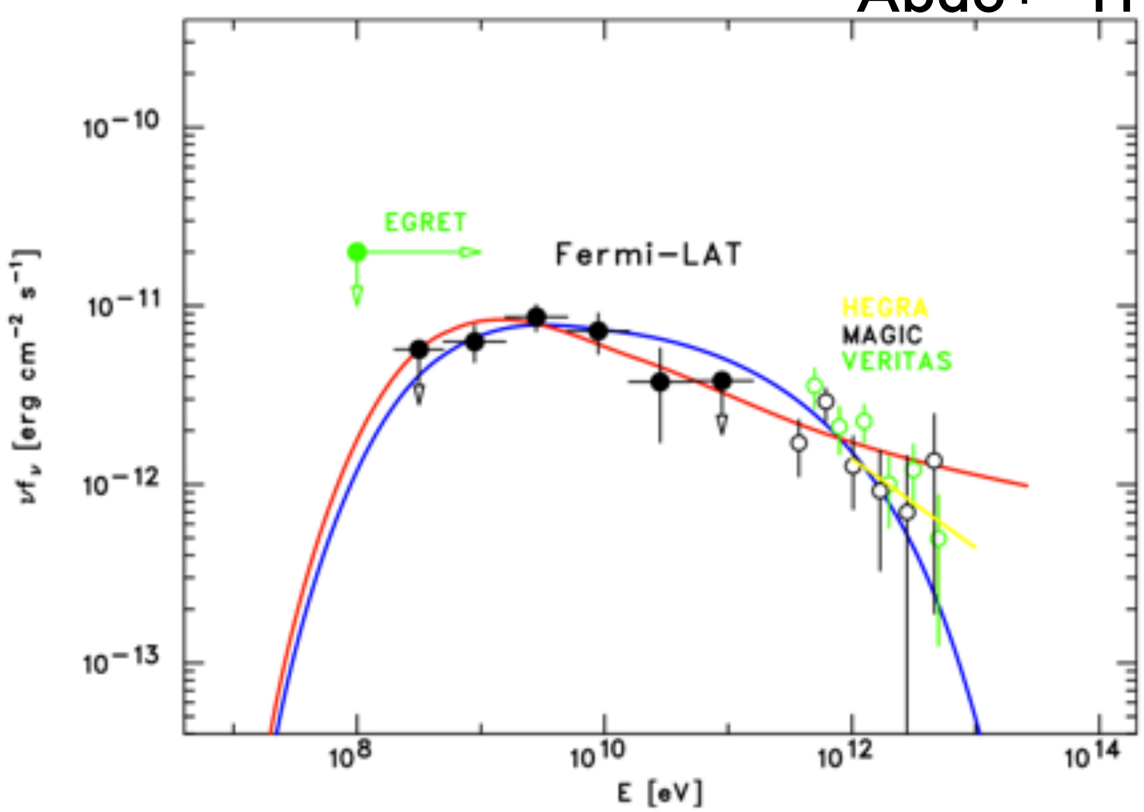


- Joint H.E.S.S.- Fermi spectrum much steeper than RXJ1713→hadronic more likely
- High densities surrounding large SNR: explosion in a cavity?
- Pion-decay emission from surrounding regions?
- Some controversy: could gamma-ray emission come from pulsar (Gotthelf+ '14)

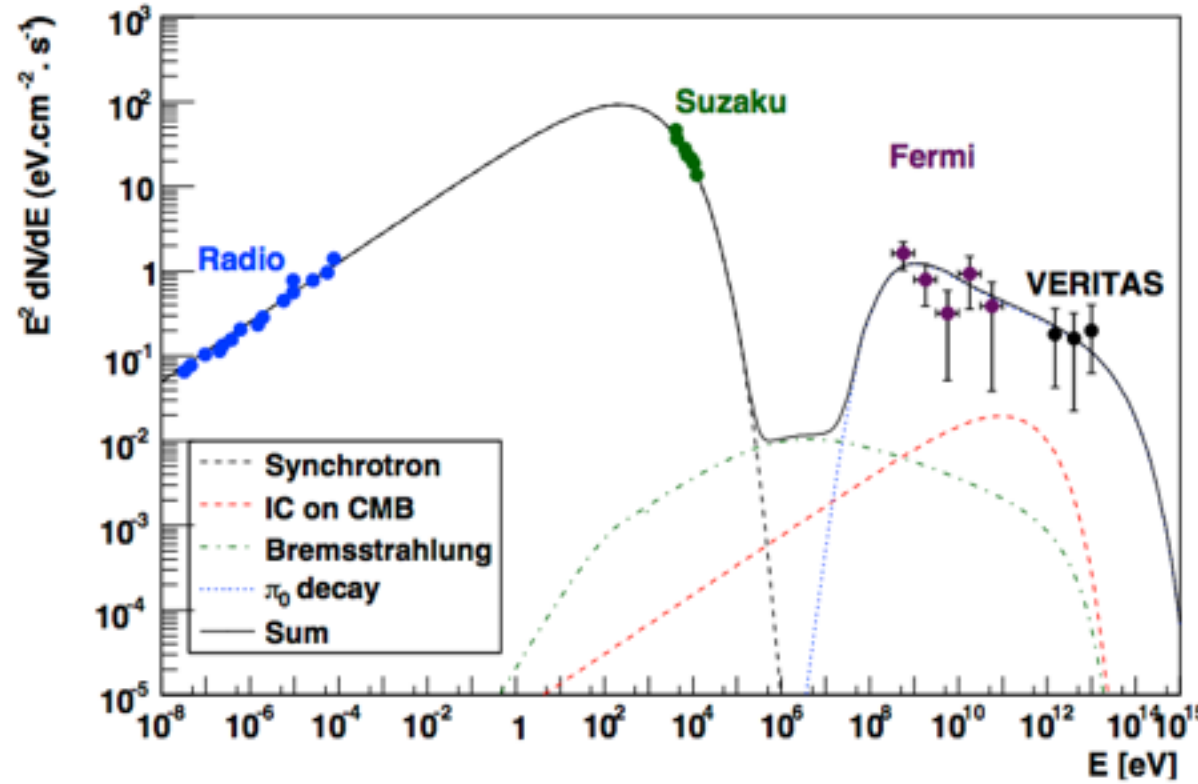
In young SNRs no evidence yet for PevaTrons!!!

