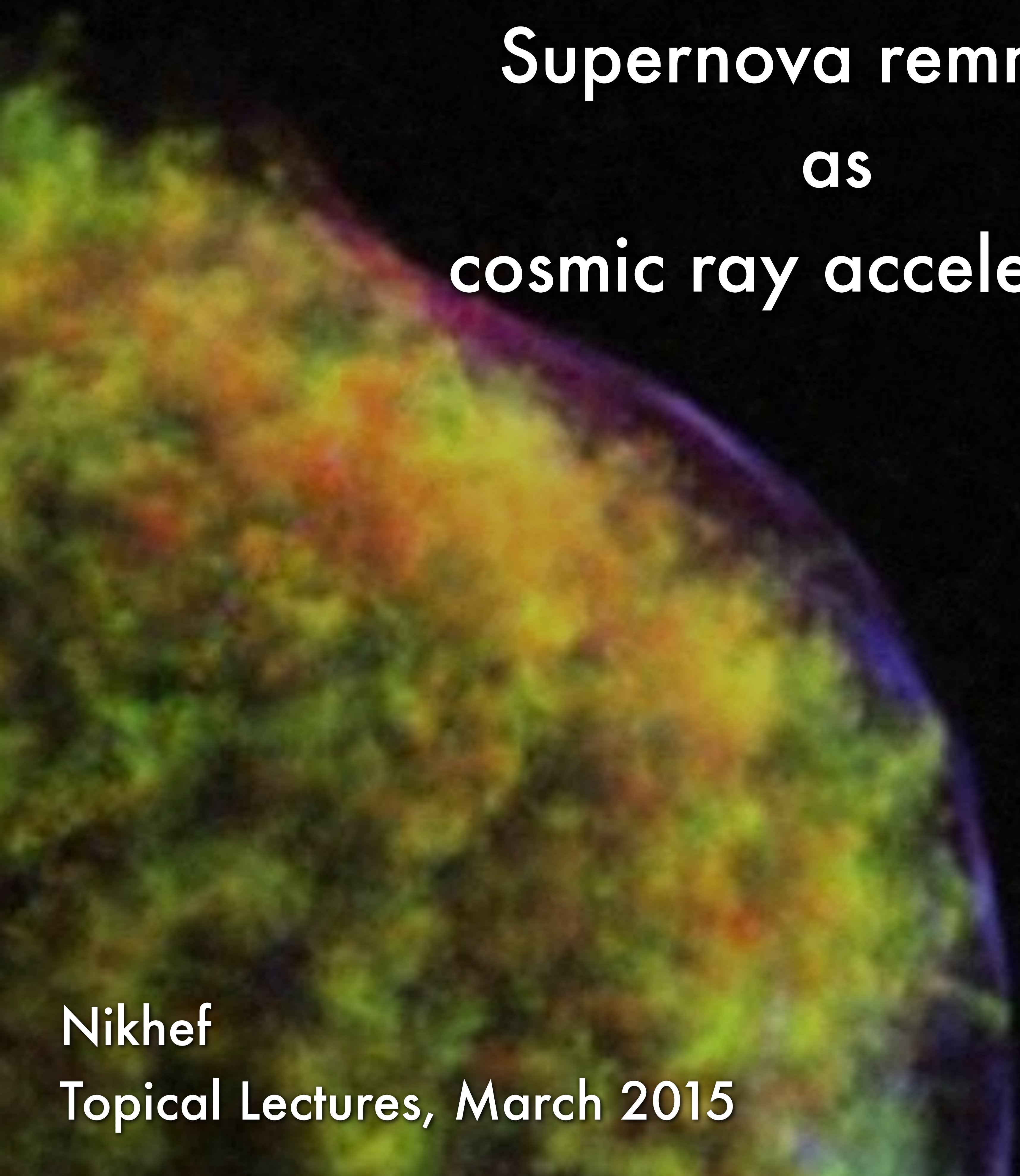
Supernova remnants as cosmic ray accelerators

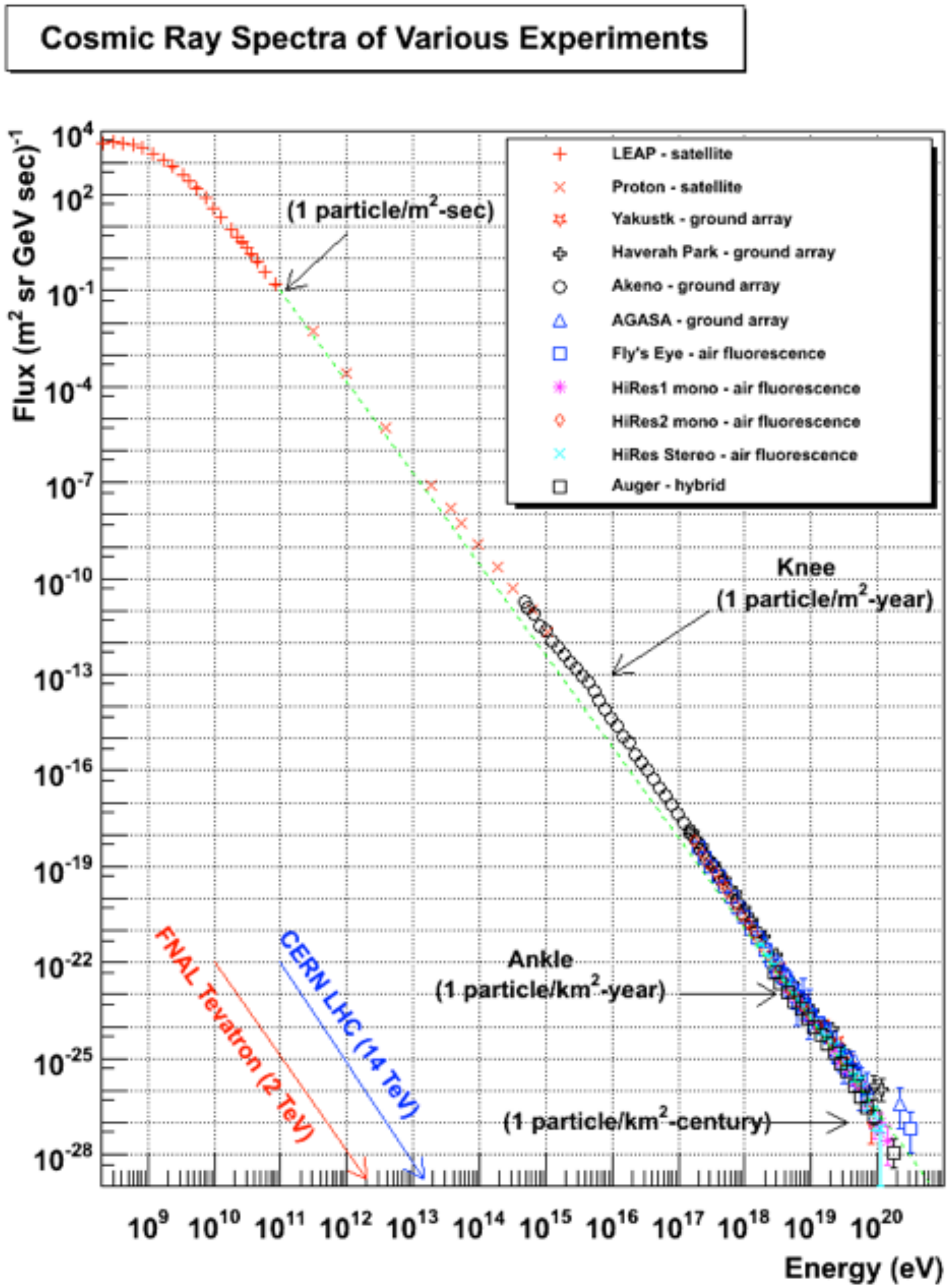


Jacco Vink

Nikhef
Topical Lectures, March 2015

GRAPPA
GRavitation AstroParticle Physics Amsterdam

The Cosmic Ray Spectrum



Voyager 1 result

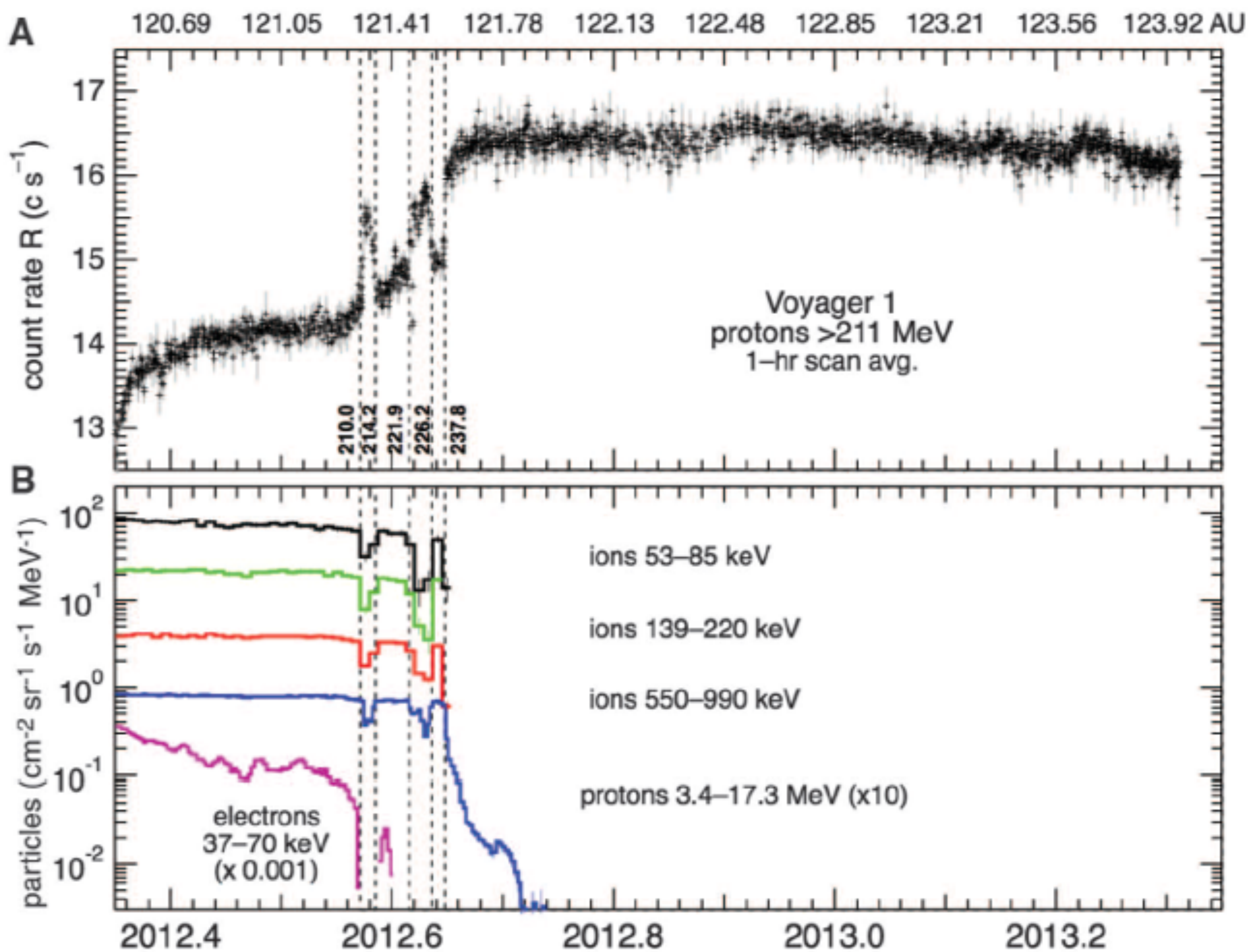
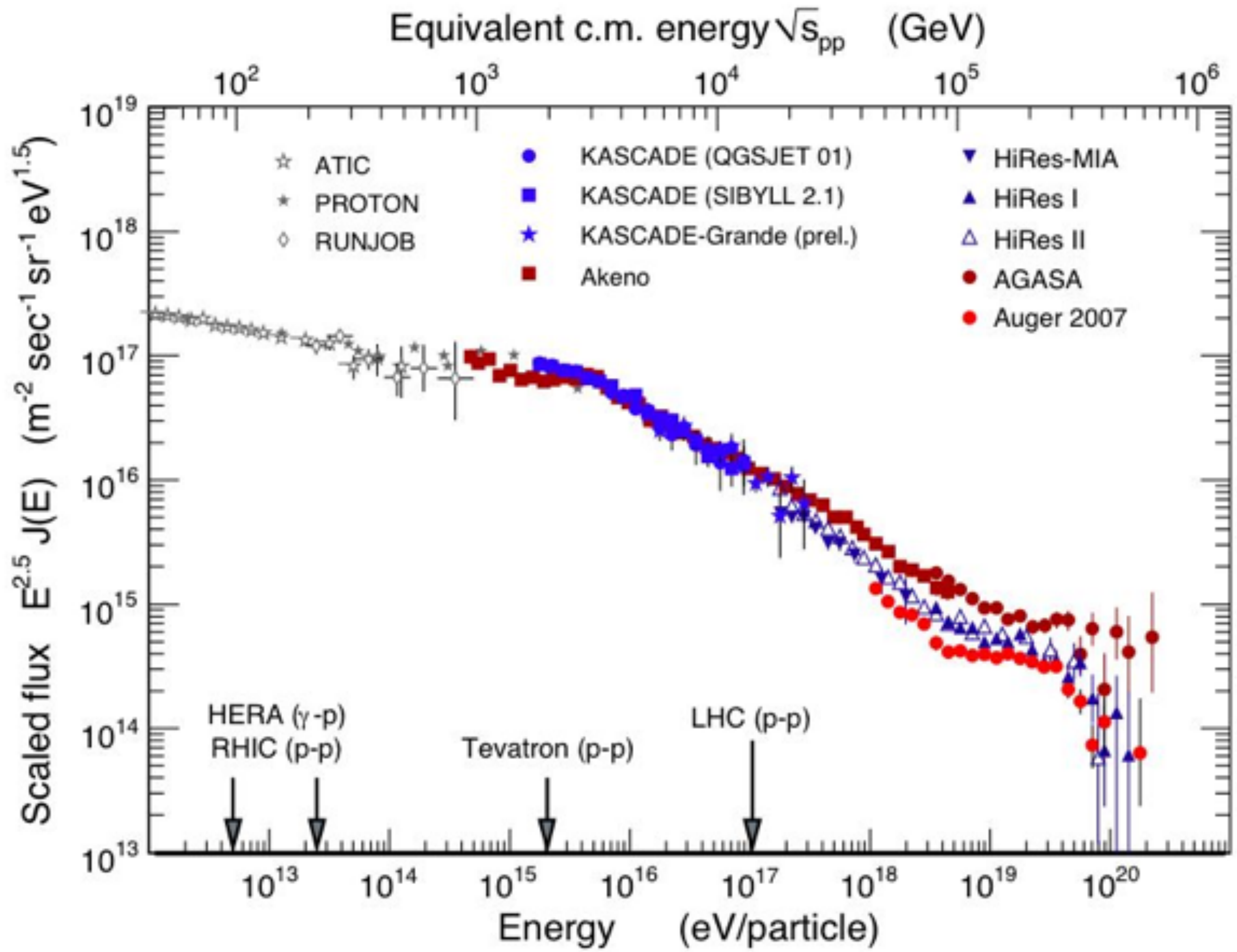


Fig. 1. Overview of energetic particle observations at V1, 2012.35 to 2013.40, showing the contrary behavior of GCRs and lower-energy particles. (**A**) Hourly averages of GCR activity and the pronounced boundary crossing on 25 August 2012 (day 238). GCR error bars are $\pm 1\sigma$. (**B**) Intensities of low- to medium-energy ions and low-energy electrons. The time evolution is very different, depending on energy and species.

The Cosmic Ray Spectrum



- Composition (S. de Jong)
- Note electrons make up about 1% of cosmic rays
- Near power law spectrum but a few features:
  - Knee ($3\text{x}10^{15}$eV): change in composition (protons → heavier elements)
  - Ankle ($3\text{x}10^{15}$eV): change to extra-galactic cosmic rays?
  - Cut-off ($5\text{x}10^{19}$eV): GZK cut-off? Maximum energy in extra-galactic sources?

From Novae to Supernovae

Walther Baade (1893 - 1960)

Frits Zwicky (1898-1974)

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely tha[...] "gravitational packing" energy in a [...] large, and, under certain circumstan[...] nuclear packing fractions. A neutron [...] most stable configuration of matter [...] hypothesis will be developed in anothe[...] some observations that tend to suppor[...] mainly of neutrons.

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

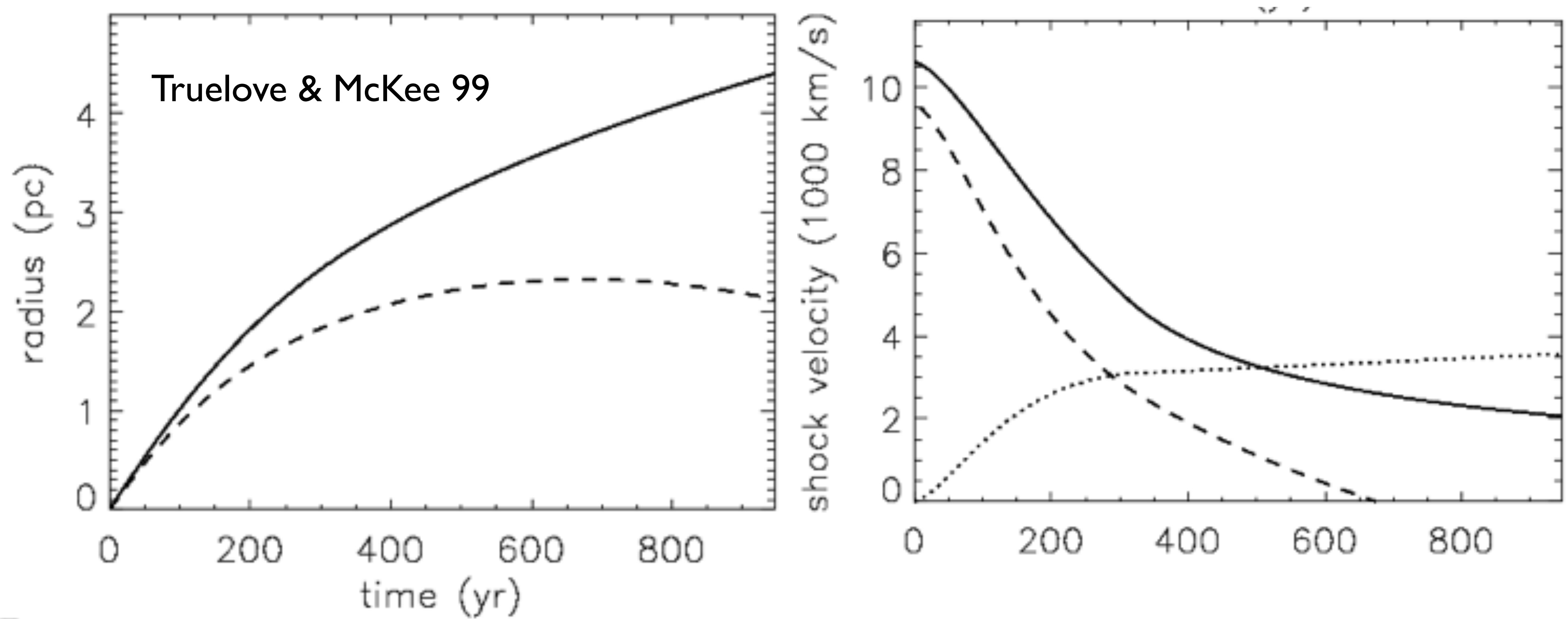
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

Supernovae

- Two basic classes of supernovae:
  - Core collapse supernovae (types II, Ib, Ic, ..):
    - Collapse of core of massive star ($M>8\ M_{sun}$)
    - Formation of neutron star
    - Energy from gravitational collapse (10^{53} erg)
    - Most energy in neutrinos
    - $\approx 10^{51}$ erg explosion energy
  - Thermonuclear supernovae (Type Ia)
    - Disruption of C/O white dwarf
    - Energy from nuclear fusion (e.g. C/O → ^{56}Ni)
    - Explosion energy=total energy ≈ 10^{51} erg

Supernova remnants



- Supernova explosion ejects material with V≈2000-20000 km/s
- Ejecta create a shock wave in interstellar medium
- Shock wave heats gas to 10^6-10^8 K, creating a hot expanding shell
- Hot shell sends also shock wave into cold supernova ejecta (reverse shock)
- Hot shell emit X-ray emission
- X-ray spectra shows material from supernova
- Mass of shell grows from few M_{sun} to 500 M_{sun}
- Shell=supernova remnant exists for 20,000-100,000 yr

Why are supernova remnants prime candidates for origin of *Galactic* cosmic rays?

