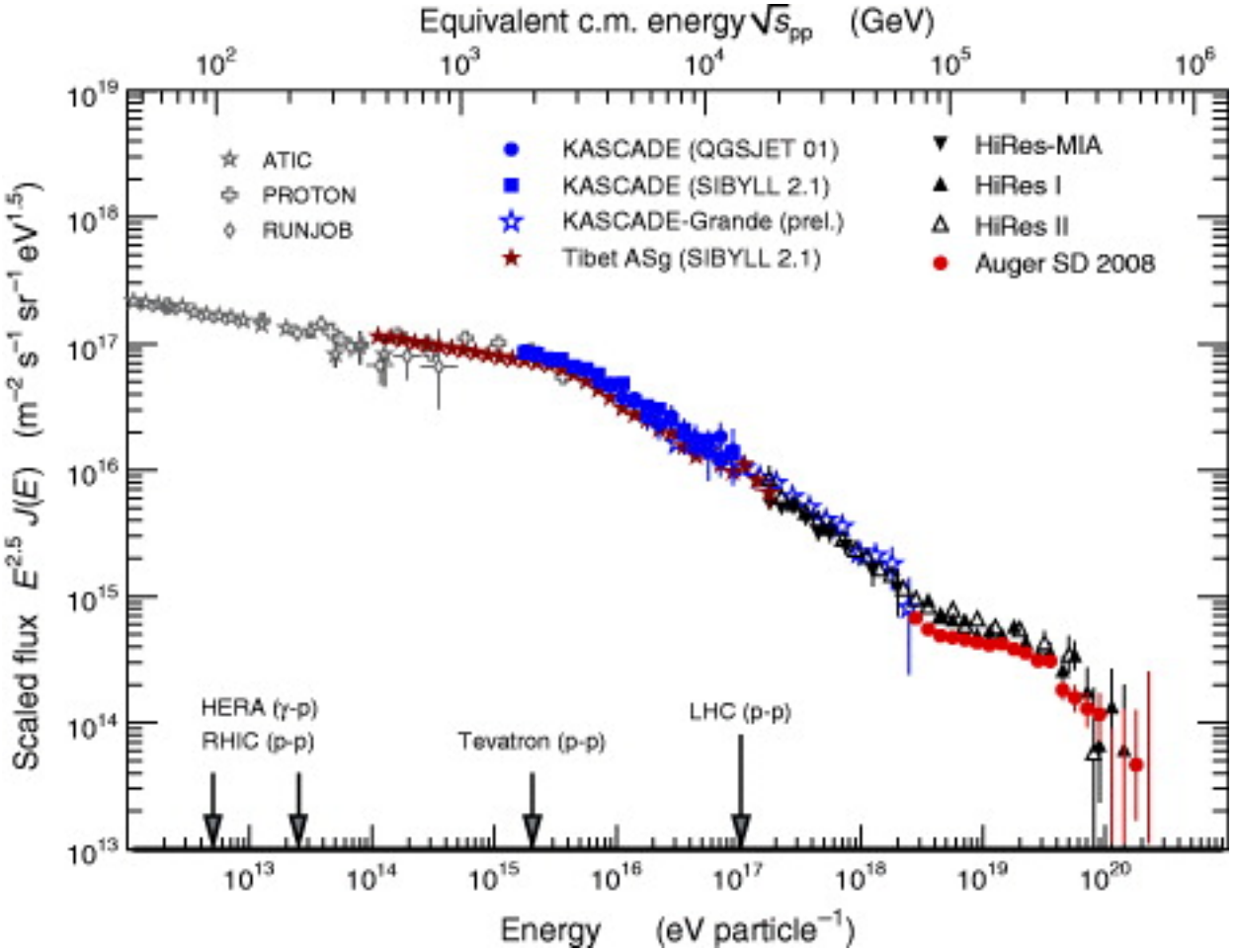
Galactic Cosmic Ray Origin Sites: Supernova Remnants and Superbubbles

Andrei Bykov
High Energy Astrophysics
Ioffe Institute, St.Petersburg, Russian Federation

Collaborators: D.C.Ellison, S.M.Osipov, Yu.A.Uvarov, A.E.Vladimirov

Cosmic Ray Spectrum



Blümer + 2010

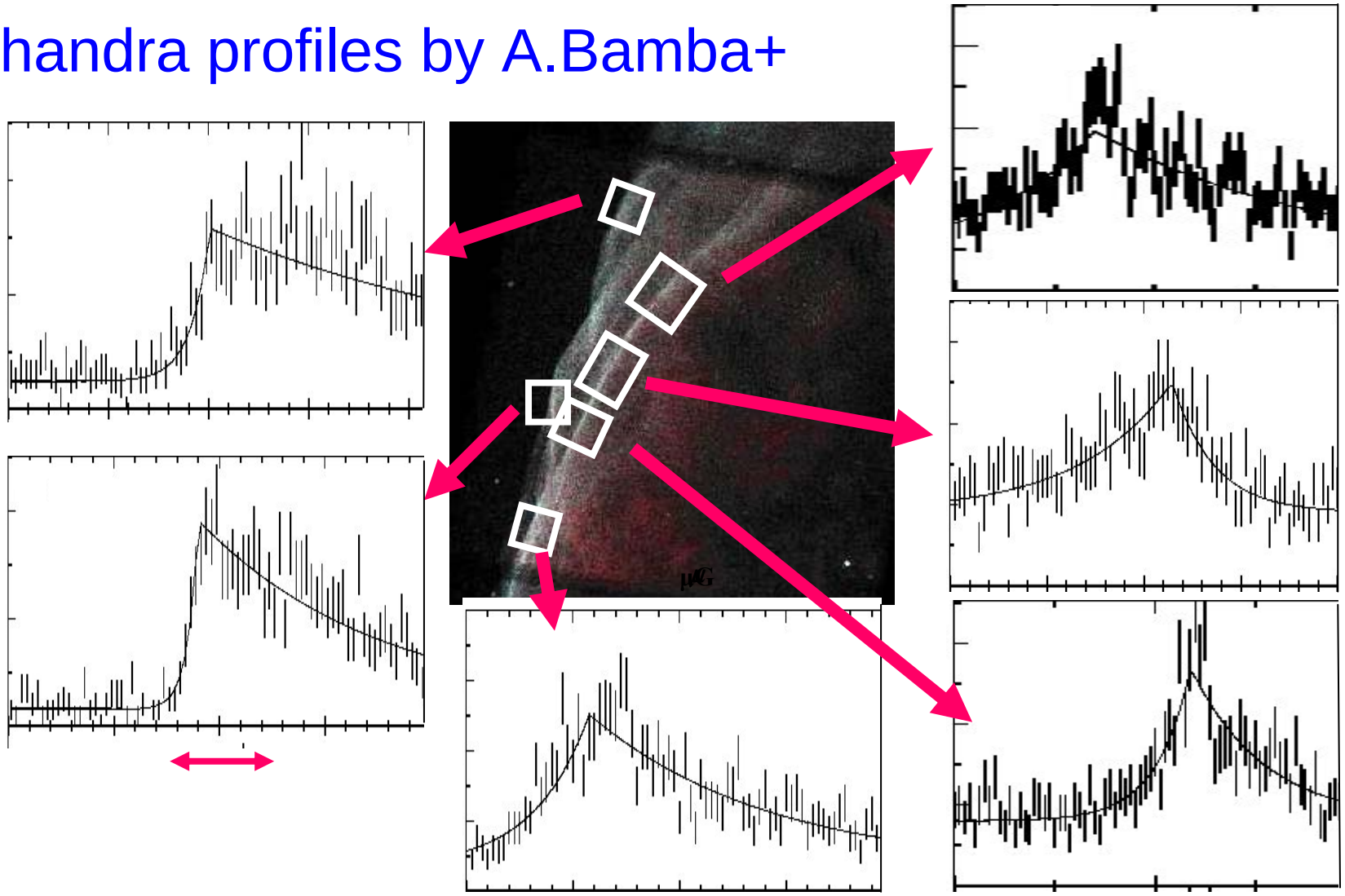
Particle acceleration and GCR origin

Non-linear mechanisms of efficient conversion of SN kinetic energy to relativistic components.

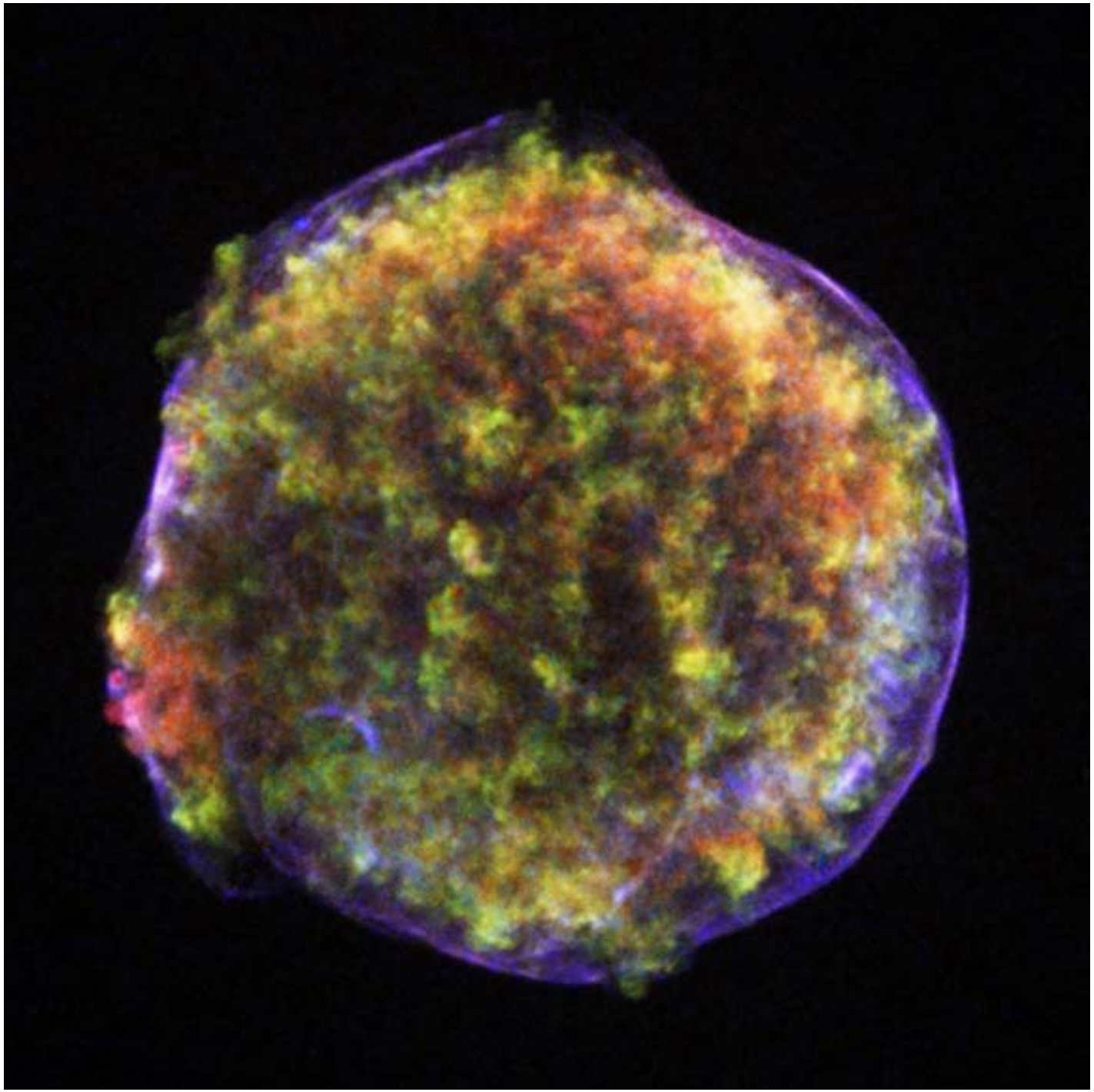
Magnetic field amplification in cosmic particle accelerators and synchrotron X-ray images of SNRs

