Processes of Gamma Ray and Microwave Emission from the Fermi Bubbles

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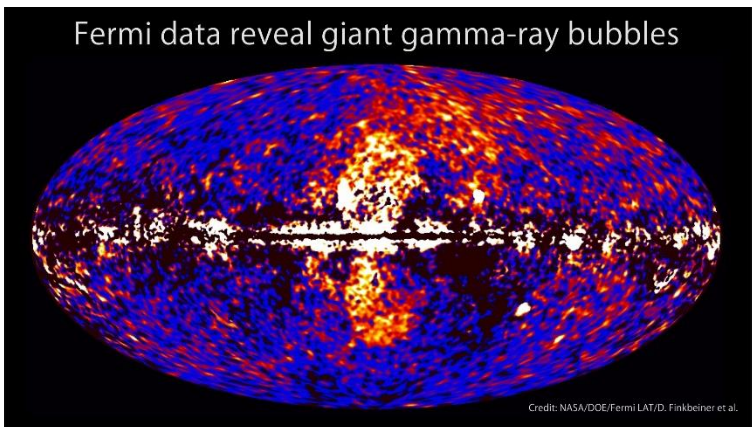
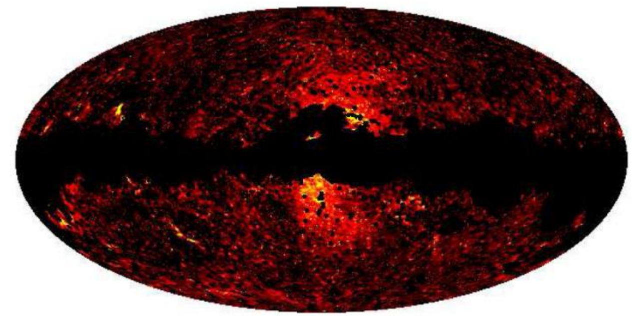
Bubbles from the Fermi and Planck data

Images of the the Fermi Bubbles (Dobler et al. 2010, Su et al. 2010)
and the
Galactic Haze at 30 and 44 GHz, extracted from the Planck observations
(Planck Collaboration, 2013) .

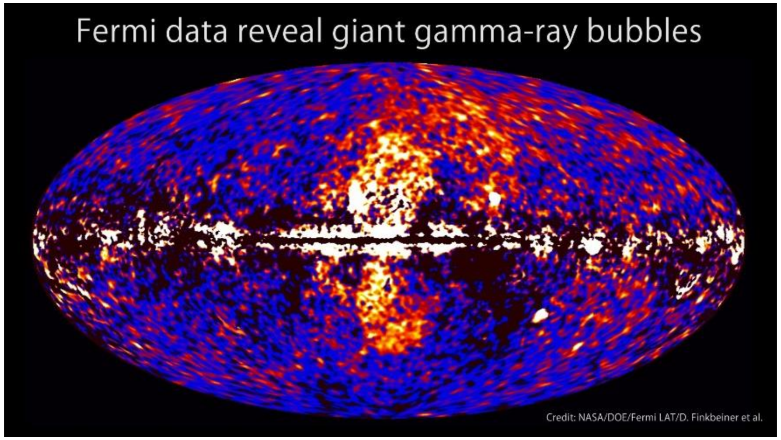


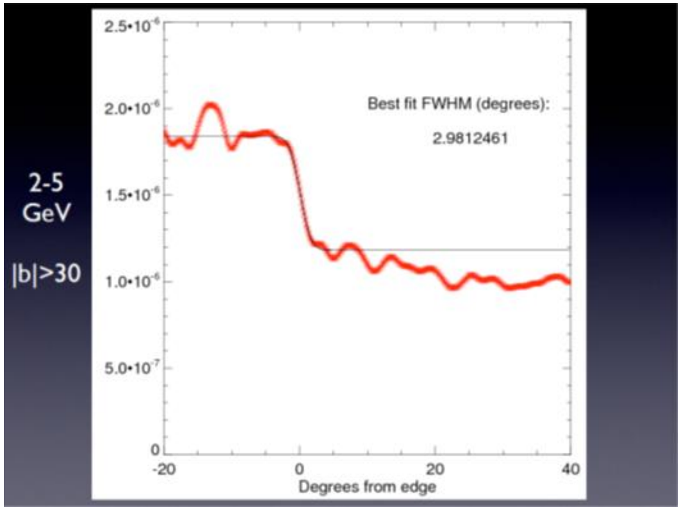


The morphology similarity and correlation between GHz and gamma-ray GeV luminosities implies that the bubbles are real and their multi-wavelength emissions have common origin. The existence of such ”haze” implies a population of anomalously hard spectrum electrons toward the GC

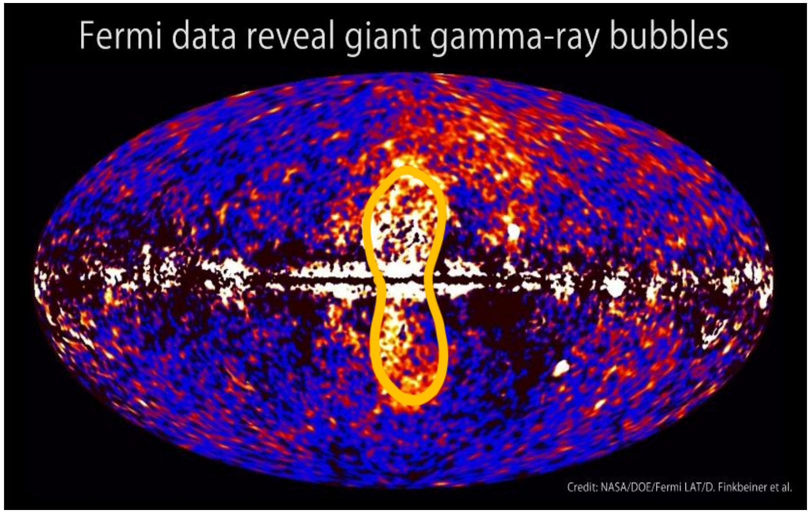
What do we need to explain?
Geometry of the Bubbles

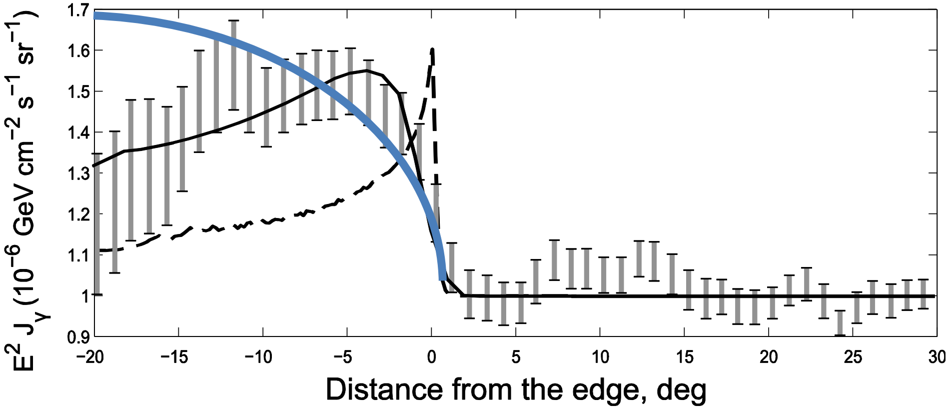
- *Double-Bubble structure*
- *Constant surface luminosity*
- *Sharp edges*





Spatial distribution of the Bubble gamma-ray emission





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Emission regions near the Bubble edges?