Cas A vs Tycho in gamma-rays

Abdo+ '11



Giordano+ '11



Cas A (SN IIb)

- Model (p/e) not clear
- $E_{cr} < 4\%\ E_{expl}$

Tycho (SN Ia)

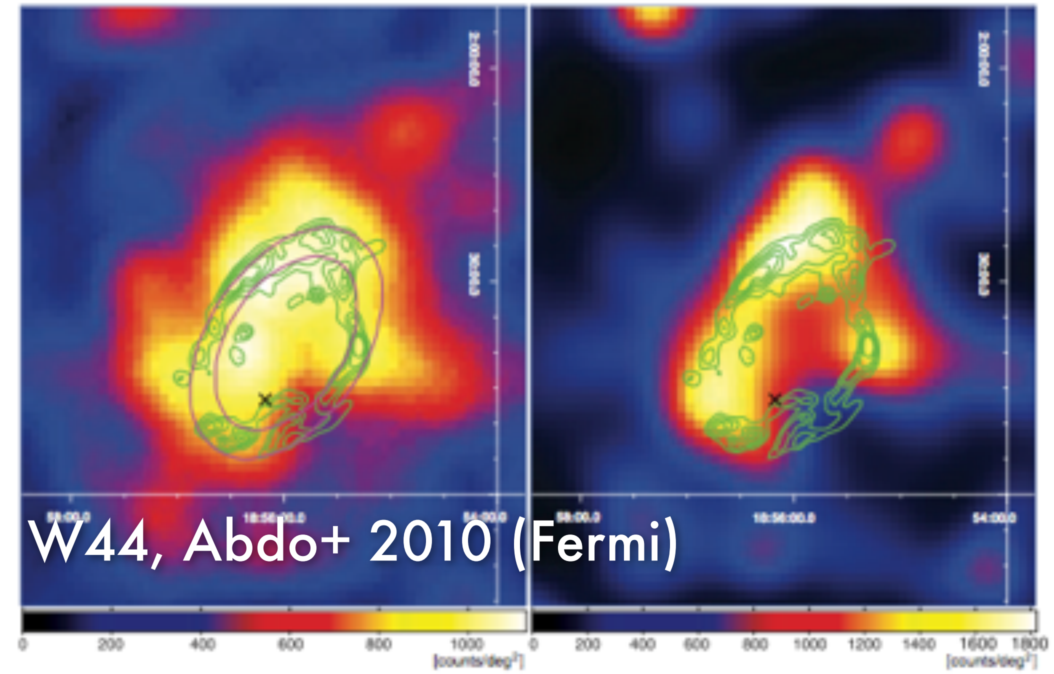
- Proton model favored (pion decay)
- $E_{cr} \approx 10\%\ E_{expl}$

Contrary to expectations the Type Ia SNR seems better in cosmic ray acceleration!

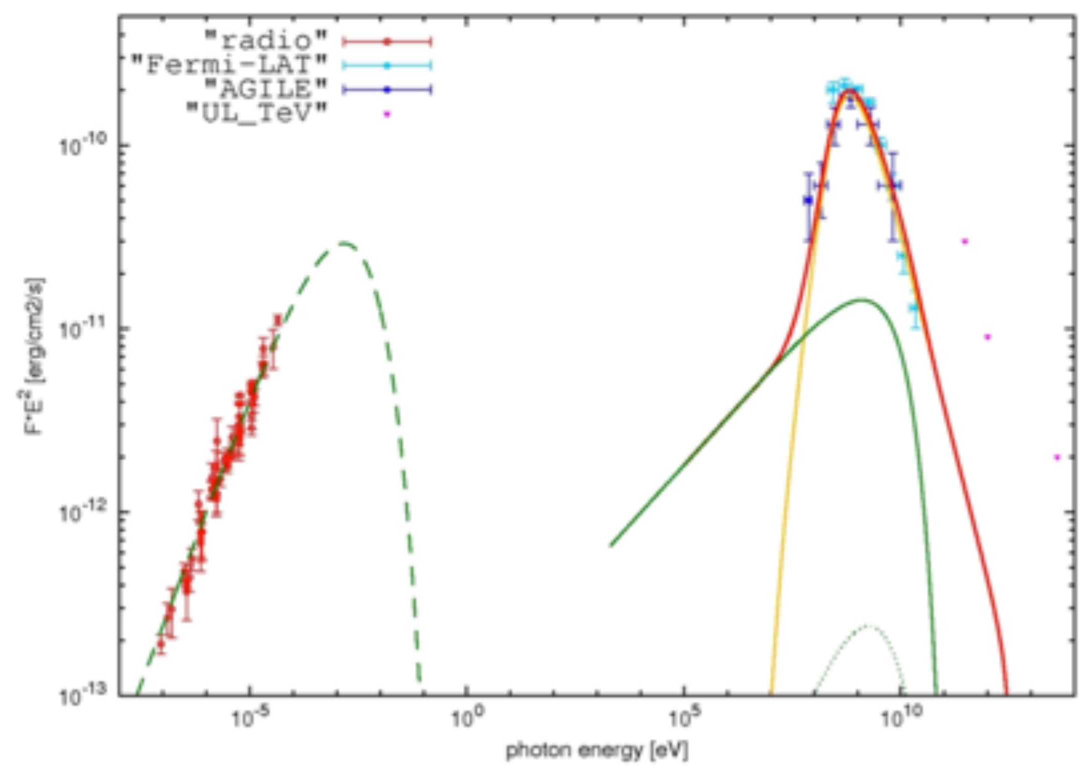
Or: is escape or environment?

Clear evidence for hadronic emission from mature SNRs

- EGRET: tentative evidence for SNR/mol. cloud associations (Esposito+ '96)
- Fermi + AGILE: many GeV detections!!
- Most prominent sources: SNRs interacting with molecular clouds
  - Examples: W44, W28, IC443
- Spectral shapes (W44/IC443):
  - Pion decay (Guiliani+ 11, Ackerman)
  - Cut-off energies 10^{10}-10^{11} GeV
  - *Suggests highest energy CRs escaped*