Cosmic ray escape from the accelerator

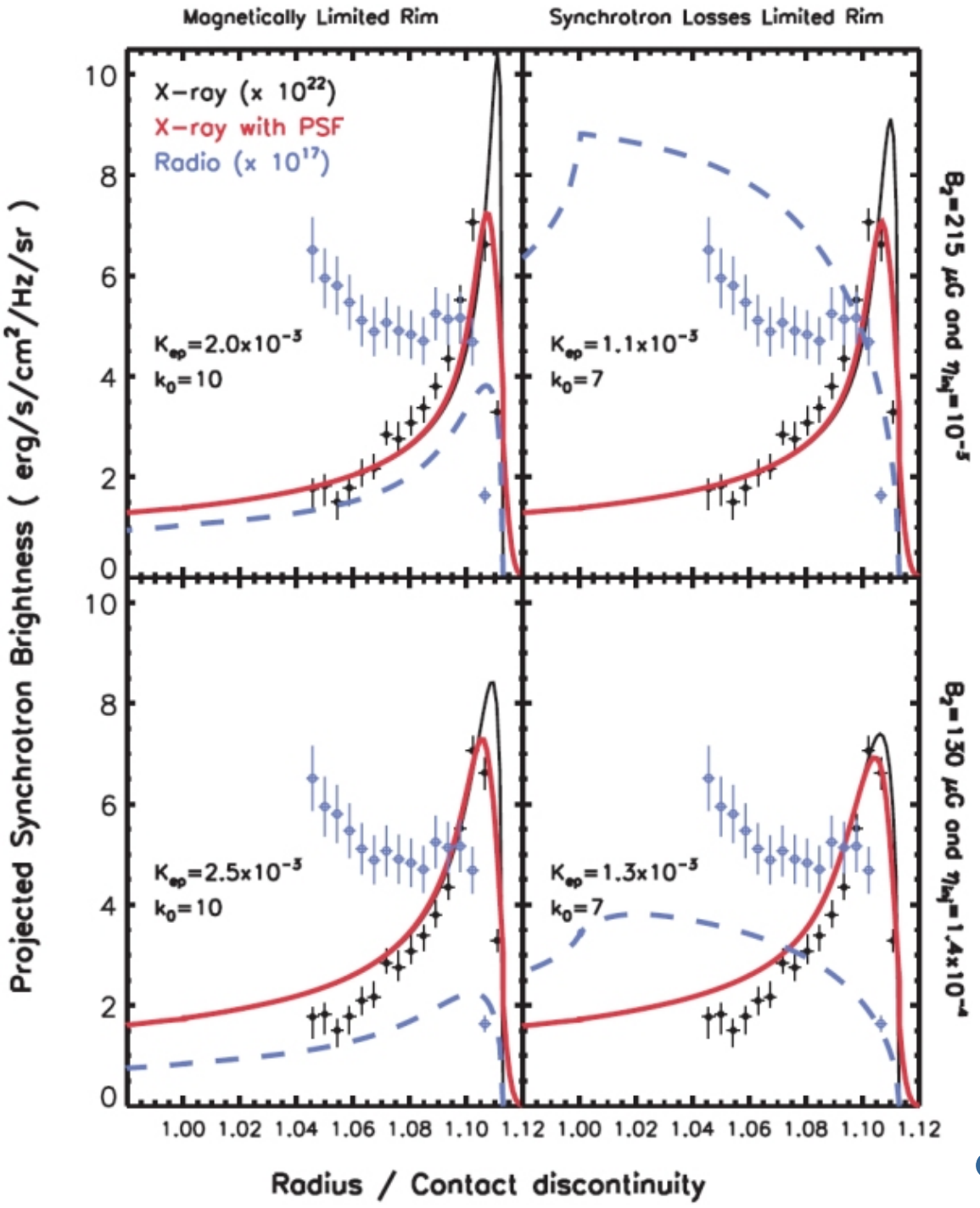
Chandra profiles by A.Bamba+



measurements of the width of synchrotron X-ray filaments in SN1006
STRONG MAGNETIC FIELD AMPLIFICATION >> 20 μG
Electron energies >> 1 TeV

