Relativistic Particles, Magnetic Fluctuations and Their Observational Appearance in Astrophysical Shocks

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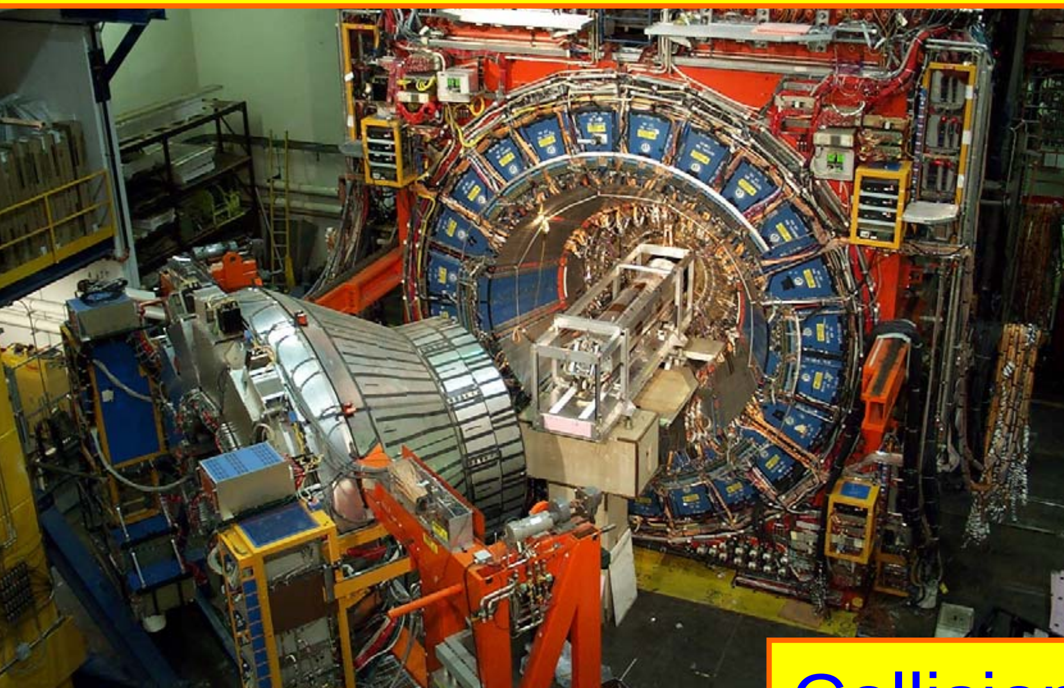
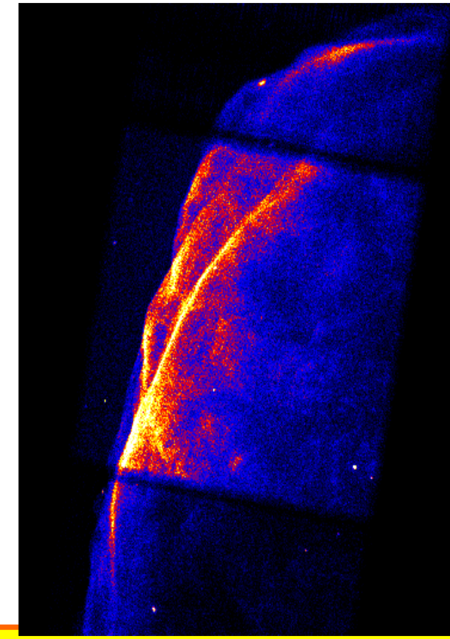
Collisionless Shocks as Particle Accelerators

- The growing body of evidences for supernova shocks to accelerate particles to very high energies ~ 100 TeV and possibly above
- The apparent morphology of X-ray structures in supernova shells indicated a super-adiabatic magnetic field amplification in the shock vicinity

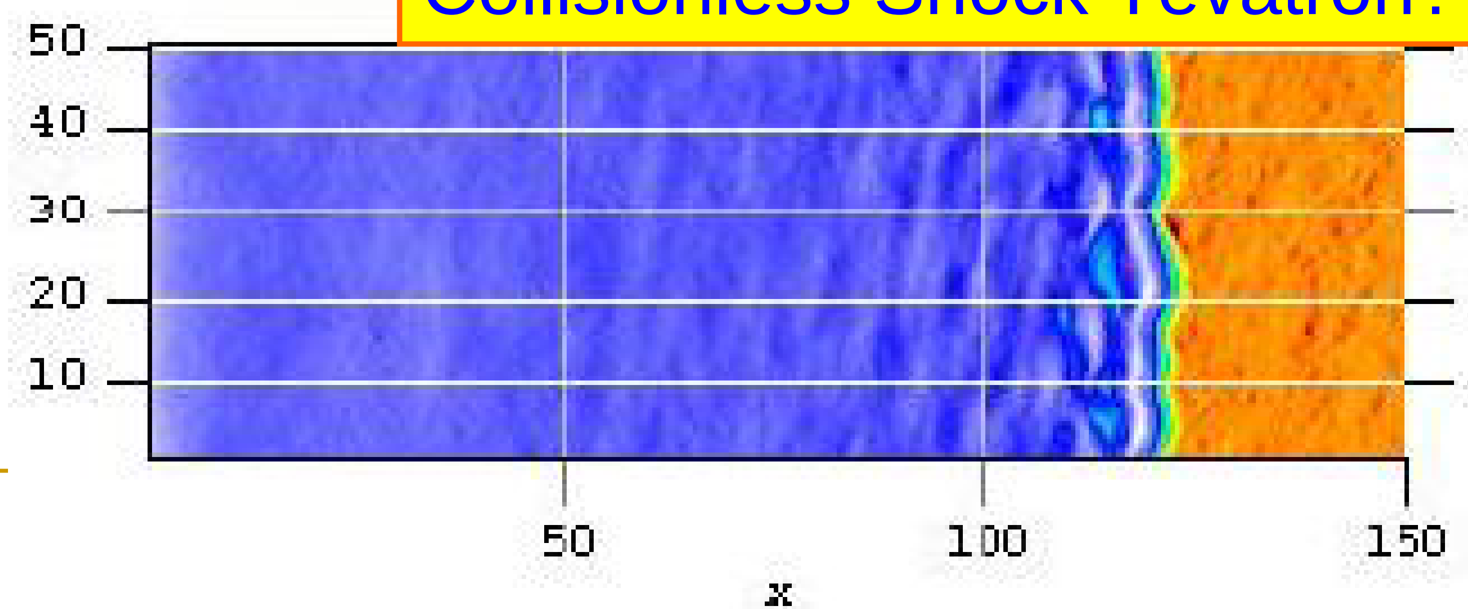
(e.g. Vink & Laming, Bamba ea, Voelk ea, Reynolds, Uchiyama, Patnaude and many others)

The Collider Detector at Fermilab (Tevatron)





Collisionless Shock Tevatron?



Diffusive Shock Acceleration

- *the Diffusive Shock Acceleration to be fast and efficient requires strong magnetic field fluctuations of scales many orders of magnitude larger than the ion inertial length (and the shock width) …*

How to produce the fluctuation?

Magnetic field amplification in DSA

Resonant models of wave generation

e.g. Wentzel (1969), Kulsrud & Cesarsky (1971), Skilling (1975), Achterberg (1981) and many others

Non-resonant models e.g. by Drury and Dorfi (1985) (long wavelength CR pressure gradient instability),

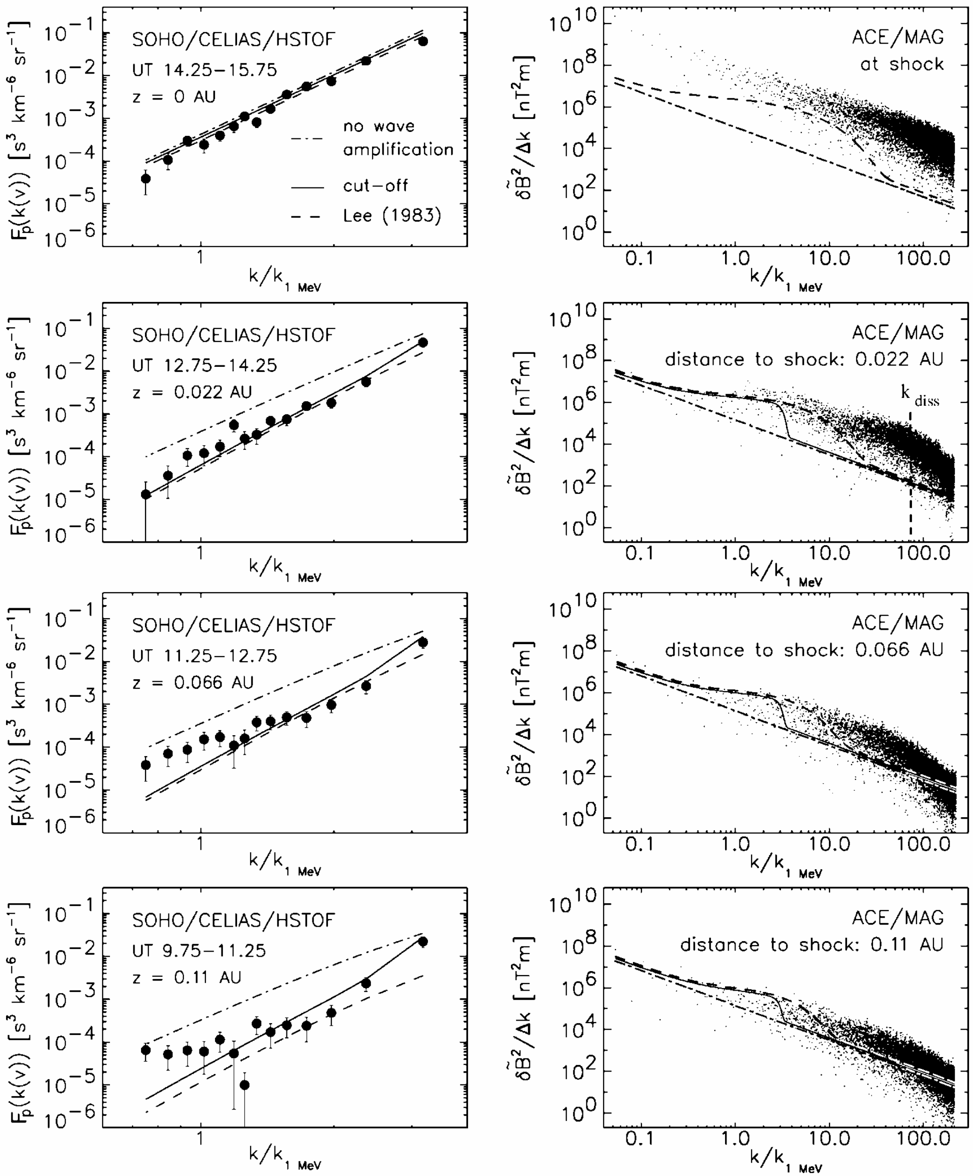
A.Bell (2004) discovered a fast efficient short-wavelength CR current instability), see also Pelletier ea (2006), Niemec, Pohl ea (2008), Requelme & Spitkovsky (2009)

Long –wavelength CR current instabilities by Bykov, Osipov, Toptygin (2005, 2009), Pelletier ea (2006), Reville et al (2007).