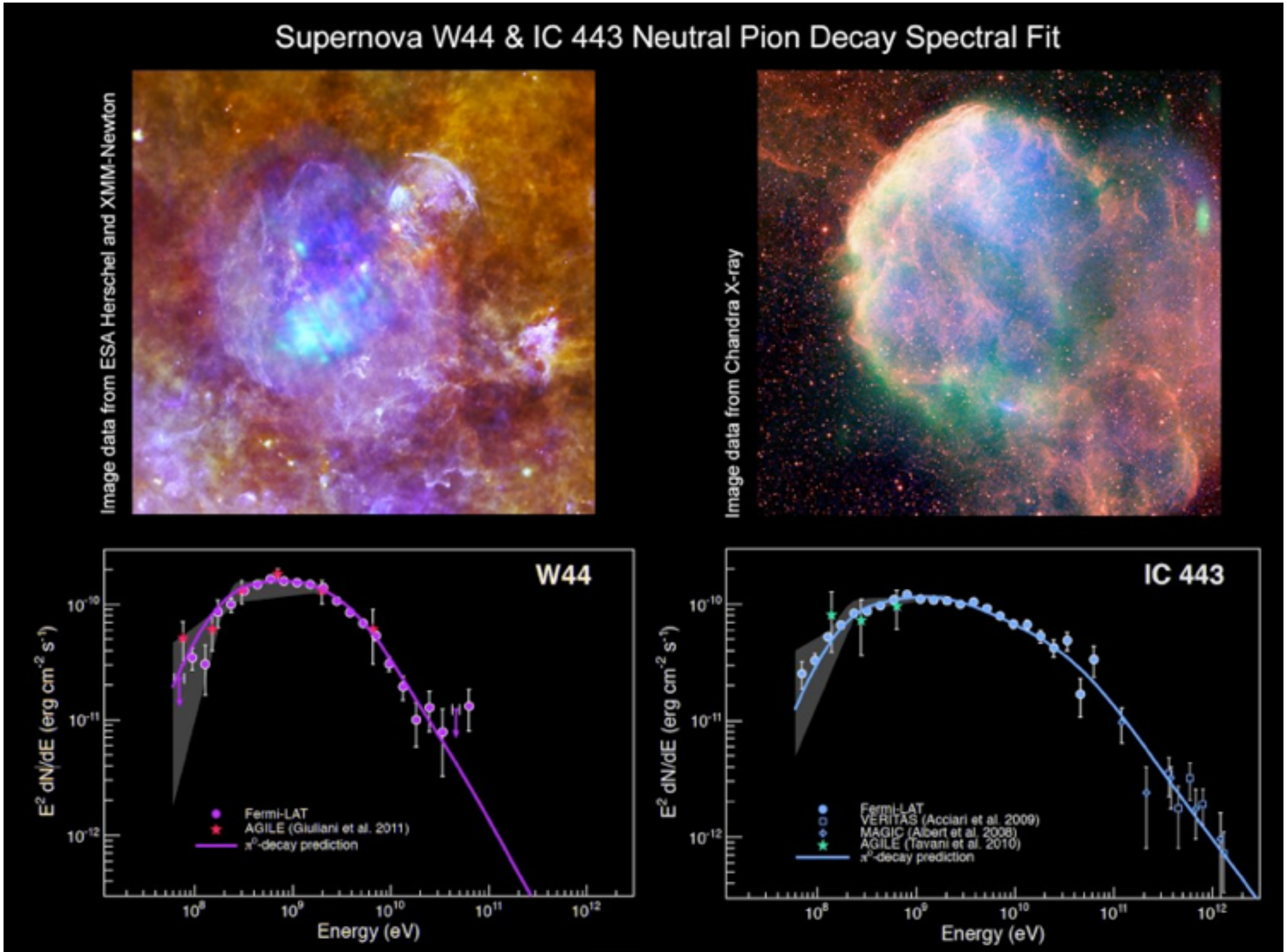
W44, Abdo+ 2010 (Fermi)



W44, Guiliani+ '11 (AGILE)

Fermi detection of pion bumps

Ackermann+ 2013



Conclusion:

Mature SNRs contain accelerated protons

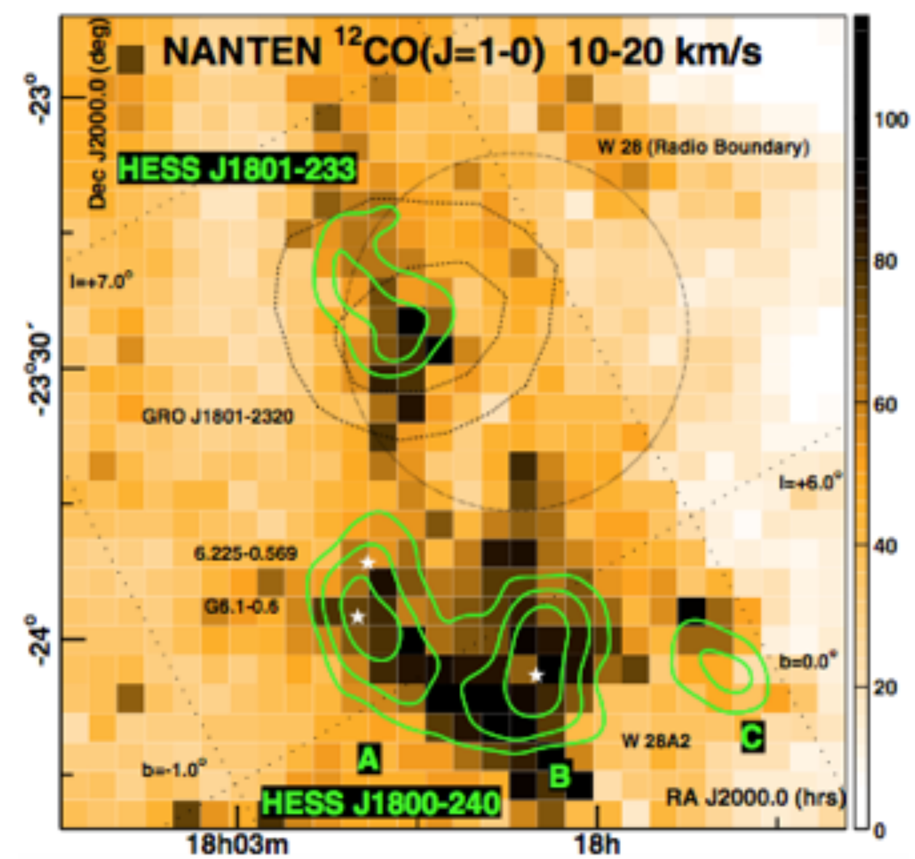
But are past their prime concerning acceleration to high energies!

Molecular clouds interacting with cosmic rays near SNR: W28

- Mature SNRs in general not TeV sources
- Perhaps surprising if TeV is hadronic and no cosmic-ray escape!

