Synchrotron X-ray structures in supernova remnants: particle acceleration probe

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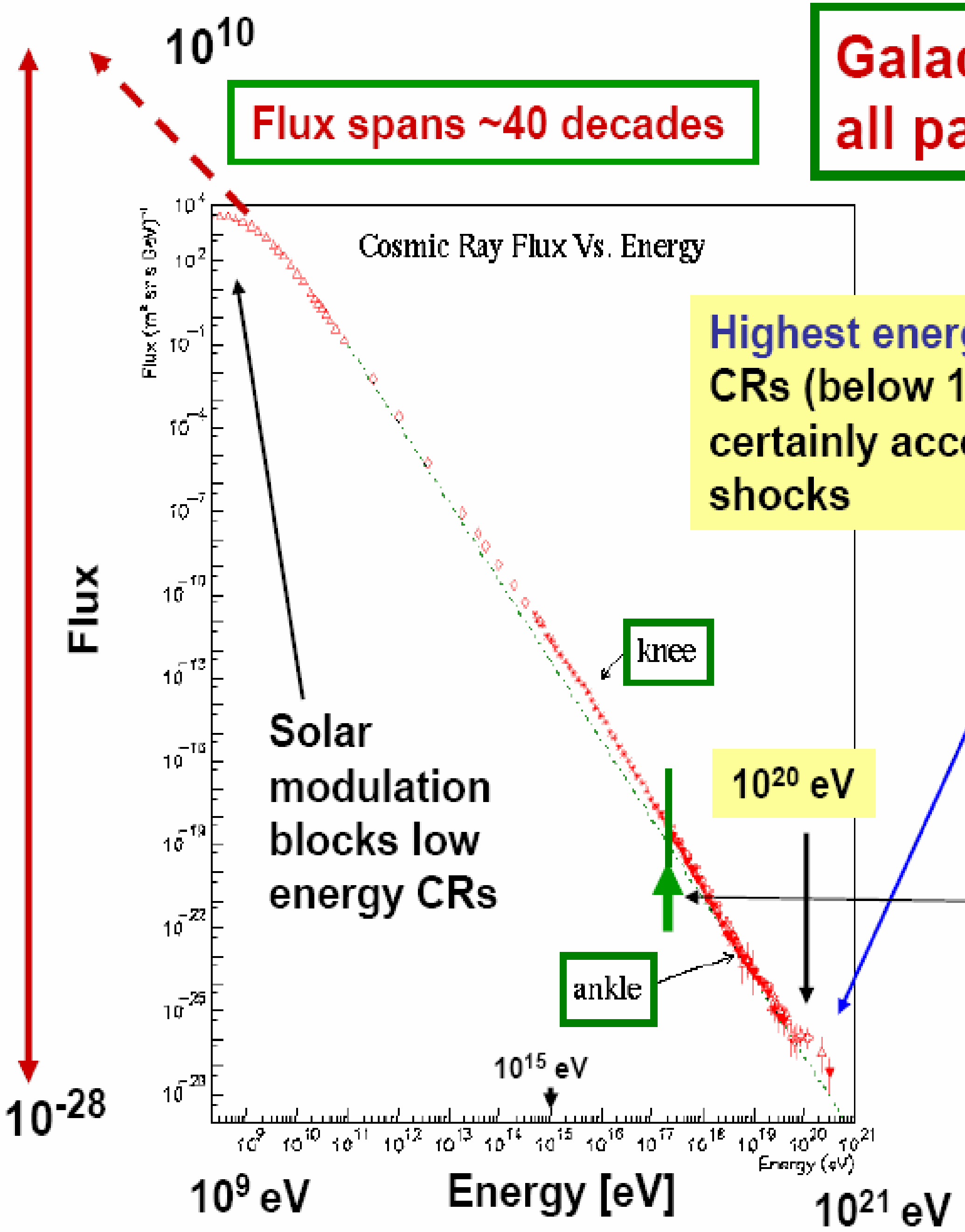
Some R&D in the fields founded by V.L.Ginzburg and S.I.Syrovatskii

Particle acceleration and the CR origin

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

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

Galactic Cosmic Ray all particle spectrum



Flux spans ~40 decades

Solar modulation blocks low energy CRs

Highest energy particles ever observed!
CRs (below 10^{15} eV at least) almost certainly accelerated in collisionless shocks

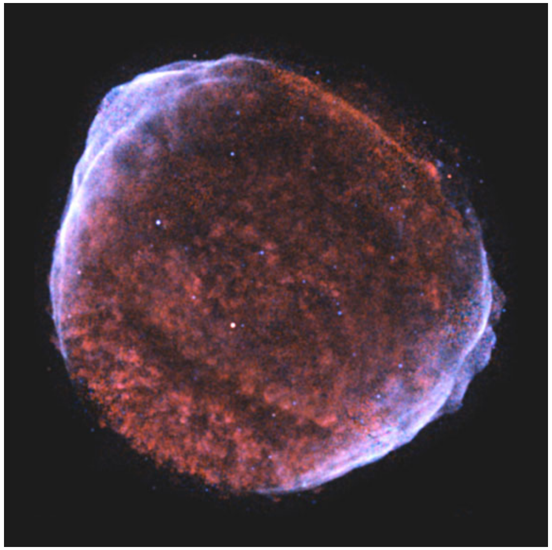
10^{20} eV

GRBs, extra-galactic radio jets, "strange" particles ???

LHC 10 TeV proton ~ 2 x 10^{17} eV cosmic ray energy

Hillas_Rev_CRs_JPhysG2005.pdf

Galactic cosmic-rays and SNR's



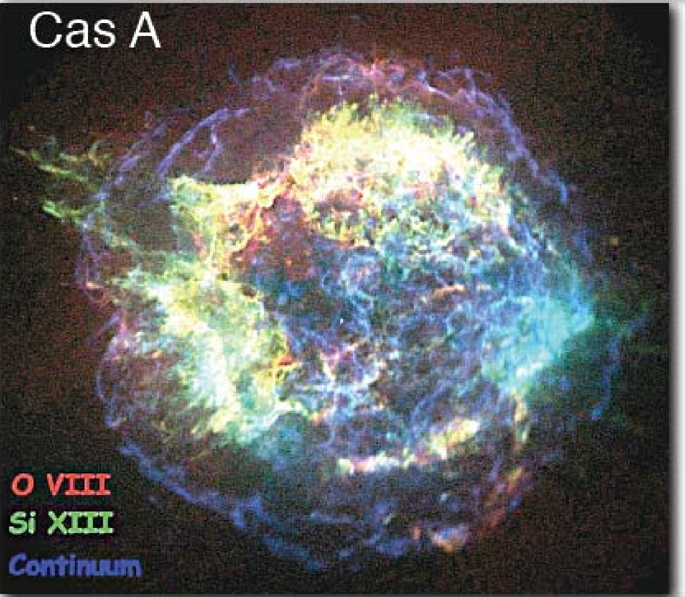
The power law, up to the "knee" at 10^{15} eV, is explained by diffusive shock acceleration at supernovae blast waves

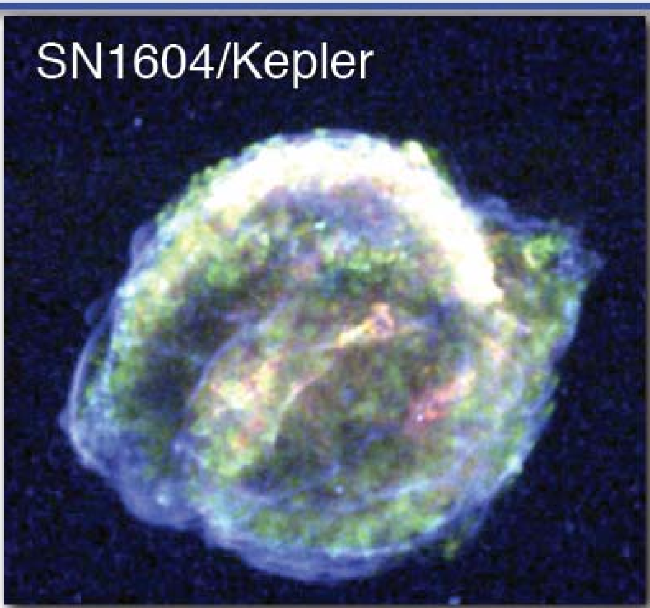
Lagage and Cesarsky estimated the maximum energy to be less than 10^{14} eV

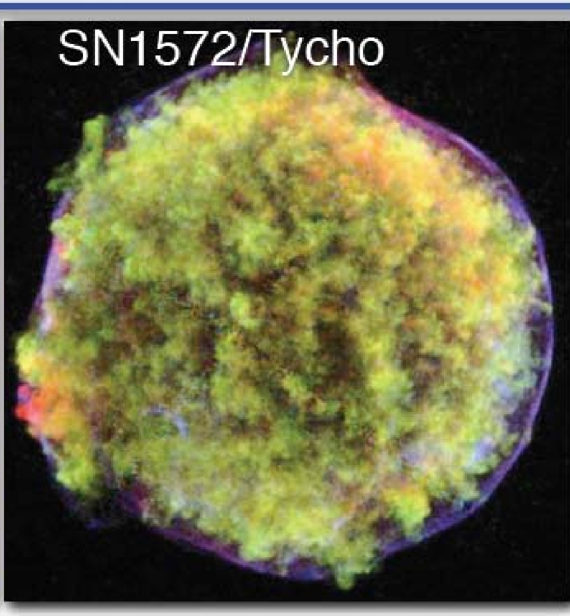
> assuming Bohm diffusion in a parallel shock geometry without magnetic field amplification

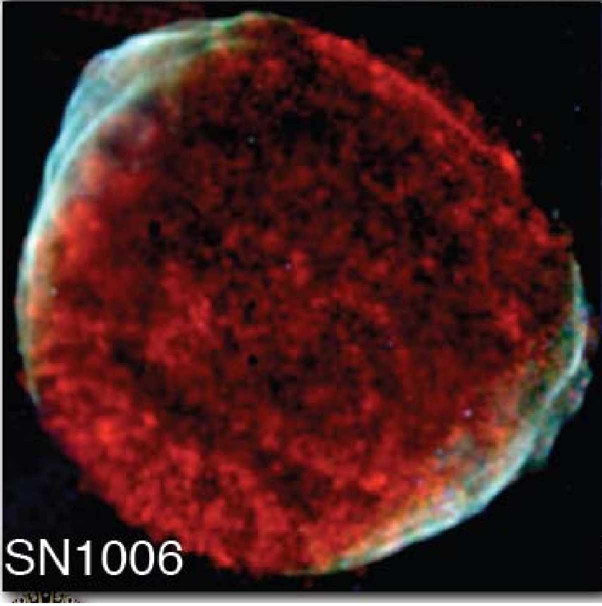
A higher maximum energy is expected for a *quasi-perpendicular* shock

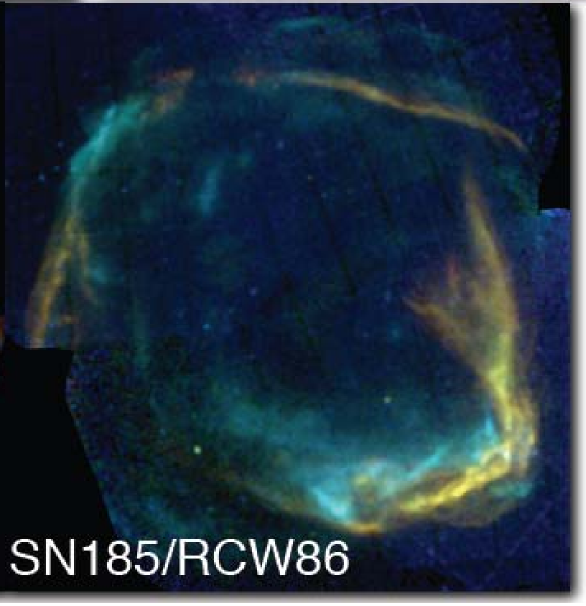
X-ray synchrotron & B-field amplification

