# PROPAGATION OF CRs INTO DIFFUSE CLOUDS

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**In collaboration with:**
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# OUTLINE

- **Penetration of cosmic rays from hot ISM into diffuse clouds**
  - Skilling & Strong (1976); Cesarsky & Voelk (1977); Everett & Zweibel (2011);
  - ***Kinetic model for the full distribution function $f_{CR}(x,p)$***
  - ***Inclusion of CR-amplification of Alfvén waves***
- **Shocks propagating into diffuse clouds**
  - ***Effect of neutral Hydrogen on the shock structure***
  - ***Slope of accelerated particles***
- **Conclusions**

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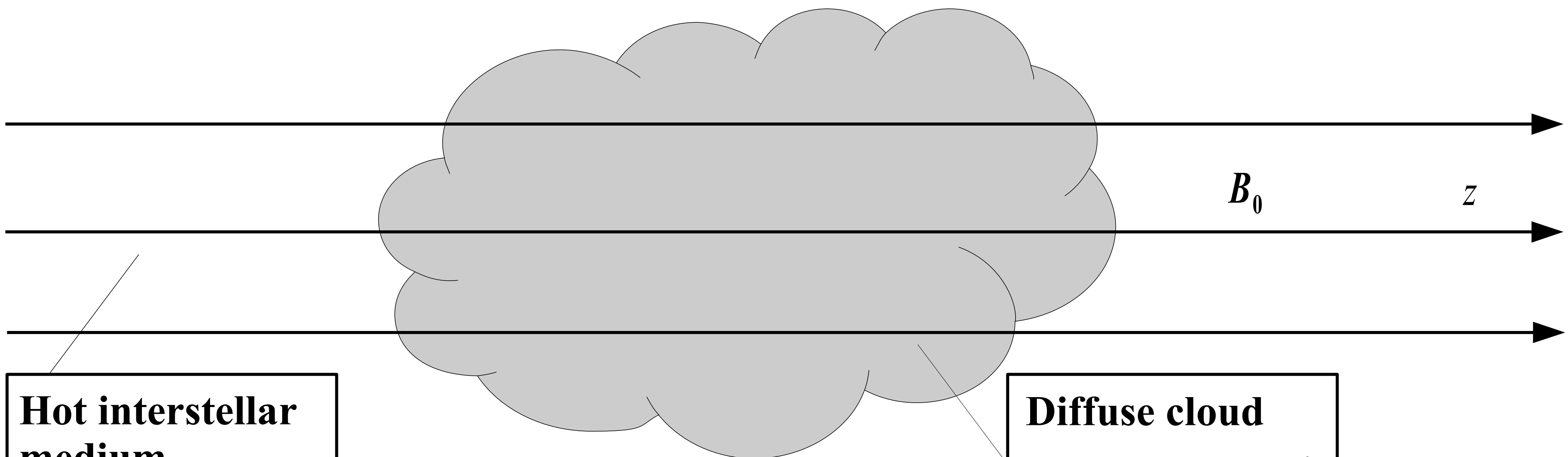
- **Conclusions**

# Set up of the model




**Hot interstellar medium**

$n \sim 0.01-0.1\,cm^{-3}$

$T \sim 10^4-10^5\,K$

$x_{ion} = 1$

**Diffuse cloud**

$n \sim 10-100\ cm^{-3}$

$T \sim 10^2-10^3\ K$

$x_{ion} \approx 10^{-3}$

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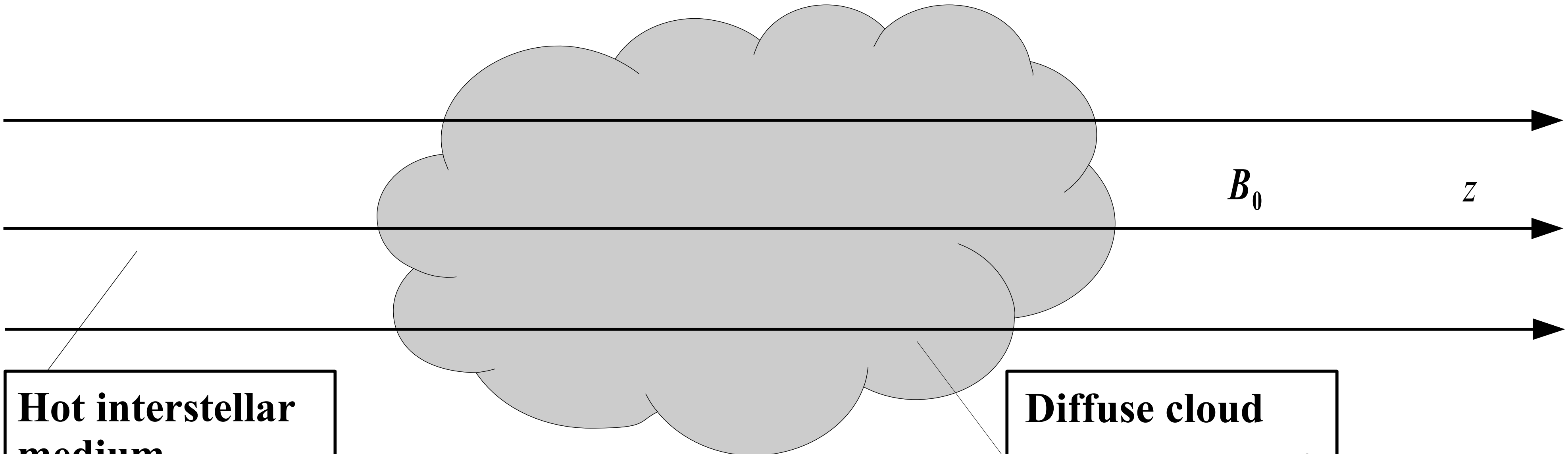


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$\boldsymbol{B_0}$ coherence length ~ 50-100 pc
Cloud size ~10 pc

→ 1-D approximation along the magnetic field lines

$\boldsymbol{B_0}$ = const = 3 μG  observations show that for low density ISM ($n$ < 300 cm$^{-3}$), the magnetic field strength is independent of the ISM density (Crutcher, 2010)

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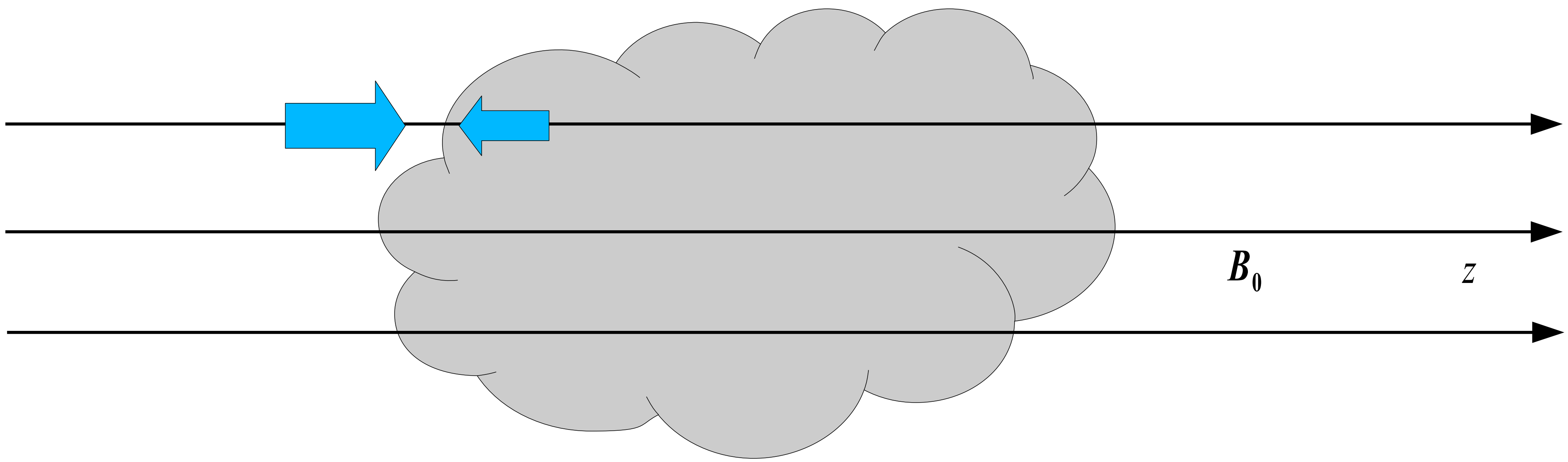


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  → The flux entering the cloud is larger than the flux escaping the cloud

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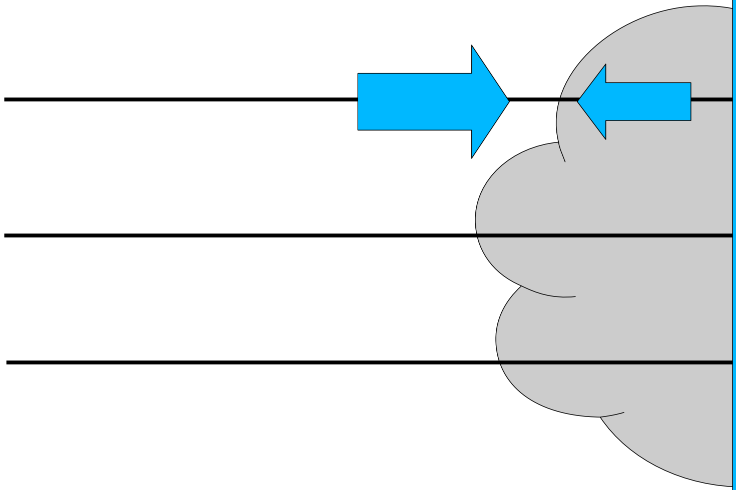
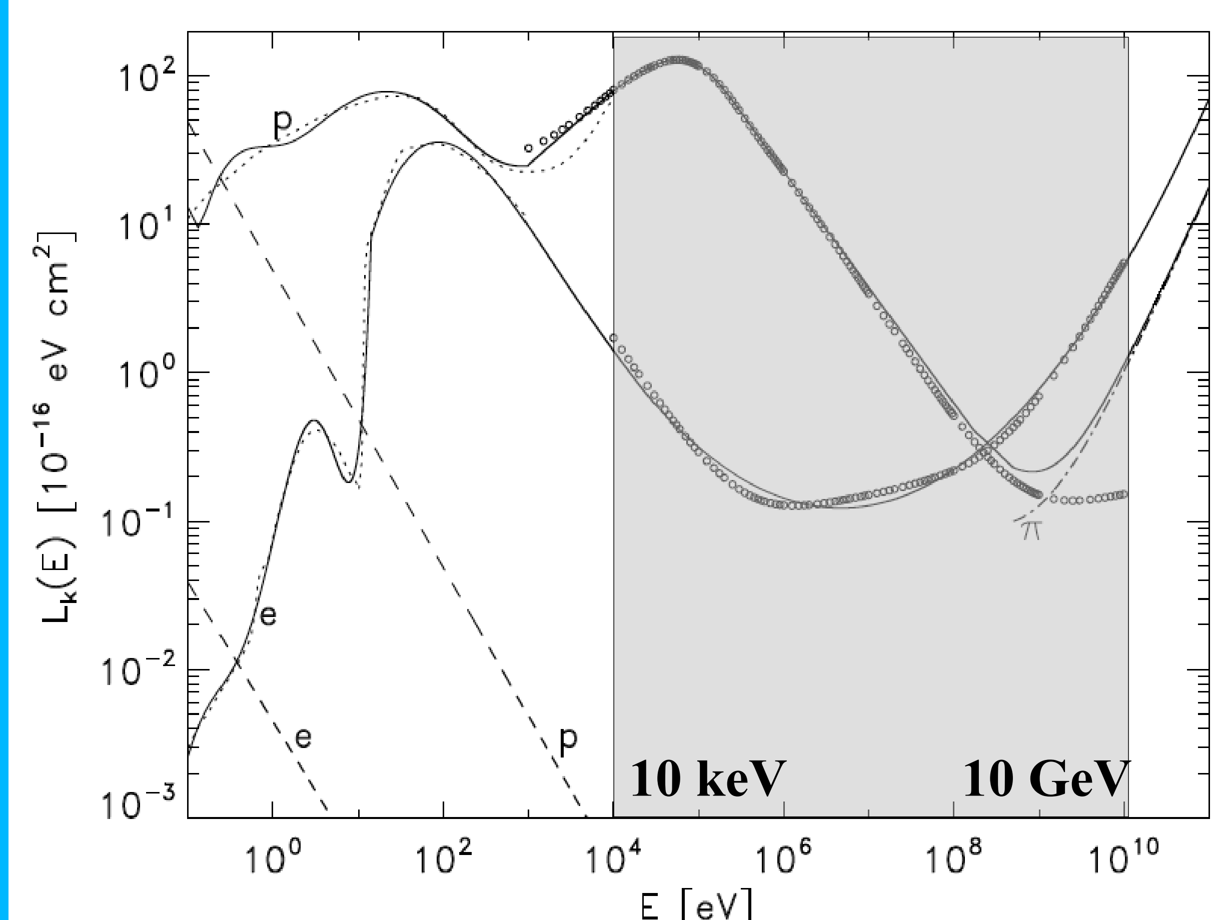


**[Padovani, Galli & Glassgold 2009, *A&A* 501, 219]**

Energy loss functions $L_e(E_e)$ and $L_p(E_p)$ for electrons and protons colliding with $H_2$ (solid curves), compared with NIST data (circles).