Long-wavelength instability by Malkov and Diamond

Ohira (2009) instability and others

Interplanetary Shock Turbulence Amplification



Bamert ea 2004

DSA with magnetic field amplification

- **The instabilities can be implemented in DSA models in an attempt to study in a consistent way the effect of magnetic fluctuation growth on particle spectra**

(e.g. Amato & Blasi '06; Vladimirov ea '06 , '08, '09; Zirakashvili ea '08 and others)

MC model of DSA

- Particle scattering rate or MFP prescription (diffusion model)

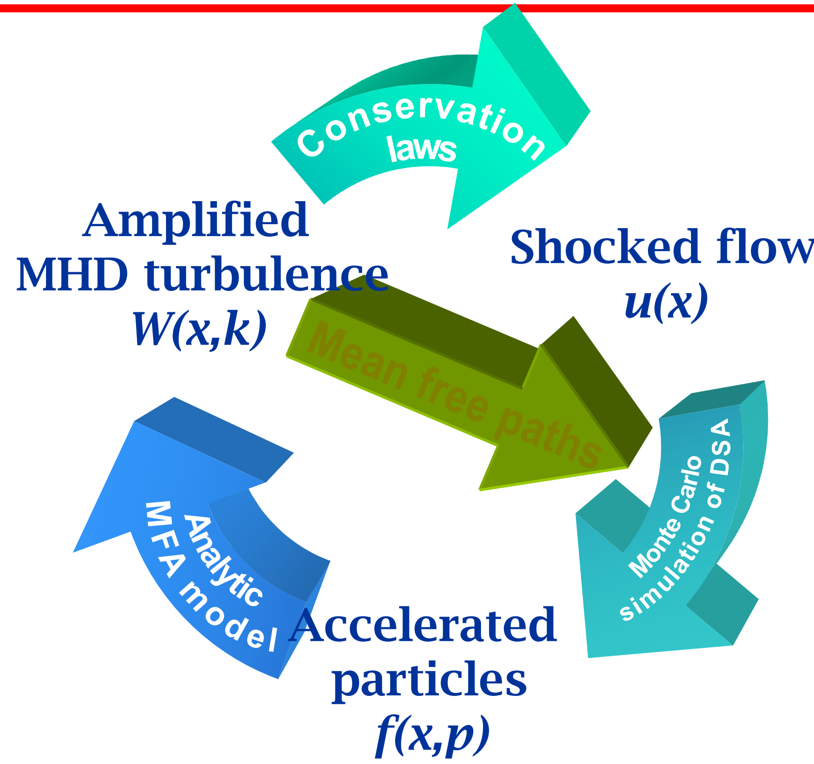
- Magnetic Turbulence Model:

(i) Turbulence amplification and dissipation

(ii) Turbulence spectral transfer

The models will be discussed by Andrey Vladimirov on the Wednesday a **nonlinear model*** of DSA based on Monte Carlo particle transport

· Magnetic turbulence, bulk flow, super-thermal particles derived consistently with each other



Vladimirov, Ellison & Bykov, 2006. ApJ, v. 652, p.1246;

Vladimirov, Bykov & Ellison, 2008. ApJ, v. 688, p. 1084

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

MC model of DSA

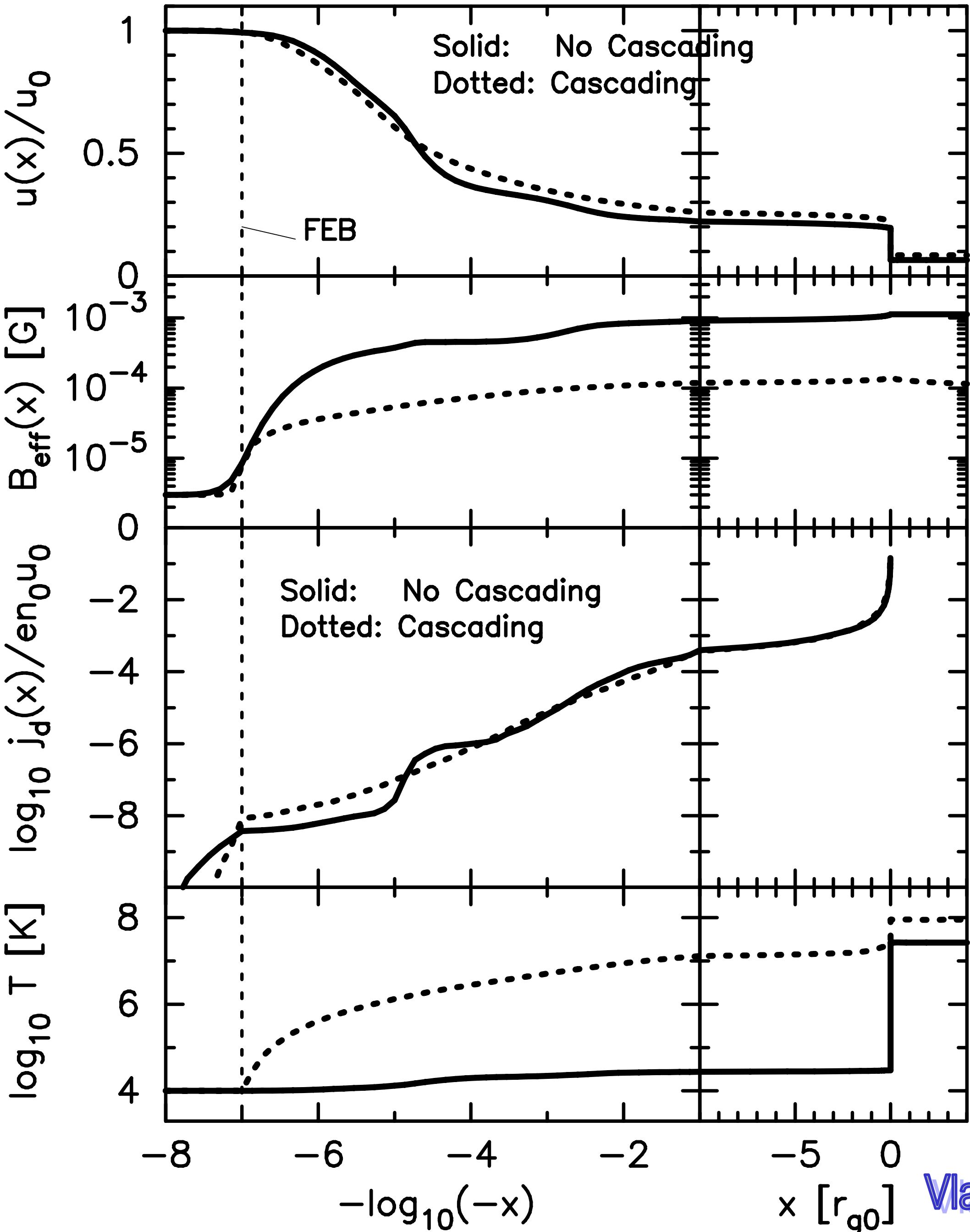
Two models of the turbulence spectral energy transfer

(i) Kolmogorov-type cascade

(ii) No-cascade in the mean-field direction

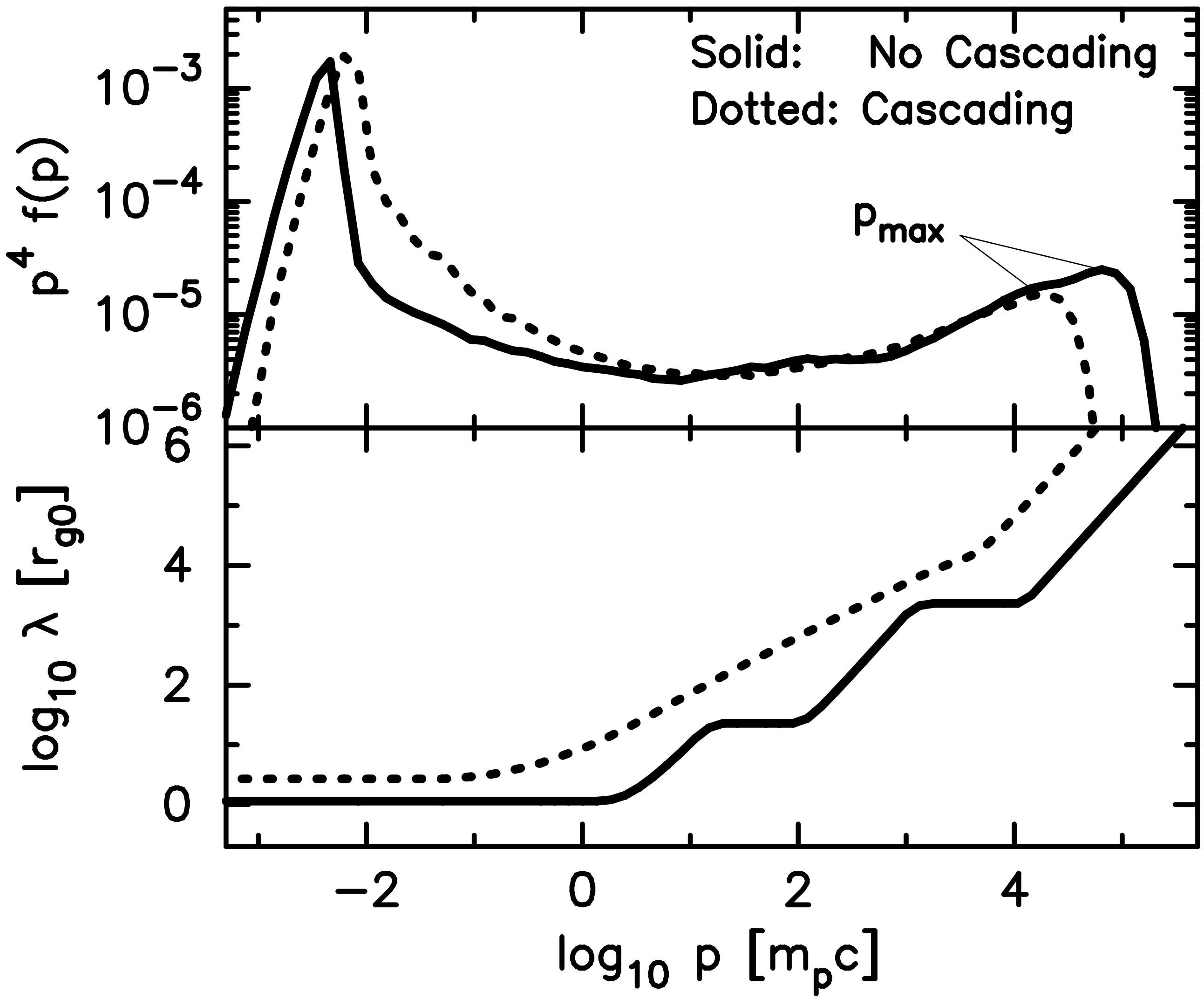
We used Bell's short wavelength instability as the magnetic field amplification mechanism

