Cosmic Ray (Stochastic) Acceleration from a Background Plasma

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Thanks to my collaborators:
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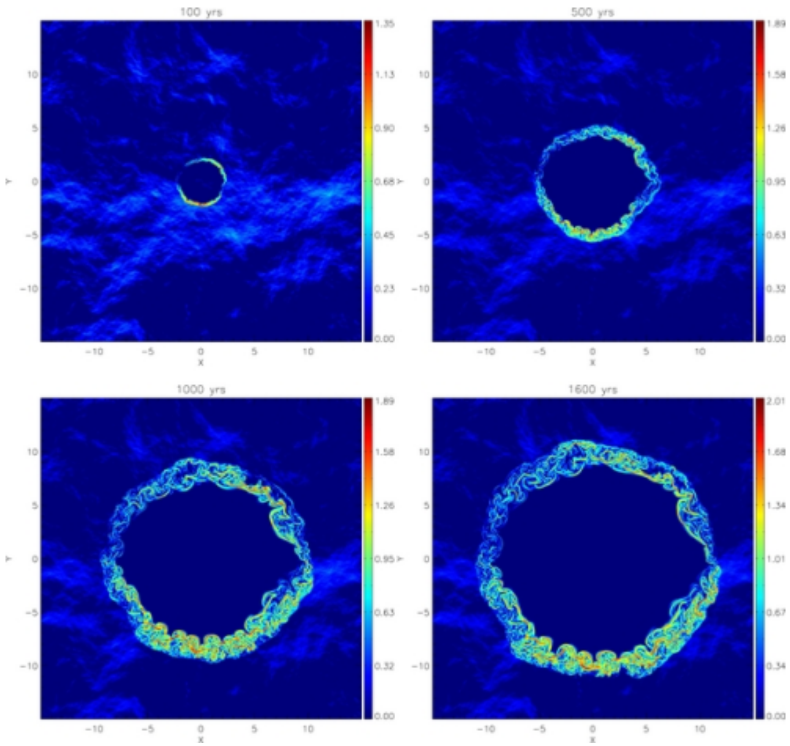
and A. W. Wolfendale (DU)

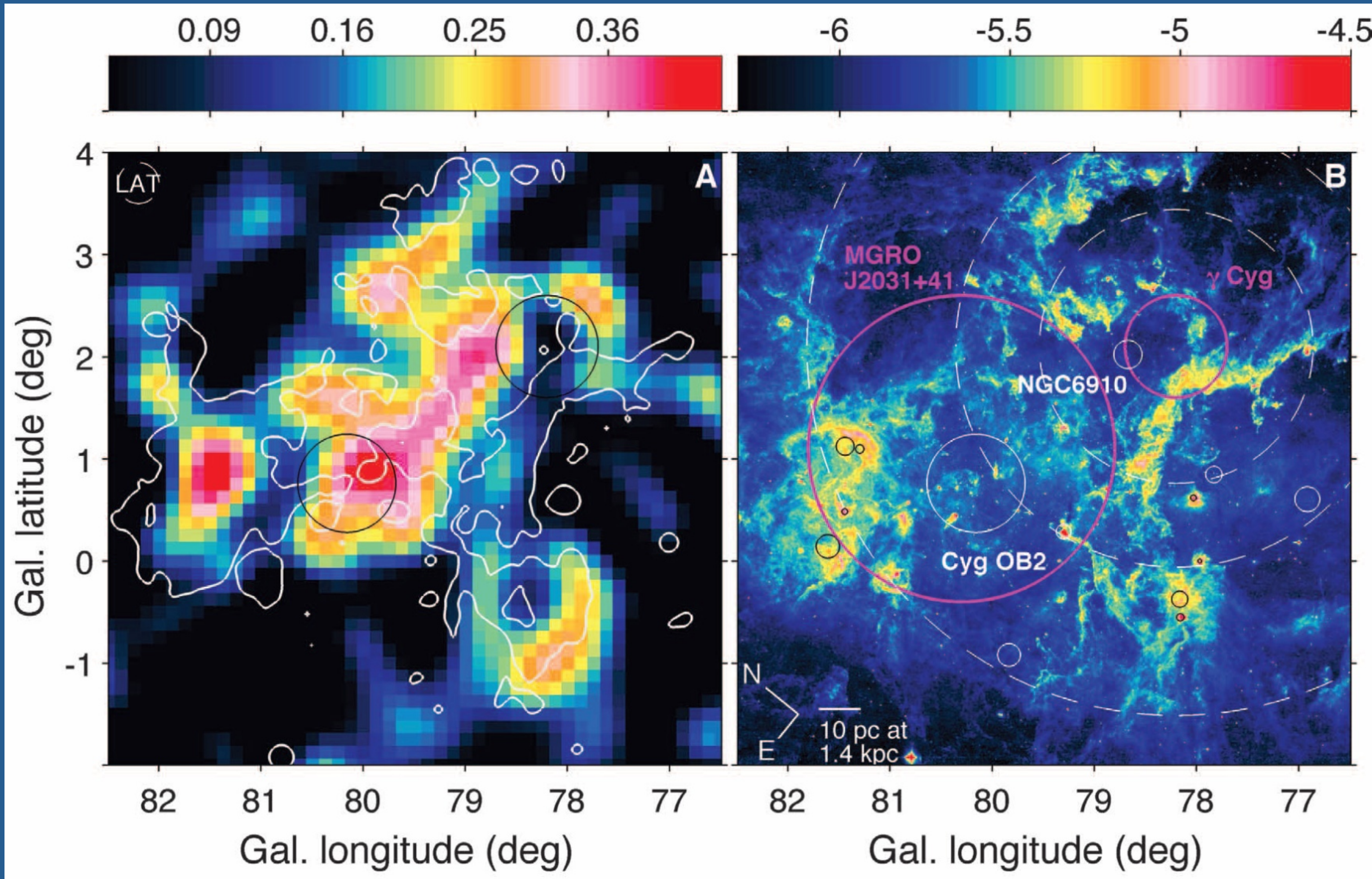
Fermi I vs Fermi II acceleration

Shock wave and stochastic acceleratio stochastic acceleration at SNR envelopes

Plasma instabilities, in particular Rayleigh-Taylor and Kelvin-Helmholtz instabilities generate turbulence at shocks of SNR envelopes (from Yang and Liu, 2013)



Gamma-Ray flux from the OB-association Cyg OB2

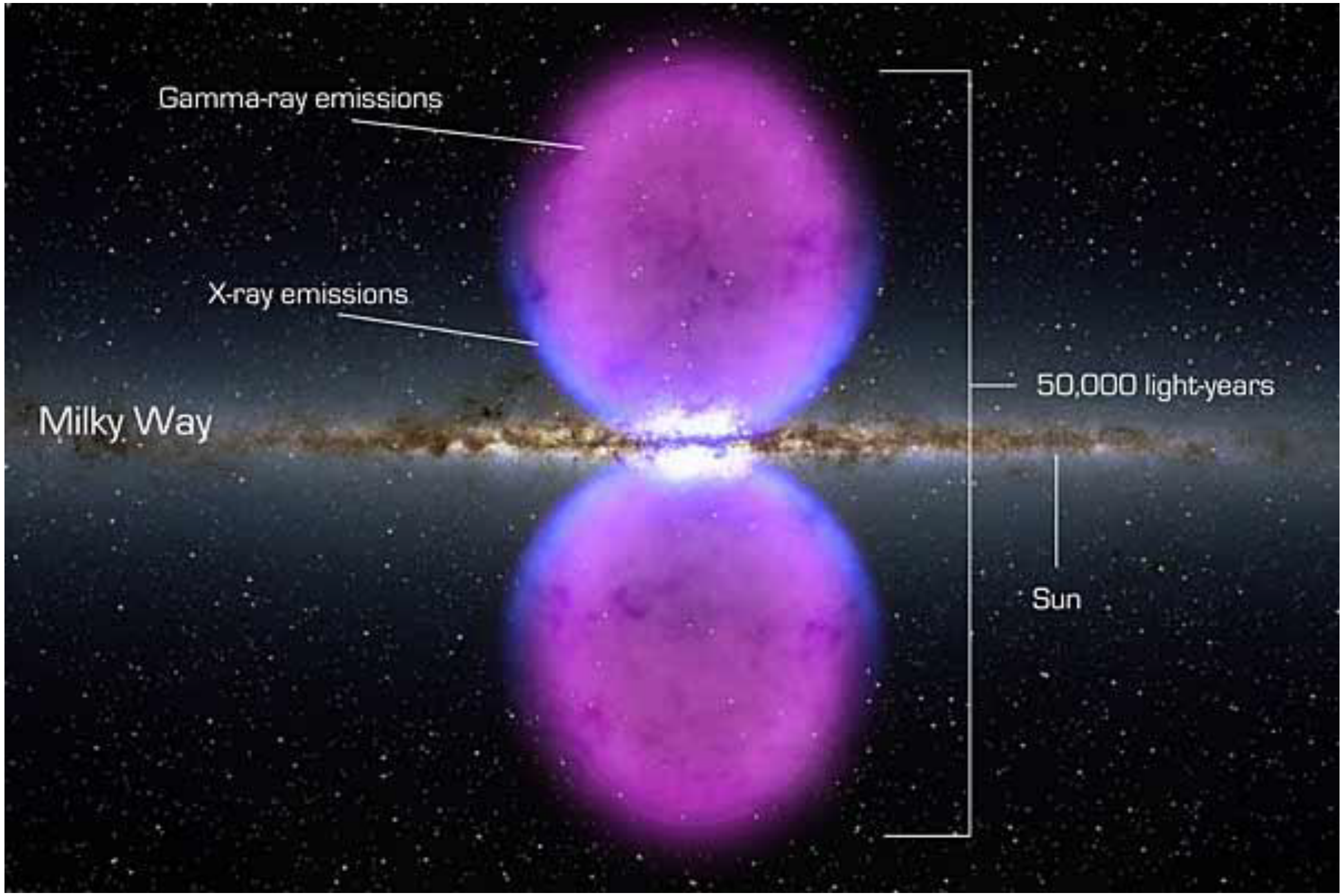


From Ackermann *et al*. 2011

OB-Association as CR Sources

- The Fermi-LAT observations reported by Ackermann *et al*. 2011, together with measurements of cosmic-ray elemental and isotopic composition, suggest that OB associations and their superbubbles are likely the source of a substantial fraction of galactic cosmic rays.
- OB associations are considered as CR accelerators from the collective action of multiple shocks from supernovae and the winds of massive stars.
- Multi-shock acceleration in OB associations by a supersonic turbulencee (combination of Fermi I + Fermi II acceleration, see Bykov and Toptygin, 1993)

FERMI bubbles



Dobler et al., 2010. Su et al., 2010

Black Hole at the center of Milky Way – Mass ~ $4x10^6$ solar masses!