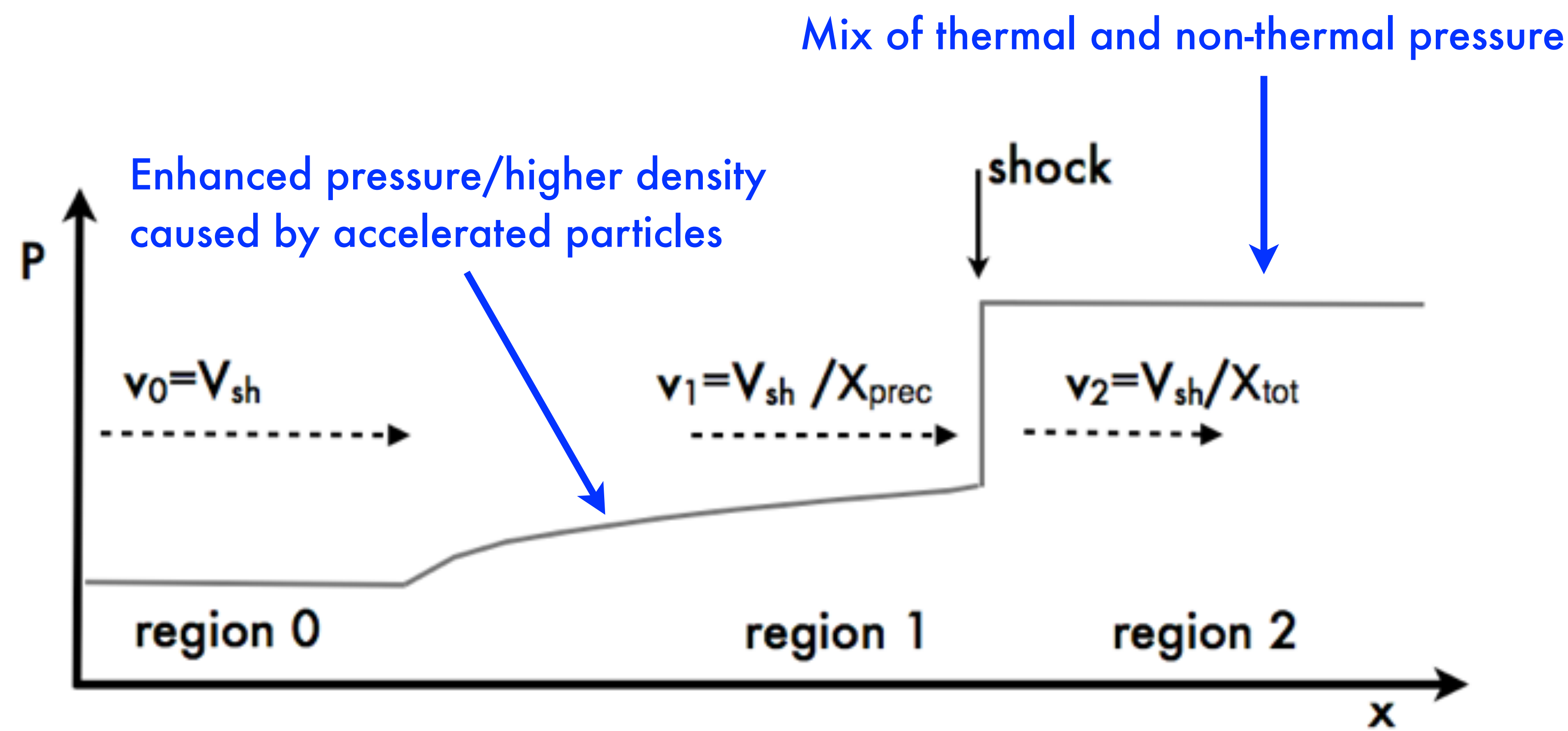
- The TeV detections of mature SNRs are SNRs/ molecular cloud associations!
- Interesting example: W28, offset between SNR and TeV source(s)
- General conclusion: highest energy (hadronic) cosmic rays seem to have escaped