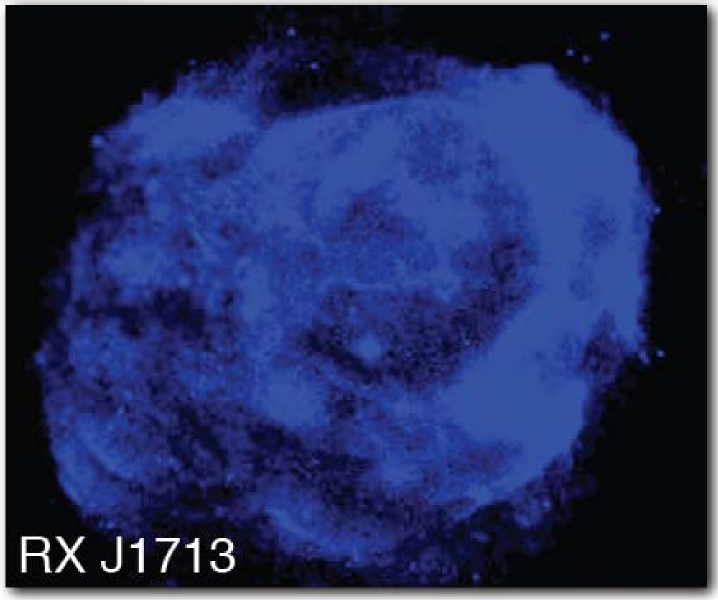

Cas A


SN1604/Kepler


SN1572/Tycho

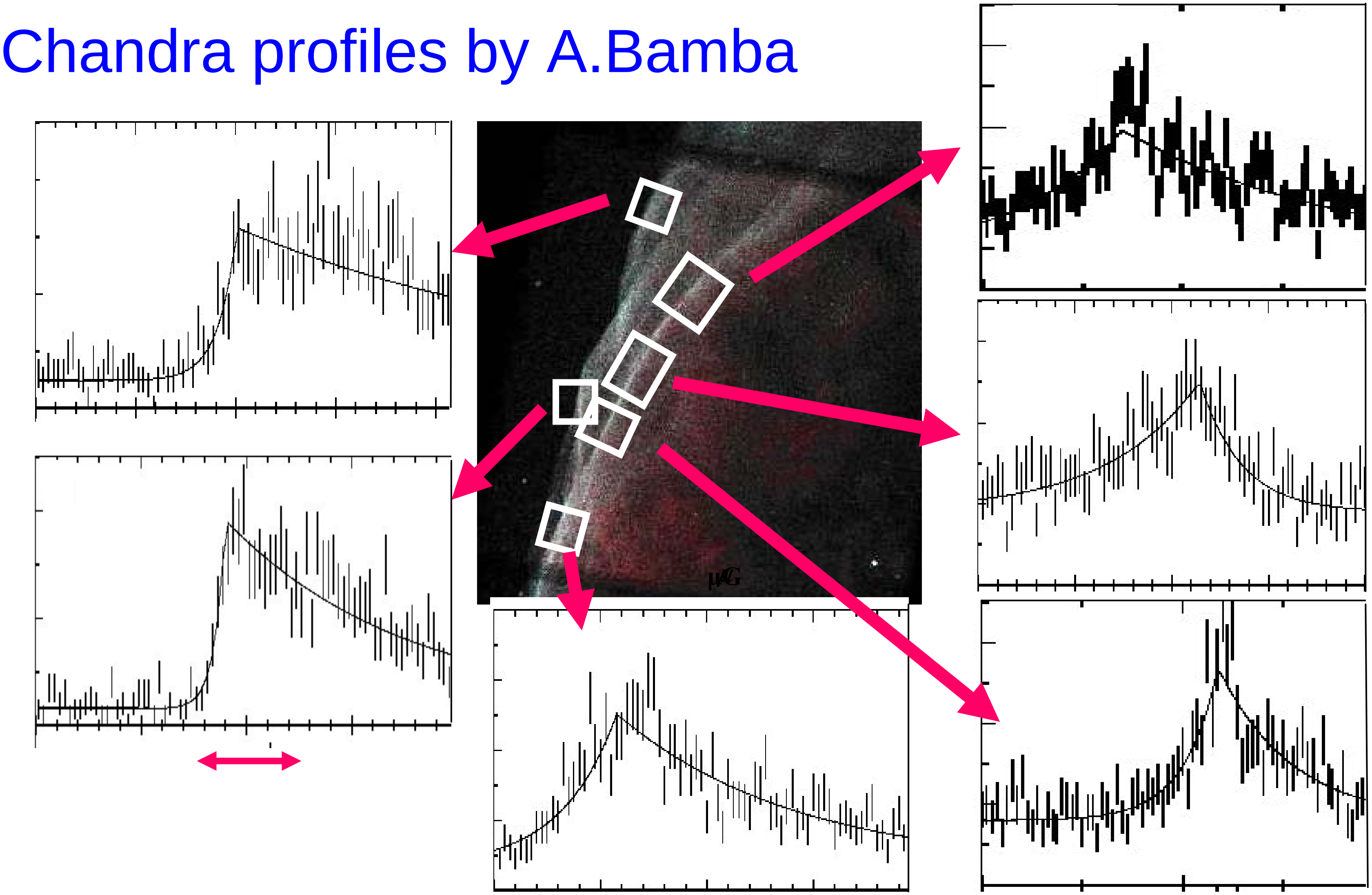

SN1006


SN185/RCW86


RX J1713

from Jacco Vink 2009

Chandra profiles by A.Bamba

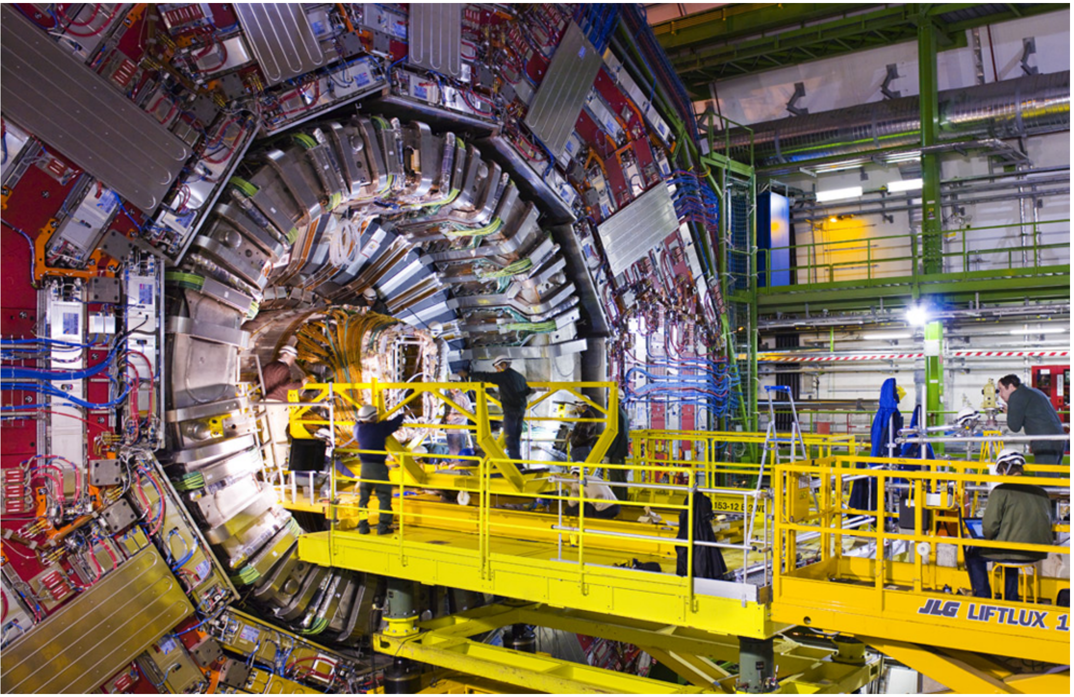


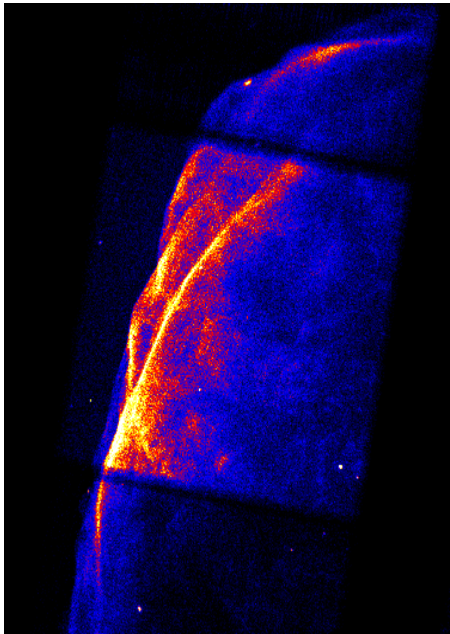
measurements of the width of synchrotron X-ray filaments ~ 0.01pc

STRONG MAGNETIC FIELD AMPLIFICATION > 20 μG

Electron energies >> 1 TeV

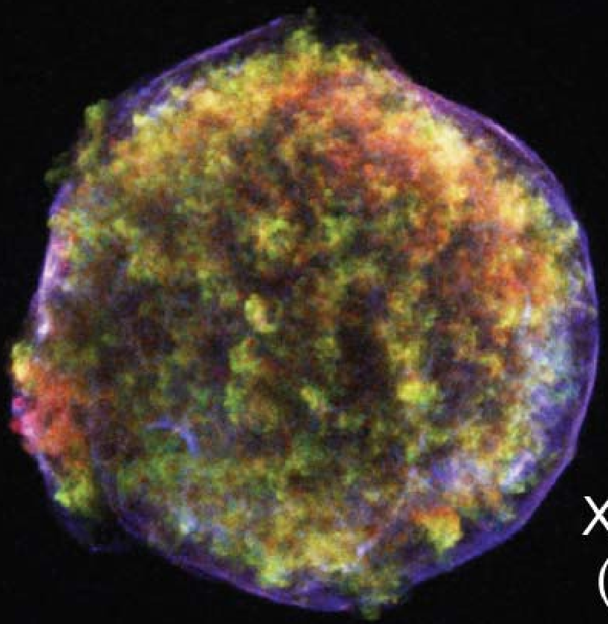
Particle accelerators – LHC– SN1006





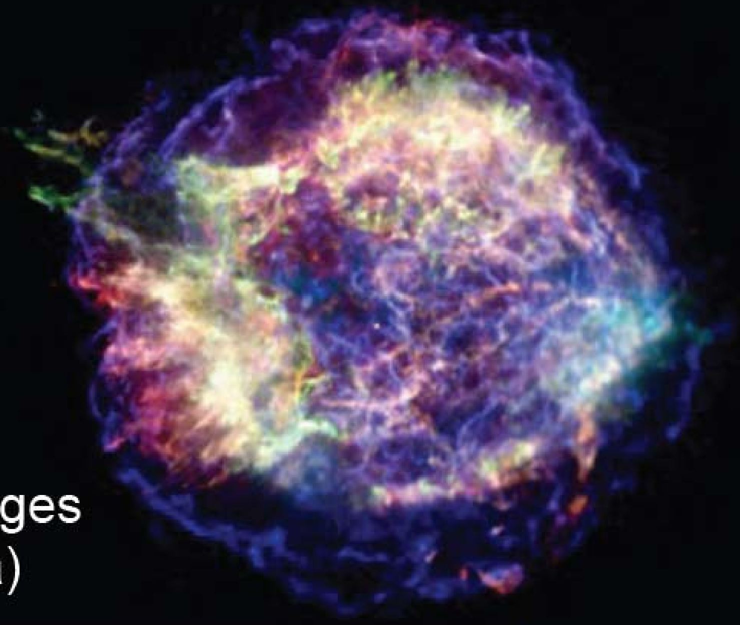
Tycho's SNR

- SN 1572
- SN type: Ia
- distance: ~3 kpc
- radius: ~3.7 pc



Cassiopeia A

- SN ~1680
- SN type: IIb
- distance: ~3.4 kpc
- radius: ~2.5 pc



X-ray Images
(Chandra)

Most parameters are reasonably well known.
→ largely help us interpret gamma-ray results.

TYCHONIS BRAHE DANI

DIE XXIV OCTOBRIS A. D. MDCI DEFUNCTI

OPERUM PRIMITIAS

DE NOVA STELLA

SUMMI CIVIS MEMOR

DENUO EDIDIT

REGIA SOCIETAS SCIENTIARUM DANICA

INSUNT EFFIGIES ET MANUS SPECIMEN TYCHONIS

HAUNIÆ
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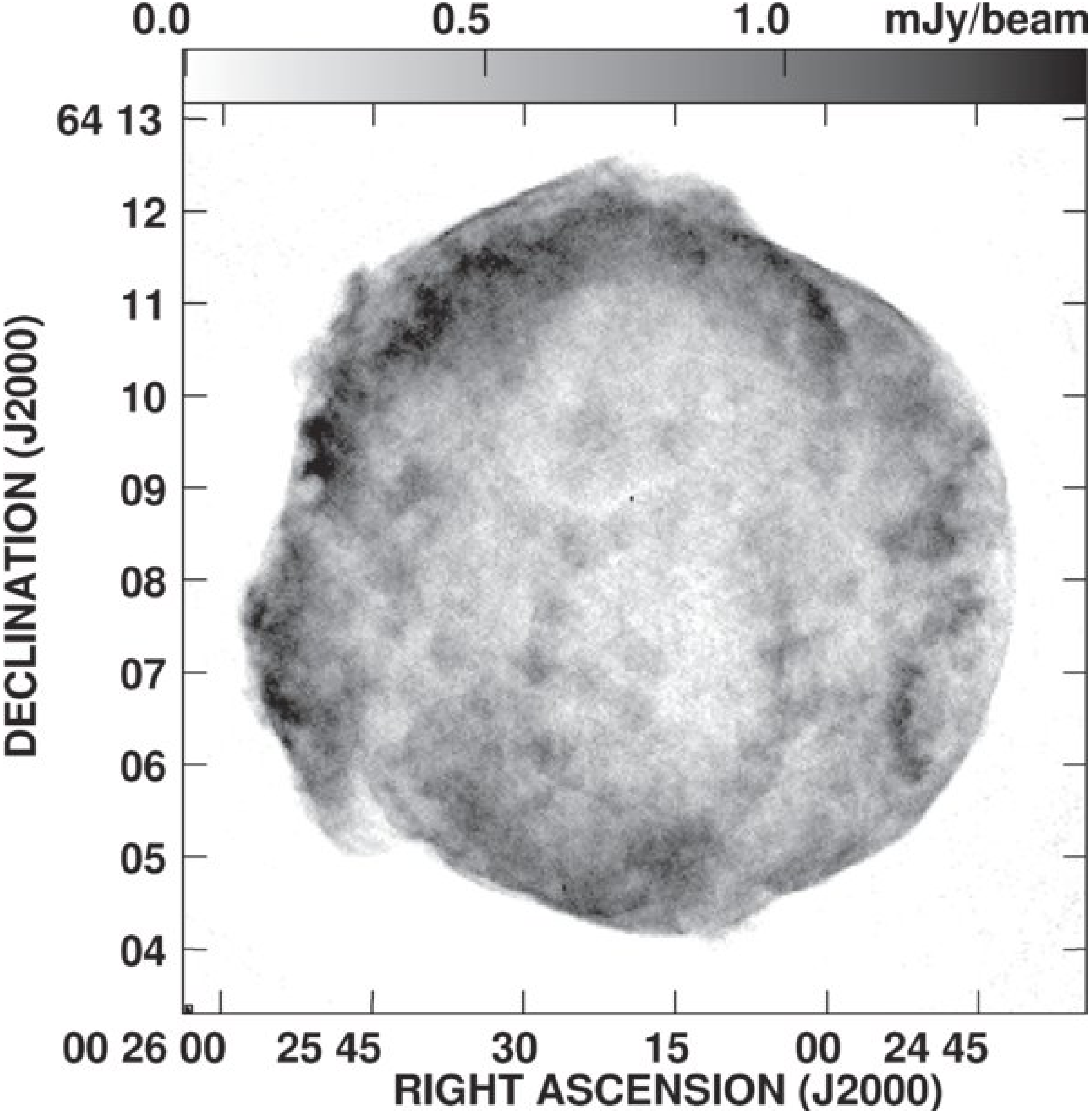
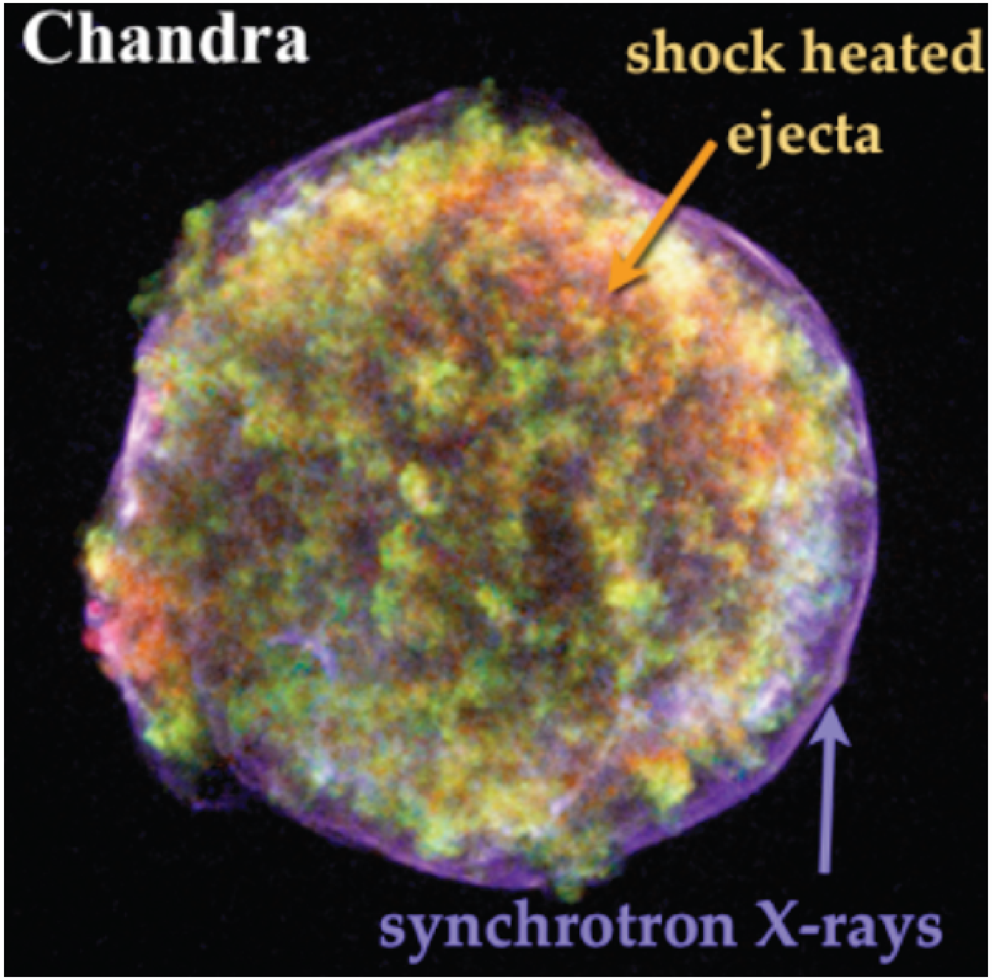
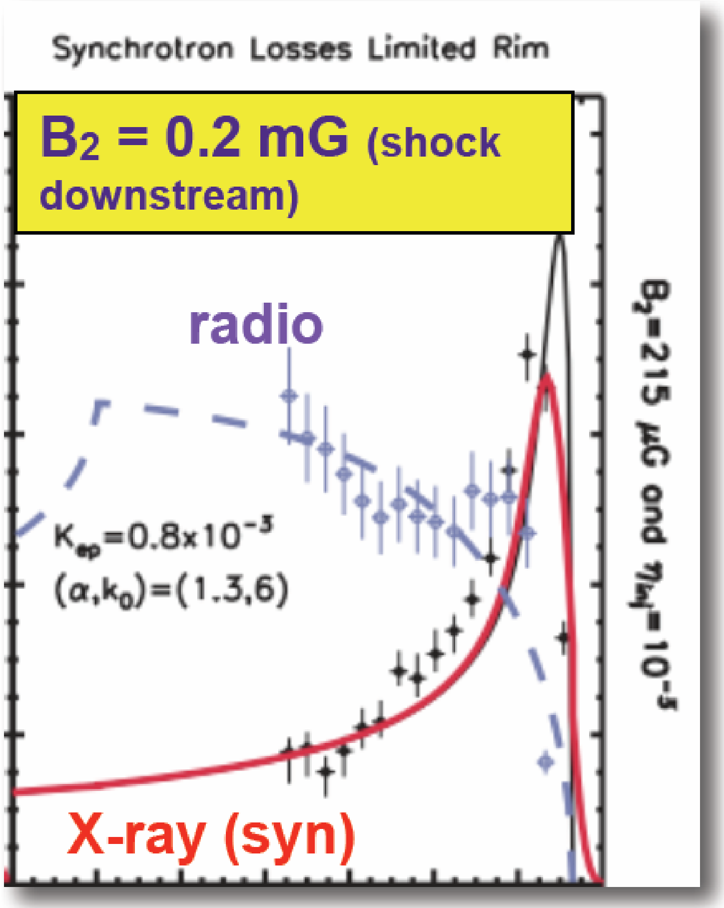