Stellar Capture. Energy Release Stage

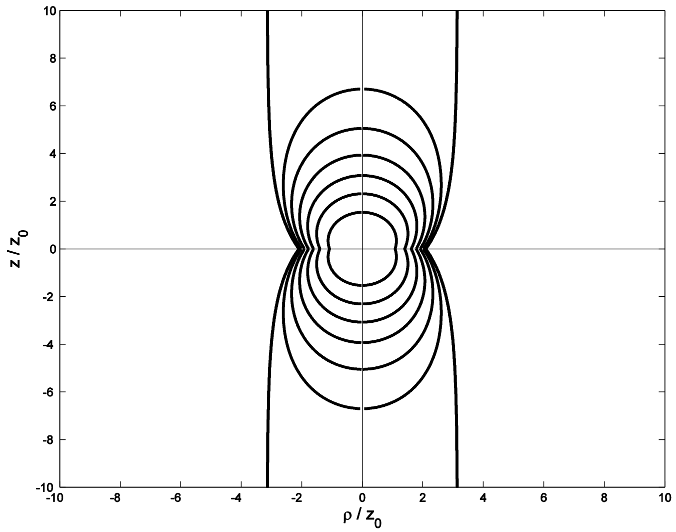
Illustration: NASA/CXC/M.Weiss

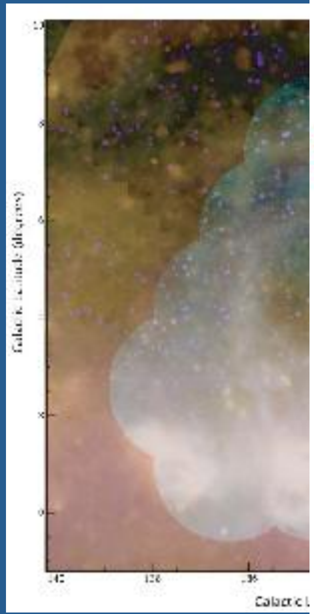
Leptonic model of star tidal disruption and shock wave acceleration (Cheng et al. 2011)

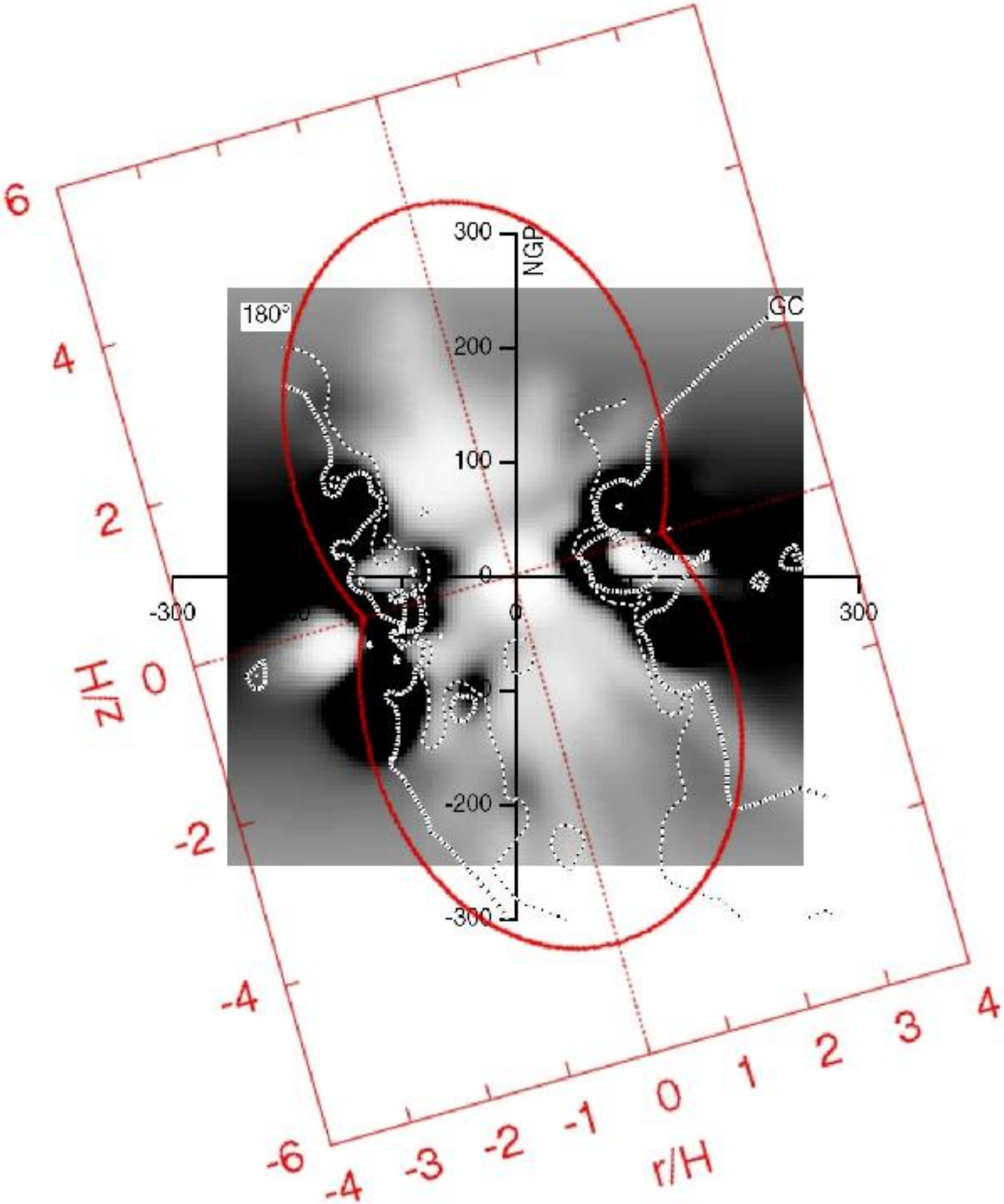
- . Energy carried away by relativistic protons of jets (Cheng et al. 2006)

$$W \sim 6 \times 10^{52} \left(\frac{\eta_p}{0.1}\right) \left(\frac{M}{M_{\odot}}\right) erg$$

- Why double –bubble structure? Shock propagation in the exponential atmosphere of the Galactic halo (Kompaneets solution, 1960)






180°
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-2
-4
-6
-4
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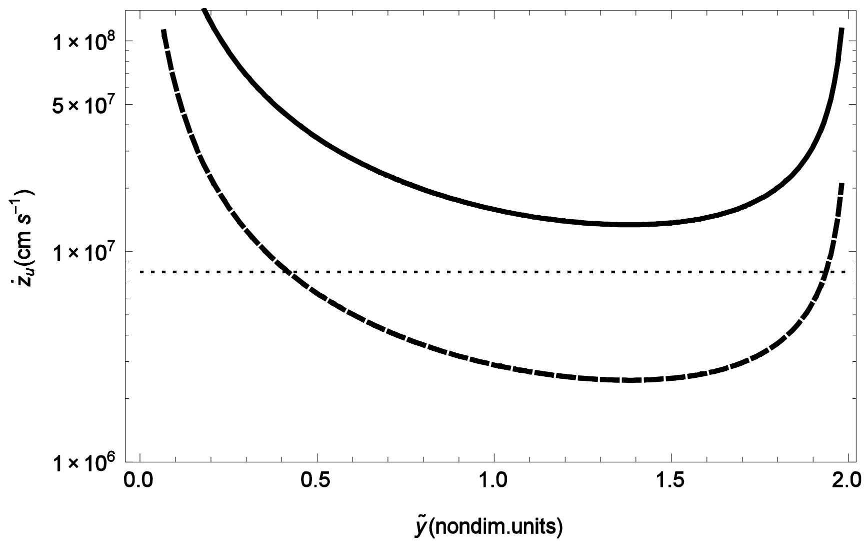
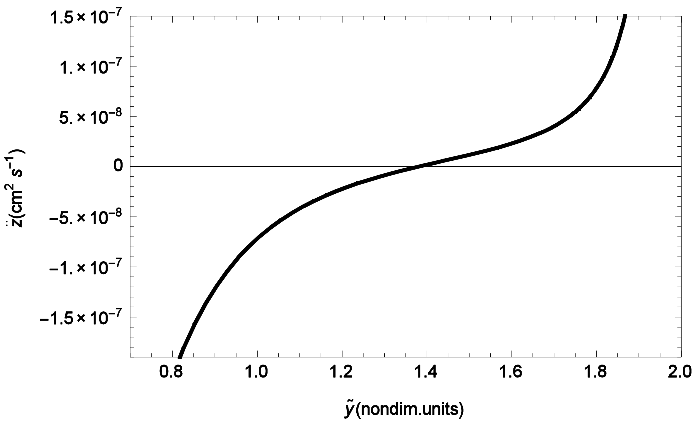
4

Velocity of the shocks in the exponential atmosphere (calculated with the solution of Baumgartner and Breitschwerdt, 2013)

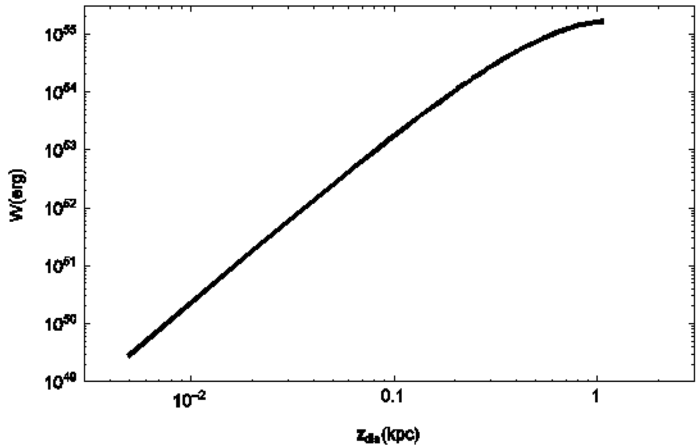


Velocity of the shock front at the top for the energy release
$W = 10^{52} erg\ and\ W = 10^{54} erg$