- See also theoretical work by Gabici et al., Torres et al



W28 region
colors: CO
contours: TeV

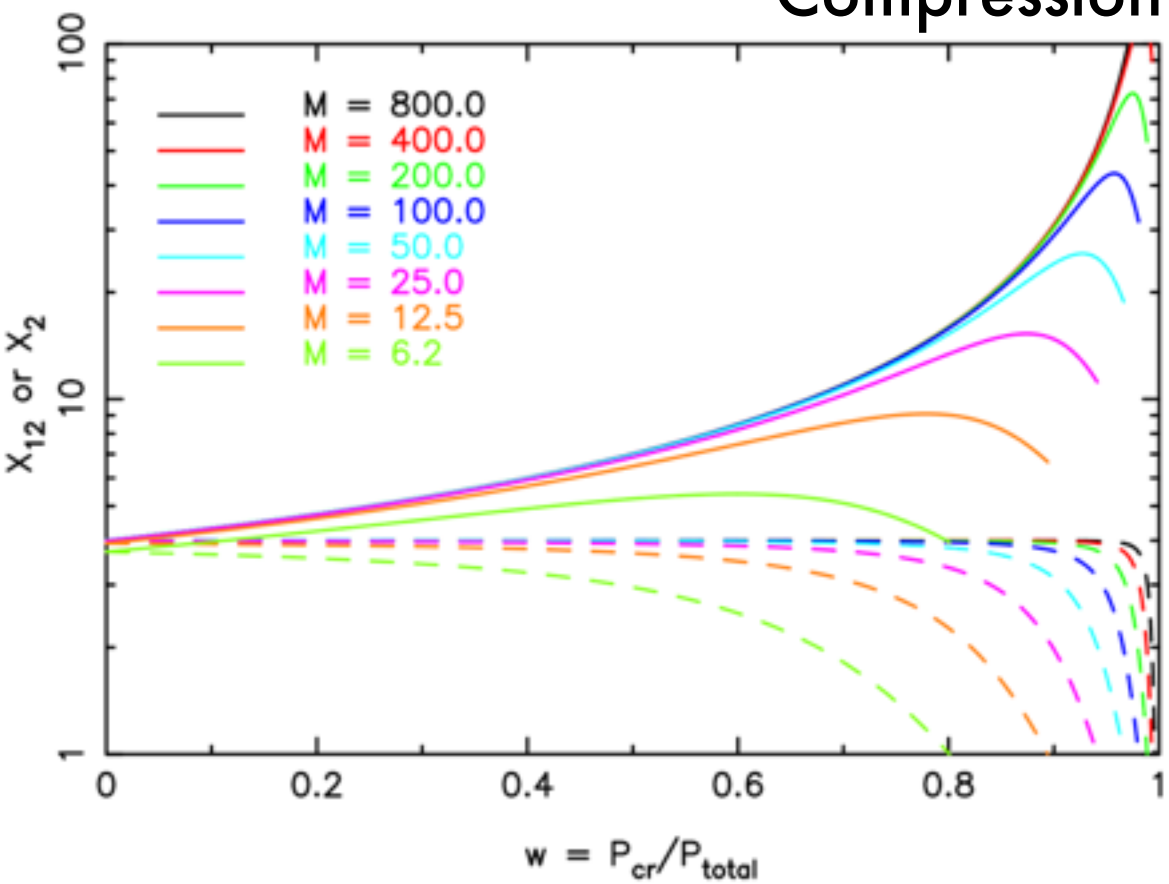
Signatures of efficient acceleration



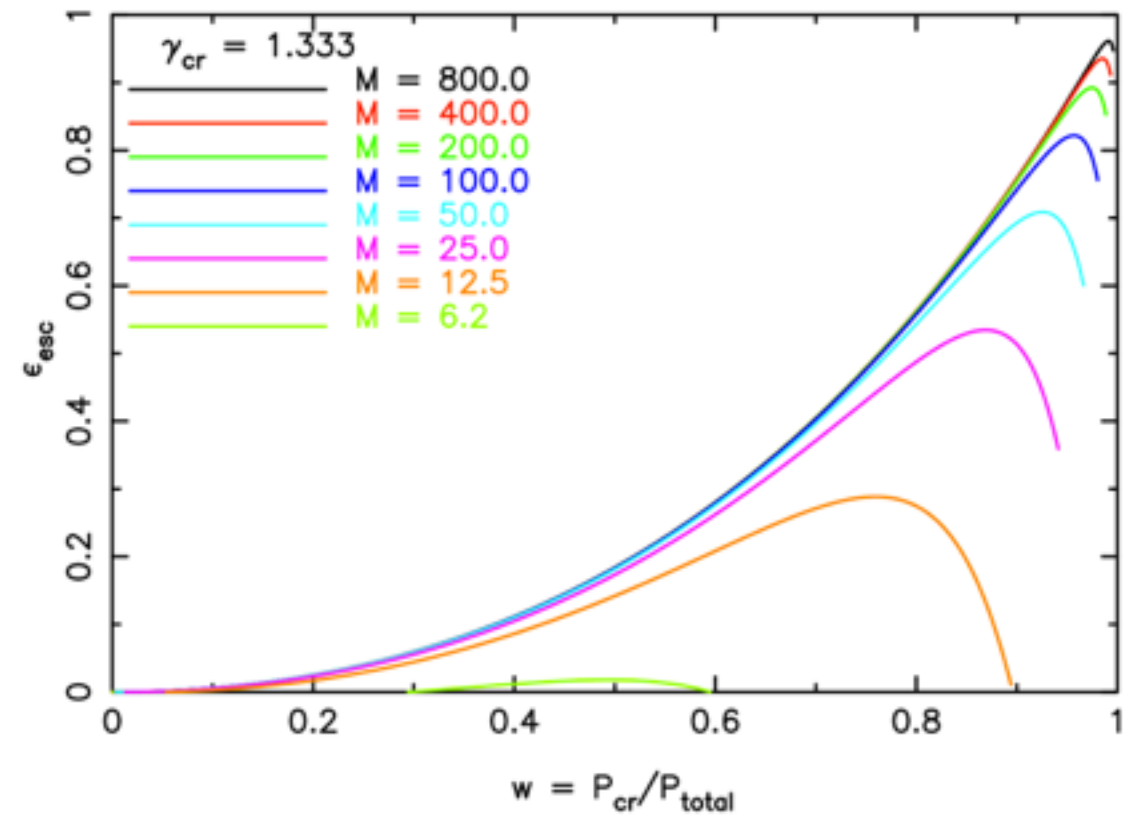
- What could be the signatures of efficient acceleration?
- Efficient acceleration results in non-linear shock structures:
  - Precursor region + heating
  - Lower post-shock plasma temperatures
  - Higher shock compression ratios