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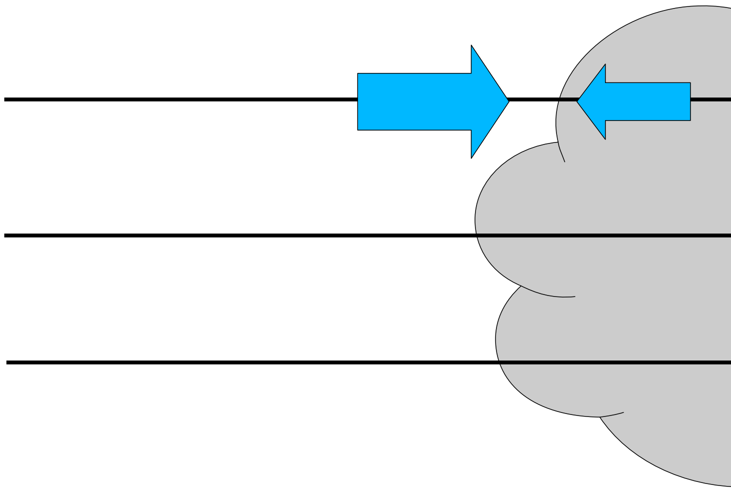

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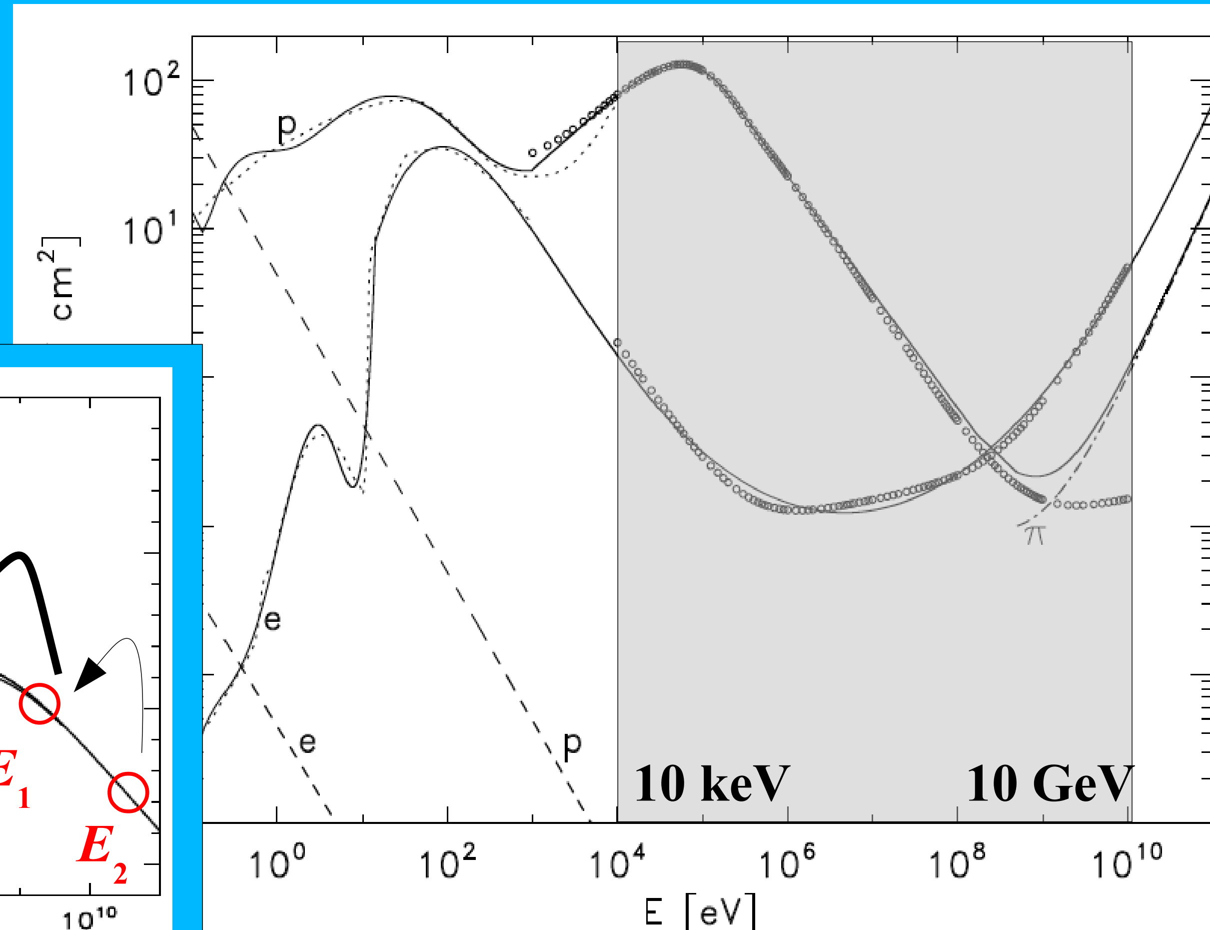


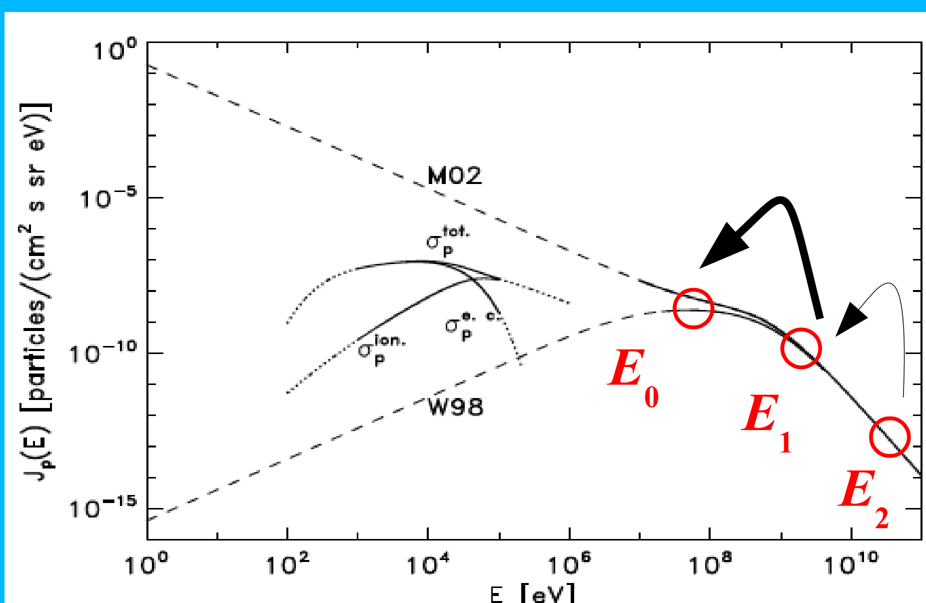

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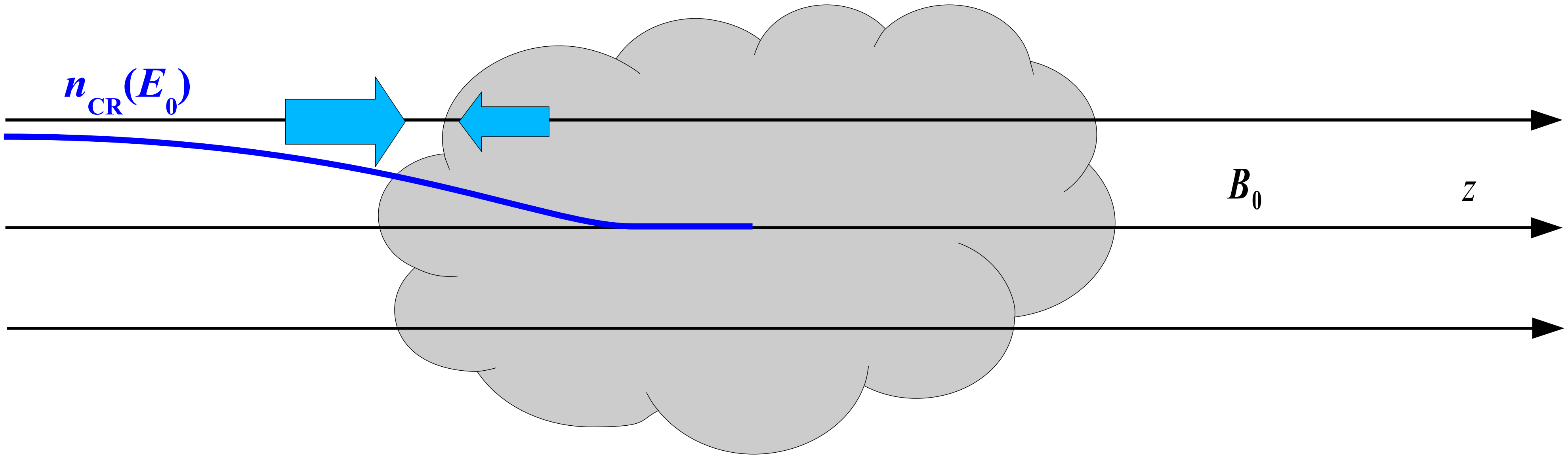


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  → a CR gradient develops outside the cloud

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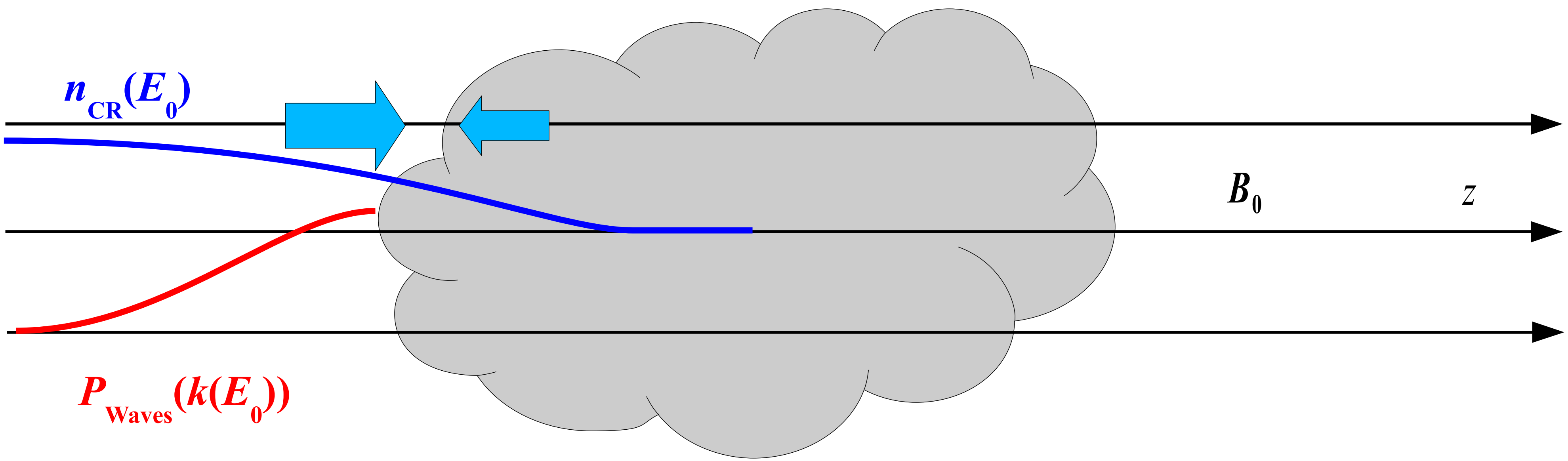