- Energy requirements for a steady CR population in Milky Ways:
  - Energy density in cosmic rays in Milky Way: $u_{cr} \approx 1$ eV/cm^3
  - Around 1 GeV: CRs remain for $\approx 10^7$ yr in Galaxy
  - Volume Galaxy: $V_{gal} = \pi R_{disk}^2 (2z) \approx 3 \times 10^{11}$ pc^3 $\approx 10^{67}$ cm^3
  - Power needed: $L = u_{cr} V_{gal} / t_{cr} = 5 \times 10^{40}$ erg/s
- Power provide by supernovae
  - 2-3 supernovae per galaxy per century
  - Energy per SN: 10^{51} erg
  - SN power: $L_{SN} = 10^{51} / t_{SN} = 6 \times 10^{41}$ erg/s

SNe provide enough power for cosmic rays if efficiency is 5-20%!

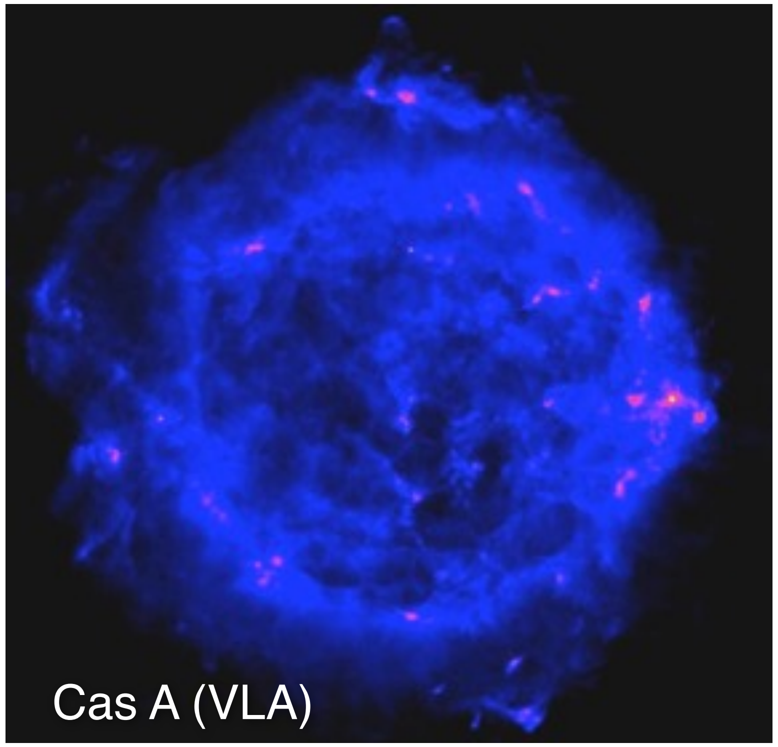
The origin of Galactic cosmic rays

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

1. SNRs should put 5-20% ($\simeq 10^{50}$ erg) of kinetic energy in cosmic rays
   ➜ *when do they do this, early, young, or Sedov stage?*
   ➜ *should collective effects be considered (super bubbles?)*

2. SNRs should be able to accelerate particles to $>3\text{x}10^{15}$eV
   ➜ *where are the Galactic Pevatrons?*

Early evidence for particle acceleration by SNRs



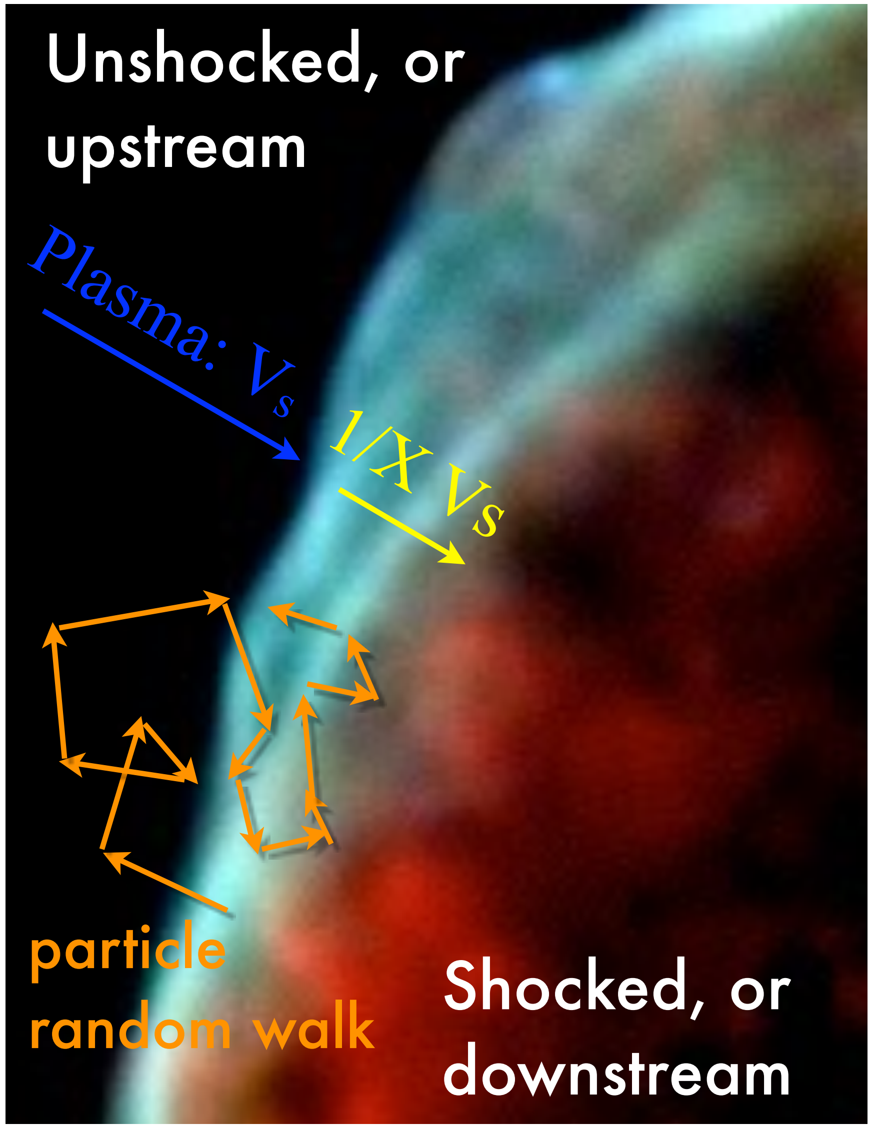
- Development of radio astronomy (1950-1960): SNRs are radio synchrotron sources
- Since 1960ies: SNe sources of energy, but acceleration inSNR stage
- Important source: Cas A
- Important: radio synchrotron radiation→ electrons of at least ≃1-10 GeV
    - *What about protons, and what about the cosmic ray knee?*

Diffusive shock acceleration (Fermi 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):
  - After each cycle, less particles make it to next cycle
- 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)
Review: Malkov & Drury 2001

First order Fermi acceleration

- Particles *elastically scatter* on either side of the shock
  - scattering centers: turbulent magnetic fields
- Particles going from upstream to downstream appear to have some excess momentum, but also the other way around: Δv v_1-v_2=(1-1/X)v_1=3/4V_s
- Lorentz transformation (with Δv=3/4V_s): $E = \gamma_{\Delta v} \left(E' + p' \Delta v \cos\theta \right)$

- Non-relativistic shock/rel. particle: $\gamma \approx 1, p = E/c.$

$$\frac{\Delta E}{E} \approx \frac{\Delta v}{c}\overline{\cos\theta} = \frac{\frac{3}{4}V_\mathrm{s}}{c}\overline{\cos\theta} \equiv \alpha$$

- After n full shock crossings (exponential growth):

$$E = E_0(1+2\alpha)^n$$

Expected particle spectrum

- There are two competing processes:
  1. recrossing shock: gaining energy
  2. particles are swept downstream → away from shock front
- Assume isotropic cosmic ray distribution
  - Number rate of particles crossing shock: $\frac{1}{4} n_{cr} c$
- Number rate of particles escaping downstream: $1/X n_{cr} V_s = 1/4 n_{cr} V_s$
  - $P_{escape=}(1/4 n_{cr} V_s/)/(1/4 n_{cr} c)$, so survival $P_{surv}=1-P_{esc}=1-V_s/c$
  - So after n cycles (exponential growth energy, exp. decay in survival)

$$E = E_0(1+2\alpha)^n, \; N = N_0(1-V_s/c)^n$$

$$n = \ln(E/E_0)/\ln(1+2\alpha) = \ln(N/N_0)/\ln(1-V_s/c)$$

  - Some manipulation (ln (1+x)≈1/x):

$$N = N_0\left(\frac{E}{E_0}\right)^{-1}, dN(E)/dE \propto E^{-2}$$

  - Taking into account shock compression X: $dN/dE = C\, E^{-(1+3/(X-1))}$
  - *Hence: power law slope spectrum* q=(1+3/(X-1))=2 for X=4!!

Acceleration time

- Upstream the particles diffuse ahead of the shock
  - They form a shock-precursor
- How long before being swept up by shock?
  - Diffusion length scale:

$$l_{\rm shock} = V_{\rm s}\Delta t_1 = \sqrt{2D_1\Delta t_1} = l_{\rm diff}$$

  - Time scale:

$$\Delta t_1 = \frac{2D_1}{V_s^2}$$

  - Hence

$$l_{\rm diff} = \frac{2D_1}{V_{\rm s}}$$

  - Diffusion coefficient:

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

  - η =fudge parameter: B-field turbulence

- Downstream:

$$\Delta t_2 = \frac{2D_2}{\left(1-\frac{1}{\chi}\right)V_{\rm s}^2} \approx \frac{2D_2}{\frac{3}{4}V_{\rm s}^2}.$$

- During one cycle gain is

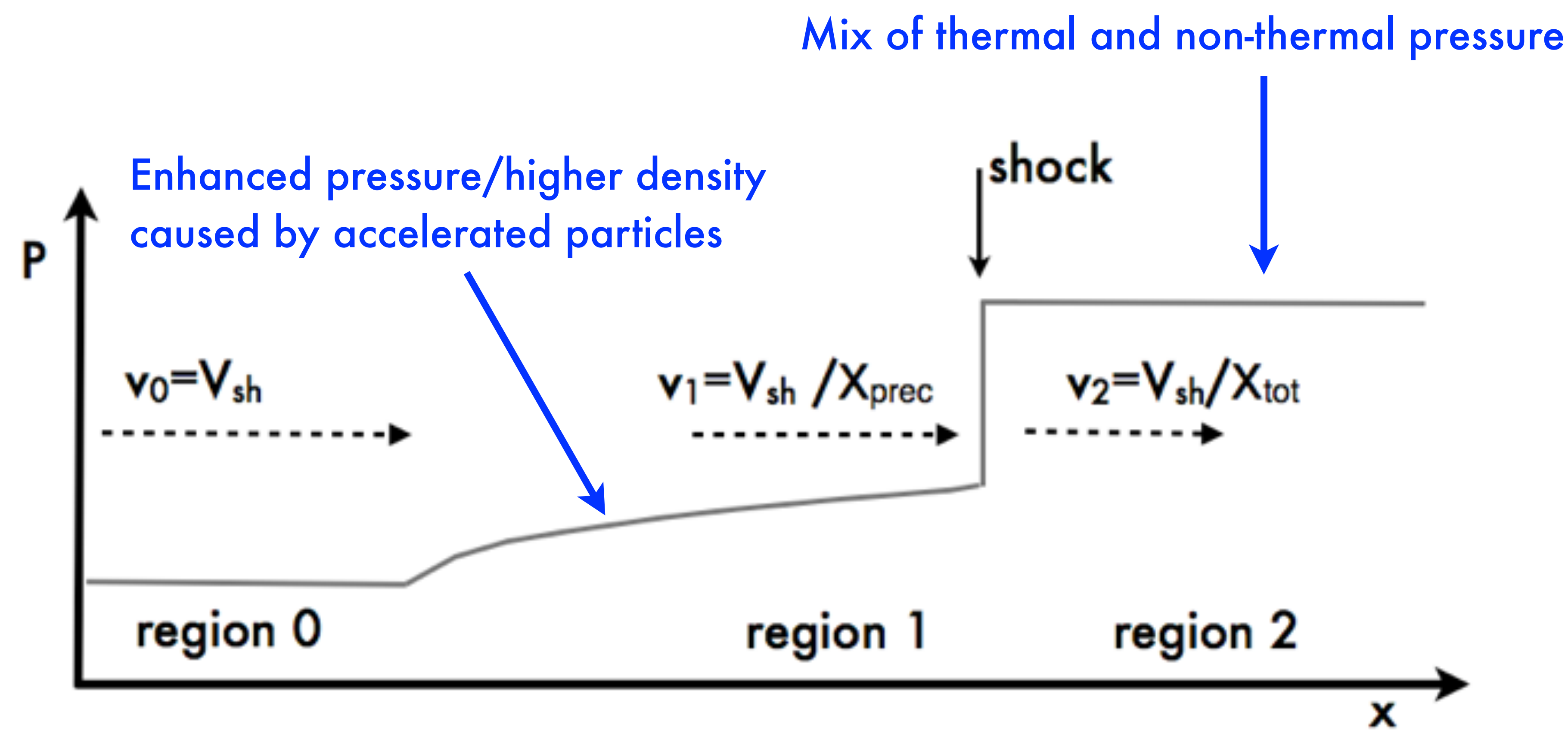
$$\frac{\Delta p}{p} \propto \frac{V_s}{c}$$

- Combining:

$$t_{\rm acc} = \frac{3}{v_1 - v_2}\int_{p_1}^{p_2}\left(\frac{D_1}{v_1} + \frac{D_2}{v_2}\right)\frac{dp}{p}$$

- Last decade in energy takes longest time (large diffusion coefficient)

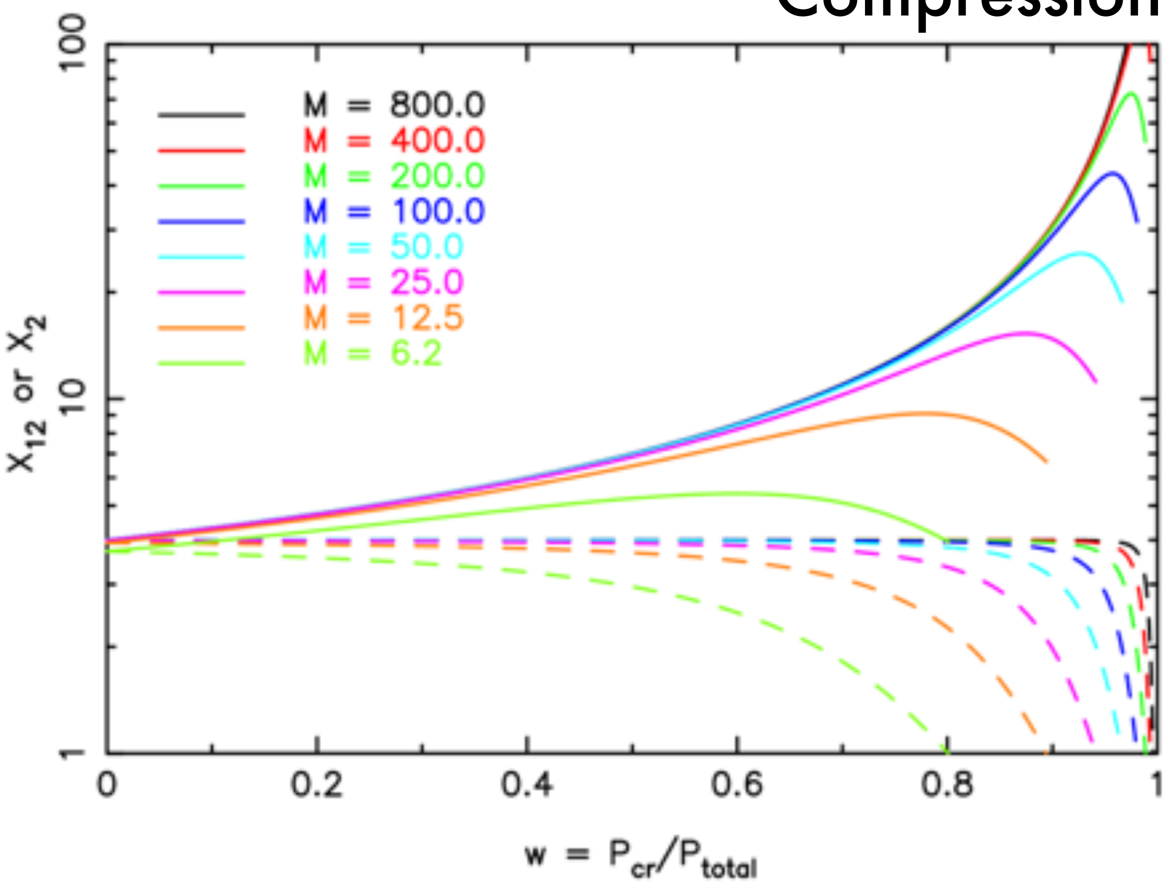
Signatures of efficient acceleration



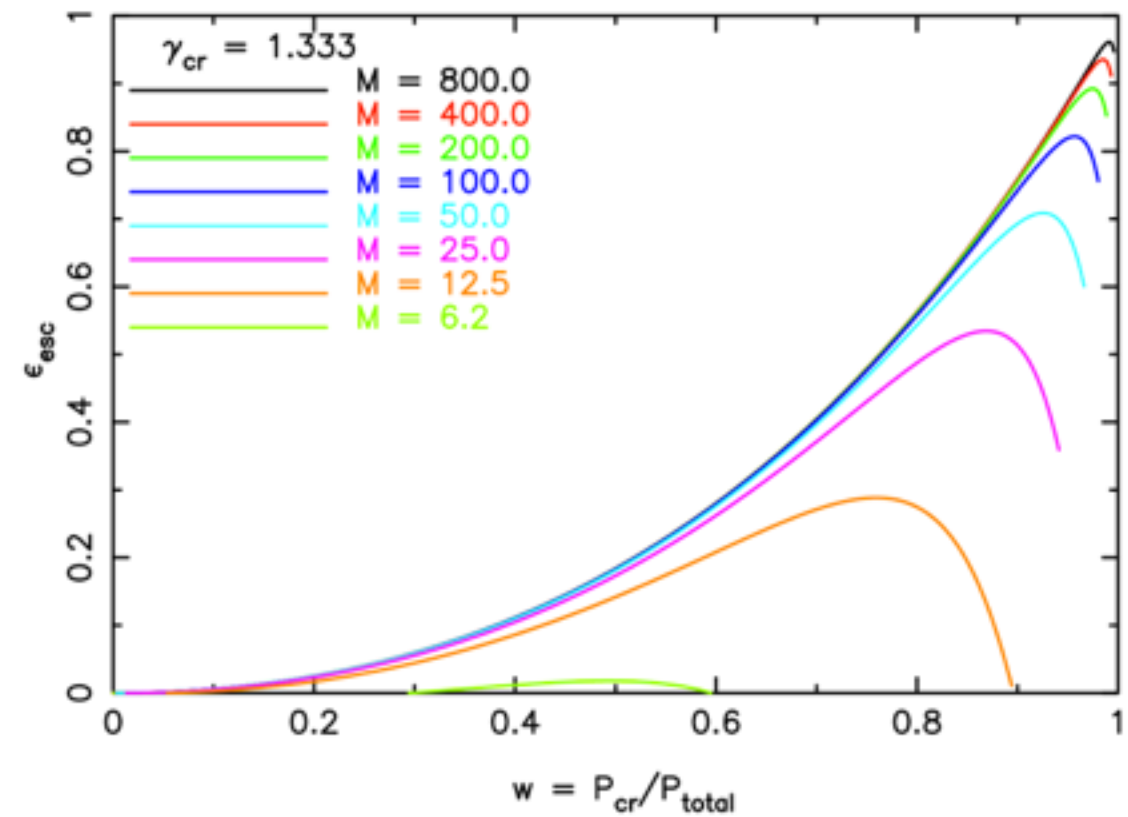
- What could be the signatures of efficient acceleration?
  - Shock structure changes: cosmic ray precursor, gas pre-heating/slowing down
- Efficient acceleration results in non-linear shock structures:
  - Precursor region + heating
  - Lower post-shock plasma temperatures
  - Higher shock compression ratios