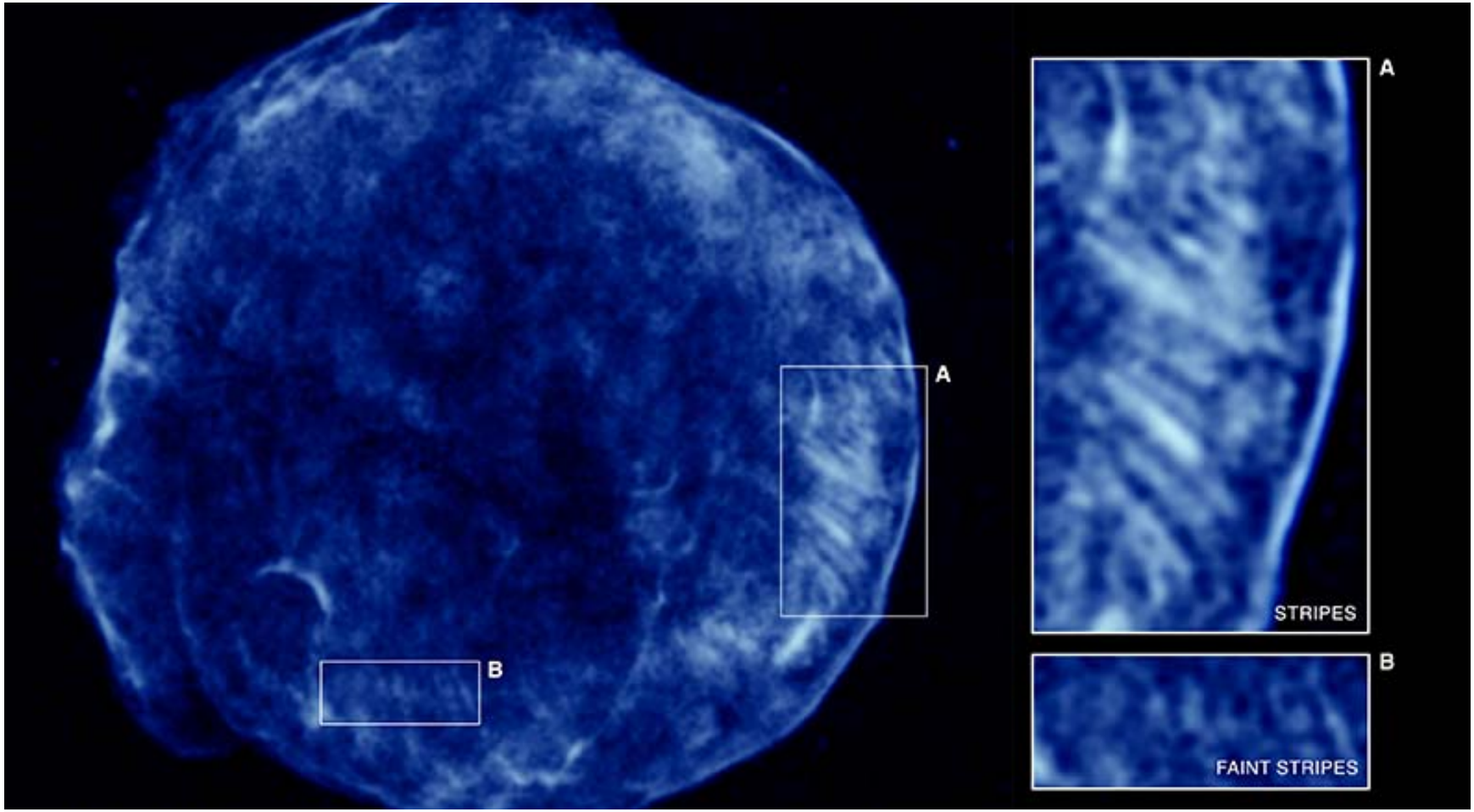


Warren & Hughes
CXO

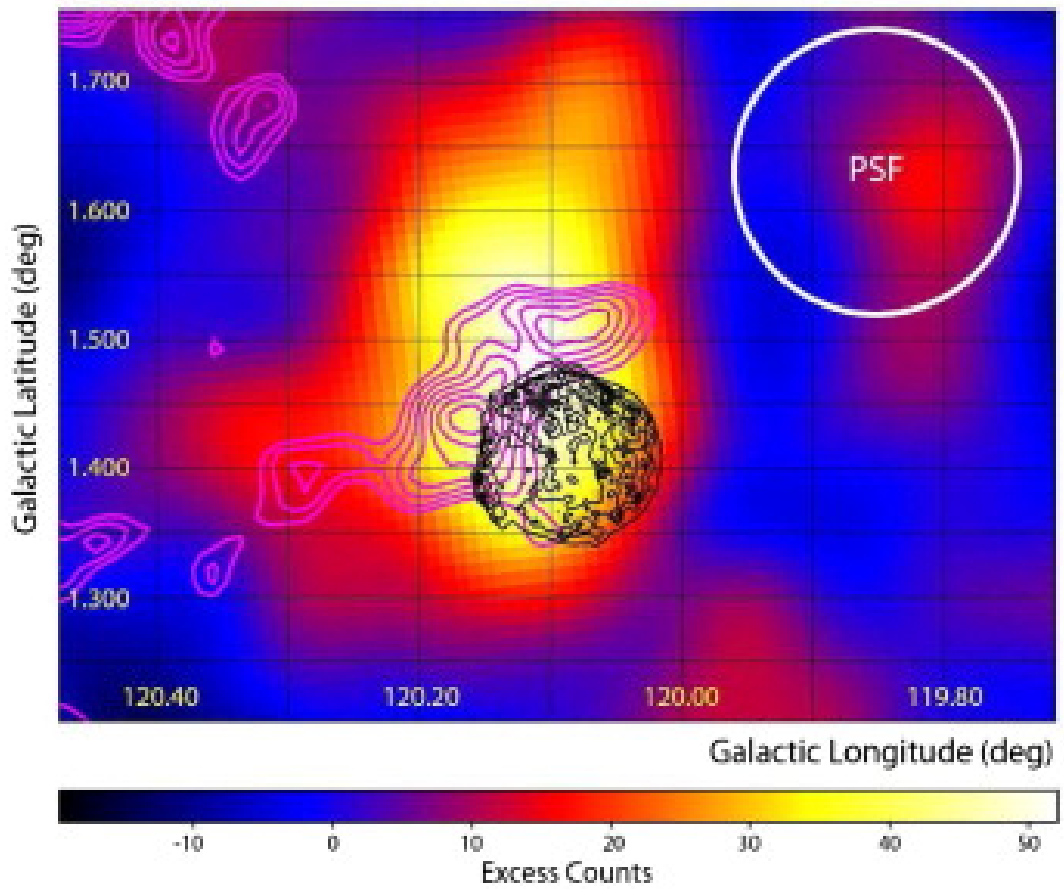


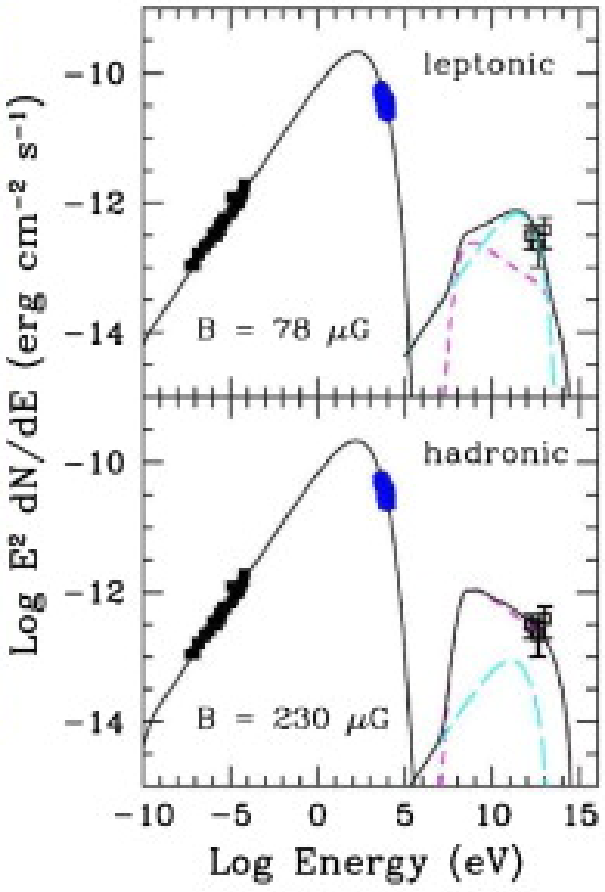
Cassam-Chenai et al 2007

Chandra 4-6 keV Image of Tycho's SNR

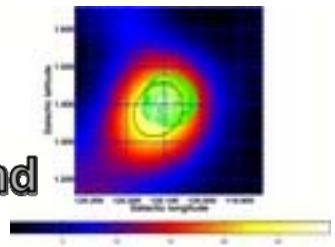


Eriksen + 2011



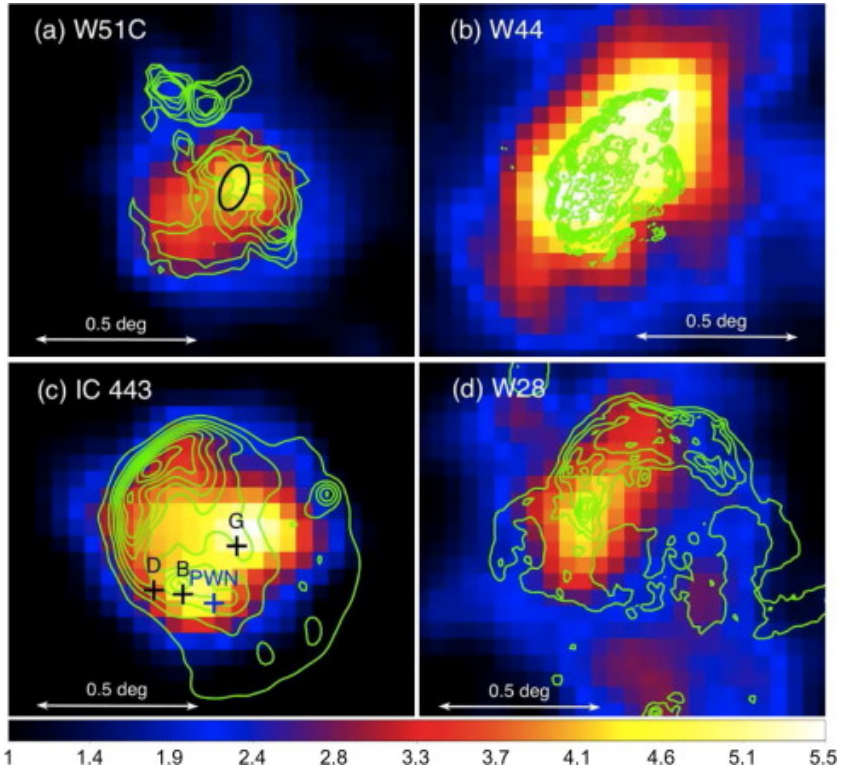


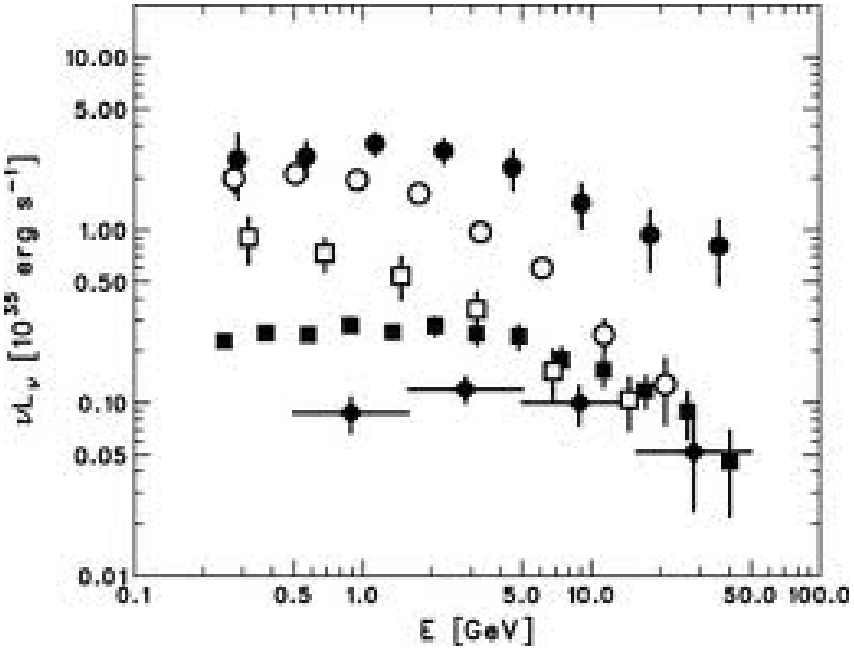
Ragan + 2012 VERITAS



F. Giordano + FERMI LAT 2012 found
Spectral index 2.3+/- 0.1
Consistent with hadronic model by Morlino & Caprioli 2012

Fermi images of “molecular” SNRs

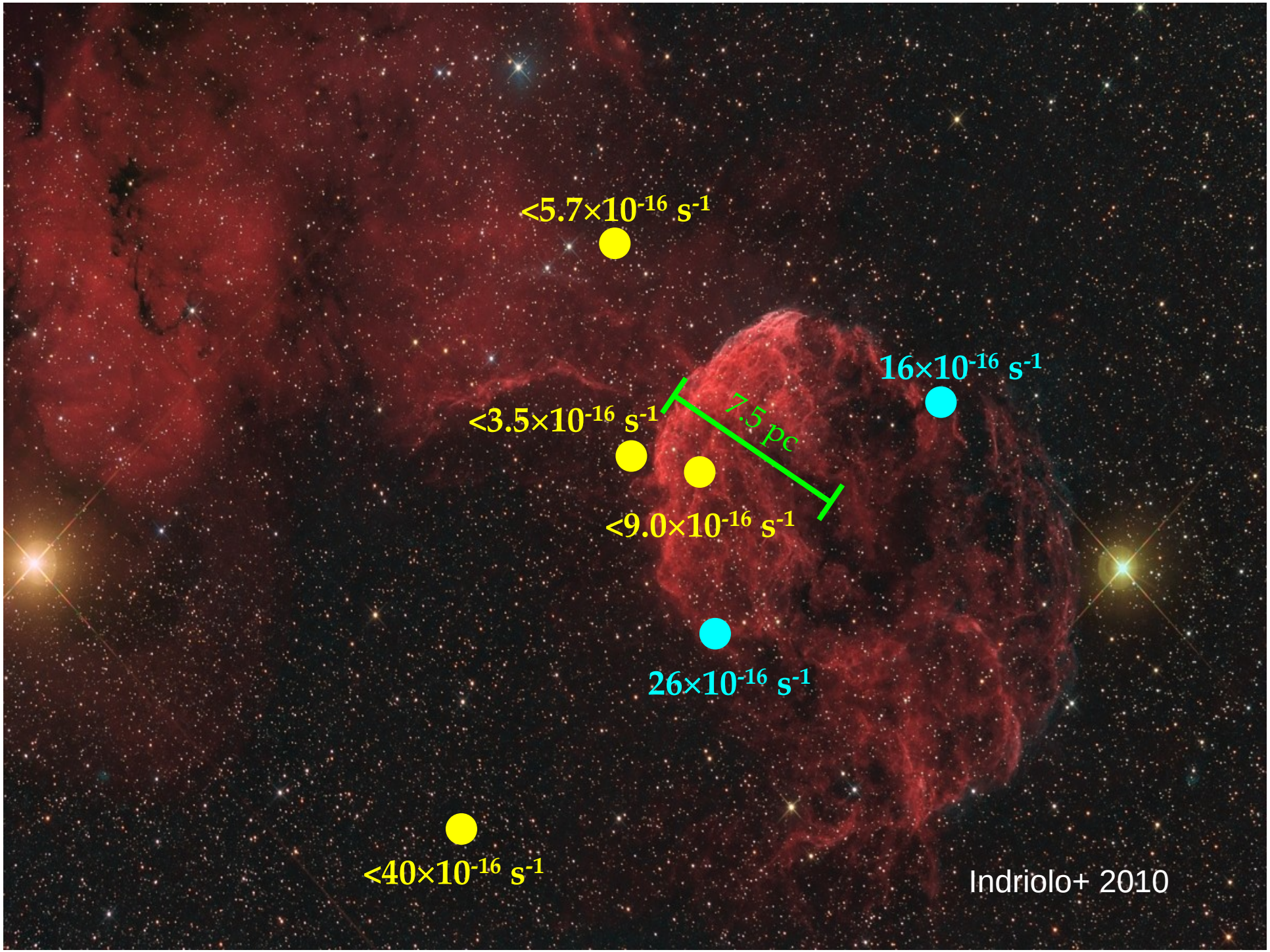




$$L_\gamma \sim 10^{34} - 10^{36} erg/s$$

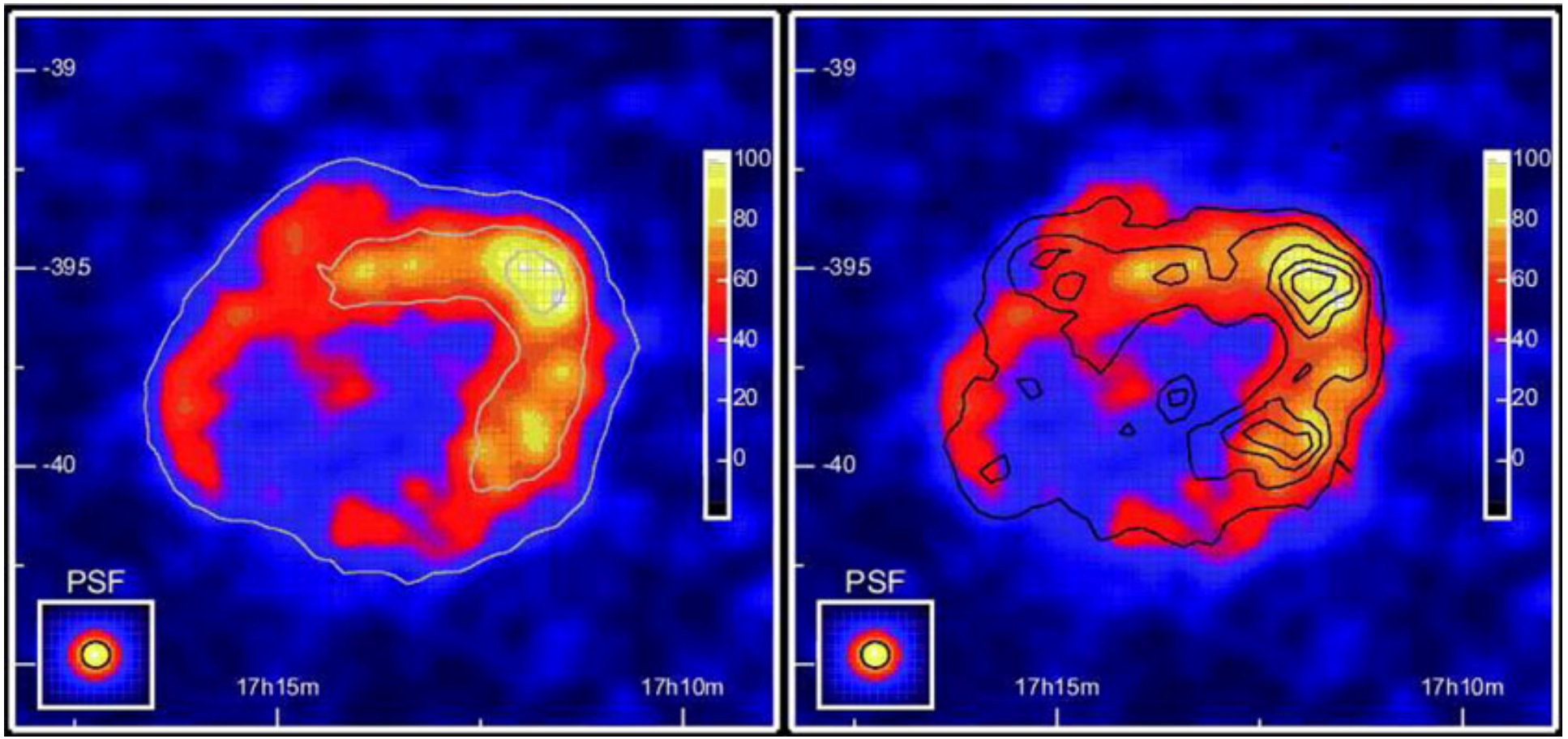
W51C (filled circles) W44 (open circles);
IC 443 (filled rectangles); W28 (open rectangles)
Cassiopeia A (filled diamonds).

Thompson Baldini Uchiyama 2012


<5.7×10-16 s-1
16×10-16 s-1
<3.5×10-16 s-1
7.5 pc
<9.0×10-16 s-1
26×10-16 s-1
<40×10-16 s-1
Indriolo+ 2010