0.0
0.5
1.0
mJy/beam
64 13
12
11
10
09
08
07
06
05
04
DECLINATION (J2000)
00 26 00
25 45
30
15
00
24 45
RIGHT ASCENSION (J2000)

Radio VLA

Warren+05



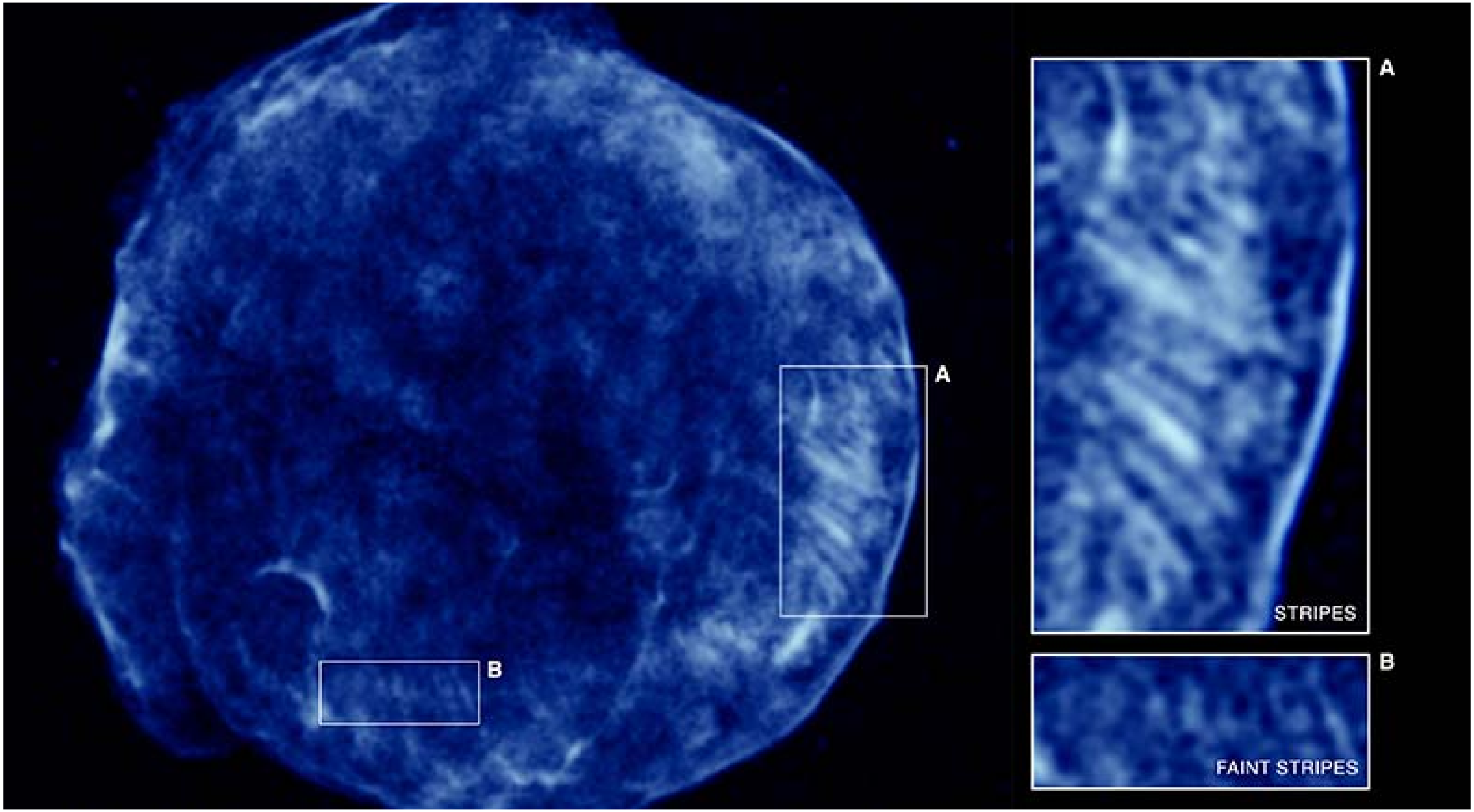
X-ray/radio radial profile



Cassam-Chenai+07

B_2 = 0.1-0.2 mG is inferred from the width of X-ray filaments

Chandra 4-6 keV Image of Tycho's SNR



Eriksen + 2011

Tycho: New GeV Detection

Fermi-LAT Detection (5σ)

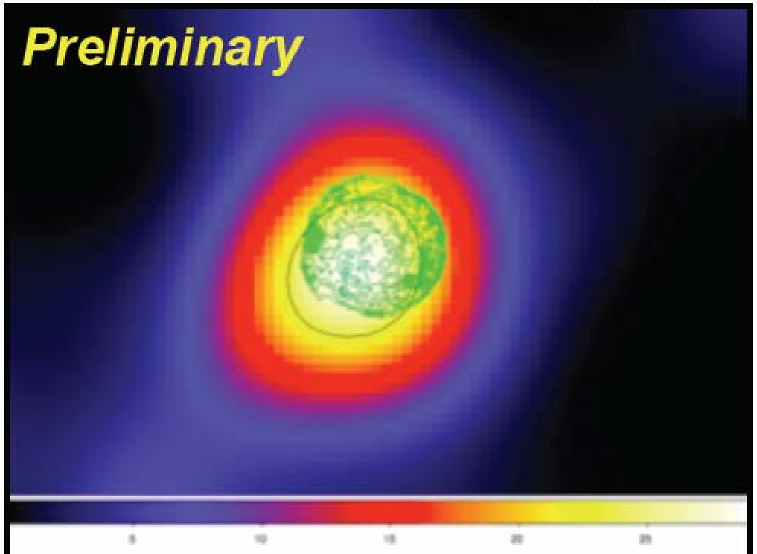
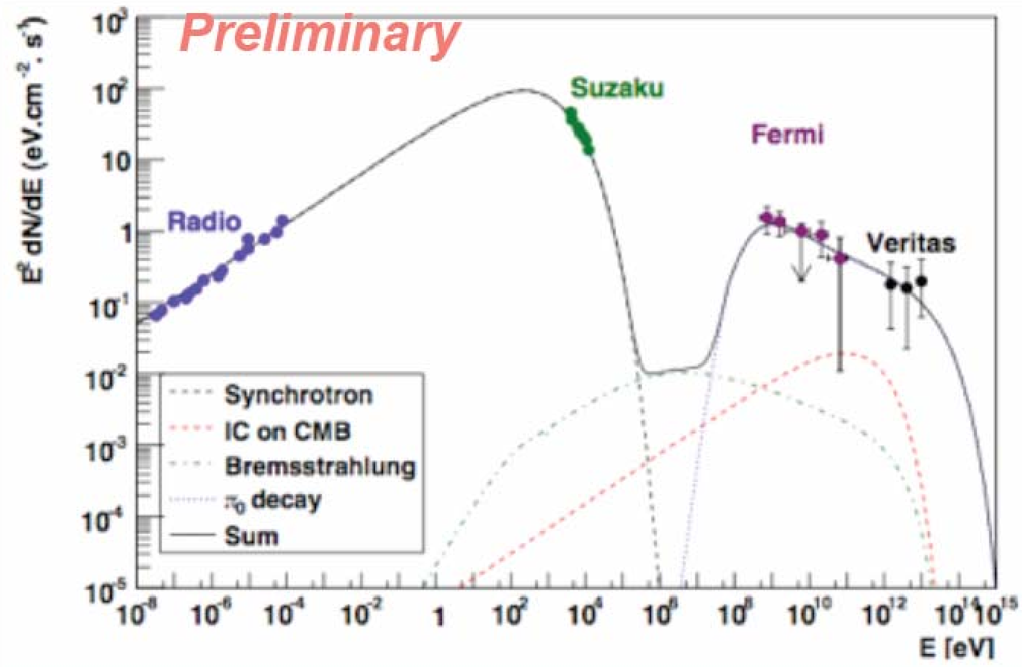


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*

See a poster by Fermi-LAT Collaboration (Naumann-Godo+)



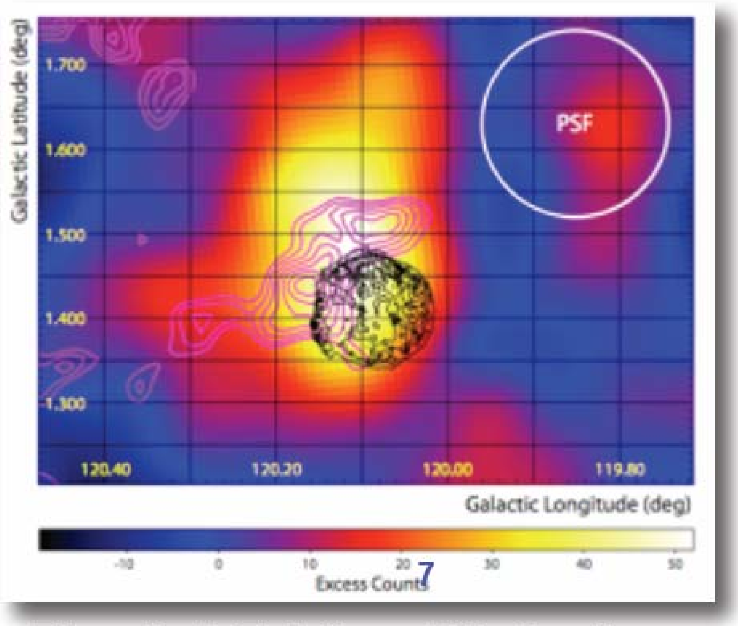
Case	D_{kpc}	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{51}erg]	K_{ep}
Far	3.50	0.24	2.0	0.150	4.5×10^{-4}
Nearby	2.78	0.30	1.0	0.061	7.0×10^{-4}

Photon index = 2.3 ± 0.1 (favors hadronic origin)

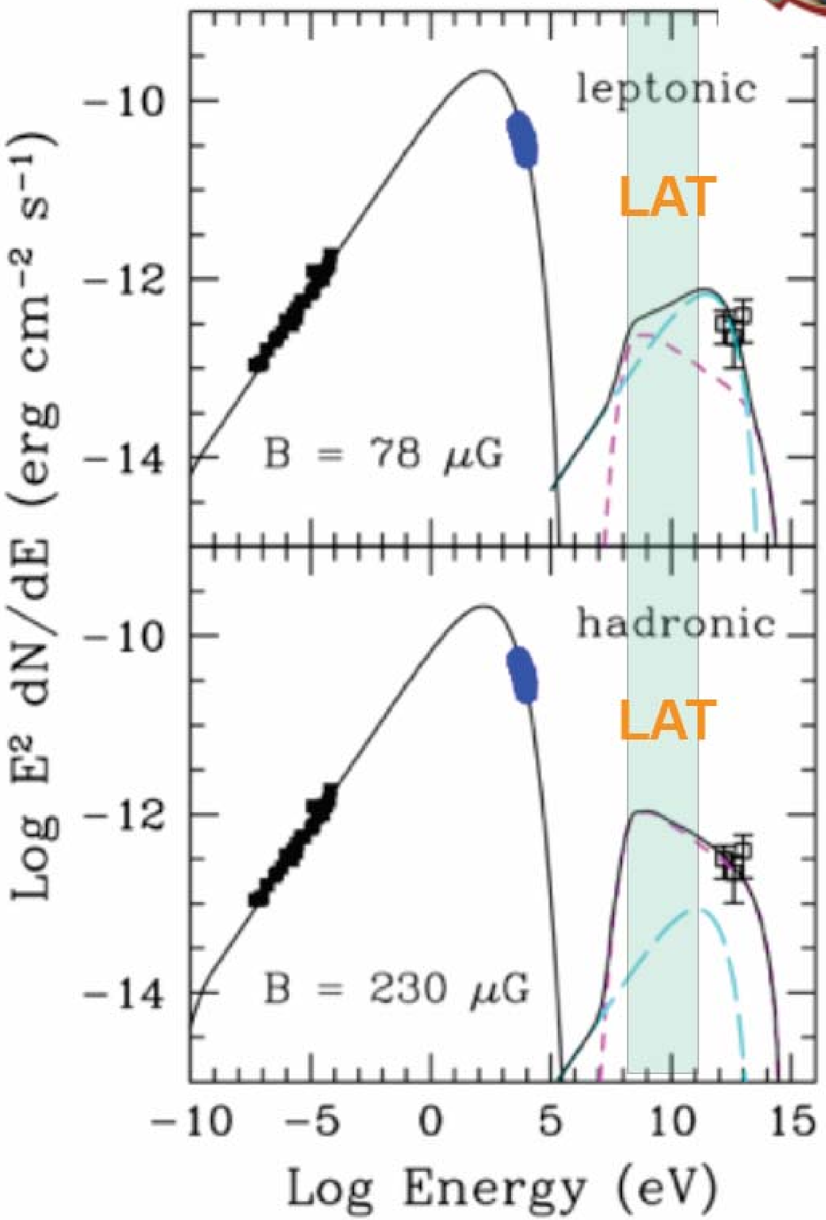
6-8% of E_{SN} transferred to CRs.

Tycho: Recent TeV Detection

VERITAS Collaboration (2011)



Flux(>1 TeV) ~ 1% Crab
5.0σ detection (post-trial)



B-field constraint put by X-ray does *not* contradict IC origin.