Results of simple Rankine-Hugoniot extensions

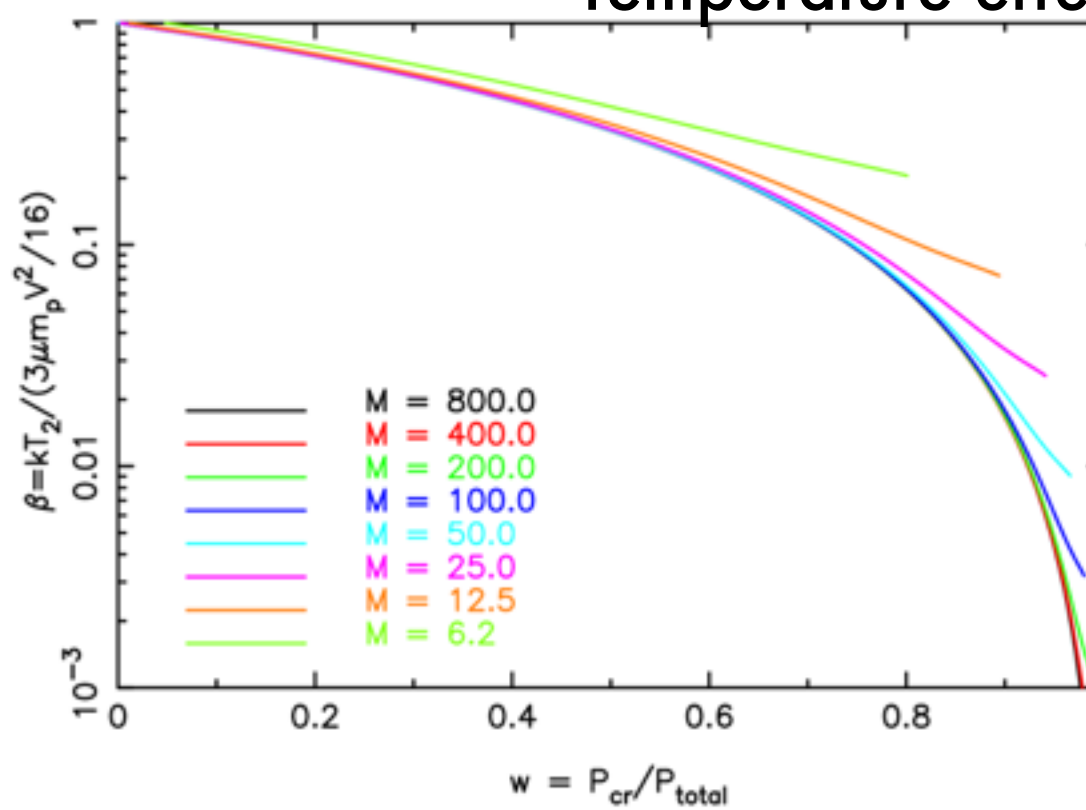
Compression



Escape



Temperature effects



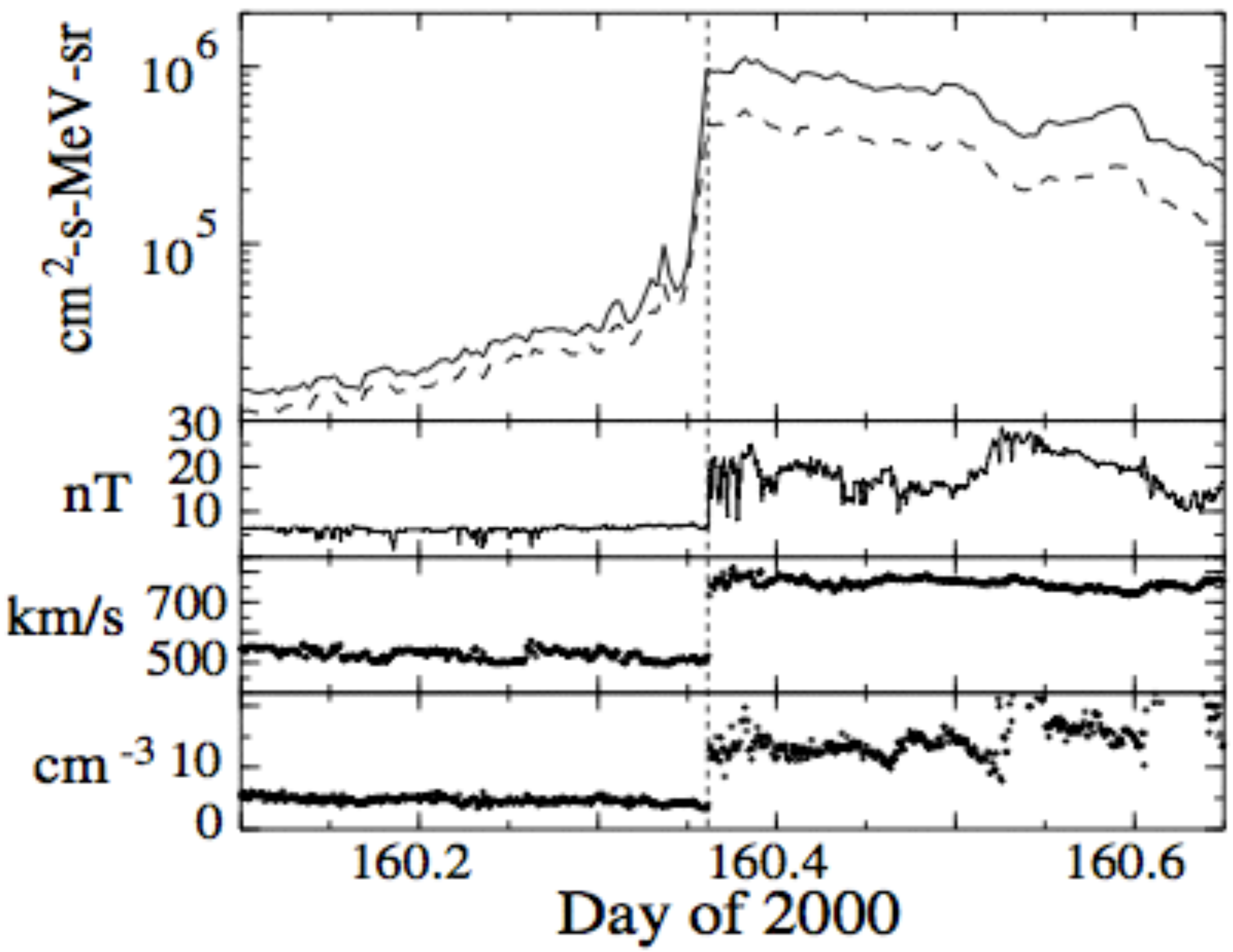
Higher acc. efficiencies

→

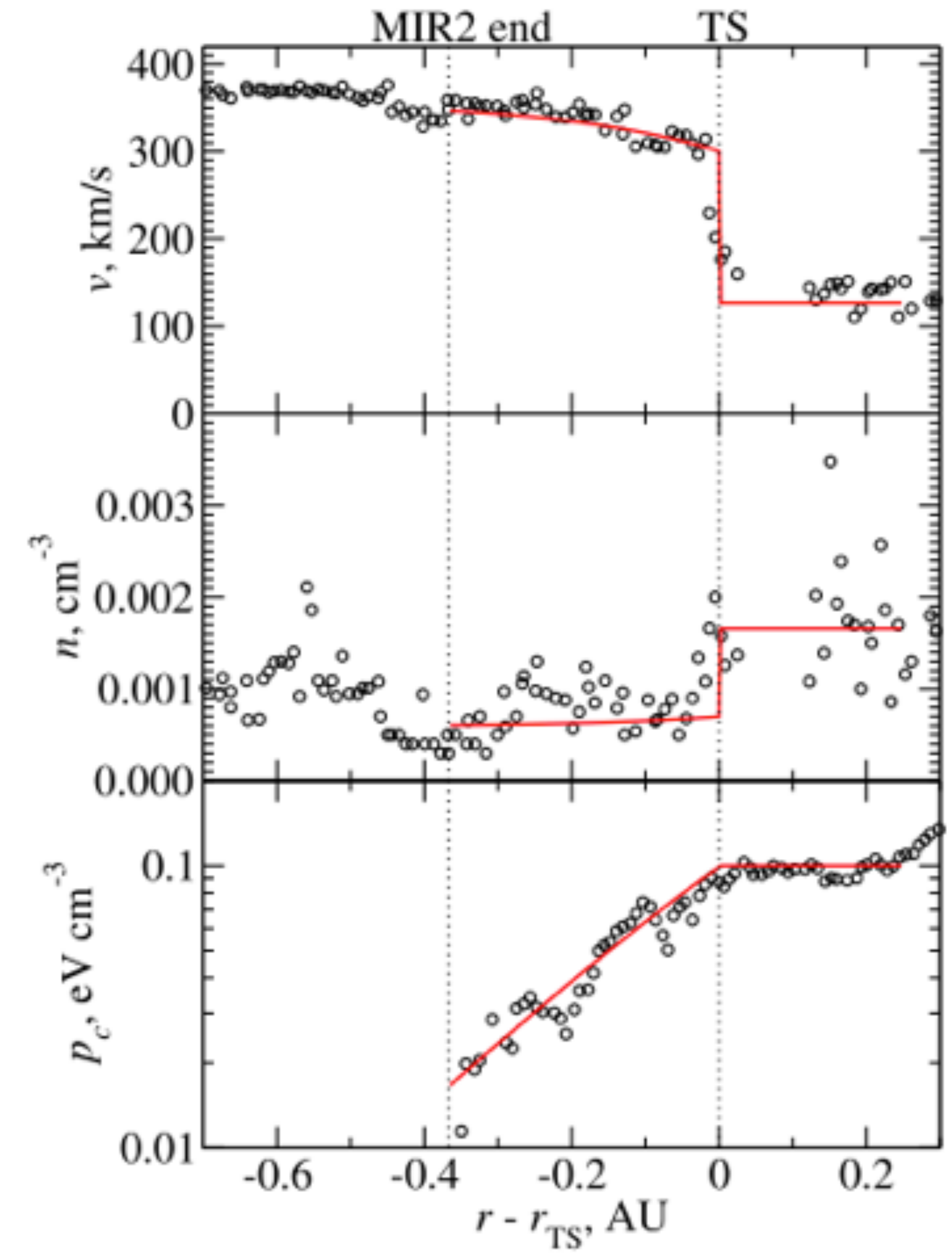
$w = P_{cr}/Ptot$

Vink+ ’10, Vink&Yamazaki ‘14

Shocks in solar system:
Fermi acceleration caught in the act!



CME induced shock (ACE, Giaccalone '12)



Solar system termination shock
(Voyager 2, Florinski+ 09)

Can SNRs accelerate up to the knee?

The maximum energy of cosmic rays accelerated by supernova shocks

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Received February 28, accepted April 11, 1983

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

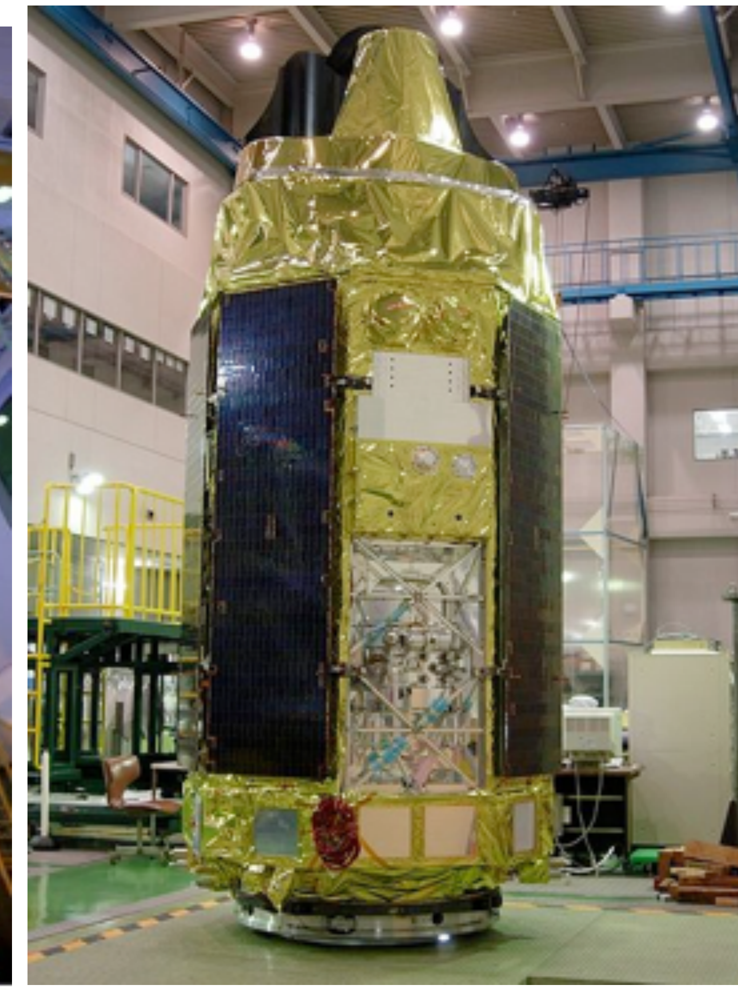
1983:

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

The X-ray revolution

Chandra (NASA, 1999)

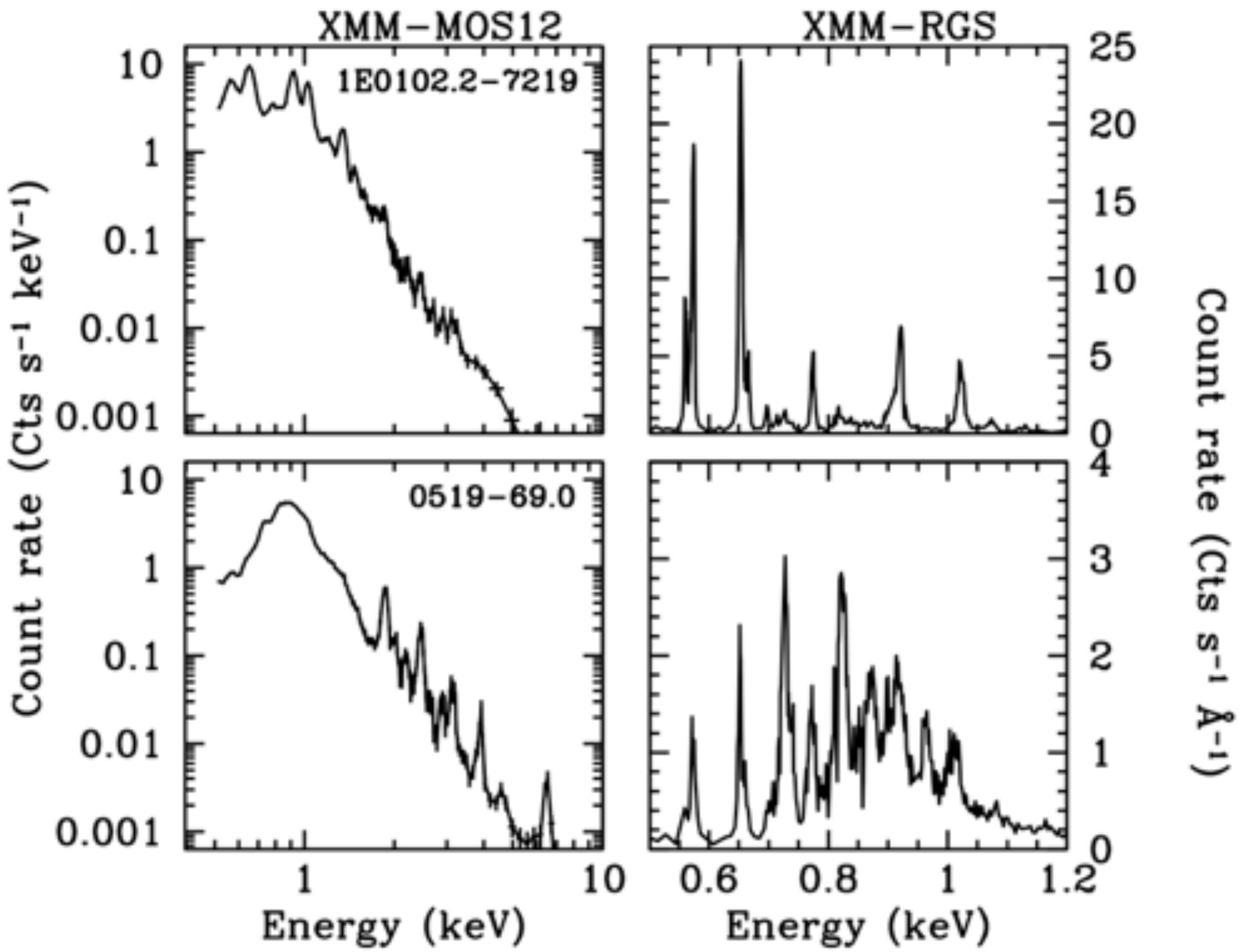
XMM-Newton (ESA, 1999)

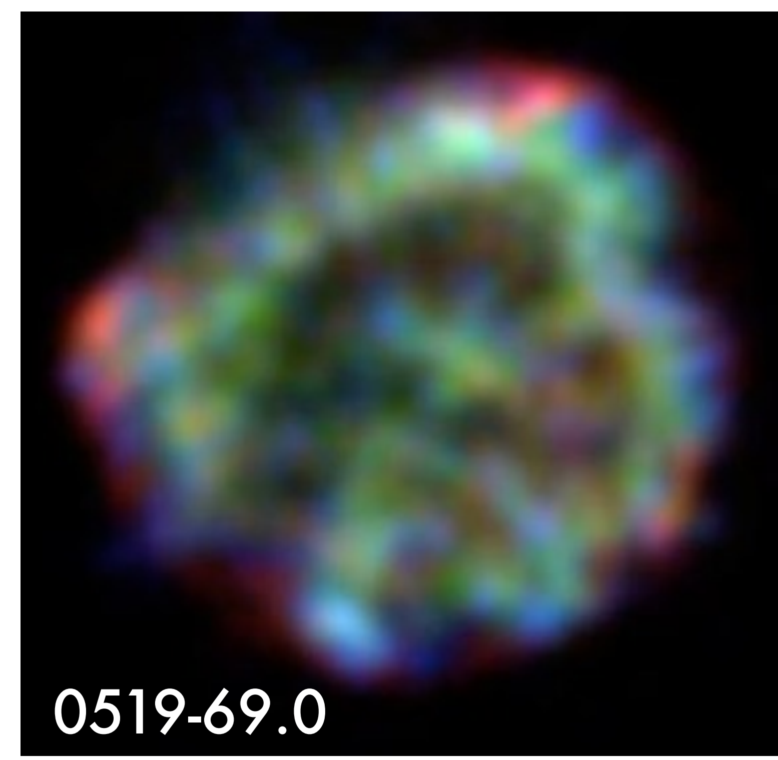


Suzaku (JAXA, 2005)

- Modern X-ray telescopes in Space:
  - High resolution imaging (especially Chandra: 0.5")
  - CCD detecors that detect the energy of the photons → imaging spectroscopy
  - Also grating spectrometers for $E/\Delta E \approx 1000$

