Particle acceleration in supernova remnants and around massive stars

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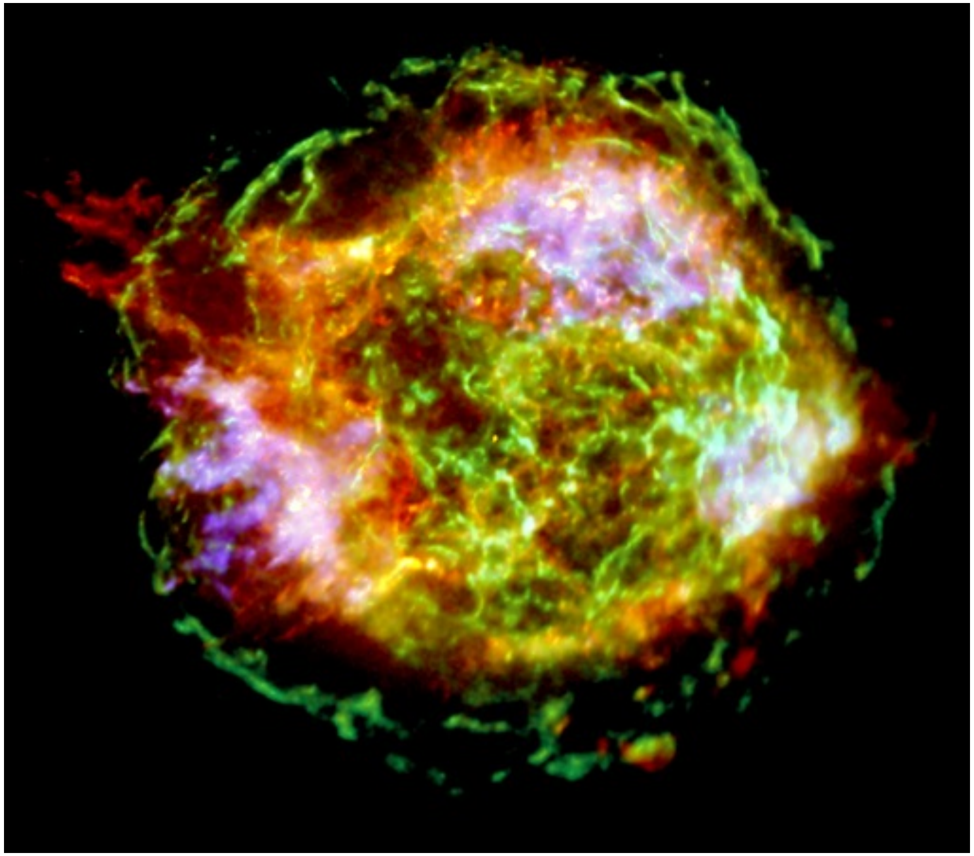
Collisionless Flows as Particle Accelerators

- There is a growing body of evidences for supernova shell flows 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

Chandra Image of Cassiopeia A



from Hwang + 2004, Jacco Vink 2009

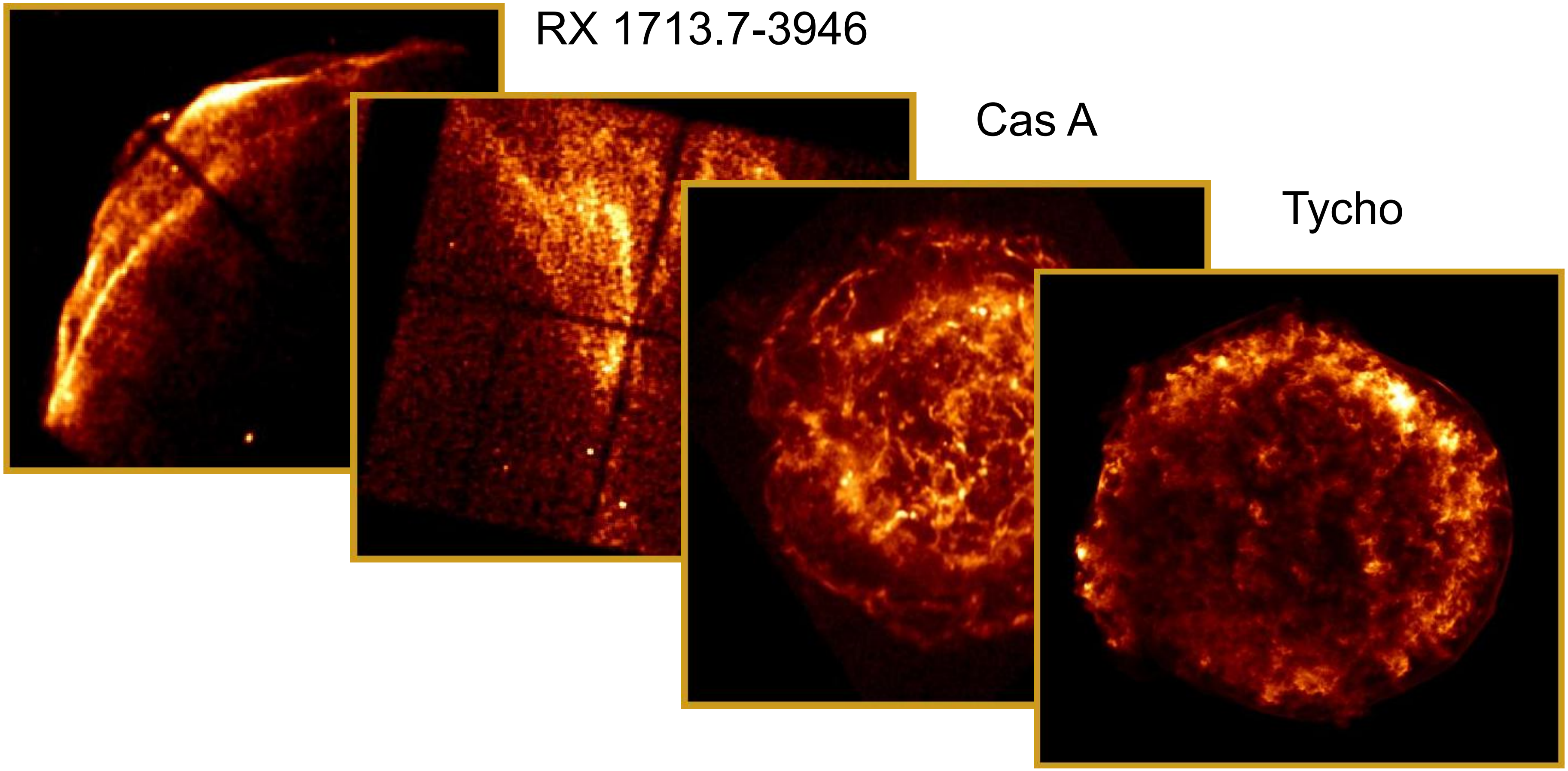
X-ray emitting synchrotron supernova remnants:

SN 1006

RX 1713.7-3946

Cas A

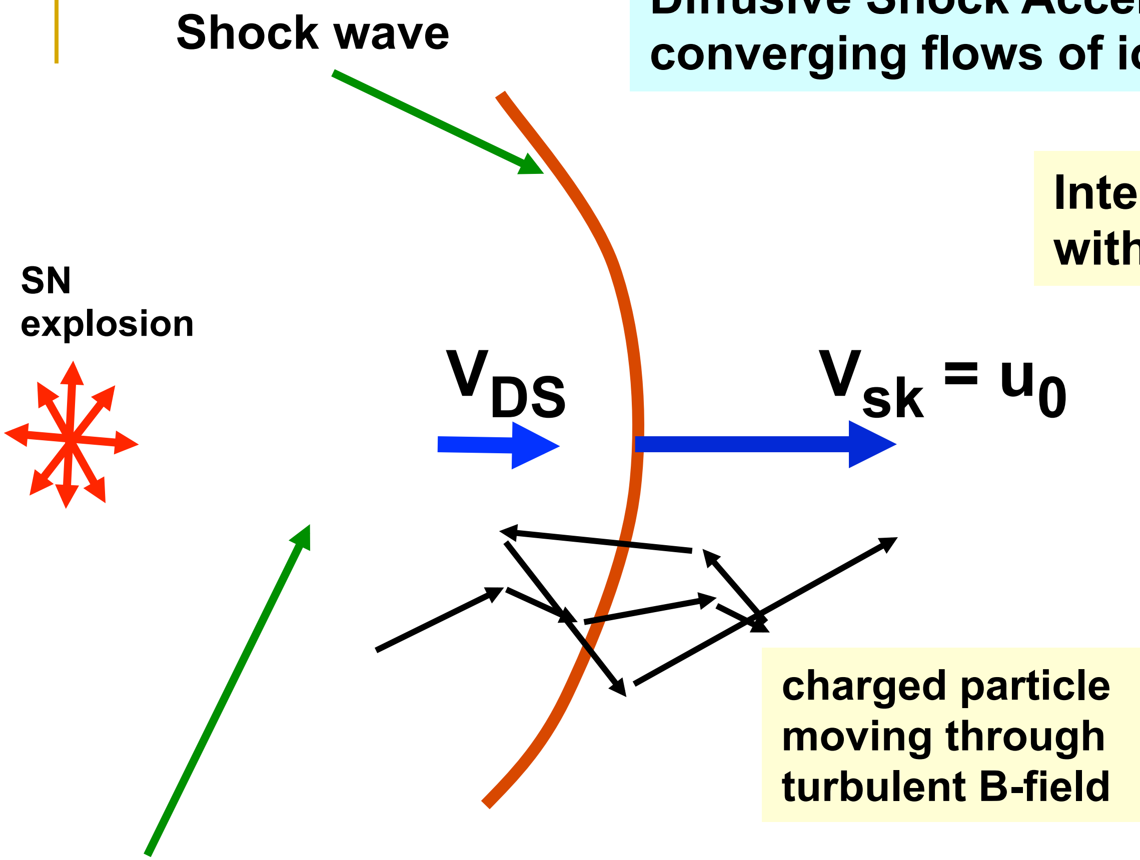
Tycho

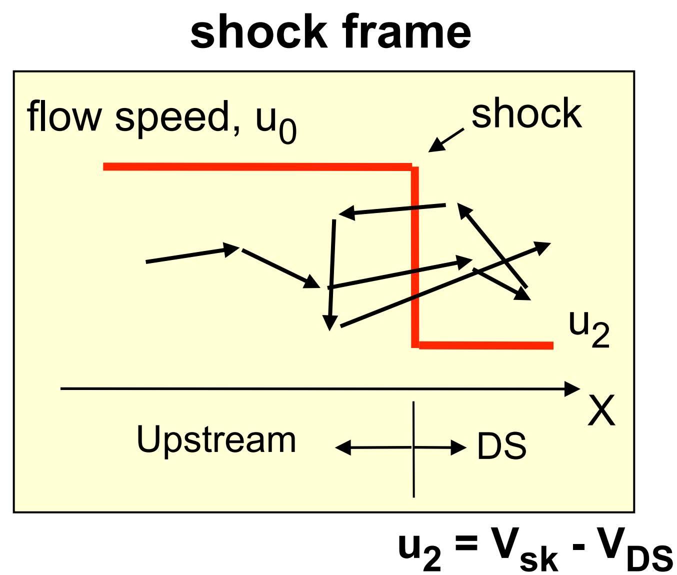


and more. And more to find.

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

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

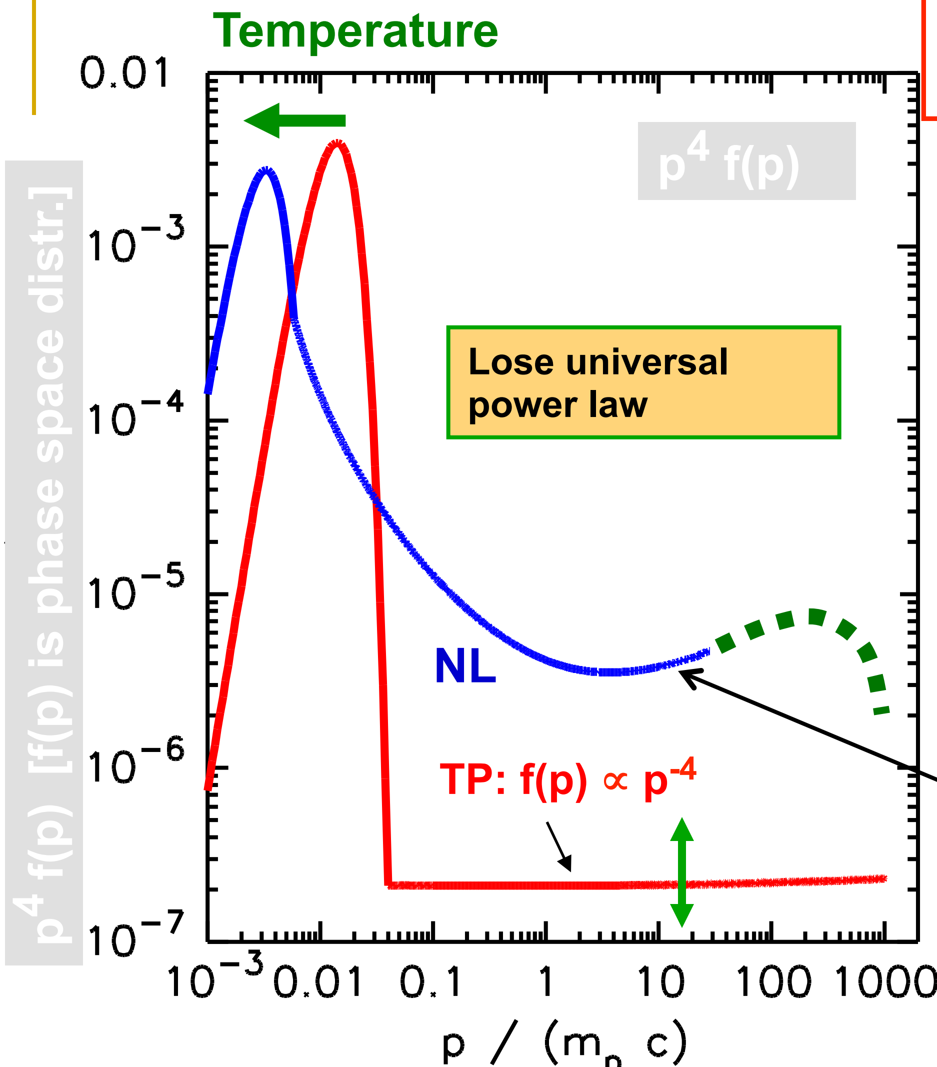


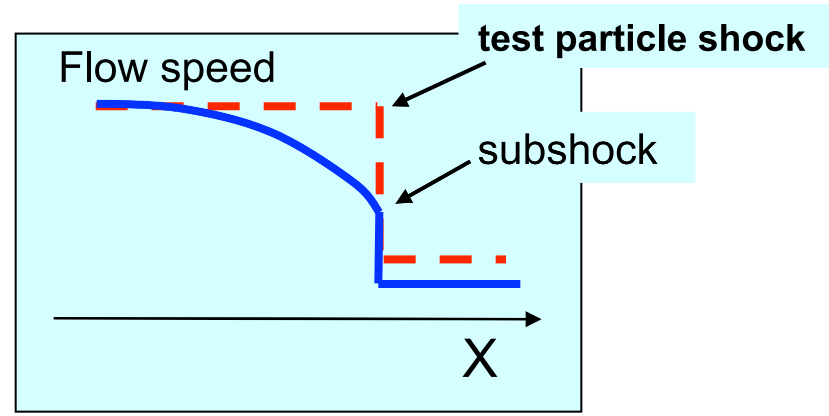


Post-shock gas → Hot, compressed, dragged along with speed $V_{DS} < V_{sk}$

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





- ► **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

DSA models in SNRs require magnetic field amplification

How to amplify magnetic fluctuations?