Shock fragmentation due to the Rayleigh-Taylor instability on the front



Shock acceleration as a function of altitude y



Altitude of shock fragmentation as a function of energy release W

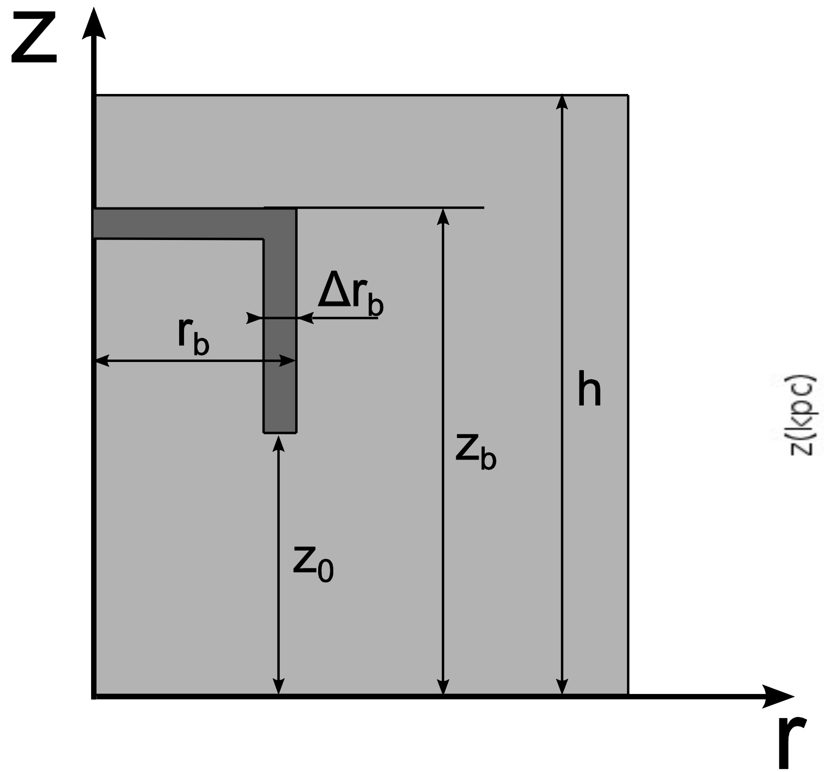
Leptonic model of stochastic acceleration in the Bubbles (Mertsch & Sarkar, 2011)

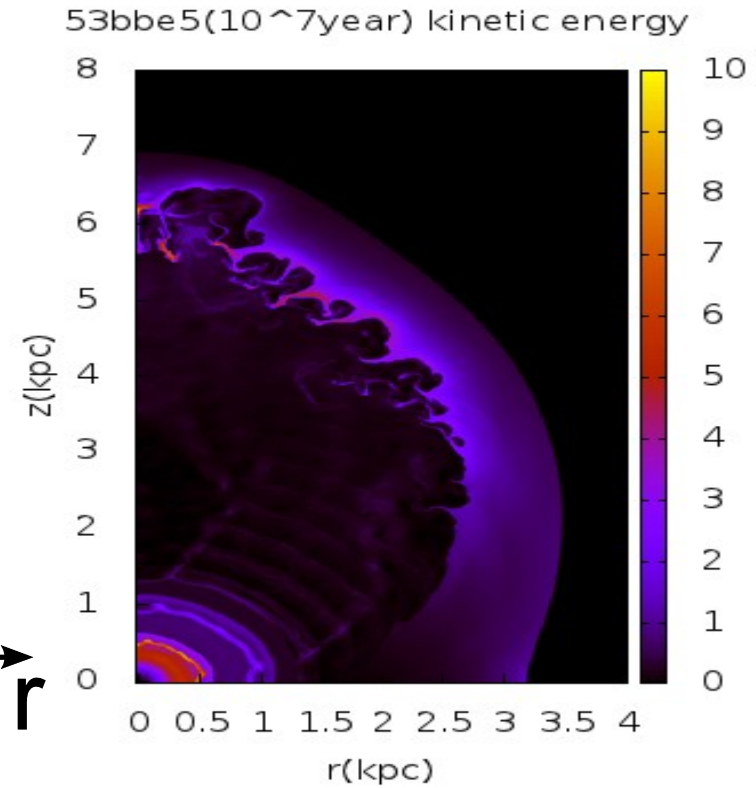
• From the ROSAT data of Snowden te al. (1997) – there is a shock front at the bubble edge moving with the velocity ~1000 km/s. The total energy release estimated from parameters of hot plasma in the Bubbles is about 10^{53} – 10^{54} erg and the age of the bubble is 10^7 yr.

•Plasma instabilities may be generated behind the shock.

•These instabilities are convected into the bubble interior by the downstream plasma flow and accelerate CRs there (Fermi II acceleration).

Region of turbulent magnetic fields in the halo behind a shock front





Equations for the Fermi II (shock acceleration) and Fermi I (stochastic acceleration by a turbulence)

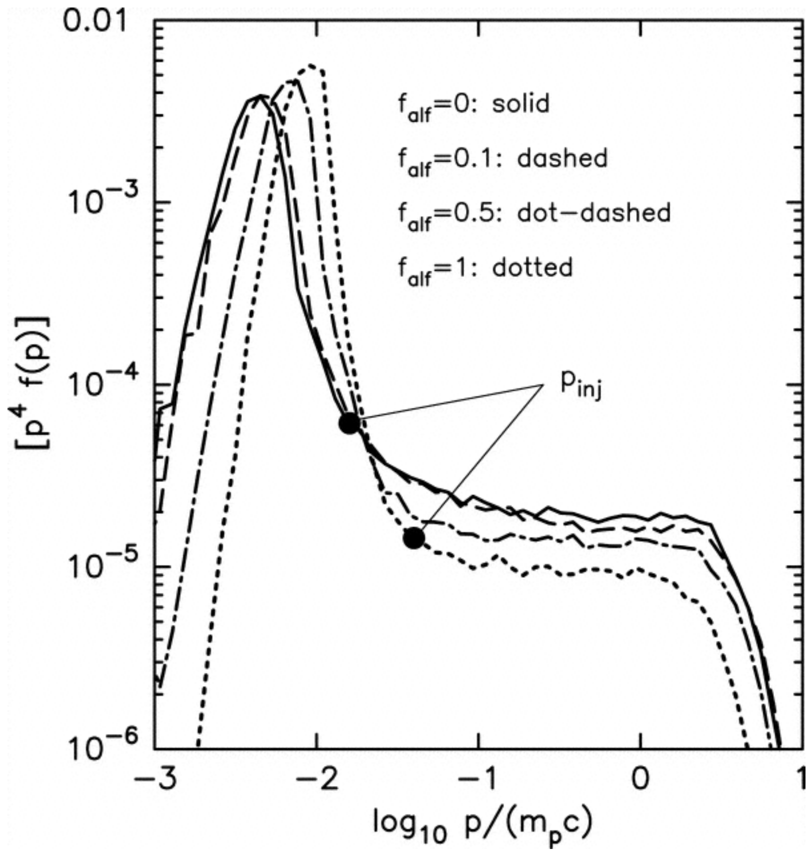
$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial x}\left(u(x)f-D\frac{\partial f}{\partial x}\right)==\frac{1}{3}\frac{du}{dx}\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^3 f\right)$$

$$\frac{\partial f}{\partial t}+\frac{1}{p^2}\frac{\partial}{\partial p}p^2\left\{\frac{dp}{dt}f-D_p(p)\frac{\partial f}{\partial p}\right\}+\frac{f}{\tau_{esc}}=0$$

Number of Accelerated Particles?

Spectrum of CRs accelerated by a shock from a background plasma (Vladimirov et al. 2006)

The number of accelerated particles is about 10^{-4} of background



$$F_i(p) = -p_i \sum_\alpha \nu_\alpha(p)(1 + \frac{m_\alpha}{m} =$$

$$= -p_i \sum_\alpha \frac{4\pi e^4 Z^2 Z_\alpha^2 n_\alpha \ln\Lambda_\alpha}{A A_\alpha^2 p p_{T\alpha}^2 m_p^2} G\left(\sqrt{\frac{A_\alpha}{A}}\frac{p}{p_{T\alpha}}\right)\left(1 + \frac{m_\alpha}{m}\right)$$

$$D_{ij}(p) = D_\parallel(p)\frac{p_i p_j}{p^2} + \frac{1}{2}\left(\delta_{ij} - \frac{p_i p_j}{p^2}\right) D_\perp(p) =$$

$$\sum_\alpha \left\{ \frac{8\pi e^4 Z^2 Z_\alpha^2 \ln\Lambda_\alpha T_\alpha}{A A_\alpha^2 p p_{T_\alpha}^2 m_p} \left[G\left(\sqrt{\frac{A_\alpha}{A}}\frac{p}{p_{T\alpha}}\right)\frac{p_i p_j}{p^2} + \right.\right.$$

$$\left.\left. + \frac{1}{2}\left(\delta_{ij} - \frac{p_i p_j}{p^2}\right)\left(\Phi\left(\sqrt{\frac{A_\alpha}{A}}\frac{p}{p_{T\alpha}}\right) - G\left(\sqrt{\frac{A_\alpha}{A}}\frac{p}{p_{T\alpha}}\right)\right)\right]\right\}$$

$$G(x) = -\frac{d}{dx}\left(\frac{\Phi(x)}{x}\right); \qquad \Phi(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-x^2} dx$$