What do we need to explain?
Spectral Characteristics

- Gamma-rays
  Flux in the range 1 -100 GeV, $F_\gamma \sim 4\ 10^{37}$ erg/s
  Spectrum $\propto E_\gamma^{-2.1}$
  Cut-off at $E_\gamma \sim 100$ GeV

- Microwave radiation
  Flux in the range 23 -61 GHz, $\Phi_r \sim (1-5)\ 10^{36}$ erg/s
  Spectrum $\propto \nu^{-0.56}$

Origin of the Bubble gamma-ray emission

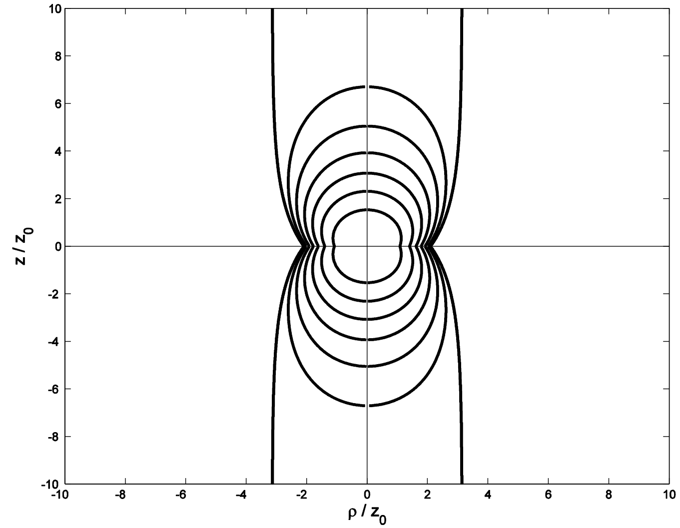
Hadronic	Leptonic
$p + p \rightarrow 2\gamma + e^{\pm}$	IC: $e + \gamma \rightarrow \gamma' + e'$
- Lifetime in the Bubbles ~10^{10}yr. Can be produced anywhere in the Galaxy. - But how to confine them in the Bubbles? - Spectrum of secondary electrons is steeper than follows from the Planck data	- Are confined in the Galaxy (< 1 Myr) - Should be produced in-situ
A) Crocker & Aharonian, 2011 **Crocker et al., 2014, Yang et al., 2014** 1) 0.04 SN/cen inside 1.5° of the GC=> 10^{40} erg/s (F_{γ}~$4x10^{37}$ erg/s) 2) "magnetic walls" (Jones et al 2012) **B) Fujita et al. (2013, 2014)** –shock **C) Thoudam (2013)** – injection +compression	**A) Su et al., 2010** Starburst или jet => giant shock from 10^{56}erg energy release **B) Guo & Mathews, 2011; Yang et al., 2012** Jet – electron propagation (almost) without scattering **C) Mertsch & Sarkar, 2011** Stochastic Acceleration (Fermi II) **D) Lacki 2013 –** starburst wind, termination shock **E) Cheng et al., 2011** Star captures=> shock wave acceleration

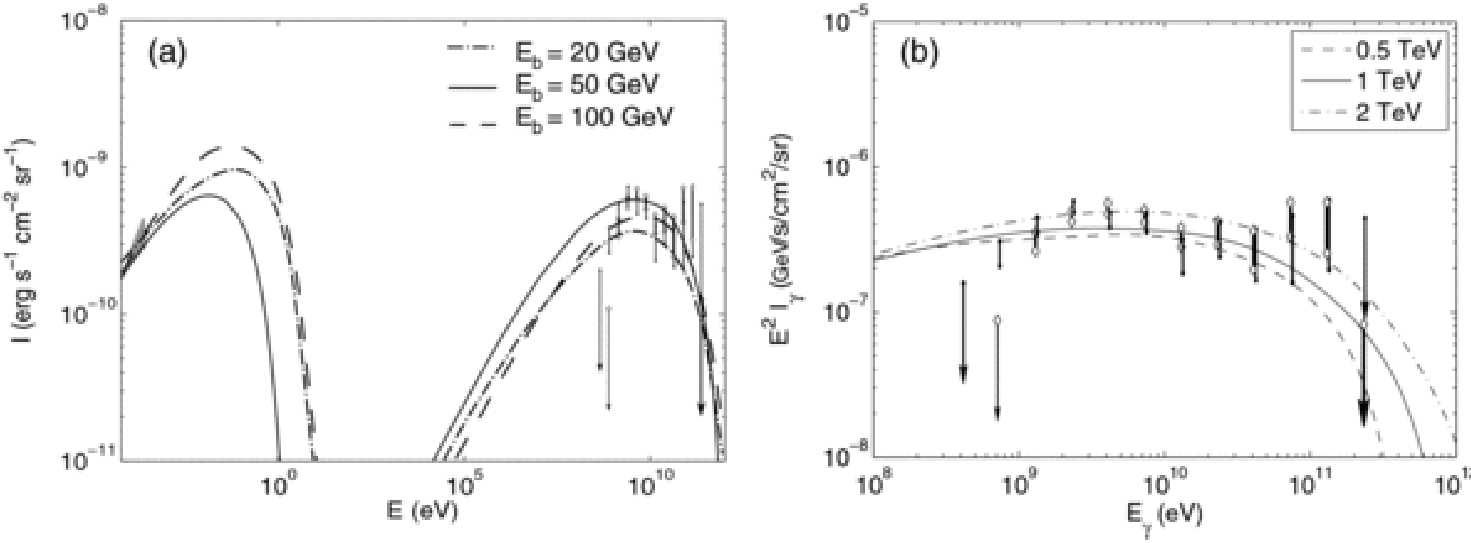
Leptonic model of tidal disruption of stars and shock wave acceleration (Cheng et al. 2011)

- . 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)




(a)
E_b = 20 GeV
E_b = 50 GeV
E_b = 100 GeV
I (erg s^-1 cm^-2 sr^-1)
E (eV)
(b)
0.5 TeV
1 TeV
2 TeV
E^2 I_γ (GeV/s/cm^2/sr)
E_γ (eV)

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

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

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

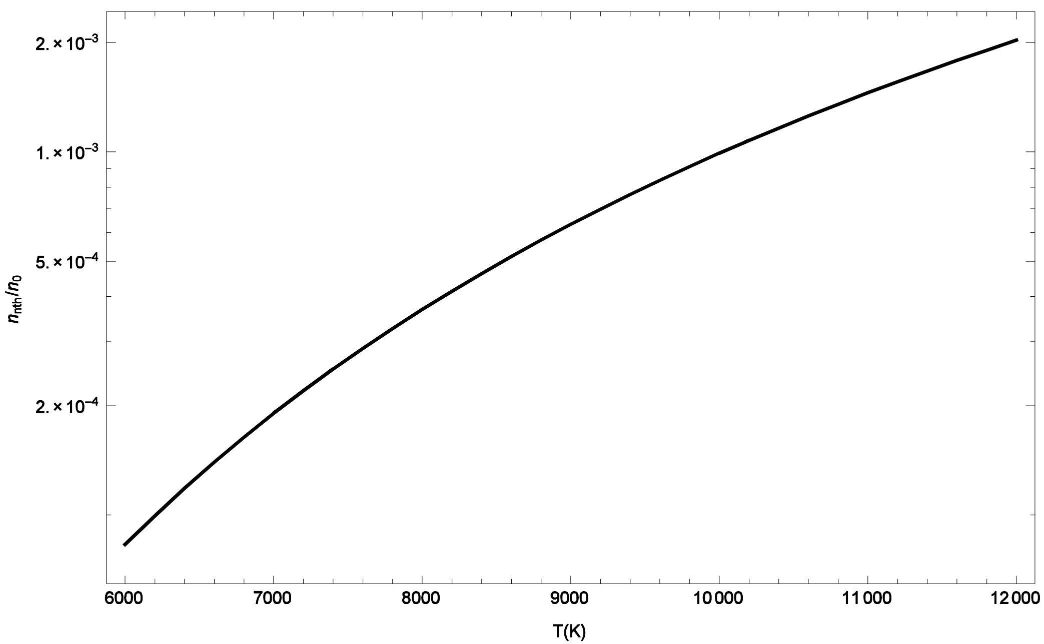
$$p_{thr} = p_T\sqrt{\frac{m_p}{m_e}}\delta^{1/3}$$