Fermi-LAT can test "leptonic vs hadronic"

Ultra-relativistic Particle Acceleration in collisionless shocks by Fermi mechanism

CR-current modified MHD waves

act as converging mirrors

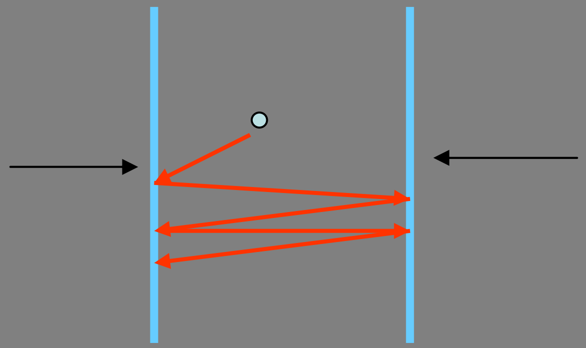
→ particles are scattered by waves

→ cross the shock many times

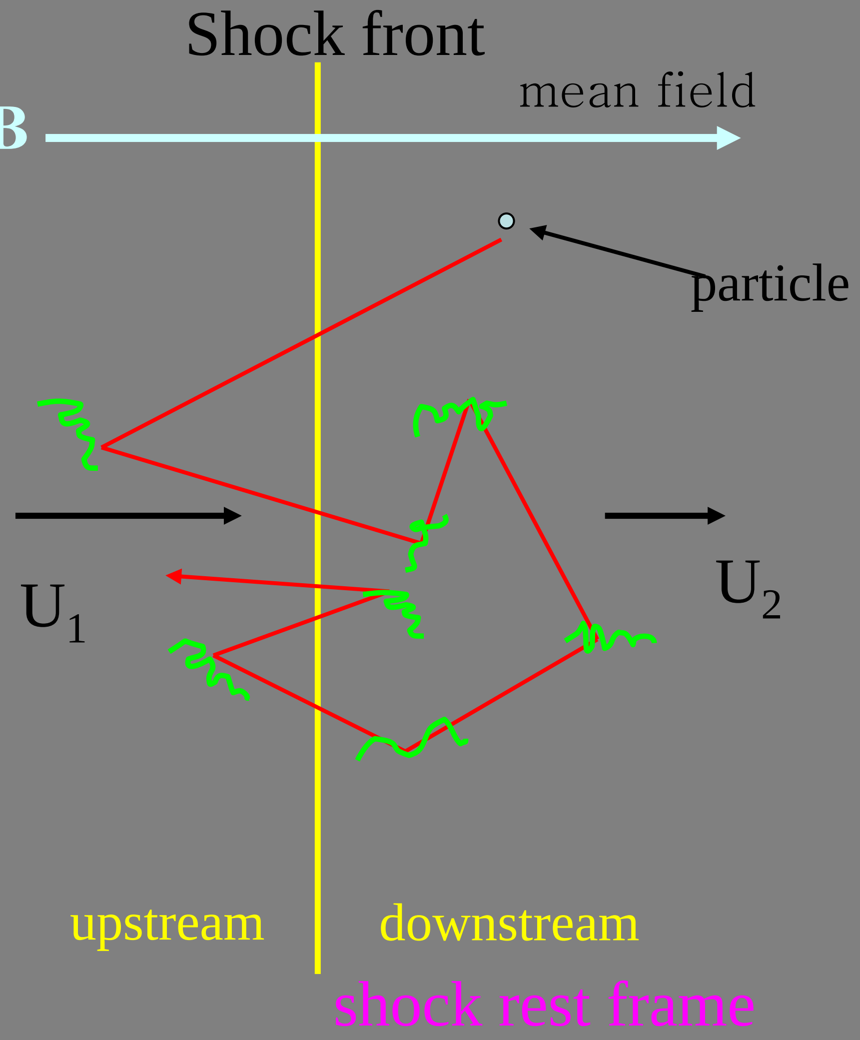
“ Fermi first order process”

$$\frac{\Delta p}{p} \sim \frac{U_s}{v}$$ **energy gain at each crossing**

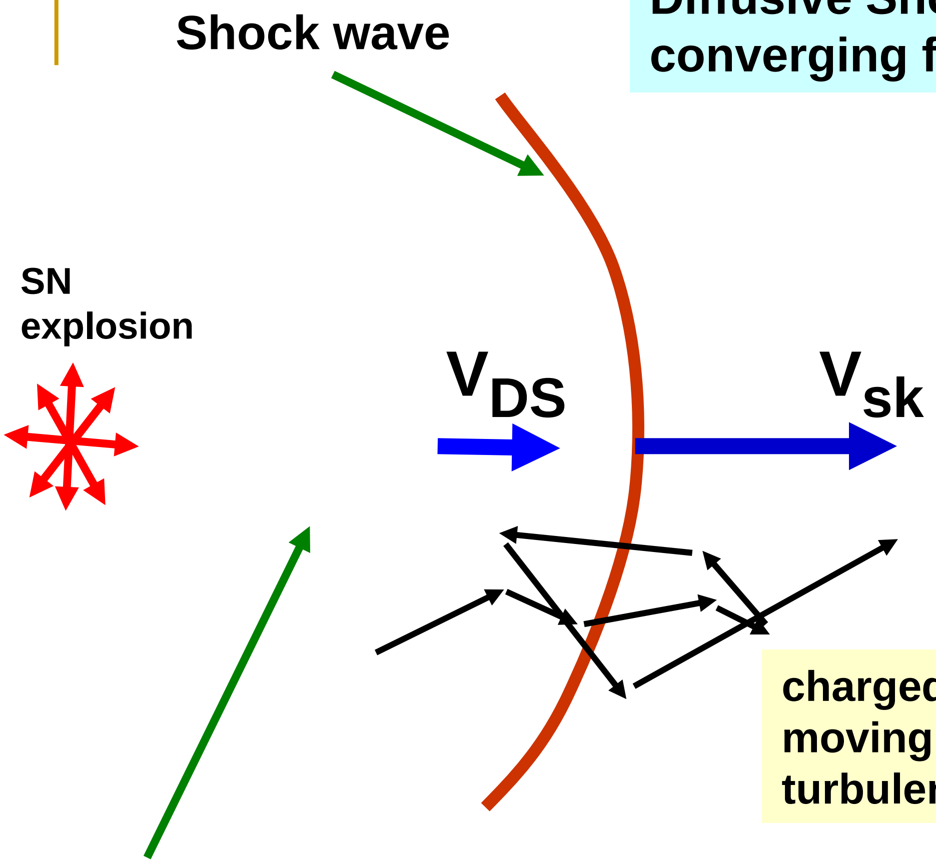
$$v \approx c$$



Converging mirrors



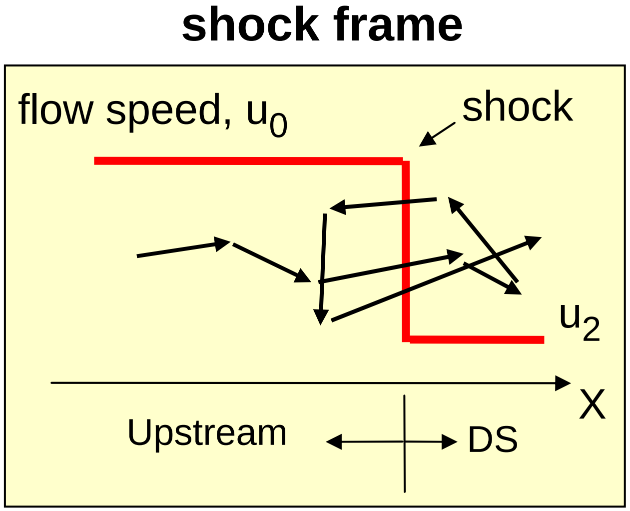
Diffusive Shock Acceleration: Shocks set up converging flows of ionized plasma



Interstellar medium (ISM), cool with speed $V_{ISM} \sim 0$

charged particle moving through turbulent B-field

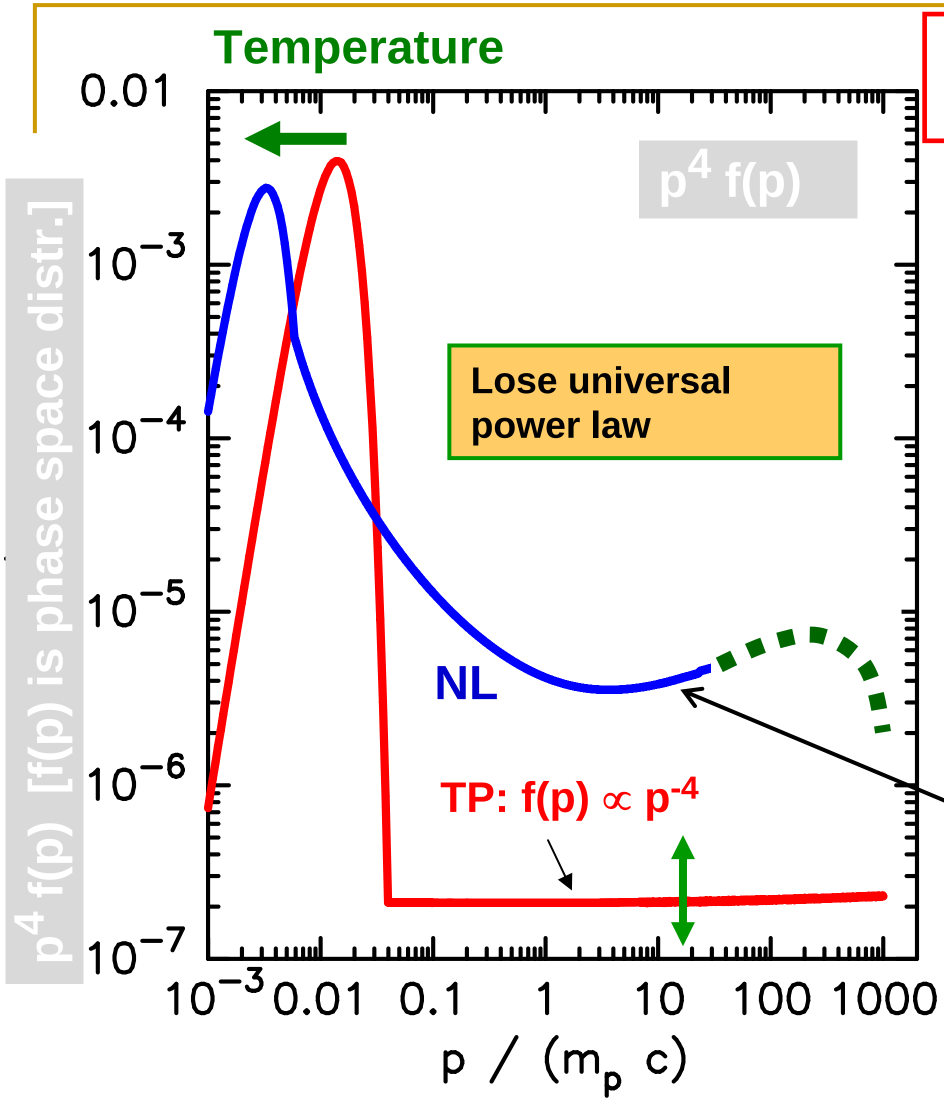
Post-shock gas → Hot, compressed, dragged along with speed $V_{DS} < V_{sk}$



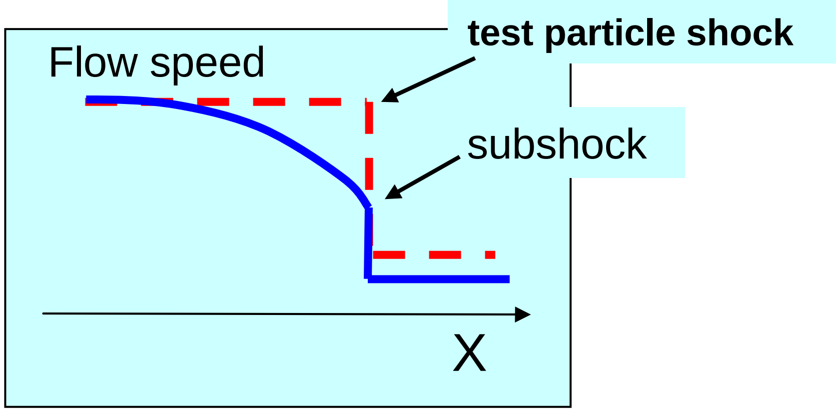
$u_2 = V_{sk} - V_{DS}$

Particles make nearly elastic collisions with background plasma ➔ gain energy when cross shock ➔ bulk kinetic energy of converging flows put into individual particle energy

If acceleration is efficient, shock becomes smooth from backpressure of CRs



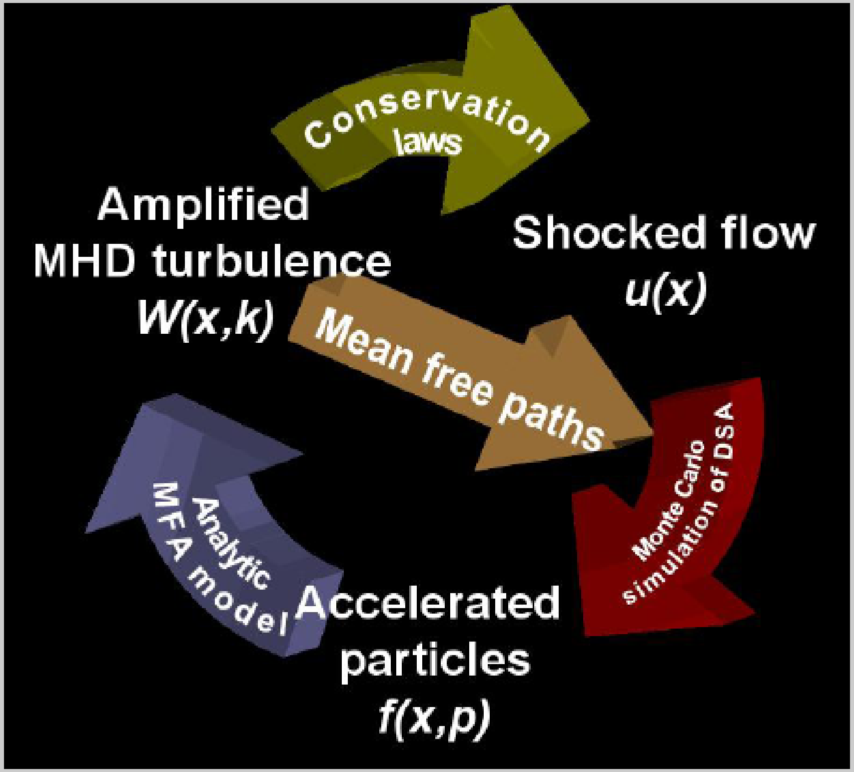
Lose universal power law



- **Concave spectrum**
- **Compression ratio, $r_{tot} > 4$**
- **Low shocked temp. $r_{sub} < 4$**

In efficient acceleration, <u>entire particle spectrum</u> must be described consistently, including escaping particles ➔ much harder mathematically BUT, connects photon emission across spectrum from radio to γ-rays

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.

Method

The Nonlinear Model

- Particle transport modeled with a **Monte Carlo simulation**;
- **Analytic, semi-phenomenological description** for magnetic field amplification, self-consistently coupled to CR distribution and MHD flow;
- Fundamental **conservation laws** used to iteratively derive a nonlinear shock modification that conserves mass, momentum and energy;

Reasoning

- We describe a **large dynamic range** in turbulence scales and particle energies;
- Elements of the model **tested** against spacecraft observations of heliospheric shocks;
- Works for highly **anisotropic** particle distributions (particle escape and injection; large gradients of u and B).
- Ability to incorporate **non-diffusive** particle transport (future work).