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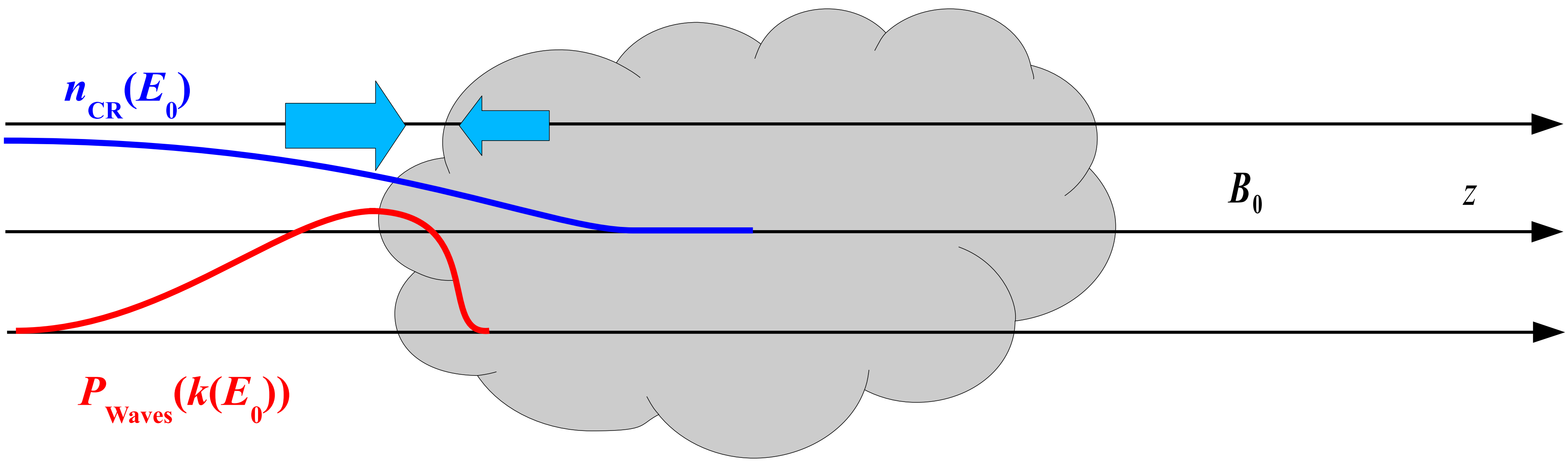


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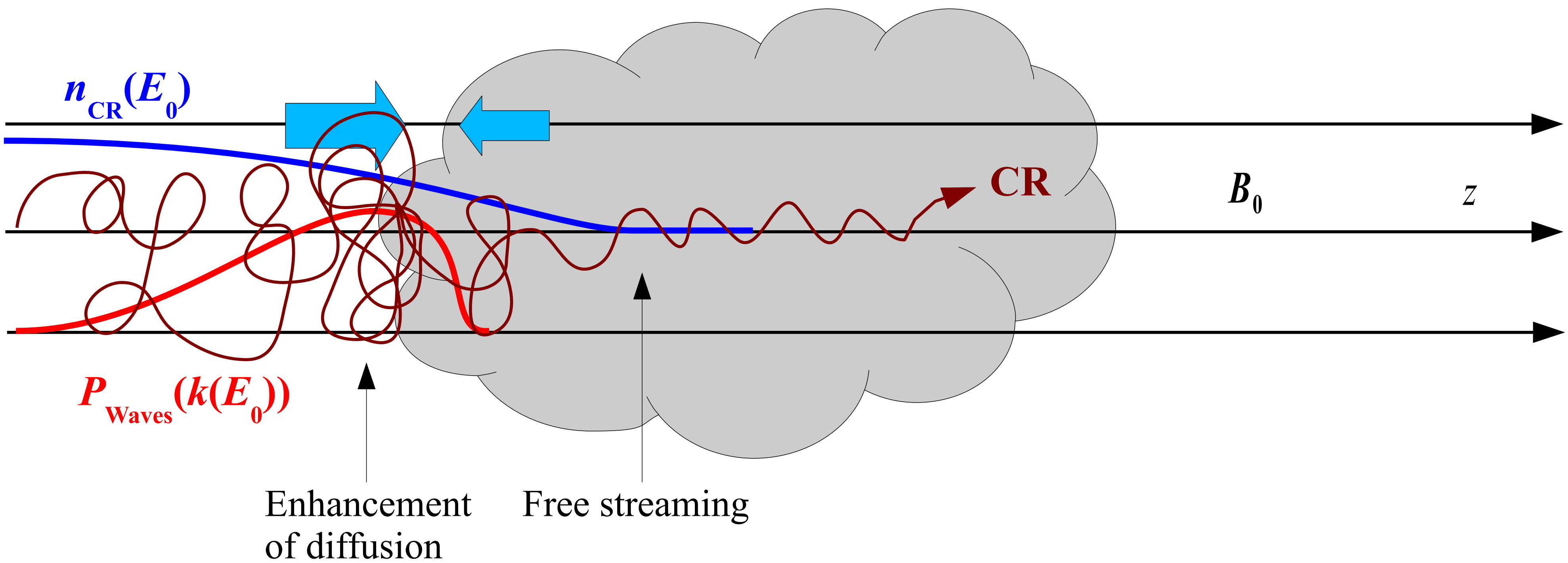


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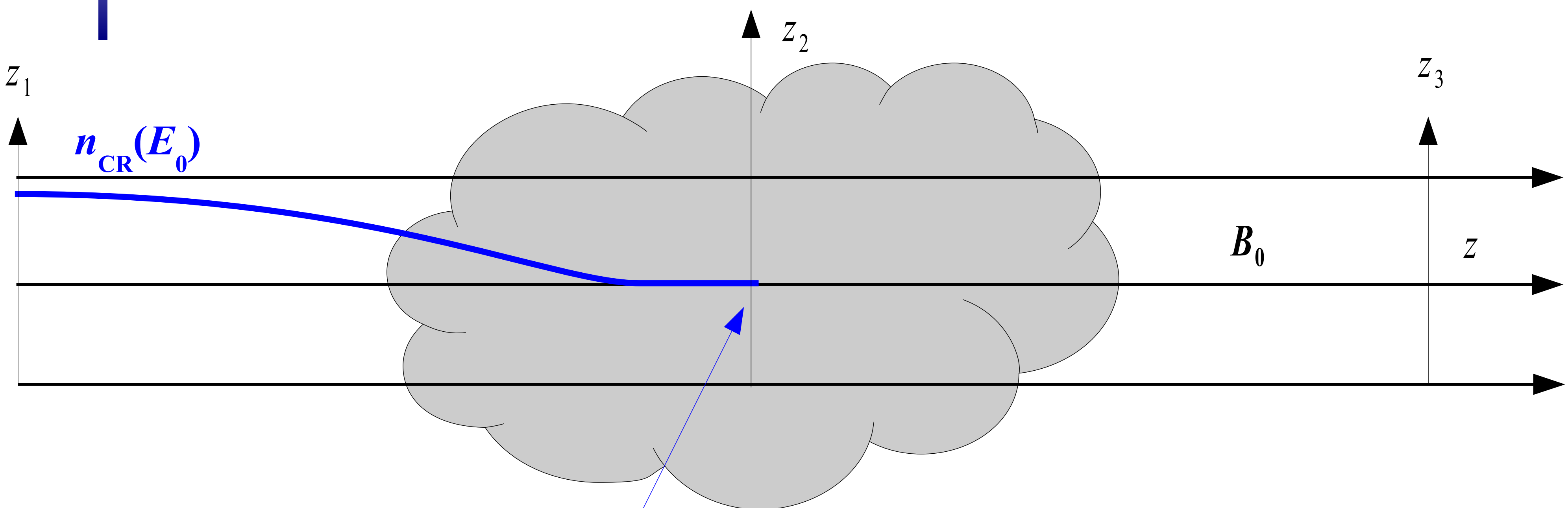


**Boundary conditions for CRs:**

$$f_{CR}(z_1) = f_{CR}(z_3) \rightarrow \left[\frac{\partial f_{CR}}{\partial z}\right]_{z=z_2} = 0$$

Symmetric condition.
We do not impose any condition on the CR gradient at $z_1$ (different from Everett & Zweibel, 2011)

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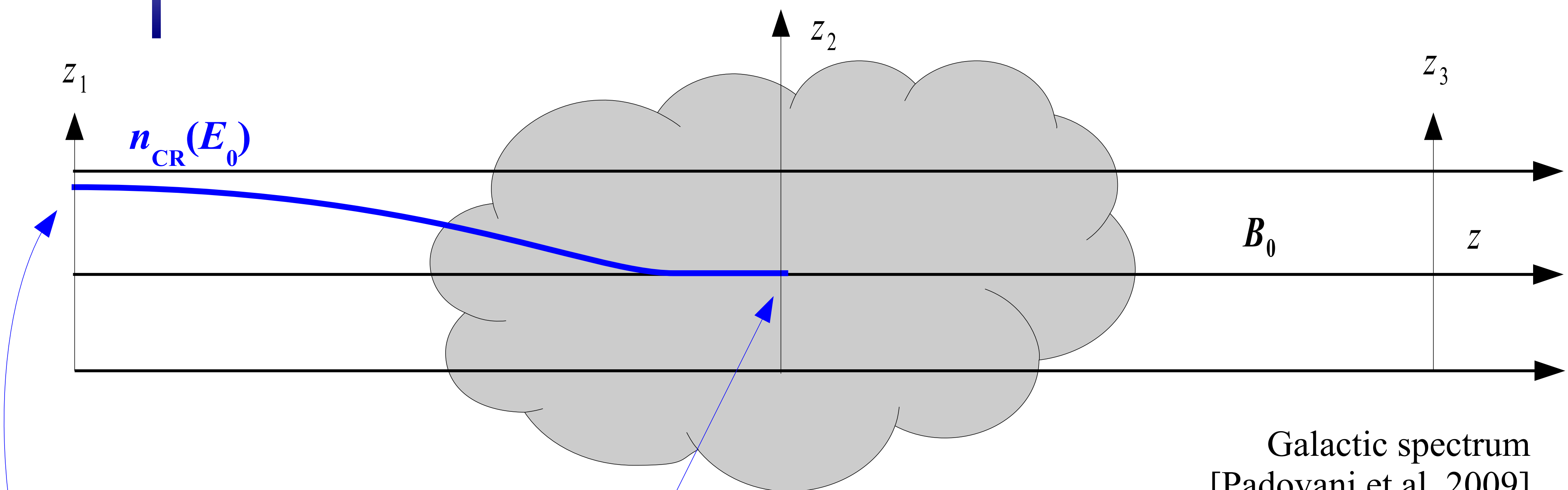
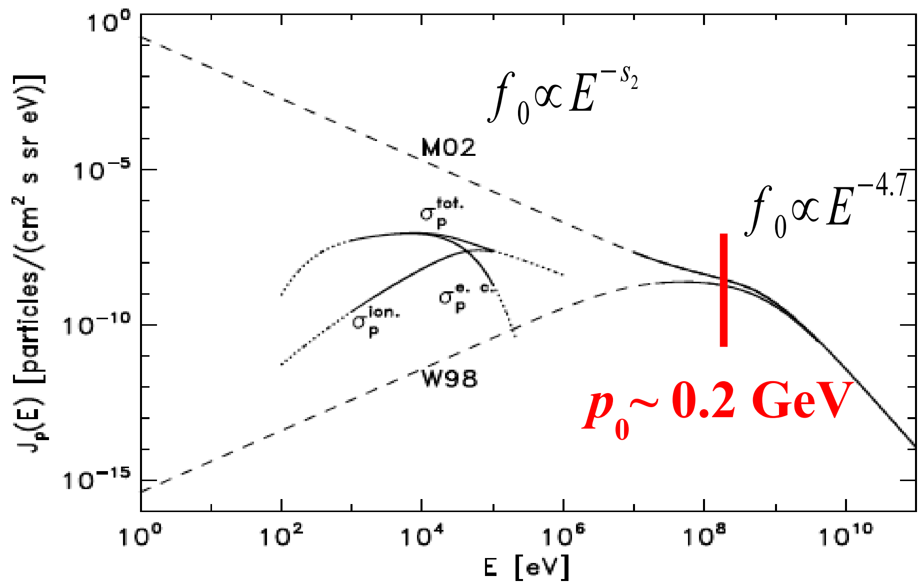