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

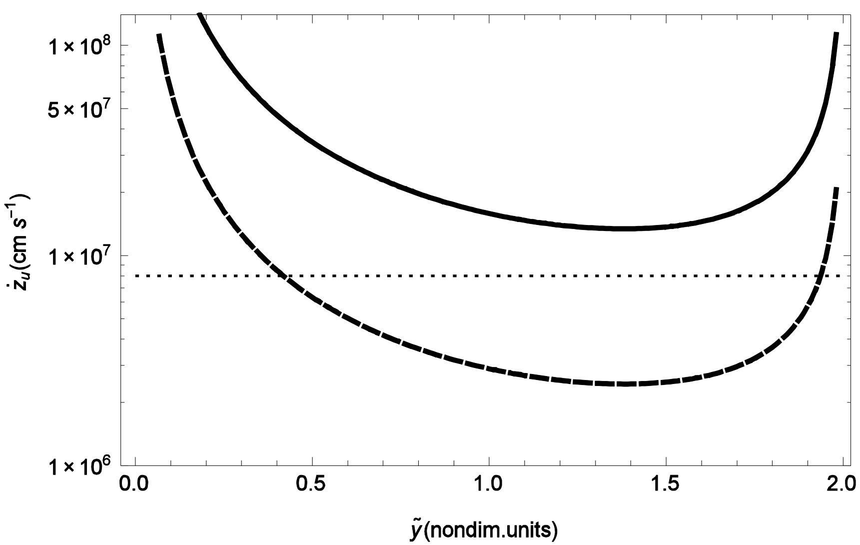
$$\nu = \frac{2\pi n_0 e^4 \Lambda}{m_e \bar{p}^3}$$

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

Acceleration from a background plasma by SNR shocks in the Galactic Disk
(Erlykin, Wolfendale and Dogiel, 2015)

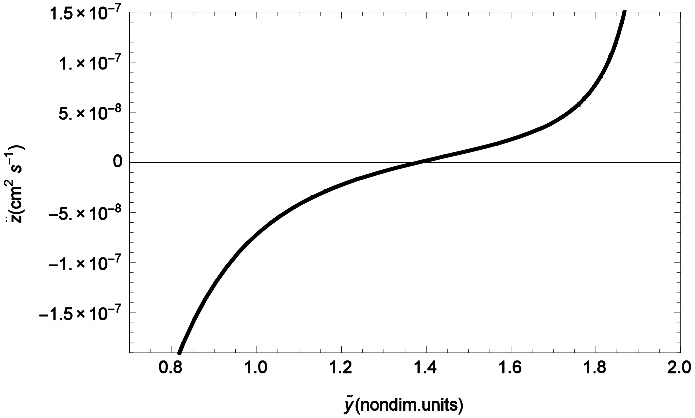


Velocity of the shocks in the exponential atmosphere (from the solution of Baumgartner and Breitschwerdt, 2013)

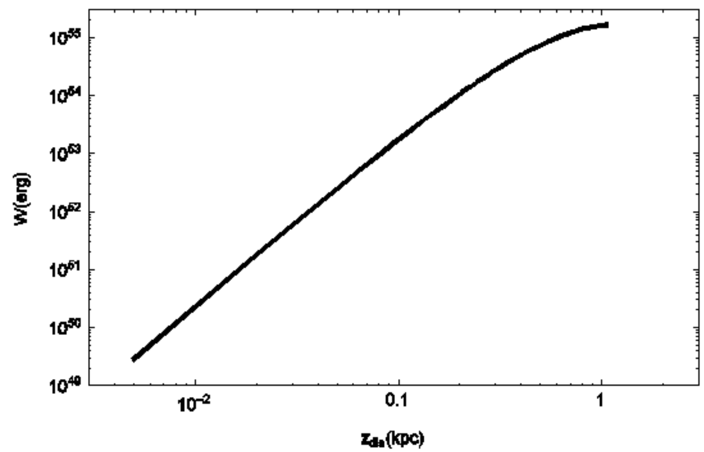


Velocity of the shock front at the top for the energy release $W = 10^{52} erg$ and $W = 10^{54} erg$

Shock fragmentation due to the Rayleigh-Taylor instability on the front (from the solution of Baumgartner and Breitschwerdt, 2013)



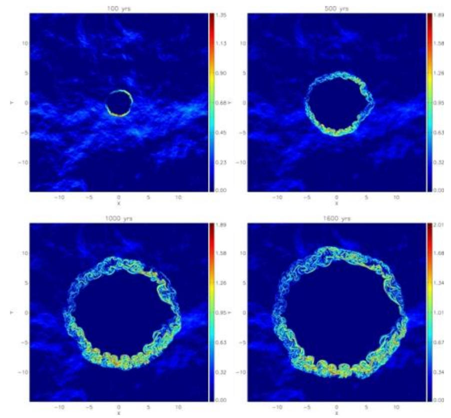
Shock acceleration as
a function of altitude y



Altitude of shock fragmentation
as a function of energy release W

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

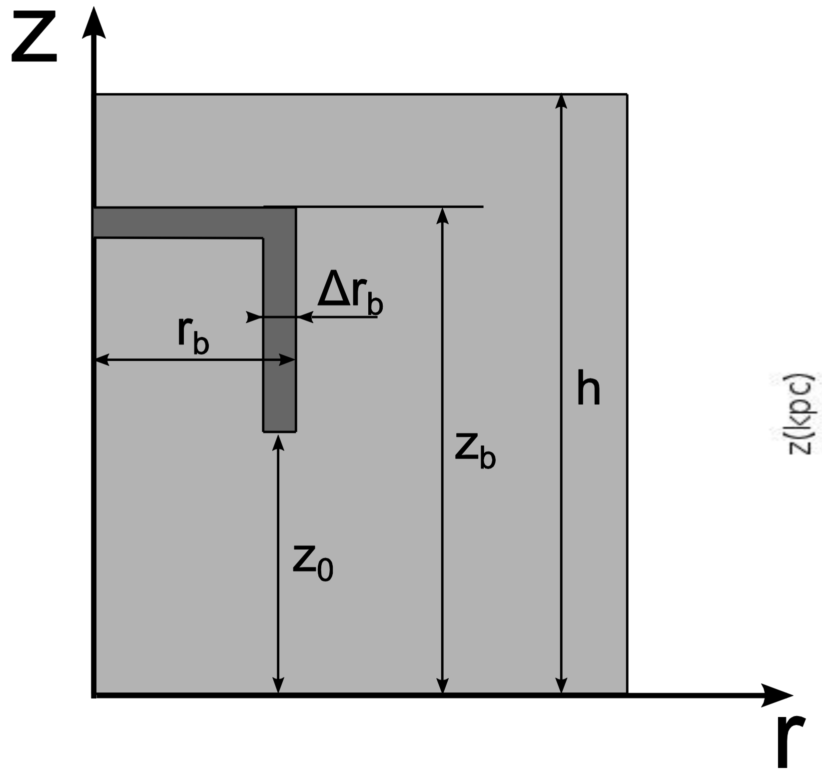
- From the ROSAT data of Snowden et al. (1997) - a shock front t at the bubble edge with the velocity ≤ 1000 km/s, the total energy estimated from parameters of the hot plasma in the Bubbles $\sim 10^{54-55}$erg, the age $\sim 10^7$ yr;
- Plasma instabilities, in particular Rayleigh-Taylor and Kelvin-Helmholtz instabilities, would then generate turbulence at the outer shock as e.g. in SNR envelopes (from Yang and Liu, 2013)