The Structure of Supersonic Flow

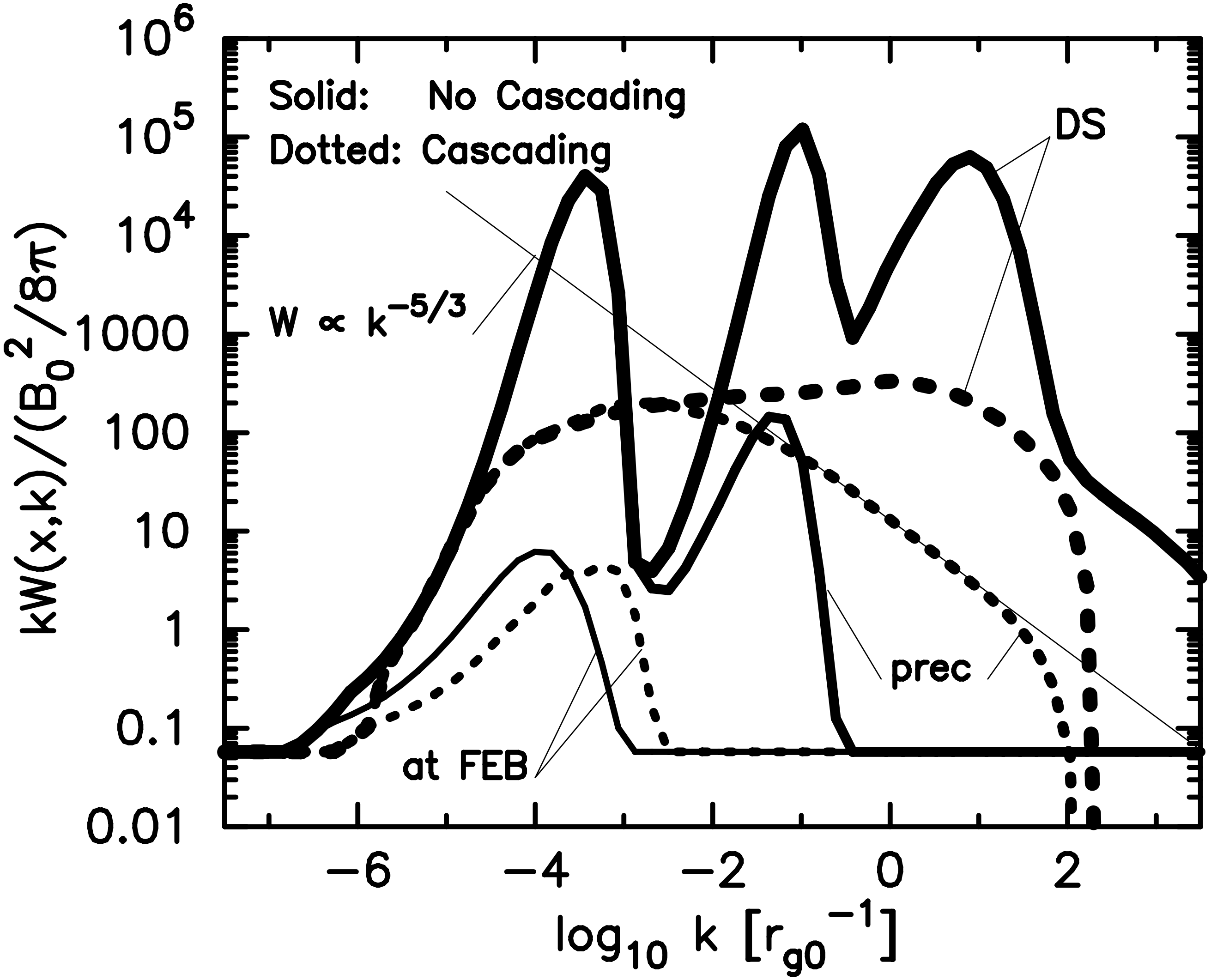


Vladimirov Bykov Ellison 2009

Particle Spectra



Magnetic Fluctuation Spectra

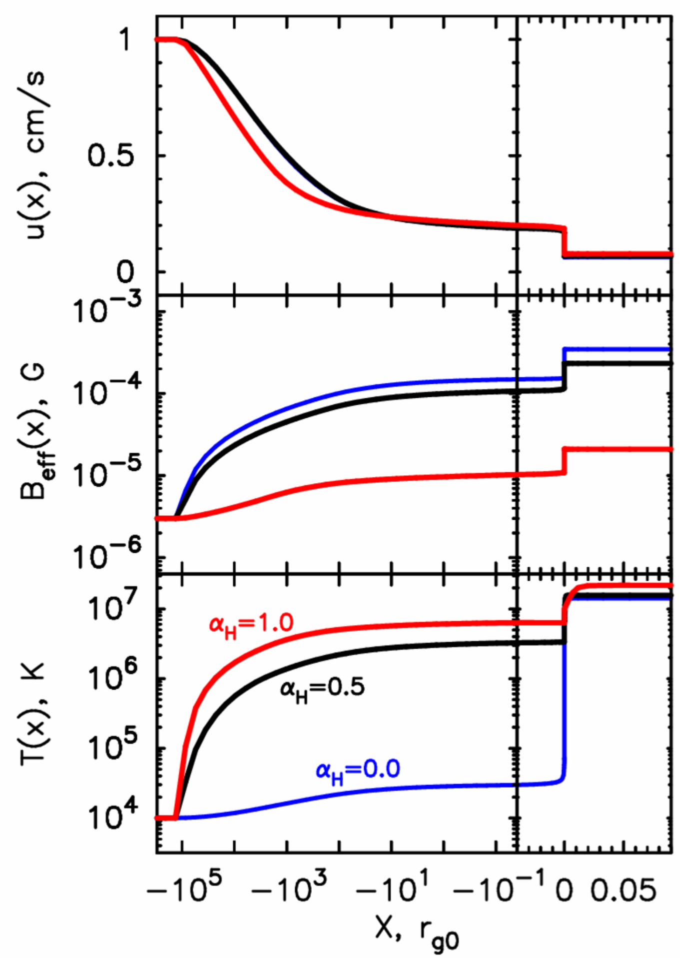


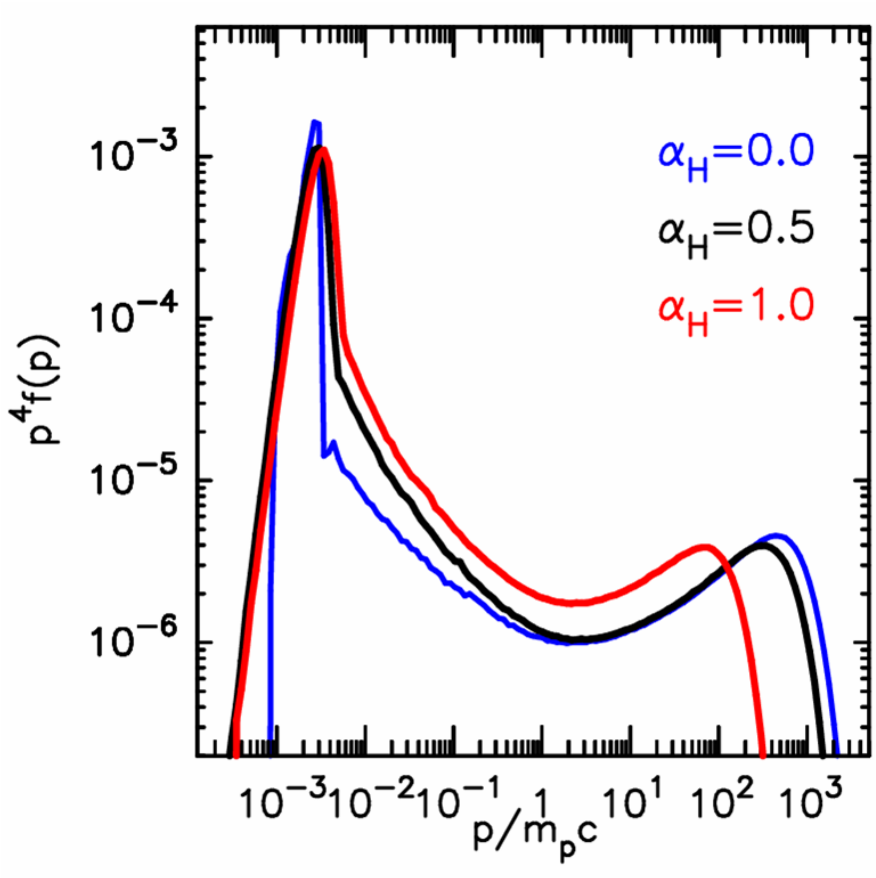
MC model of DSA

How the turbulence dissipation may change the flow and particle spectra?

MC Simulations

- Here the shock structure and injection are determined self-consistently (momentum and energy are conserved).





Vladimirov Bykov Ellison 2008

Optical and UV absorption and emission spectra and the line shapes are the natural tools to constrain the magnetic field dissipation in the shock upstream

What about synchrotron?

Efficient DSA is accompanied with strong magnetic turbulence where stochastic m-field amplitude is well above the regular m-field in the shock upstream

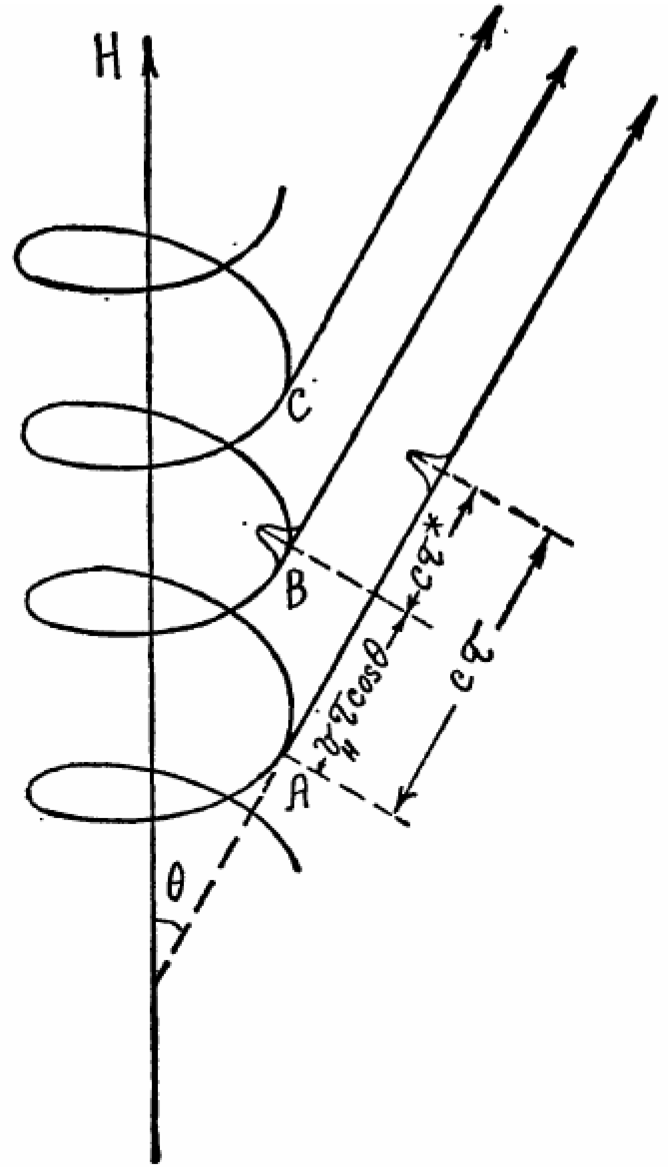
How that stochastic field affects

the X-ray synchrotron emission?

Work done with Yu.A. Uvarov and D.C.Ellison

Bykov, Uvarov & Ellison, 2008. ApJ, v. 689, L133

Synchrotron Radiation:



Ginzburg and Syrovatskii 1969

Synchrotron Radiation Stockes Parameters:

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

Local Synchrotron Emissivity for a power-law electron distribution:

$$I_{syn}(\nu,\mathbf{r}) \sim N_e \cdot (B\sin\chi)^{(\alpha+1)/2} \cdot \nu^{-(\alpha-1)/2}$$

$$N(\gamma) = N_e \cdot \gamma^{-\alpha}$$

Note the strong dependence of the emissivity I on B

in the spectral cut-off regime !

Because of the strong dependence of the emissivity I on B in the cut-off spectral regime a strong local magnetic field enhancement could even dominate the integral over the line of sight…

High statistical moments of the magnetic field distribution are important… intermittency

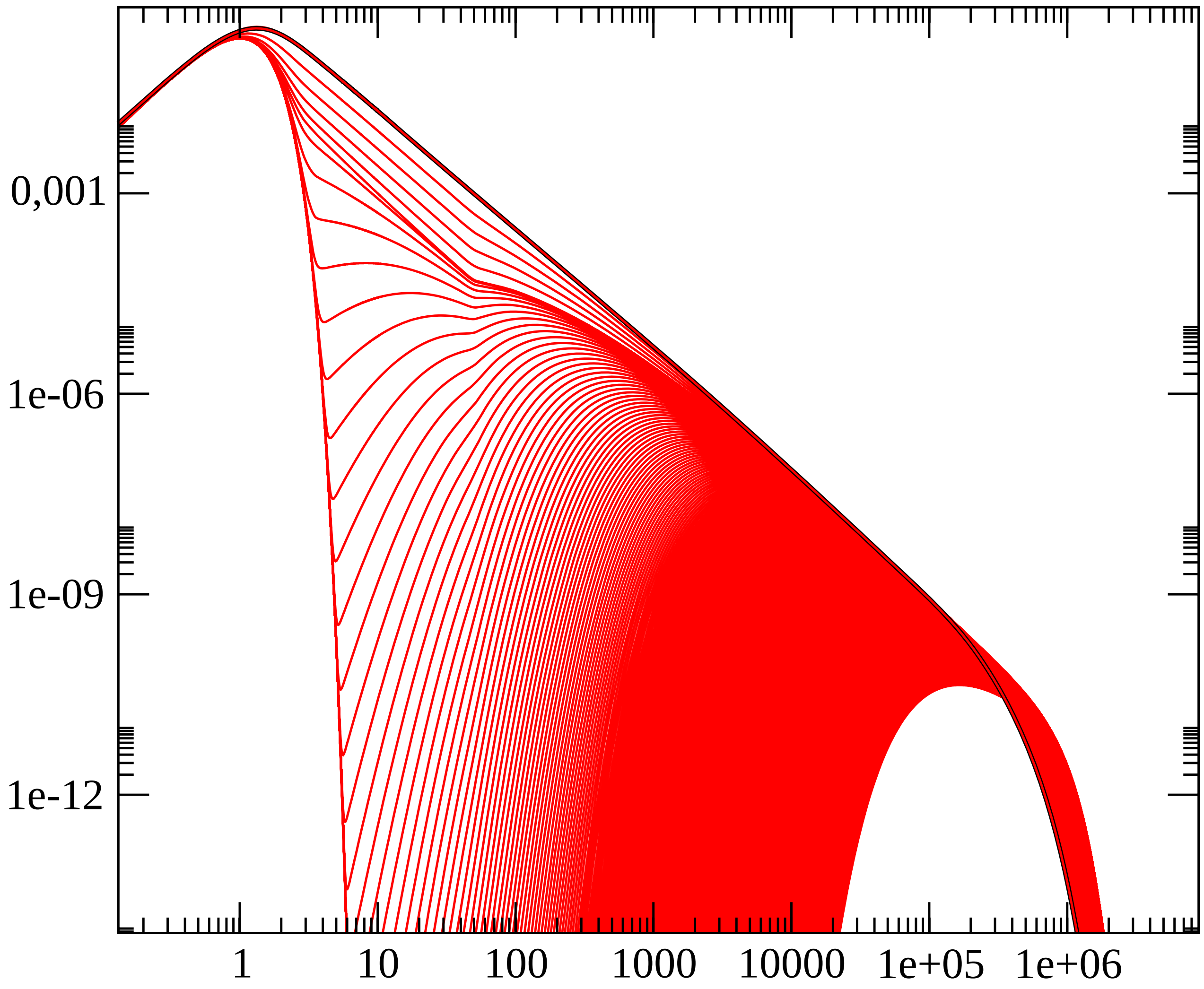
Synchrotron Radiation Stockes Parameters:

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

- Electron Distribution/Spectra in the SNR Shock vicinity Simulated with the Kinetic Equation Model

- Shock velocity is 2,000 km/s,
- Bohm diffusion model

Ele

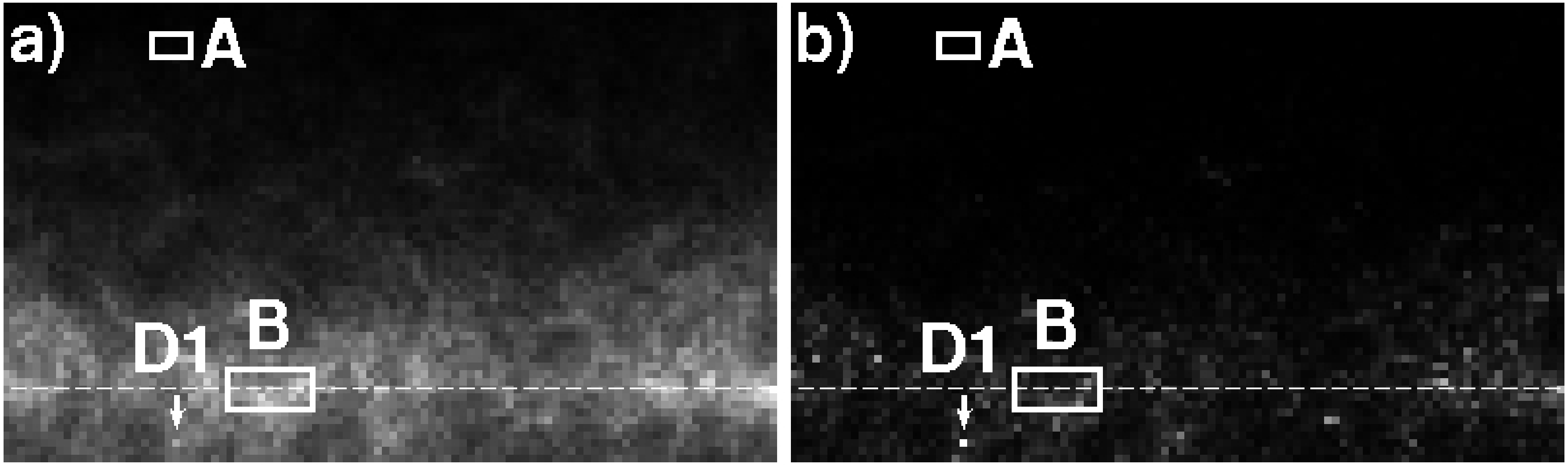


- A model of stochastic magnetic field

We simulated random magnetic fields with given fluctuation spectra and Probability Distribution Function in four decade wave-number band

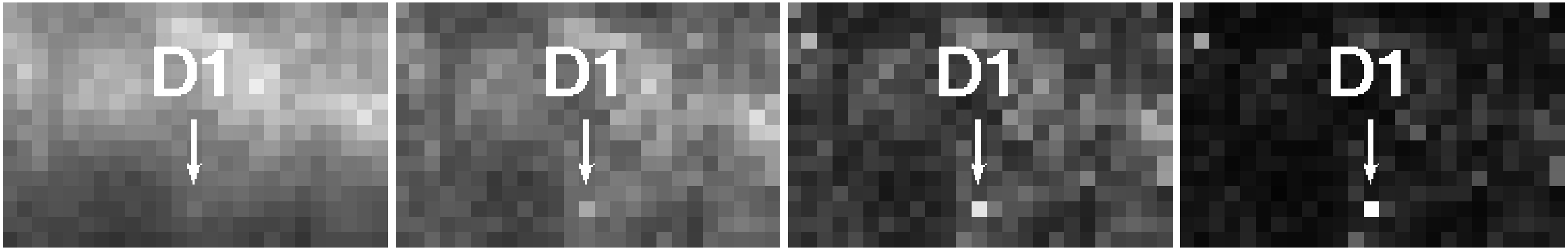
- Synchrotron Emission Images and Spectra

Synchrotron Emission Images



BUE 2008

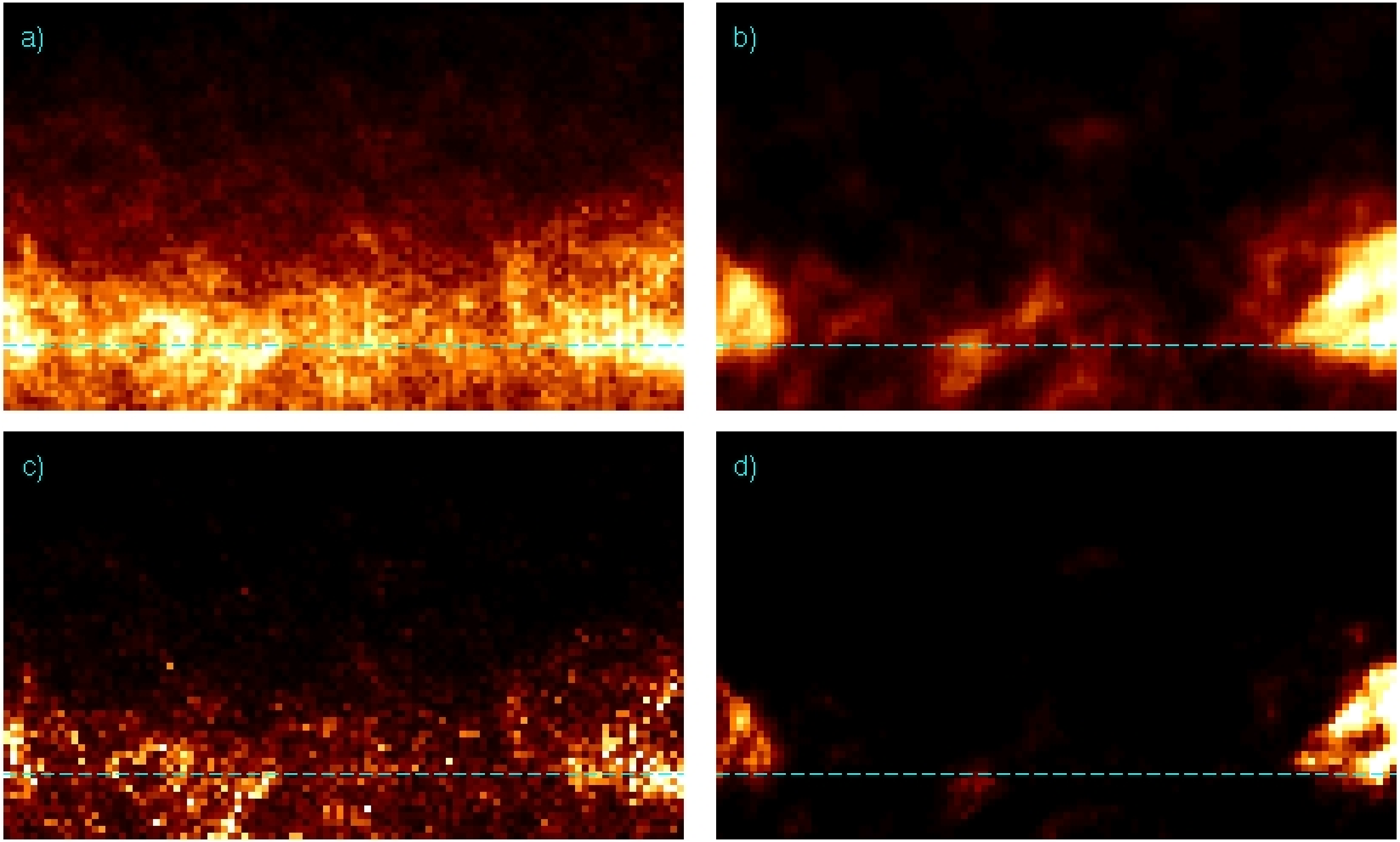
Synchrotron Emission Images (Zoom)