Galactic spectrum
[Padovani et al. 2009]

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$$f_{CR}(z_1) = f_{CR}(z_3) \rightarrow \left[\frac{\partial f_{CR}}{\partial z}\right]_{z=z_2} = 0$$

$$f_{CR}(z_1) = K \left(\frac{p}{p_0}\right)^{-s_1} \left[1+\left(\frac{p}{p_0}\right)^{s_1-s_2}\right]^{-1}$$

$$for \quad p > p_0 = 0.2\,GeV \rightarrow s = s_1 = 4.7$$

$$for \quad p < p_0 \rightarrow s = s_2 \; (a.\,par.)$$

$$K = normalization \leftarrow \epsilon_{CR} = 1\,eV/cm^3$$

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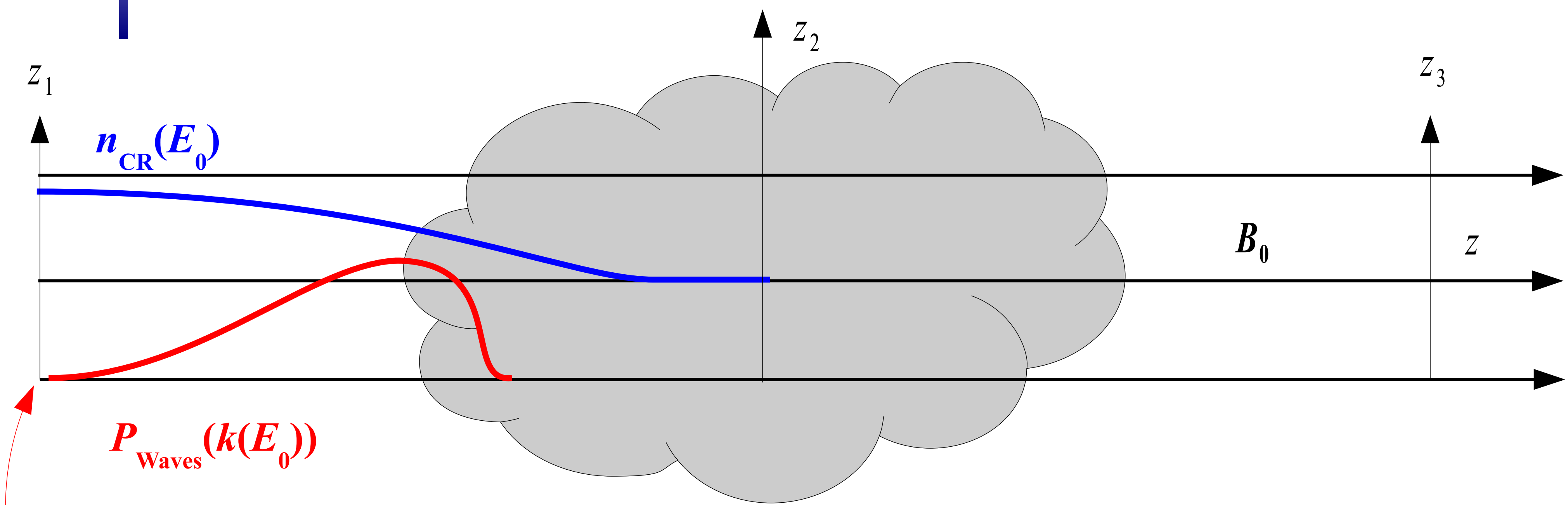


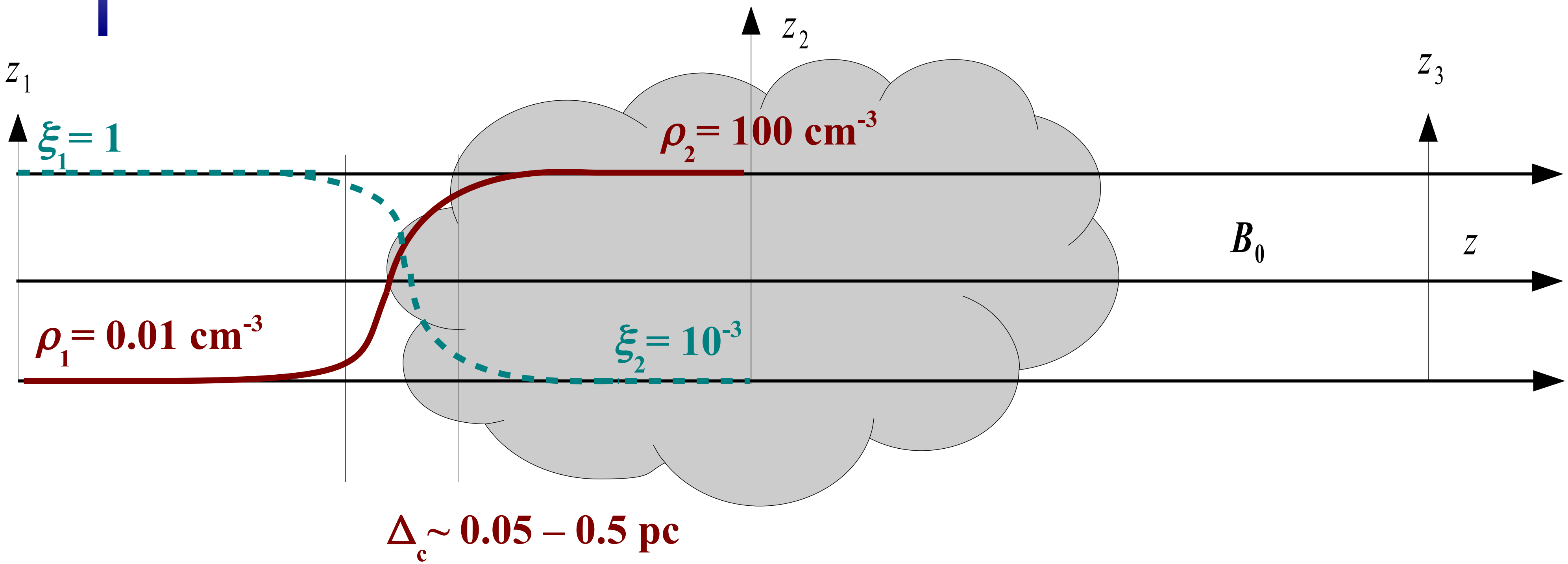

**Boundary conditions for magnetic turbulence:**

$$P_w(k, z_1) = \eta_W P_{B,0} \frac{2}{3} (k L_{tur})^{2/3}$$ Kolmogorov spectrum with $L_{tur} = 50$ pc $\rightarrow D(p) \propto p^{1/3}$

$$\eta_W = \frac{8\pi}{B_0^2} \int P_w(k) \frac{dk}{k}$$ Normalization chosen to have: $D(1 GeV) = 10^{28} cm^2/s$

$$\int P_w(k) \frac{dk}{k} = \frac{\delta B^2}{8\pi}$$

# Set up of the model



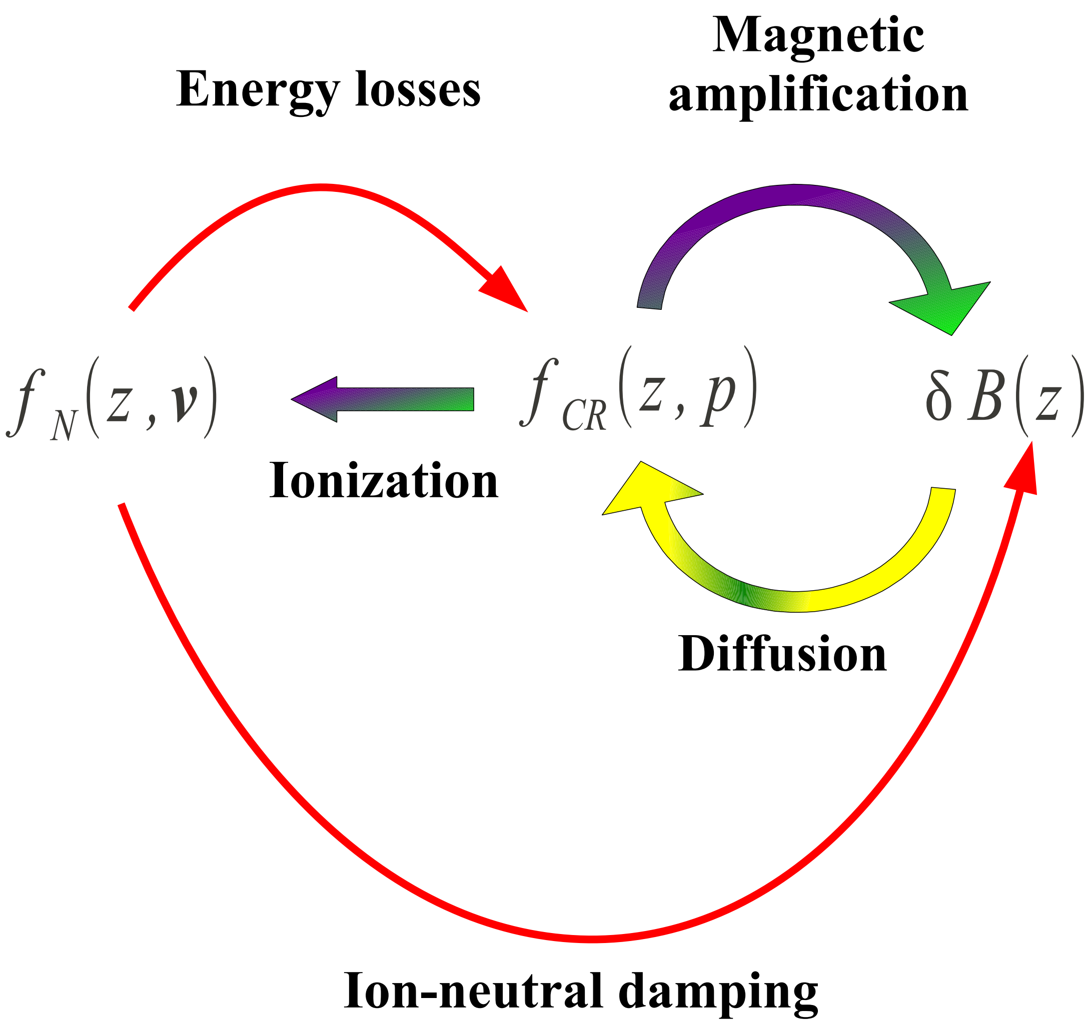

**Density profile of the cloud:**

$$\rho_{tot}(z) = \rho_1 + \frac{\rho_1 - \rho_2}{2}\left[1 + \tanh\left(\frac{z - z_c}{\Delta_c}\right)\right]$$ Total density

$$\xi_{ion}(z) = \xi_1 + \frac{\xi_1 - \xi_2}{2}\left[1 + \tanh\left(\frac{-(z - z_c)}{\Delta_c}\right)\right]$$ Ionization fraction

From Everett & Zweibel (2011)

# Interaction scheme



# Transport equation for CRs

**Stationary transport equation for CRs in 1-D with losses:**

$$\frac{\partial}{\partial z}\left[D(z,p)\frac{\partial f_{CR}}{\partial z}\right] - (u+v_A)\frac{\partial f_{CR}}{\partial z} + \frac{1}{3}\frac{d(u+v_A)}{dz}p\frac{\partial f_{CR}}{\partial p} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[\dot{p}\,p^2 f\right] = 0$$

Diffusion — Advection — Adiabatic compression — Energy losses

$$D(z,p) = \frac{4}{3\pi}\frac{v(p)\; r_L(p)}{P_B(z,\bar{k}(p))/P_{B_0}}$$

Diffusion coefficient in linear approximation $\delta B \ll B_0$

$$u = 0$$

The plasma is at rest

$$v_A(z) = \frac{B_0}{\sqrt{4\pi\rho_i}}$$

Alfvén speed depends only on the ion density: for $k > \frac{\nu_{in}}{v_A}\frac{1+n_i/n_H}{\sqrt{1+\delta B^2/B_0^2}}$ ion and neutrals are decoupled $\rightarrow E(k) < 10$ GeV