Results of simple Rankine-Hugoniot extensions

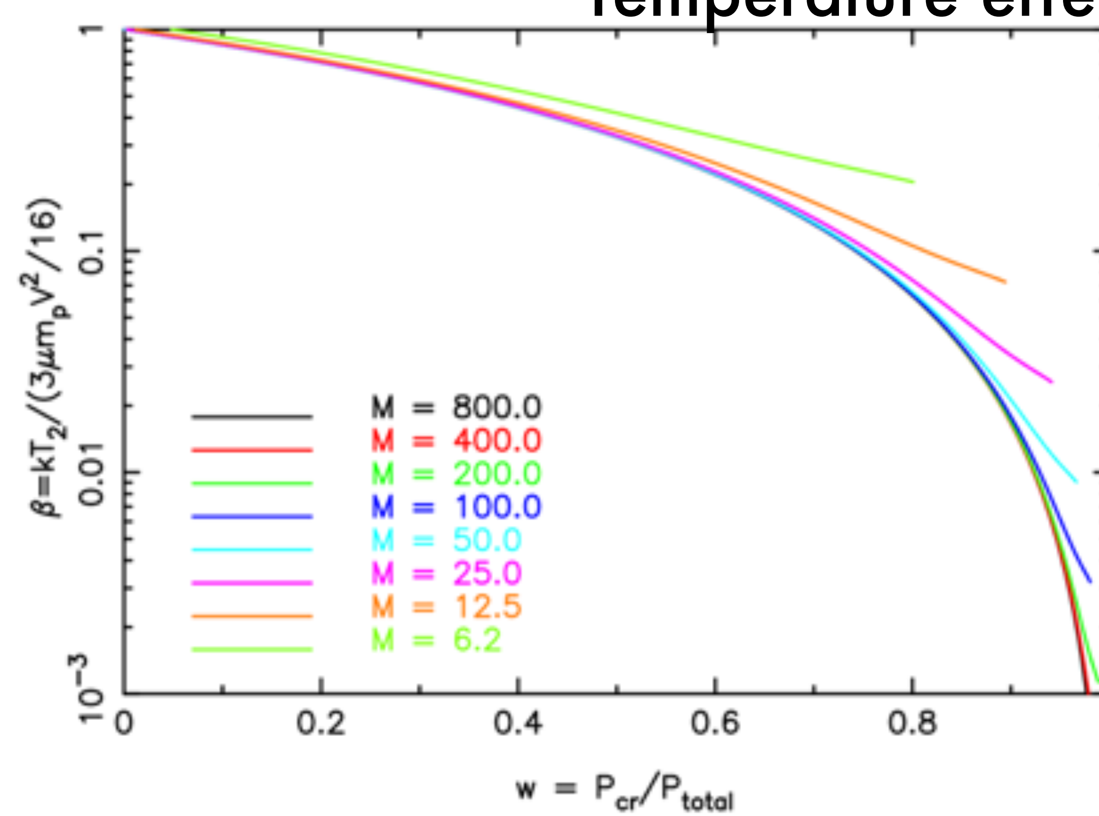
Compression



Escape



Temperature effects

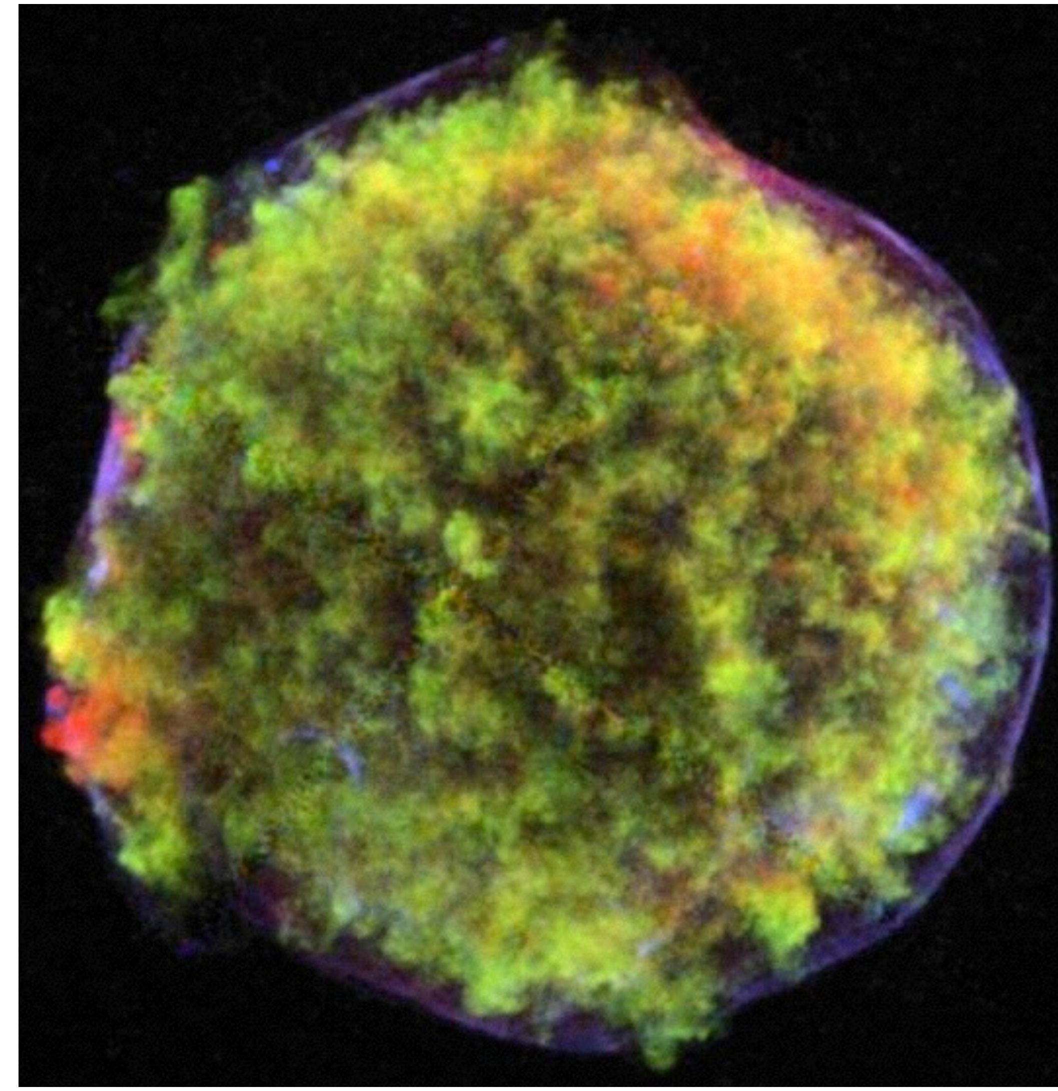


Higher acc. efficiencies

$w = P_{cr}/Ptot$

Vink+ '10, Vink&Yamazaki '14

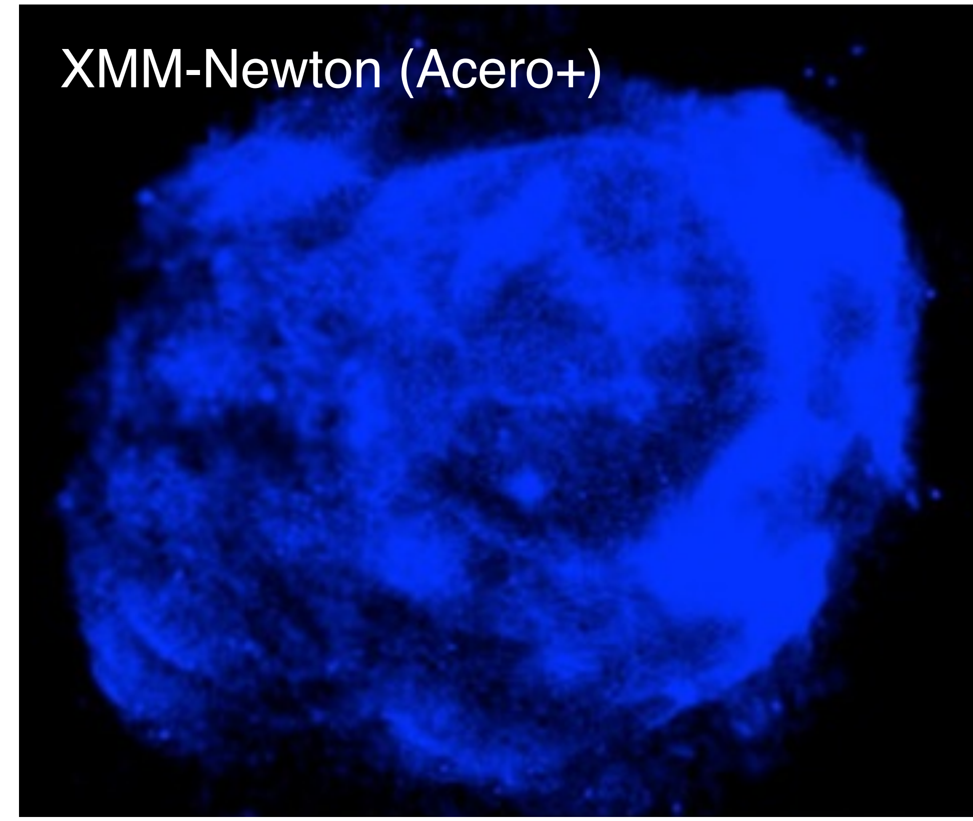
Evidence for high compression ratios



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

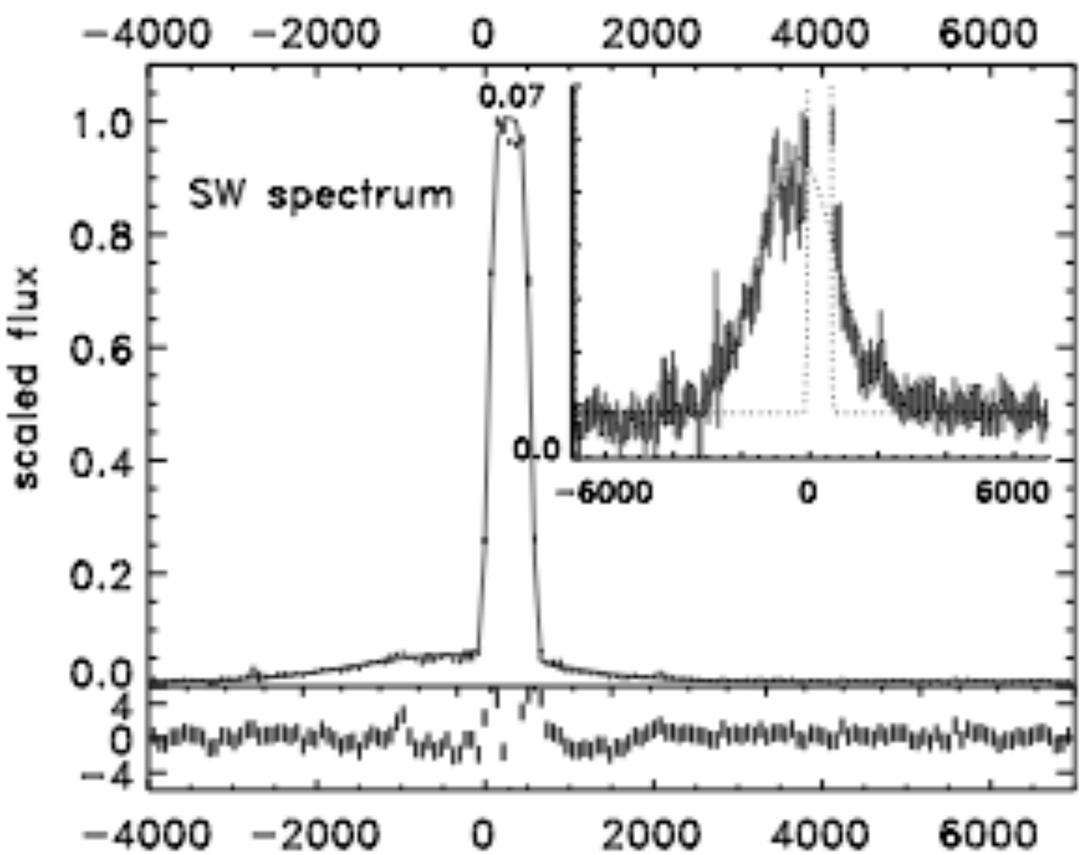
- X-ray evidence for Tycho's SNR:
  - Ejecta too close to shock front
    →need high compression ratio!
- SN1006: effect seen as well
  (even outside X-ray synchrotron rims)
- Caveat:
  - hydro-instabilities (Rayleigh-Taylor fingers) & clumpy ejecta may also bring ejecta close to forward shock → Orlando+ '12
  - expect harder gamma-ray spectra: not seen!