0.5 keV 5 keV 20 keV 50 keV

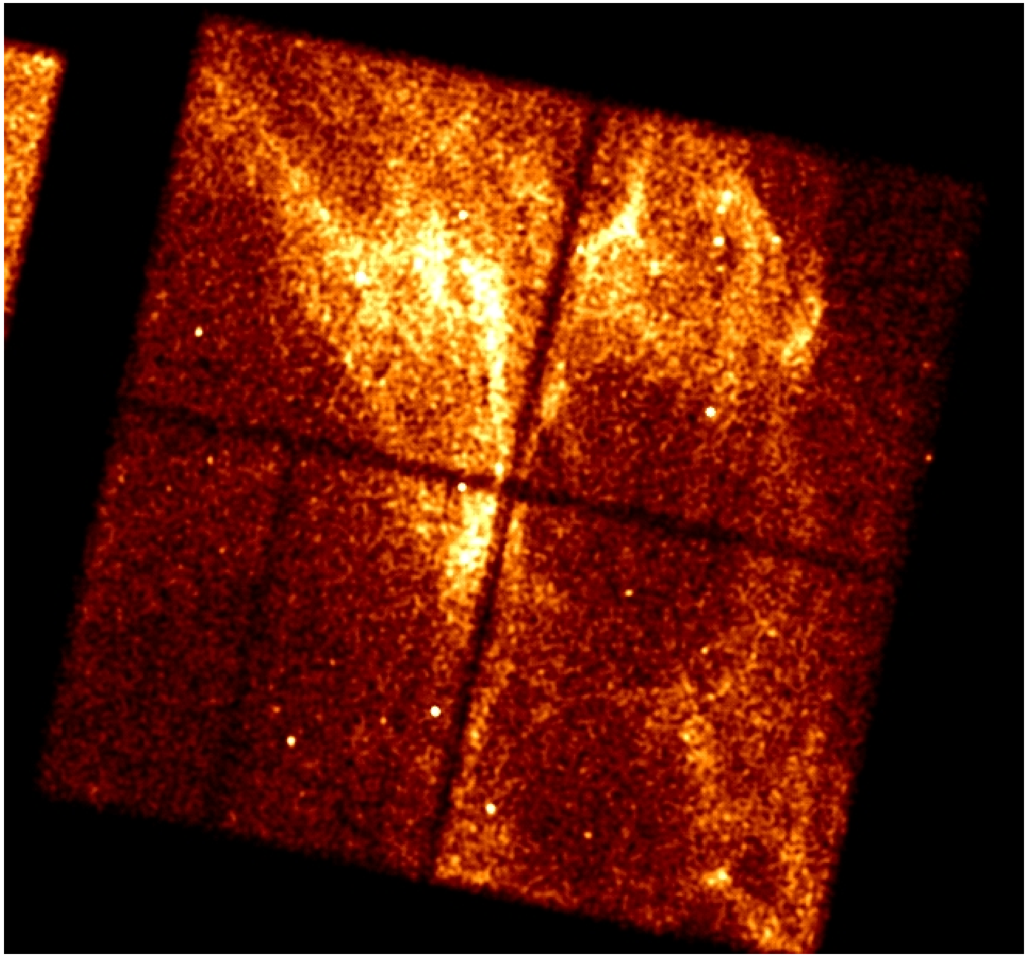
BUE 2008

Synchrotron Images for different turbulence spectra

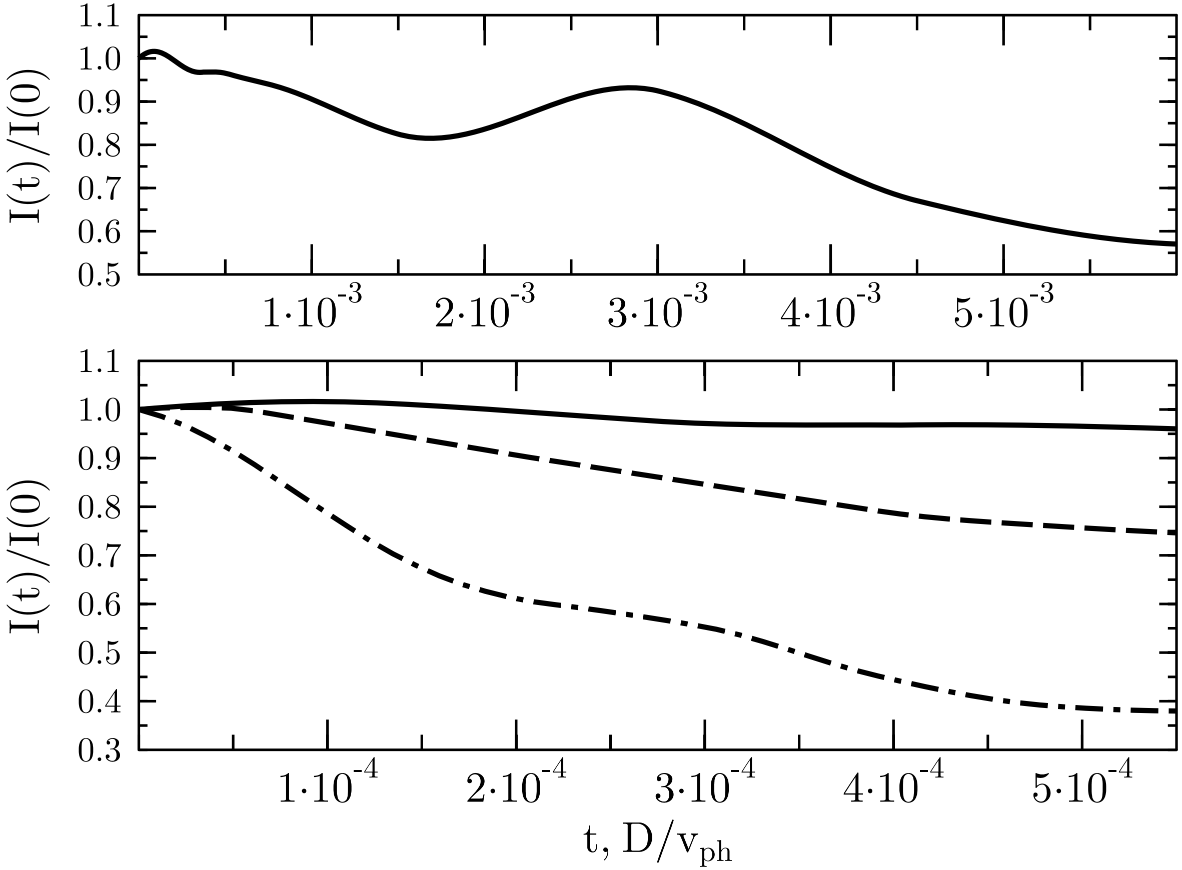


$\delta = 1.0$ $\delta = 2.0$

Chandra image of RXJ1713 NW



Light Curves for Clump D1



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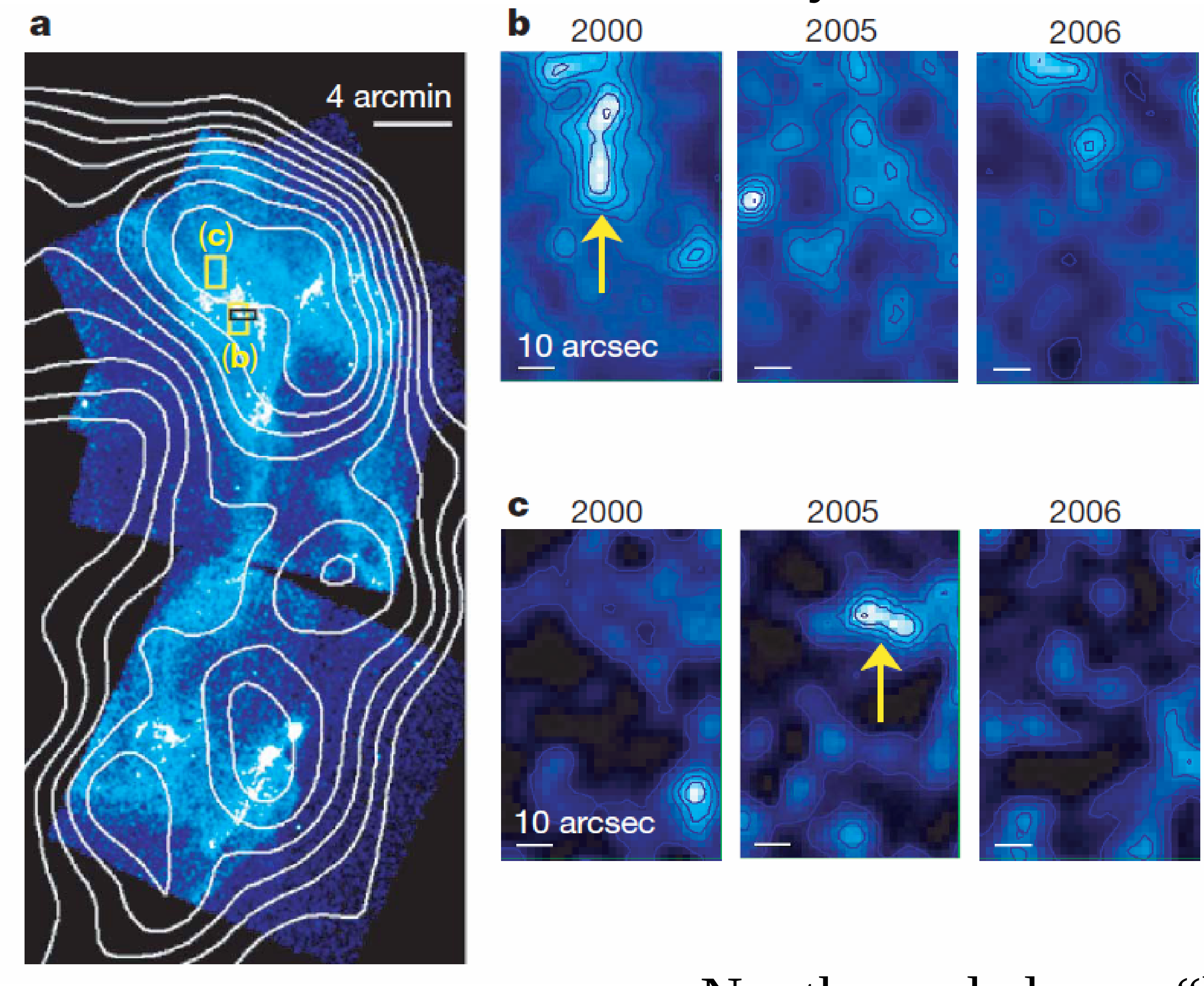
- Variability time scale is about a year

- ***RX J1713.7-3946***

Uchiyama et al. 2007



Nonthermal clump “lifetime” ~ 1yr !!

RX J1713.73946 What is the cause for the fast variability?

Uchiyama et al. 2007, Nature, 449, 576

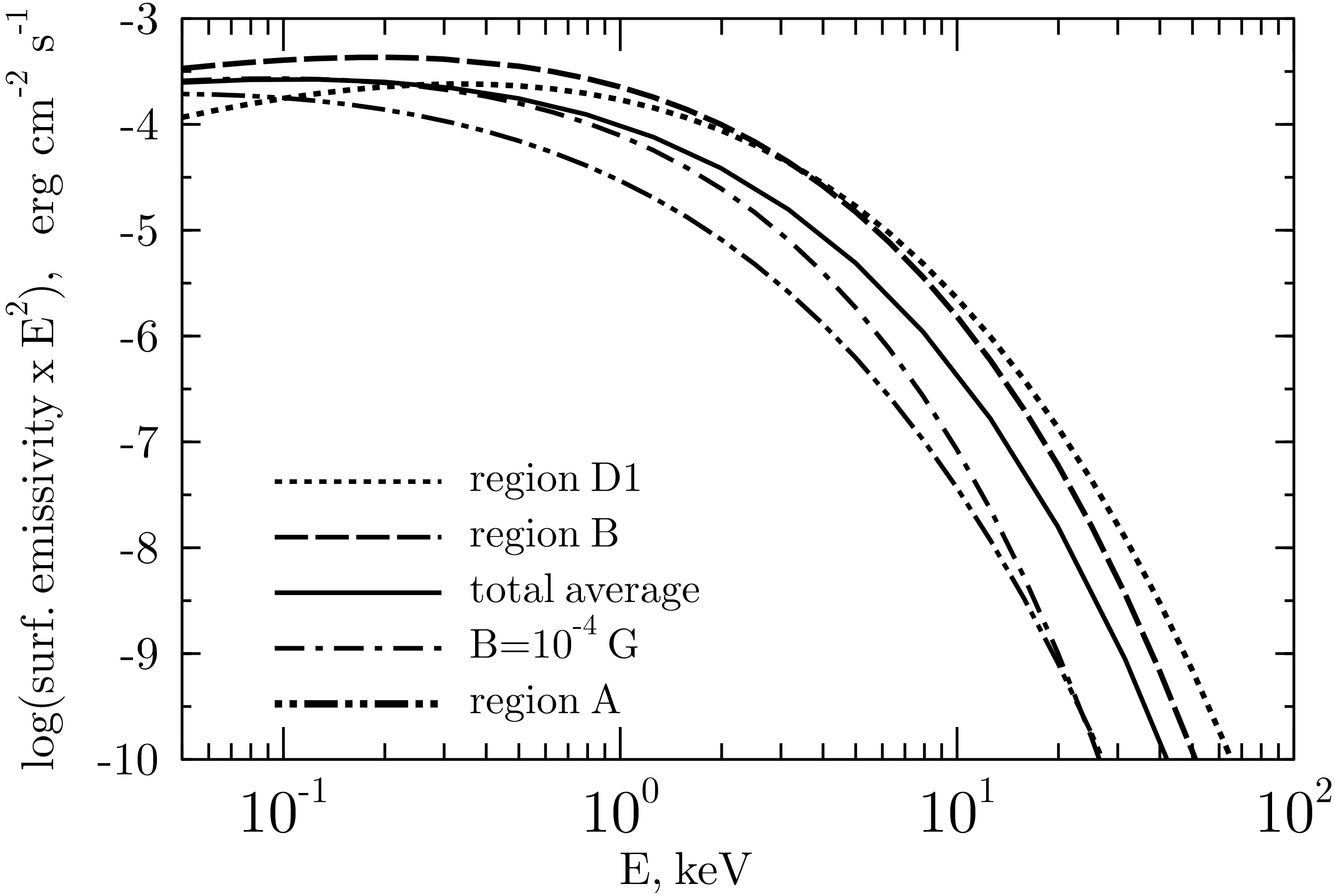
$$t_{synch} \approx 1.5\,(B/\mathrm{mG})^{-1.5}\;(\varepsilon/\mathrm{keV})^{-0.5}\;\;\mathrm{years}$$

Synch. cooling time ~ 1yr result in high ~ mG regime magnetic field??