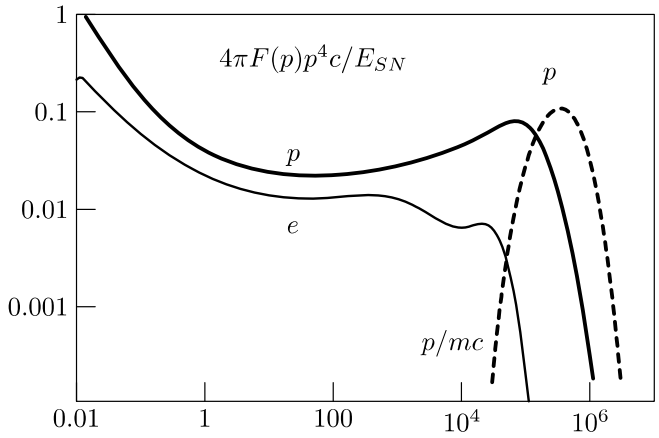
CR Core Collapsed SNR

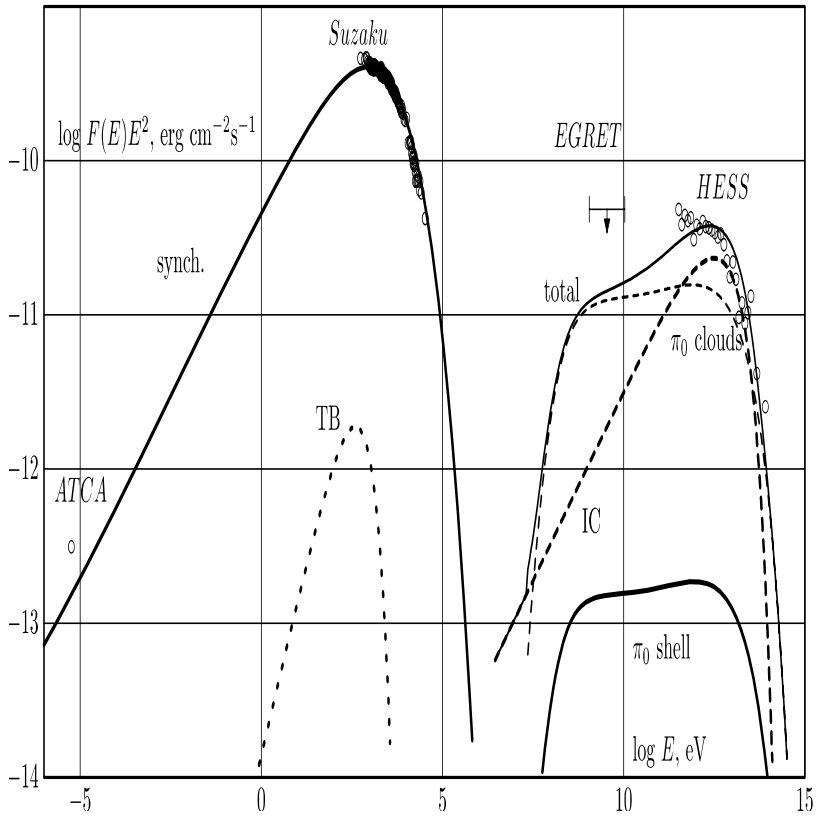
H.E.S.S. image of RX J1713.7-3946



Aharonian + 2006

Model for CR acceleration and non-thermal emission from RX J1713.7-3946





Both hadronic and leptonic scenaria are plausible

Zirakashvili Aharonian 2010

Non-thermal emission from RX J1713.7-3946

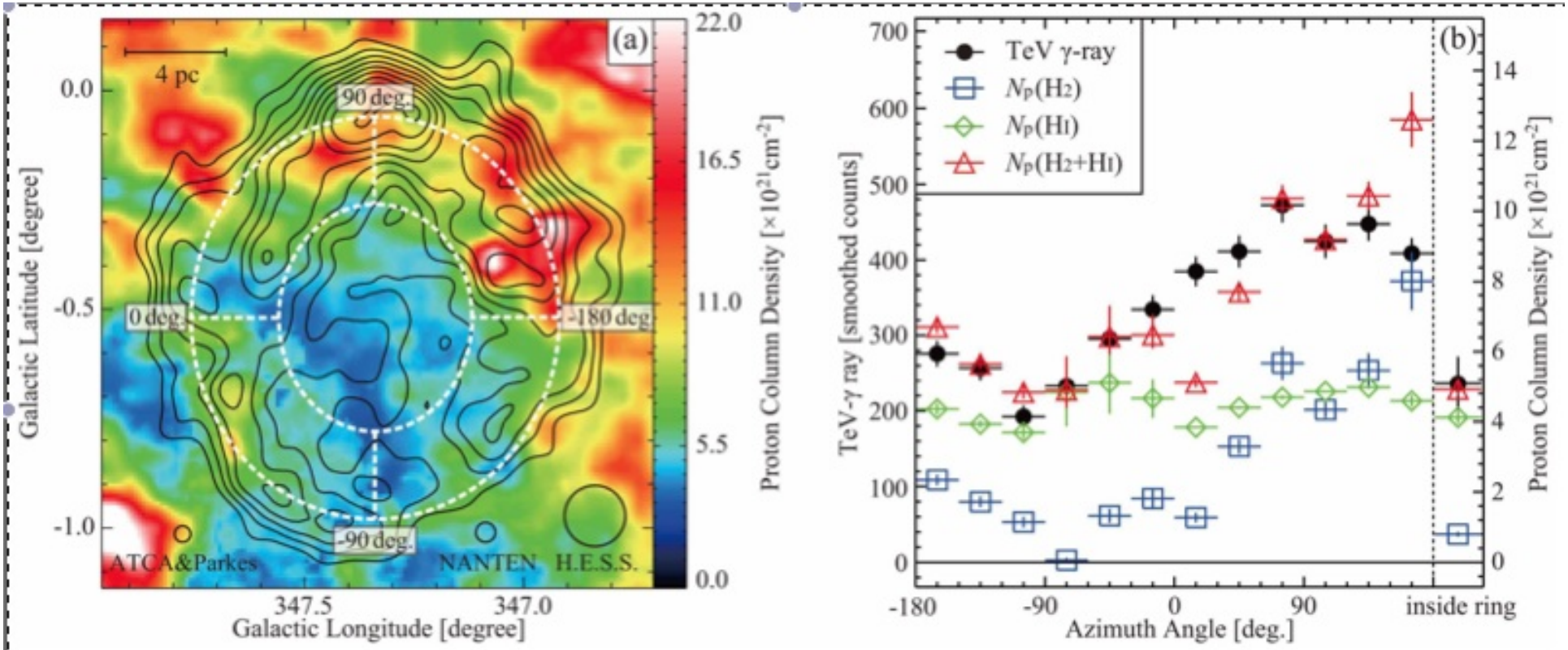


FIG. 8.— (a) Distributions of column density of the total ISM protons $N_p(H_2+H\ I)$ in a velocity range from -20 km s^{-1} to 0 km s^{-1}. Contours are the same as in Figure 1(a). (b) Azimuthal distributions of $N_p(H_2)$, $N_p(H\ I)$, $N_p(H_2+H\ I)$ and TeV γ-ray smoothed counts per beam between the two elliptical rings shown in Figure 8(a). The proton column densities are averaged values between the rings (see text). Semi-major and semi-minor radii of the outer ring are 0.46 degrees and 0.42 degrees, respectively, and the radii of the inner ring are half of them. The same plots inside the inner ring are shown on the right side of Figure 8(b).

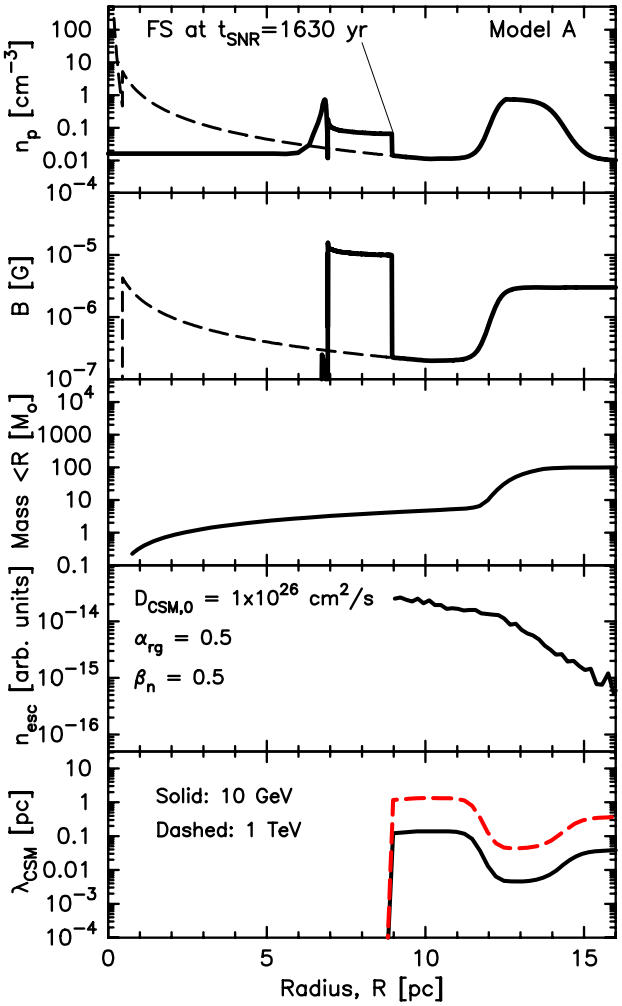
Hadronic scenario is prefered by Fukui et al (2012) due to apparent correlation of ISM matter distribution and the observed profile of TeV emission

Core Collapsed SNR

Circumstellar Medium (CSM) may strongly affect the spectra of non-thermal emission of the remnants of CC SN Ib/c and SNIIb.

Magnetic field in the wind of the progenitor massive star may be well below the average ISM values of a few micro-Gauss alleviating an apparent contradiction between the low post-shock magnetic field values required by the IC scenario and strong magnetic field amplification in the efficient DSA models.

Core Collapse SNR Model for RX J1713.7-3946



$$B_0 = \frac{\sqrt{\sigma_{wind} V_{wind} \dot{M}}}{R},$$

$$\sigma_{wind} \propto \frac{V_{rot}^2}{V_{wind}^2} B_*^2$$

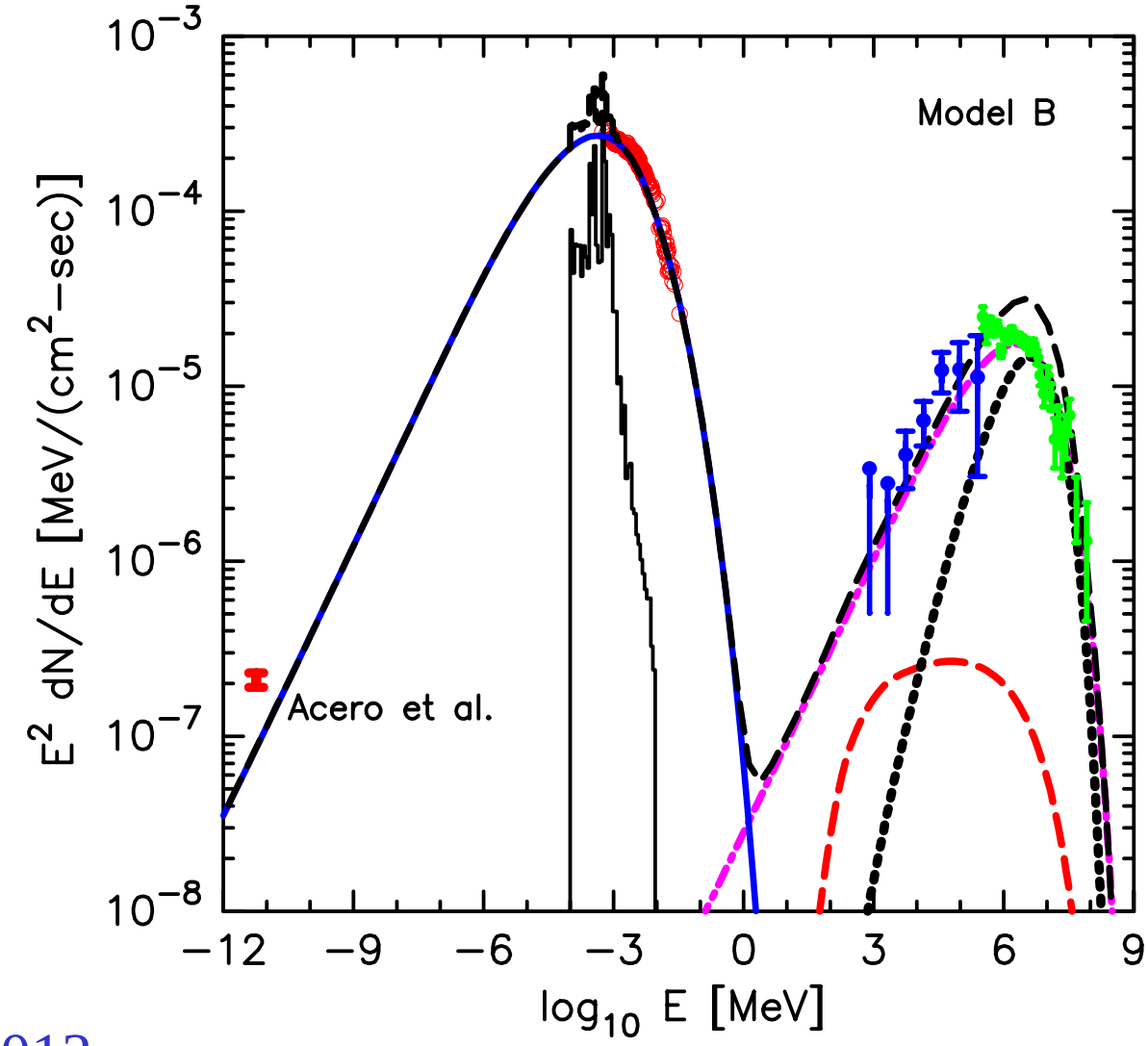
$$\sigma_{wind} \sim 0.03$$

Ellison + 2012

Core Collapse SNR Model for RX J1713.7-3946

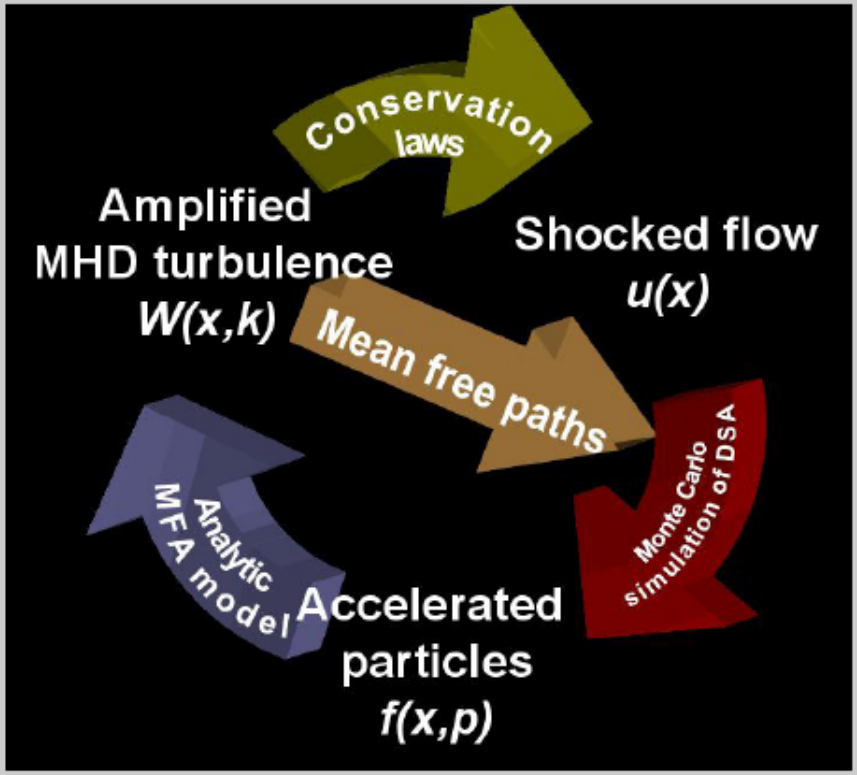
10 muG shock downstream magnetic field in the model by Ellison et al (2012) is about 50 times amplified wind magnetic field. That reconcile the efficient CR acceleration and the low MF required by the IC model. It may also provide relatively wide (a parsec-scale size) profile of the IC TeV emission consistent with the observed TeV profile.