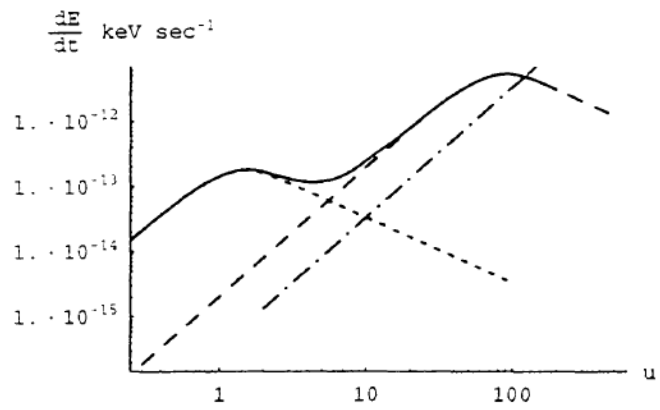


Figure 1. The rate of change of energy of the test proton in a two-component plasma which consists of protons and electrons in the Coma halo. The rate of stochastic acceleration for the parameter $\alpha_0 = 7.4 \cdot 10^{-17}$ *sec*$^{-1}$ *is shown by the dashed-dotted line. Here u is the dimensionless particle velocity.*

Particle injection

The thermal spectrum of particle is formed by Coulomb collisions which determine ionization losses of particles and their momentum diffusion (Landau and Livshitz, Kinetics)

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left(-F_i f + D\frac{\partial f}{\partial p}\right) \ \textit{for Coulomb collisions}$$

$$D = \frac{kT}{v}F_i \ \textit{and in the equilibrium state we have the equilibrium Maxwell distribution}$$

$$f = \exp\left(-\frac{E}{kT}\right)$$

$$F_i = \frac{dE}{dt} = -\frac{nZ^2e^4}{4\pi m_e v}\left[\ln\left(\frac{2\gamma^2 m_e v^2}{I}\right) - \frac{v^2}{c^2}\right] = \frac{\nu_0}{\sqrt{E}}$$

E_{inj} Definition

If we have an acceleration ***dE/dt=αE*** we can induce the energy of injection, E_{inj} which can be derived from the equality

$$E_{inj} \sim \left(\frac{\nu_0}{\alpha} \right)^{2/3}$$

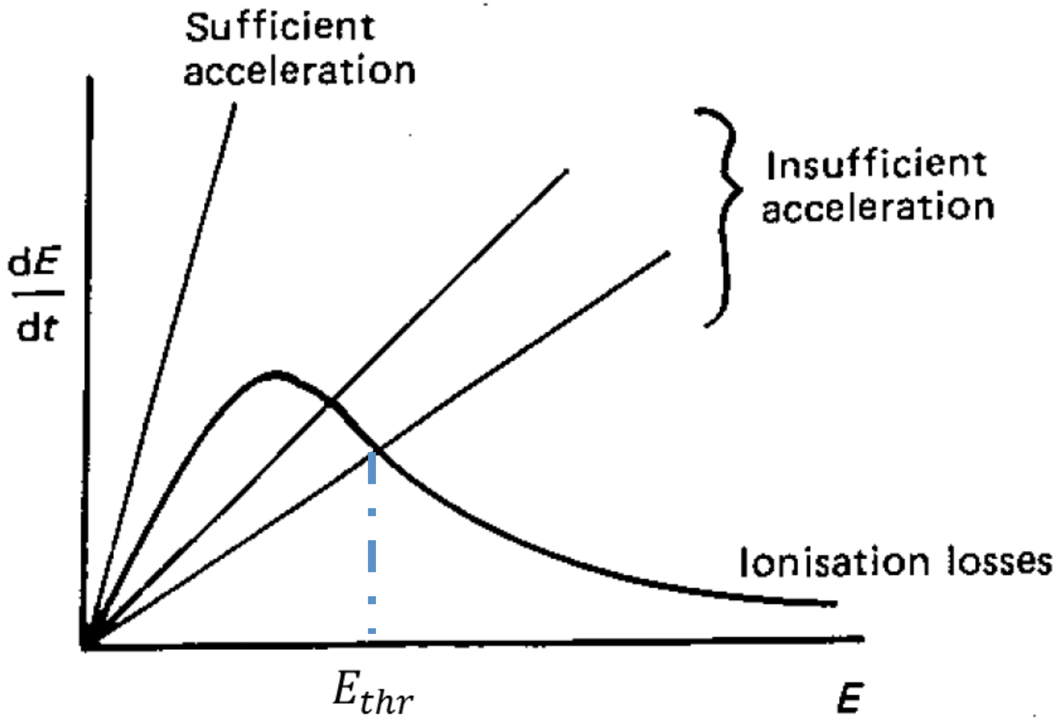
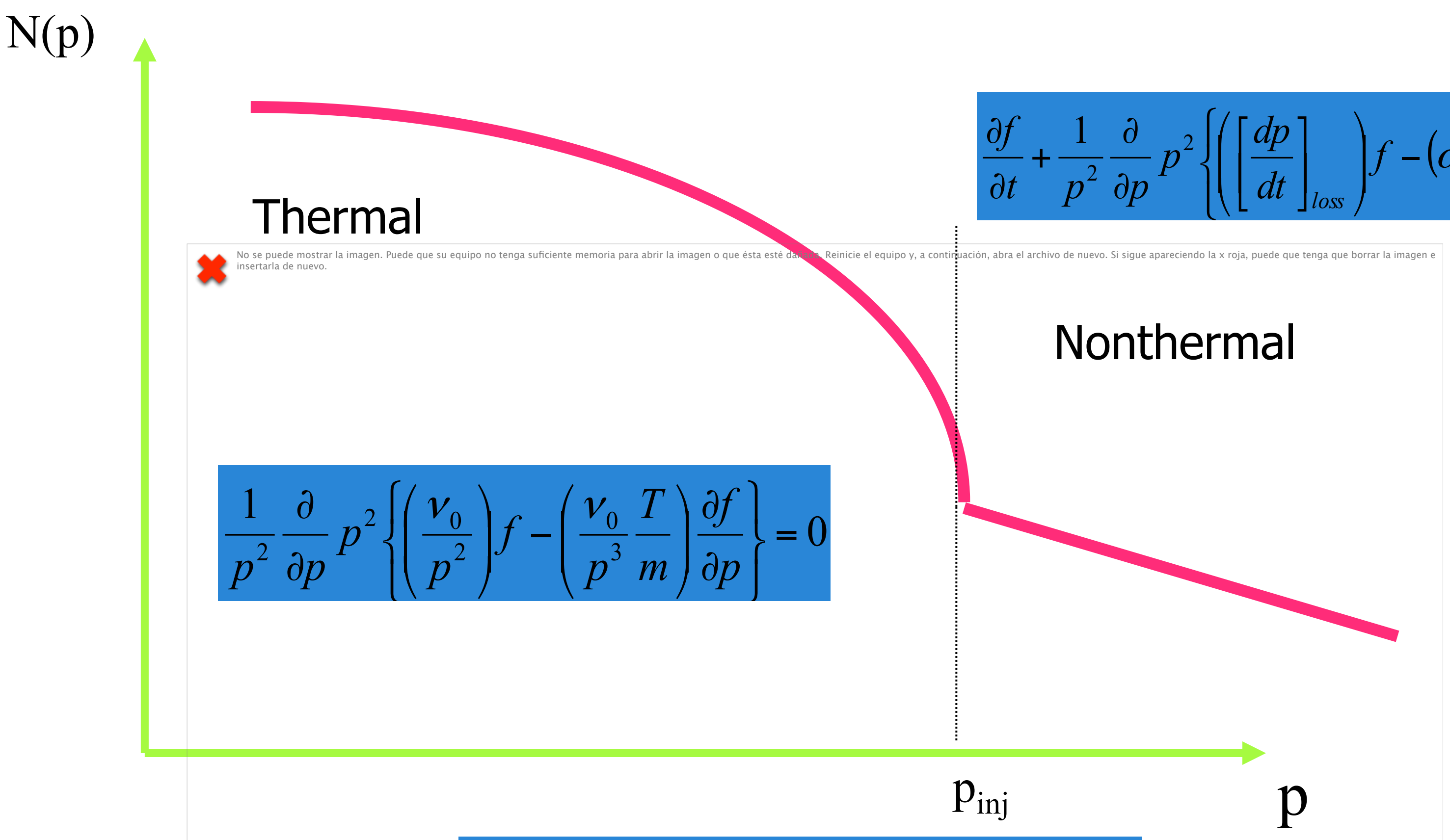


Figure 21.2. Comparison of the acceleration rate and energy loss rate due to ionisation losses for a high energy particle.

- $\left(\frac{dE}{dt}\right)_i = -\frac{2\pi n e^4}{m_e\sqrt{E}}\Lambda$
  $\left(\frac{dE}{dt}\right)_F = \alpha E$
- $\left(\frac{dE}{dt}\right)_i = \left(\frac{dE}{dt}\right)_F \rightarrow E_{thr}$
- Number of accelerated particles
  $N_{nth} \sim exp\left(-\frac{E_{thr}}{kT}\right)$

- The question is how correctly estimate the number of particles accelerated from background plasma



$$\frac{\partial f}{\partial t} + \frac{1}{p^2}\frac{\partial}{\partial p} p^2 \left\{ \left(\left[\frac{dp}{dt}\right]_{loss} \right) f - (\alpha(p)) \frac{\partial f}{\partial p} \right\} = 0$$

$$\frac{1}{p^2}\frac{\partial}{\partial p} p^2 \left\{ \left(\frac{\nu_0}{p^2}\right) f - \left(\frac{\nu_0}{p^3}\frac{T}{m}\right)\frac{\partial f}{\partial p}\right\} = 0$$

$$N_{acc} = \exp\left(- 1/2\alpha_0 \right)$$

Is it correct?!!!