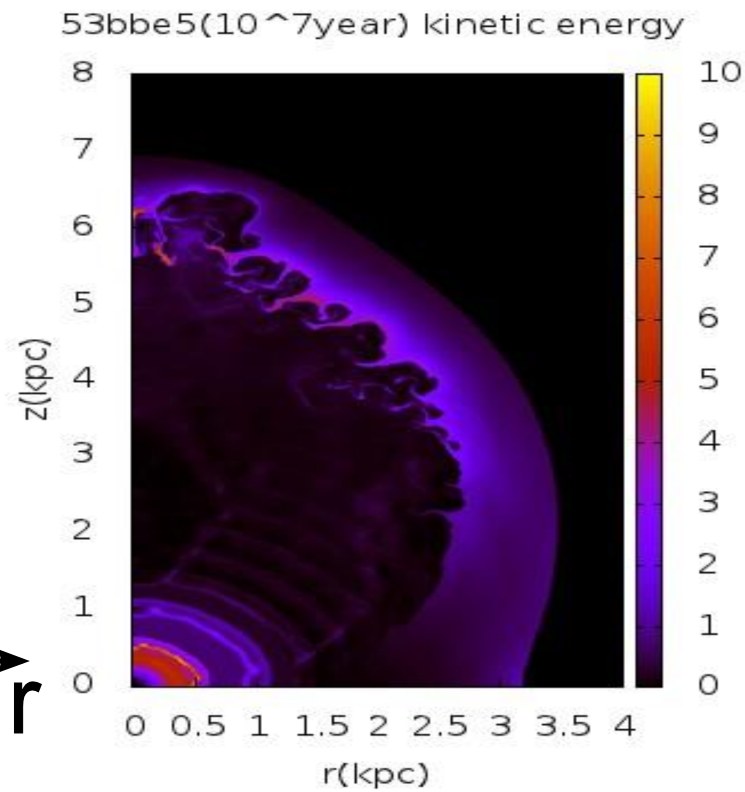


- The instabilities are convected into the bubble interior by the downstream plasma flow;
- Then the equation is

$$\frac{\partial f}{\partial t} - \frac{\partial}{\partial p}\left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{f}{p^2}\right) - \frac{f}{t_{esc}} + \frac{\partial}{\partial p}\left(\frac{dp}{dt} f\right) = 0$$

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





The Model of Stochastic Acceleration

Is the model able to provided needed number of relativistic electrons?

- Two cases:
- a) Acceleration from background plasma;
- b) Re-Acceleration of Relativistic Electrons emitted by SNRs

Equations

Acceleration from background plasma

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

Reacceleration of SNR electrons

$$-\nabla D(r,z,p)\nabla f + \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\frac{dp}{dt}f - \kappa(r,z,p)\frac{\partial f}{\partial p}\right] = Q(p,r)\delta(z)$$

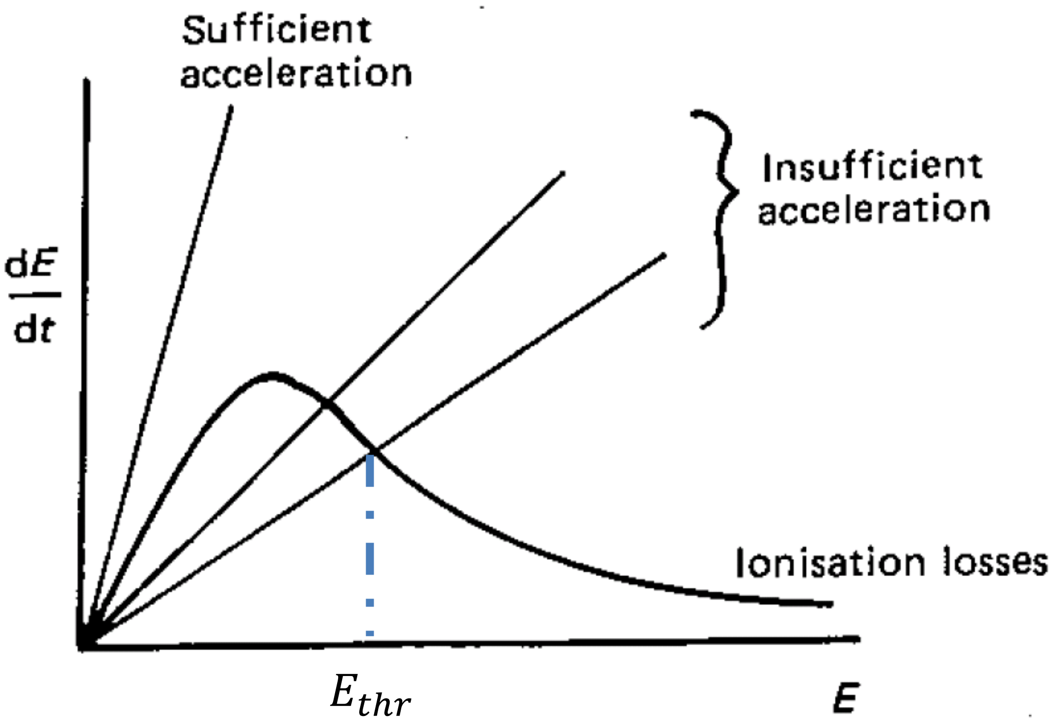


Figure 21.2. Comparison of the acceleration rate and energy loss rate due to ionisation losses for a high energy particle.