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$$\frac{d v_A}{dz}\,p\frac{\partial f}{\partial p}$$

→ produces acceleration on timescale $t_{acc} = \frac{D(E)}{v_A^2} \approx 10^{10}\, yr \gg t_{dyn}$

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Diffusion — Advection — Adiabatic compression — Energy losses

(Adiabatic compression + Energy losses) $= Q(z,p)$

**Formal solution:**

$$f(z,p) = f_0(p) + \int_{z_1}^{z}\frac{dz'}{D(z',p)}\int_{z'}^{z_2} Q(z'',p)\exp\left[-\int_{z'}^{z''}\frac{v_A}{D(y,p)}dy\right]dz''$$

**Can be solved iteratively**

# Transport equation for Alfvén waves

**Transport equation for magnetic field**

$$\frac{\partial F_w}{\partial z} = u \frac{\partial P_w}{\partial z} + \sigma_{CR}(k,z) - \Gamma(k,z) \; P_w$$

$$\begin{cases} P_w(k) = \dfrac{\delta B^2(k)}{8\pi} & \text{Magnetic pressure of Alfvén waves} \\ F_w(k) = (3u+2v_A) P_w(k) & \text{Magnetic energy flux of Alfvén waves} \end{cases}$$

$$\begin{cases} \sigma(z,k) = \dfrac{4\pi}{3} \; v_A(z) \left[ p^4 v(p) \dfrac{\partial f_{CR}}{\partial z} \right]_{p=\bar{p}(k)} \\ \Gamma(z,k) = \dfrac{\nu_{in}}{2} = 4.2\times 10^{-9} \left( \dfrac{T}{10^4 K} \right)^{0.4} \left( \dfrac{n_H}{cm^{-3}} \right) s^{-1} \end{cases}$$

Amplification due to CR streaming

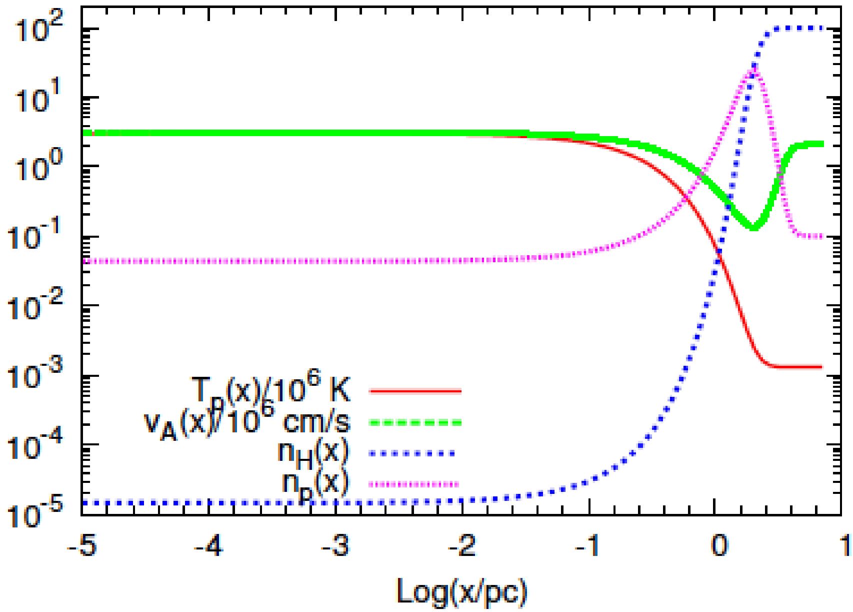
Ion-neutral damping in the weak coupling limit. Constant in frequency for $\bar{p}(k) < 10\, GeV$

**Solution**

$$P_w(z,k) = P_{w,0}(k) + \int_{z_1}^{z} \left[ \sigma - P_{w,0} \left( \Gamma + 2 \frac{\partial v_A}{\partial z'} \right) \right] \exp\left[ -\int_{z'}^{z} \frac{\Gamma}{2 v_A} \right] dz'$$

# Results

$\Delta_c = 0.5\ pc$



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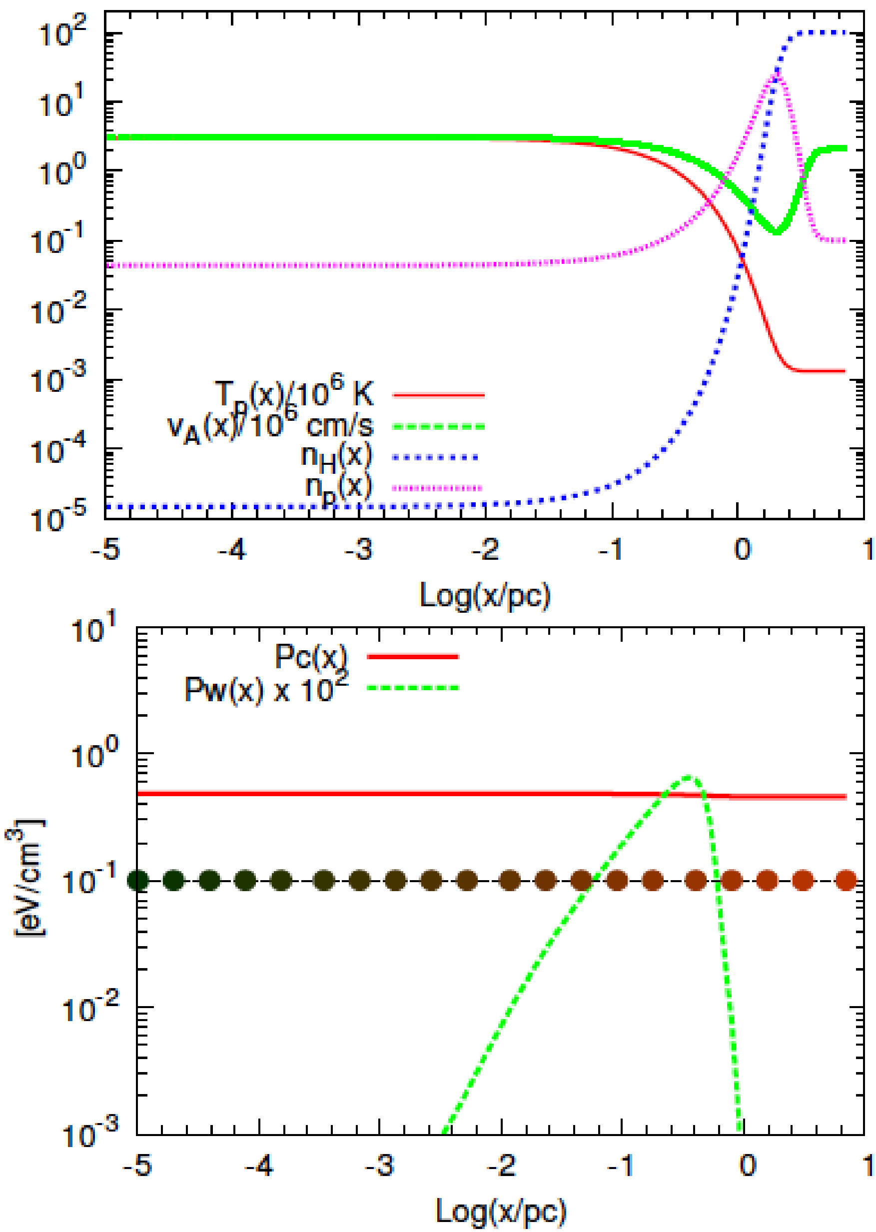

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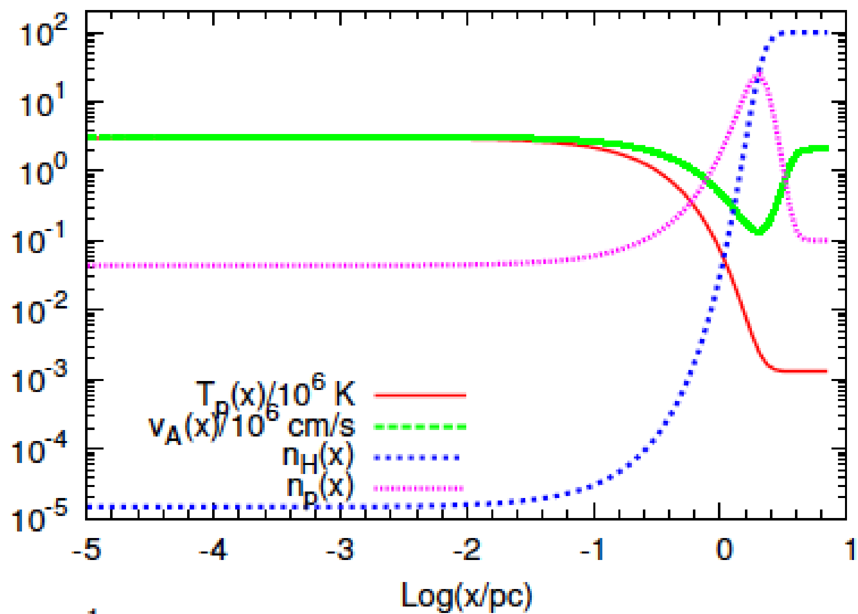