Core Collapse SNR Model for RX J1713.7-3946



Ellison + 2012

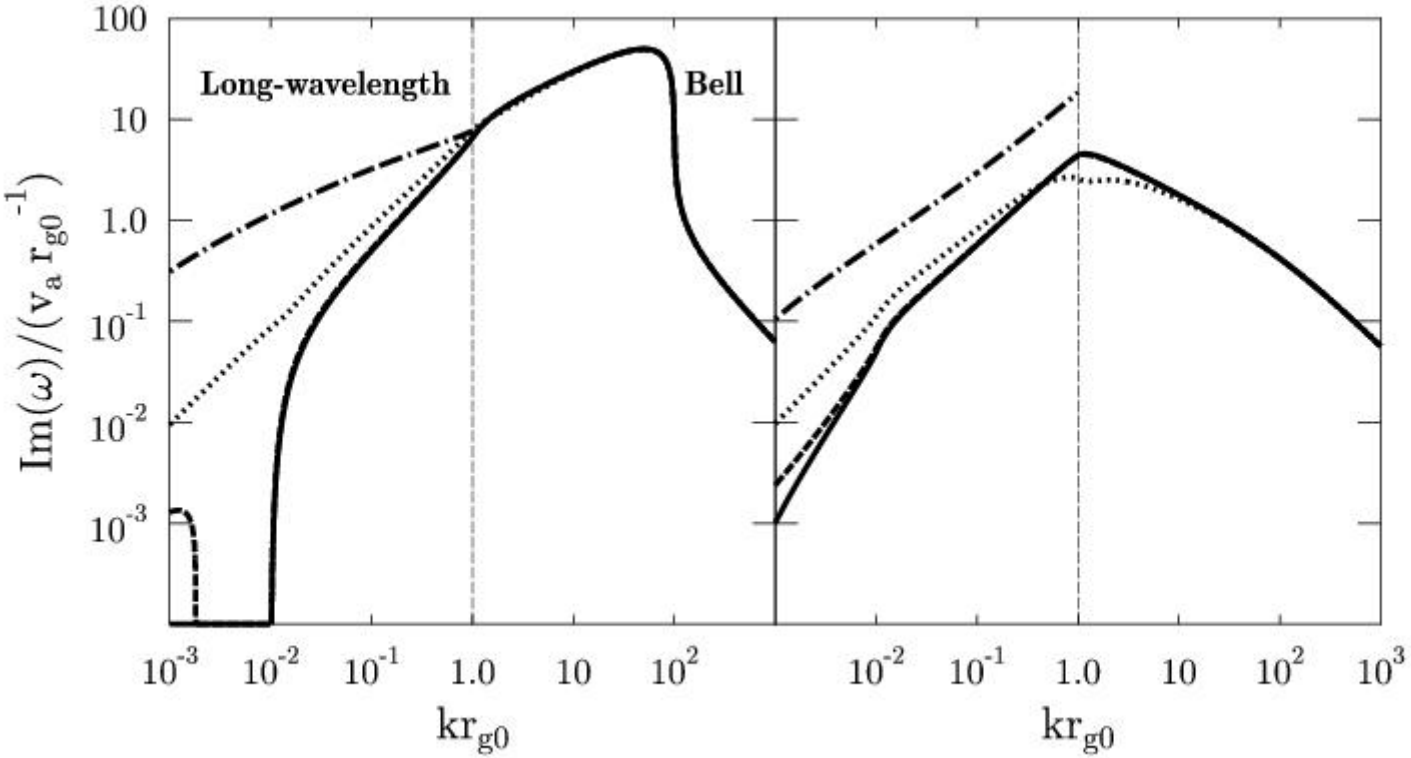
Nonlinear Models of Ultrarelativistic Particle Acceleration with CR driven instabilities



- Our model simulates **particle acceleration**, **turbulence generation** and **shocked flow** all consistently with each other;
- A **Monte Carlo (MC) code** describes particle transport and acceleration;
- **Diffusion coefficient** used in the MC code coupled to turbulence spectrum;
- **Turbulence generation** driven according to particle transport simulated in MC.

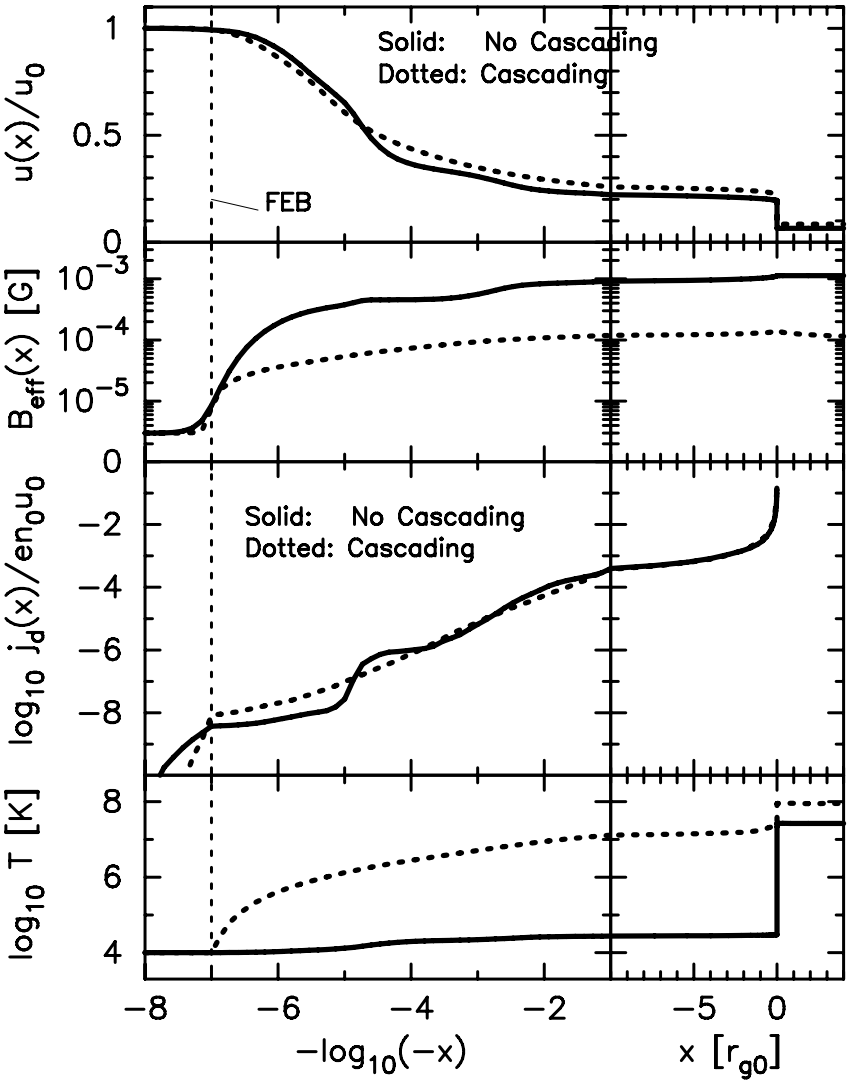
- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

CR driven modes



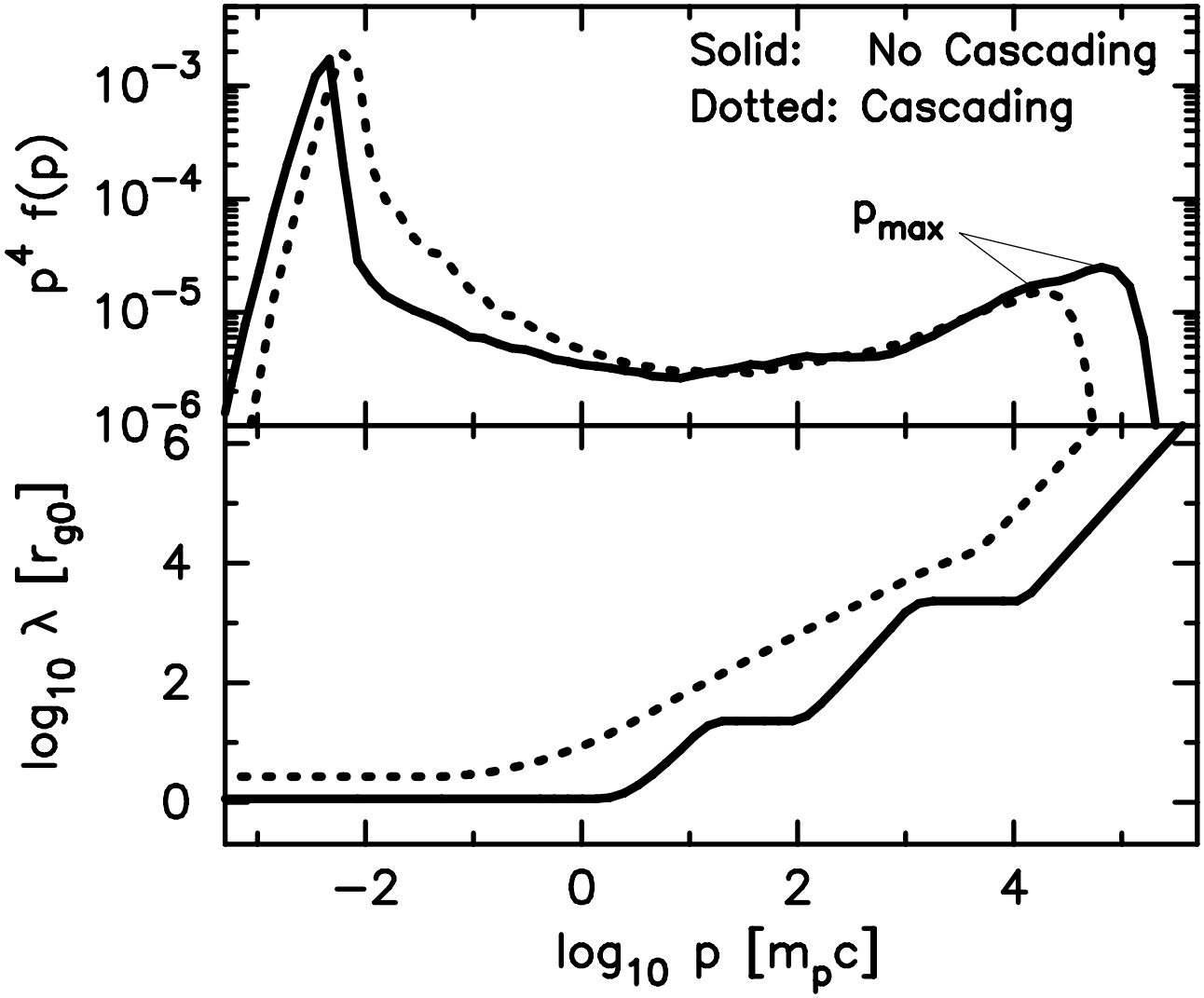
Bell' 04 AB+05, Marcowith+ 06, AB+11 Schure +11,