Effect of Acceleration on Equilibrium (Maxwellian) Distribution of Background Particles

Run-away particles (Gurevich 1960)

- We investigate the kinetic equation for energies E>kT
- The rate of ionization losses is $\nu(\epsilon) = \nu_0(\epsilon - \frac{3}{2}kT)\left(\frac{kT}{\epsilon}\right)^{3/2}$
- The dimensionless equation f $\nu_0 = \frac{4\pi n_0 e^4}{(kT)^{3/2} m^{1/2}} \ln\left(\frac{kTD}{e^2}\right)$

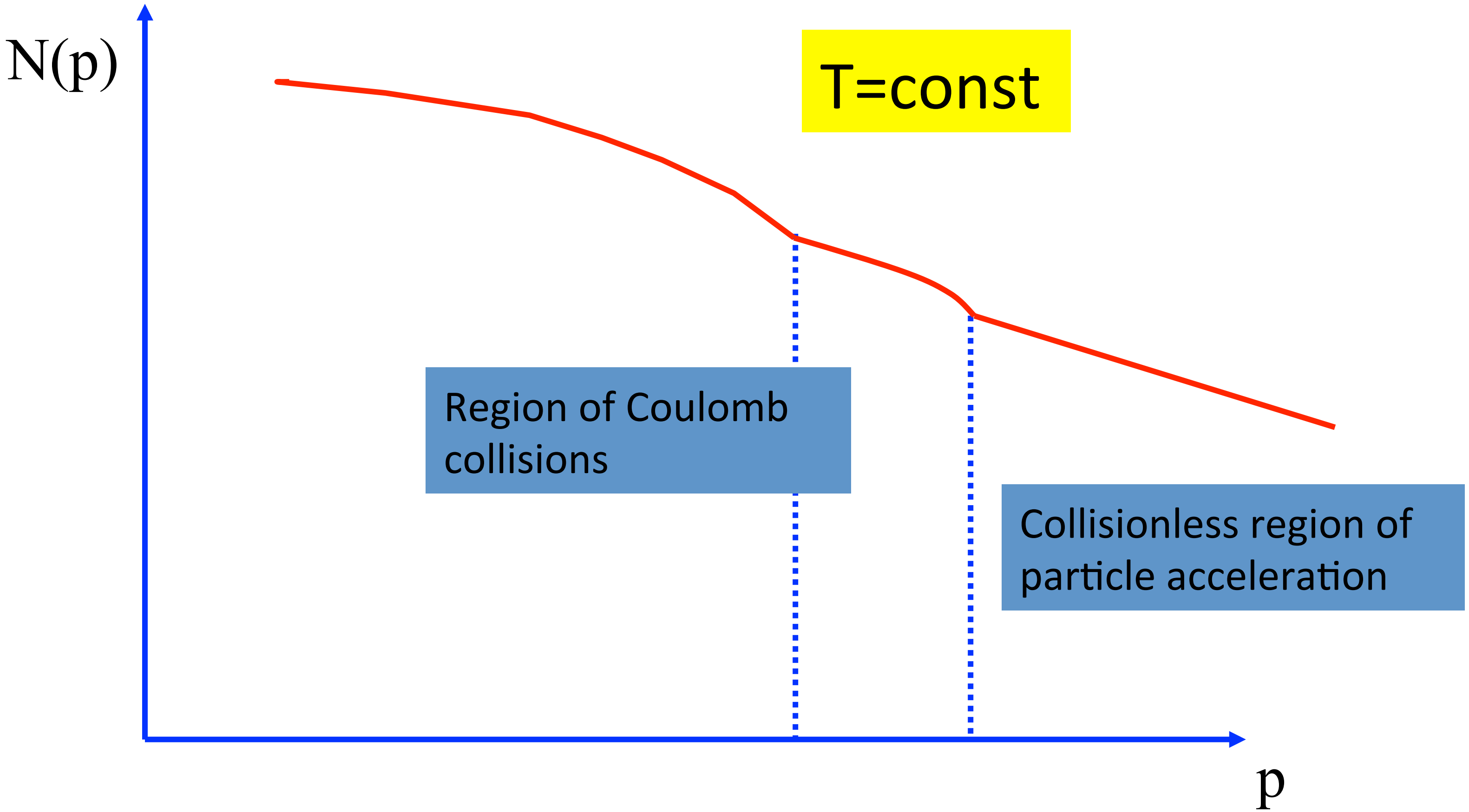
$$\frac{\partial f}{\partial \tau} - \frac{1}{u^2}\frac{\partial}{\partial u}\left\{\left(\frac{1}{u} + u^2\alpha(u)\right)\frac{\partial f}{\partial u} + f\right\} = 0$$

$$u = \frac{v}{\sqrt{kT/m}}, \qquad \tau = \nu_0 t$$

$$\alpha(u) = \frac{D_0}{\nu_0} u^\eta = \alpha_0 u^\eta$$

Spectrum of particles in the case of acceleration from a background plasma (Gurevich 1960)

$$\frac{\partial f}{\partial t} + \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\left(\frac{dp}{dt}\right)_C f - \{D_C + D_F(p)\}\frac{\partial f}{\partial p}\right] = 0$$



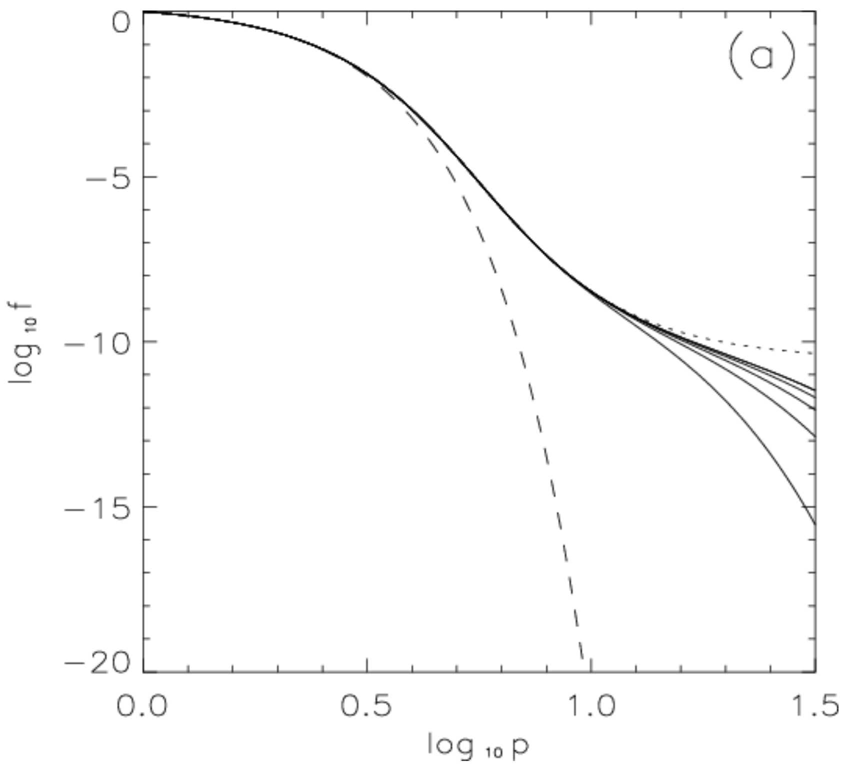
In the general case

$$\frac{\partial f}{\partial \tau} - \frac{1}{u^2}\frac{\partial}{\partial u}\left(A(u)\frac{\partial f}{\partial u} + B(u)f\right) = 0 \Rightarrow$$

$$f(u,\tau) = \sqrt{\frac{2}{\pi}}N(\tau)\exp\left[-\int_0^u \frac{B(u)}{A(u)}du\right]\times$$

$$\times\left\{1 - \int_0^u \frac{dv}{A(v)}\left(\exp\left[\int_0^v \frac{B(t)}{A(t)}dt\right] \Big/ \int_0^\infty \frac{dv}{A(v)}\exp\left[\int_0^v \frac{B(t)}{A(t)}dt\right]\right)\right\}$$

$$S_0 = \sqrt{\frac{2}{\pi}}N(\tau)\int_0^\infty \frac{dv}{A(v)}\exp\left[\int_0^v \frac{B(t)}{A(t)}dt\right]$$

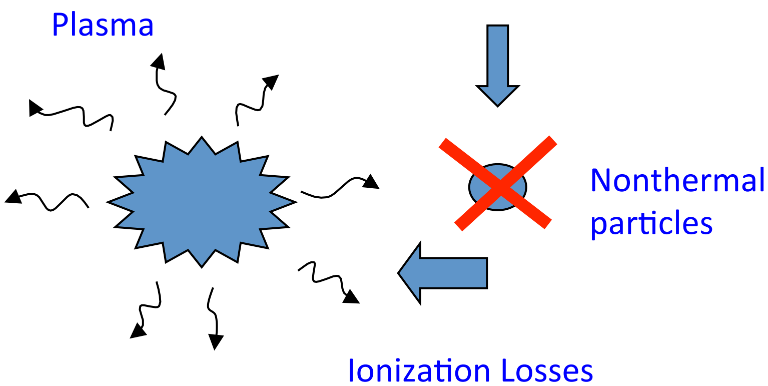


From VD et al.2007

T=const !!?

Acceleration from background plasma for the case when $T = \Phi(f) \neq const$

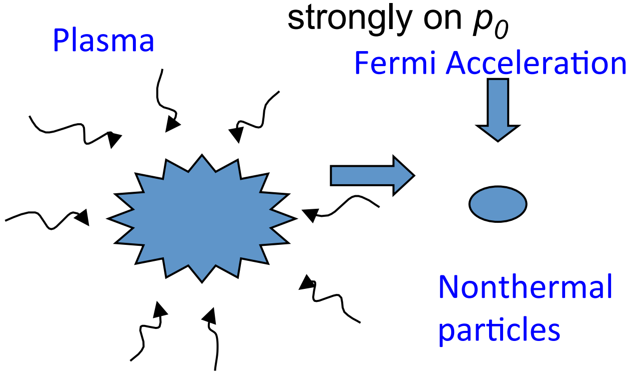
- **Wolfe & Melia (2006) and Petrosian & East (2008):** The energy gained by the particles is distributed to the whole plasma on a timescale much shorter than that of the acceleration process itself. Because of the relatively inefficiency of bremsstrahlung for cooling the accelerated electrons, this tail is quickly dumped into the thermal body of the background plasma (plasma overheating without a prominent tail of accelerated particles) .