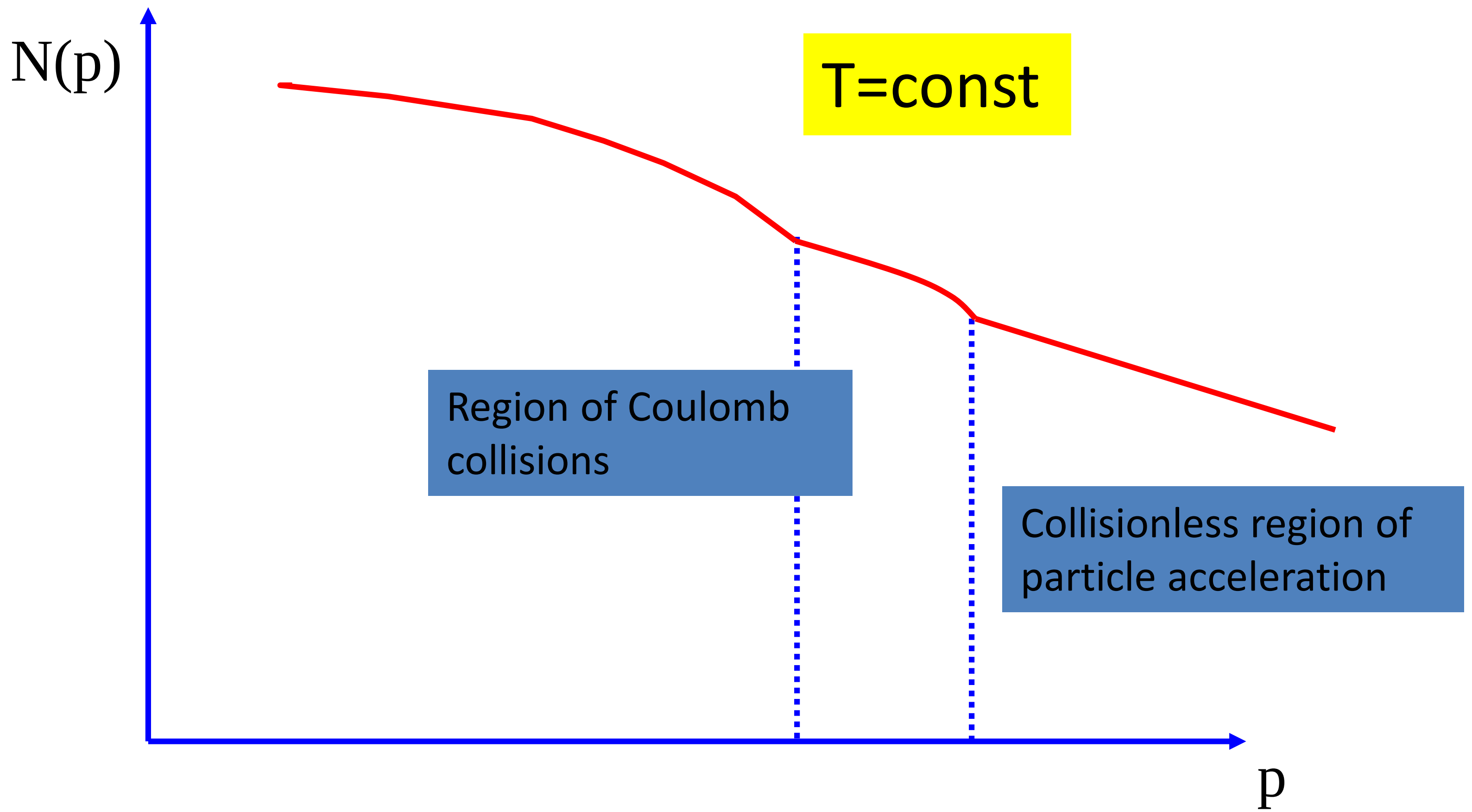
- $\left(\frac{dE}{dt}\right)_i = -\frac{2\pi n e^4}{m_e\sqrt{E}}\Lambda$
  $\left(\frac{dE}{dt}\right)_F = \alpha E$
- $\left(\frac{dE}{dt}\right)_i = \left(\frac{dE}{dt}\right)_F \rightarrow E_{thr}$
- Number of accelerated particles

  $N_{nth} \sim exp\left(-\frac{E_{thr}}{kT}\right)$

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

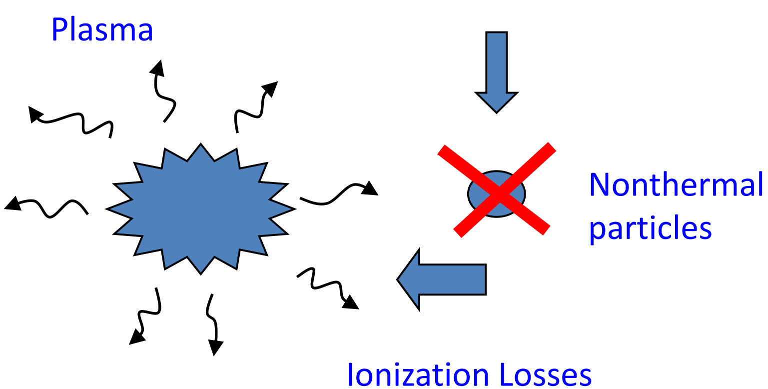
Spectrum of particles in the case of acceleration from a background plasma (Gurevich 1960)

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



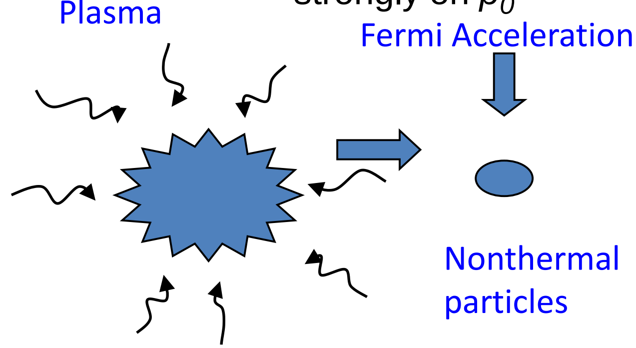
Acceleration from background plasma for the case when $T = \Phi(f) \neq const$

- **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) .

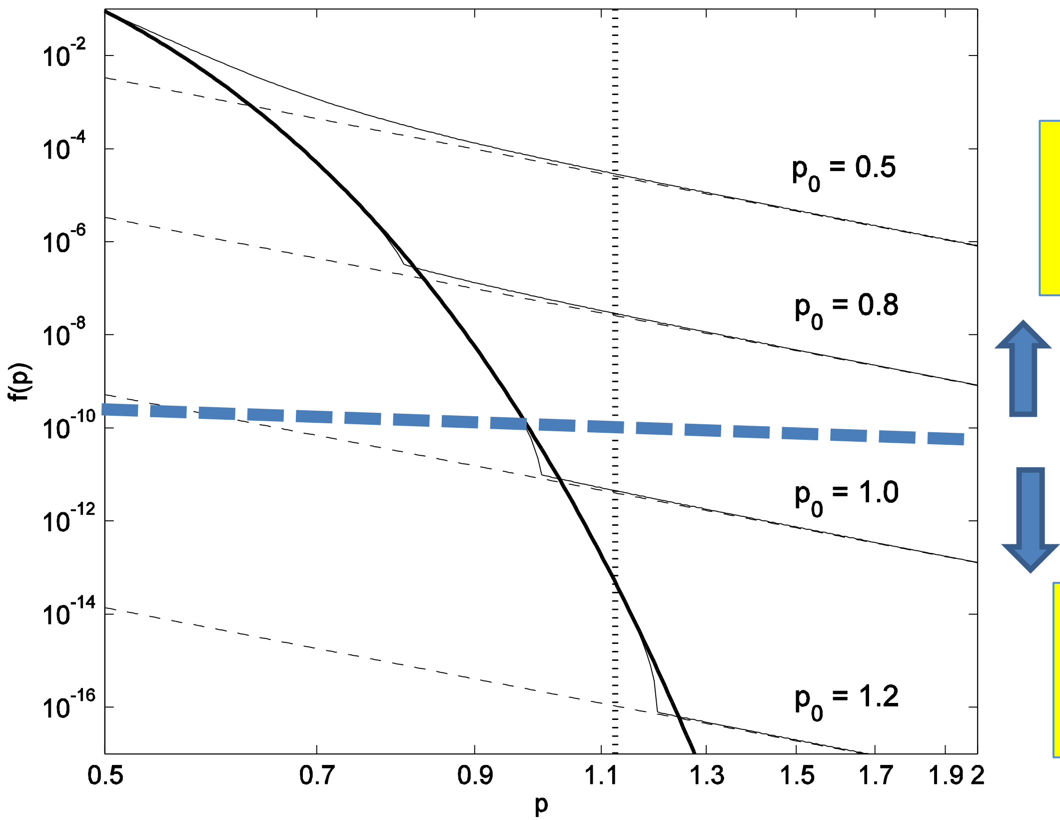


- **Chernyshov, Dogiel & Ko (2012):** For a high value of the acceleration momentum p_0 the run-away flux of thermal particles cools the plasma down from the very beginning. In spite of energy supply by external sources the plasma temperature drops down (analogue to Maxwell demon). Acceleration with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