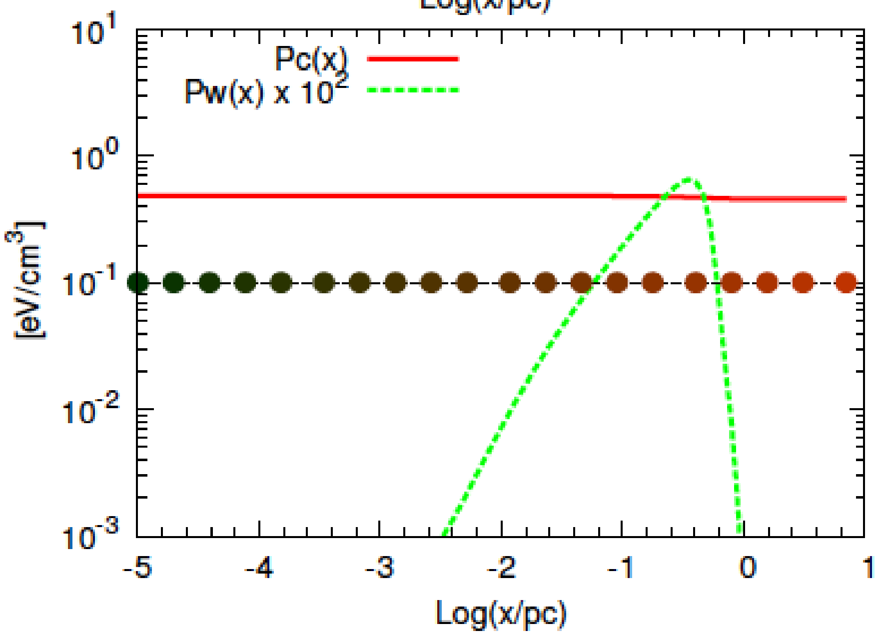


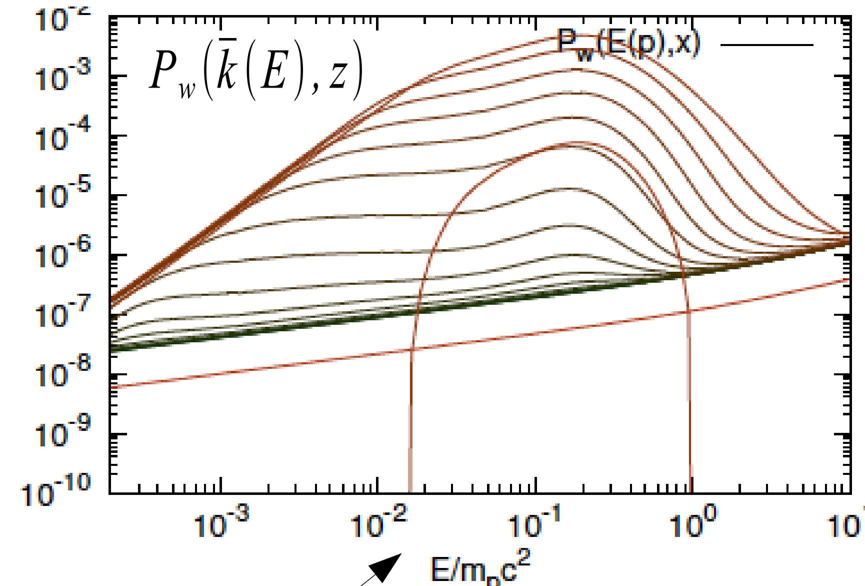


Energy corresponding to the resonant condition

$$E \rightarrow k = \bar{k}(E) = 1/r_L(E)$$

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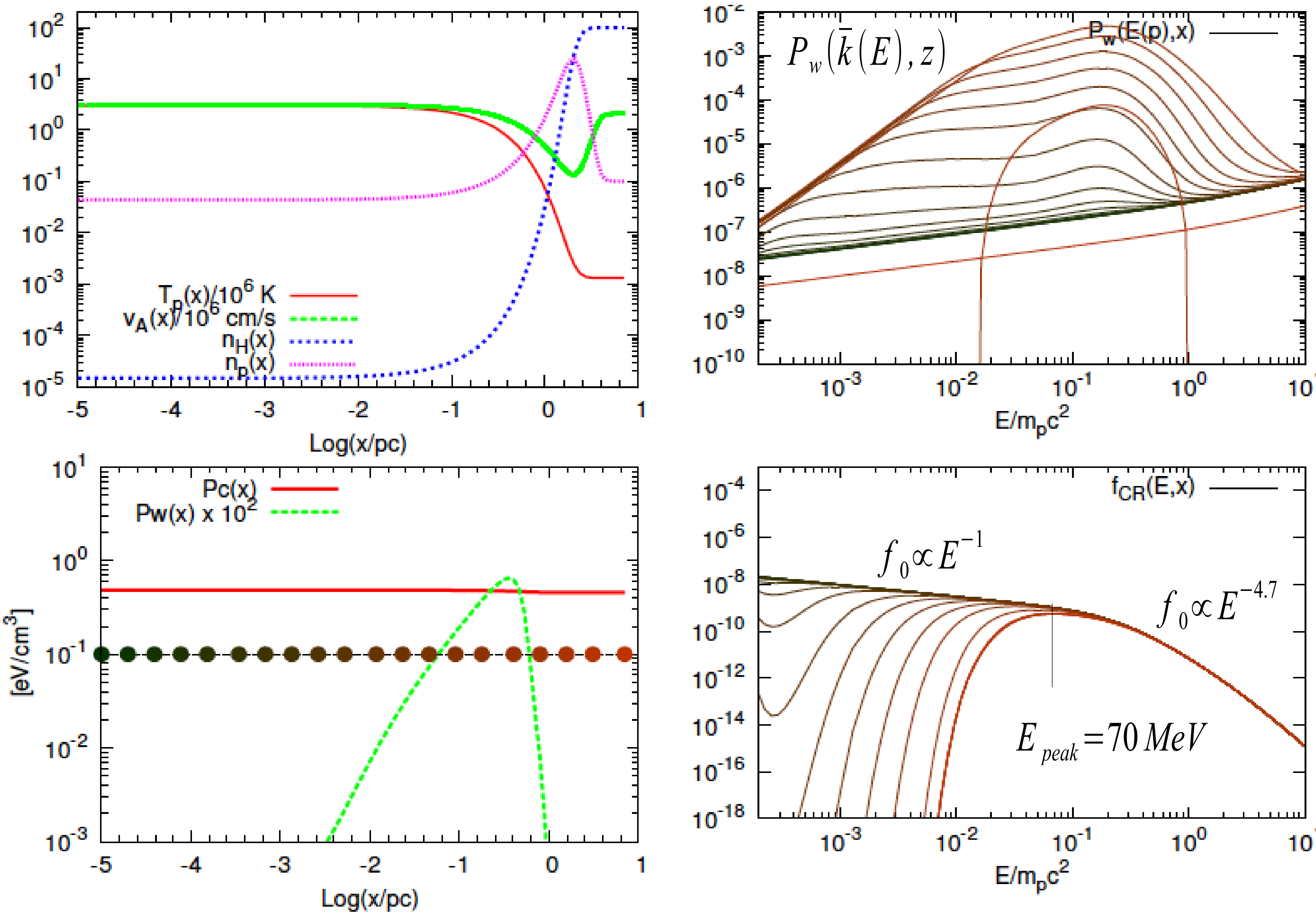

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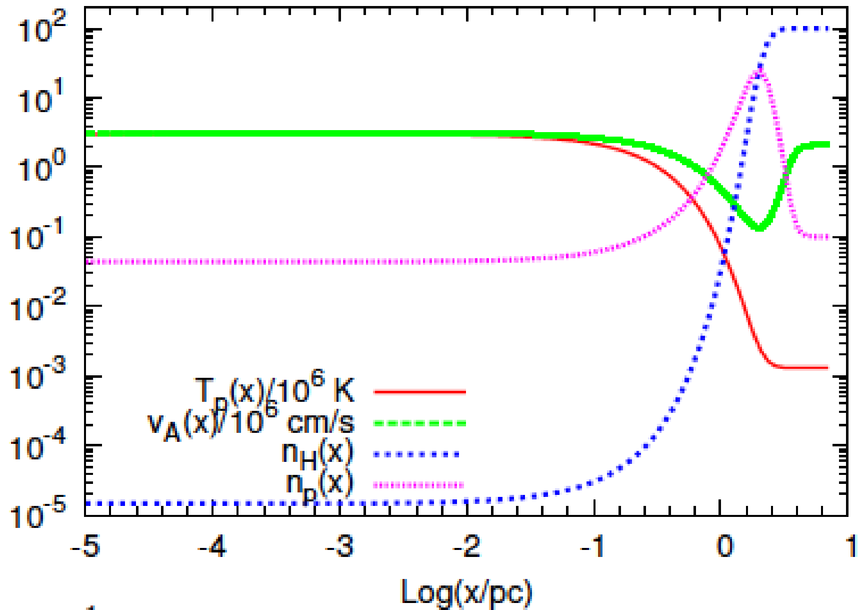


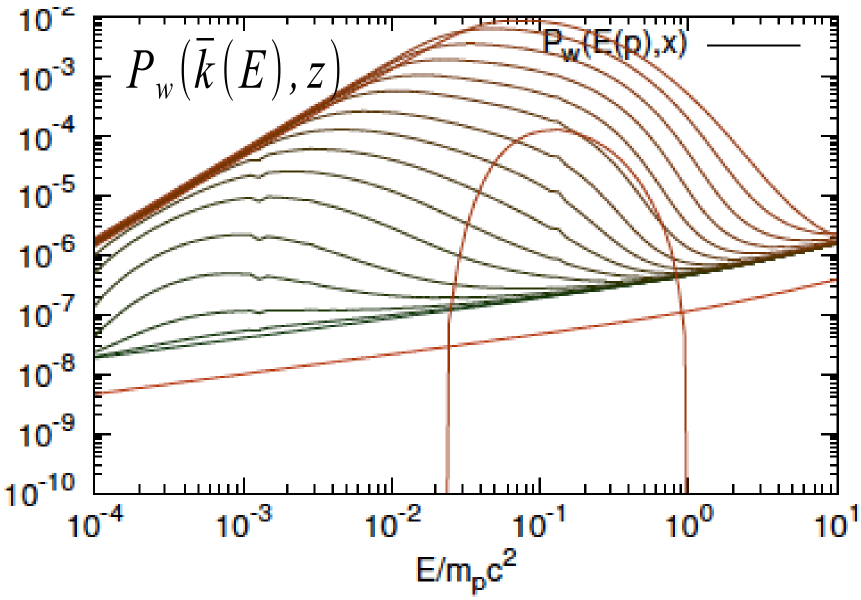


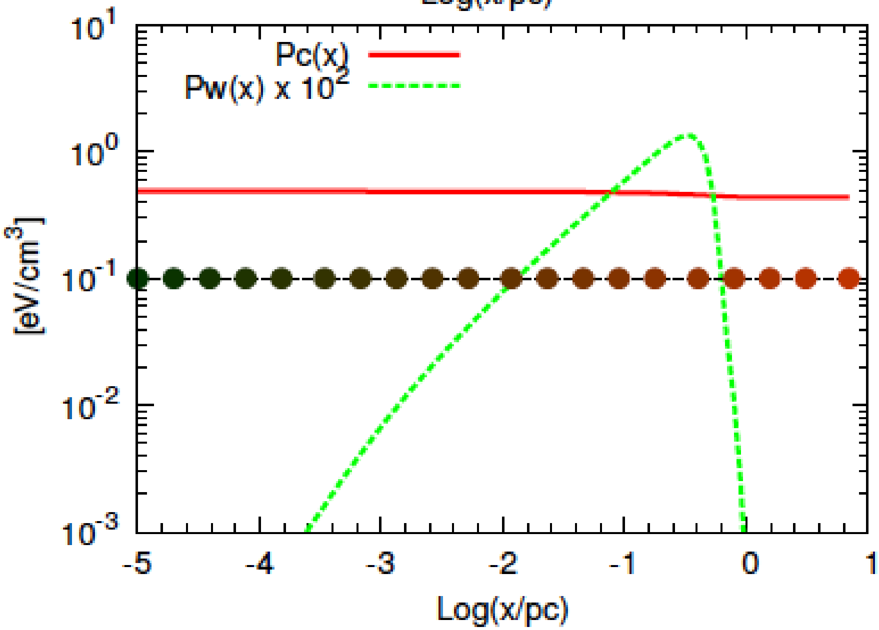


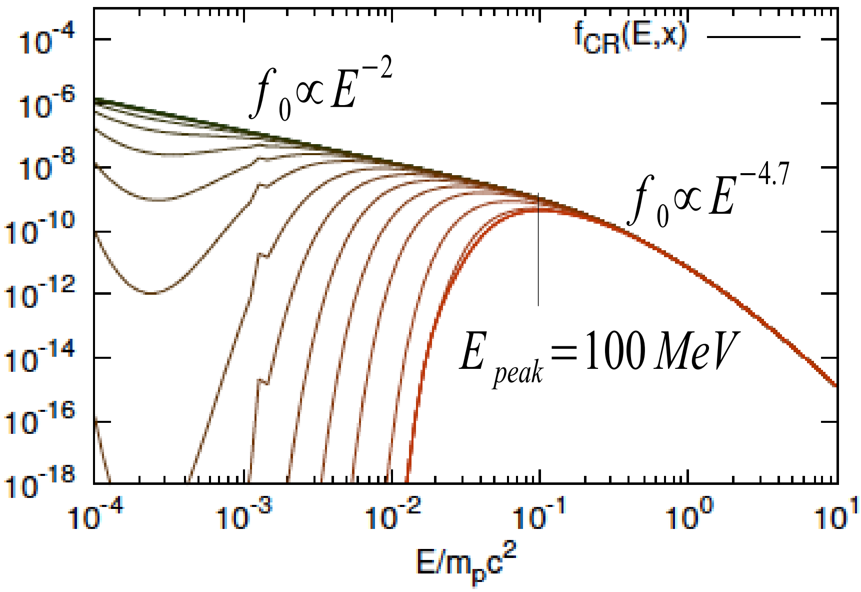

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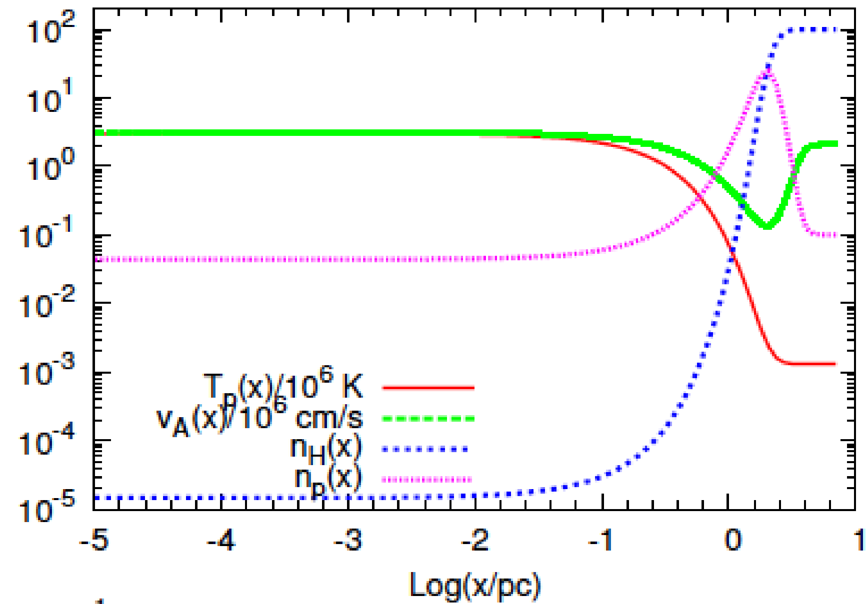