resonant streaming (e.g. Wentzel, Kulsrud, Skilling, Zweibel, Ptuskin, Zirakashvili ea)

non-resonant instability due to CR pressure gradient (Dorfi-Drury ea)

non-resonant CR current instabilities (Bell'04) in the shock upstream and downstream (Marcowith, Pelletier, Amato, Blasi ea)

MHD instabilities in the shock downstream

Plasma Instabilities Induced by CR Streaming

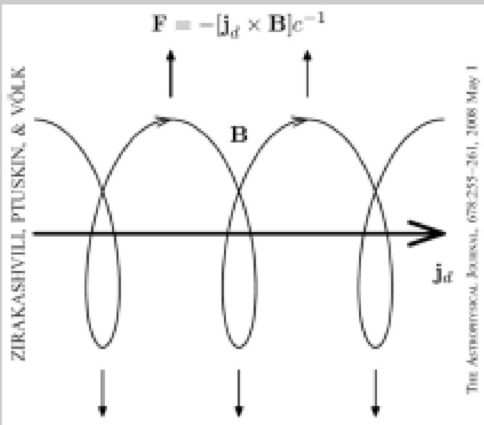
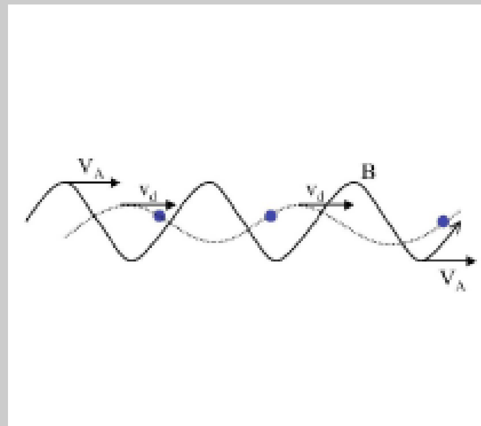
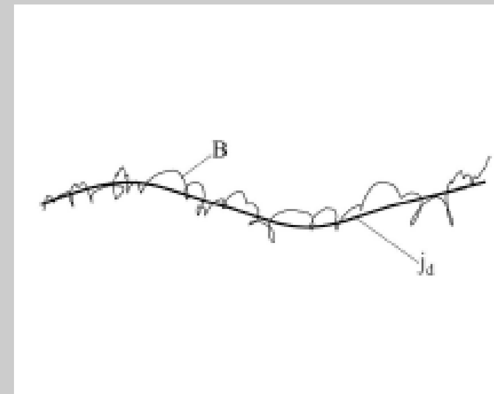


FIG. 1.—Explanation of the nonresonant streaming instability. The magnetic spiral (*thin solid line*) is stretched by the Lorentz force $F = -(j_d \times B)c^{-1}$ that appears due to the diffusive cosmic-ray electric current j_d.





short wavelength

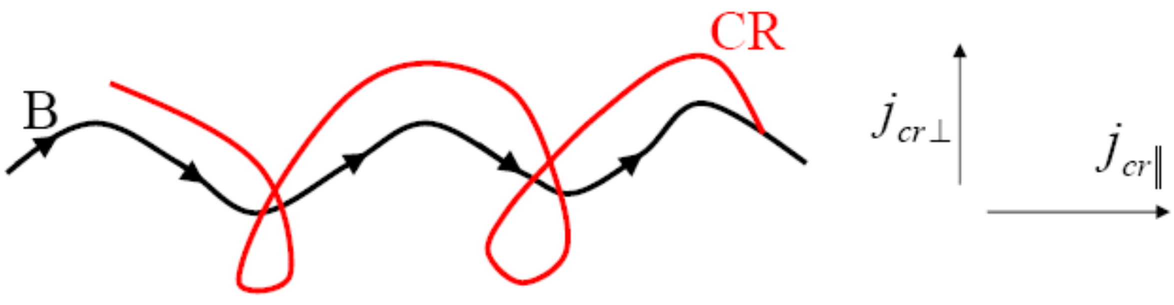
Resonant

Long-Wavelength

Non-resonant Bell instability

CR currents drive instability

$$\rho\frac{\partial u}{\partial t} = -\nabla p - \frac{1}{\mu_0}B\times(\nabla\times B) - j_{cr\perp}\times B - j_{cr\parallel}\times B$$



Resonance enhances $j_{cr\perp}$

If CR streaming along magnetic field $j_{cr\perp}\times B$ drives Alfven waves

$j_{cr\parallel}\times B$ dominates for shock acceleration in SNR

A.R.Bell 2004

CR driven instabilities

- ***the Bell's non-resonant instability is fast, but short- scale. To determine the maximal energies of cosmic rays accelerated at MHD shocks one need to know about the long-wavelength instabilities.***

Consider the plasma dynamics averaged over strong fluctuations produced by the fast small scale Bell instability

Large-scale Dynamics

$$\frac{\partial \overline{\mathbf{V}}}{\partial t} + (\overline{\mathbf{V}}\nabla)\overline{\mathbf{V}} = -\left\langle (\mathbf{v}\nabla)\mathbf{v} \right\rangle + \frac{1}{4\pi\rho}\left\langle (\nabla\times\mathbf{b})\times\mathbf{b} \right\rangle - \frac{1}{\rho}\nabla P - \frac{1}{c\,\rho}(\overline{\mathbf{j}}^{cr} - e\,n_{cr}\overline{\mathbf{V}})\times\overline{\mathbf{B}} + \frac{1}{4\pi\rho}(\nabla\times\overline{\mathbf{B}})\times\overline{\mathbf{B}},$$

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = c\nabla\times\overline{\boldsymbol{\mathcal{E}}} + \nabla\times(\overline{\mathbf{V}}\times\overline{\mathbf{B}}) + \nu_m \Delta\overline{\mathbf{B}}.$$

$\mathcal{E} = \dfrac{1}{c}\left\langle \mathbf{v}\times\mathbf{b} \right\rangle$ – *the mean* **electromotive force** .

Large-scale Dynamics and ponderomotive forces

$$\frac{\partial\overline{\mathbf{V}}}{\partial t}+(\overline{\mathbf{V}}\nabla)\overline{\mathbf{V}}=-\frac{1}{\rho}\nabla P-\frac{1}{c\,\rho}((\overline{\mathbf{j}}^{cr}-e\,n_{cr}\overline{\mathbf{V}})\times\overline{\mathbf{B}})+\frac{1}{4\pi\rho}((\nabla\times\overline{\mathbf{B}})\times\overline{\mathbf{B}})+$$

$$+\frac{\eta_t}{c\rho}(\overline{j}_x^{cr}\mathbf{e}_y-\overline{j}_y^{cr}\mathbf{e}_x)+\frac{\zeta_t}{c\rho}\left(\frac{\partial\overline{j}_x^{cr}}{\partial x}\mathbf{e}_z+\frac{\partial\overline{j}_y^{cr}}{\partial y}\mathbf{e}_z-\frac{\partial\overline{j}_z^{cr}}{\partial x}\mathbf{e}_x-\frac{\partial\overline{j}_z^{cr}}{\partial y}\mathbf{e}_y\right)+\tau_{cor}\langle\mathbf{v}\cdot\nabla\times\mathbf{v}\rangle\left(\frac{\partial\overline{V}_z}{\partial y}\mathbf{e}_x-\frac{\partial\overline{V}_z}{\partial x}\mathbf{e}_y\right)+$$

$$+\tau_{cor}\frac{\langle v^2\rangle}{2}\left(\frac{\partial^2\overline{\mathbf{V}}}{\partial x^2}+\frac{\partial^2\overline{\mathbf{V}}}{\partial y^2}\right)+\nu\nabla\overline{\mathbf{V}}-\frac{1}{c\,\rho}\langle(\mathbf{j}^{cr}-e\,n_{cr}\mathbf{v})\times\mathbf{b}\rangle\ldots,$$

$$\eta_t=\tau_{cor}\int_0^\infty dk_z\frac{1}{\sqrt{4\pi\rho}}\sqrt{k_1|k_z|}\langle\mathbf{b}^2(k_z)\rangle \qquad \zeta_t=\tau_{cor}\int_0^\infty dk_z\frac{1}{\sqrt{4\pi\rho}}\sqrt{\frac{k_1}{|k_z|}}\langle\mathbf{b}^2(k_z)\rangle$$

AB+, 2009,2011

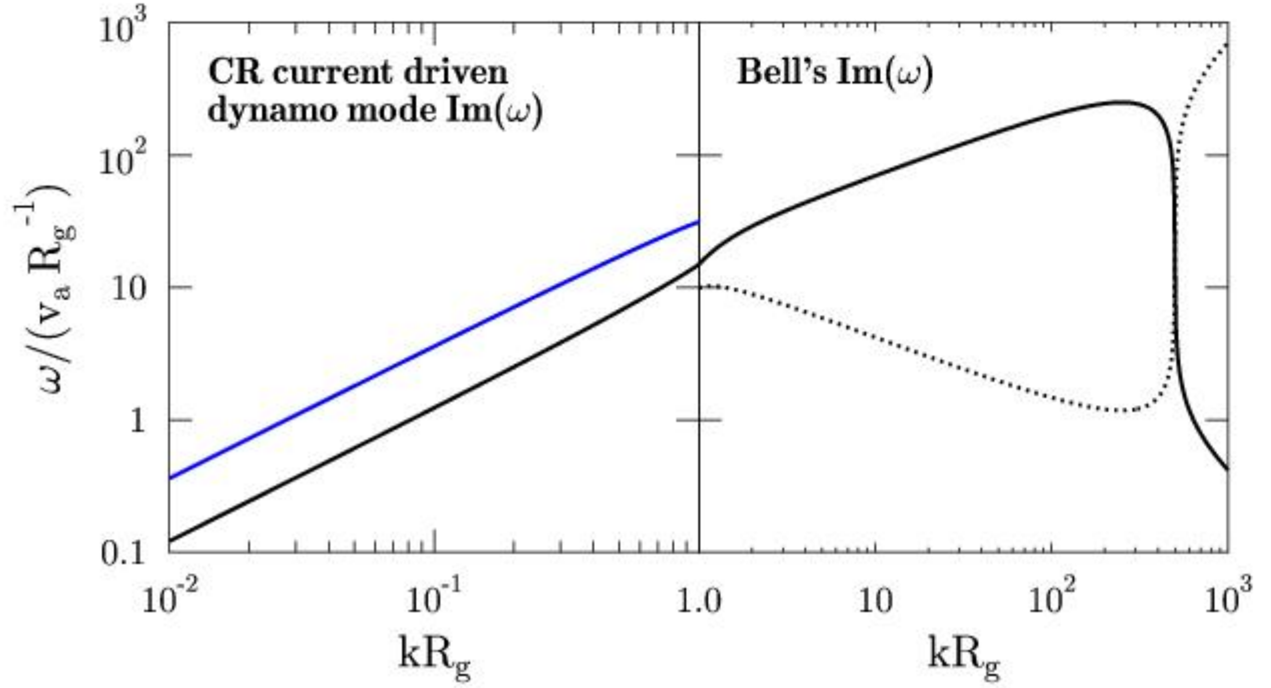
$$c\frac{\partial \overline{\mathcal{E}}}{\partial t} = \left\langle \frac{\partial \mathbf{v}}{\partial \mathbf{t}} \times \mathbf{b} \right\rangle + \left\langle \mathbf{v} \times \frac{\partial \mathbf{b}}{\partial \mathbf{t}} \right\rangle.$$

E.Blackman & G.B.Field, 2002

CR driven instabilities

- ***the ponderomotive forces result in long-wavelength instability that is slower than the short-wavelength Bell instability but fast enough to influence E_{max} of CRs in DSA***