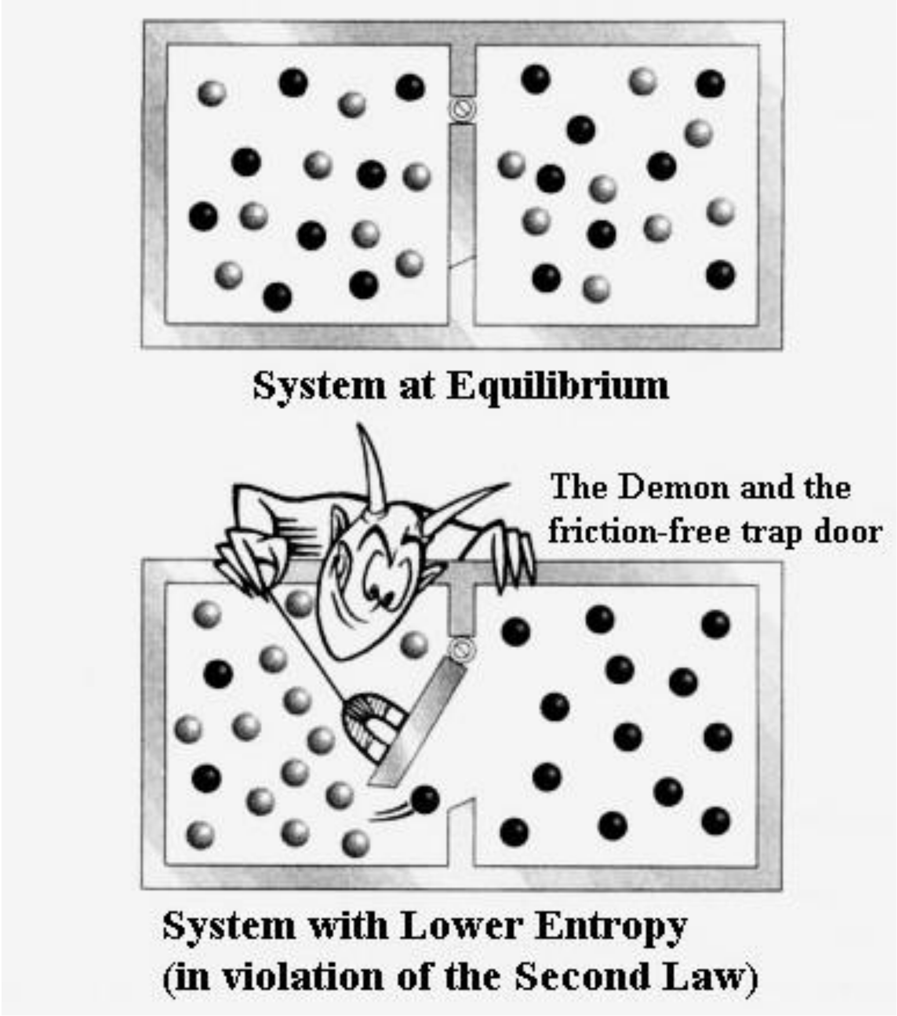
Spectrum of thermal and nonthermal particles (from Chernyshov et al. 2012 and Cheng et al. 2014)



Plasma overheating
No acceleration

Plasma Cooling
Stochastic acceleration

Maxwell demon



Wave Absorption by CRs

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

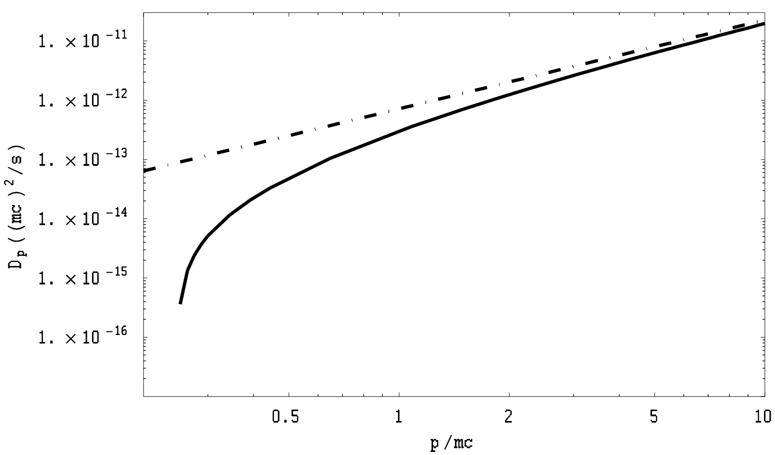
$$\frac{d}{dk}\left[\frac{C\left(k^{3/2}W(k)\right)^{3/2}}{\rho V_A}\right] = -2\Gamma_{cr}\mathrm{W} + \Phi\delta(k-k_0)$$

- 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)

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

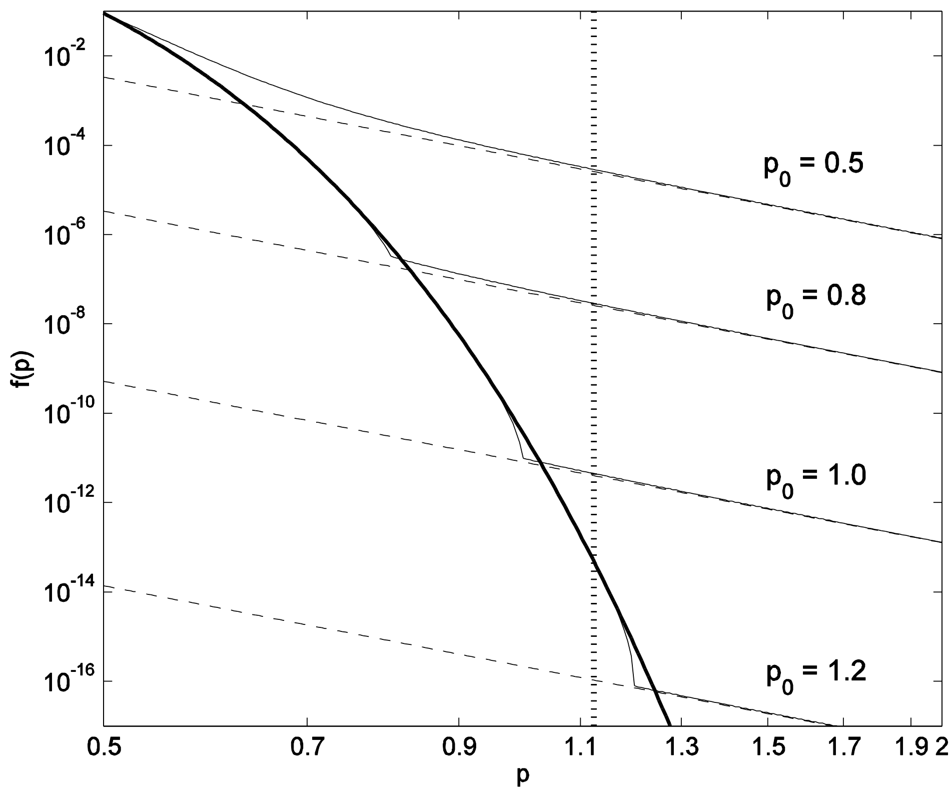


From Cheng et al. 2014

The momentum diffusion coefficient

Total spectrum of particles for the case of stochastic acceleration from a background plasma with a cut-off acceleration parameter $D(p) = D_0 p^{\varsigma} \theta(p - p_0)$