Evolution of Waves in the Precursor

Definitions

We describe turbulence by $W(x,k)$ – spectral energy density of turbulent fluctuations, and separate it into

$$W = W_M + W_K = \sum_{i \in \mathrm{modes}} W_M^{(i)} + \sum_{i \in \mathrm{modes}} W_K^{(i)}.$$

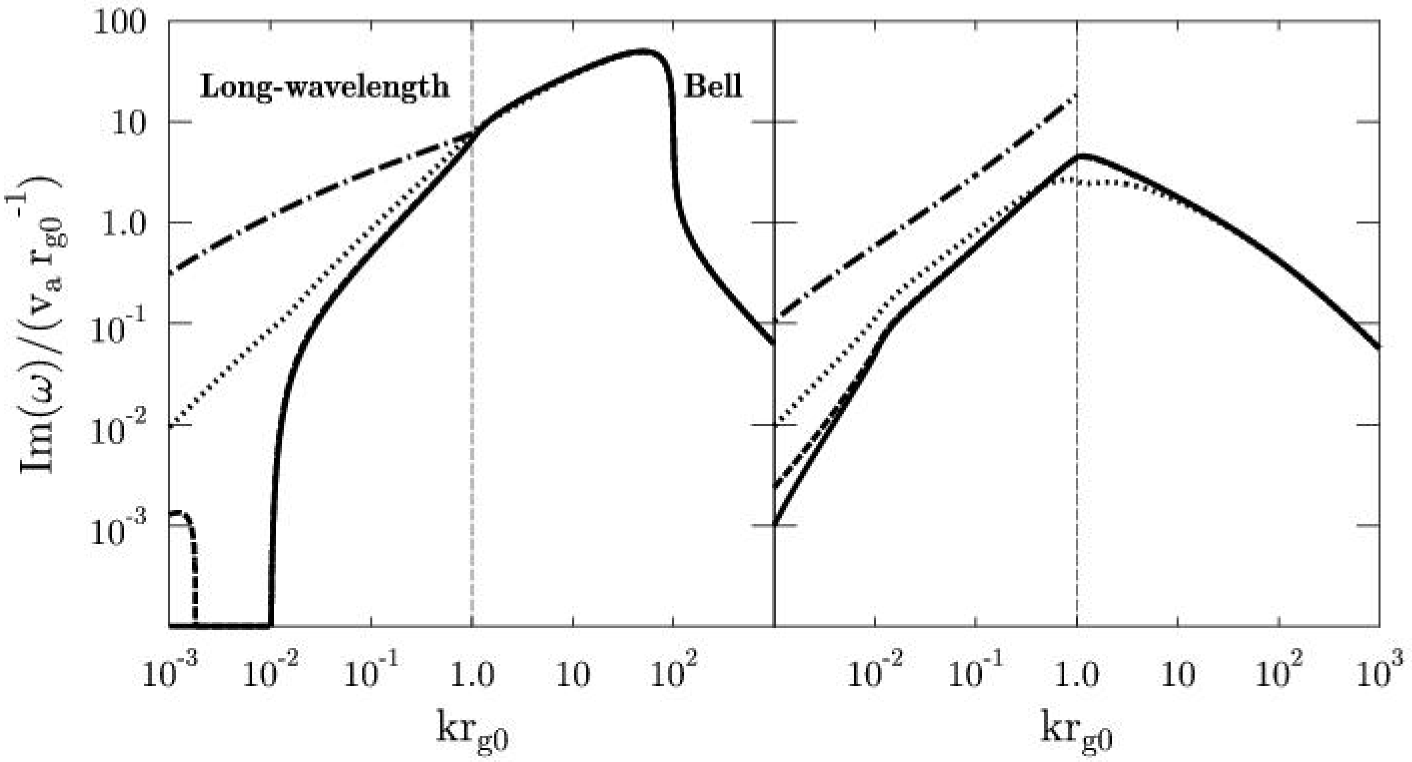
W_M – magnetic fluctuations, W_K – associated plasma velocity fluctuations, and (i) runs over the three types of waves (A – Alfvén waves, B – Bell's modes, C – [redacted]'s modes).

Equations

Evolution for each mode is given by the equation for $W^{(i)} = W_M^{(i)} + W_K^{(i)}$:

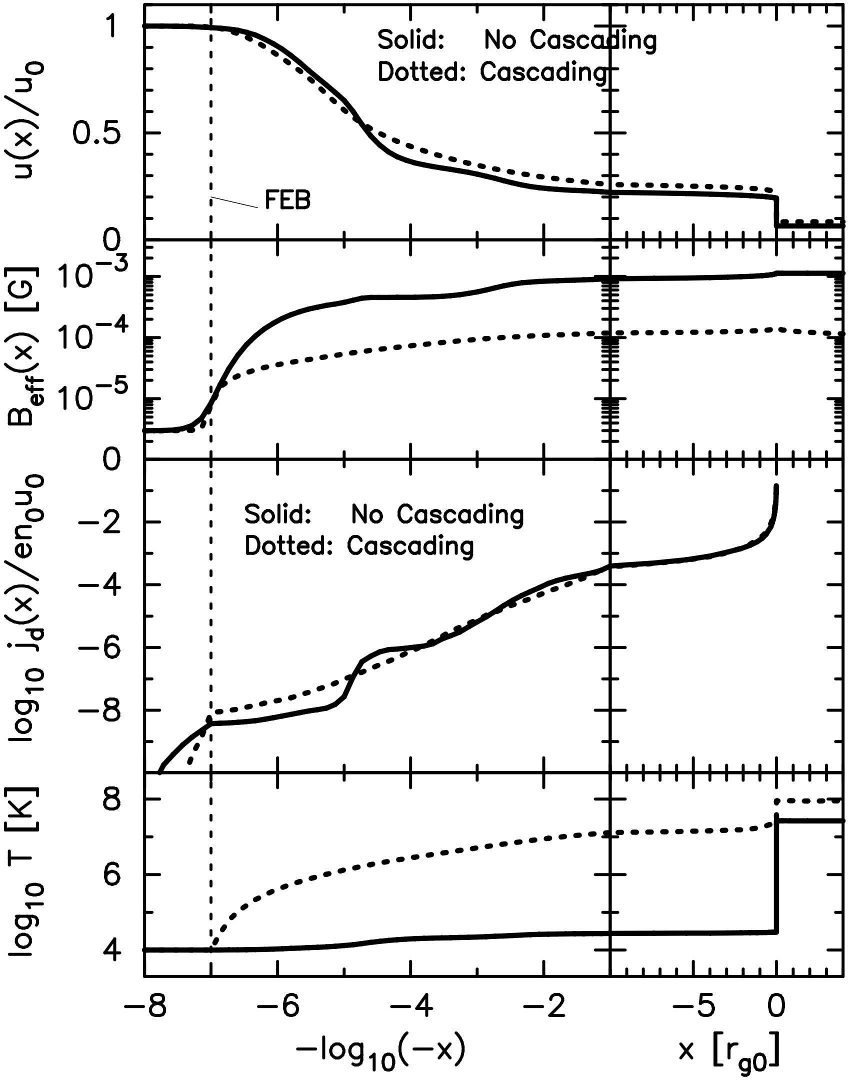
$$u\frac{\partial W^{(i)}}{\partial x} = \gamma^{(i)} W^{(i)} - L^{(i)} + \left[-\alpha^{(i)} W^{(i)} + \frac{\partial}{\partial k}\left(k W^{(i)}\right) \right] \frac{du}{dx} - \frac{\partial \Pi^{(i)}}{\partial k} \qquad (1)$$

CR driven modes



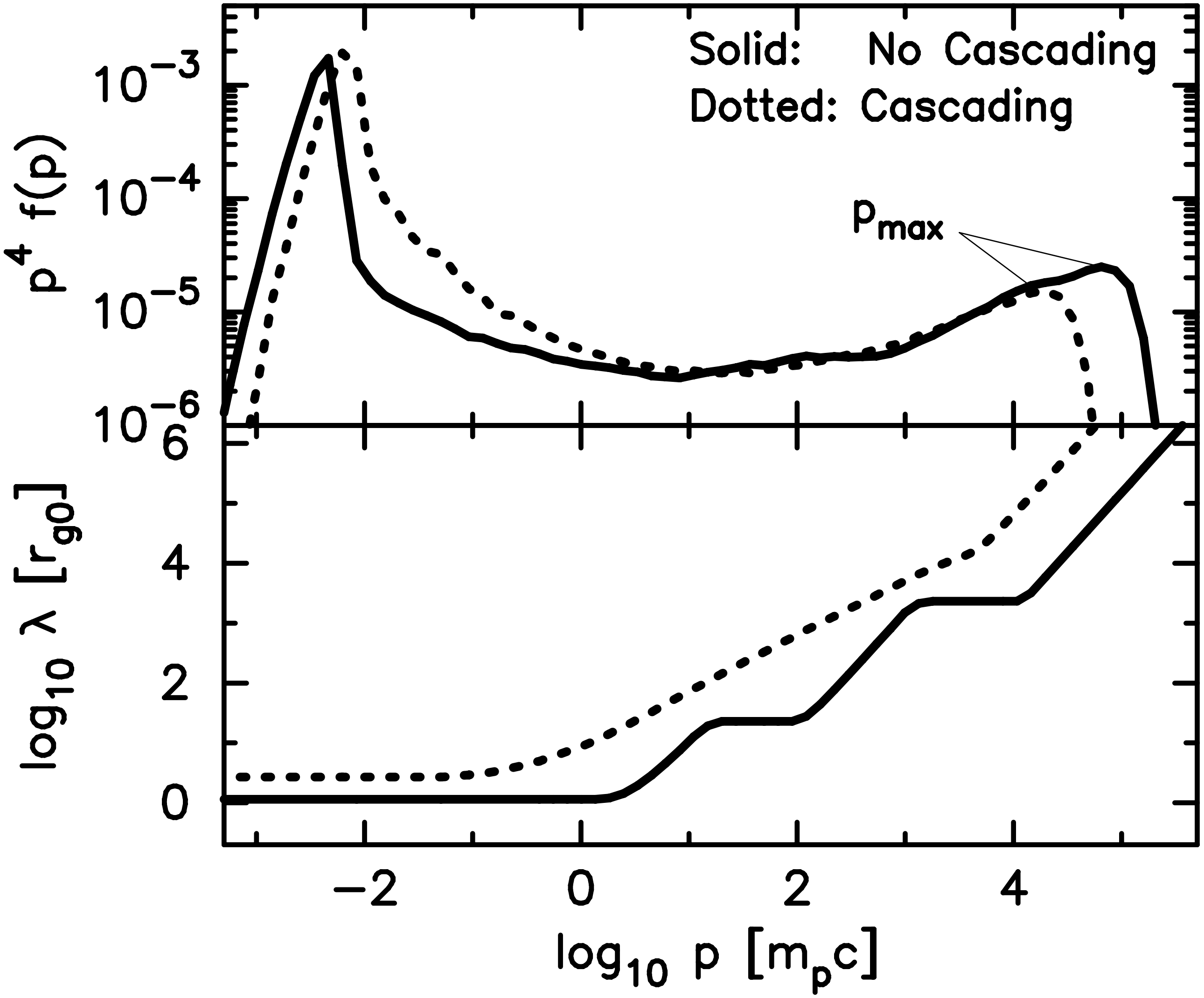
Kulsrud 69, Bell' 04, AB+05, Marcowith+ 06, Zirakashvili & Ptuskin 08, AB+11

CR modified shock

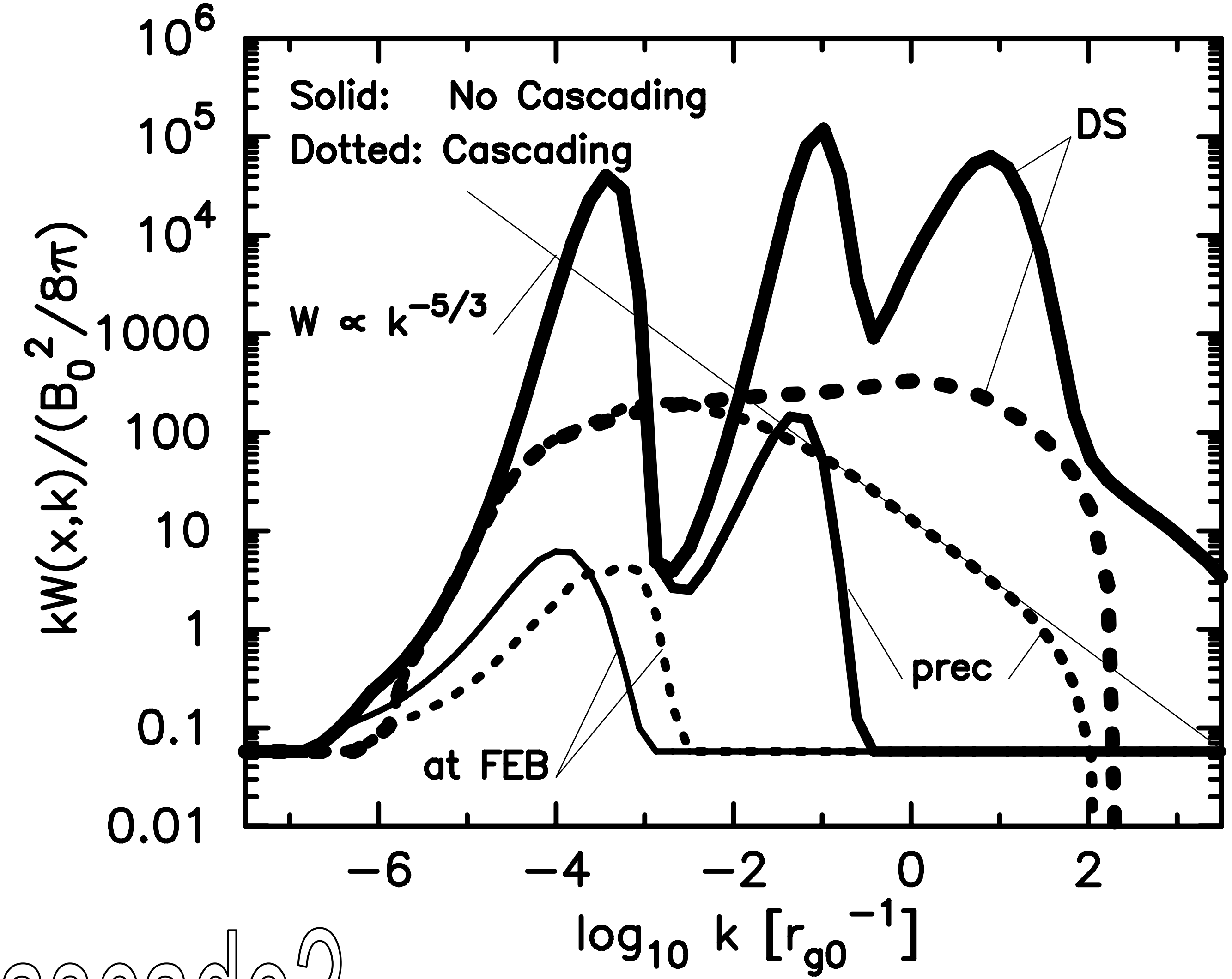


- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

Particle Spectra



Magnetic Fluctuation Spectra



No cascade?