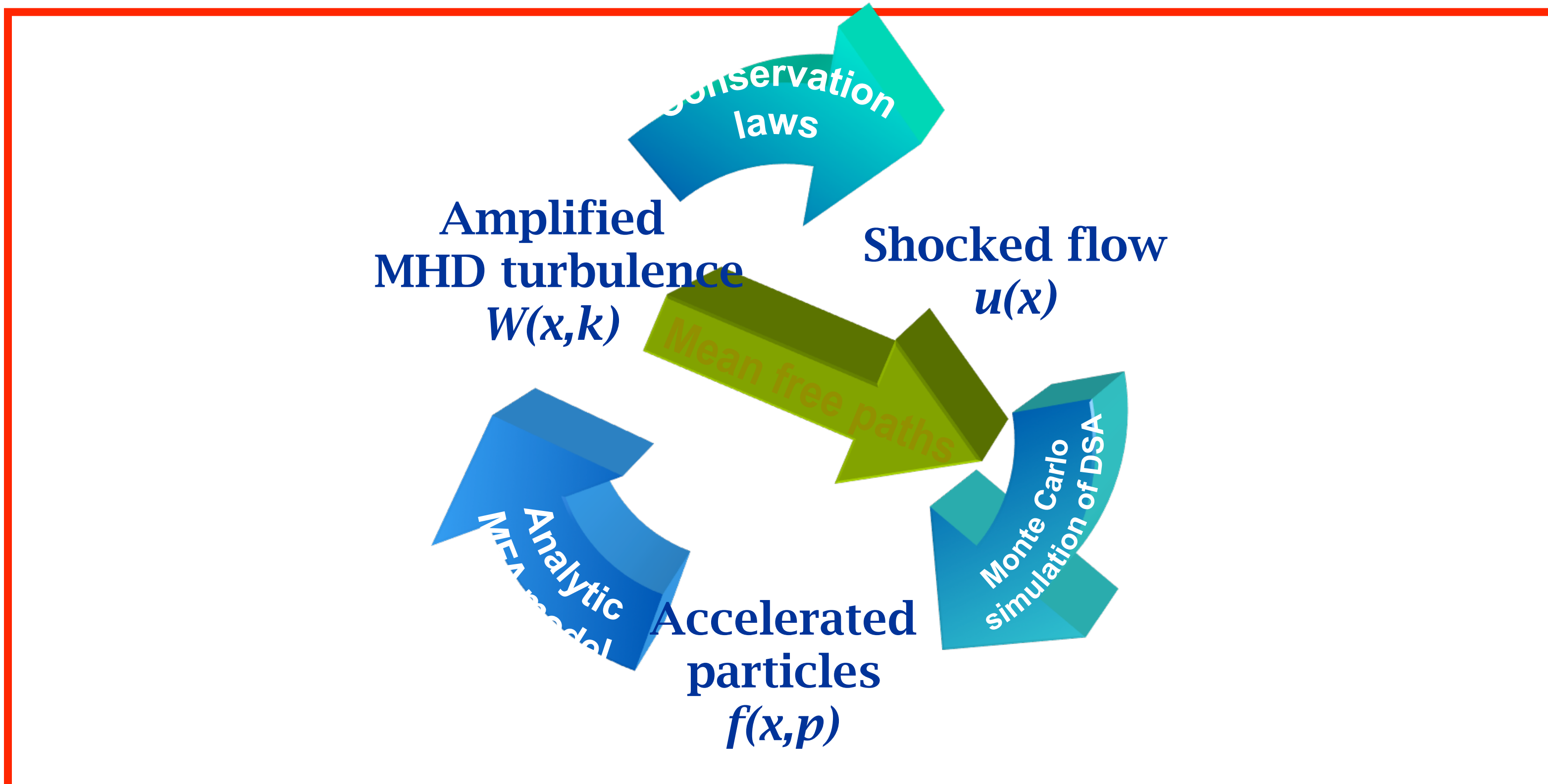
Magnetic field amplification rates



AB+11

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

Method

The Nonlinear Model

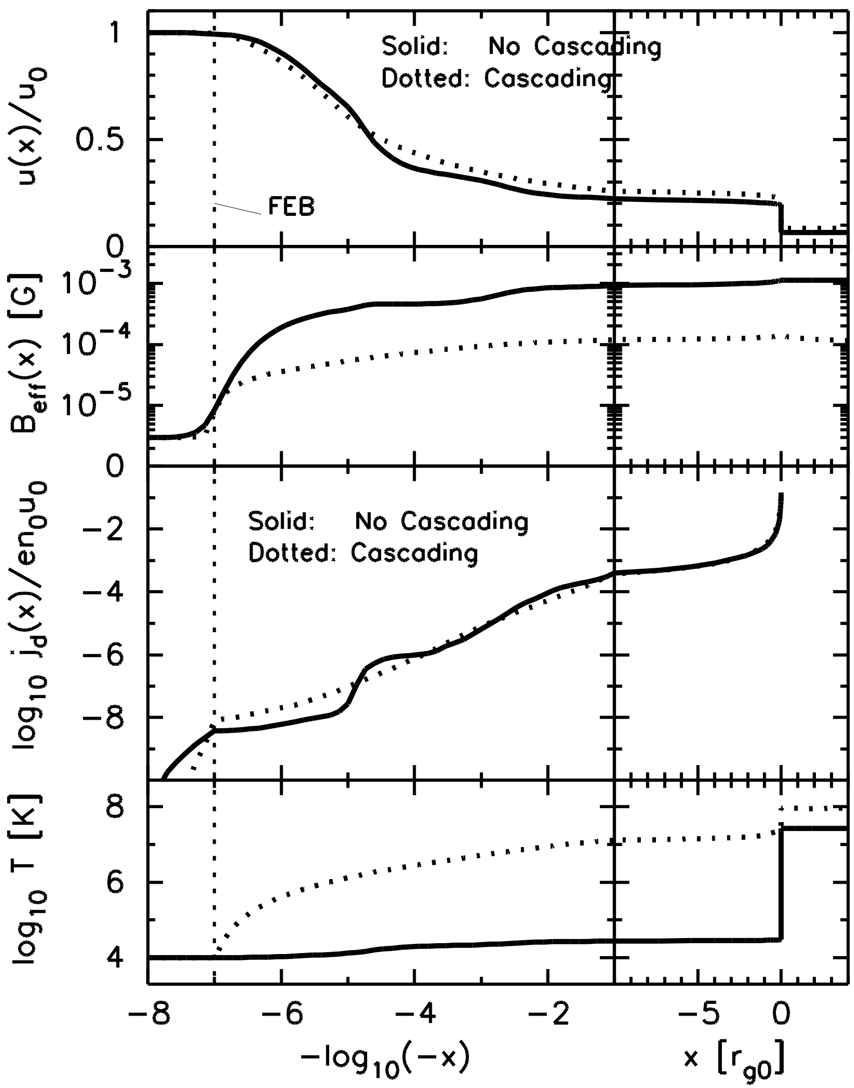
- Particle transport modeled with a **Monte Carlo simulation**;
- **Analytic, semi-phenomenological description** for magnetic field amplification, self-consistently coupled to CR distribution and MHD flow;
- Fundamental **conservation laws** used to iteratively derive a nonlinear shock modification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

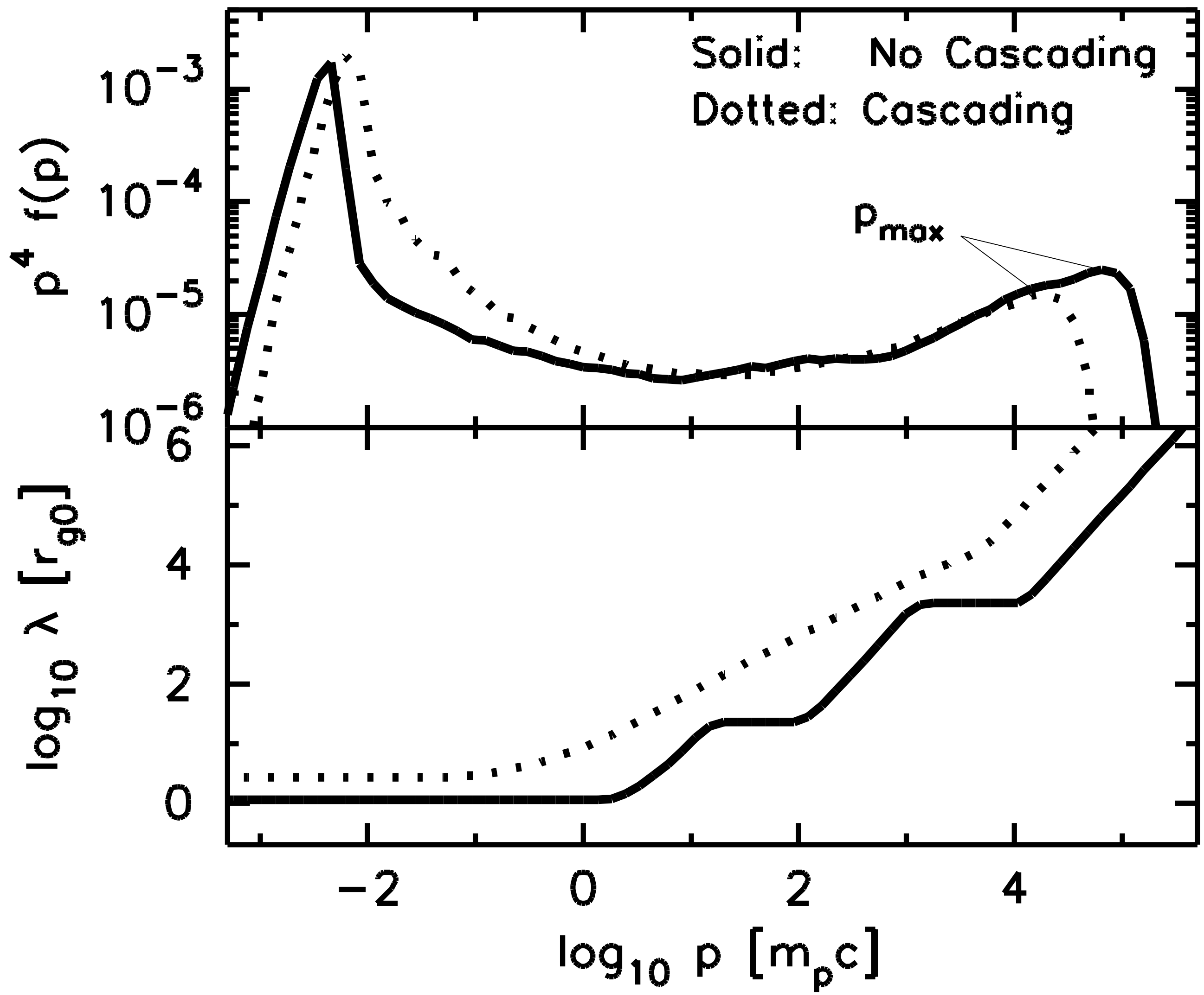
Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