From Chernyshov et al. 2012 and Cheng et al. 2014



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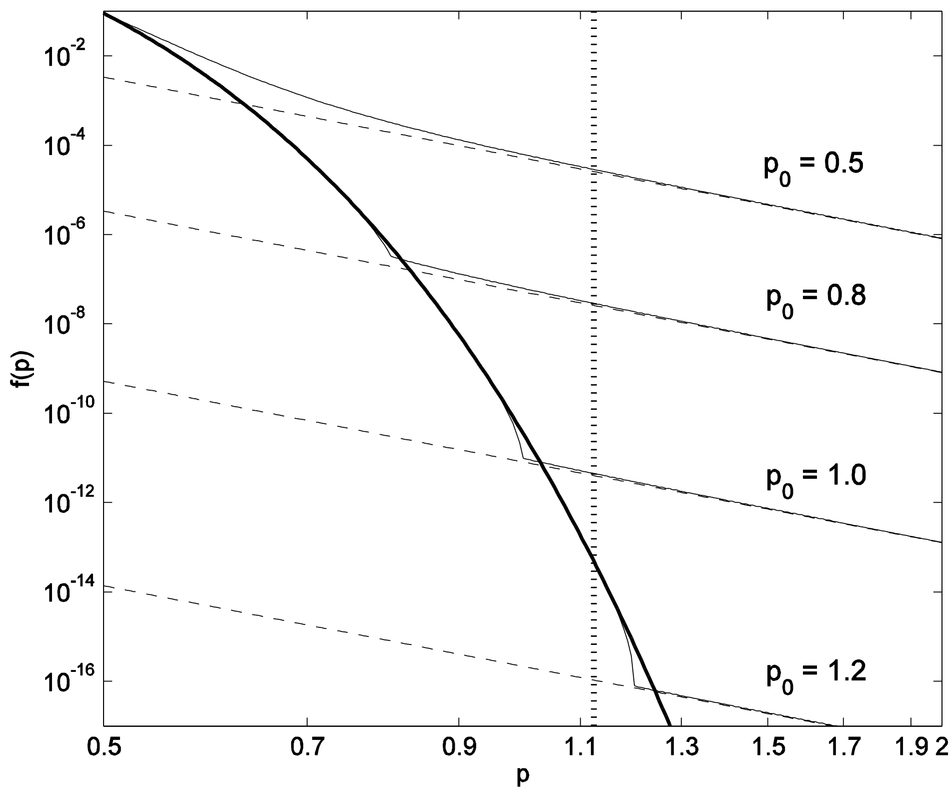

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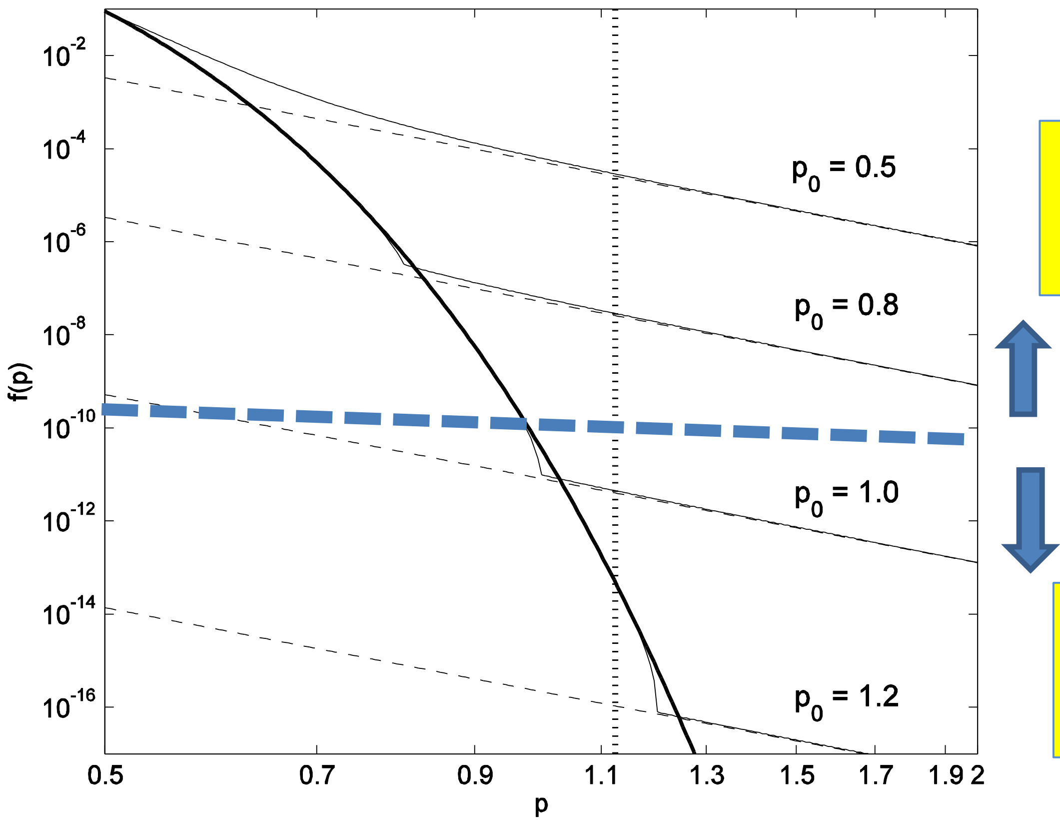


Plasma overheating
No acceleration

Plasma Cooling
Stochastic acceleration

Parameters of the model of stochastic acceleration

- Acceleration time $\tau \sim 3\ 10^6$ yrs, source power $\dot{W} \sim 5\ 10^{39}$erg/s, but (!) $p_0 \sim 0.34$ mc
- A very precise parameter of acceleration p_0 is needed to reproduce the gamma-ray spectrum from the Bubble if electron are stochastically accelerated from the background plasma.

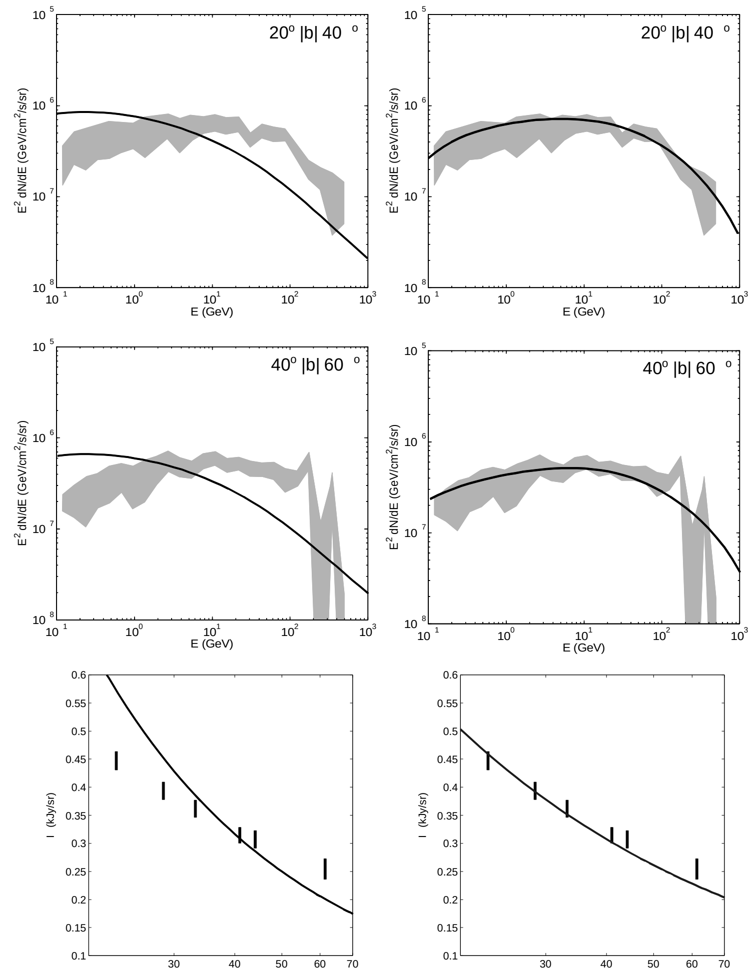
Re-Acceleration of Relativistic Electrons emitted by SNRs (diffusion+convection)