CR modified shock

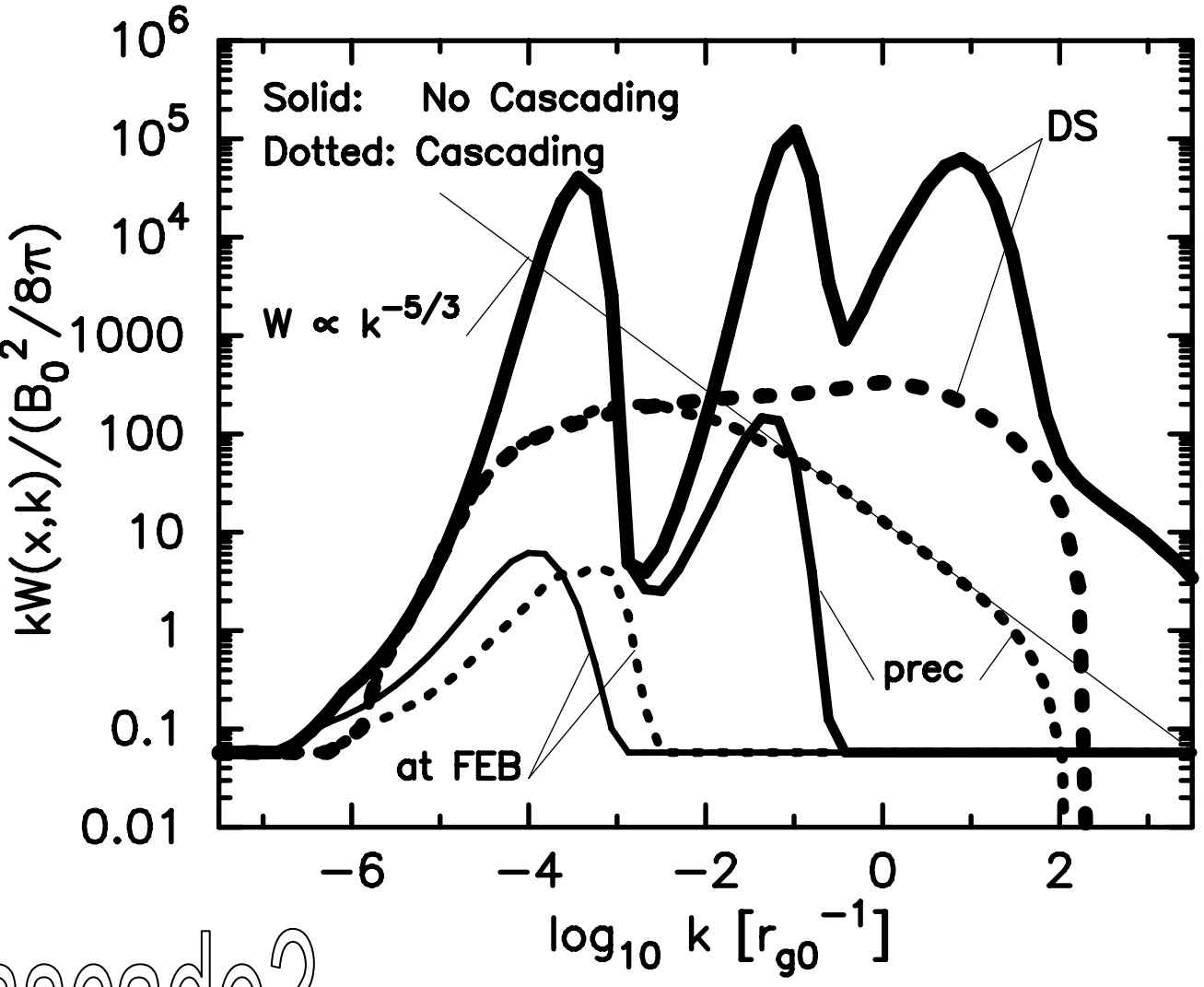


- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

Particle Spectra



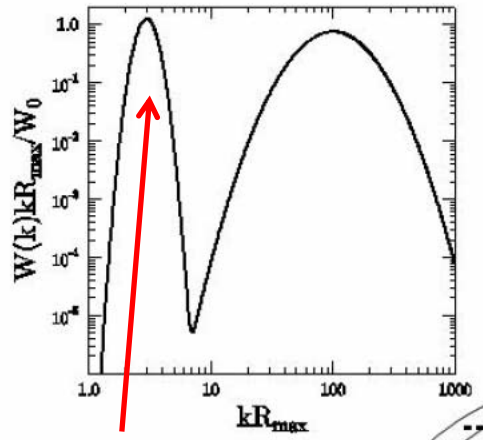
Magnetic Fluctuation Spectra



No cascade?

- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

AB+ ApJL v.735, L40,2011

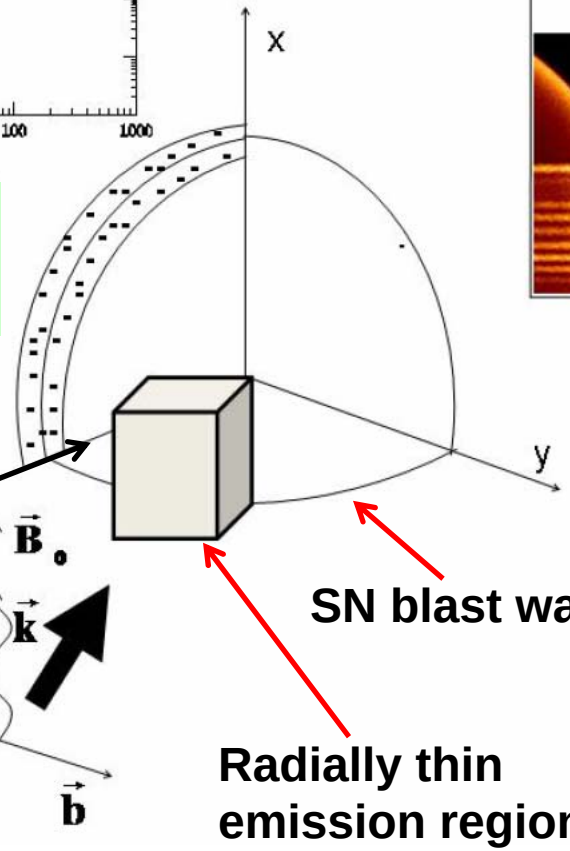


Narrow peaks in turb. spectrum with no cascading

Simulated strips

Efficient, NL shock acceleration producing ~100 TeV protons

Steep electron spectrum to avoid strips in radio



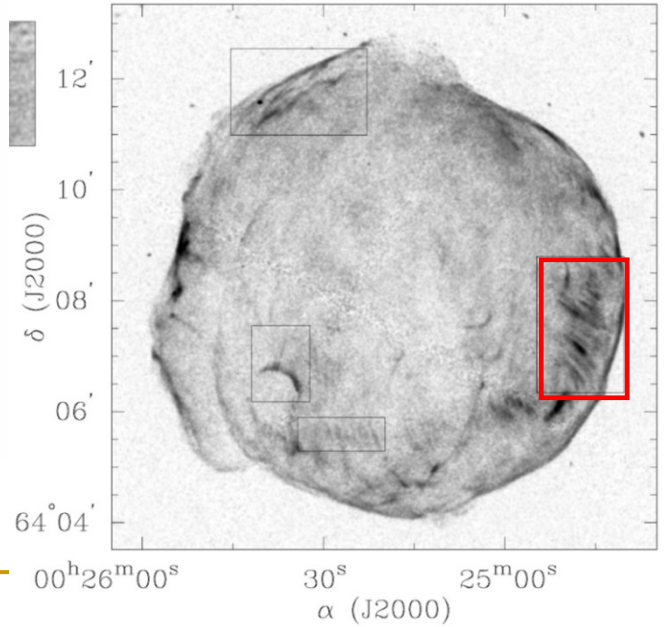
Perp. B-field outside shock precursor

Line of sight

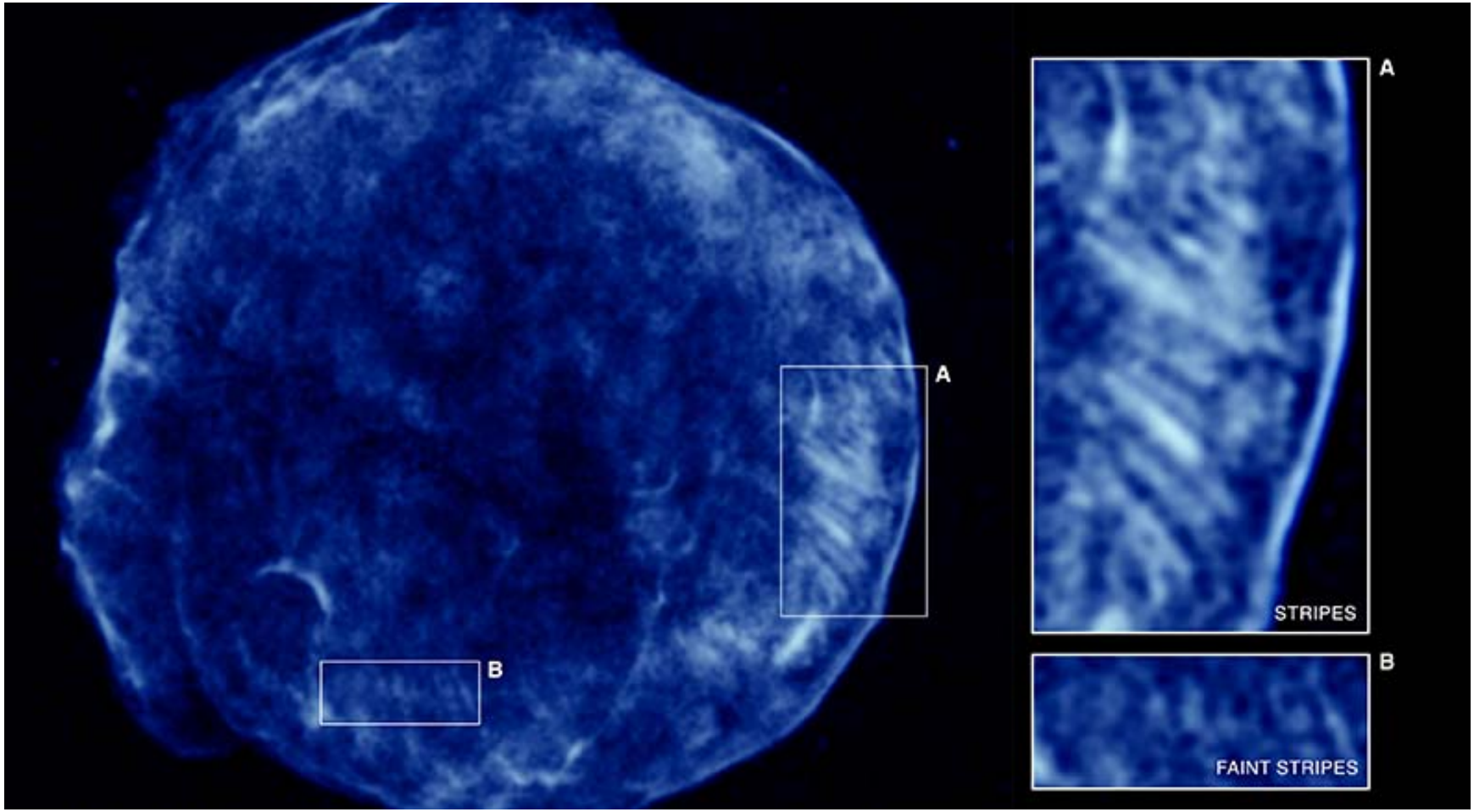
SN blast wave

Linearly polarized waves with long coherence length

Radially thin emission region

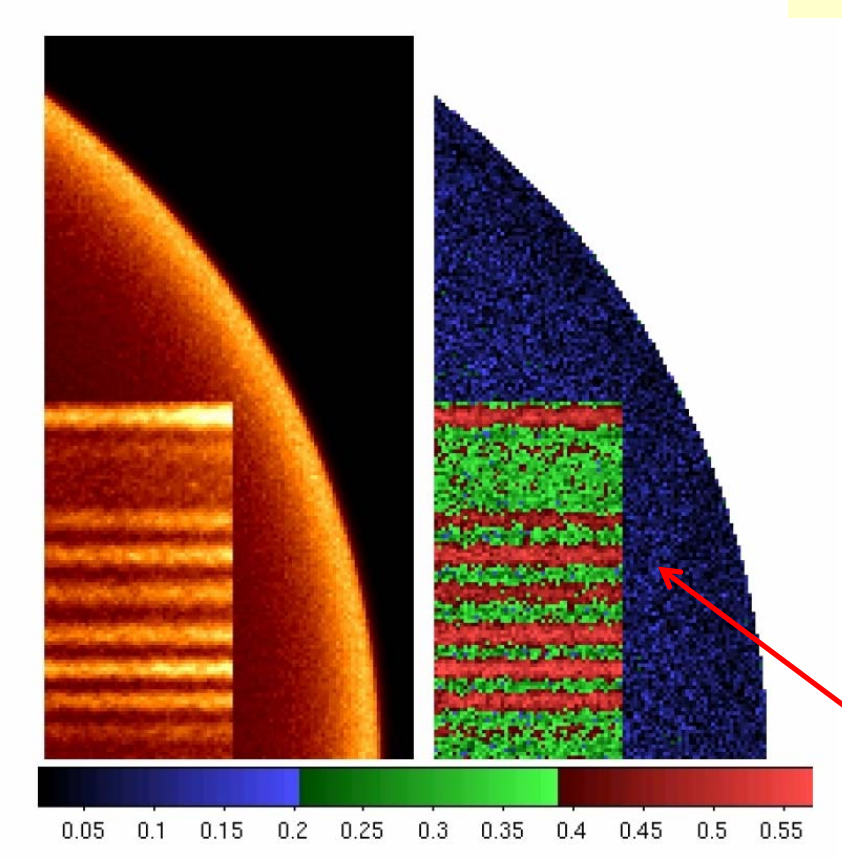


Chandra 4-6 keV Image of Tycho's SNR



Eriksen + 2011

AB+ ApJL v735, L40, 2011



Polarization fraction

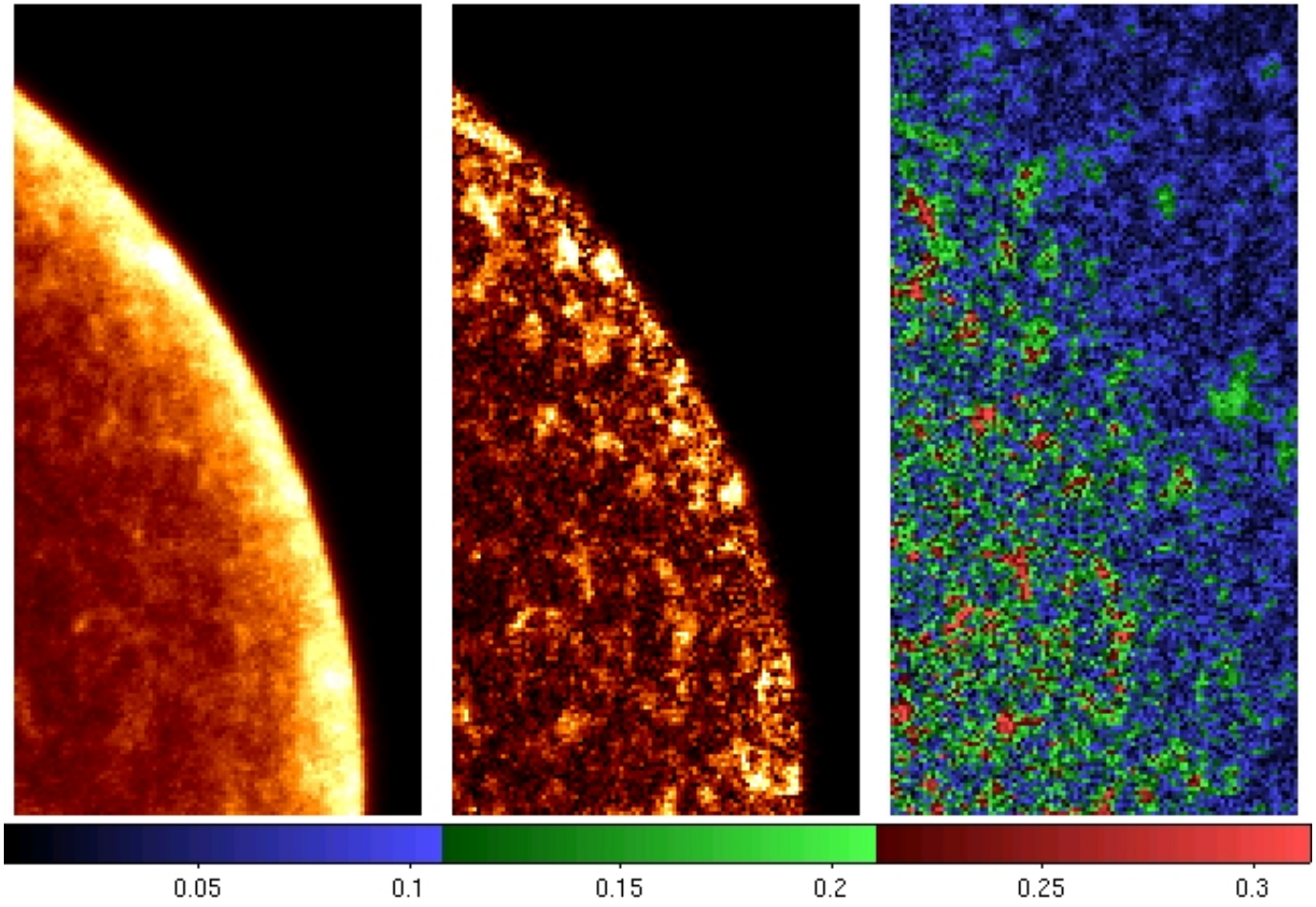
A possible explanation of strips

➔ **Some shock and turbulence properties must come together to produce coherent structure on this scale. Transverse part of the shock, anisotropic cascade, high Pmax**

Strong predictions:
Quasi-perpendicular upstream B-field

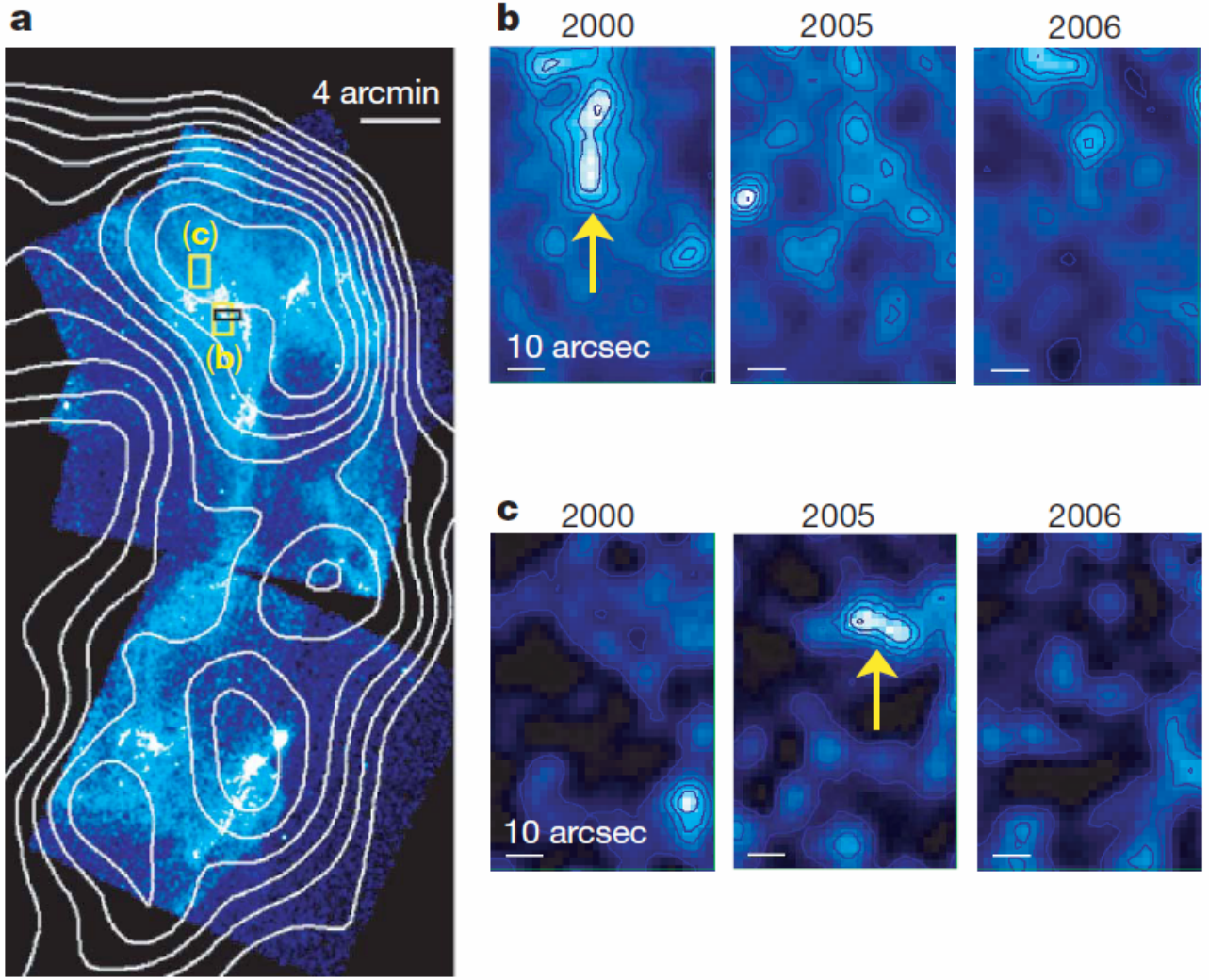
Strong linear polarization in strips

SNR synchrotron shells:
X-ray Imaging & Polarization at 5 keV



AB+ MNRAS v.399, 1119, 2009

Uchiyama Aharonian et al. Nat. 2007

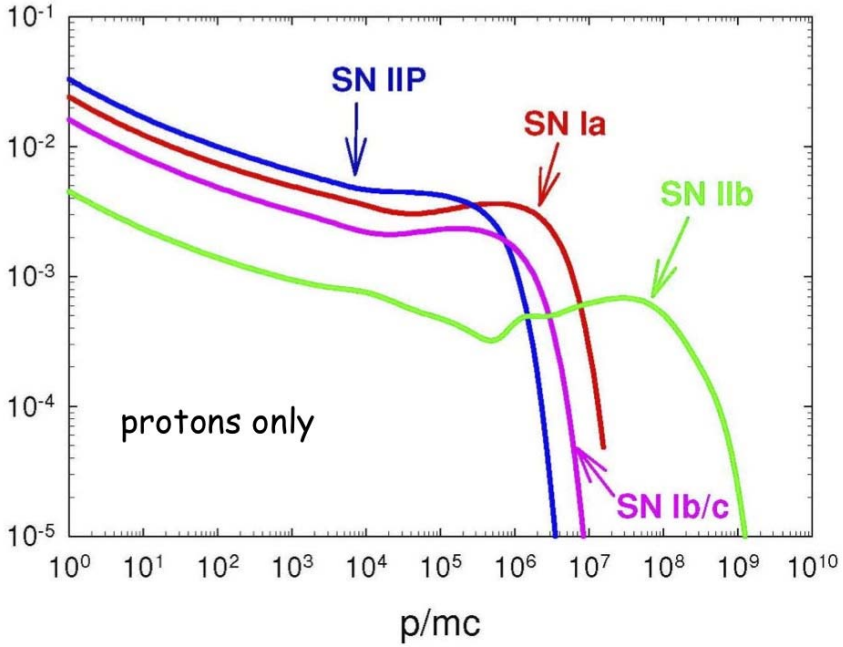


Nonthermal clump "lifetime" ~ 1yr

CR acceleration beyond the knee

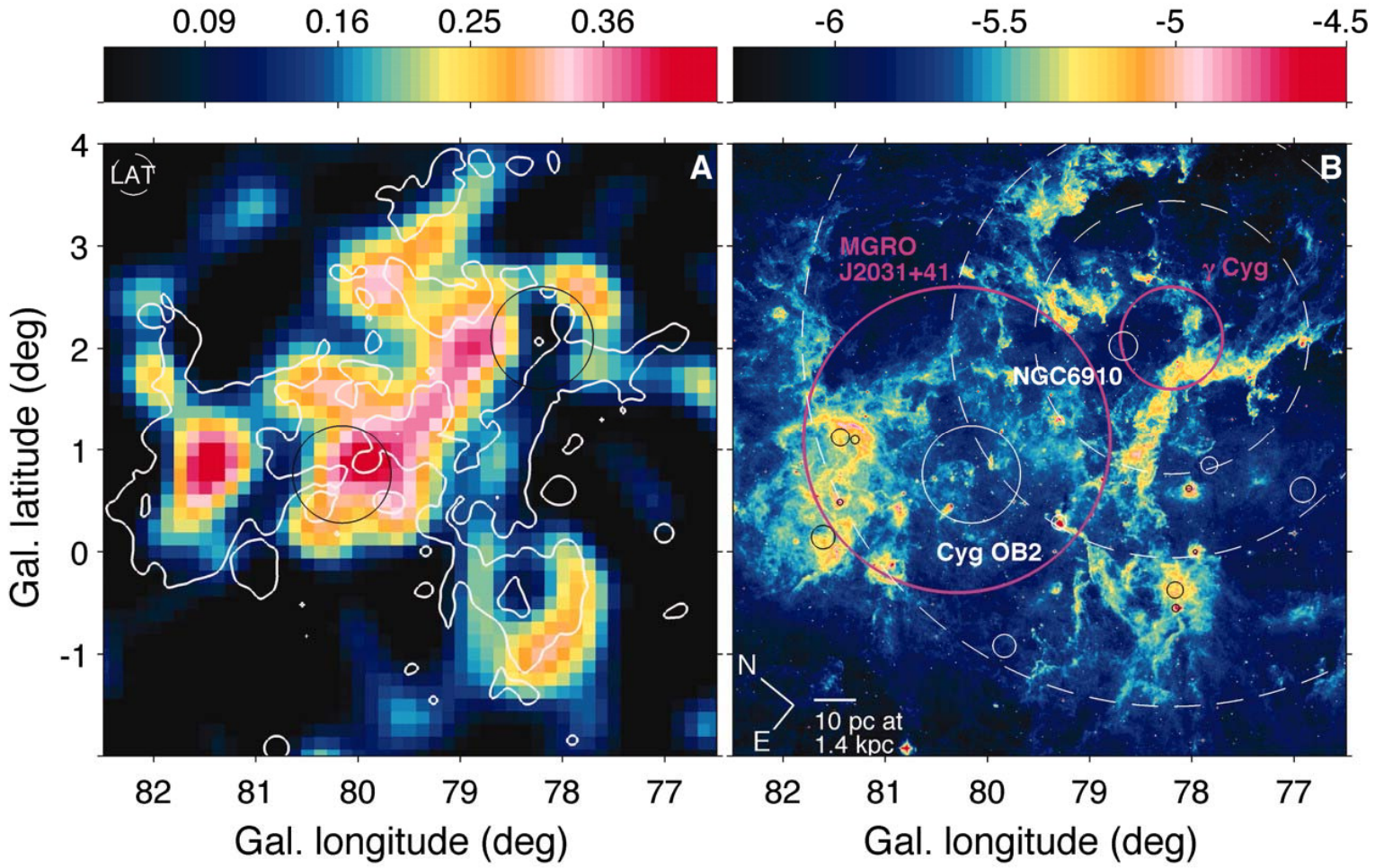
Young SN exploded in CSM wind?