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

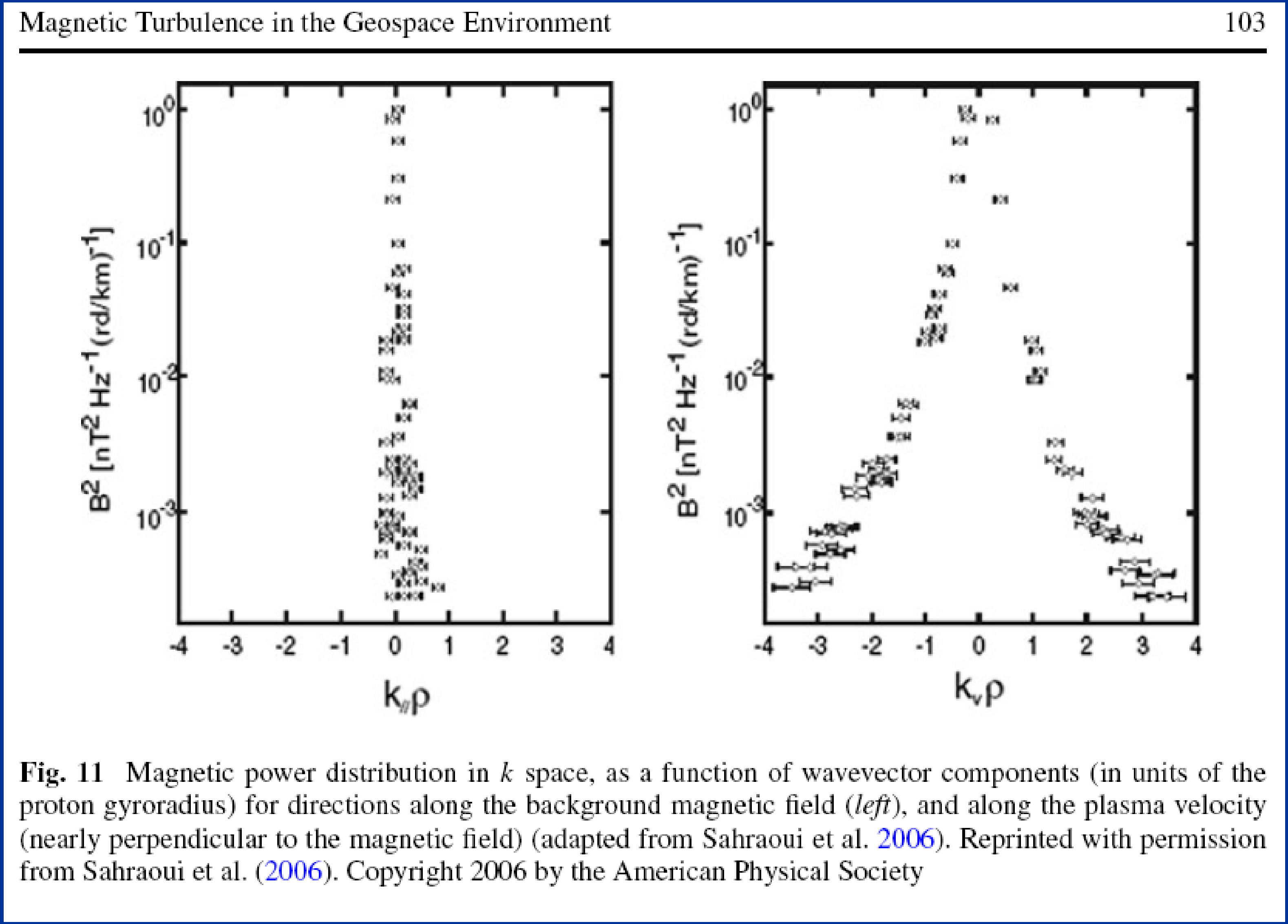
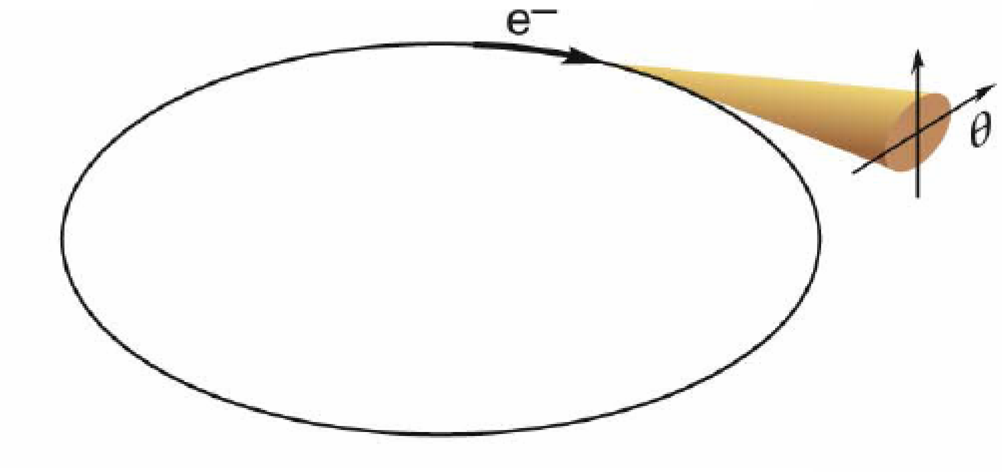


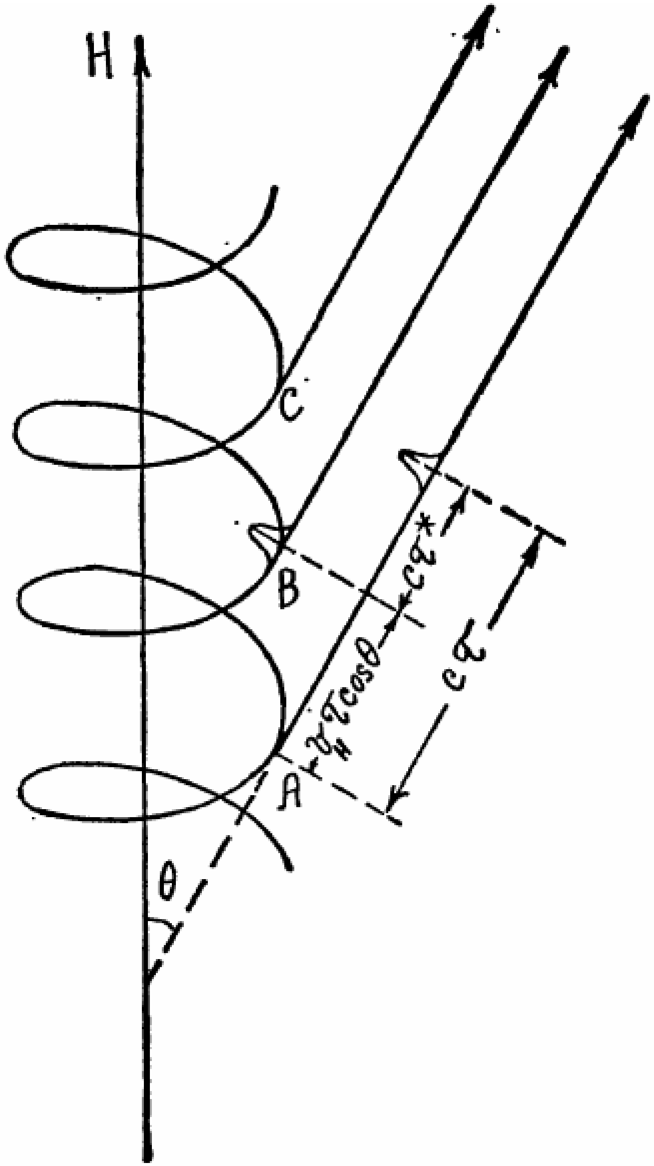
Fig. 11 Magnetic power distribution in k space, as a function of wavevector components (in units of the proton gyroradius) for directions along the background magnetic field (*left*), and along the plasma velocity (nearly perpendicular to the magnetic field) (adapted from Sahraoui et al. 2006). Reprinted with permission from Sahraoui et al. (2006). Copyright 2006 by the American Physical Society

Zimbardo + 2010

No parallel cascade…

Synchrotron Radiation:





e.g. Ginzburg and Syrovatskii 1969

The Synchrotron radiation is polarized

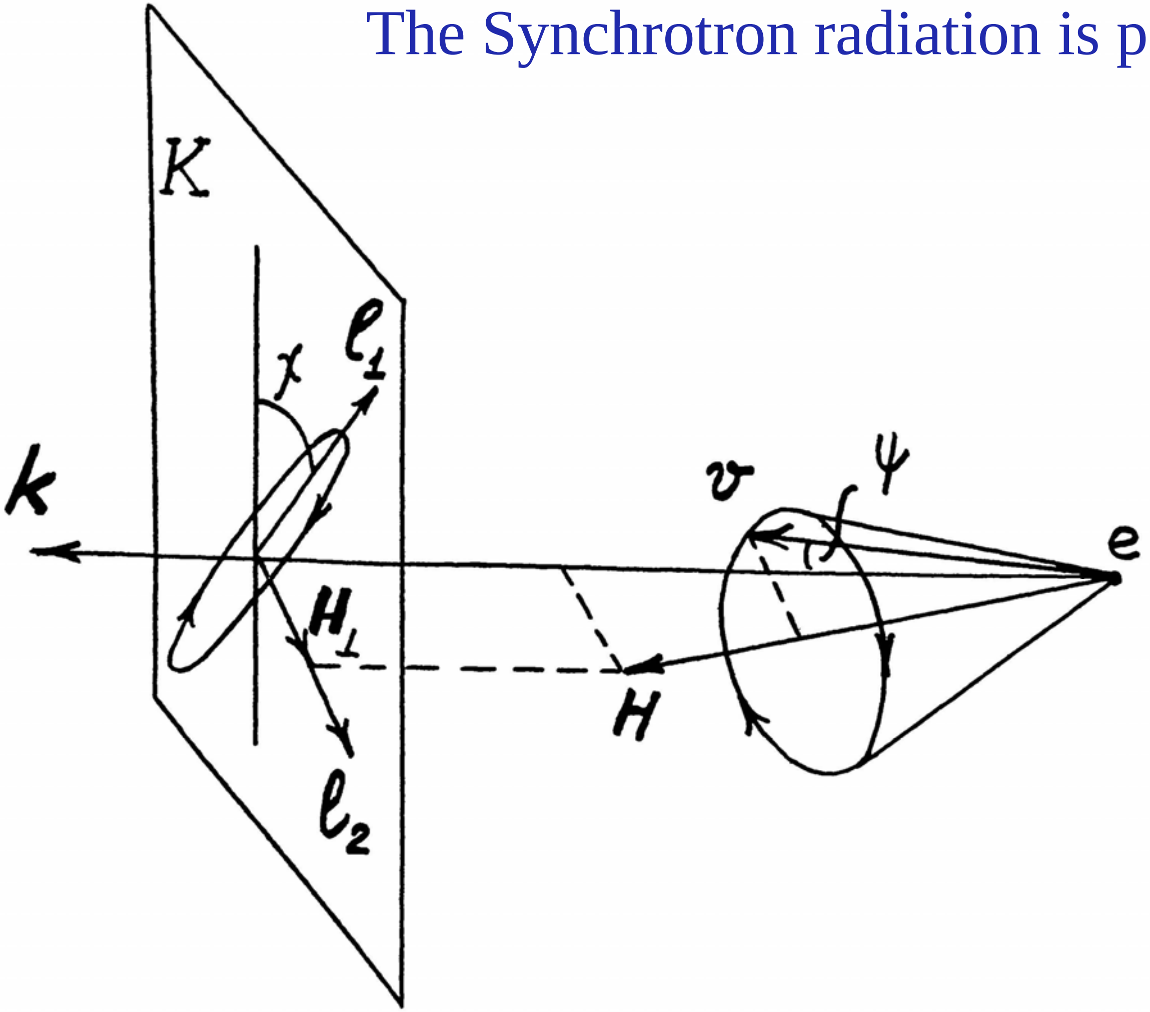


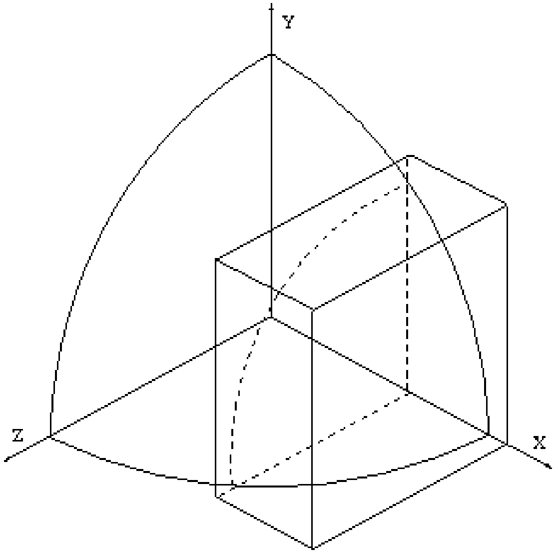
FIG. 5. Oscillation ellipse of the electric vector in a wave radiated by particles moving in a magnetic field, where the charge is taken as a positive. For negatively charged particles (electrons) the direction of rotation is opposite to that shown. The plane K is the plane of the figure (the plane perpendicular to the direction of the radiation or, equivalently, to the direction of the observer), and $\boldsymbol{l}_1$ and $\boldsymbol{l}_2$ are two mutually orthogonal unit vectors in the plane of the figure, of which $\boldsymbol{l}_2$ is directed along the projection of the magnetic field $\boldsymbol{H}$ on the plane K.

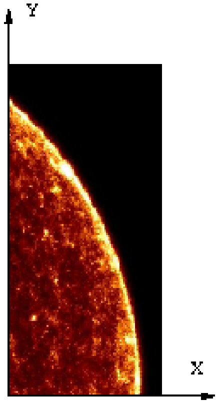
Synchrotron Radiation Stockes Parameters:

$$\hat{\hat{S}} = \begin{pmatrix} \tilde{I}(\mathbf{r},t,\nu) \\ \tilde{Q}(\mathbf{r},t,\nu) \\ \tilde{U}(\mathbf{r},t,\nu) \\ \tilde{V}(\mathbf{r},t,\nu) \end{pmatrix} = \begin{pmatrix} p_\nu^{(1)} + p_\nu^{(2)} \\ (p_\nu^{(1)} - p_\nu^{(2)}) \cdot \cos 2\chi \\ (p_\nu^{(1)} - p_\nu^{(2)}) \cdot \sin 2\chi \\ (p_\nu^{(1)} - p_\nu^{(2)}) \cdot \tan 2\beta \end{pmatrix}$$

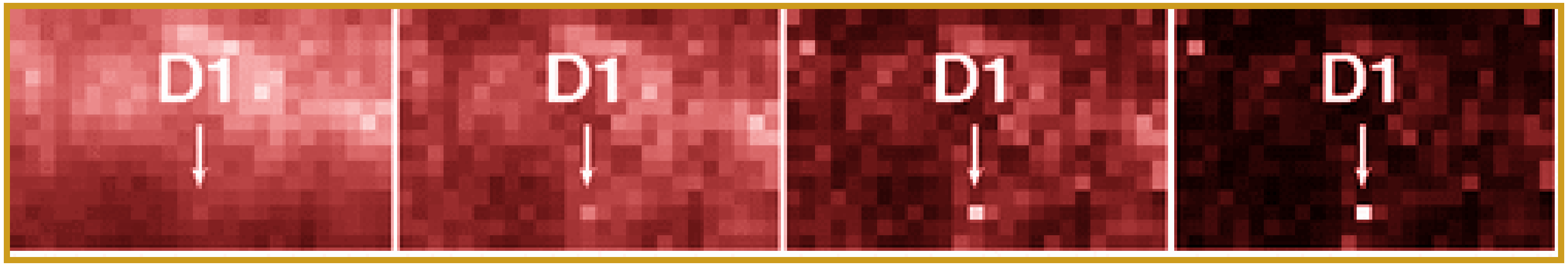
$$\hat{S}(\mathbf{R}_\perp, t, \nu) = \int dl\, d\gamma\, N(\mathbf{r}, \gamma, t')\, \hat{\hat{S}}(\mathbf{r}, t', \nu, \gamma), \quad t' = t - |\mathbf{r} - \mathbf{R}_\perp|/c.$$

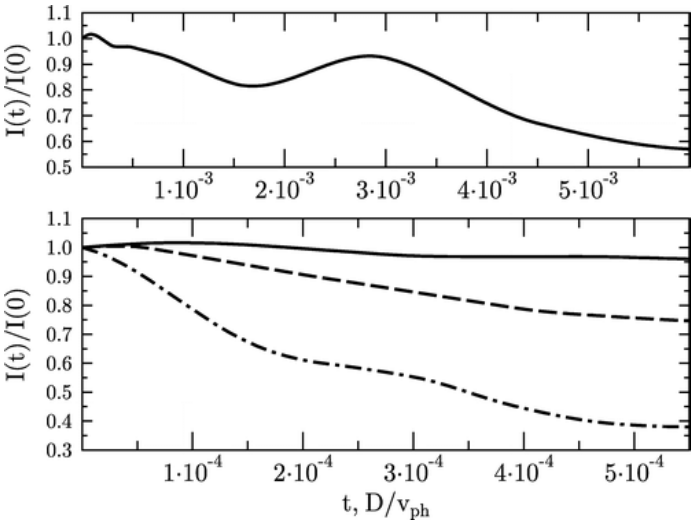
To construct the synchrotron emission image we simulated stochastic magnetic field in a SNR shell





Time evolution. Lightcurves.