X-ray spectra of supernova remnants



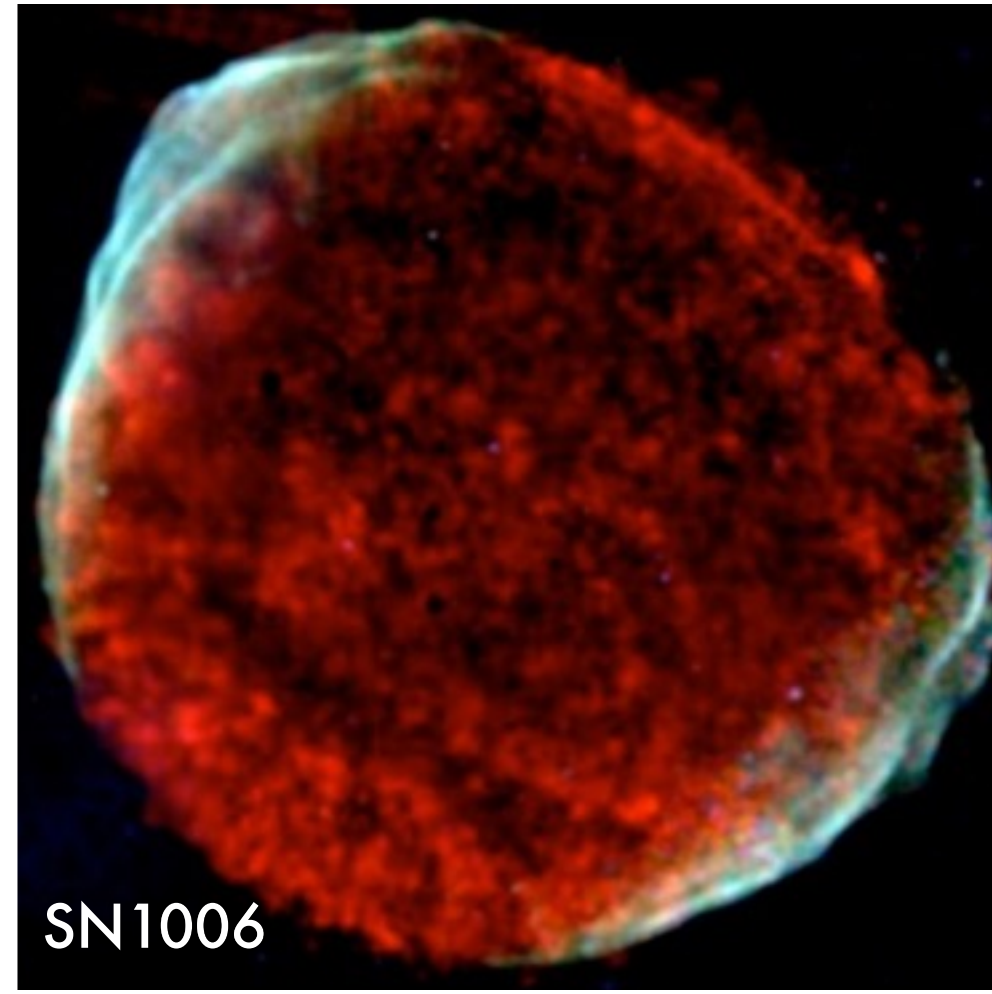


- Core collapse SNRs are rich in O, Ne, Mg
- Core collapse SNR appear irregular

- Type Ia SNRs are *iron-rich*
- Type Ia SNRs appear more regular/structured

e.g. Hughes ’95, Flanagan+ ‘04, Park+ ’02;04, Kosenko,Helder,JV ‘10

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)

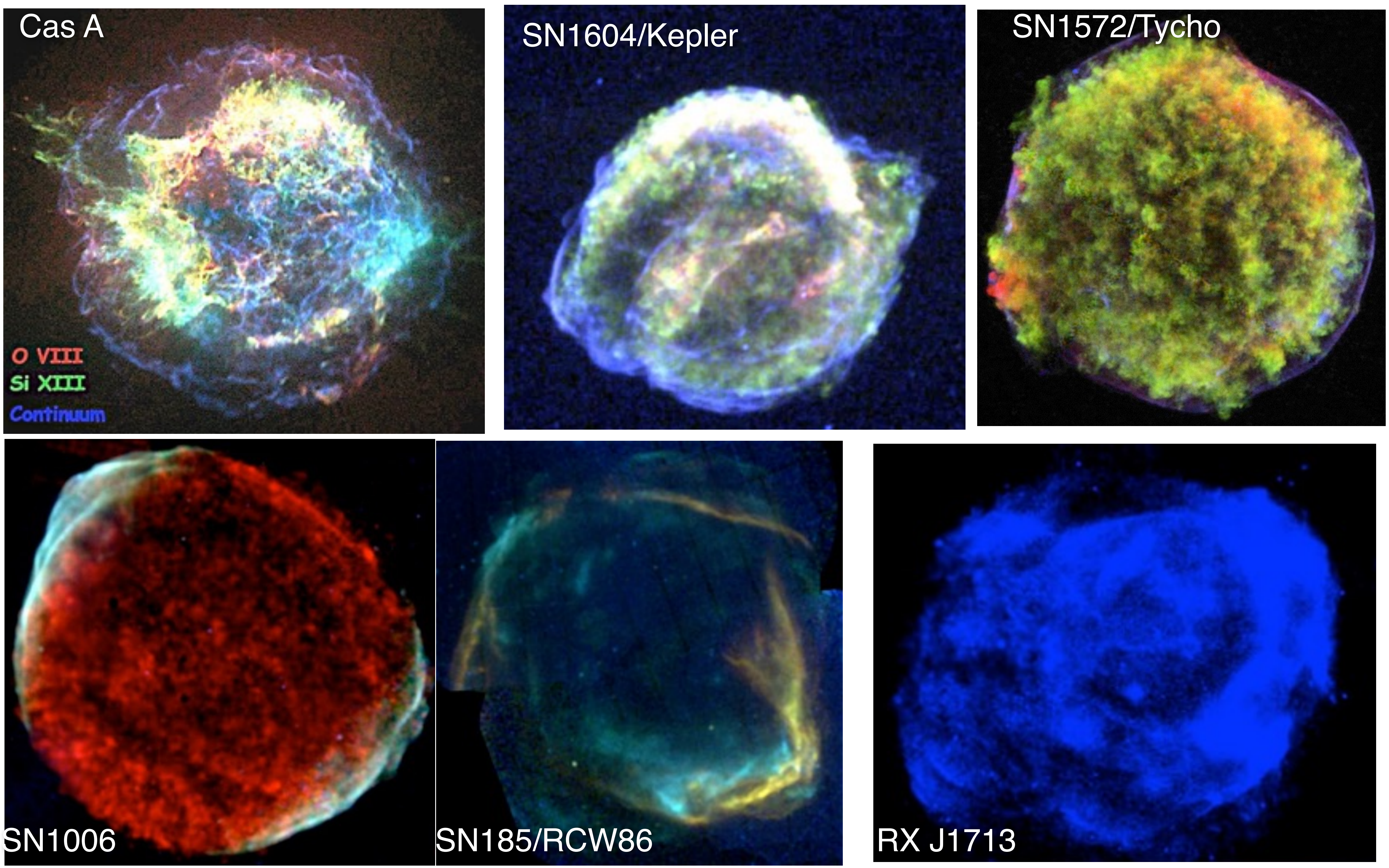
$$\tau_{\rm acc} \approx 1.83 \frac{D_2}{V_{\rm s}^2}\frac{3\chi^2}{\chi - 1} = 124\eta B_{-4}^{-1}\left(\frac{V_{\rm s}}{5000\ {\rm km\,s^{-1}}}\right)^{-2}\left(\frac{E}{100\,{\rm TeV}}\right)\frac{\chi_4^2}{\chi_4 - \frac{1}{4}}\ {\rm yr.}$$

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

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

- 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!

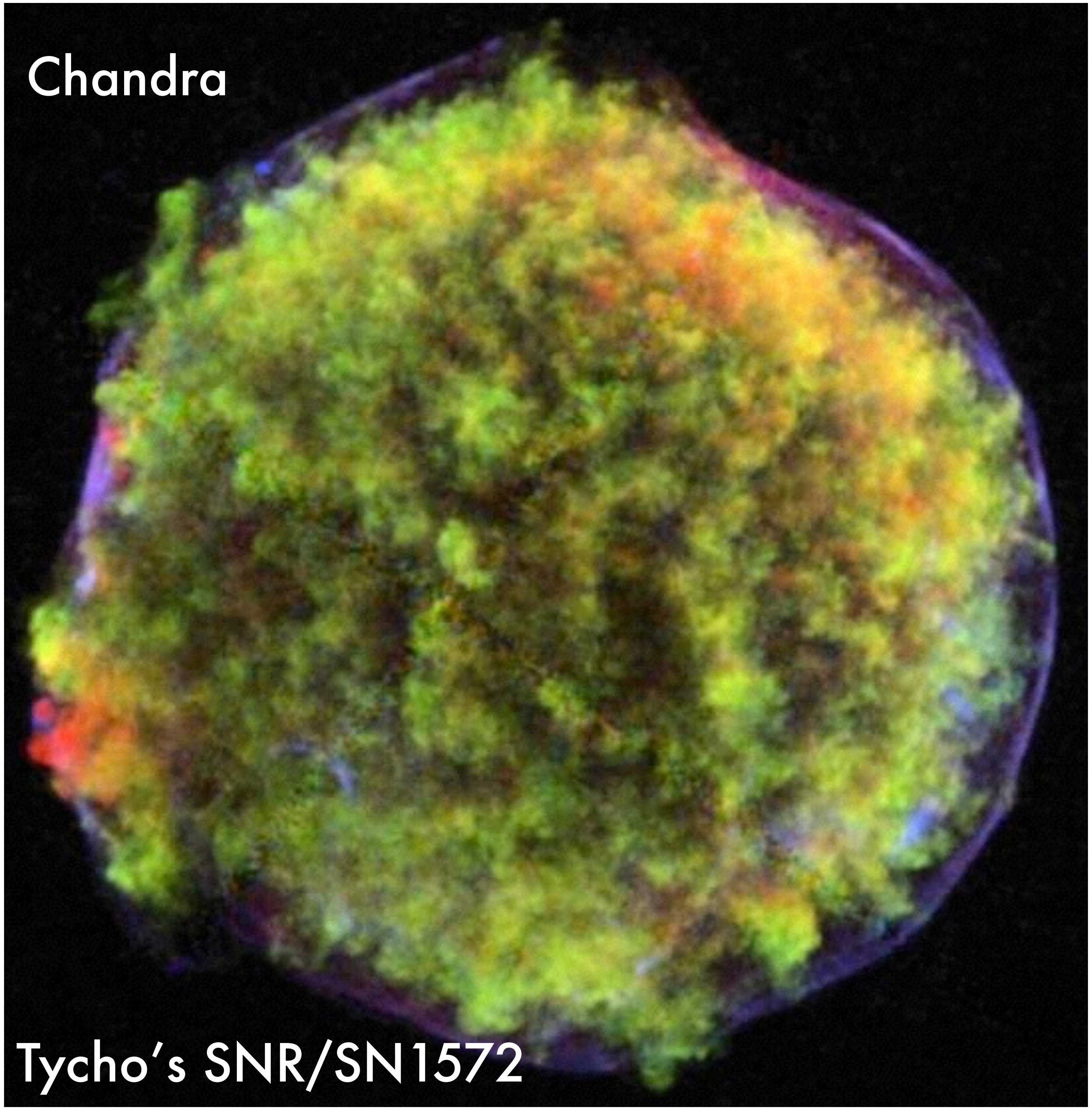
$$\eta \lesssim 10$$

- 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:

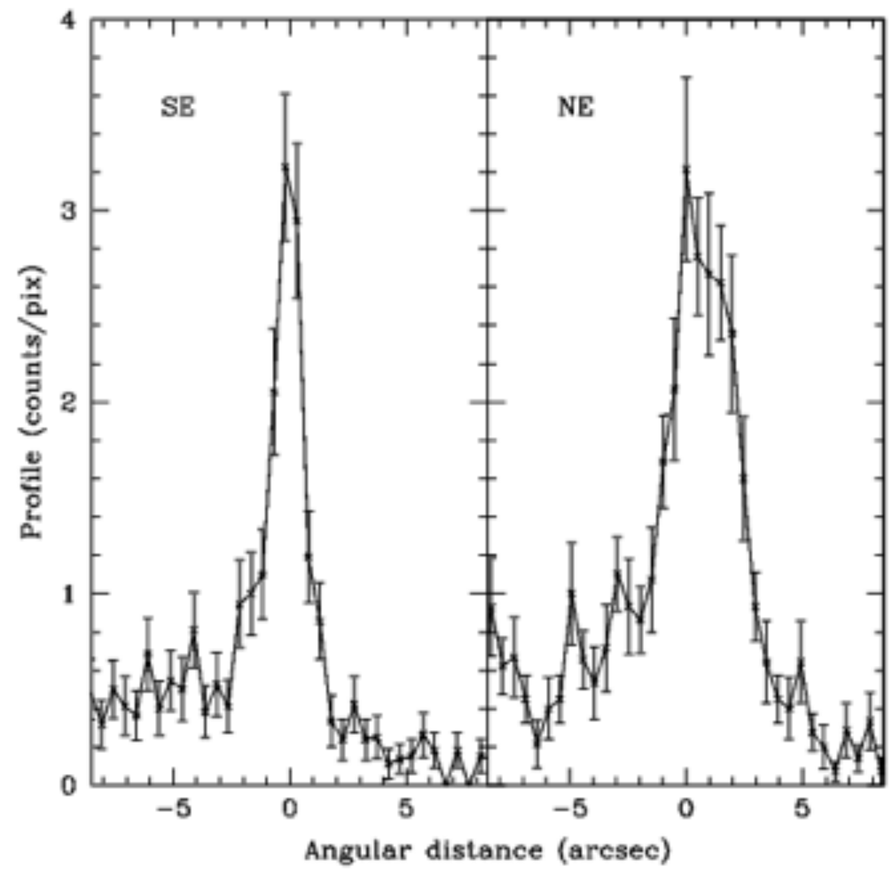
$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1}\left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}\ {\rm yr}.$$

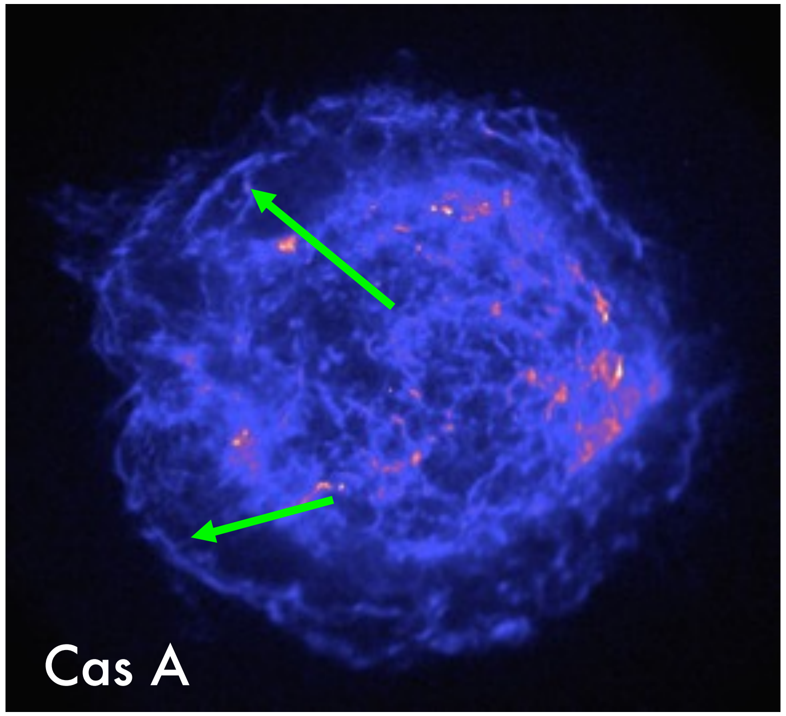
X-ray synchrotron emission tells us that
- electrons can be accelerated fast
- that acceleration is still ongoing (loss times 10-100 yr)
- that particles can be accelerated at least up to 10^{14} eV

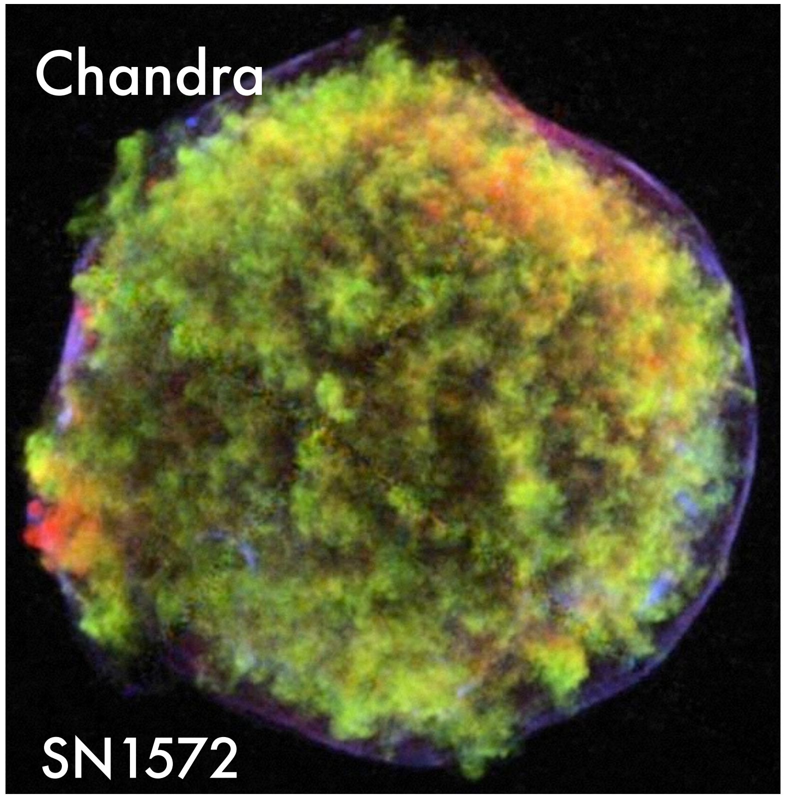
Beautiful Tycho's supernova remnant (SN1572)



Narrowness of X-ray synchrotron filaments





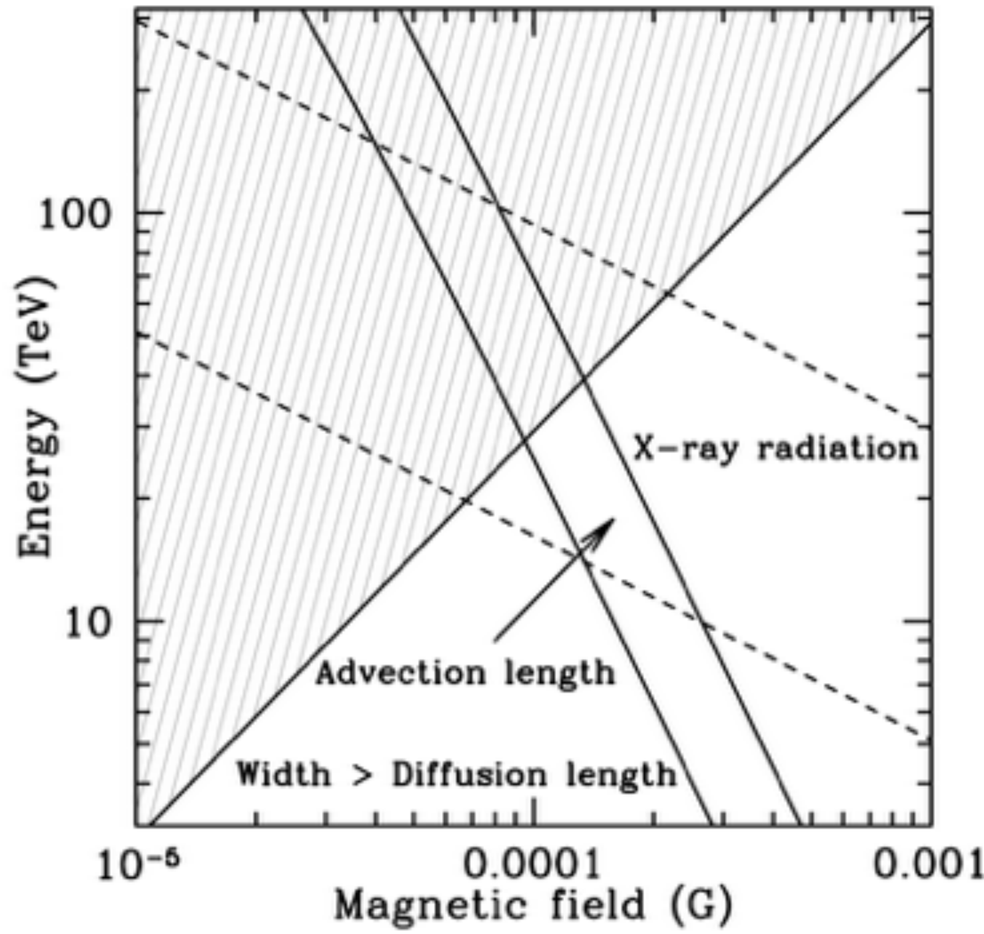


- In many cases X-ray synchrotron filaments appear very narrow (1-4")
- Including deprojections implies $l \approx 10^{17}$cm