Ptuskin, Zirakashvili & Seo 2010



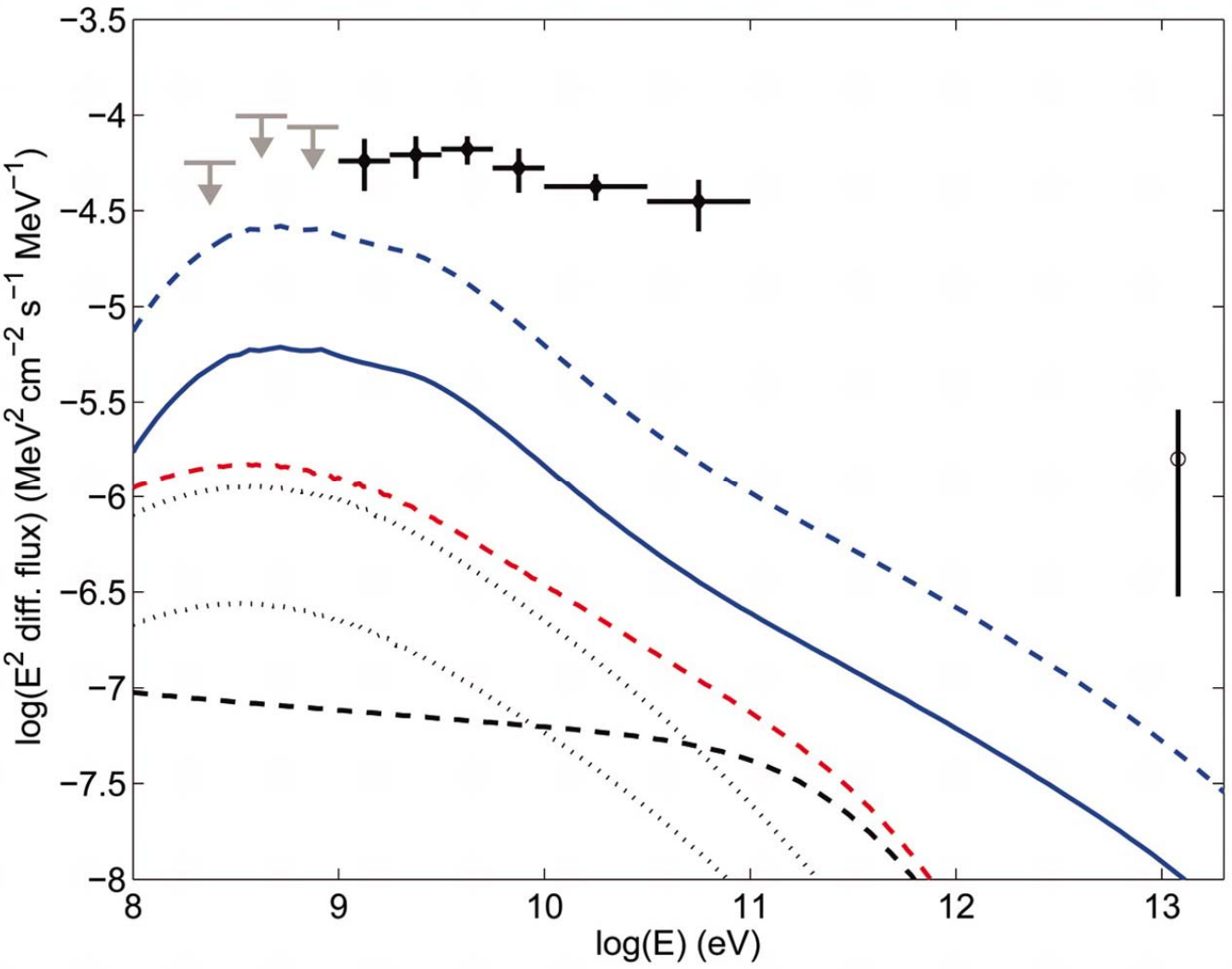
or (re)acceleration in Superbubbles?

Fermi image of Cygnus superbubble



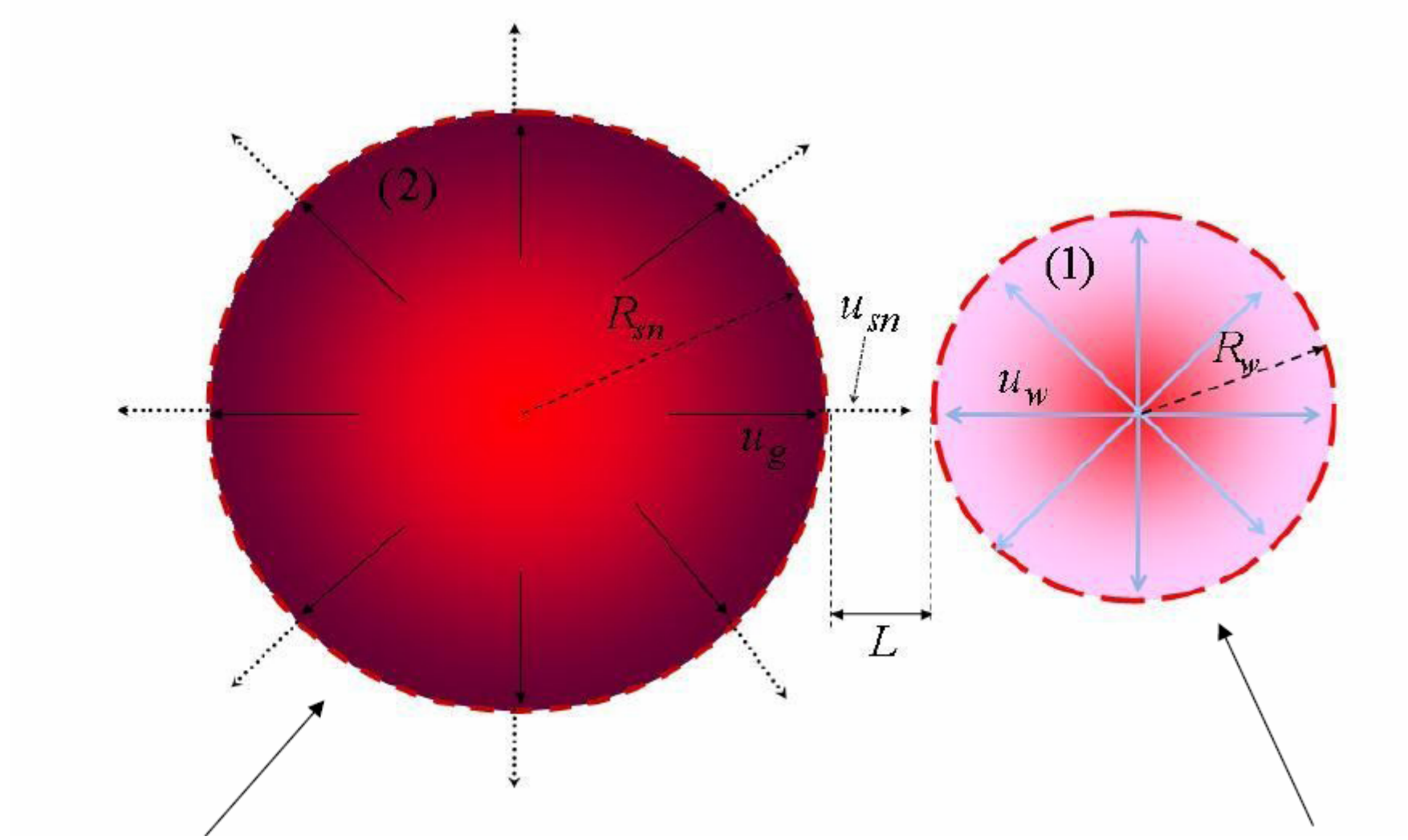
Ackermann + 2011

Fermi spectrum of Cygnus superbubble



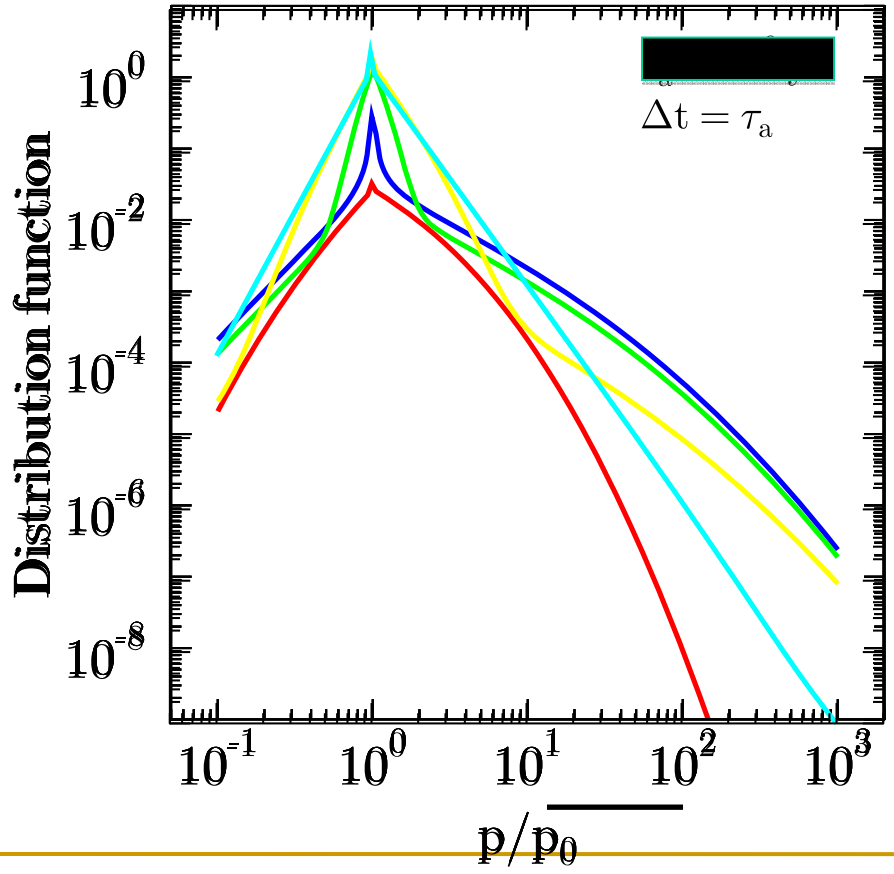
Ackermann + 2011

SNR-stellar wind accelerator



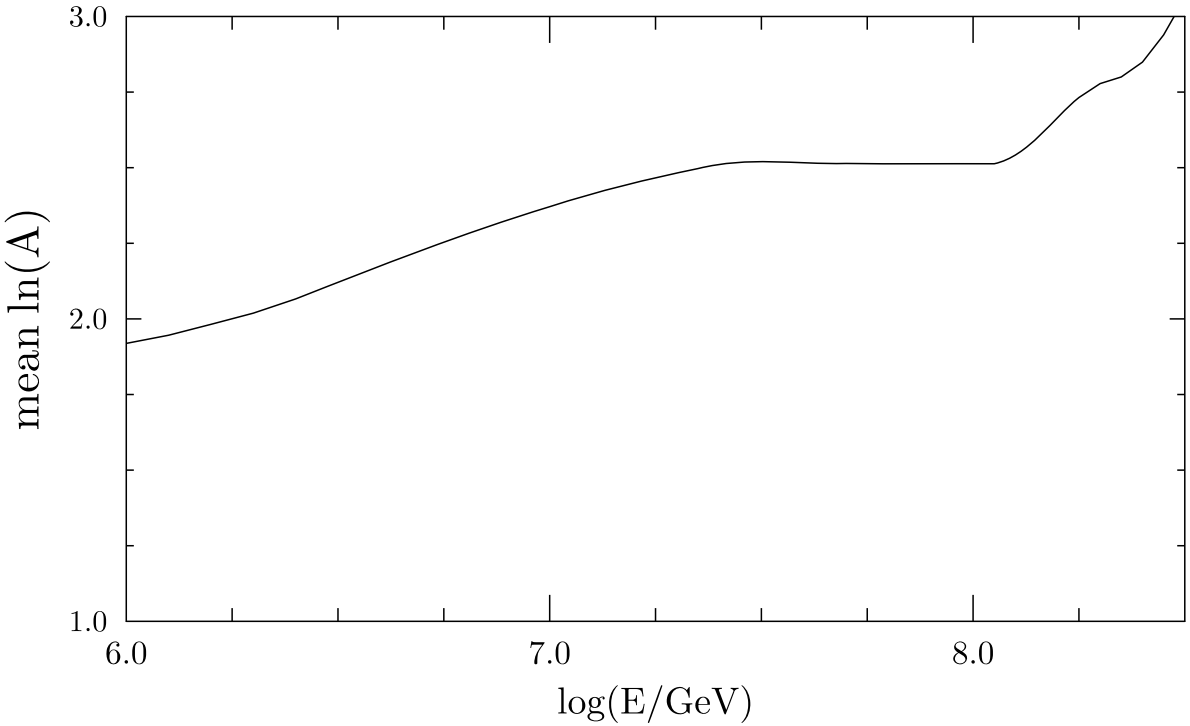
AB Gladilin Osipov MmSAI 2011

Temporal Evolution of SB Particle Spectra



Space Sci. Rev. v.99, 317, 2001

CR composition in superbubble model



Astron. Lett. v.27, p.625