CR modified shock

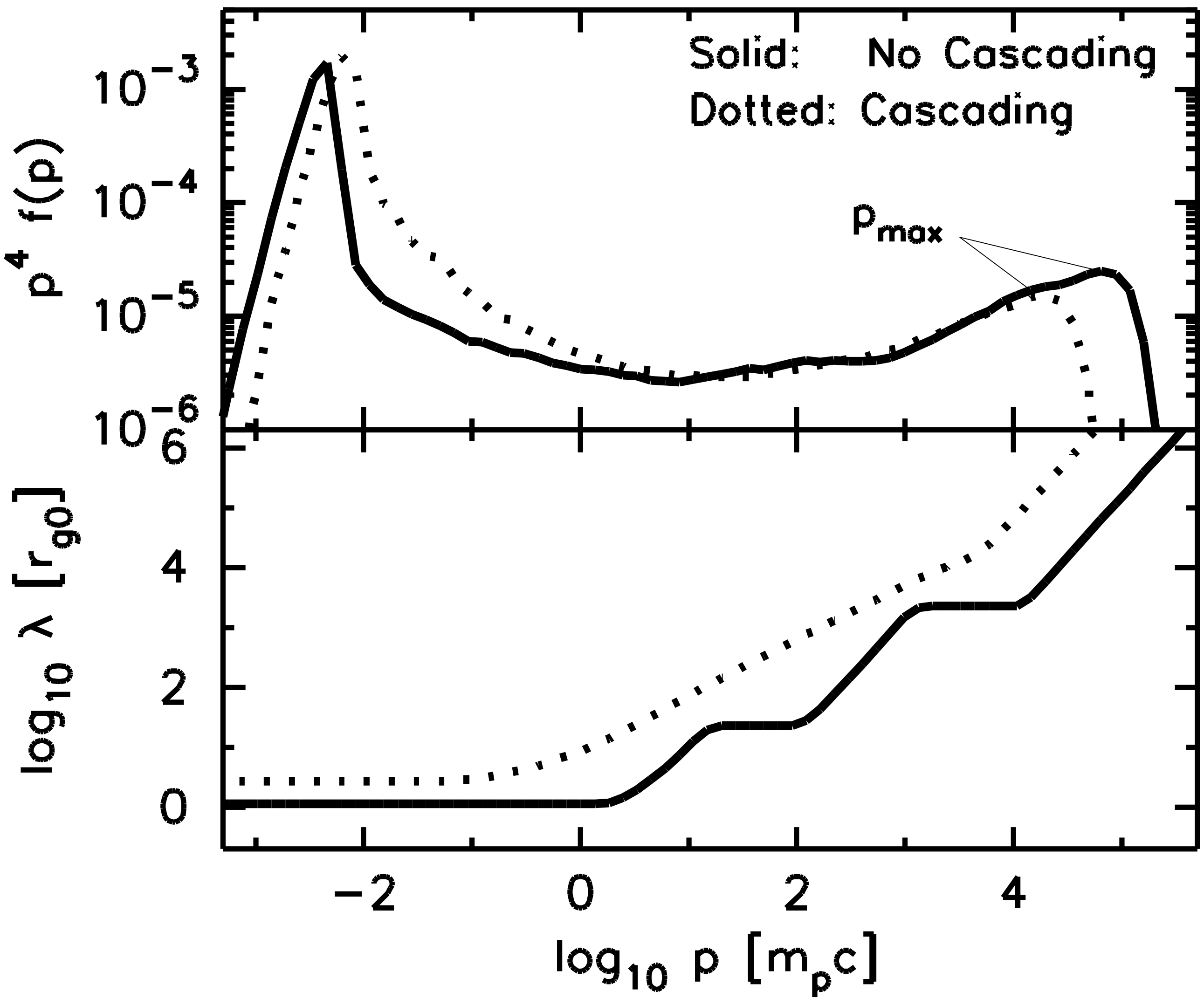


- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

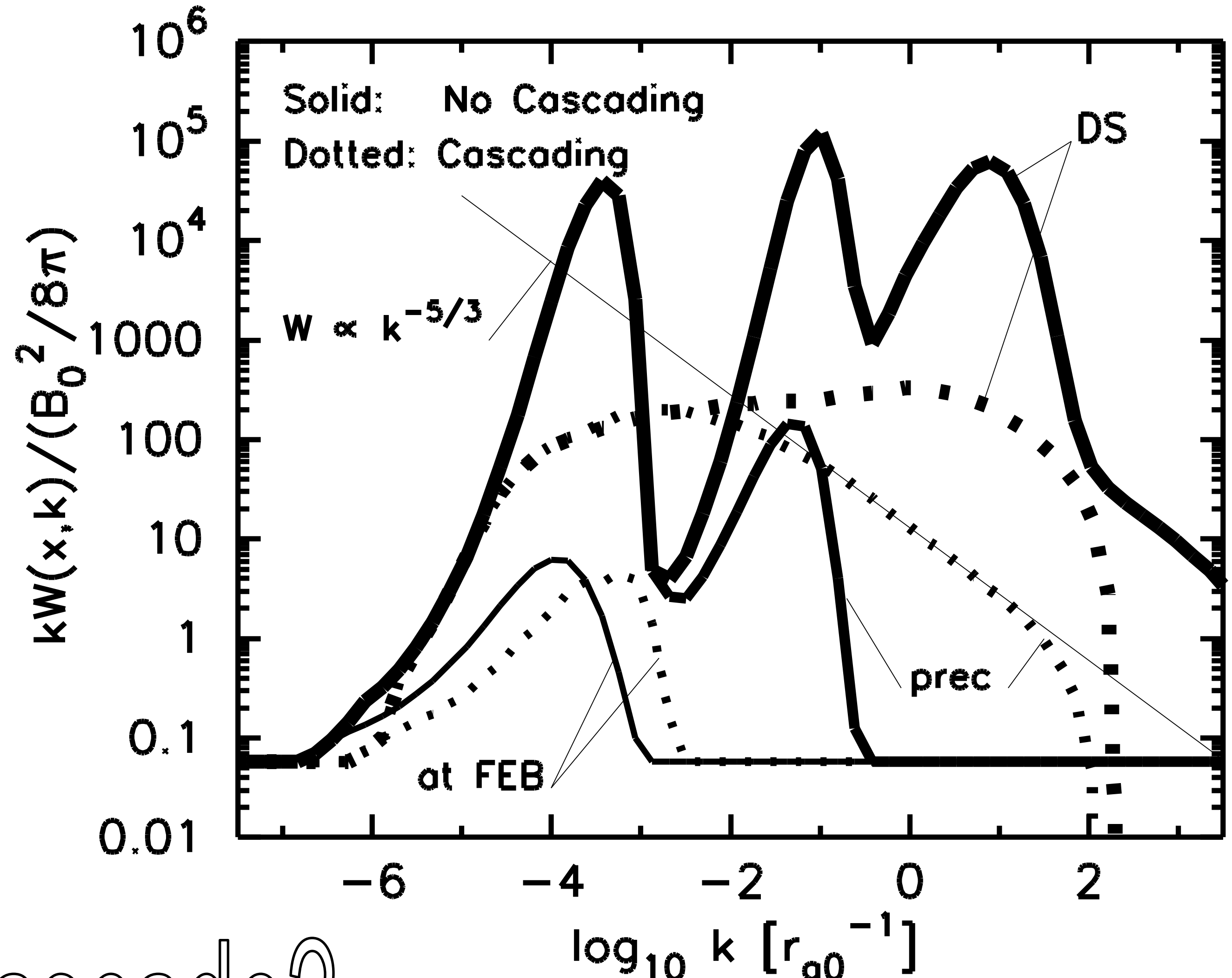
Particle Spectra



Particle Spectra



Magnetic Fluctuation Spectra



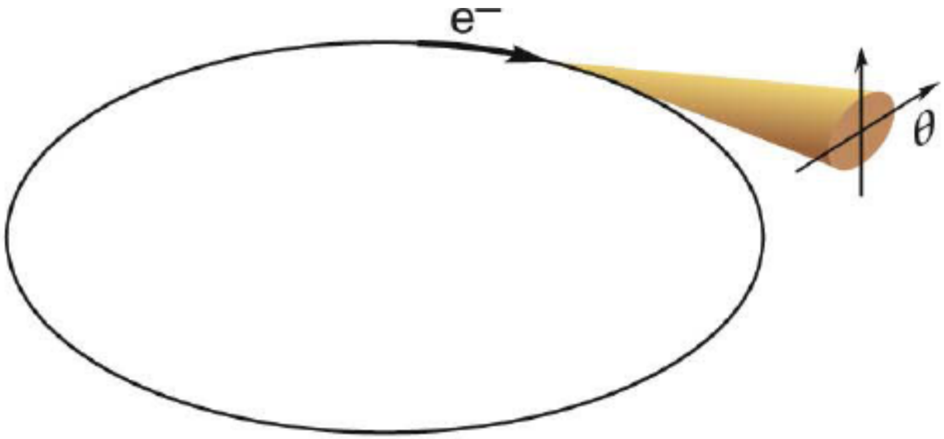
No cascade?

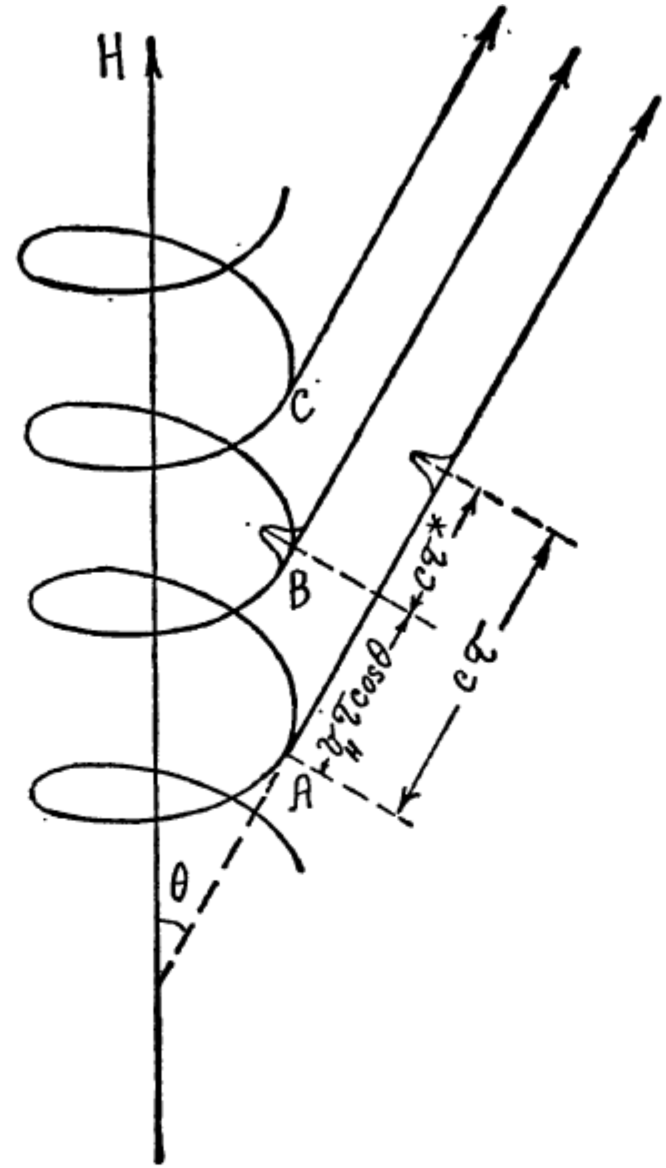
- Vladimirov, Bykov & Ellison, 2009. ApJ, v. 703, L29

How do the stochastic magnetic fields affect the X-ray synchrotron emission in SNRs?

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

Synchrotron Radiation:





e.g. Ginzburg and Syrovatskii 1969

The Synchrotron radiation is polarized

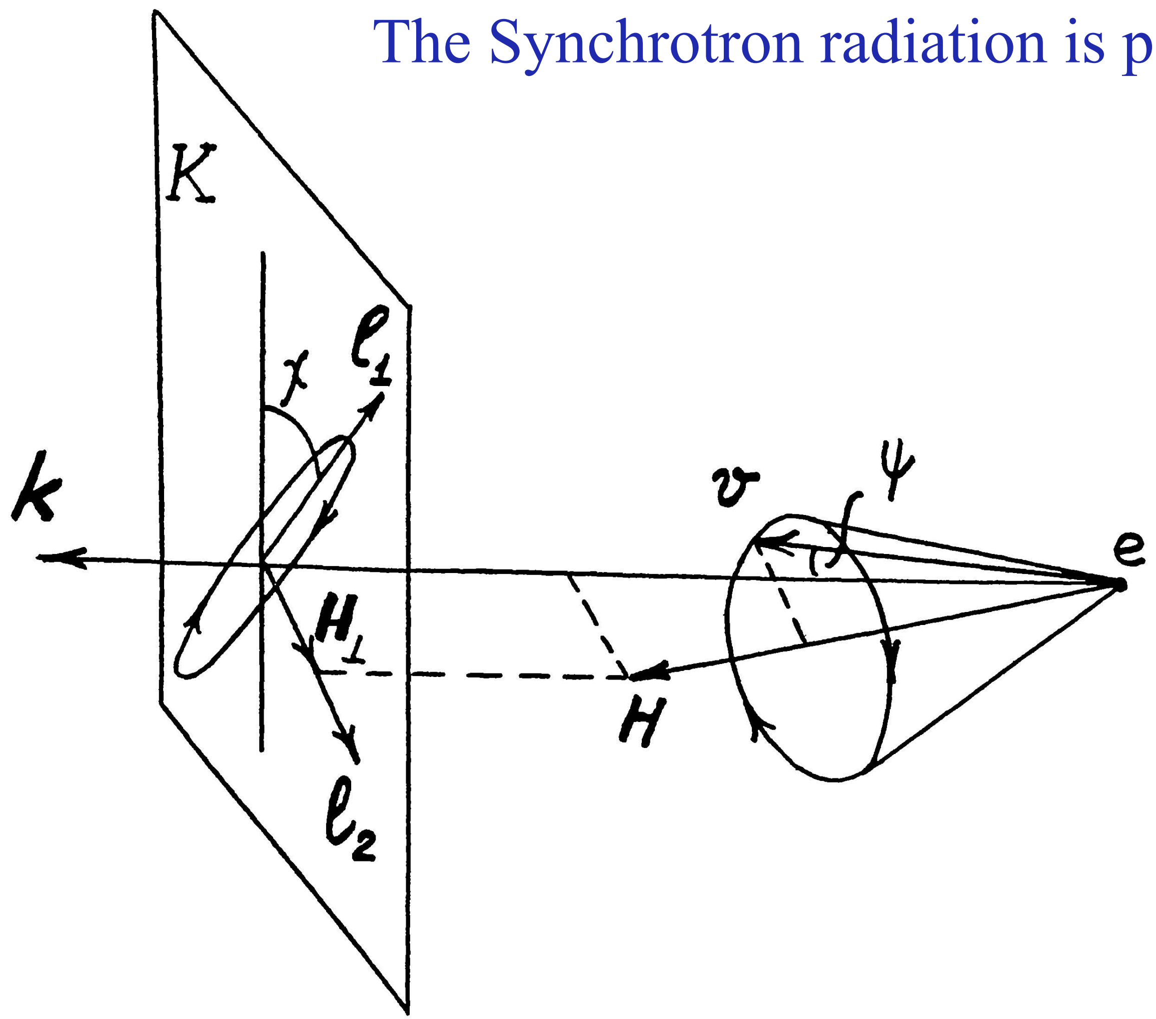
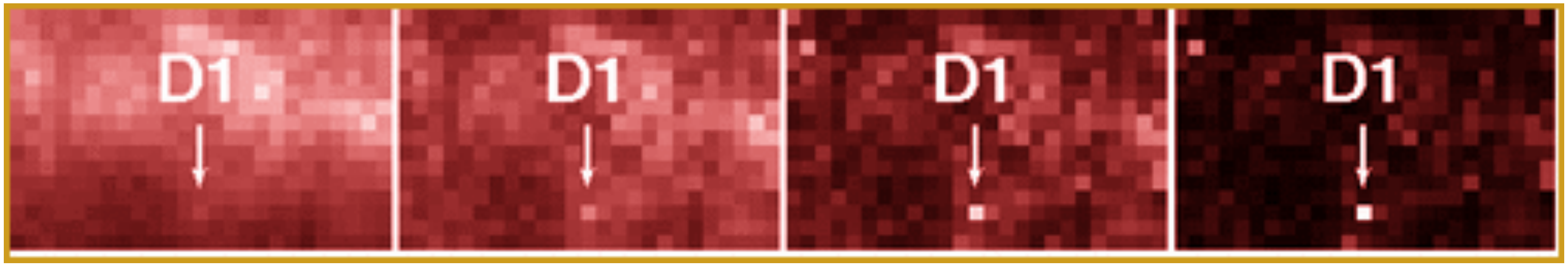


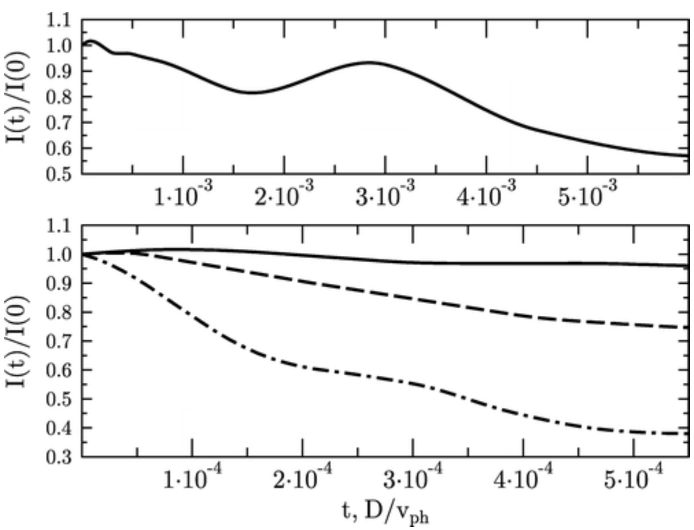
FIG. 5. Oscillation ellipse of the electric vector in a wave radiated by particles moving in a magnetic field, where the charge is taken as a positive. For negatively charged particles (electrons) the direction of rotation is opposite to that shown. The plane K is the plane of the figure (the plane perpendicular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

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

Time evolution. Lightcurves.