- **Chernyshov, VD & Ko (2012):** For a high value of the acceleration momentum cut-off p_0 the run-away flux of thermal particles cools the plasma down from the very beginning. In spite of energy supply by external sources the plasma temperature drops down (analogue to Maxwell demon). Acceleration with a prominent tail of accelerated particles.

$$D(p) = D_o p^{\varsigma} \theta(p - p_0)$$

- The regime of acceleration depends strongly on p_0



Solutions of the system of nonlinear equations with back reaction of accelerated particles of the plasma density and temperature (see Chernyshov, VD & Ko, 2012**)**:

$$1.\quad \frac{\partial f}{\partial t}+\frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\left(\frac{dp}{dt}\right)(p,n,T)f-[D(p,n,t)+D_F(p)]\frac{\partial f}{\partial p}\right]=0$$

$$2.\quad n=n(f),\quad T=T(f)$$

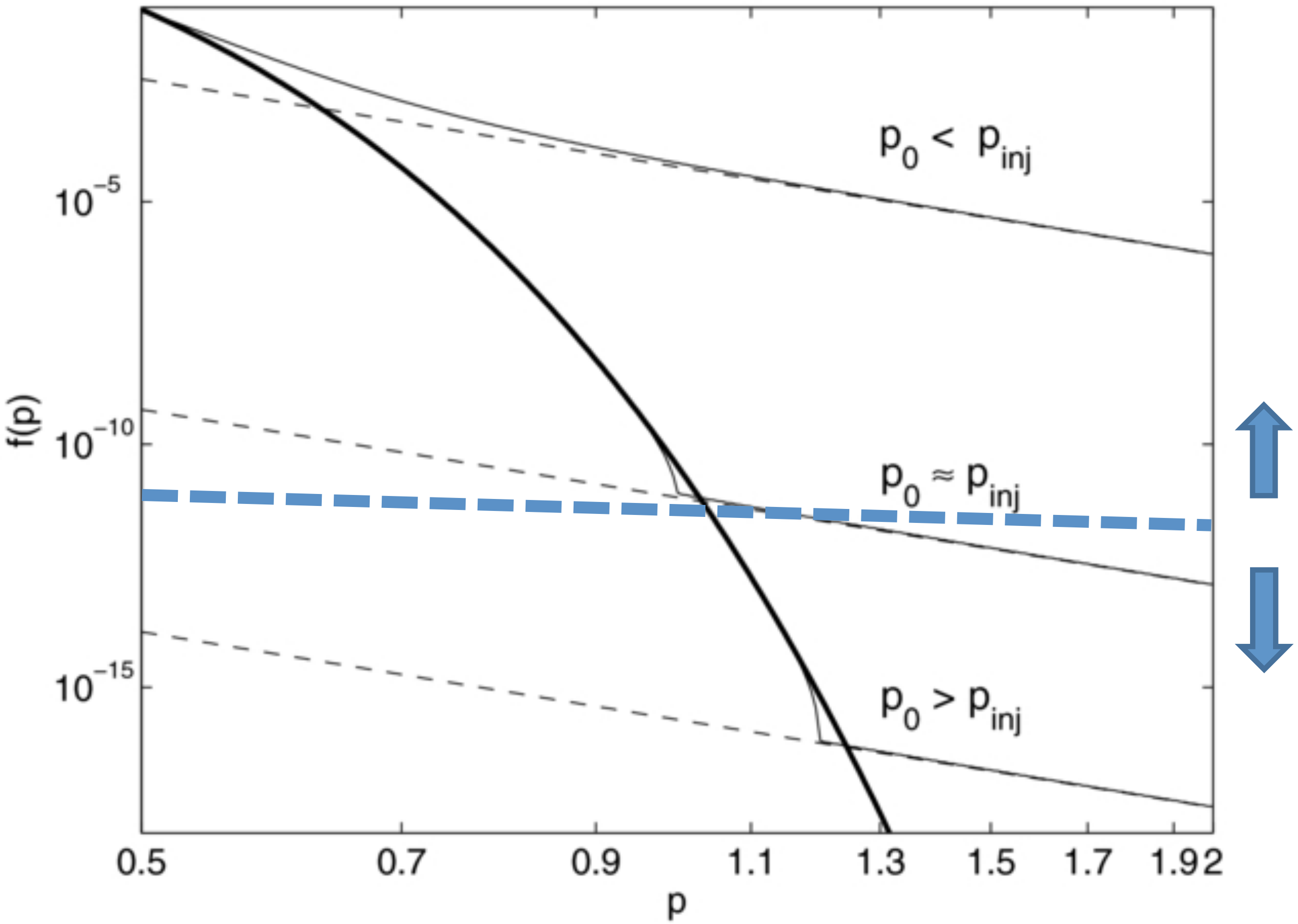
$$3.\quad \frac{dp}{dt}(p,n,T)=-\frac{A(n)(p^2+1)}{p^2}\left[erf\left(\sqrt{\frac{E}{T}}\right)-\sqrt{\frac{4E}{\pi T}}\exp\left(-\frac{E}{T}\right)\right]$$

$$D(p,n,T)=-\frac{T\sqrt{p^2+1}}{p}\frac{dp}{dt}(p,n,T)$$

$$D_F=\alpha p^{\varsigma}\theta(p-p_0)$$

acceleration from a background plasma with a cut-off acceleration parameter $D(p) = D_0 p^{\varsigma} \theta(p - p_0)$

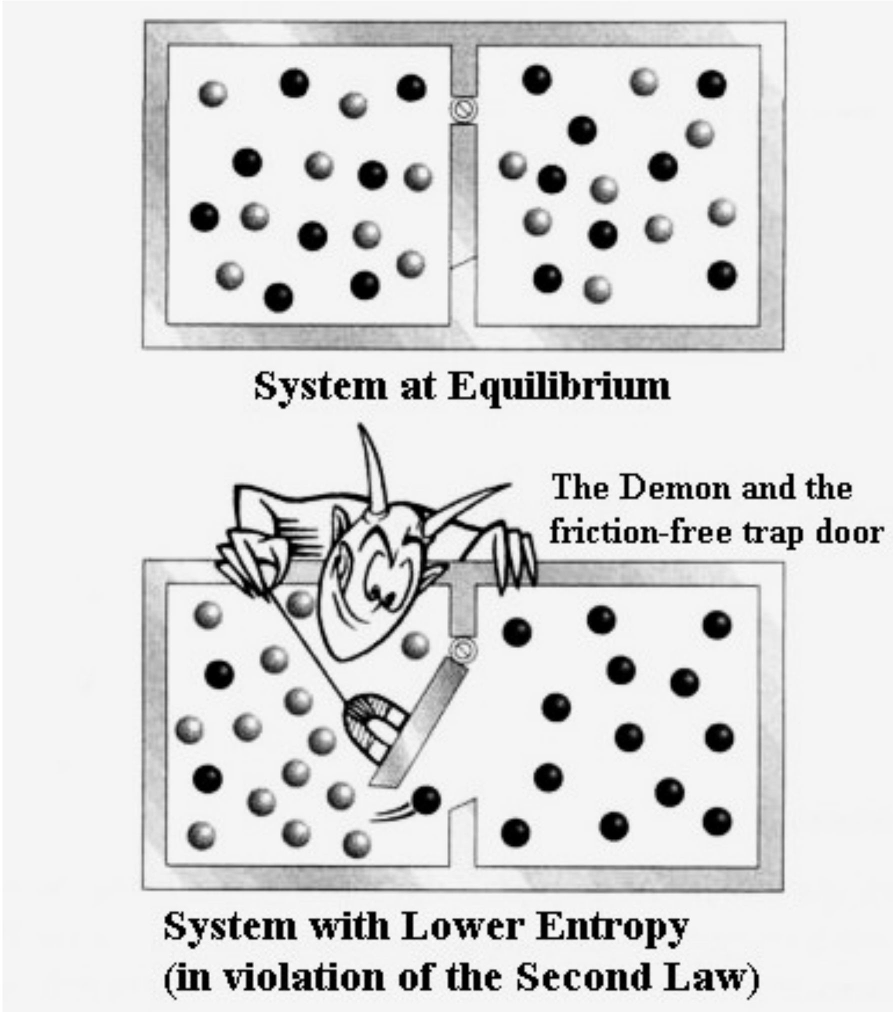
(from Chernyshov,VD & Ko 2012)

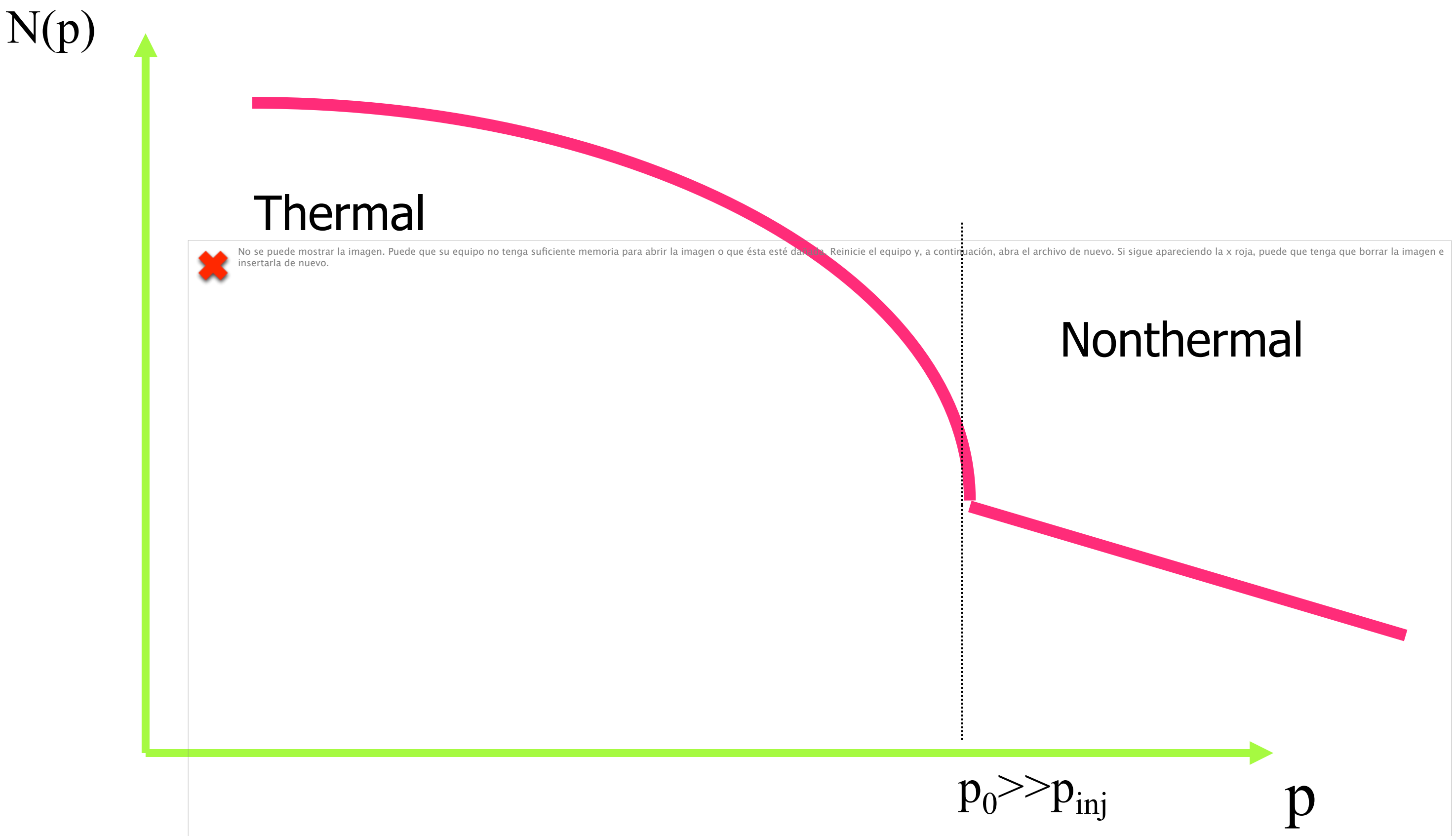


Plasma overheating
No acceleration

Plasma Cooling
Stochastic acceleration

Maxwell demon





No se puede mostrar la imagen. Puede que su equipo no tenga suficiente memoria para abrir la imagen o que ésta esté dañada. Reinicie el equipo y, a continuación, abra el archivo de nuevo. Si sigue apareciendo la x roja, puede que tenga que borrar la imagen e insertarla de nuevo.