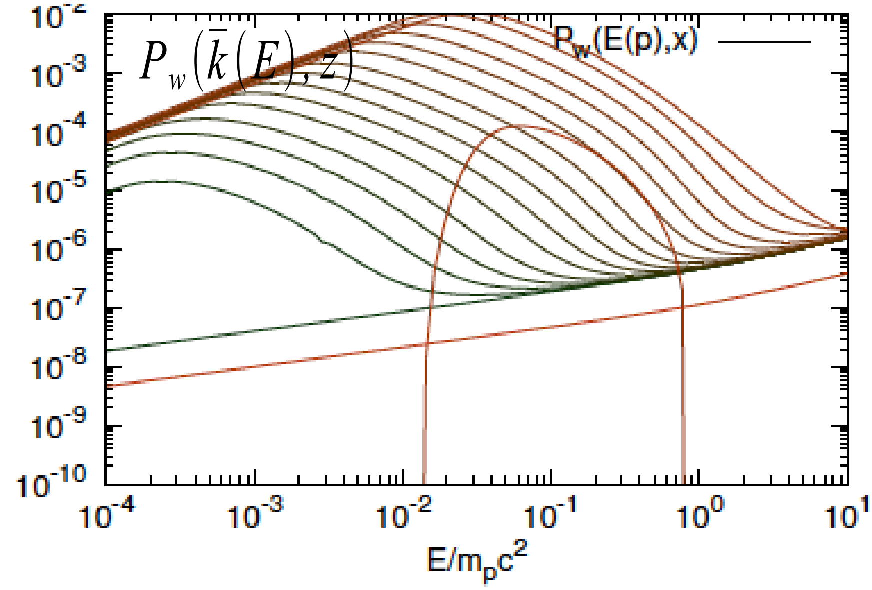


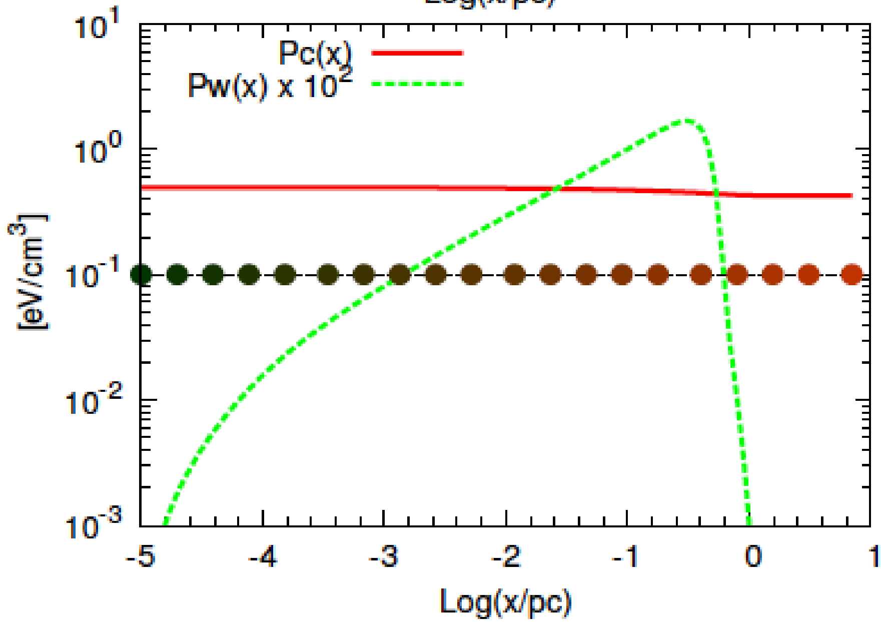


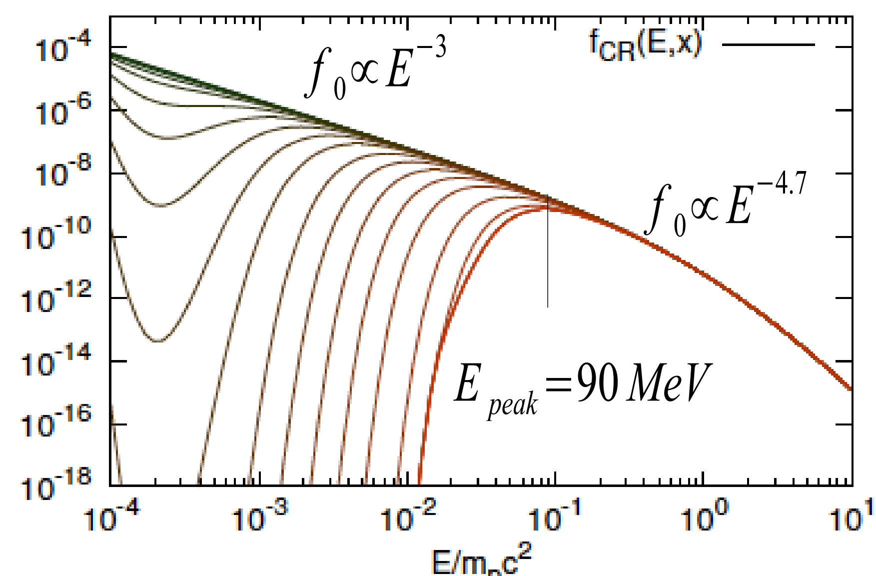

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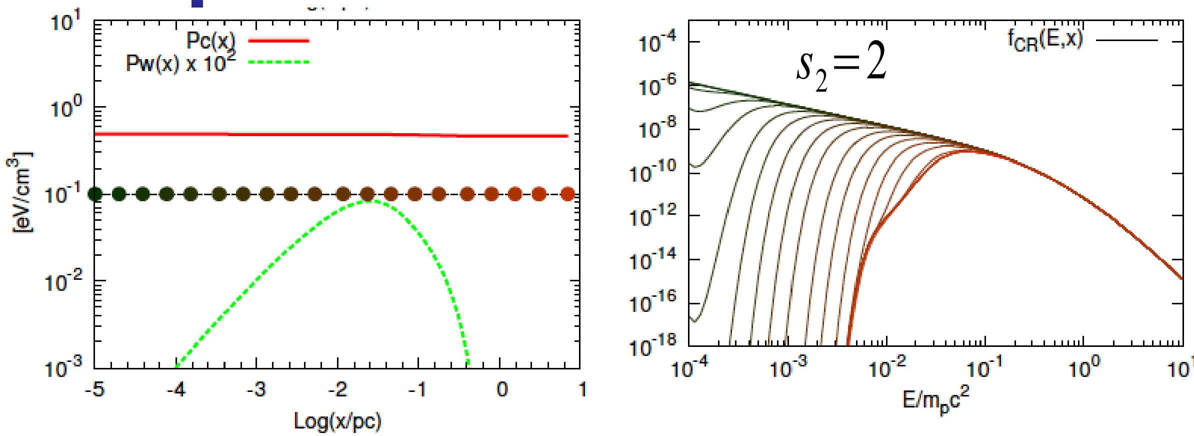
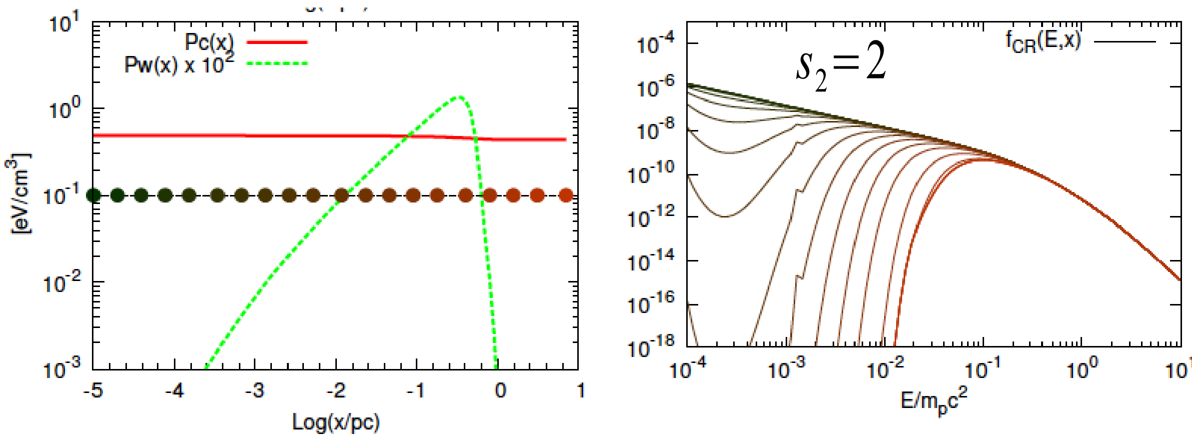
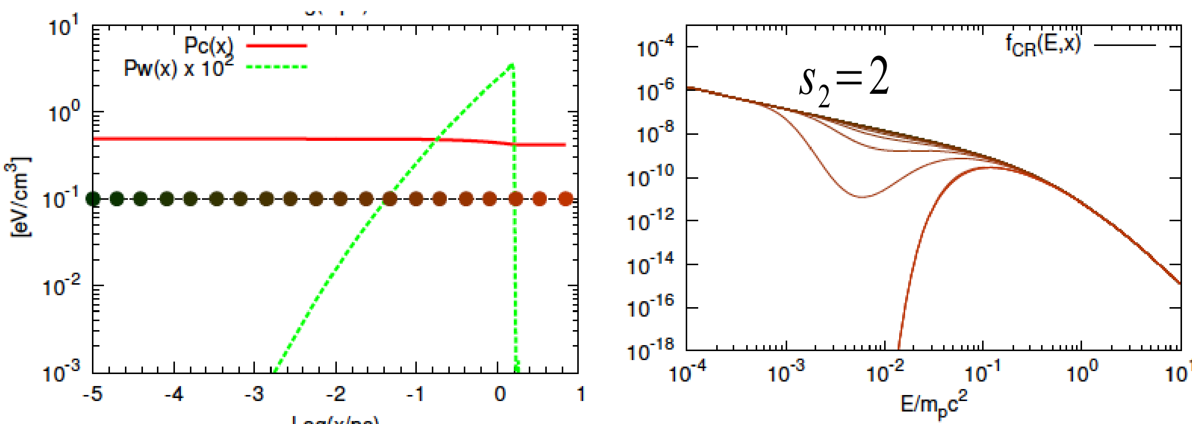