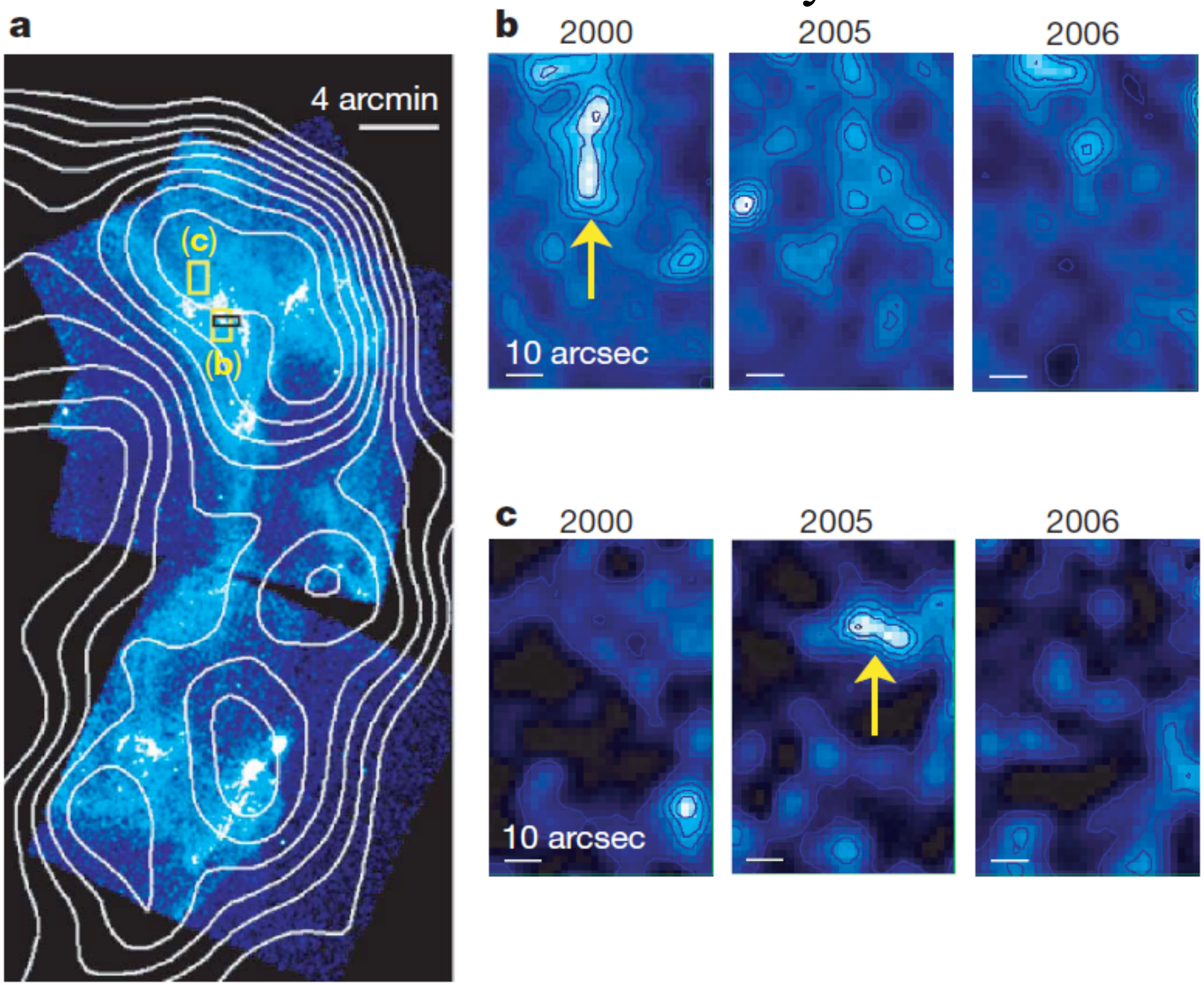




Synchrotron X-ray images at energies 0.5, 5, 20, 50 keV (from left to right). Dot like feature D1 is clearly seen at high energies and it is smeared in at low energies. Left panels show lightcurves of D1 feature at 5 keV (solid curve), 20 keV (dashed curve) and 50 keV (dot-dashed curve).

AB+ ApJL 2008

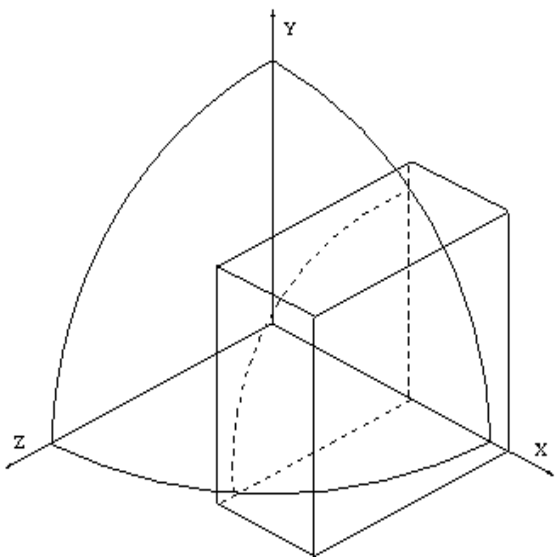
Uchiyama Aharonian et al. 2007

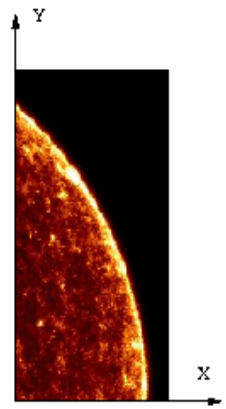


Nonthermal clump "lifetime" ~ 1yr

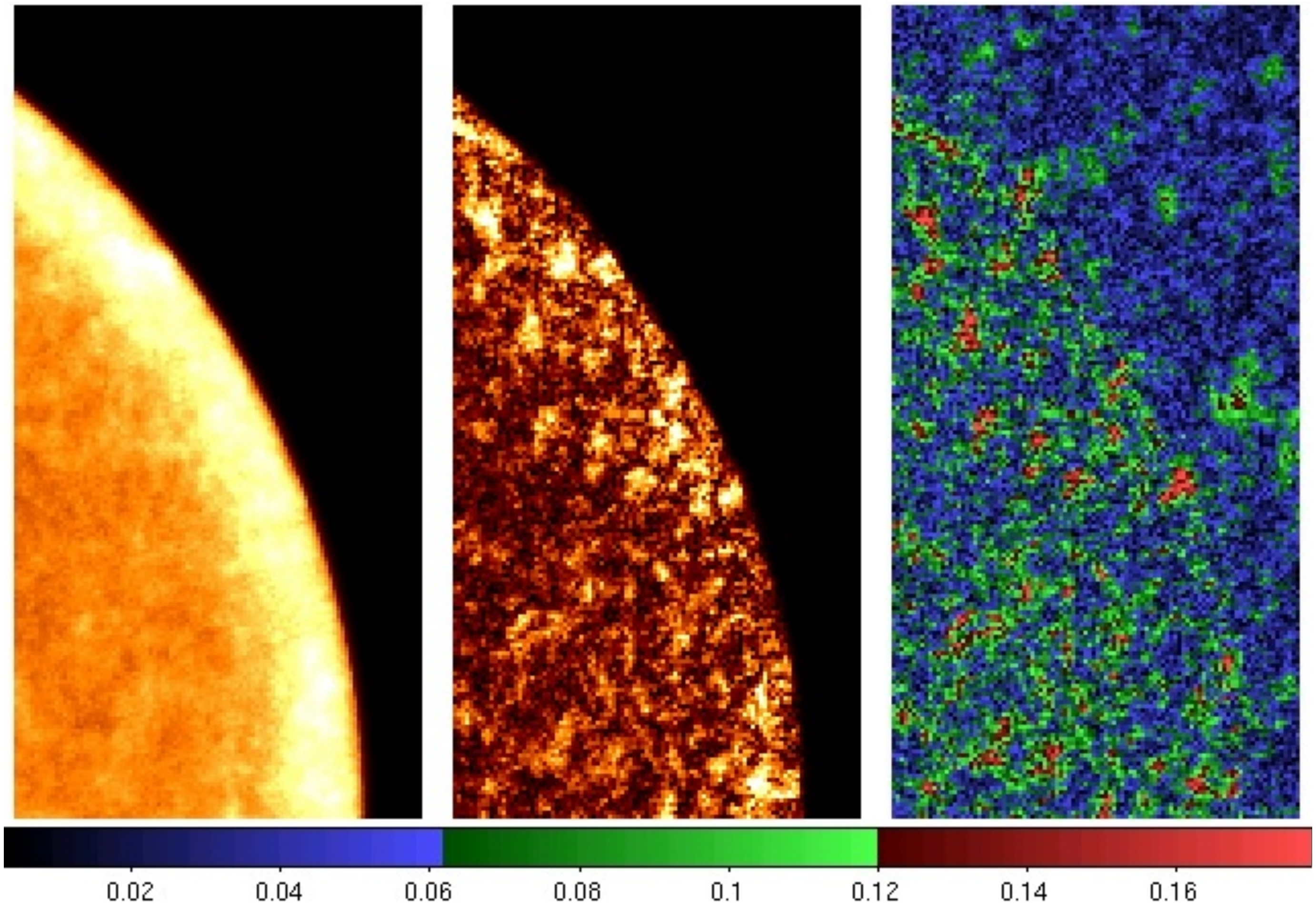
It can be produced with magnetic field well below 1 mG ..

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



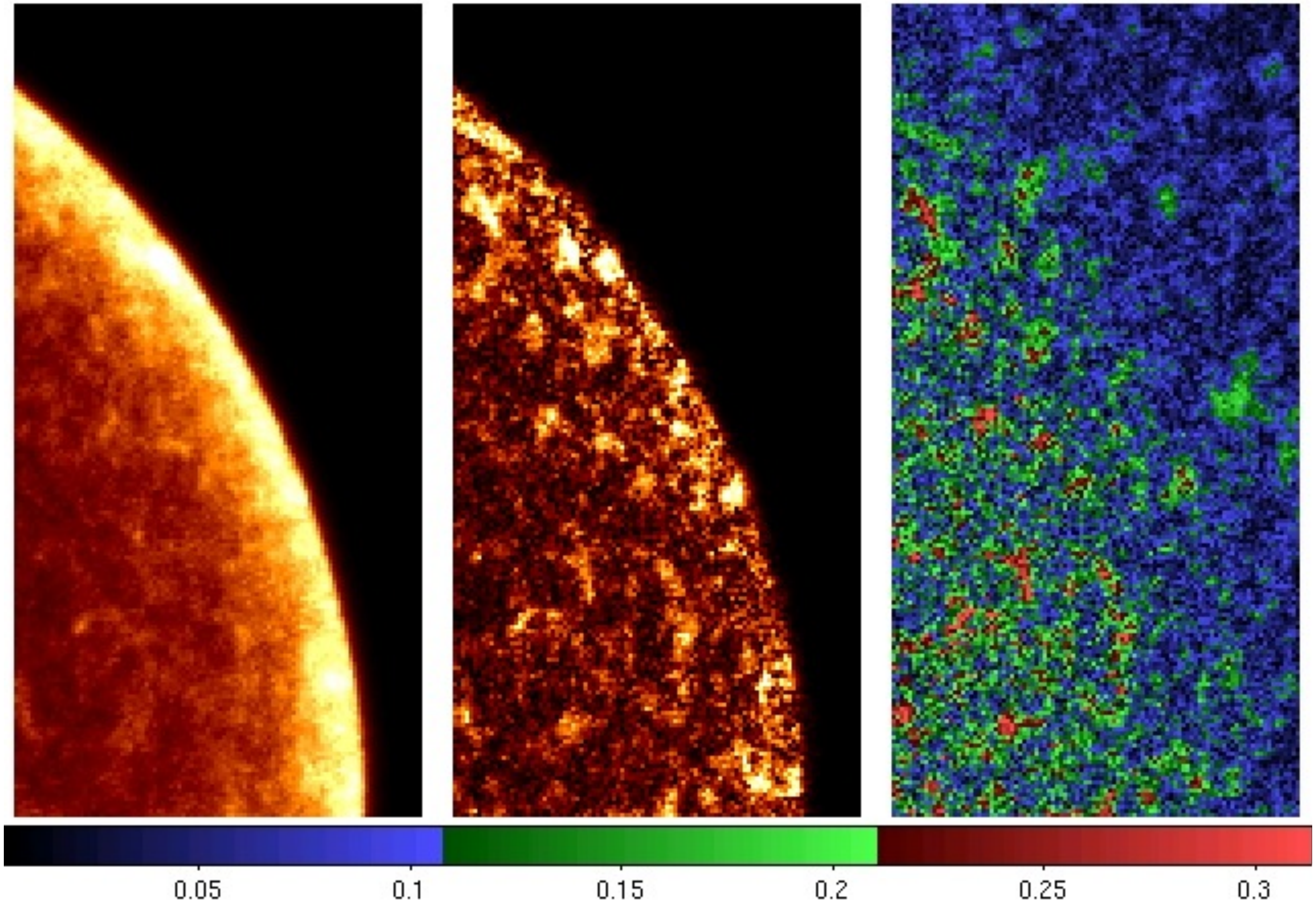


X-ray Polarization Modeling



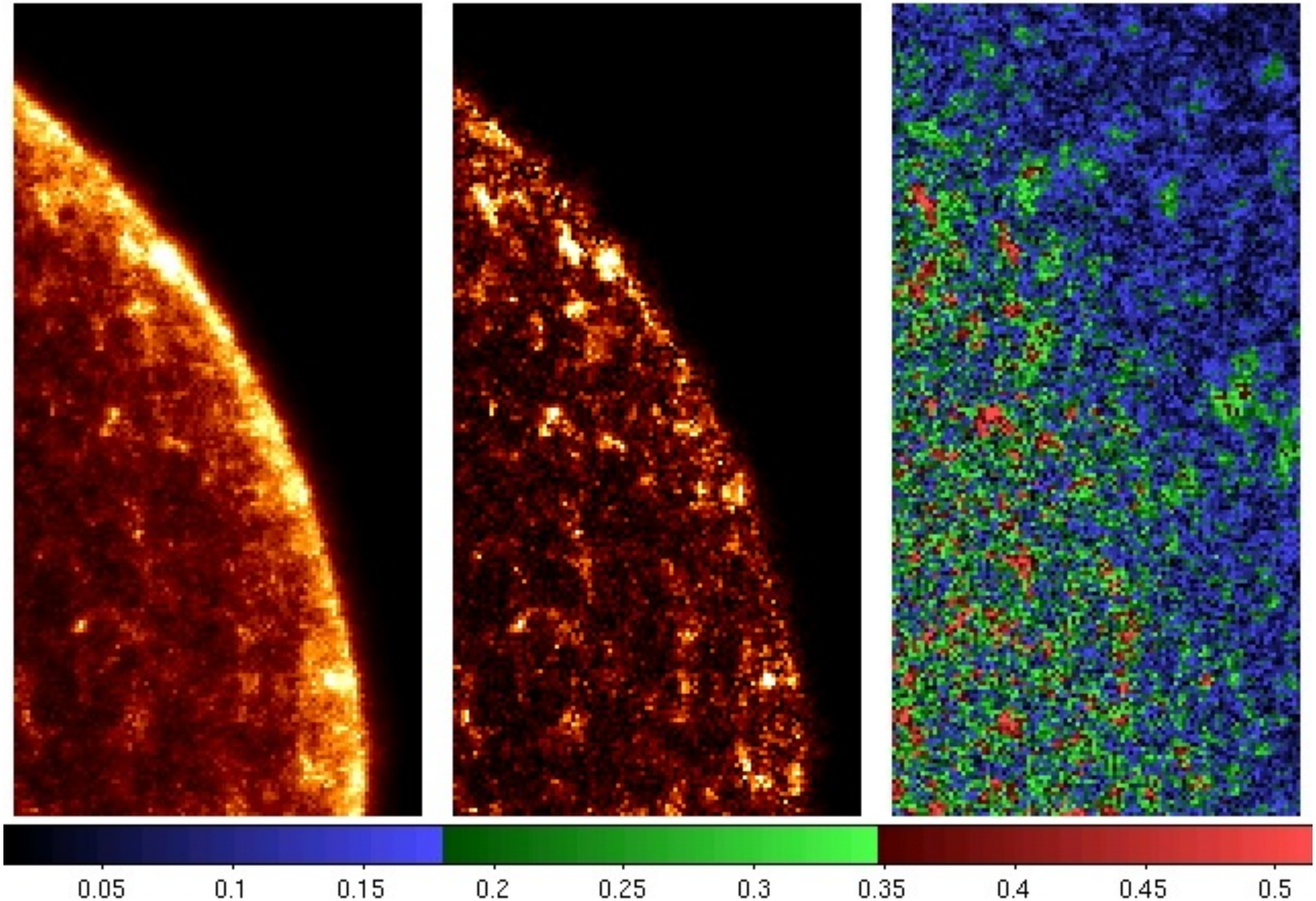
Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v.399, 2009