Is it correct?!!!

Wave Absorption by CRs

- Equation for the spectrum of MHD fluctuation for the Krachnann spectrum of turbulence (Normann & Ferrara 1996)

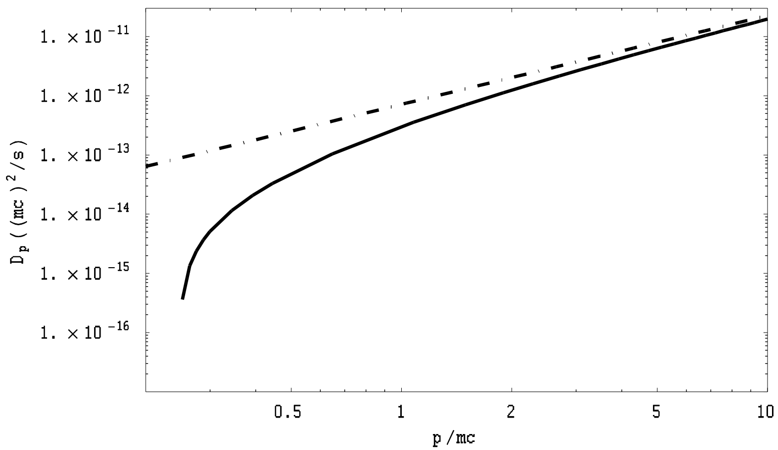
$$\frac{d}{dk}\left[\frac{C\left(k^{3/2}W(k)\right)^{3/2}}{\rho V_A}\right] = -2\Gamma_{cr}\mathrm{W} + \Phi\delta(k-k_0)$$

- Wave absorption increment

$$\Gamma_{cr} = \frac{\pi Z^2 e^2 V_A^2}{2kc^2}\int_{p_{res}}^{\infty}\frac{dp}{p}F(p)$$

- Coefficient of momentum diffusion (stochastic acceleration)

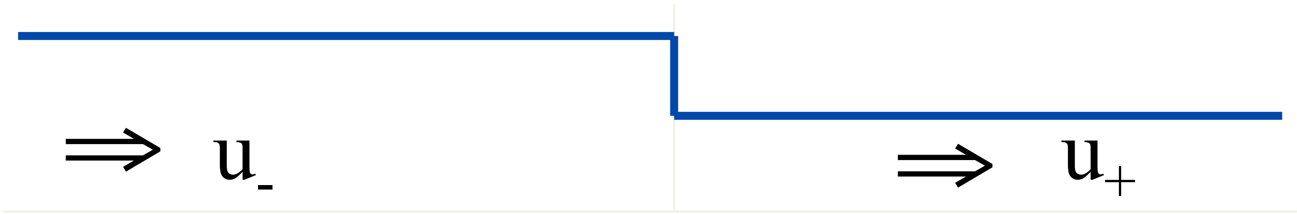
$$D(p) = p^2\,\frac{12\pi V_A^2 k_{res} W(k_{res})}{v r_L B^2}$$



Cheng ,Chernyshov, VD, Ko 2014

The momentum diffusion coefficient

Shock Wave Acceleration (Bulanov and Dogiel, 1979)



$$\frac{\partial}{\partial x}\left(u(x)f - D\frac{\partial f}{\partial x}\right) - \frac{\nu_0 (mkT)^{3/2}}{p^2}\frac{\partial}{\partial p}p^2\left\{\frac{1}{p^2}f - \frac{1}{p^3}\frac{T}{m}\frac{\partial f}{\partial p}\right\} =$$

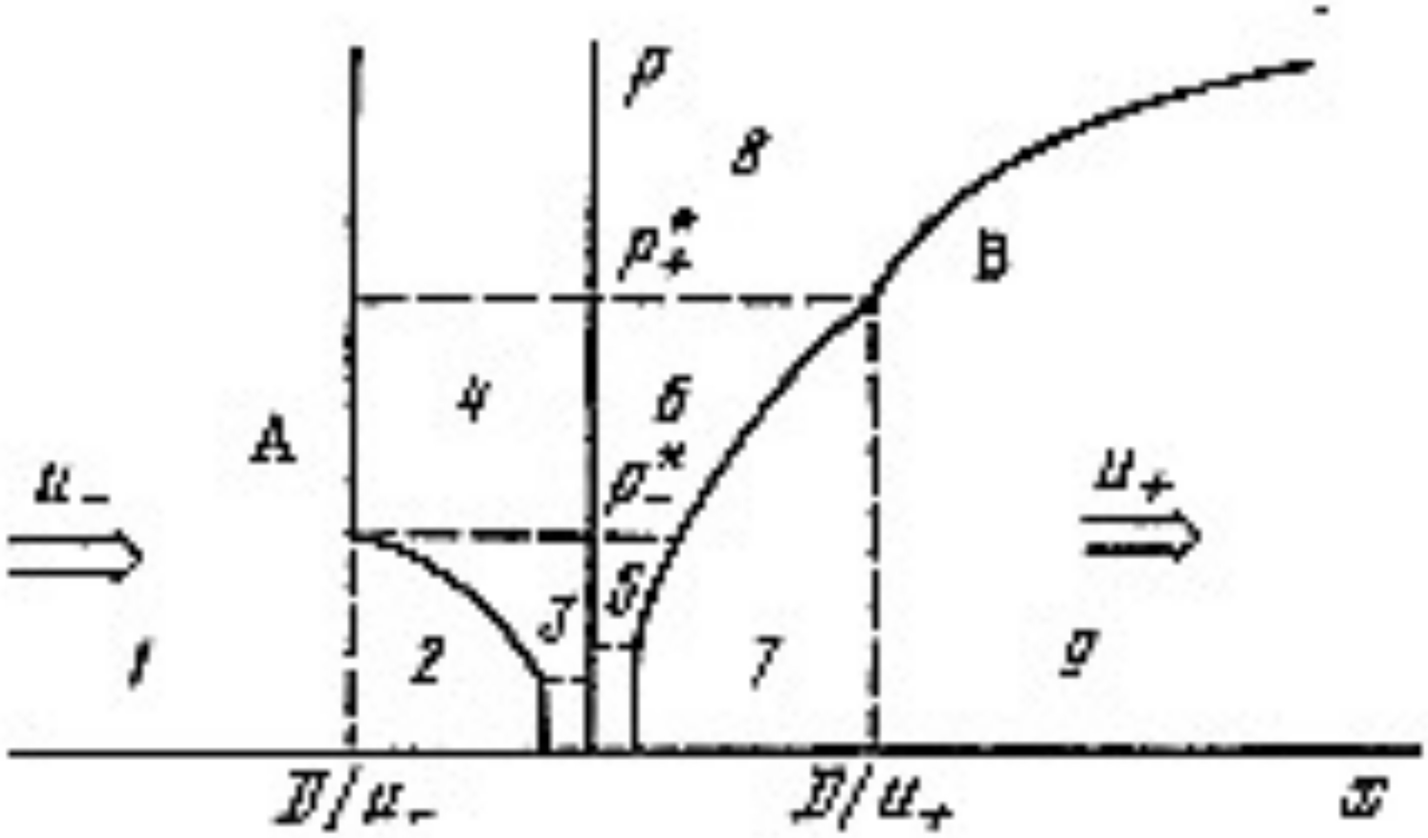
$$= \frac{1}{3}\frac{du}{dx}\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^3 f\right)$$

Regions of Different Analytical Solutions:

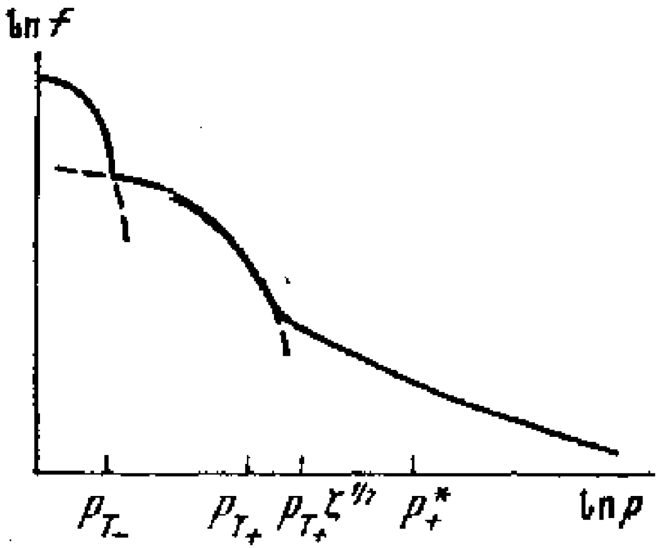
Thermal Maxwellian Spectrum;

Quasi-Thermal Spectrum

Nonthermal Power-Law Spectrum



Spectrum of Particles Accelerated by Shocks



- Acceleration from background plasma - the particle spectrum differs from a simple sum of thermal + nonthermal

The Number of accelerated particles?