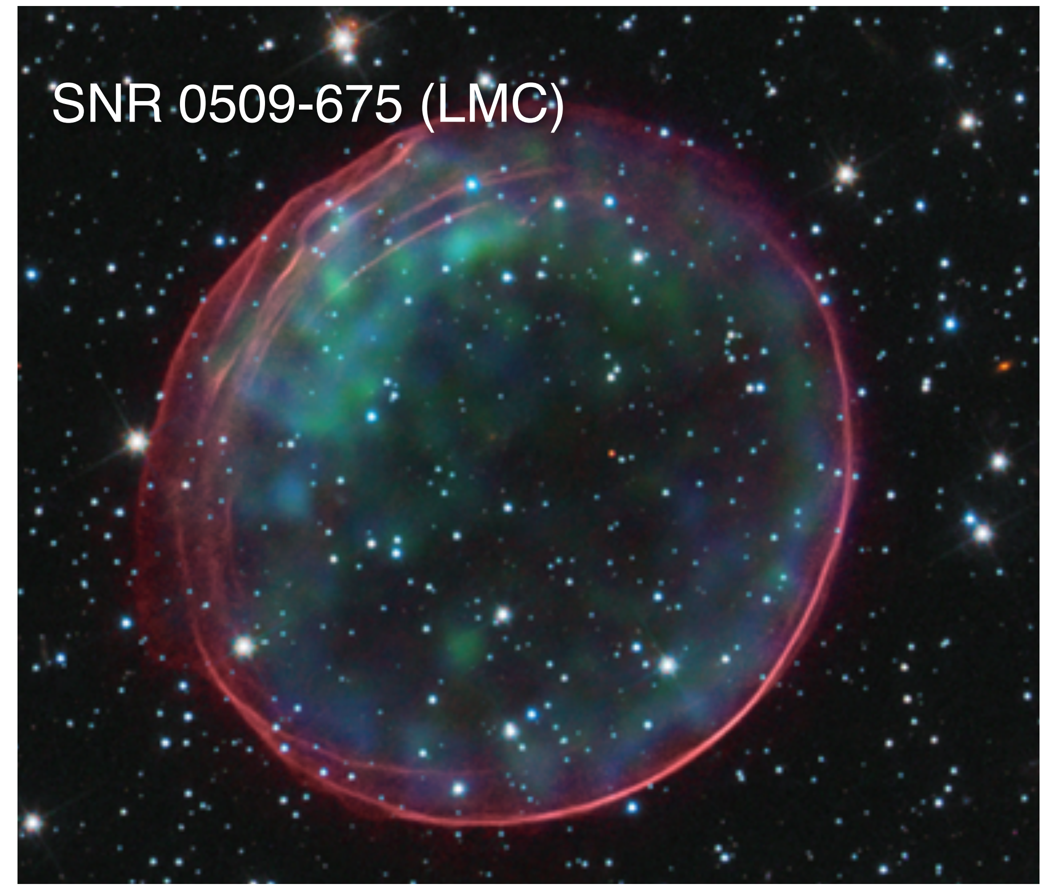
What about lower temperatures?



- In general measured temperatures too low (X-rays)
- Measured kT = *electron* temperature
- What about protons?
- Can measure proton temperatures from thermal Doppler broadening
- Relies on presence of neutrals entering the shock:
  - Charge exchange → Hα line emission
  - Raymond+ '11, Blasi+ '12, Morlino+ '13/'14