Extremely fast acceleration of cosmic rays in a supernova remnant

Well, that is possible, but not necessarily. Strong fluctuations of random magnetic field could produce twinkling clumps of synchrotron emission

Synchrotron Emission Spectra

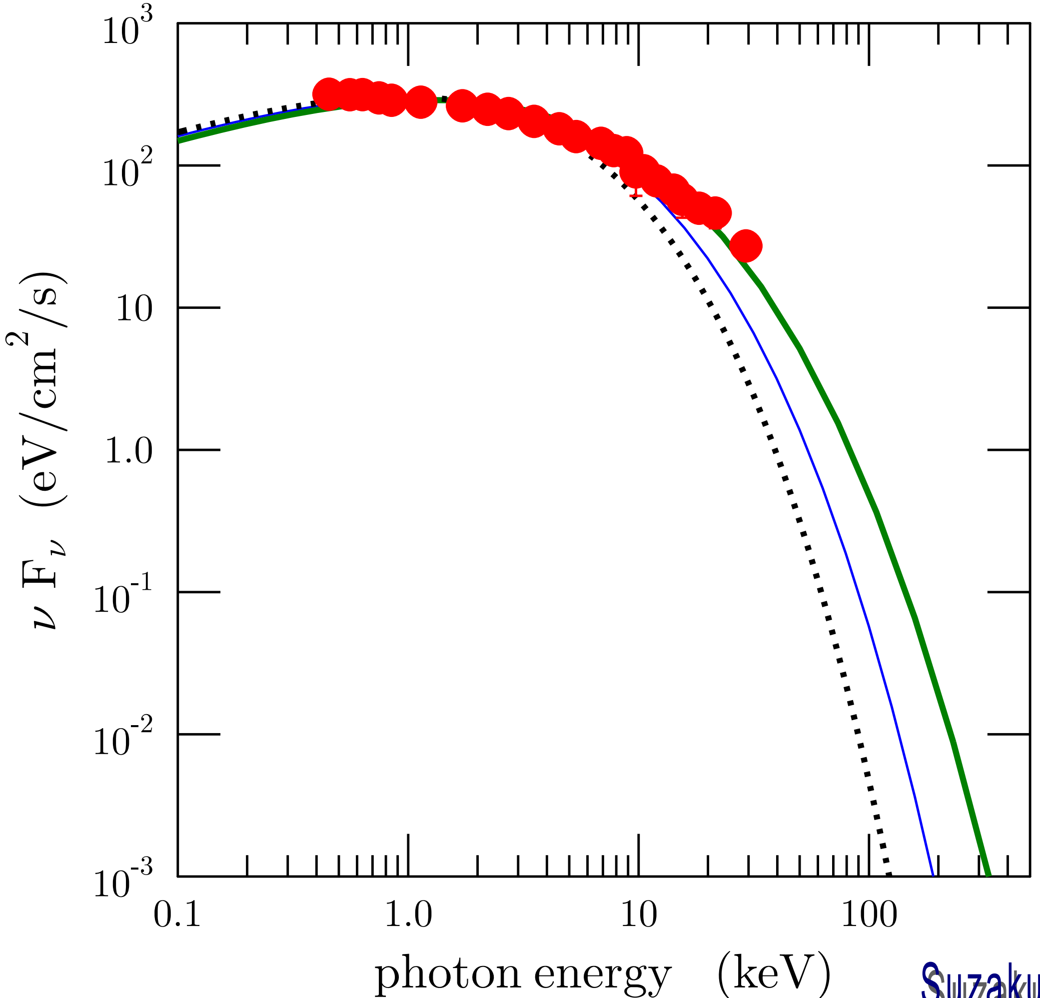


BUE 2008

The account for magnetic field magnitude fluctuations (not just the random field directions of a homogeneous field, as it was done before) result in a very strong enhancement of synchrotron surface brightness in the spectral cut-off regime.

The effect should be accounted for in the models that are making the turbulent magnetic fields estimations using the observed roll-off frequency…

Synchrotron Spectra Simulated for Different PDFs of Fluctuation against Suzaku data on RXJ1713



Suzaku data from Tanaka et al '08

The Synchrotron radiation is polarized

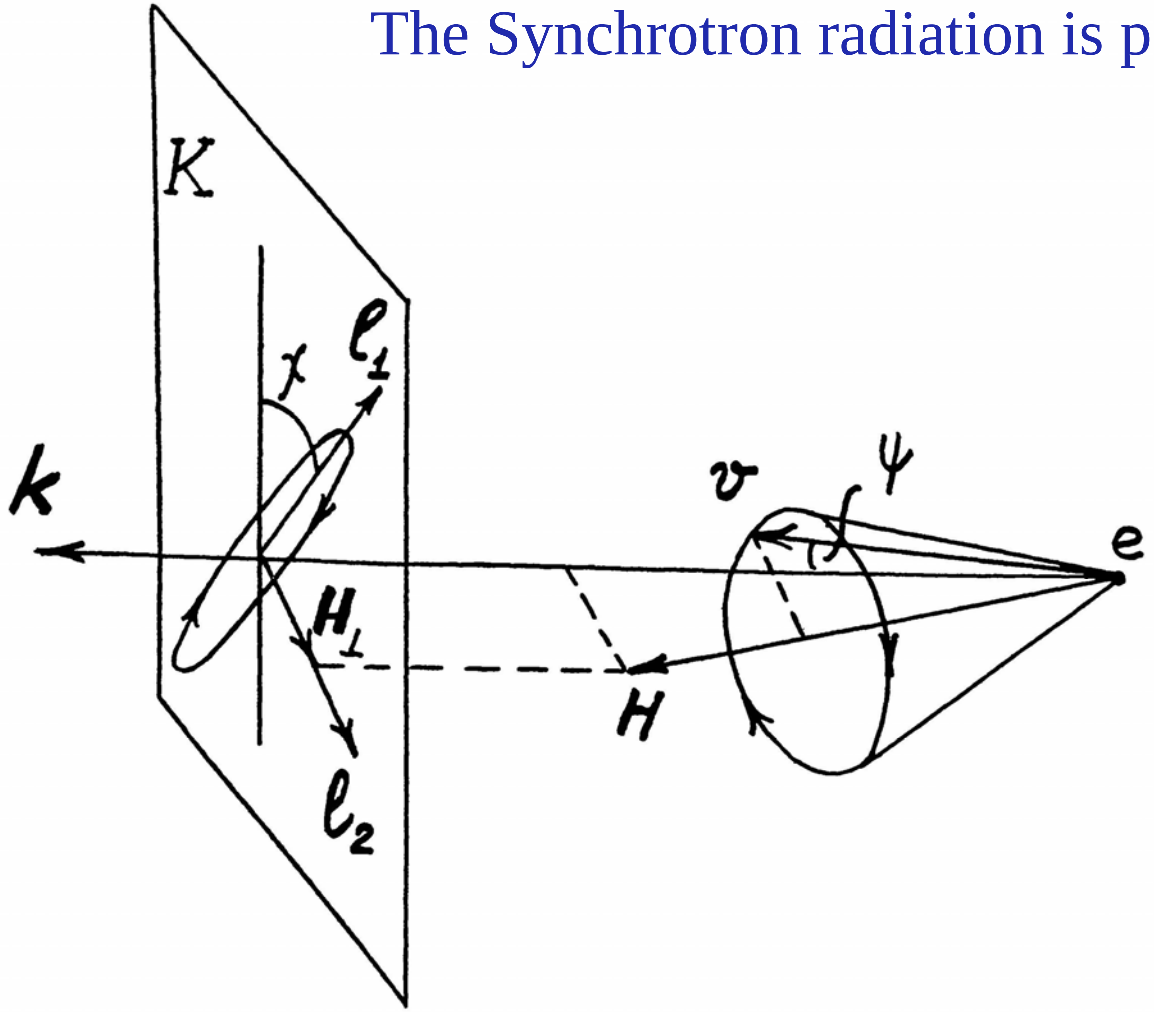
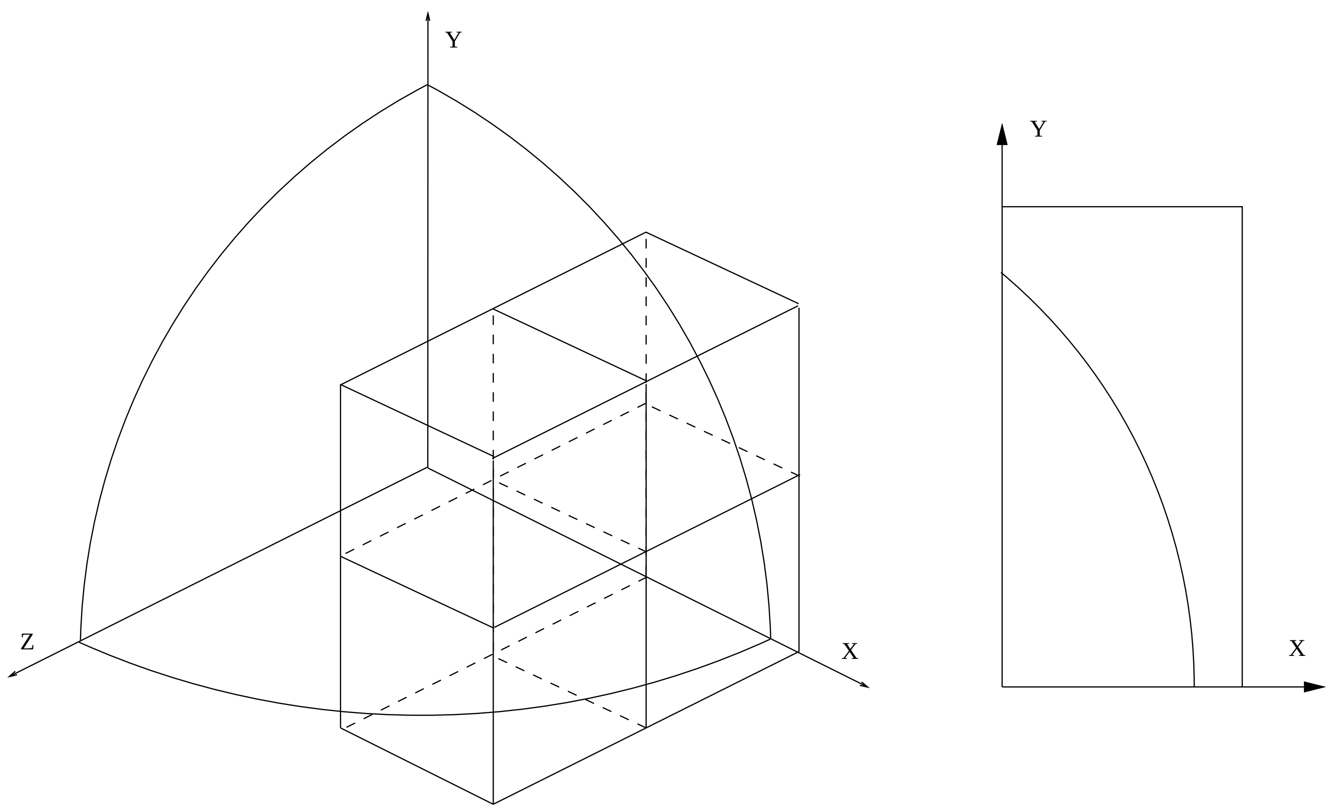
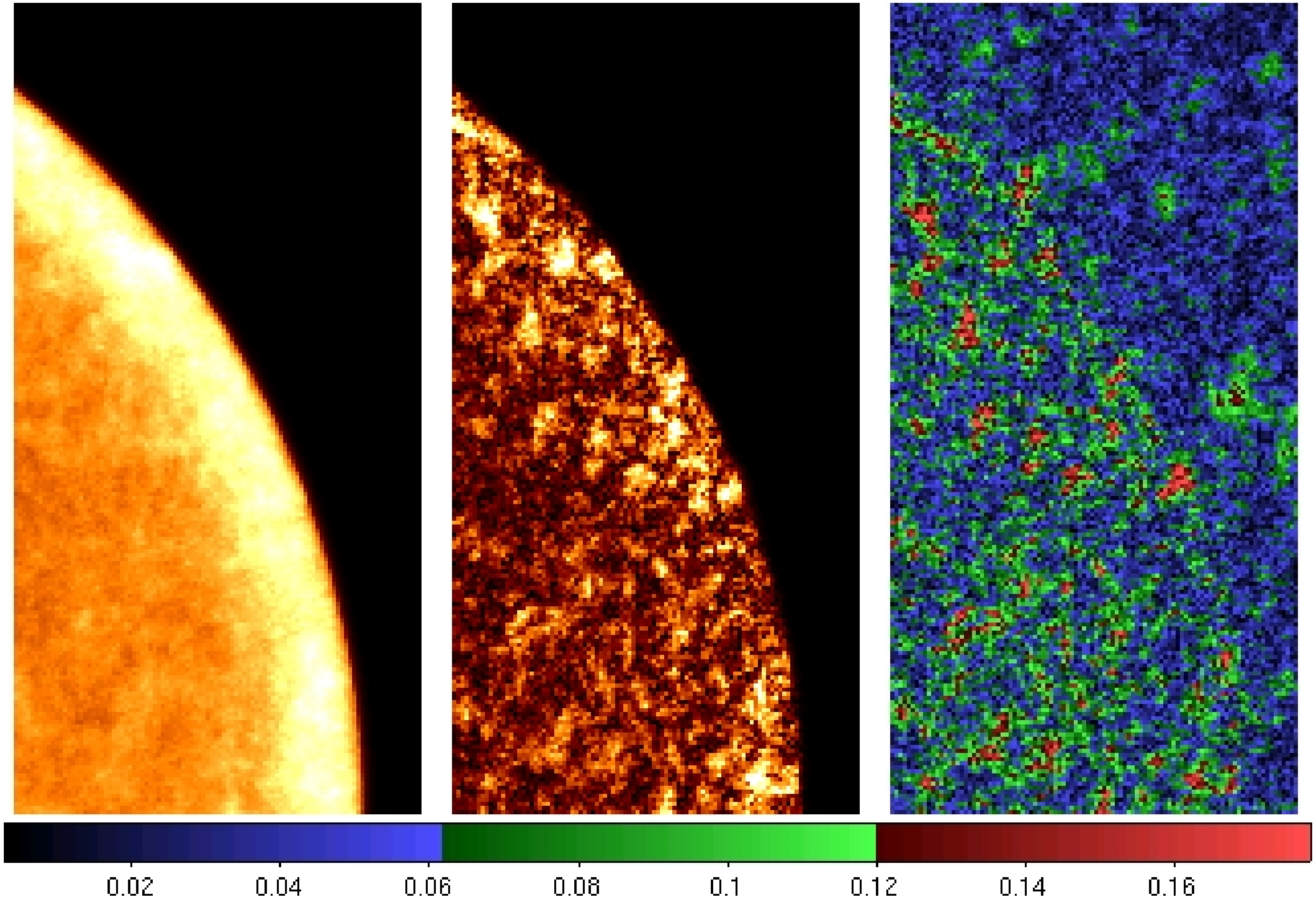