(Bulanov and Dogiel,1979)

- Equation for shock acceleration from background plasma

$$\frac{\partial}{\partial x}\left(u(x) - D\frac{\partial f}{\partial x}\right) - \frac{1}{p^2}\left[\left(\frac{dp}{dt}\right)_C f + D_C\frac{\partial f}{\partial p}\right] = -\frac{\nabla \boldsymbol{u}}{3}\frac{1}{p^2}\frac{\partial}{\partial p}(p^3 f)$$

- The number of particles accelerated from a background plasma

$$\frac{n_{CR}}{n_0} \sim \frac{p_T}{p_{thr}}\left(\frac{m_e}{m_p}\right)\delta^{1/3} exp\left\{-\delta^{1/2}\left(1 + \frac{1}{2} ln\left[\left(\frac{m_p}{m_e}\right)^2 \frac{1}{3\delta}\right]\right)\right\}$$

$$p_T = \sqrt{2kTm_p}$$

$$p_{thr} = p_T\sqrt{\frac{m_p}{m_e}}\delta^{1/3}$$

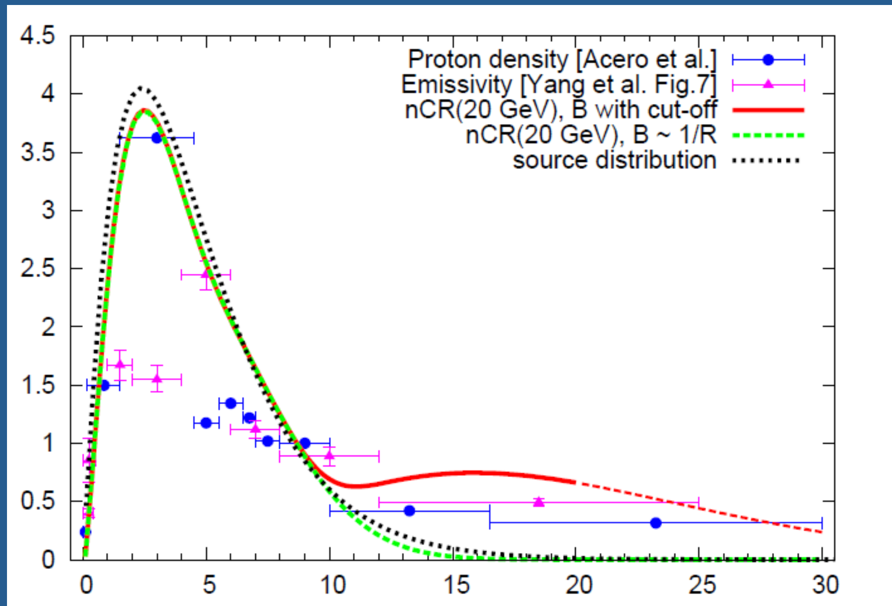
$$\delta = \frac{D\nu}{u^2}$$

$$\nu = \frac{2\pi n_0 e^4 \Lambda}{m_e \bar{p}^3}$$

$$\bar{p} = m_p\sqrt{\frac{2kT}{m_e}}$$

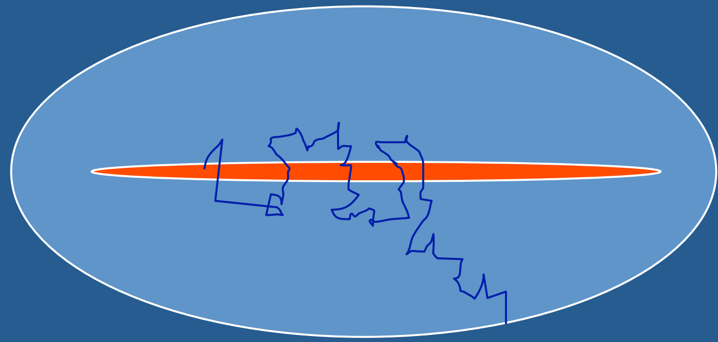
CR Gradient in the Galactic Disk as an Effect of Background Plasma Temperature

The problem of difference between the gradients of CRs and sources is live one.

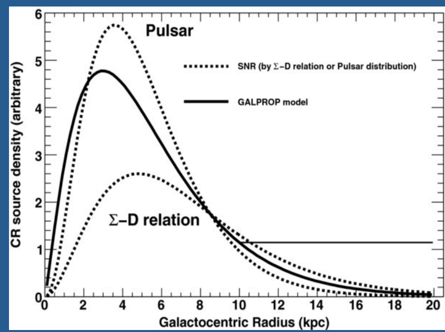


From Recchia et al.2015

•VD & Uryson 1988; Strong et al., 1988, Bloemen, et al.,1993 - Huge CR Halo (global CR gradient) + parameters of CR propagation in the Galaxy (GALPROP + talks of Blasi, Morlino, Evoli)

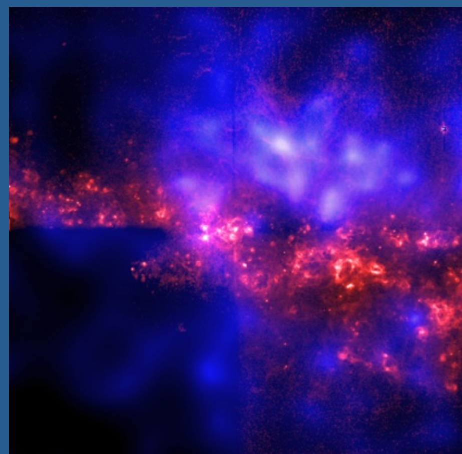


•Strong et al. 2000 – unseen SNR at the periphery of the Galactic disk



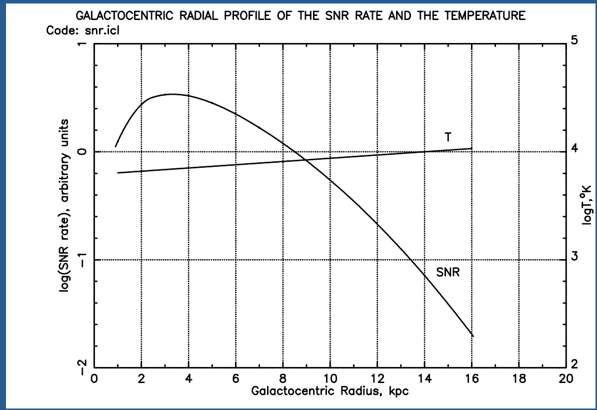
From Ackermann et al.2011

•Breitschwerdt, VD & Voelk 2002 – effect of the Galactic wind (see also similar but more developed model of Recchia et al. 2016)

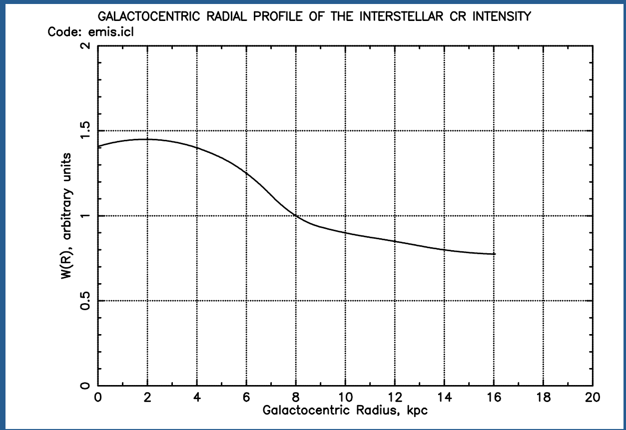


Chandra image

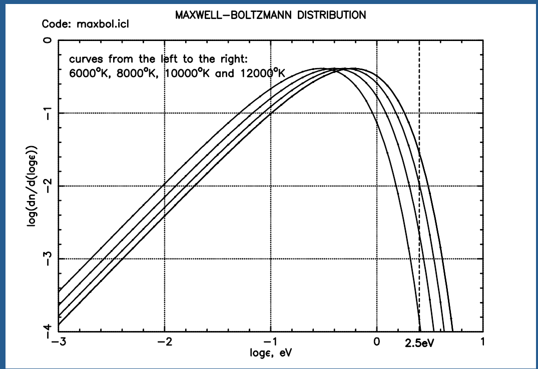
Density of SNRs (Green 2012) and the temperature of background electrons (Quiresa 2006) as functions of the Galactocentric radius.

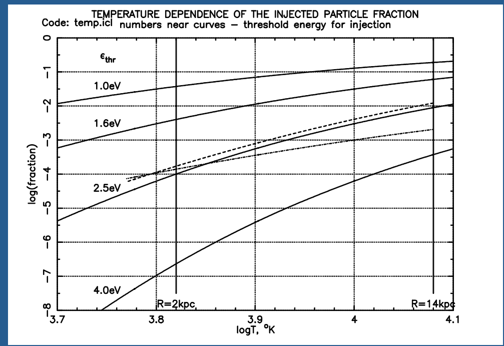


Distribution of CR density in the Disk (summary observations)

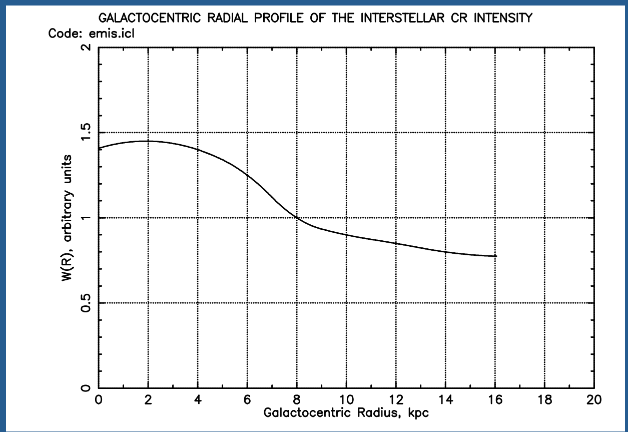


In some models of particle injection into SN shocks the temperature of the ambient ISM has relevance (Berezhko et al.,1996; Kang et al., 2002). Therefore Erlykin, Wolfendale and VD (2016) suggested an alternative model - the effect is due to different fractions of CRs accelerated from a background plasmadepending on the background temperature in the Disk





$E_{inj} = 2.5$ eV gives a reasonable coincidence with the Galactic CR gradient but there are a number of uncertainties and a more detailed analysis is required



Thank you for your attention!
Grazie!