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:

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

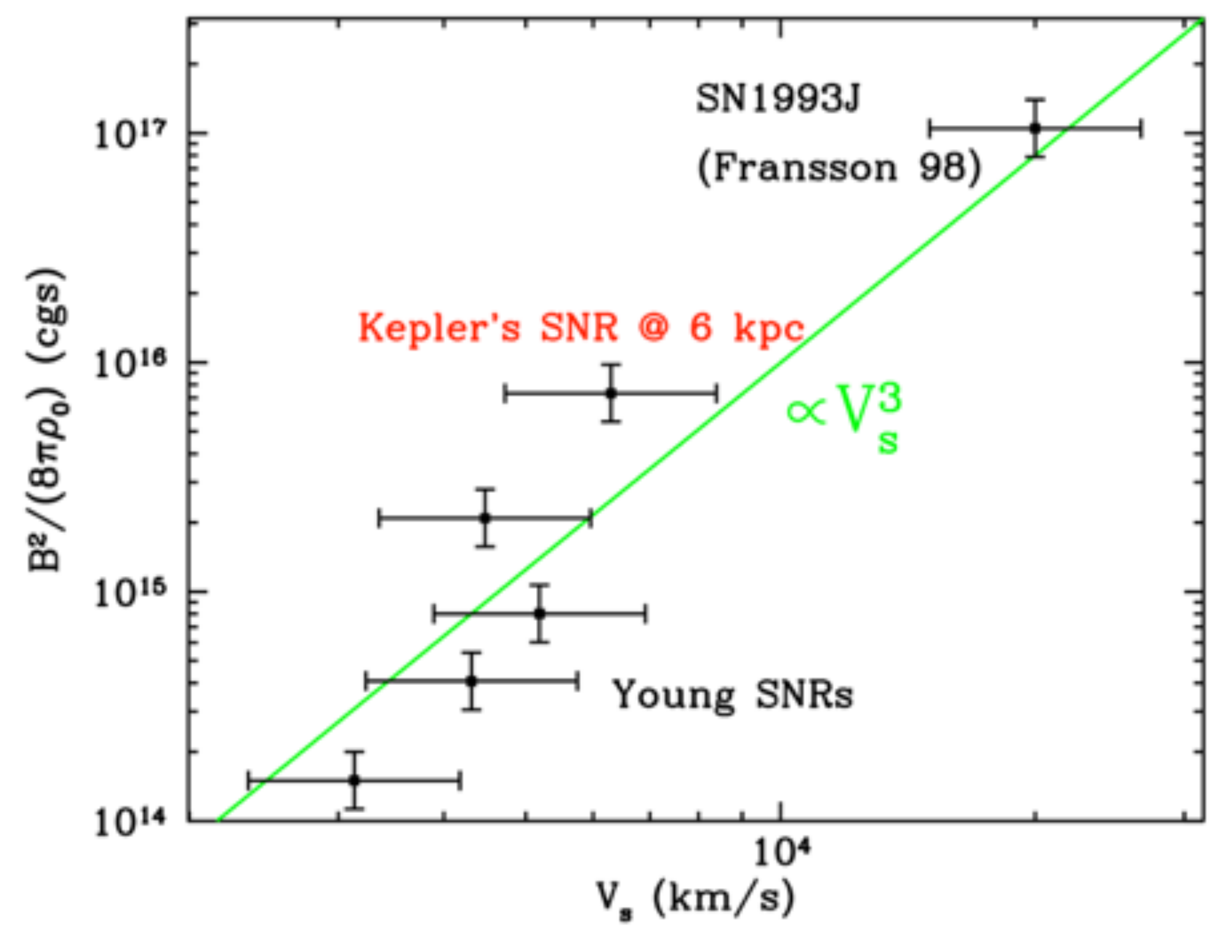
- Narrow rims → high B-field

- 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?

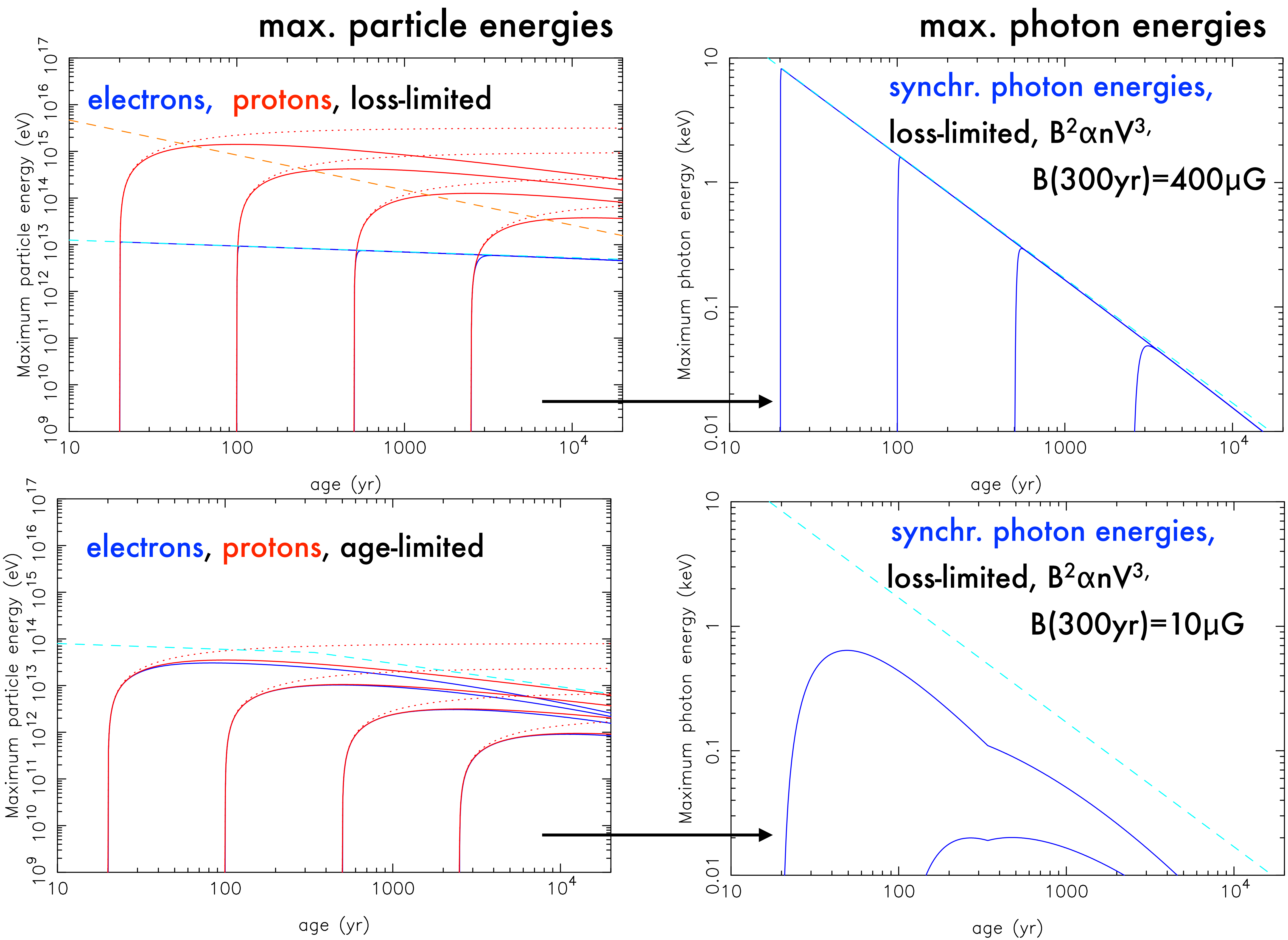
- High B-field likely induced by cosmic rays (e.g. Bell '04)
- High B-fields are a signature of efficient acceleration
- Optimistic scenario of Lagage & Cesarky seems to be realistic!

Magnetic field amplification

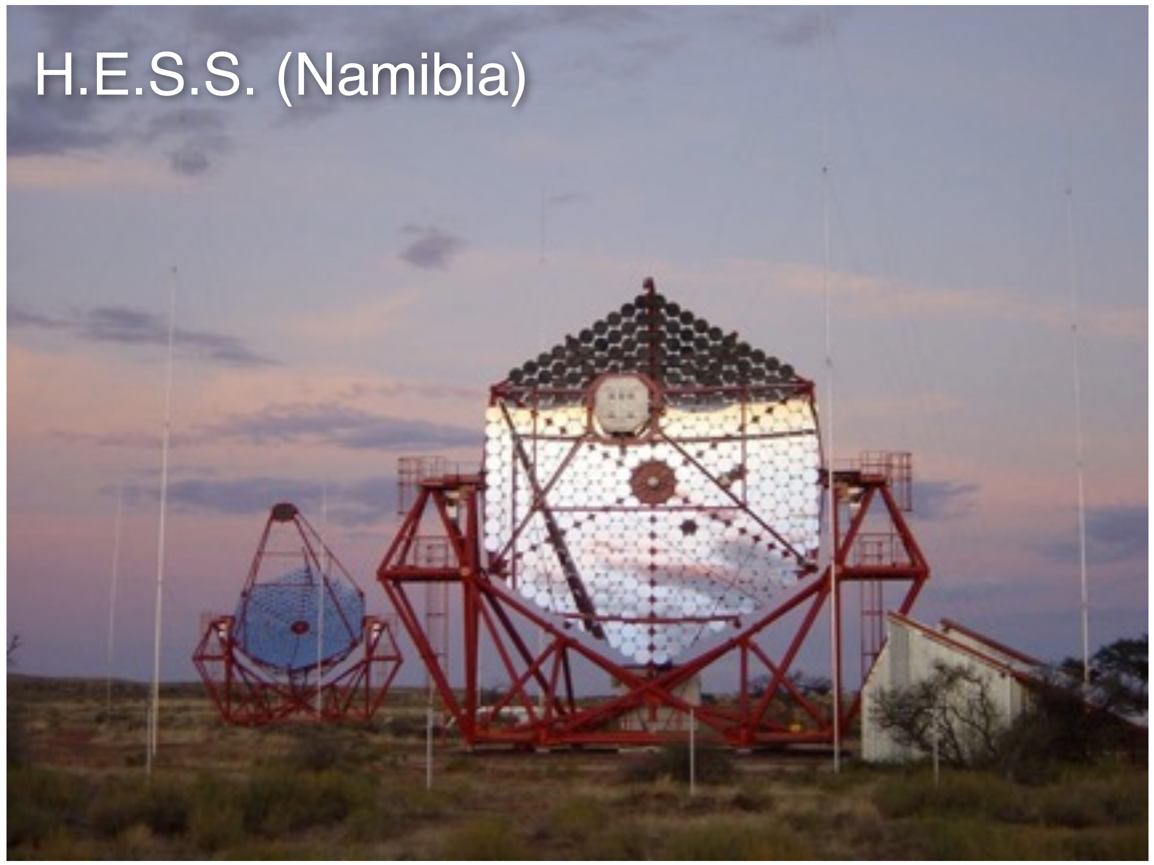


- Clear correlation between ρ, V and B
- In rough agreement with predictions (e.g. Bell 2004)
- Relation may even extend to supernovae ($B^2 \propto \rho V_s^3$?)
  (Völk et al. '05, Vink '08)
- SNRs: little dynamic range in V_s

CR Knee can be reached when SNRs very young?

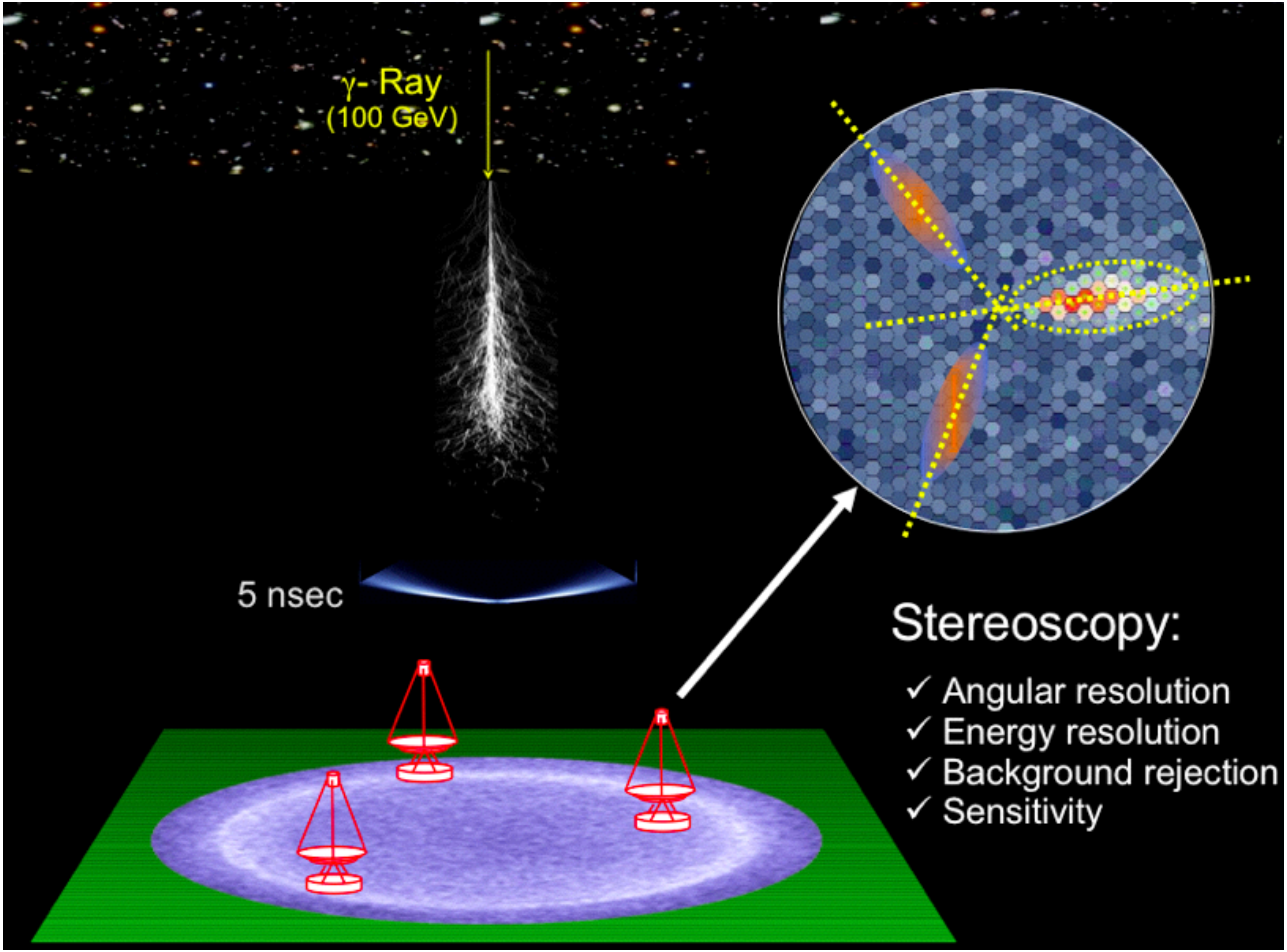


The coming of age of Gamma-ray observatories: Cherenkov Telescope (TeV) and the Fermi and Agile satellites (GeV)

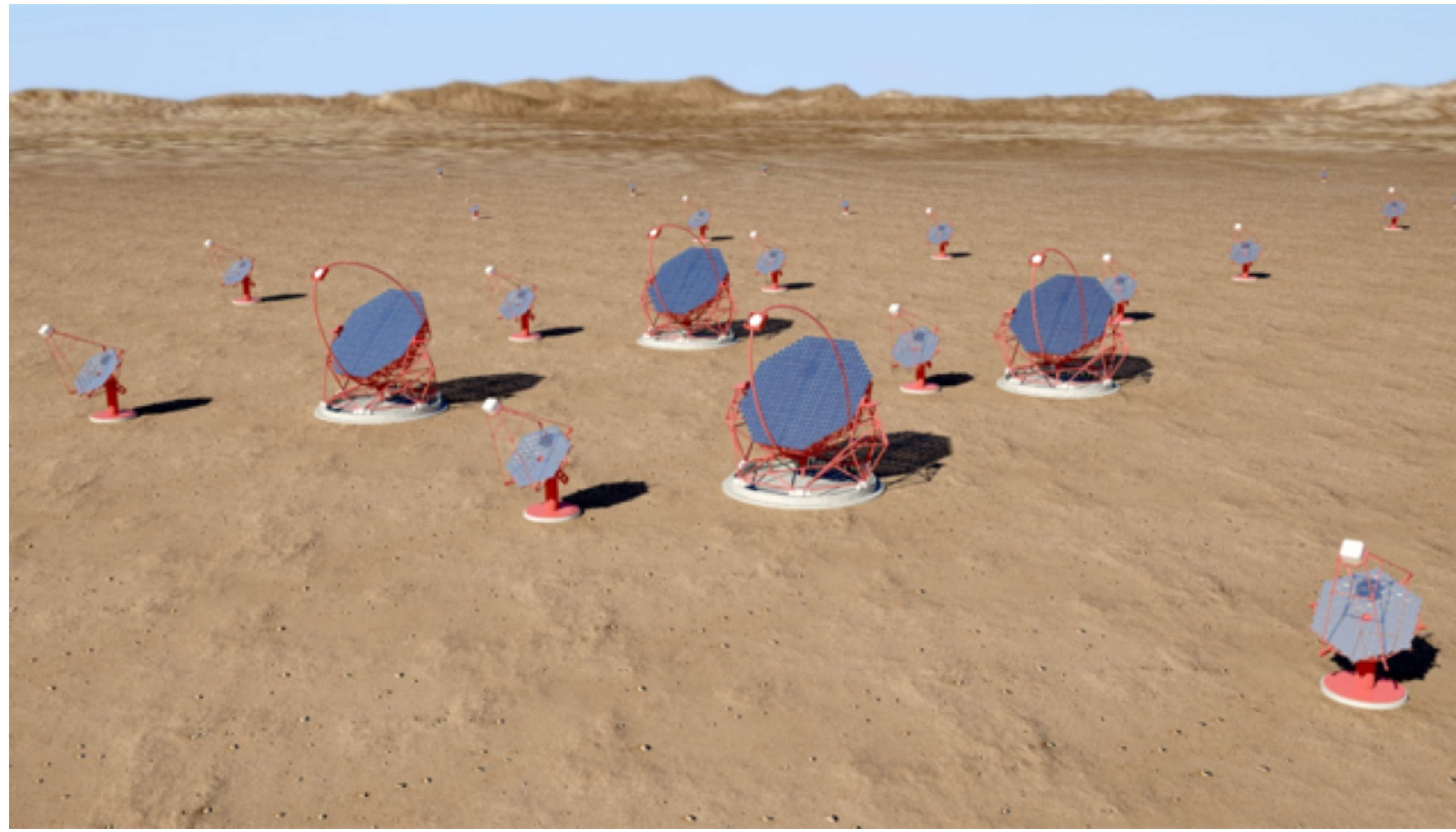


- Gamma-ray photons give more direct proof of high energy particles:
  - $E_{photons} \approx 10\% \ E_{particles}$
- Gamma-rays can provide direct proof for accelerated *ions* (hadronic cosmic rays)