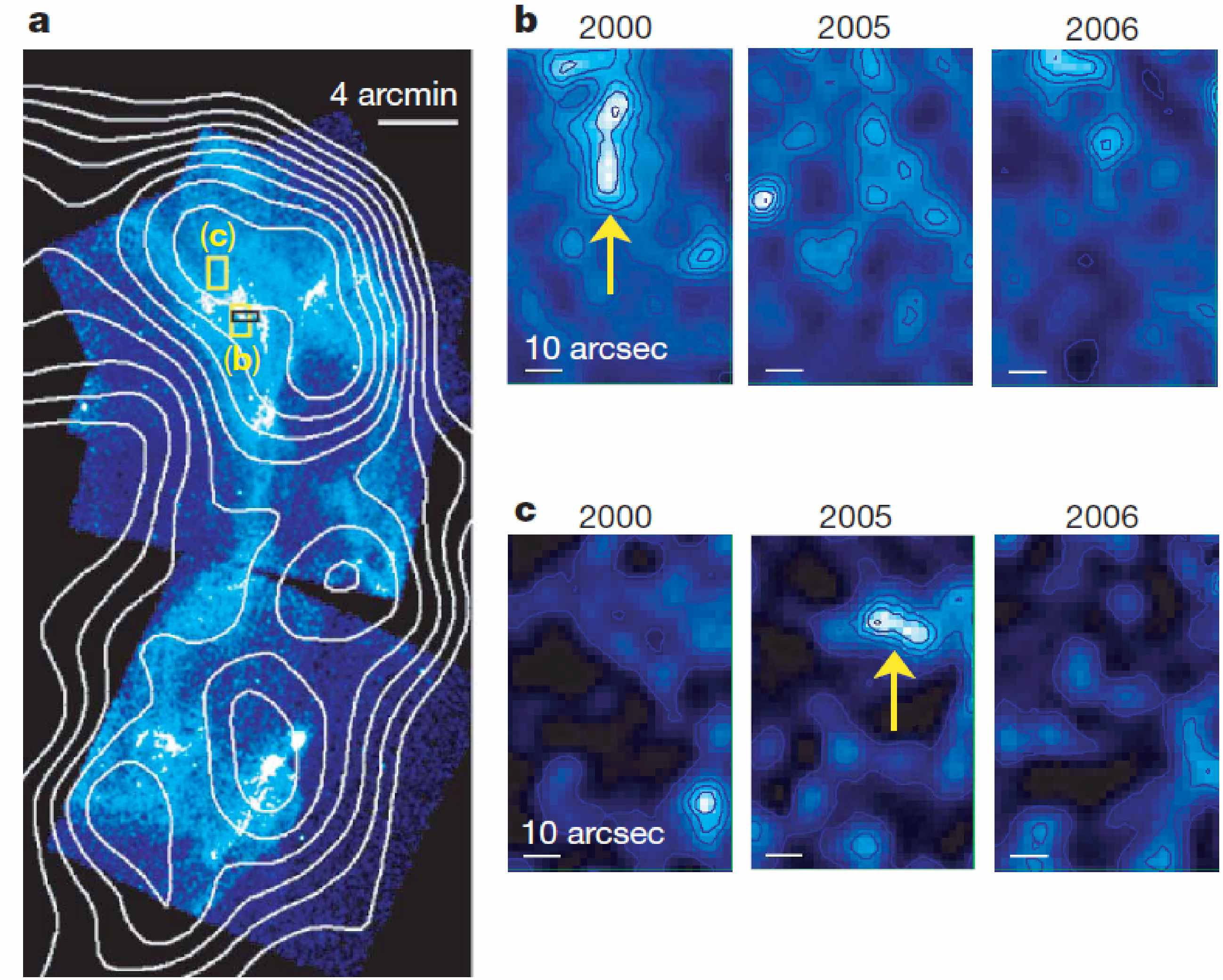




Synchrotron X-ray images at energies 0.5, 5, 20, 50 keV (from left to right). Dot like feature D1 is clearly seen at high energies and it is smeared in at low energies. Left panels show lightcurves of D1 feature at 5 keV (solid curve), 20 keV (dashed curve) and 50 keV (dot-dashed curve).

AB+ ApJL 2008

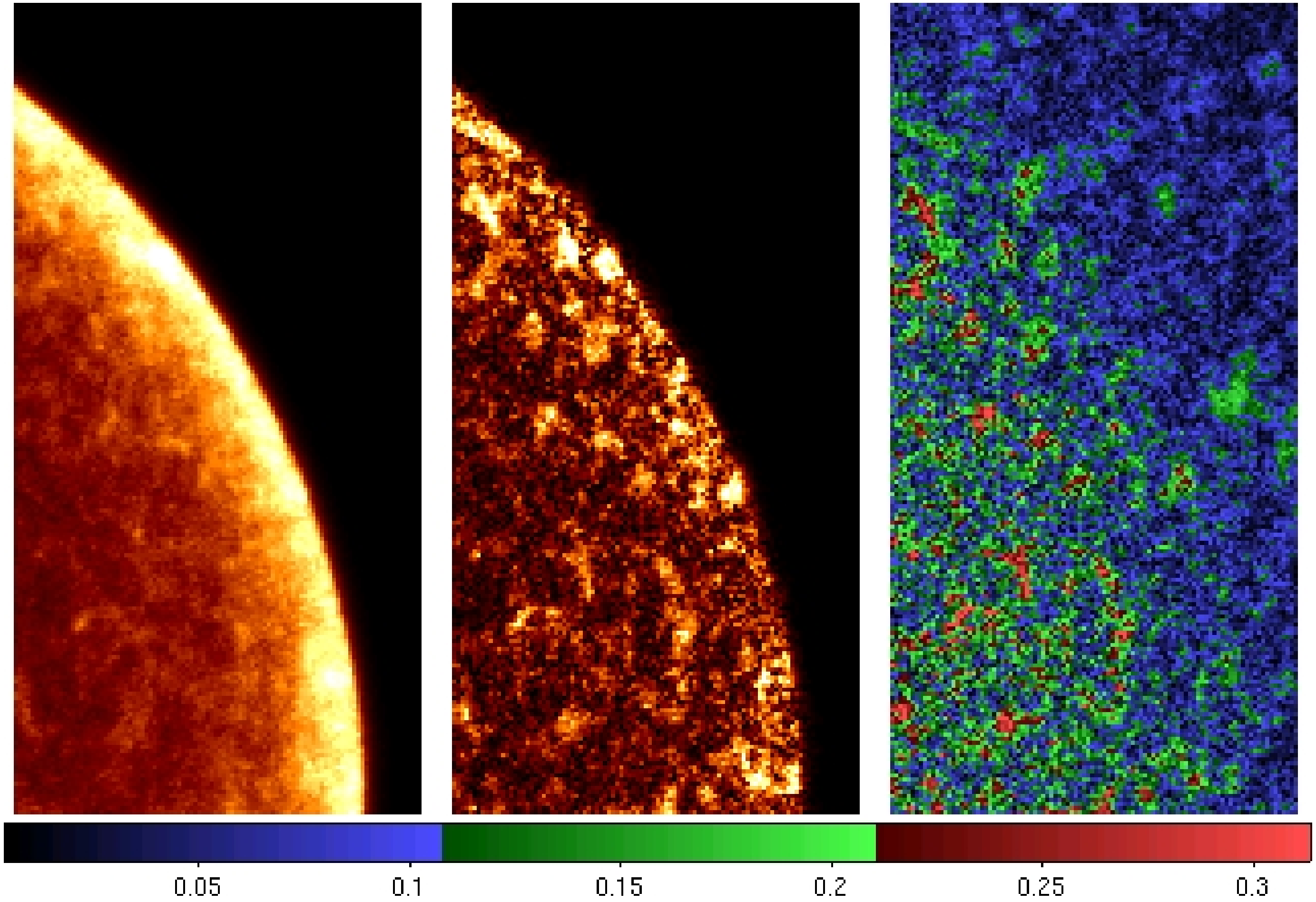
Uchiyama Aharonian et al. 2007



Nonthermal clump "lifetime" ~ 1yr

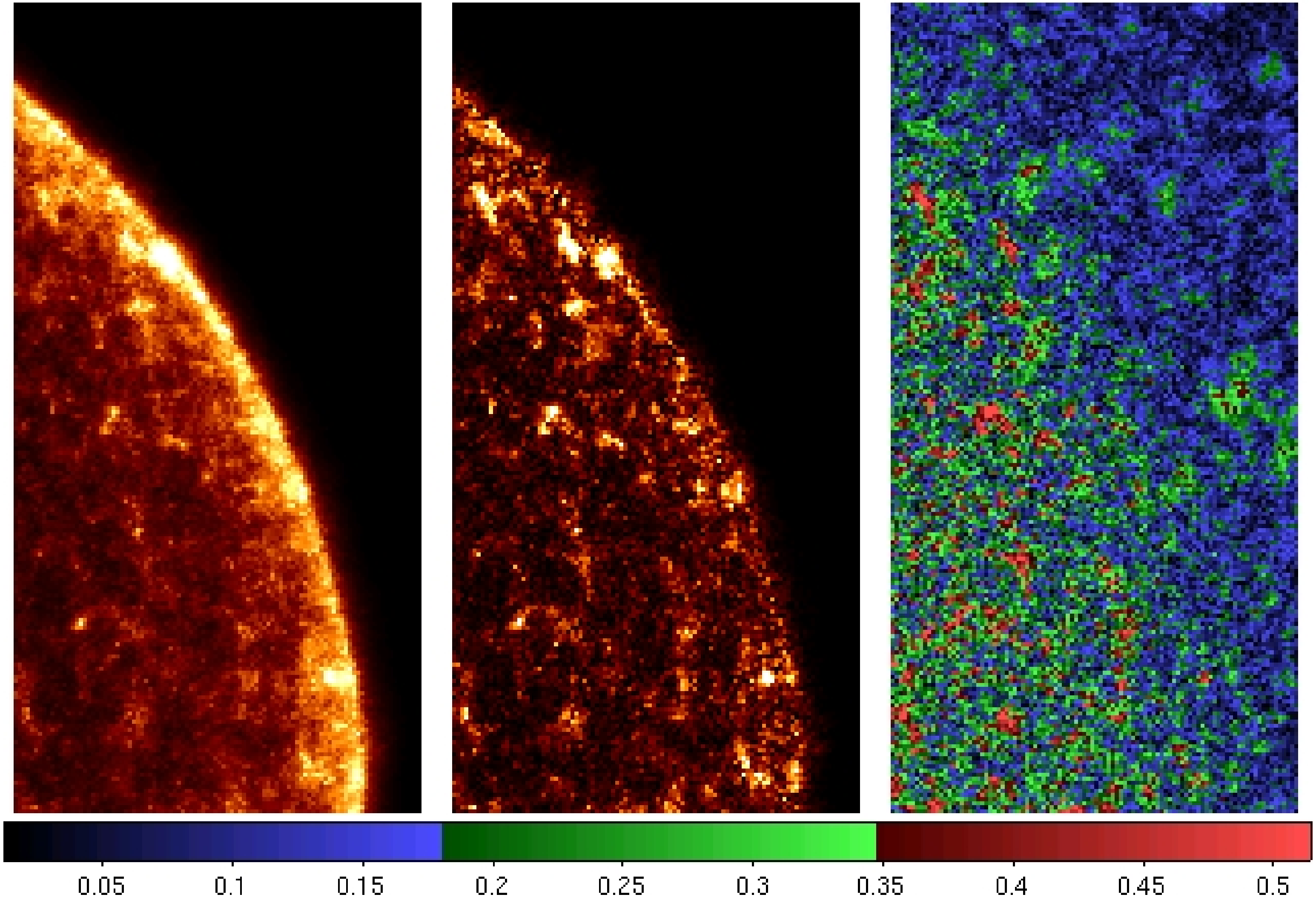
It can be produced with magnetic field well below 1 mG ..

X-ray Polarization at 5 keV



AB+ MNRAS v399, 2009

X-ray Polarization at 50 keV



$\delta = 1.0$

X-ray strips in Tycho’s SNR (Eriksen etal 2011)

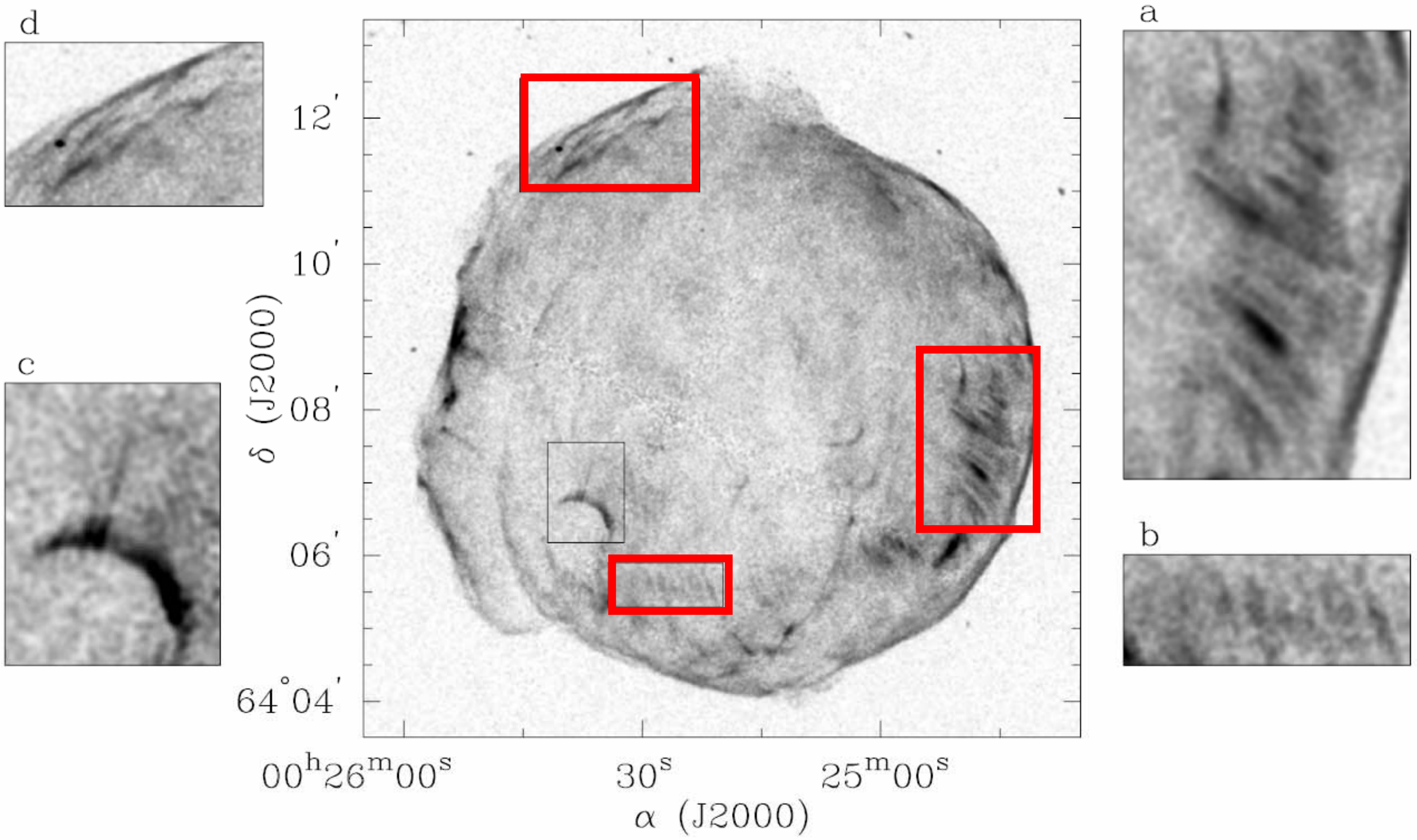
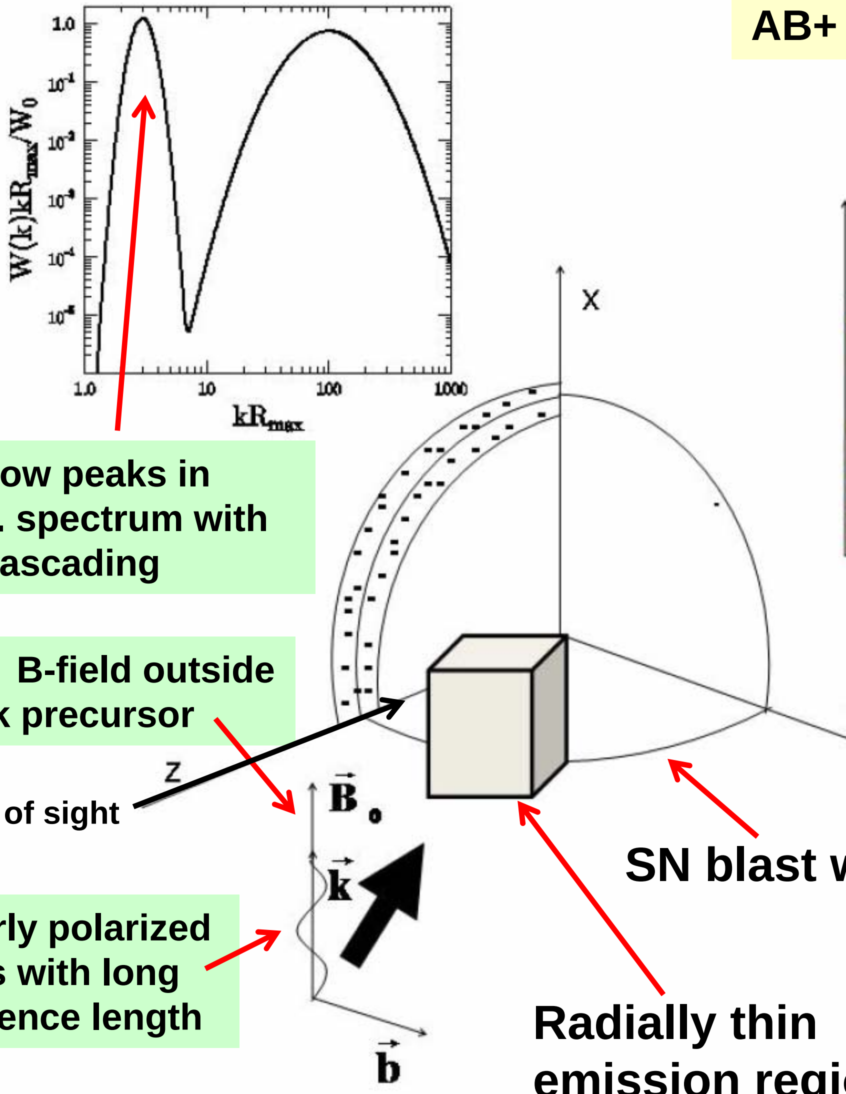