H-α from fastest known SNR shock

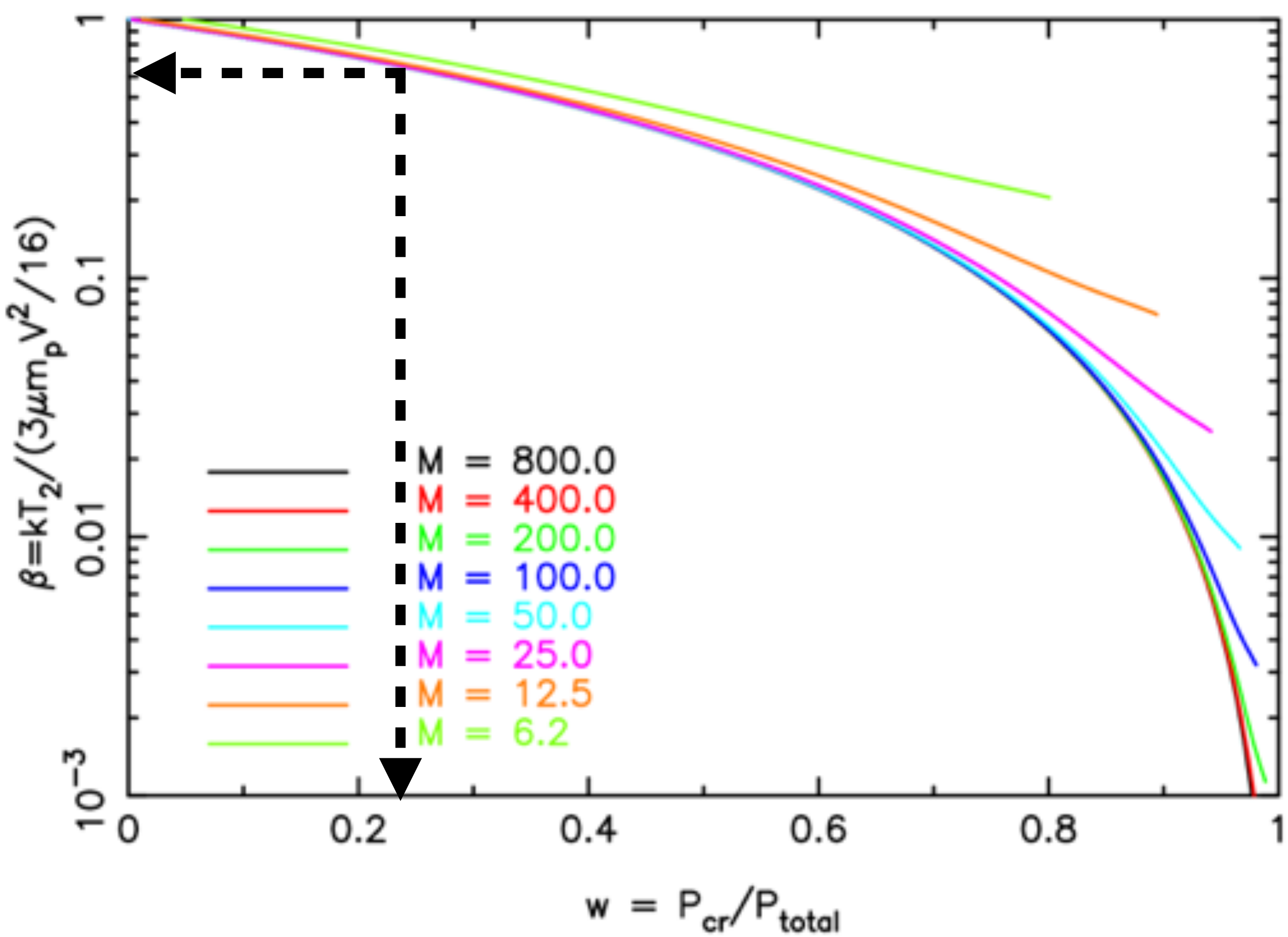




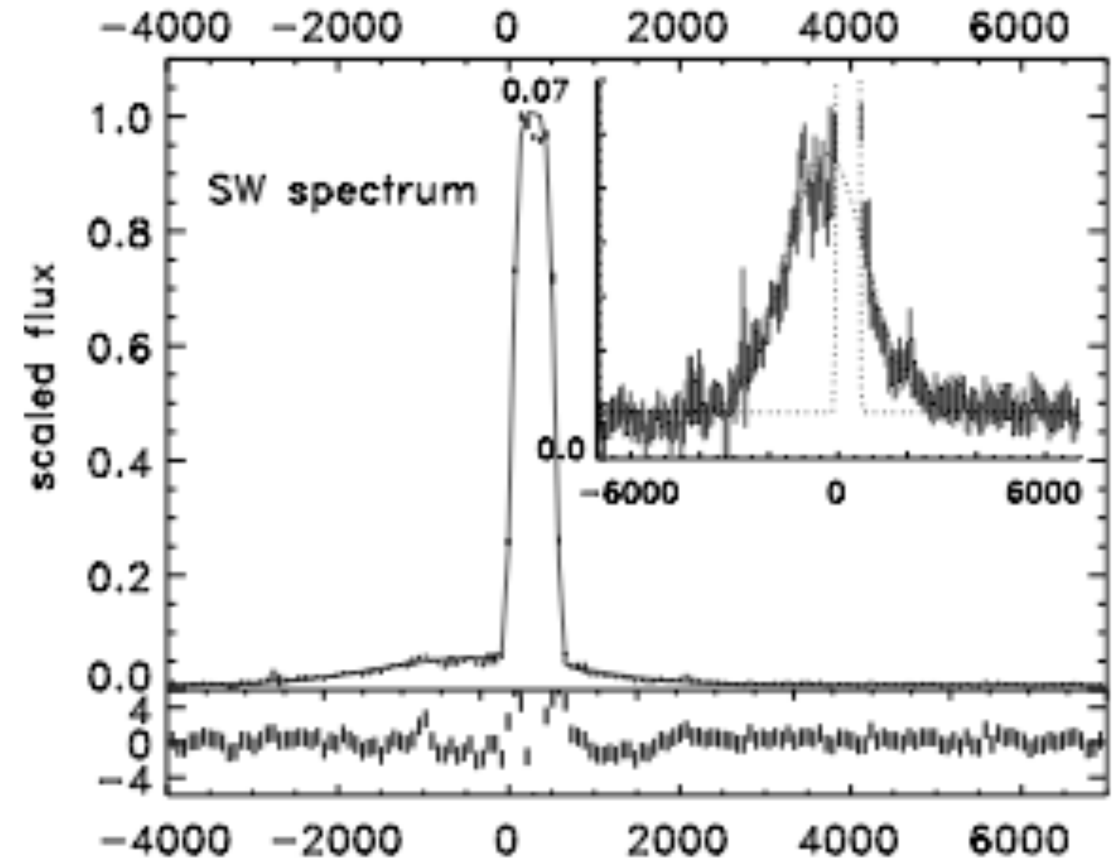
Helder, Kosenko, Vink '10

- Distance known (LMC, 50 kpc)
- Shock velocity: X-ray line broadening + Chandra expansion: V_s> 5000 km/s
- One of the fastest shocks in a known SNR
- J.P. Hughes private communication V_s=6500 km/s
- H-alpha broad line widths: 2680 ± 70 km/s (SW), 3900 ± 800 km/s

A measurement of the cosmic-ray efficiency in a fast supernova remnant shock 0509-675



Helder, Kosenko, Vink '10



- Distance known (LMC, 50 kpc)
- Shock velocity: X-ray line broadening + Chandra expansion: Vs> 5000 km/s
  - One of the fastest shocks in a known SNR!
- Hα broad line widths: 2680 ± 70 km/s (SW), 3900 ± 800 km/s
- Discrepancy in kT: $kT_{measured}/kT_{exp} \leq 0.7$
- Hence: cosmic-ray efficiency w≥25%

Summary and conclusions

- For SNRs to be the sources of Galactic cosmic rays:
  - 5-10% of explosion energy in cosmic rays
  - acceleration of protons beyond the knee
- No full proof (yet) that SNRs satisfy criteria, but a lot of progress made:
  - X-ray synchrotron emission young SNRs
    - → Acceleration electrons beyond 10 TeV
    - → Requires turbulent magnetic field $\eta < 10$
    - → Narrow rims → high B-fields → fast acceleration
  - TeV Gamma-rays
    - → >10 TeV particles present
    - → Debate over nature emission (inverse Compton vs Pion decay)
  - GeV gamma-rays
    - → few clear cases for pion decay → protons accelerated
    - → mature SNRs: cut-off around 10 GeV
    - → Spectrum affected by cosmic ray escape: acceleration early on
  - Cosmic-ray acceleration efficiency
    - → High compression ratios: inconclusive evidence
    - → Optical emission: hints for ≈25% acceleration efficiency