Imaging Cherenkov Telescope Arrays

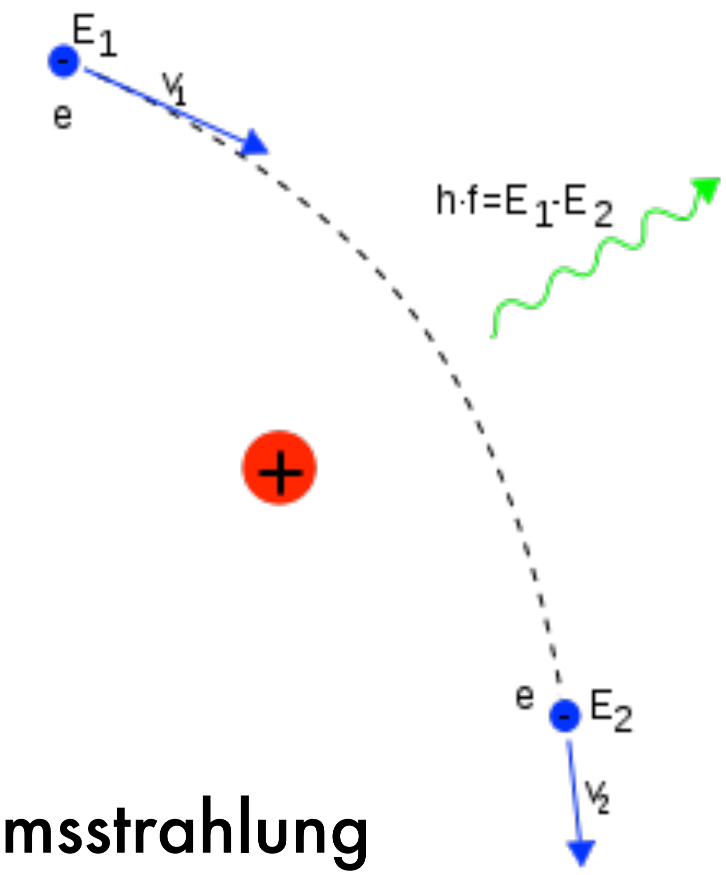


Future VHE gamma-ray detector: Cherenkov Telescope Array (CTA)

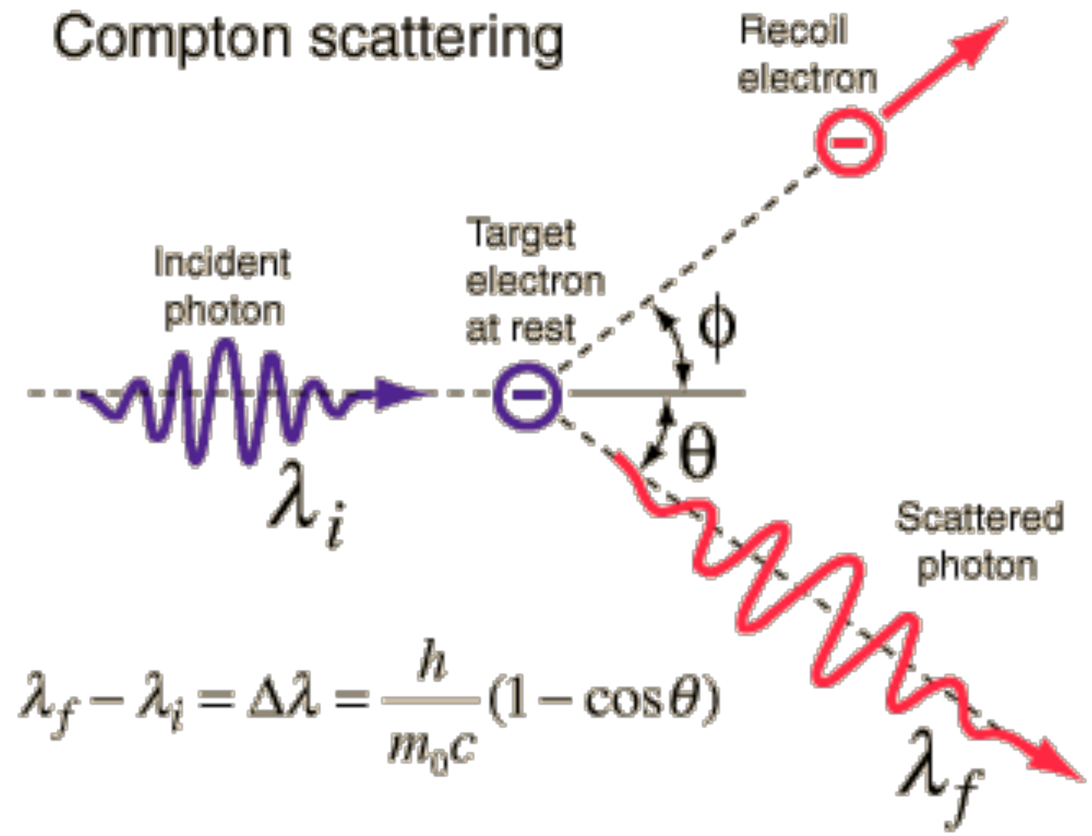


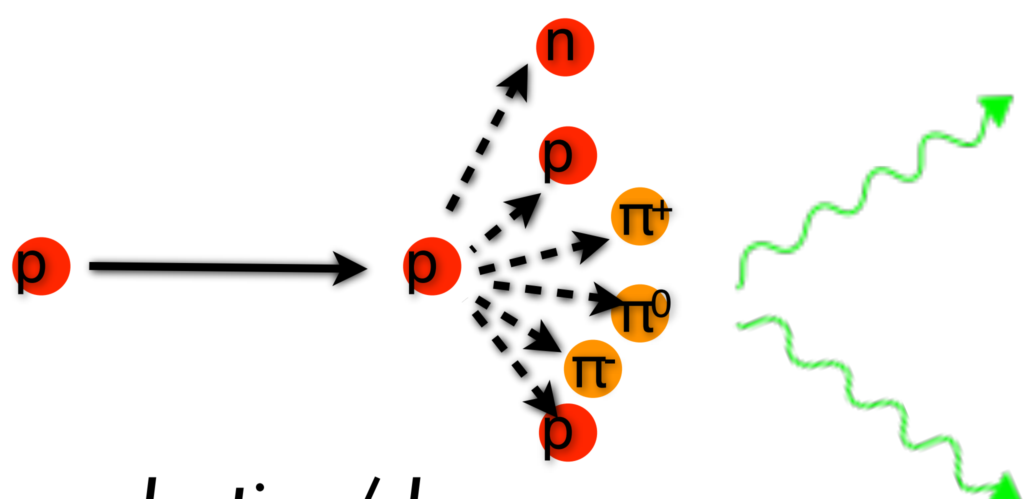
- Southern and Northern array foreseen
- Southern array: Namibia or Chili
- Detection principle: image Cherenkov shower induced by gamma-photon
- Mix of three types of telescopes: about 70 small-, 20 medium-, 4 large-sized

Gamma-ray radiation processes



Bremsstrahlung

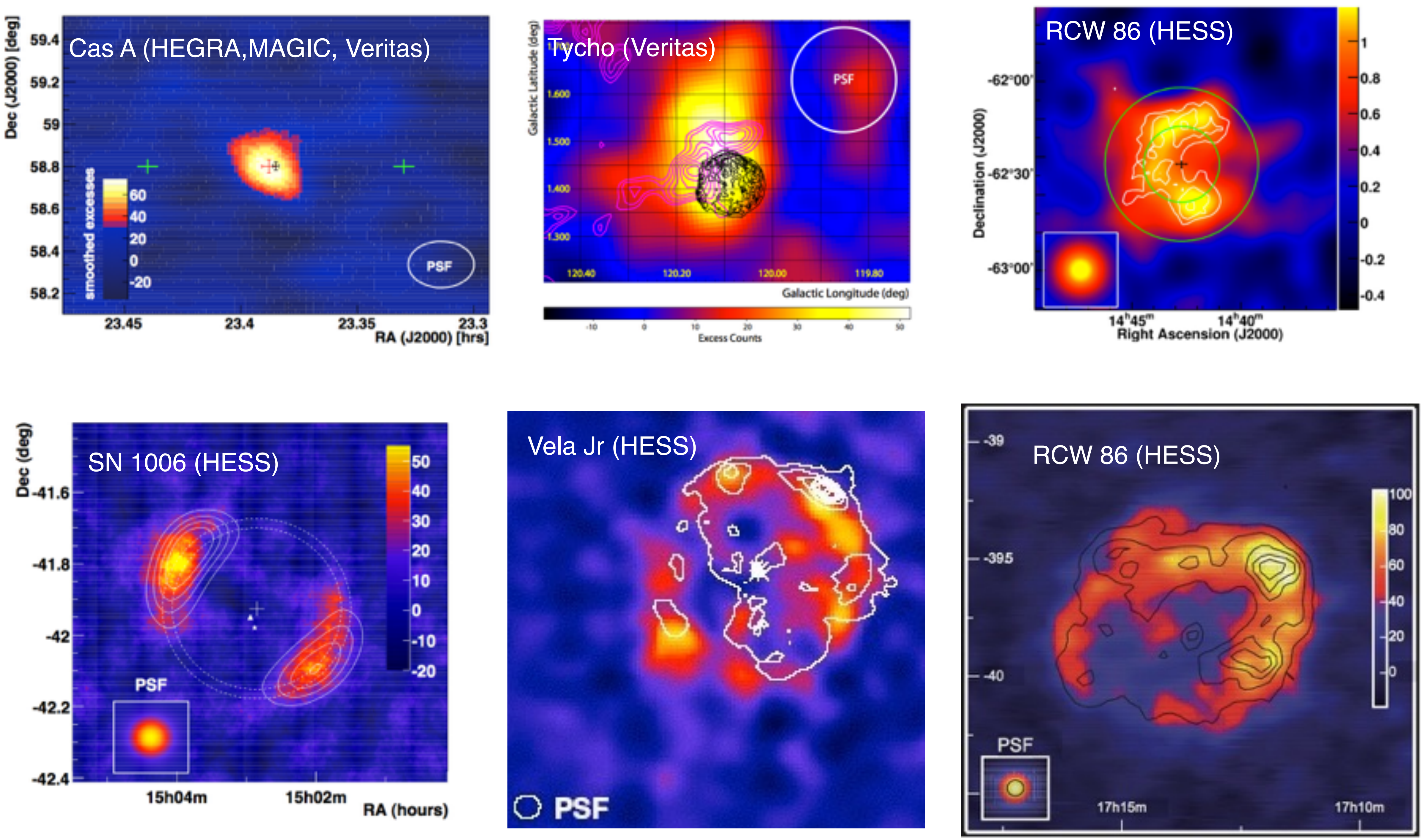




$$
\begin{aligned}
\pi^0 &\rightarrow 2\gamma \\
\pi^+ &\rightarrow \mu^+ + \nu_\mu \\
&\quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\
&\quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\end{aligned}
$$

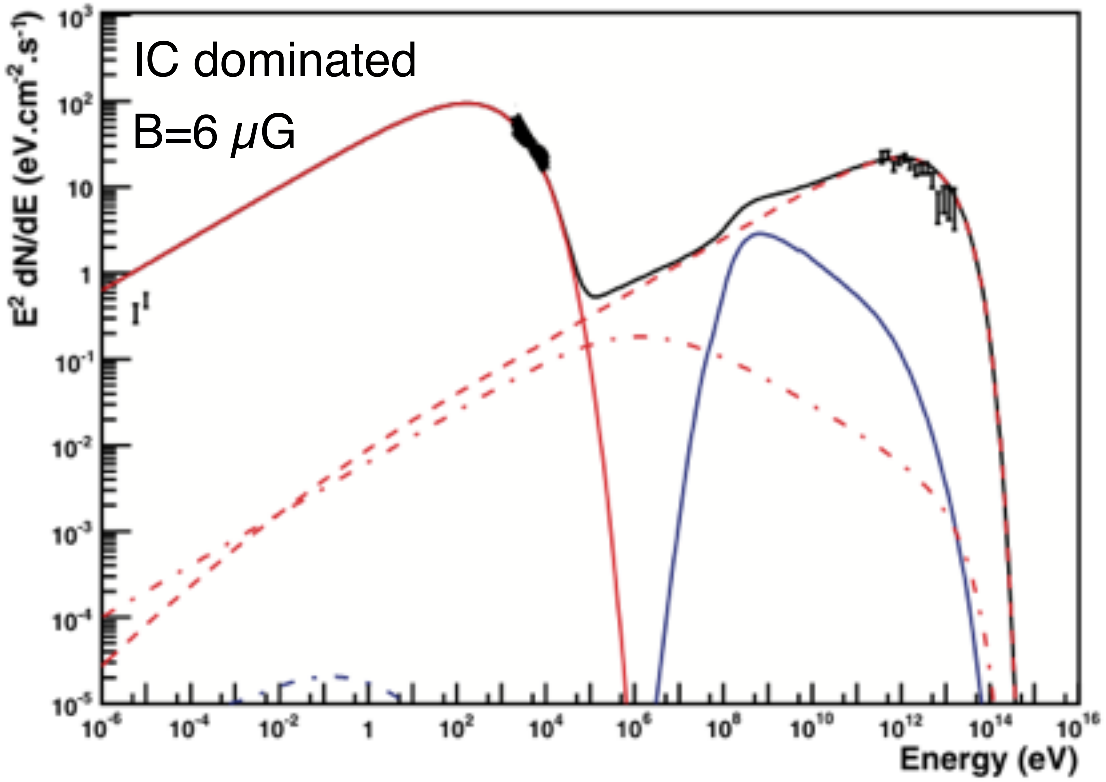
Neutral pion production/decay

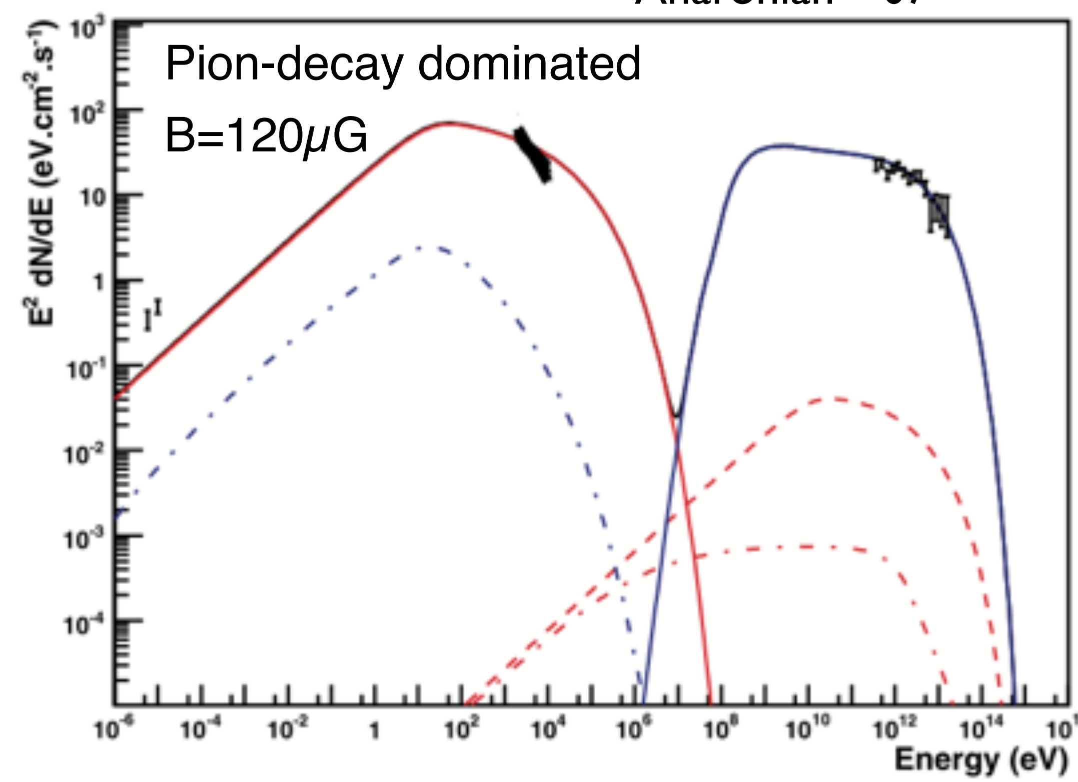
Some young SNRs in TeV gamma-rays

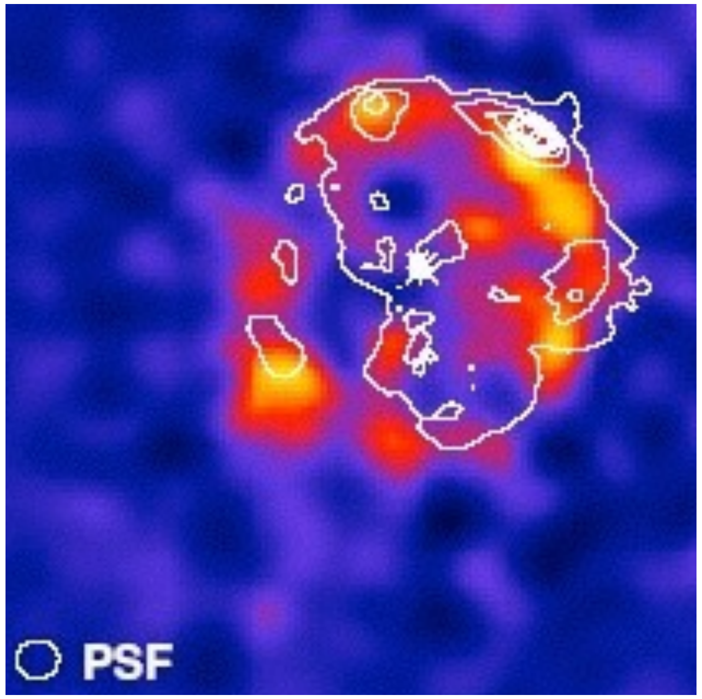


Gamma-rays detected: but are these leptons or hadrons?

Aharonian+ '07







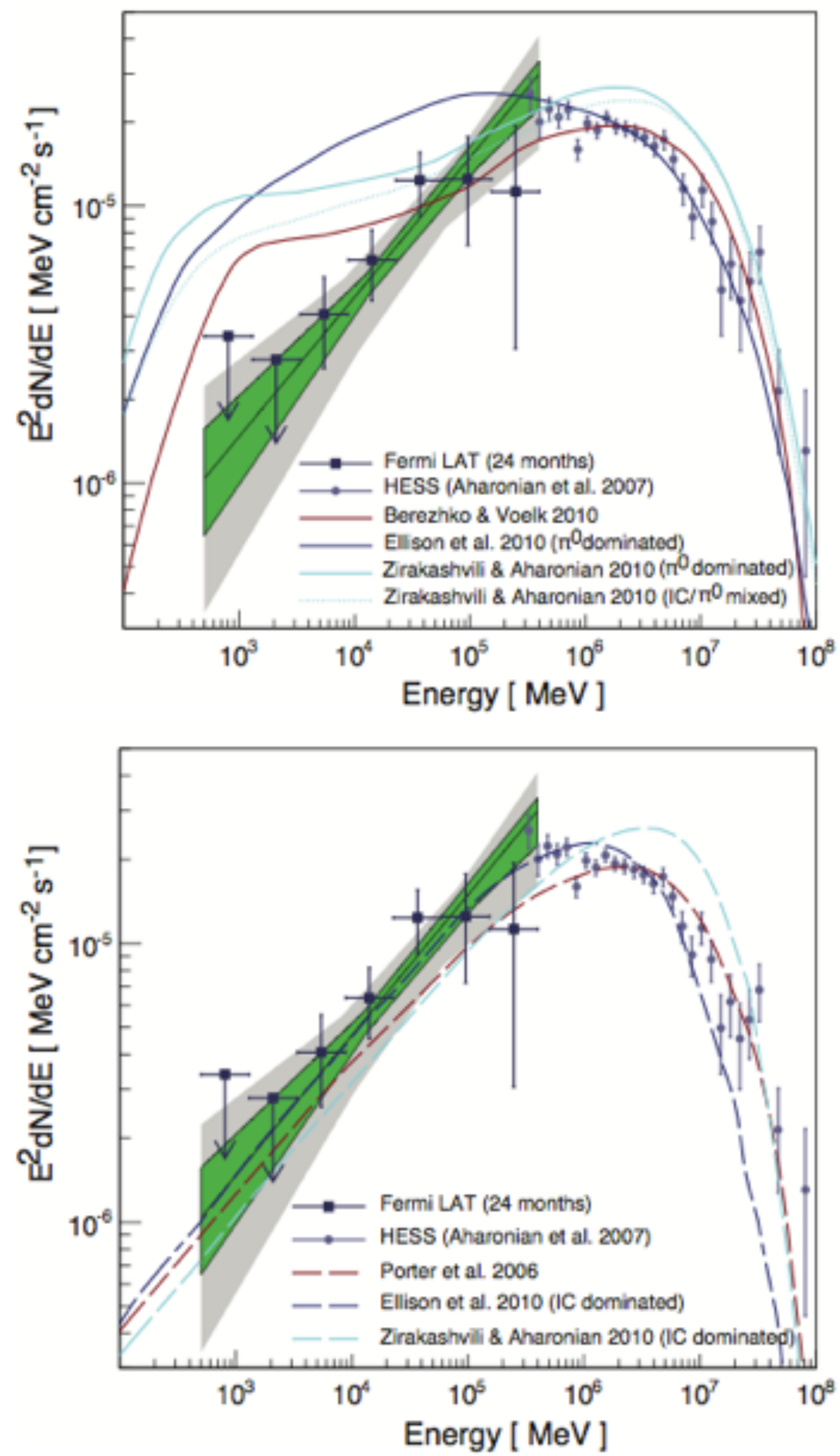
- Debates on the nature of most TeV SNRs
- Most heated: RXJ1713 and Vela Jr
- Heated debates on gamma-ray emission
    - pion decay:requires high densities/high B-fields