X-ray Polarization at 5 keV



MNRAS v399, 2009

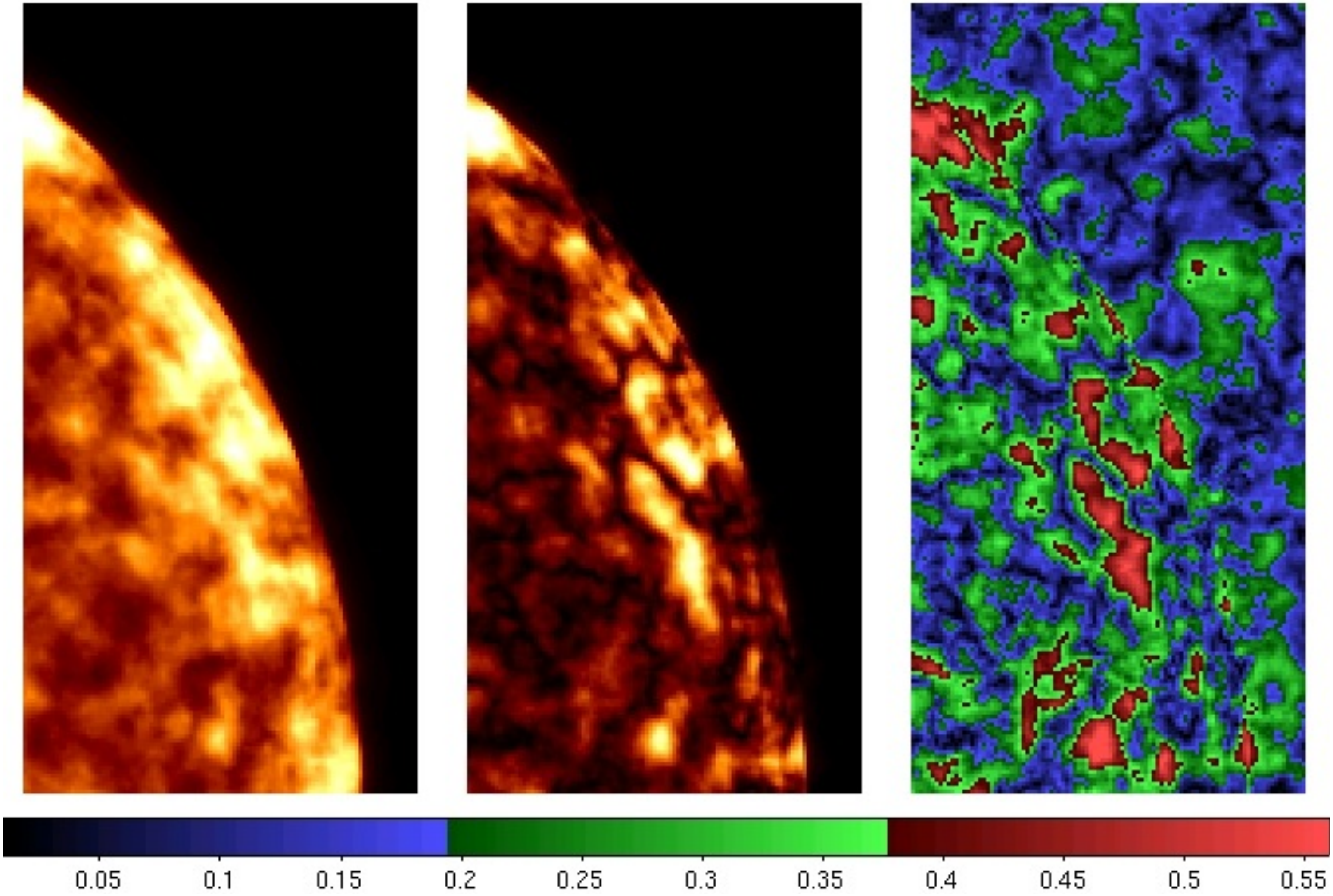
X-ray Polarization at 50 keV

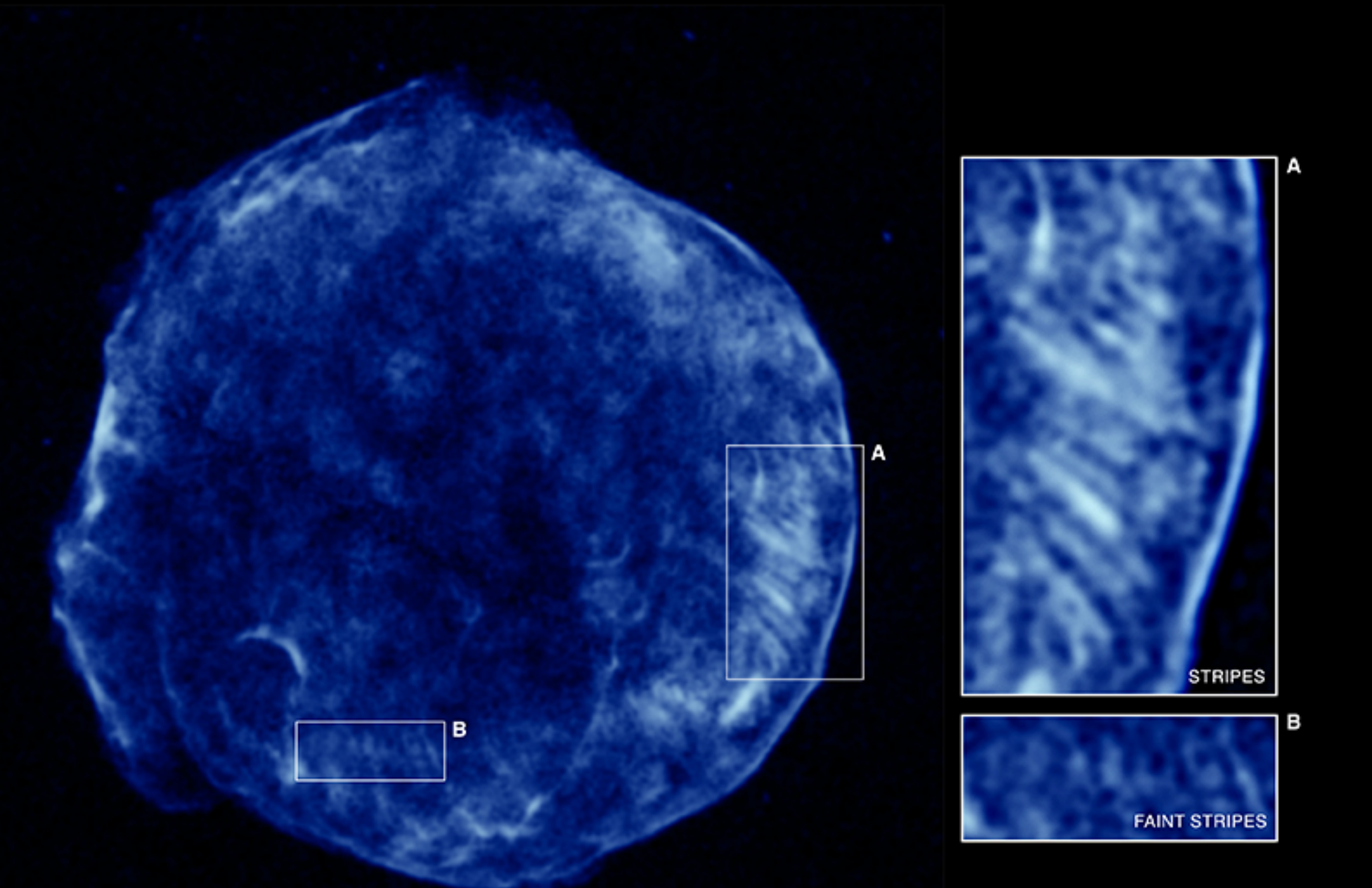


MNRAS v399, 2009

$\delta = 1.0$

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





Chandra image of Tycho's SNR by Eriksen ea 2011

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

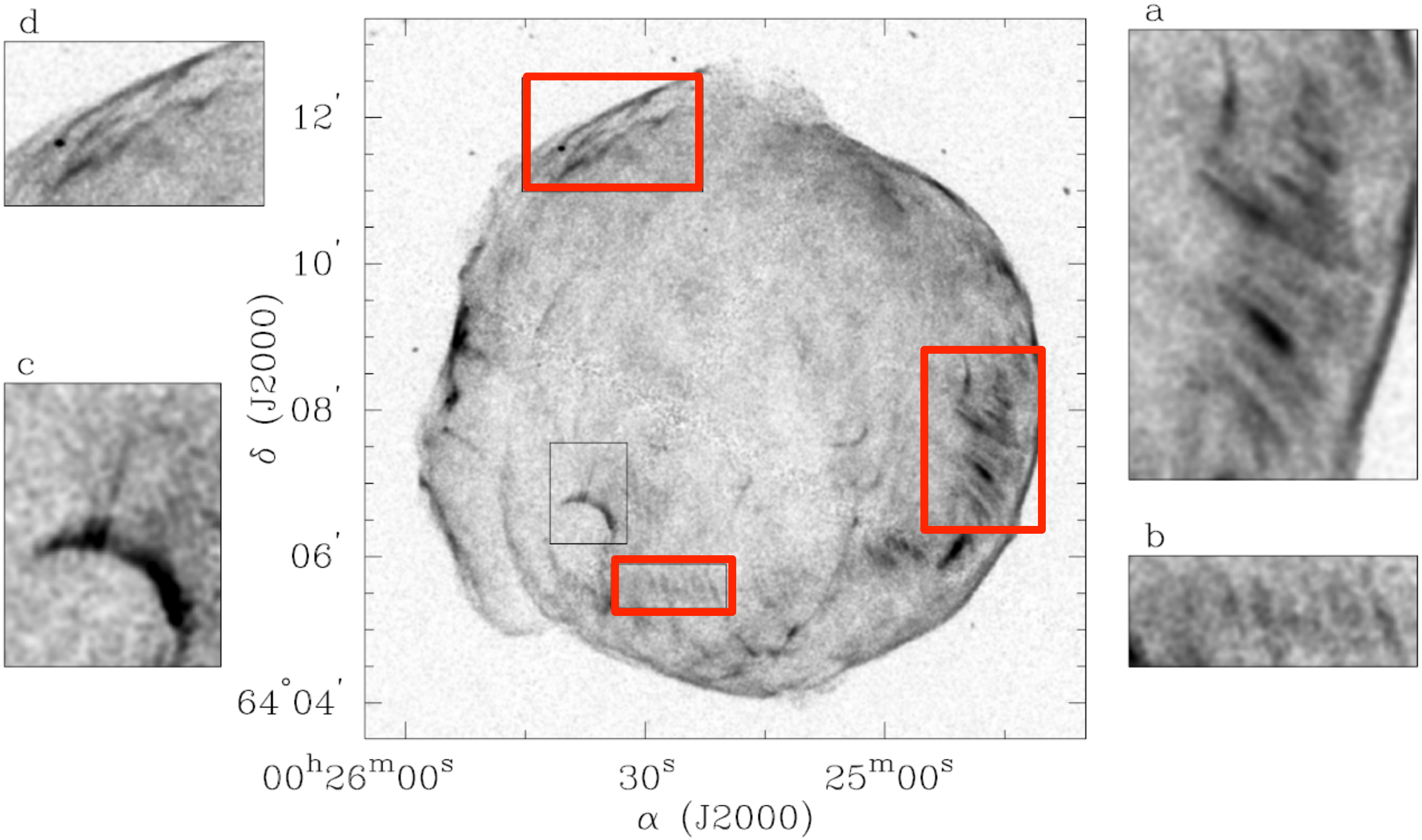
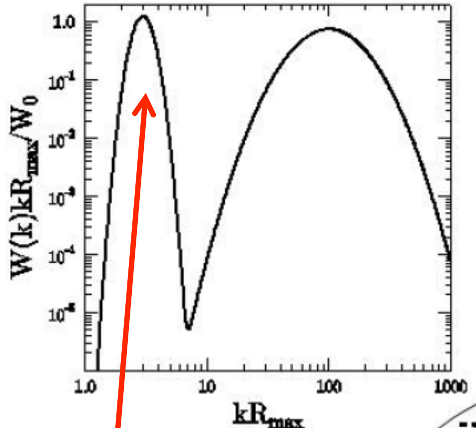