FIG. 1.— *Chandra* X-ray 4.0–6.0 keV image of the Tycho supernova remnant, smoothed with a ~ 0.75″ Gaussian and displayed with an *arcsinh* scaling, showing various regions of striping in the nonthermal emission. Clockwise from the upper right: a) The main western stripes discussed in this Letter; b) A fainter ensemble of stripes; c) a previously-known bright arc of non-thermal emission, with our newly discovered streamers; d) filaments of “rippled sheet” morphology common in optical observations of middle-aged SNRs.

Chandra 4-6 keV X-rays

AB+ ApJL v.735, L40,2011



Narrow peaks in turb. spectrum with no cascading

Perp. B-field outside shock precursor

Line of sight

Linearly polarized waves with long coherence length

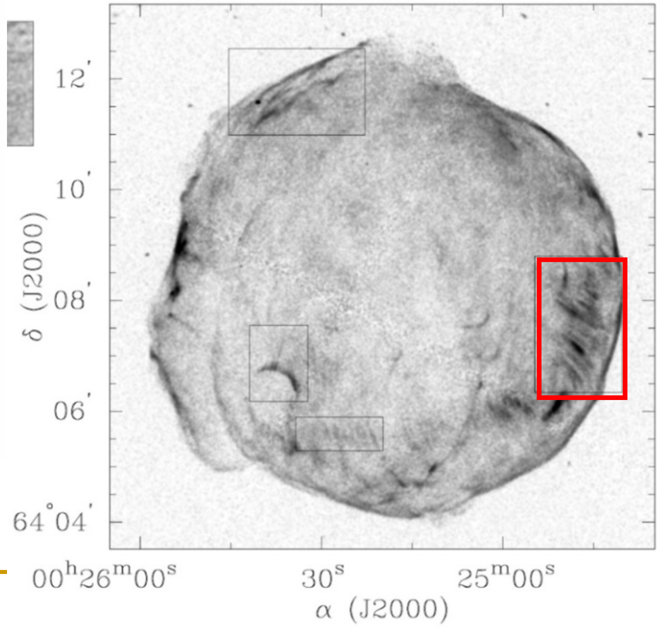
SN blast wave

Radially thin emission region

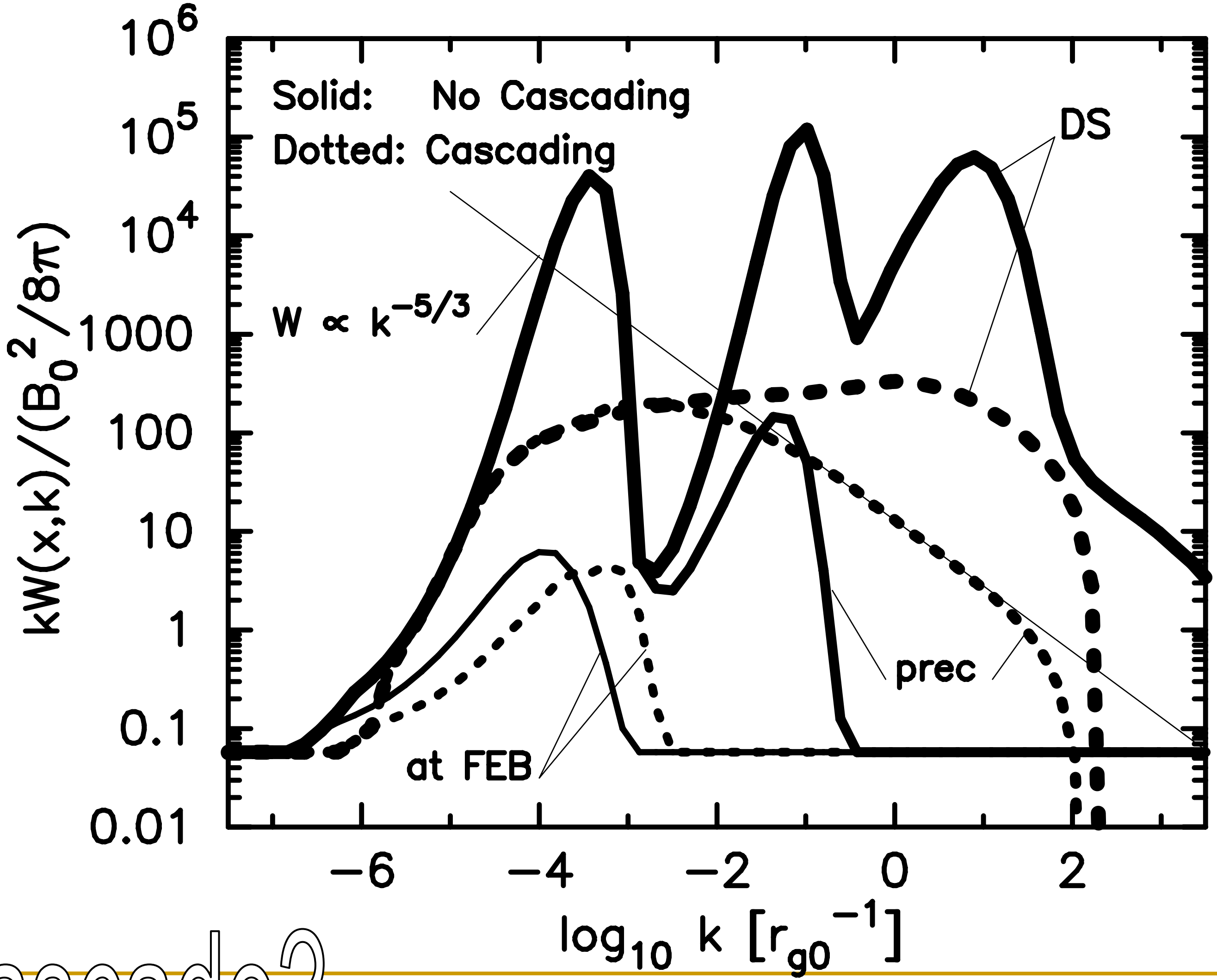
Simulated strips

Efficient, NL shock acceleration producing ~100 TeV protons

Steep electron spectrum to avoid strips in radio



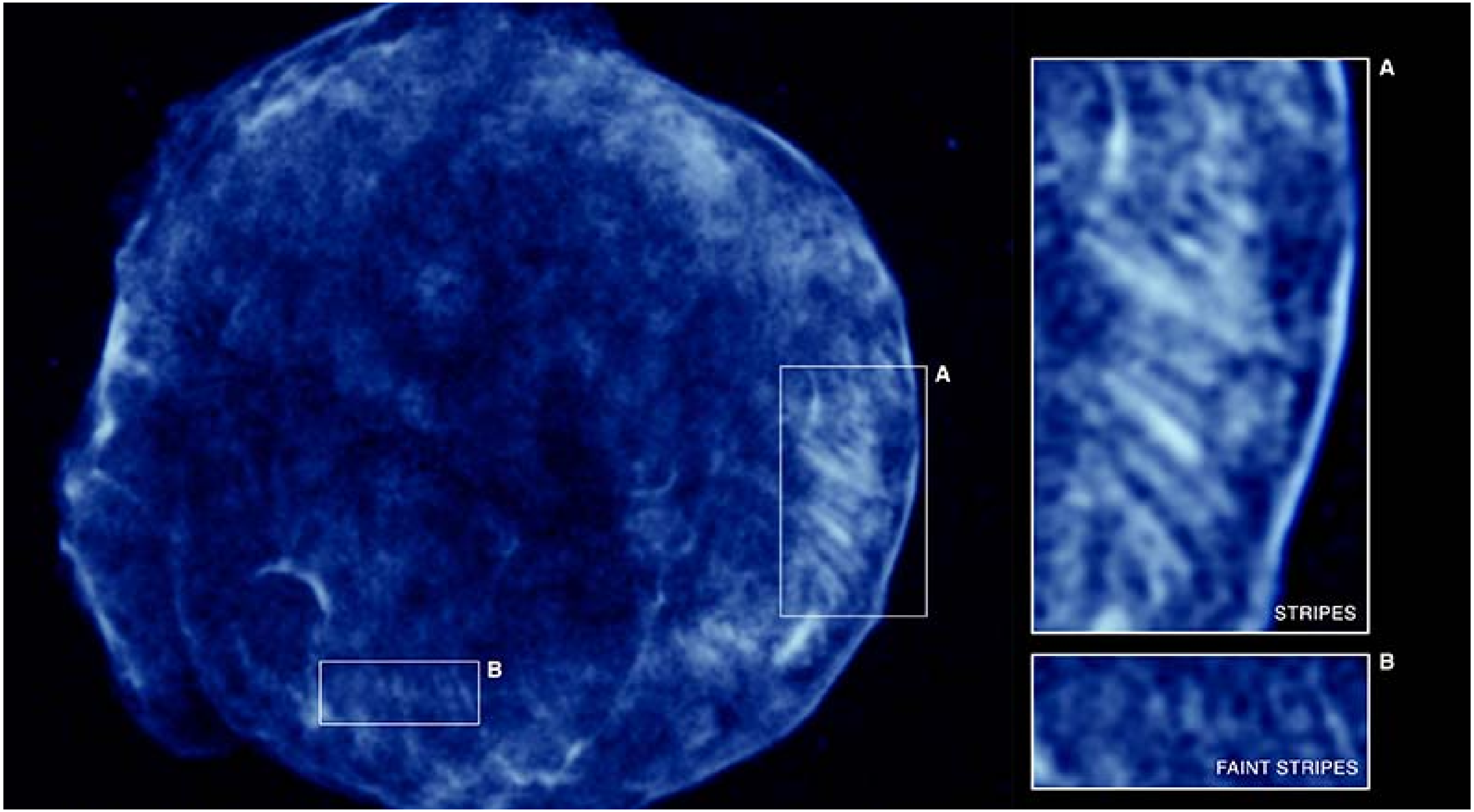
Magnetic Fluctuation Spectra



No cascade?

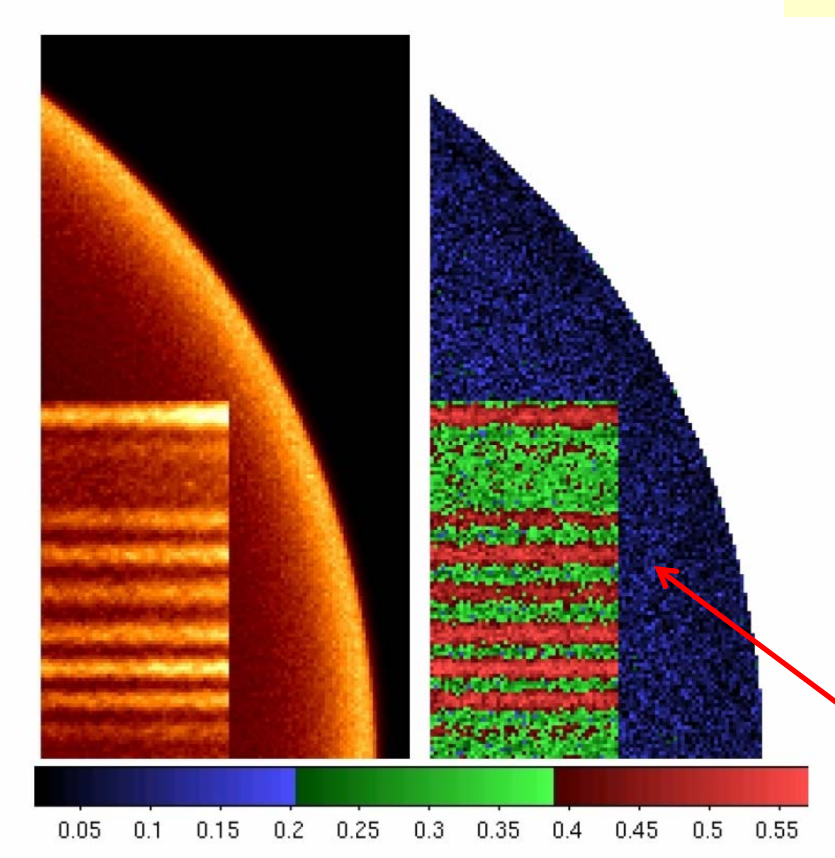
- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

Chandra 4-6 keV Image of Tycho’s SNR



Eriksen + 2011

AB+ ApJL v735, L40, 2011



Polarization fraction

No simple explanation of strips !

➔ Many shock and turbulence properties must come together to produce coherent structure on this scale.

Strong predictions:
Quasi-perpendicular upstream B-field

Strong linear polarization in strips