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*

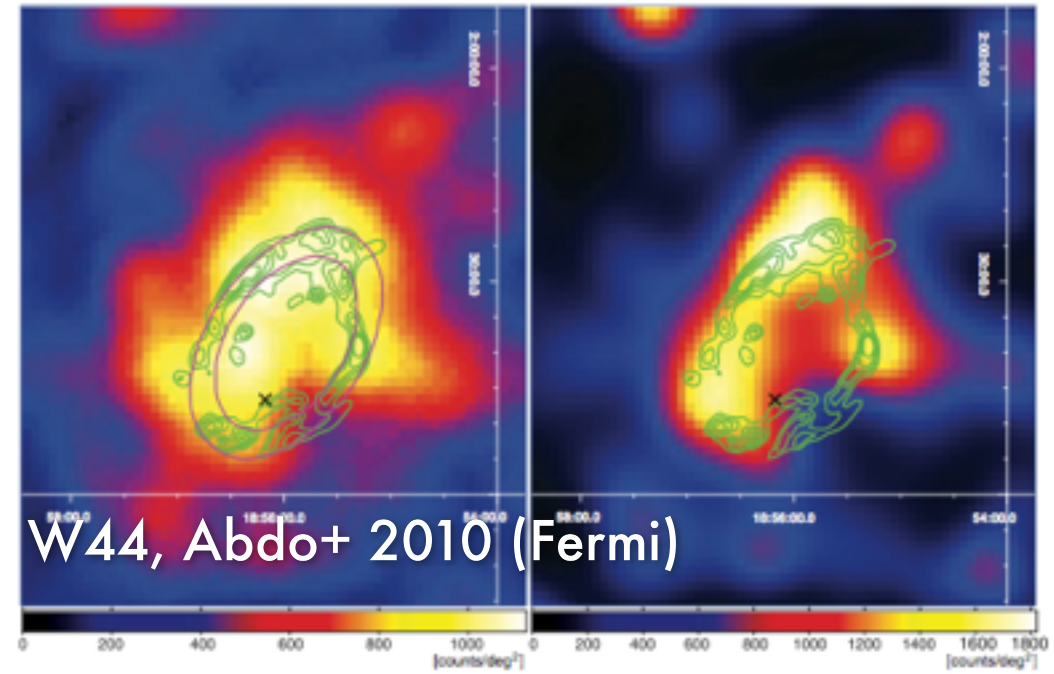
- Has controversy ended?
  - IC models do not fit very well TeV-end of spectrum
  - Hadronic model does not follow initial predictions
  - Hadronic model may still be valid with more complicated scenarios: e.g. dense clumps in empty cavity (Inoue+ 2013, Gabici&Aharonian '14)

Abdo+ '11

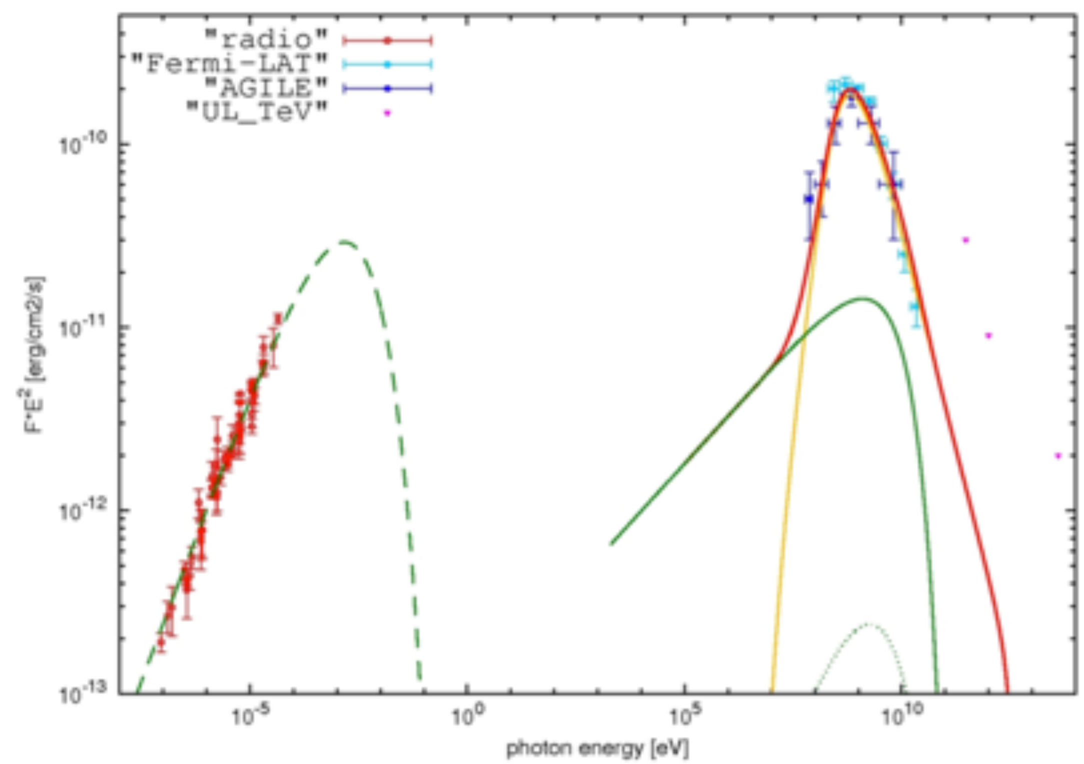


Clear evidence for hadronic emission from mature SNRs

- 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*



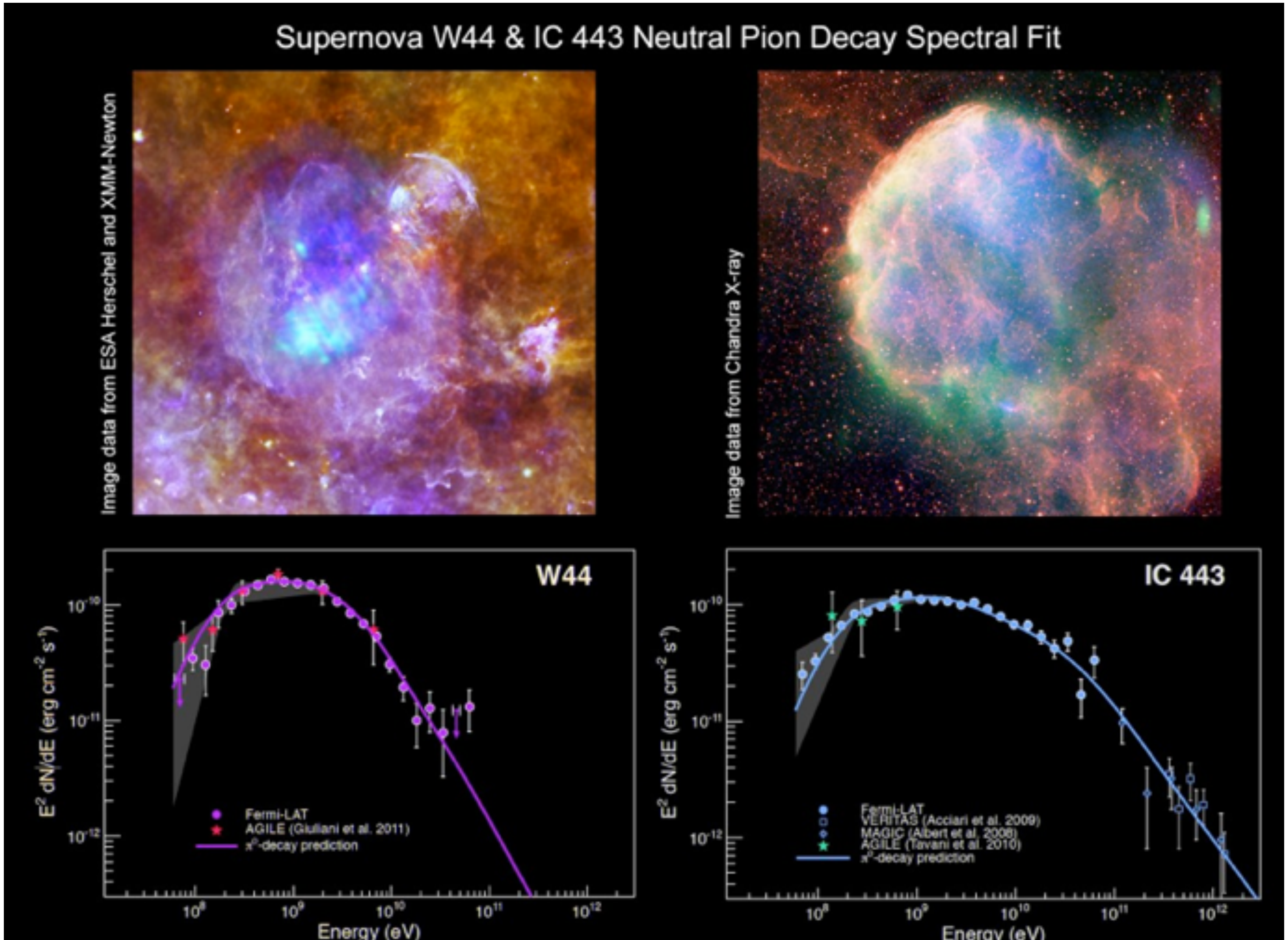
W44, Abdo+ 2010 (Fermi)



W44, Guiliani+ '11 (AGILE)

Fermi detection of pion bumps

Ackermann+ 2013



Conclusion:

Mature SNRs contain accelerated protons

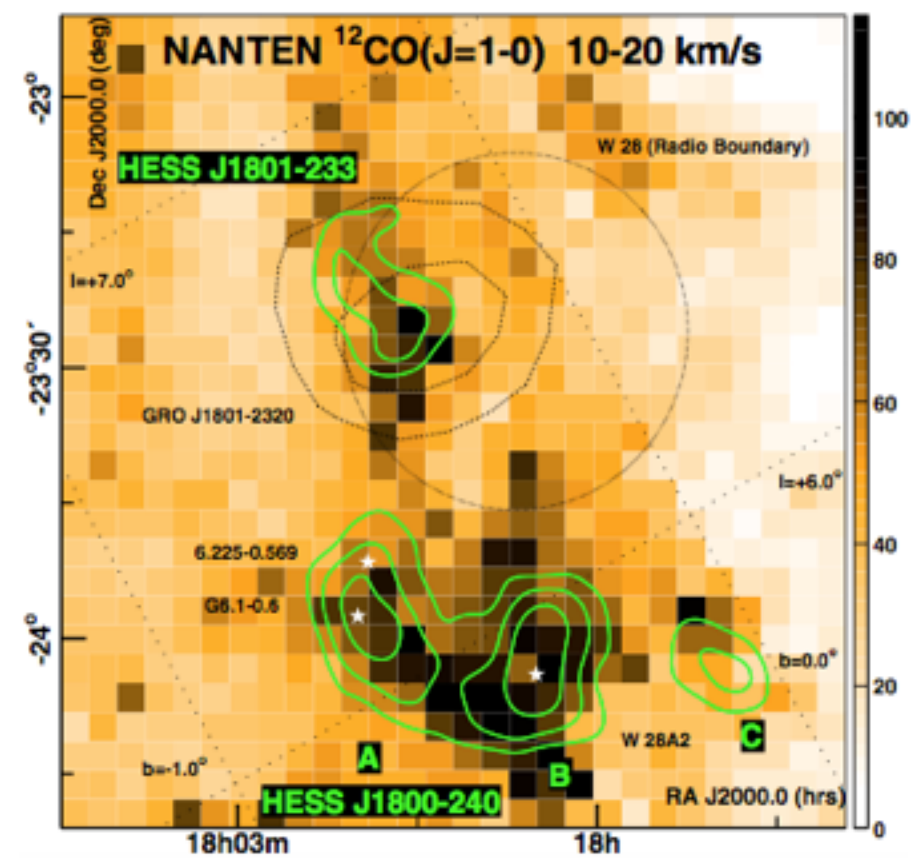
But are past their prime concerning acceleration to high energies!

Where have the high energy protons gone?

Molecular clouds interacting with cosmic rays near SNR: W28, a case of early CR escape

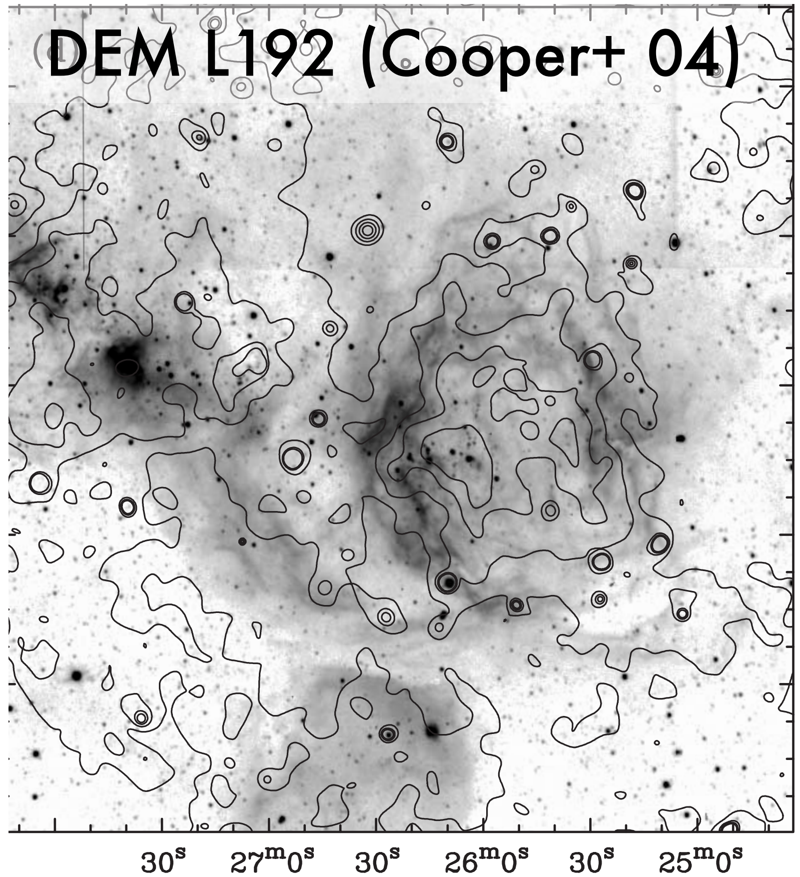
- Mature SNRs in general not TeV sources
- Perhaps surprising if TeV is hadronic and no cosmic-ray escape!

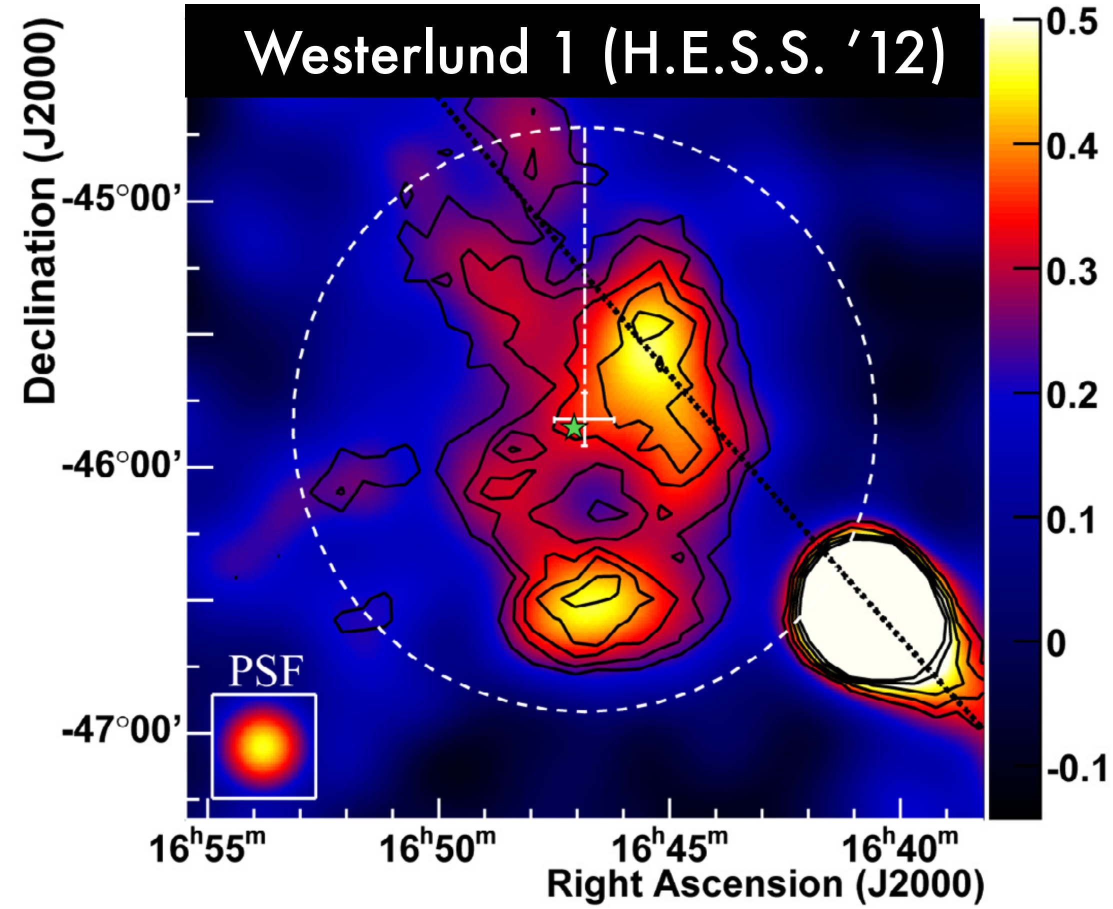
- The TeV detections of mature SNRs are SNRs/ molecular cloud associations!
- Interesting example: W28, offset between SNR and TeV source(s)
- General conclusion: *highest energy (hadronic) cosmic rays seem to have escaped lighting up molecular clouds nearby*



W28 region
colors: CO
contours: TeV

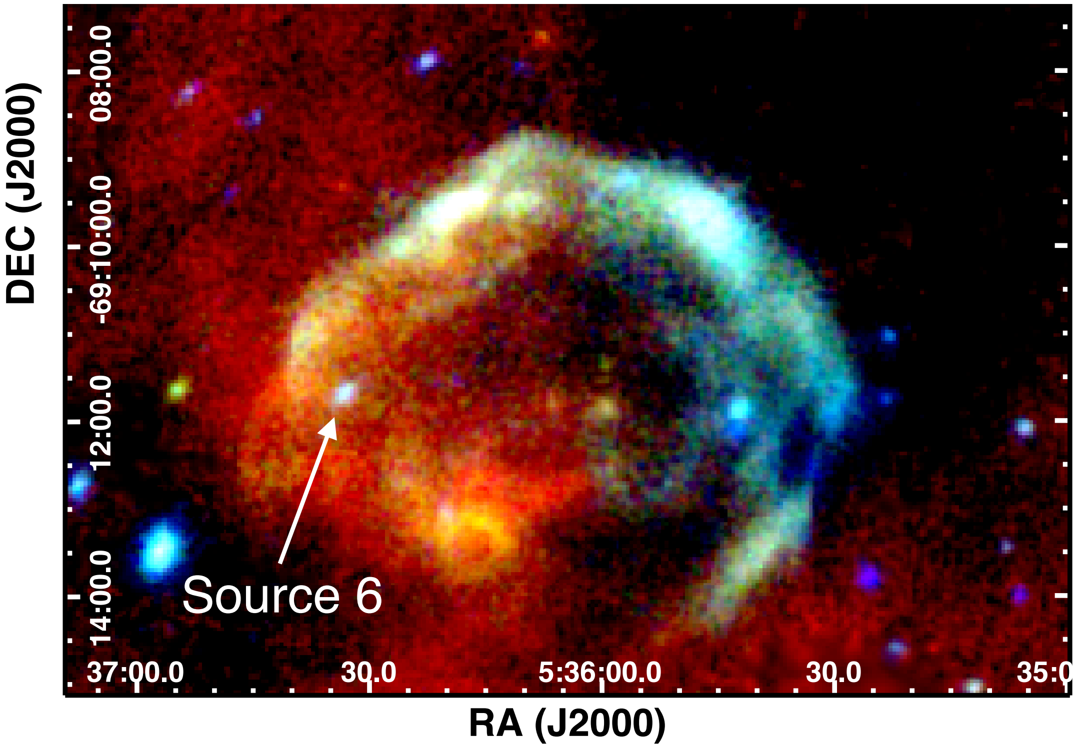
Are collective effects important: from supernova shell to super shell