FIG. 5. Oscillation ellipse of the electric vector in a wave radiated by particles moving in a magnetic field, where the charge is taken as a positive. For negatively charged particles (electrons) the direction of rotation is opposite to that shown. The plane K is the plane of the figure (the plane perpendicular 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.

SNR shell polarized emission modeling

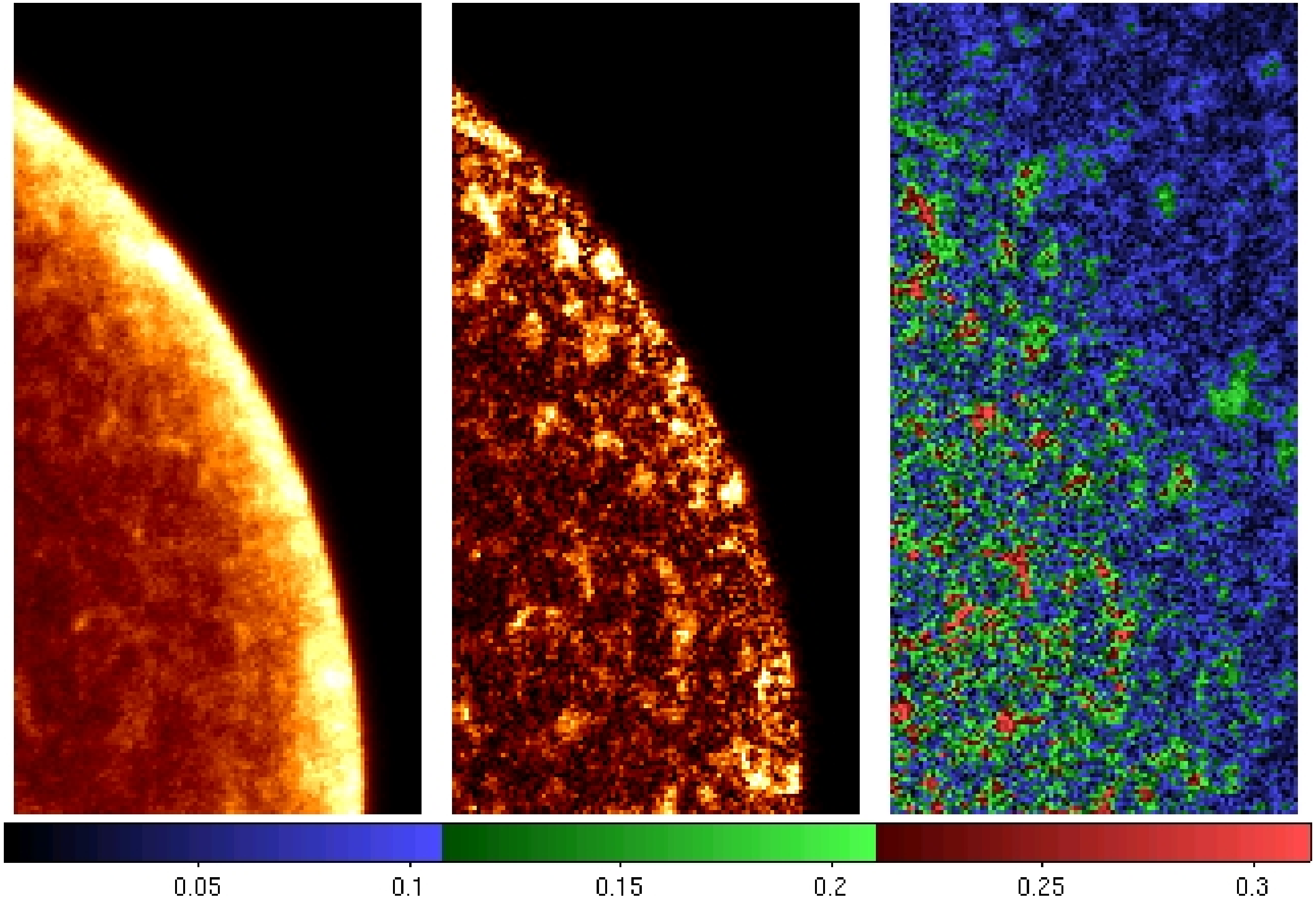


X-ray Polarization Modeling



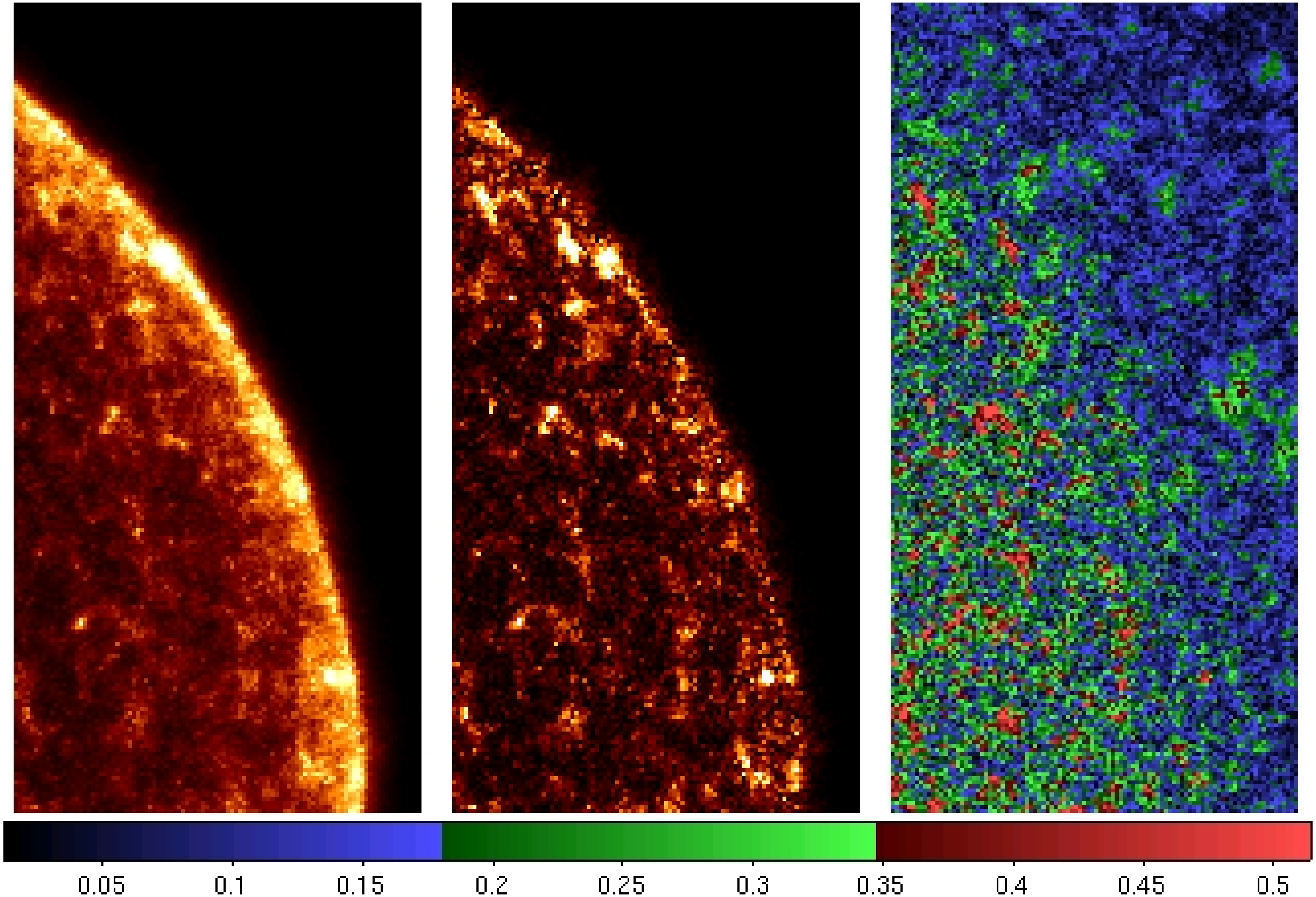
Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v.399, 2009

X-ray Polarization at 5 keV



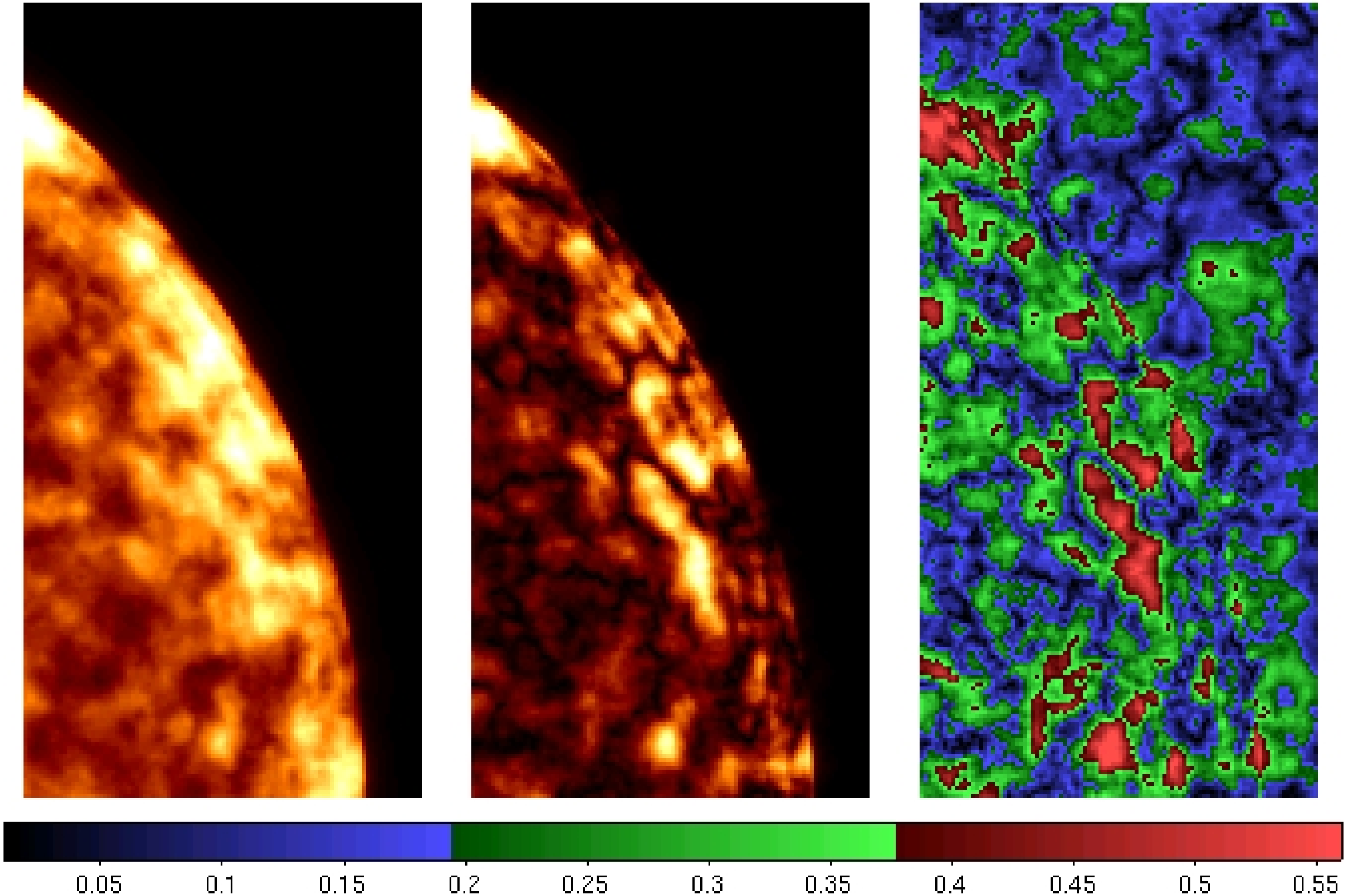
Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v399, 2009