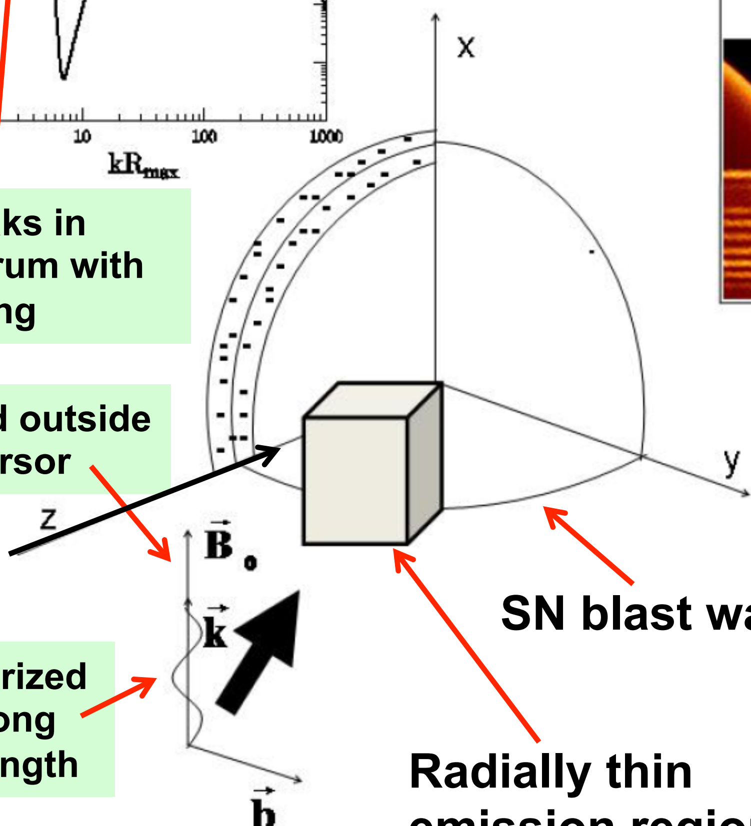
FIG. 1.— *Chandra* X-ray 4.0–6.0 keV image of the Tycho supernova remnant, smoothed with a $\sim 0.75''$ Gaussian and displayed with an *arcsinh* scaling, showing various regions of striping in the nonthermal emission. Clockwise from the upper right: a) The main western stripes discussed in this Letter; 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

Bykov, Ellison, Osipov, Pavlov, Uvarov, ApJL v.735, L40,2011



Narrow peaks in turb. spectrum with no cascading



Perp. B-field outside shock precursor

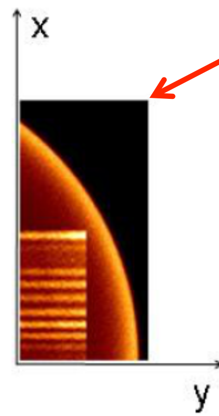
Line of sight

Linearly polarized waves with long coherence length

SN blast wave

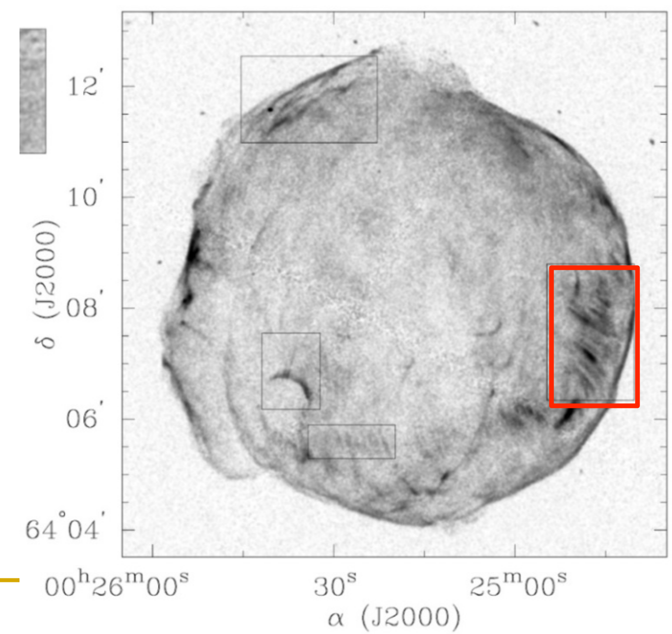
Radially thin emission region

Simulated strips

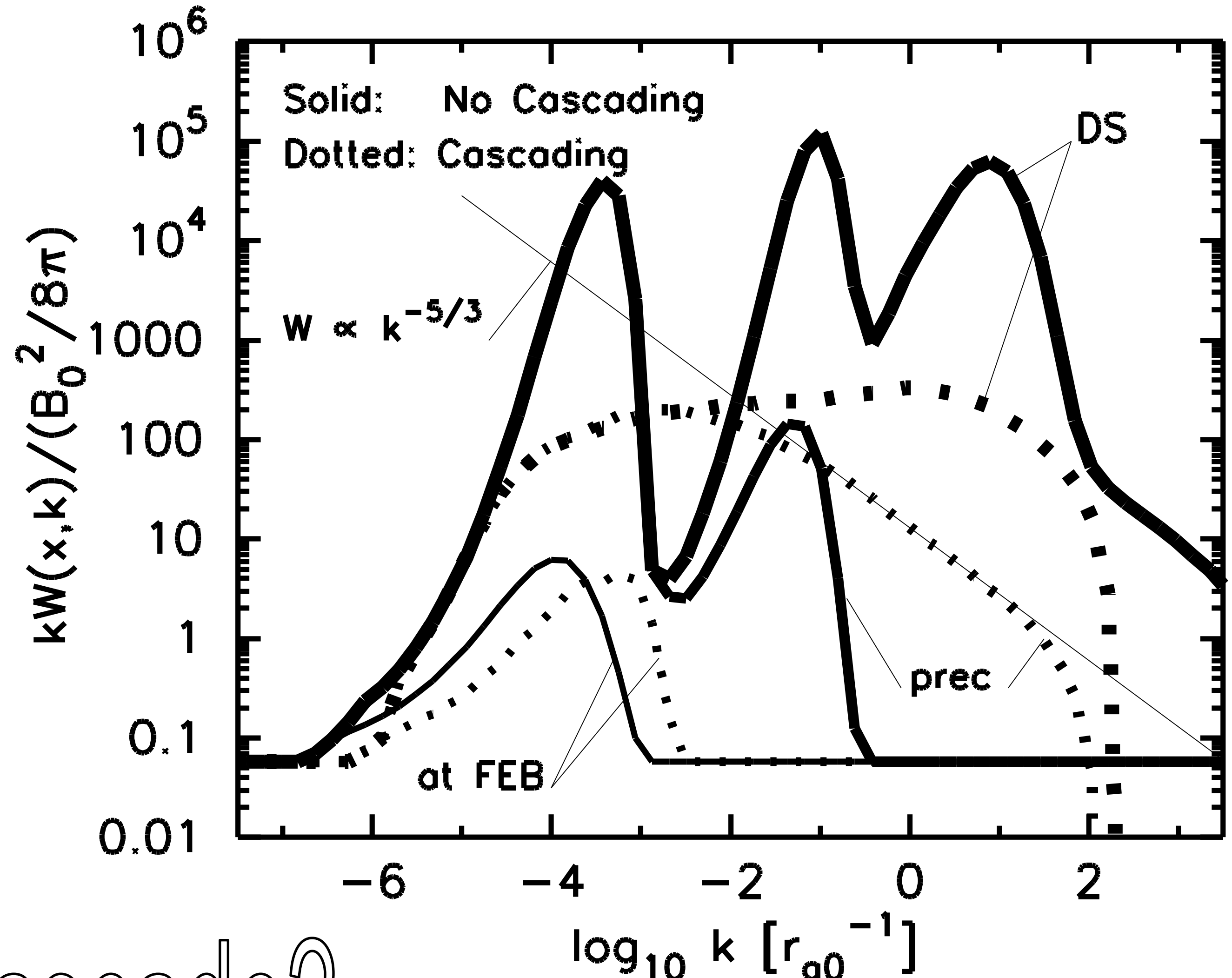


Efficient, NL shock acceleration producing ~100 TeV protons

Steep electron spectrum to avoid strips in radio



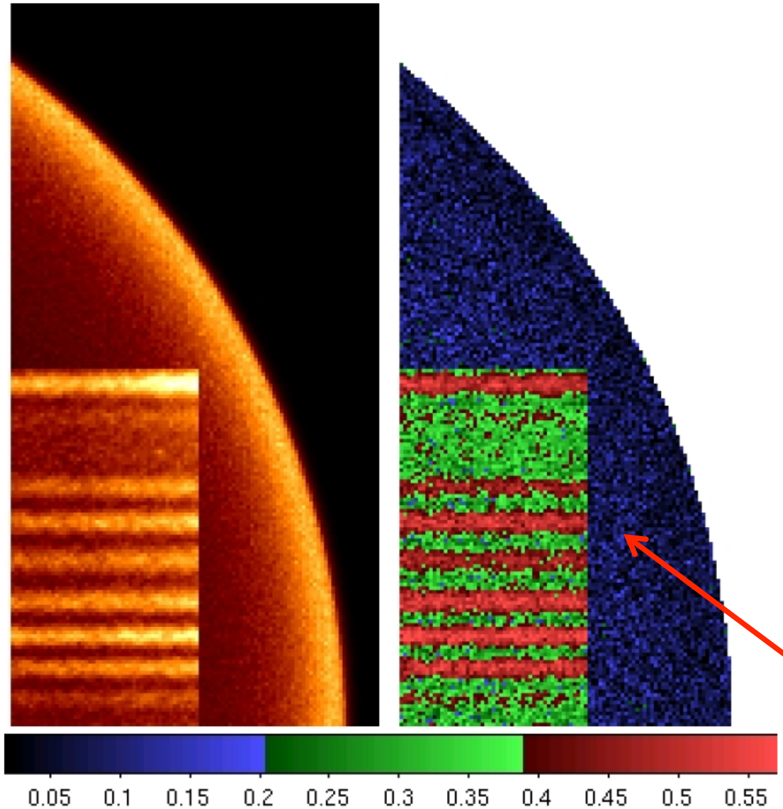
Magnetic Fluctuation Spectra



No cascade?

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

,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

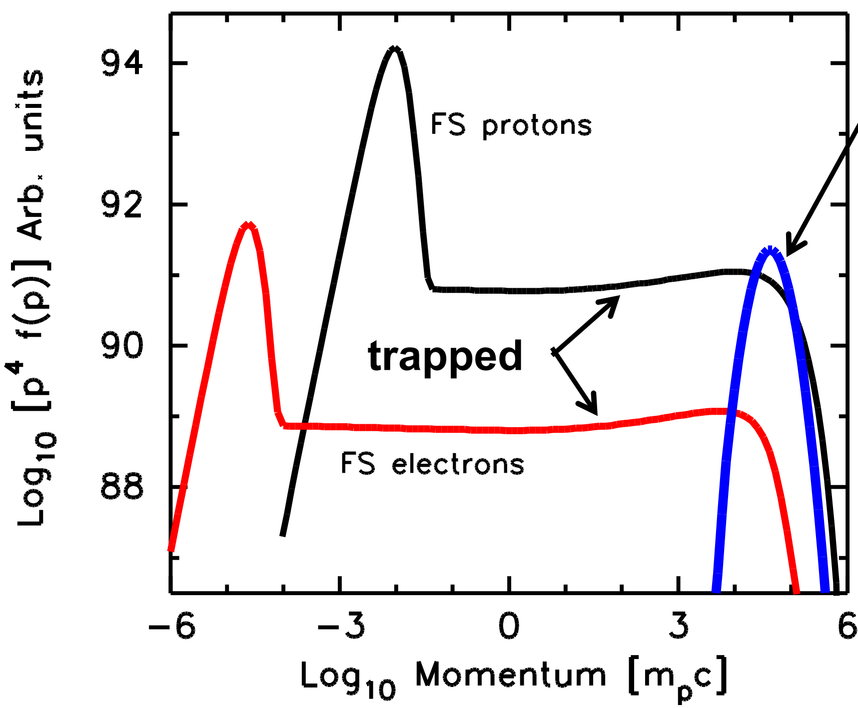
- ***In the model the stripes appearance is sensitive to the geometry of the mean magnetic field.***
- ***The number of stripes constrains the magnetic field amplification scale size and its coherence length***

- ***What about CRs?***

Forward shock of SNR produces 3 particle distributions that will contribute to the photon emission

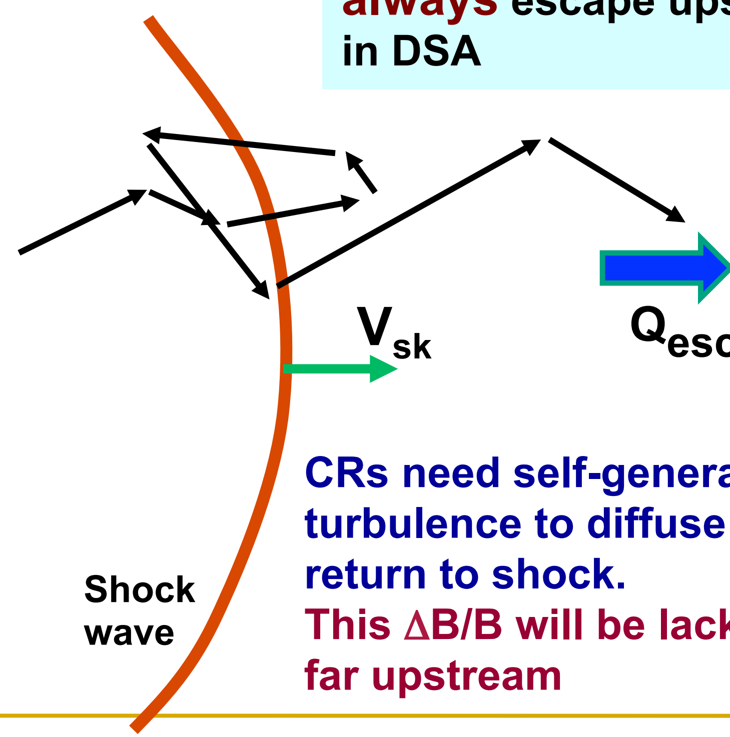
1) Ions accelerated and trapped within SNR
2) Electrons accelerated and trapped within SNR
3) CRs escaping upstream (mainly ions)

If the shock is producing relativistic particles, some fraction of the highest energy CRs **will always** escape upstream in DSA