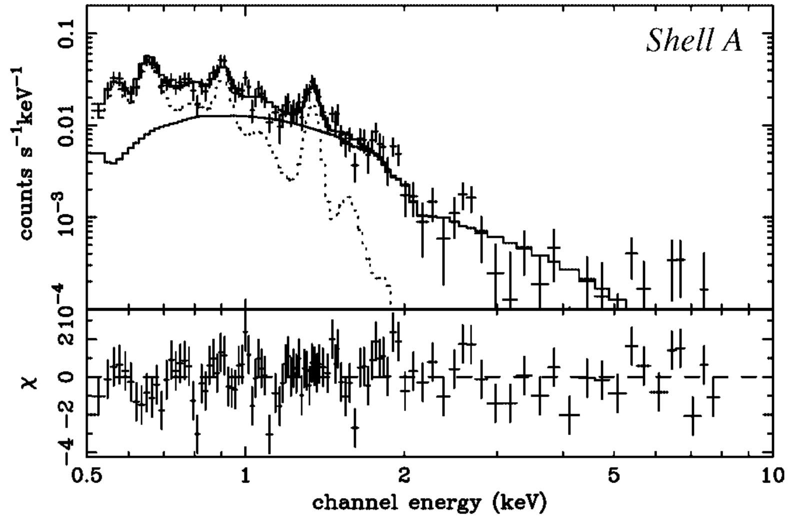


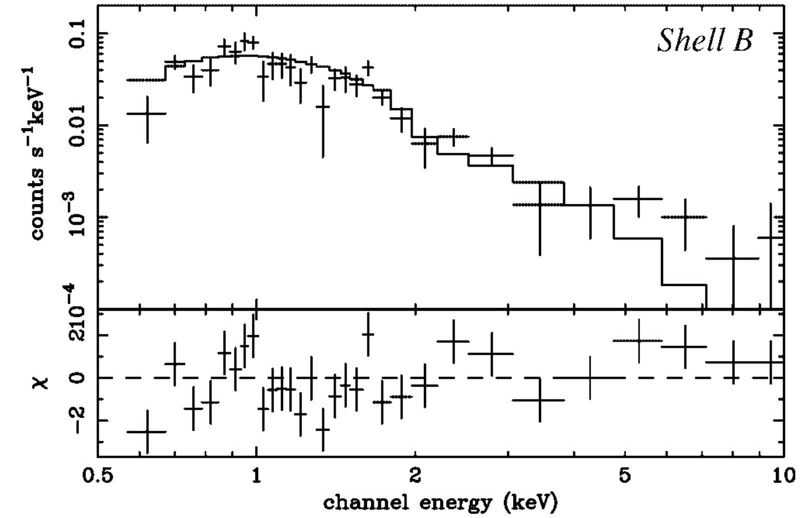


- Super shells: collected by many stars and supernovae
- Up to now: little evidence for acceleration in super shells
- Last decade some progress:
  - Lack of energy inside DEML192 (Cooper+ 04)
    -2/3 of energy in cosmic rays?
  - TeV ϒ-rays from Westerlund 1 and 2 OB associations (H.E.S.S. + 11/12)
    -Uncertainty about the source, OB cluster or individual sources?
    -Line of sight effects?
  - *X-ray synchrotron emission from 30DorC (Bamba+ 04)*

X-ray synchrotron emission from 30Dor C





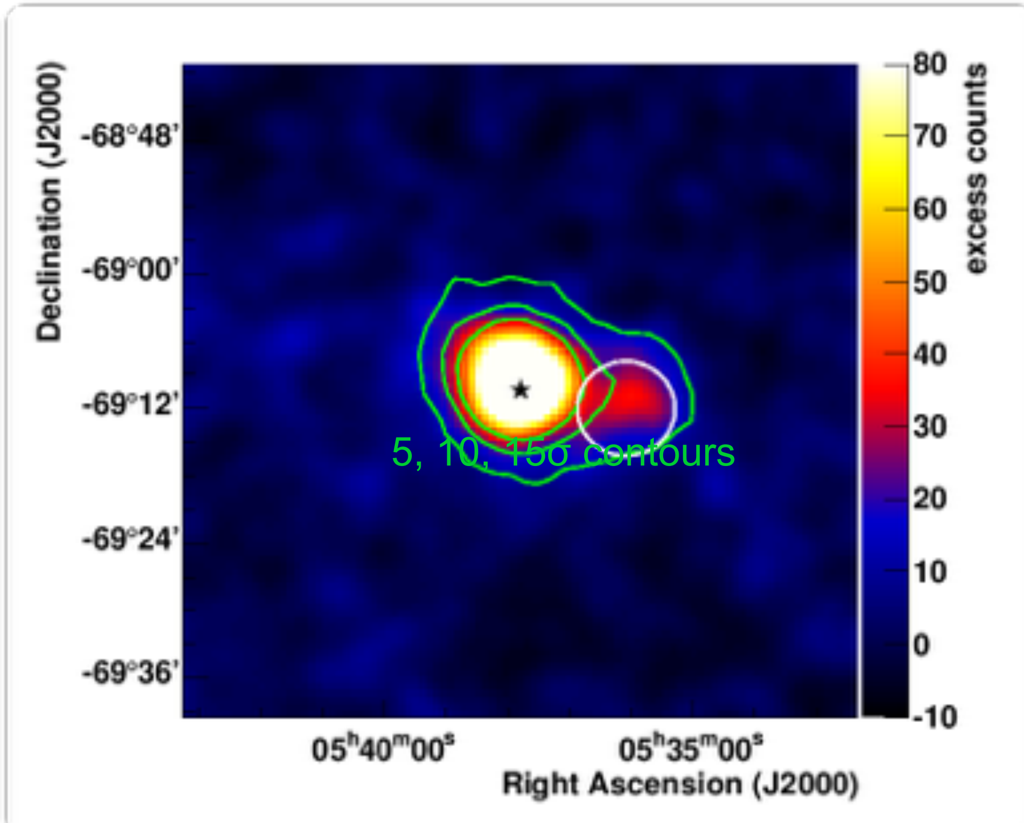


Bamba+ ‘04

Kavanagh+ ‘14

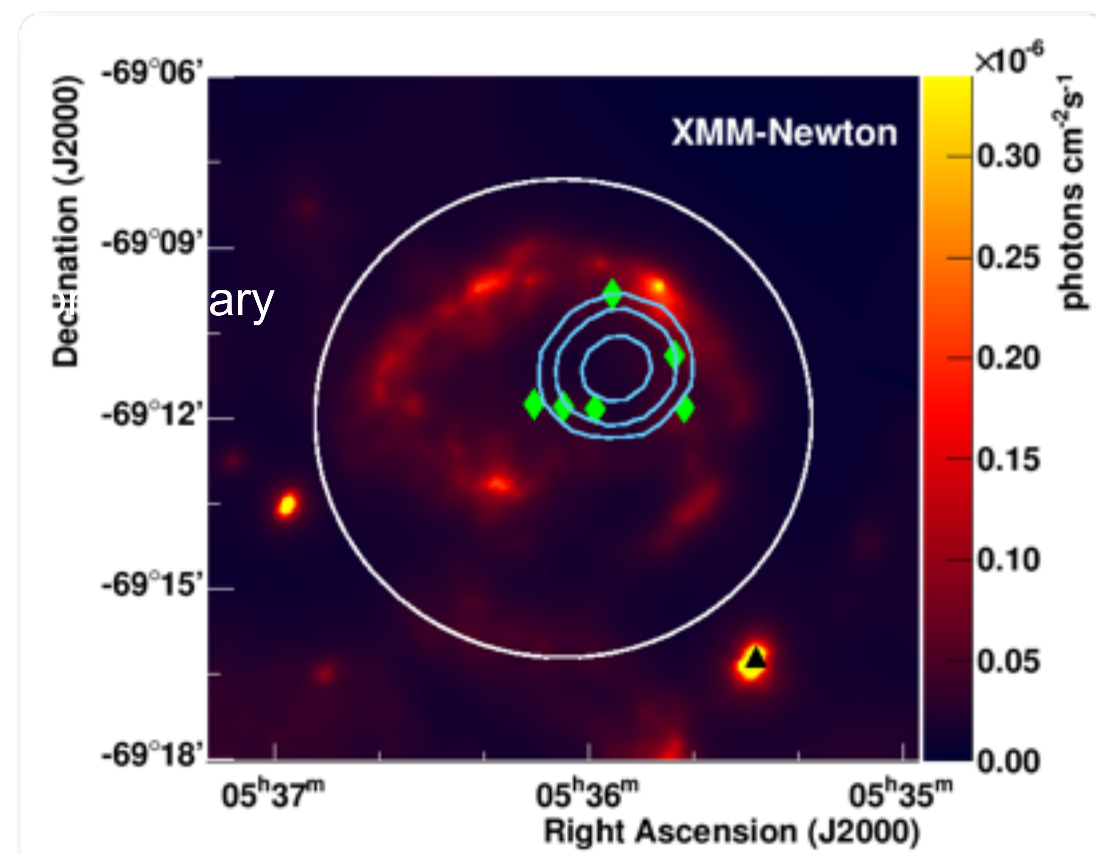
- X-ray imaging spectroscopy: northwest spectrum non-thermal
  Bamba+ 04, Yamaguchi+ 09, Kavanagh+ ’14
- *Shell is large R=47 pc*
- How X-ray synchrotron possible: need V_s>3000 km/s?
  Much higher than typical SB shells (10 km/s)
  - Solution Yamaguchi+: a SNR not a super bubble

H.E.S.S. detection of the superbubble 30Dor C

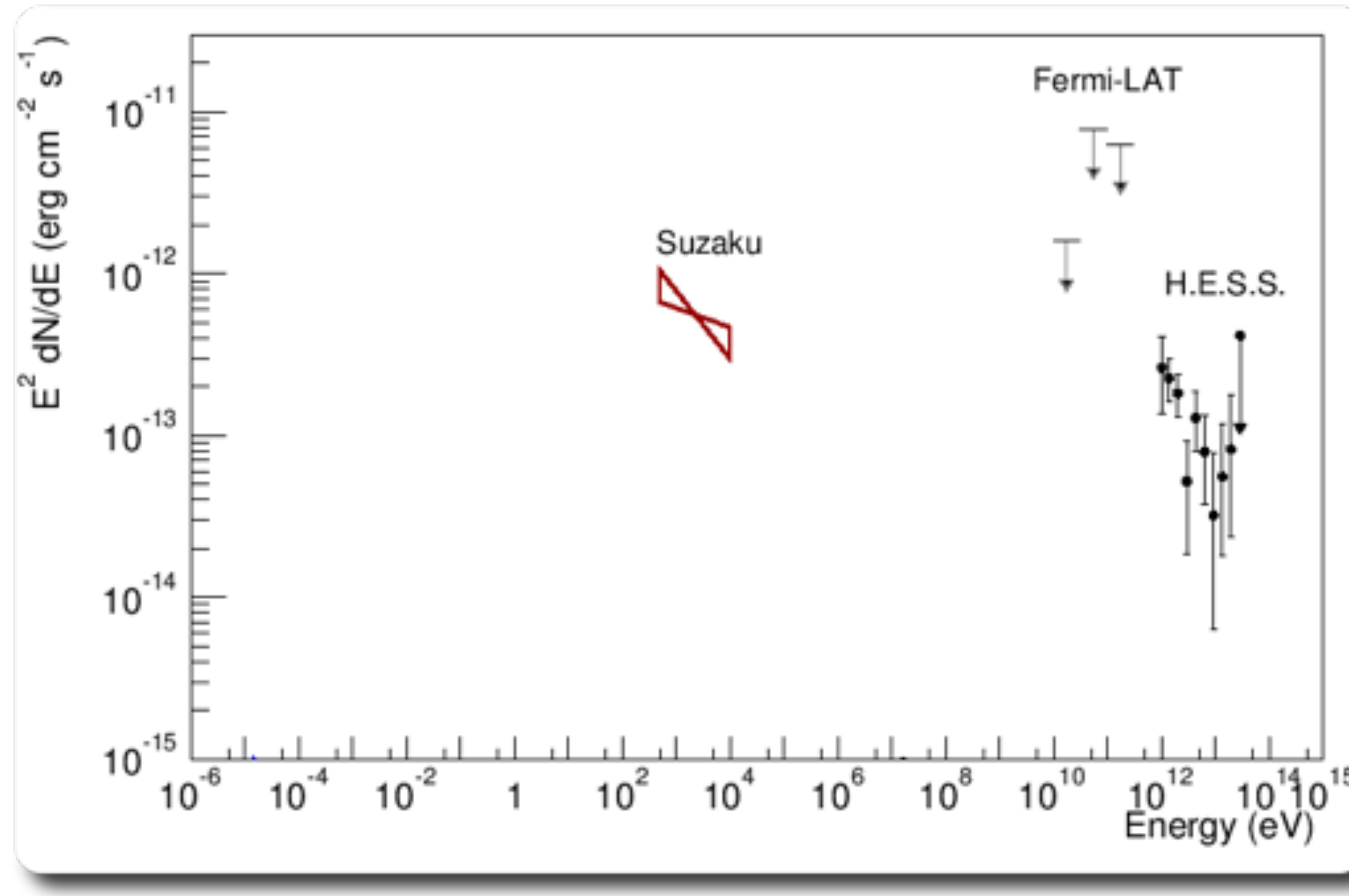


- additional emission SW of PWN
  - 130 pc at 50 kpc
- >5 σ above spill-over
- two-source morphology favoured at 8.8σ

- position (contours) compatible with
  - shell of superbubble 30 Dor C
  - star clusters of LH 90
- note: angular resolution does not allow conclusion on morphology

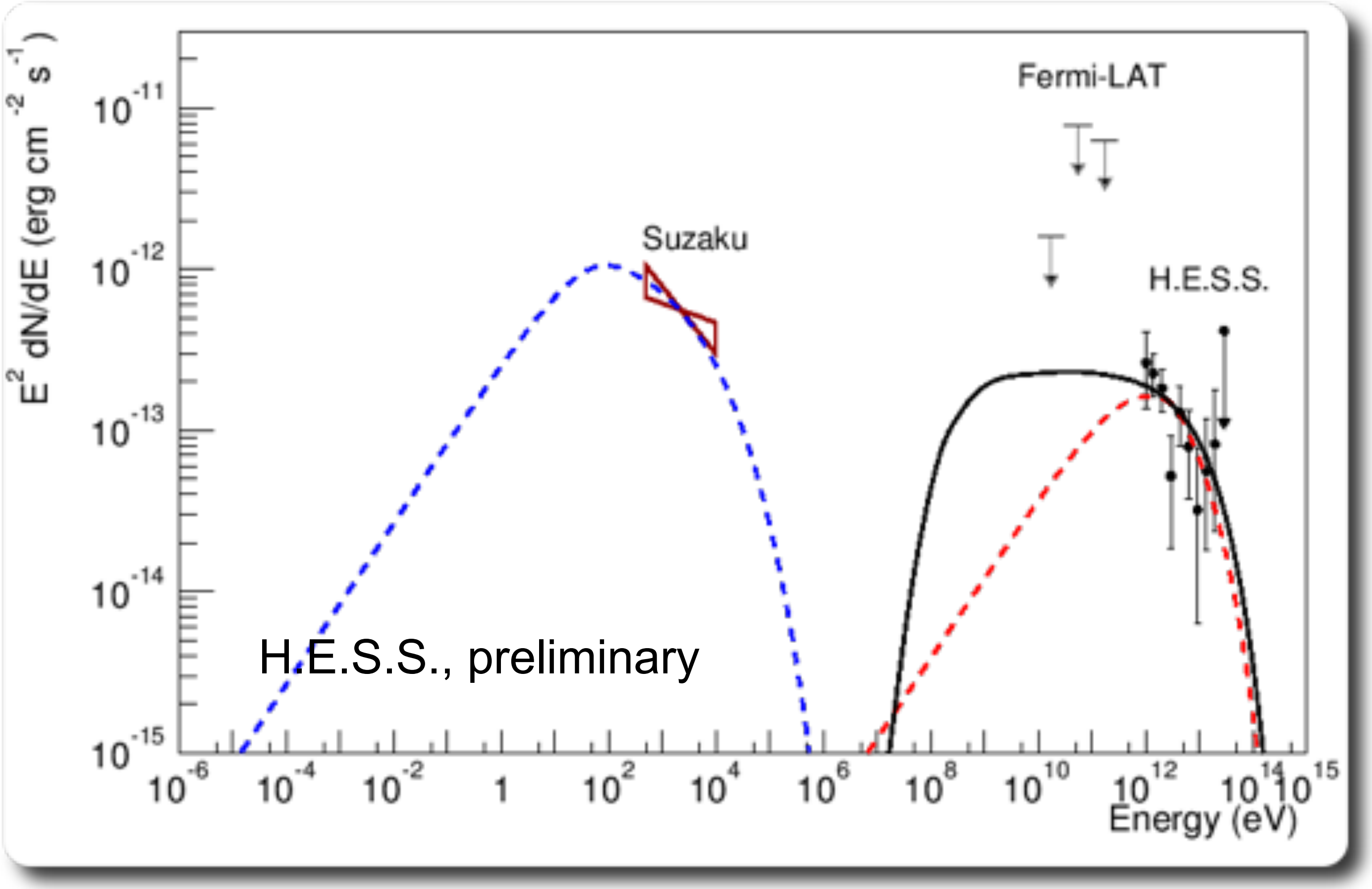


H.E.S.S. detection of the superbubble 30Dor C



- power-law spectrum (183 h acceptance corrected exposure)
- spectral index 2.6 ± 0.2
- Φ(1 TeV) = (1.6±0.4) x 10-13 $cm^{-2}s^{-1}TeV^{-1}$
- $L_{1\text{-}10\ TeV}$(50 kpc) = (9 ± 2) 10^{34} erg/s
- corrected for N 157B spill-over

Interpretation TeV Υ-ray emission 30DorC



- **hadronic scenario**
  - energy in protons
  - W_{pp} = (0.7 – 25) x 10^{52} (n_H /cm^{-3})$^{-1}$ erg
  - even for 5 supernova explosions high density needed: n_H > 20 cm^{-3}
  - thermal X-rays indicate low density: n_H ~0.4 cm^{-3}
    Bamba+ 04, Kavanagh+ '14
- **leptonic scenario**
  - low magnetic field: ~15 μG
  - 4 x 10^{48} erg in electrons

Are super bubbles the main source of Galactic cosmic rays? Remaining issues.

- Collective effects?
  f_{cr}(superbubble)> N_{snr} f_{cr}(SNR)?
  Observational evidence to look for:
  - highest energies! ➜ *could be searched for*
  - *overall efficiency* ➜ *difficult to assess*

- 30Dor C proof that super bubbles are the main sources of cosmic rays?
  - Perhaps exceptional
  - Many SNRs seen in gamma-rays, just a few/one super bubble(s)
    But: lack of super bubbles may be observational bias (low densities)

- If super bubbles extend CR to beyond > 3×10^{15} eV:
  - **why is the cosmic ray spectrum a smooth power law up to 3×10^{15} eV**?
    -Young SNRs accelerate up to 10^{14}eV
    -Not all SNRs are in super bubbles (what fraction is?)
    -Type Ia SNRs also fast accelerators (SN1006, Tycho!)
    ➜ *expect several features associated with difference sources/environments*

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:
  - No Galactic PeVatrons known!
- 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
  - Not discussed: Cosmic-ray acceleration efficiency
    - → Optical emission: hints for ≈25% acceleration efficiency