X-ray Polarization at 50 keV

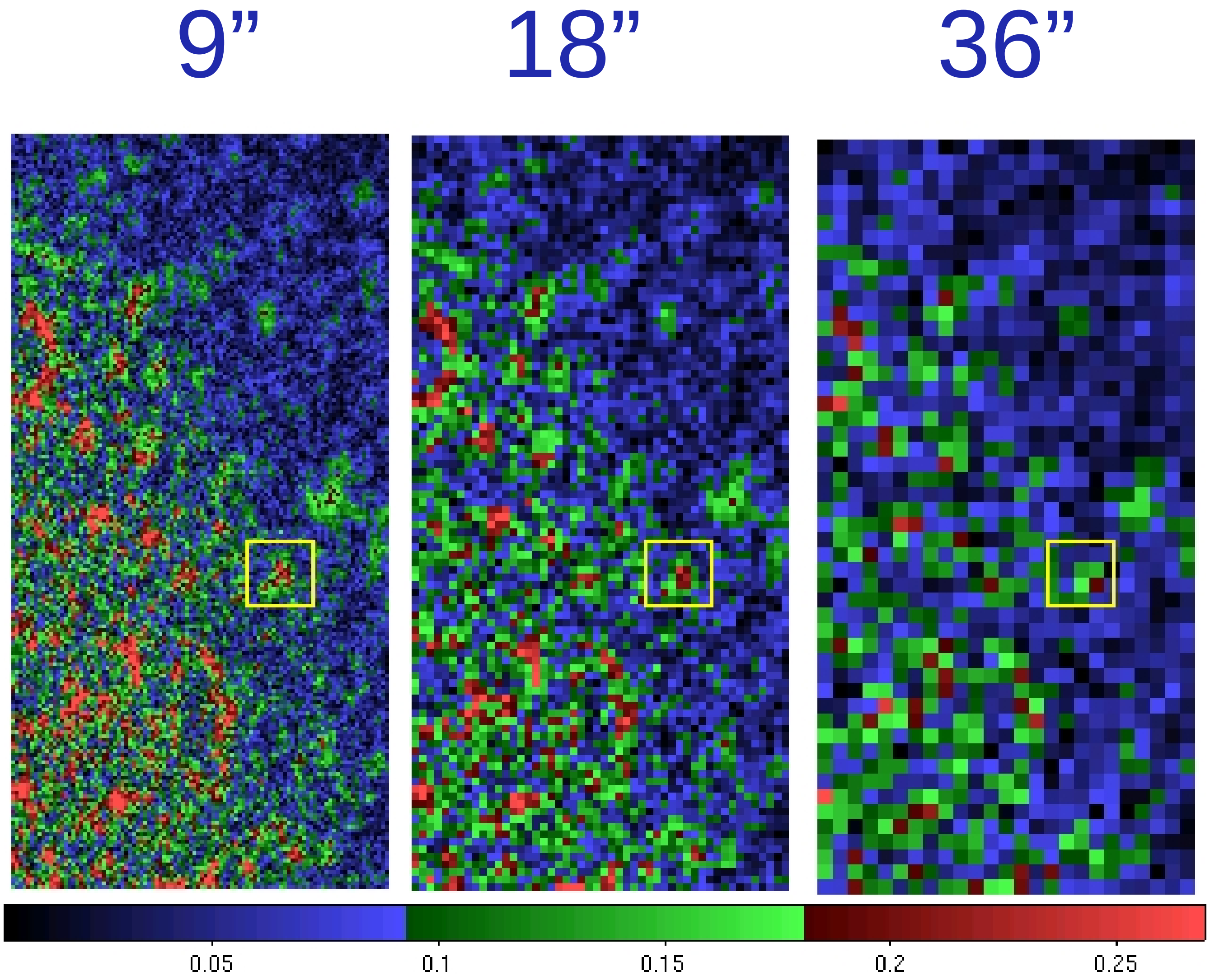


$\delta = 1.0$

X-ray Polarization @5 keV $\delta = 2.0$

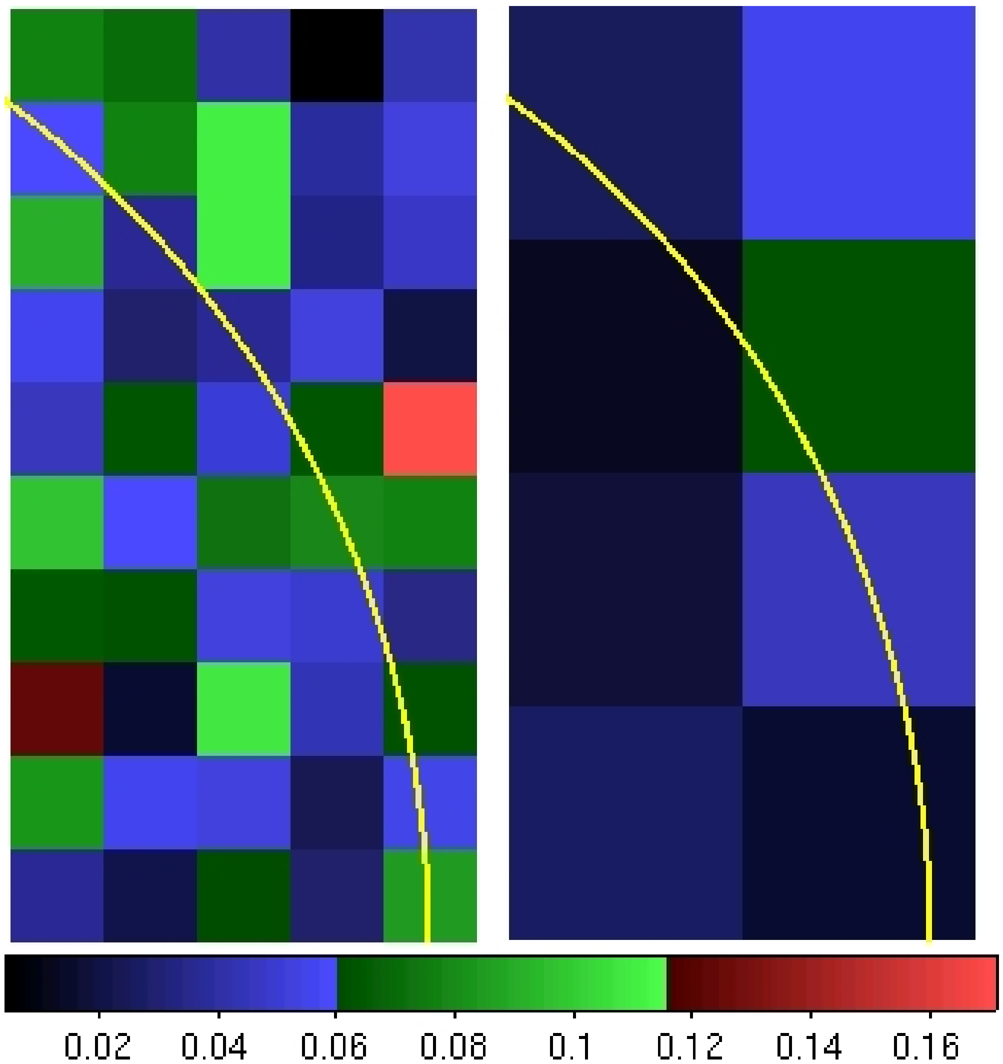


X-ray Polarimetry with IXO?



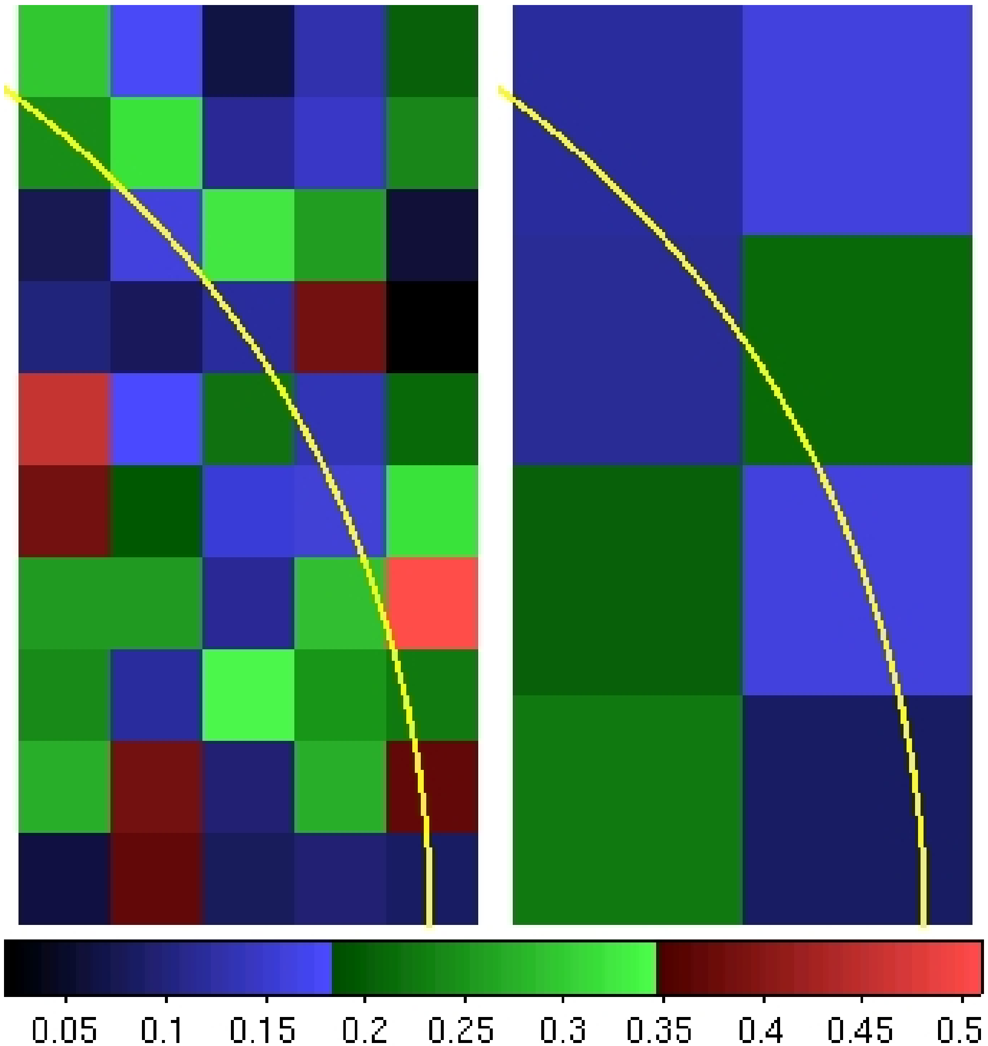
Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v.399, 2009

X-ray Polarization with GEMS?
3’ and 7.5’ pixels



$\delta = 1.0$

Pixel sizes: 3’ 7.5’



$$\delta = 2.0$$

Sensitive High Resolution X-ray Observations of Synchrotron Radiation from SNR Shells can provide unique Information on Magnetic Fluctuations and the DSA

Thank You for Attention!