Reacceleration of SNR electrons in the wind model

$$\nabla(u(z)f - D(r,z,p)\nabla f) + \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\left(\frac{dp}{dt}\right)f - \frac{\nabla \boldsymbol{u}}{3}pf - \kappa(r,z,p)\frac{\partial f}{\partial p}\right] = Q(r,p)\delta(z)$$

If $v(z)=v_0 z$, $dv/dz \neq 0$

Spectra of re-accelerated CRs without (left column) and with the Galactic wind (the gradient parameter $v_0 = 10^{-15} s^{-1}$, right column) From Cheng, Chernyshov, Dogiel and Ko, 2015



Convective outflow from Galactic Center in the Bubble:

- Model assumption about wind outflow from the GC with v ~ 1000 km/s (Crocker and Aharonian, 2011; Carretti et al. 2013);
- Hubble observations of UV absorption lines: v>900 km/s (Fox et al., 2015)

Convection in the Galactic halo and the velocity gradient:

- Hydrodynamics with CRs (Breitschwerdt, McKenzie, Voelk,1991): $v(z)=v_0 z$, $dv/dz \neq 0$;
- Convection and the velocity gradient from the CR chemical composition (Bloemen, Dogiel, Dorman , Ptuskin, 1993): $v_o \sim 10^{-15} s^{-1}$;
- Convection and the velocity gradient in the halo from the outflow velocity in the Galactic disk (Breitschwerdt, Dogiel, Voelk, 2002)

Hadronic Model (Crocker & Aharonian, 2011-present)

- Lifetime of protons generating 100 GeV gamma-ray photons ~10^{10}yr, that of electrons ~10^{5}yr;
- Protons distribution in the bubbles is uniform. (*However, the protonic scenario requires some sort of magnetic structure ("magnetic walls") able to confine the Bubbles' protons for long times*.);
- Flattening of the gamma-ray spectrum at E_γ< 1 GeV (the pp reaction threshold);
- Sources of CRs – star formation region in the inner $1^\circ \times 1^\circ$CG region. Total power injected by SN there is estimated as $\sim 10^{40}$ erg/s, that gives ~ 10^{39} in CRs and about 4×10^{37}in 1 to 100 GeV gamma ;
- Electrons are secondary which are transported to the halo form the disk. There synchrotron luminosity in the 20-60 GHz derived from gamma is 2×10^{36}erg/s.
- If the characteristic time of transport by advection is < the time of synchrotron losses (z<3 kpc) then $\Phi_\nu \propto \nu^{-0.5}$, otherwise an additional electron component is necessary.

Problem of the hadronic model is a relatively hard microwave spectrum $\nu^{-0.5}$ →

spectrum of radiating electrons E^{-2}

spectrum of secondary electrons E^{-3}

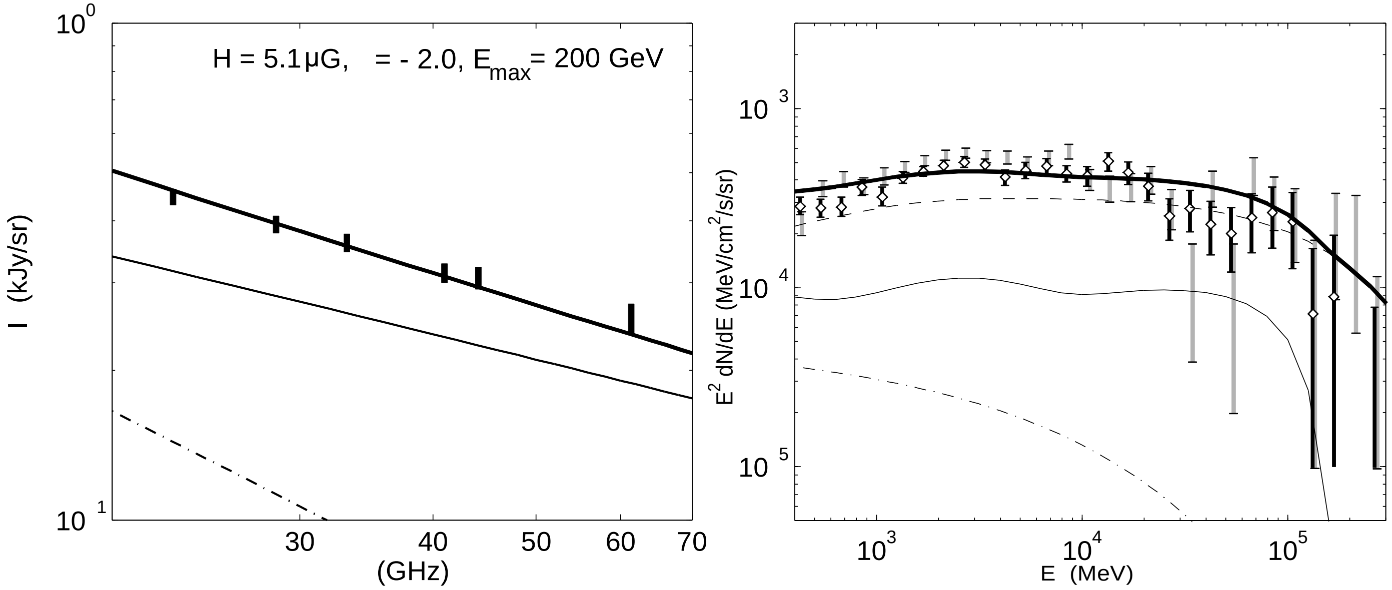
$$N \propto E^{-\gamma}$$

$$\Phi \propto \nu^{-\alpha}$$

$$\alpha = \frac{\gamma - 1}{2} = 1$$

Additional component of primary electrons is necessary

- The pure hadronic model is unable to reproduce the gamma-ray and radio fluxes from the FBs because the secondary electrons have too-soft spectrum $\propto E_e^{-3}$
- An additional component of primary electrons with a hard spectrum $\propto E_e^{-2}$ is necessary



- The range magnetic field permitted for the hadronic model is within the 2–7 μG region.
- *pp* collisions can only provide about 80% of the FB gamma-ray flux under the most favorable conditions when *H*~5 μG which decreases for higher and lower values of H. The *pp* mechanism is unable to generate the Bubble gamma ray flux if H> 7 μG or H< 2 μG.

Conclusion

- One of the main question is whether suggested processes of particle acceleration are able to produce enough high energy protons/electrons needed to generate the observed gamma/microwave fluxes from the Bubbles.
- Shock wave model reproduce reasonably well parameters of the Bubble emission but more detailed analysis of processes is needed.
- For the case of hypothetical stochastic acceleration of electrons from background plasma a shortage of the model is that parameters of acceleration is strongly restricted. Either acceleration does not produce enough electrons or instead, the acceleration overheats the background plasma (no nonthermal tails).
- An advantage of stochastic re-acceleration of electrons emitted by SNRs in the Disk is that the injection energy of electrons is about 1 GeV (cf with the case of acceleration from background plasma where the injection energy is about hundred eV). However in this case effective adiabatic losses are required in order to get necessary spectral characteristic of the emission.
- The problem of hardonic model is a very steep spectrum of secondary electrons. Therefore an additional component of primary electrons with a hard spectrum is needed. In this case the protons produce no more than 70% of the total gamma-ray flux, the rest is produced by hypothetical component of primary electrons. The contribution of protons into the gamma-ray flux depends strongly on the magnetic field strength which should be in the limits 2–7 μG.

Thank You!