Escaping CRs

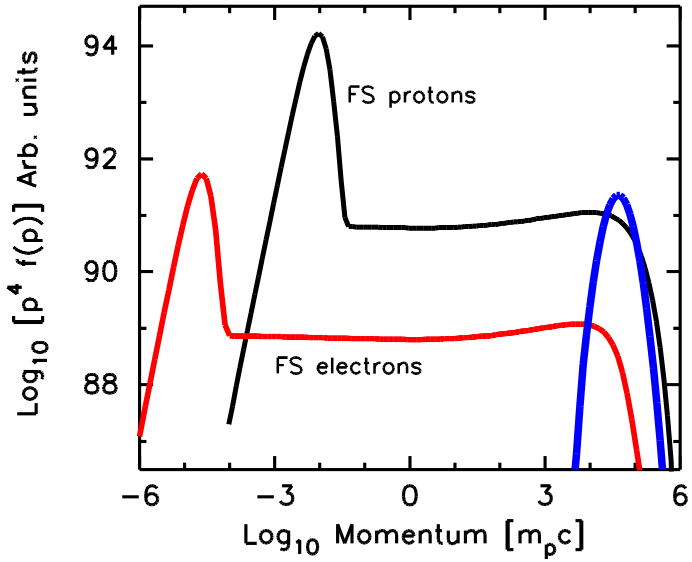
Ellison & Bykov 2011

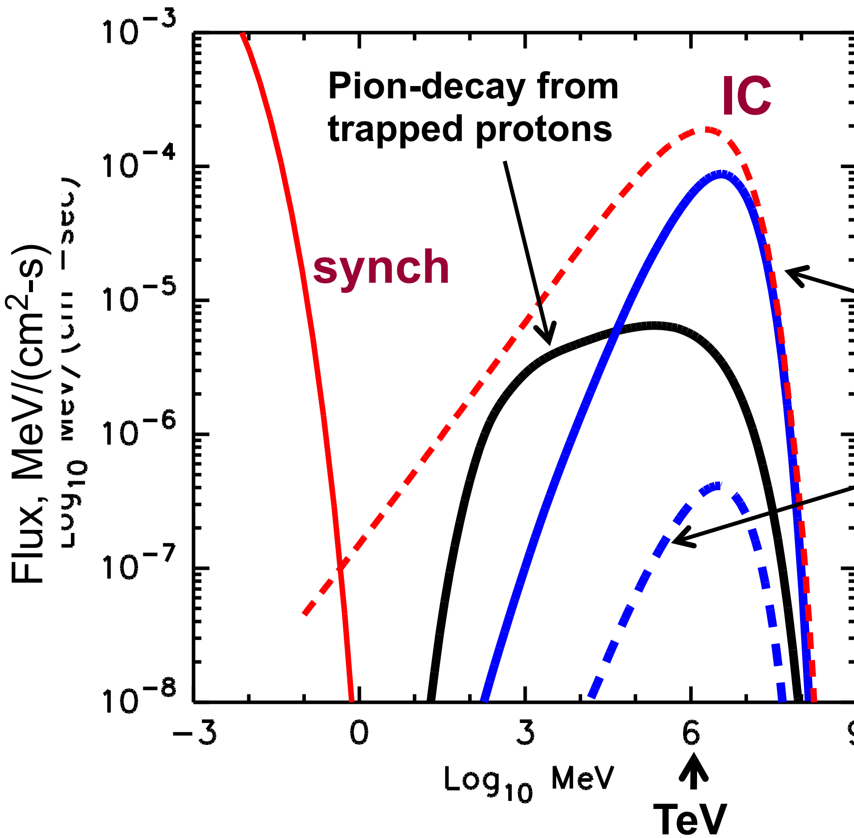


CRs need self-generated turbulence to diffuse and return to shock.
This $\Delta B/B$ will be lacking far upstream

Trapped CRs interact with compressed ISM within SNR

Escaping CRs may interact with dense external material: molecular cloud, shell from pre-SN wind





Pion-decay from escaping protons (cf Gabici Aharonian) :
From dense external shell
From low-density, uniform ISM

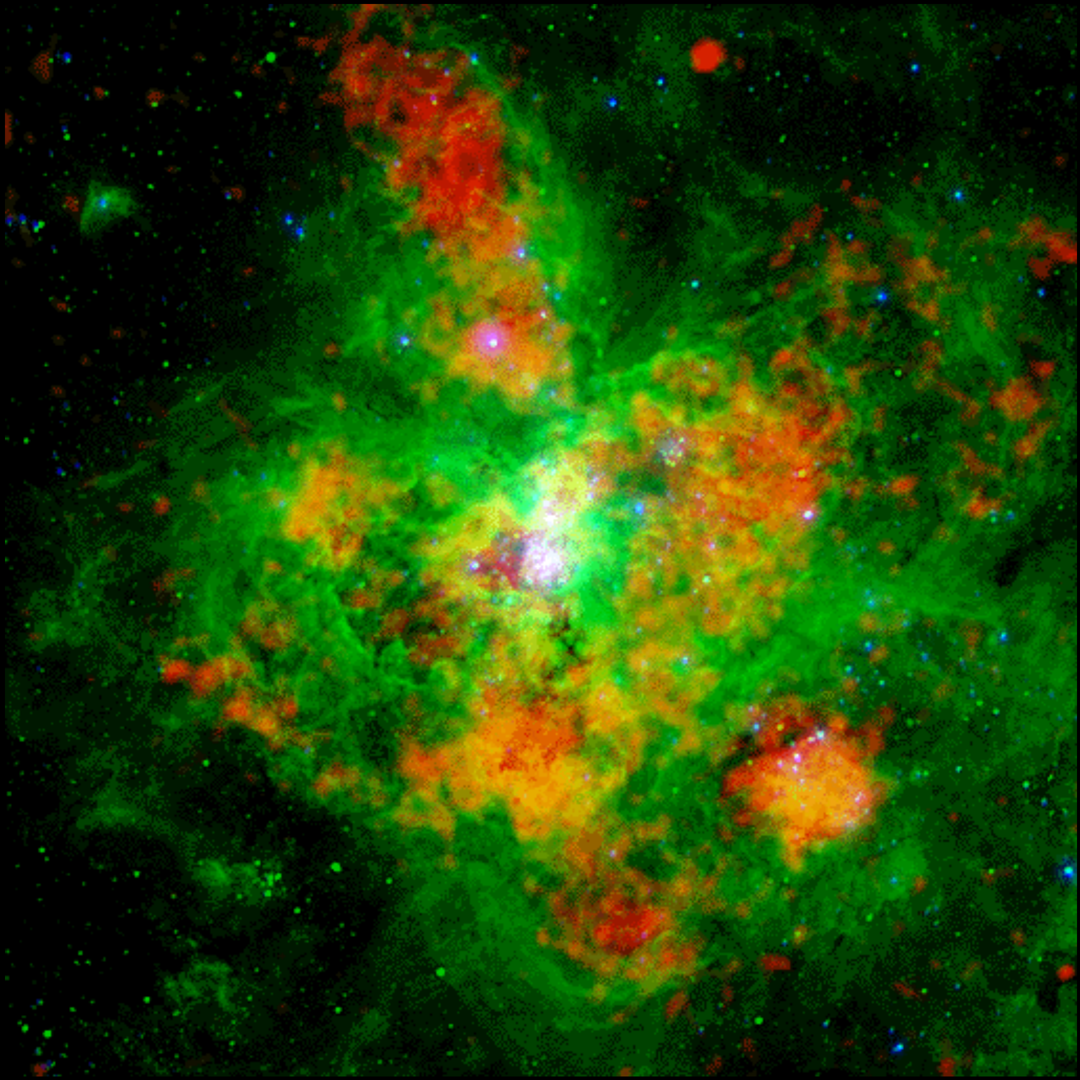
Other parameters: B, K_{ep}, n_p determine relative importance of IC (electrons) vs. pion-decay (protons)

Ellison & Bykov 2011

- ***Stellar winds from young massive stars and SNRs in massive star clusters and in star-forming regions may accelerate CR particles (e.g. Cesarsky & Montmerle, H.Voelk, Casse & Paul, AB & Fleishman, Axford, Klepach ea ea)***

· supershells in the 30 Doradus nebula (R.Kennicutt)

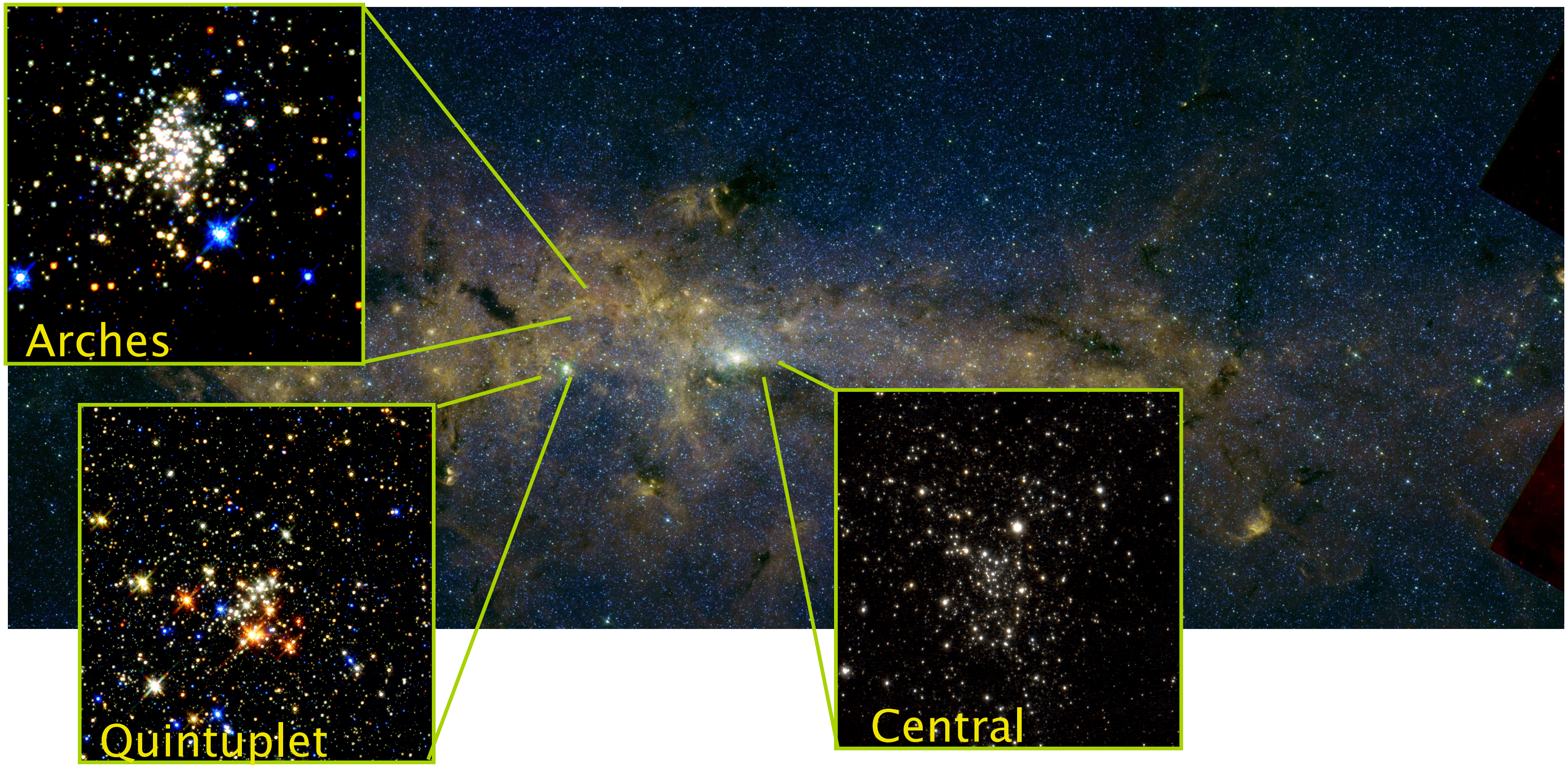
ESO – VLT +FORS



Ha + X-rays (D. Wang)

Star formation

Background: Spitzer/IRAC; Insets: HST/NICMOS & Keck laser AO

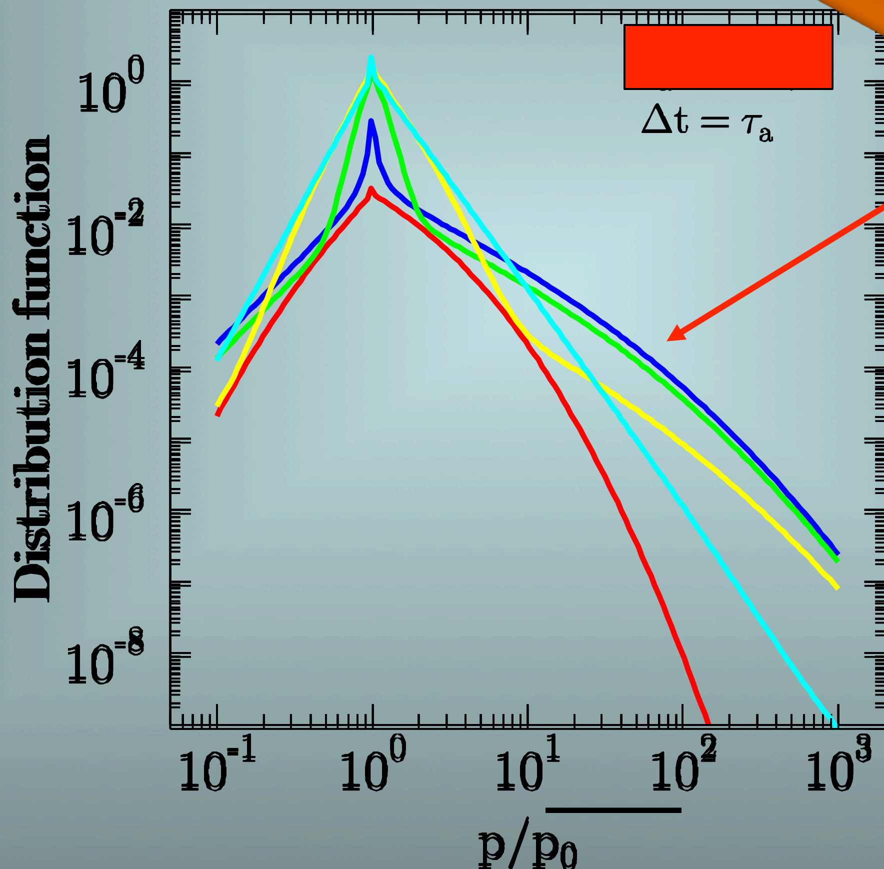


- Star formation: 0.02-0.1 M_{sun} yr^{-1}.

(Gusten 1989; Figer et al. 2004).

Temporal Evolution of Particle Spectrum in a Superbubble

Soft-Hard-Soft



AB 01

Acceleration time is about 300 kyrs