$\Delta = 0.7\ pc \ \rightarrow\ E_{peak} = 60\ MeV$




$\Delta = 0.5\ pc \ \rightarrow\ E_{peak} = 90\ MeV$




$\Delta = 0.1\ pc \ \rightarrow\ E_{peak} = 110\ MeV$

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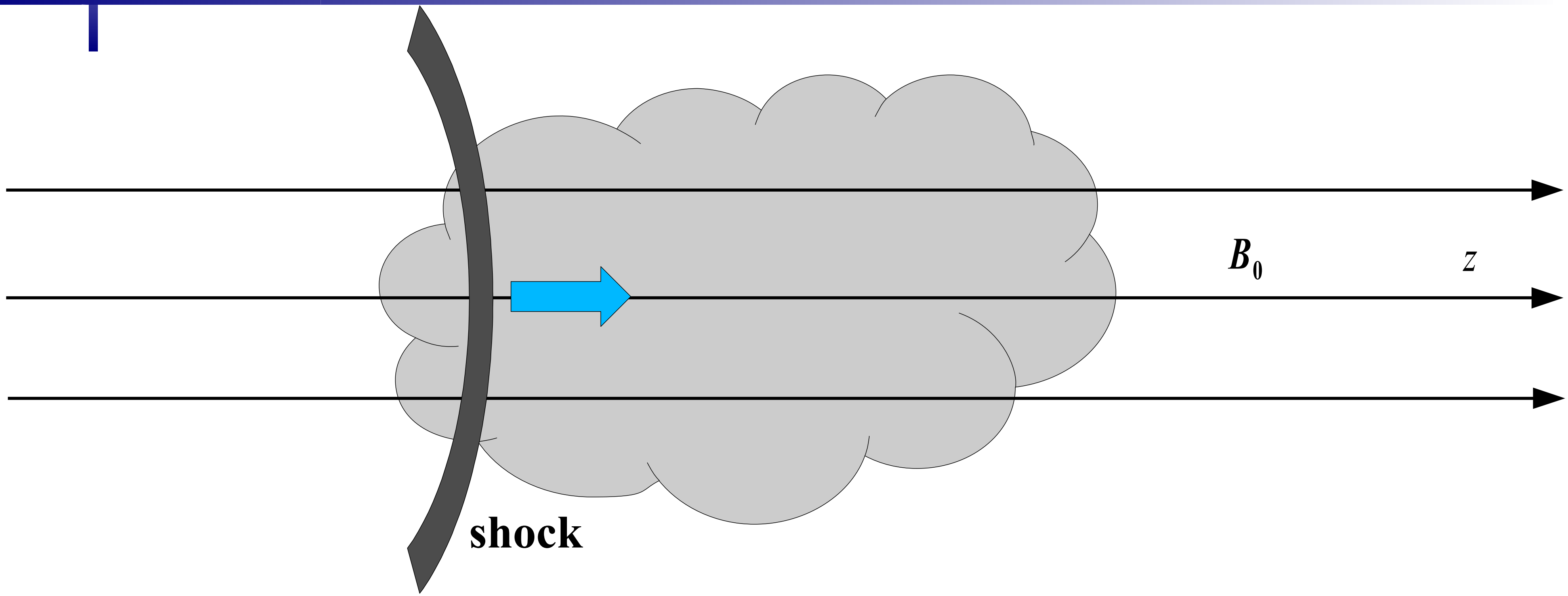
# Shocks propagating through clouds



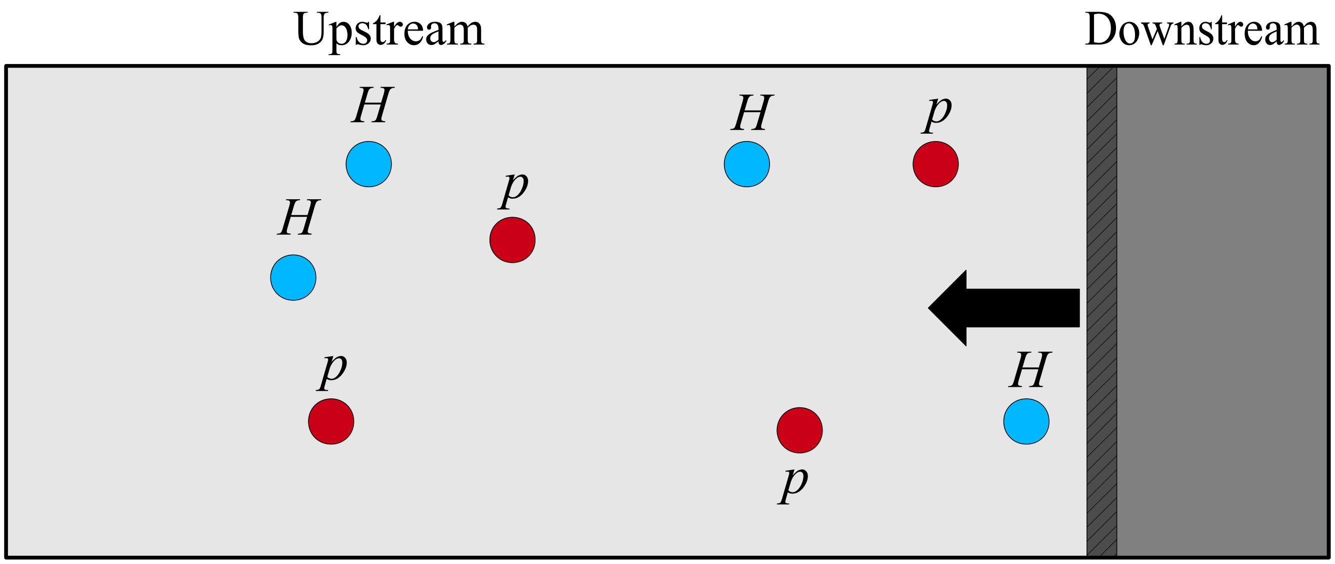

Can shocks propagating through a dense cloud accelerate particles?

The physics involved in much more complicated than shocks in fully ionized media.

- ion fraction in the cloud → injection of particles
- diffusion properties inside the cloud
- (CR amplification vs. ion-neutral damping; pre-existing turbulence?)
- neutral Hydrogen affects the shock dynamics

# Basic physics of Balmer shocks

[Chevalier & Raymond(1978); Chevalier et al (1980)]



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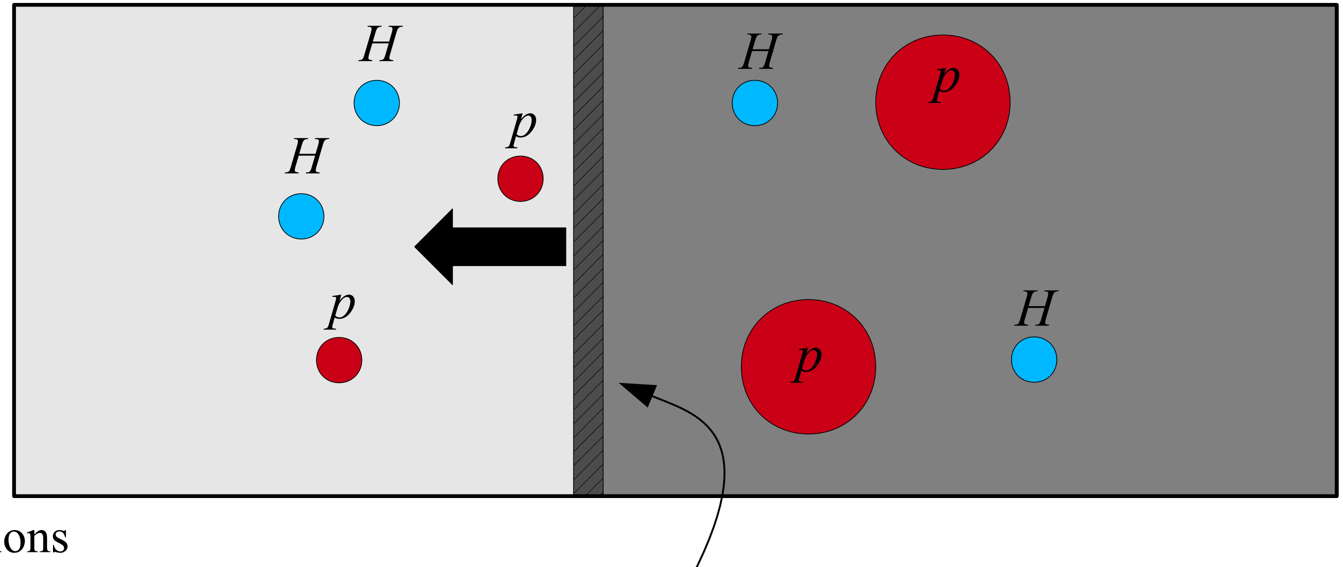


• Collisionless shocks heats up only ions

**Shock thickness:**

$$\lambda \approx \xi r_{L,th} \approx 10^{10} \left(\frac{B}{\mu G}\right)^{-1} \left(\frac{T}{10^8 K}\right)^{1/2} cm \ll \lambda_{coll}$$

**Collisional length scale**
**(ionization or charge-exchange):**

$$\lambda_{coll} \approx \frac{u_{sh}}{(n \sigma_{coll} v_{rel})} \approx 10^{15-16}\, cm \left(\frac{n}{1\, cm^{-3}}\right)^{-1}$$

Collisionless shocks are mediated by electromagnetic plasma processes
→ At zeroth order the neutral component does not feel the shock discontinuity

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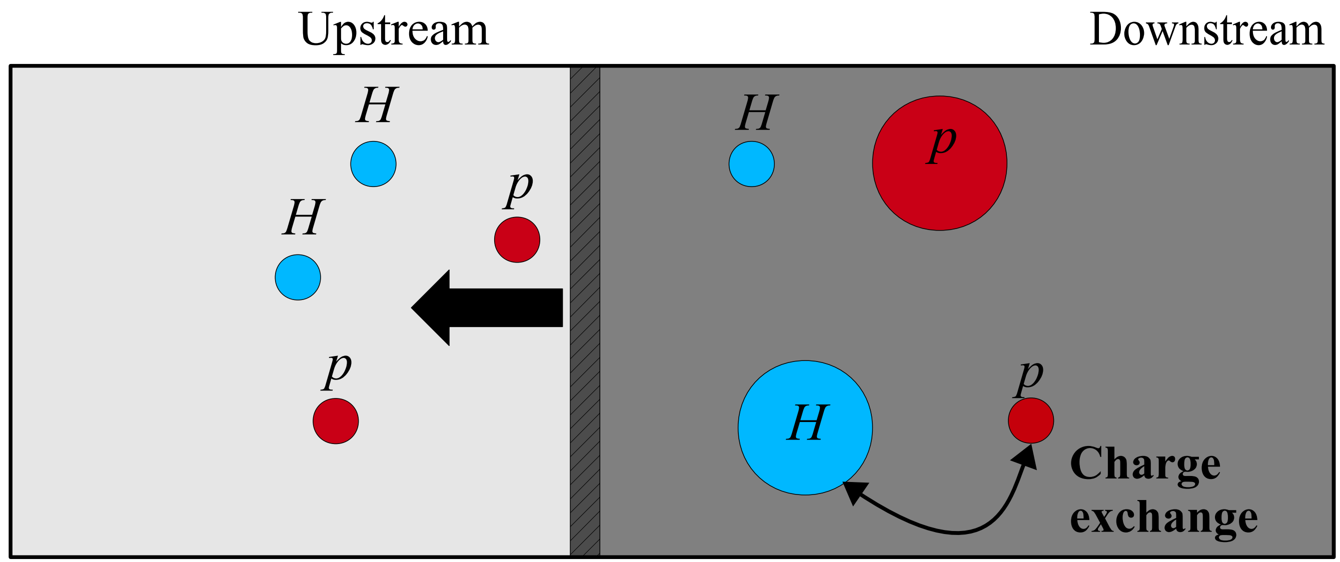


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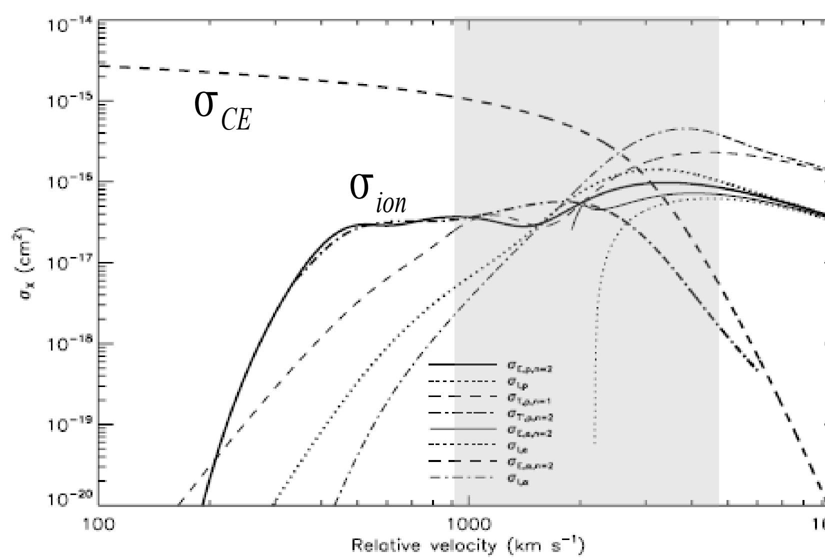
- Charge exchange can occur before ionization is completed because $\sigma_{ce} > \sigma_{ion}$ $\rightarrow$ a new population of hot hydrogen arises



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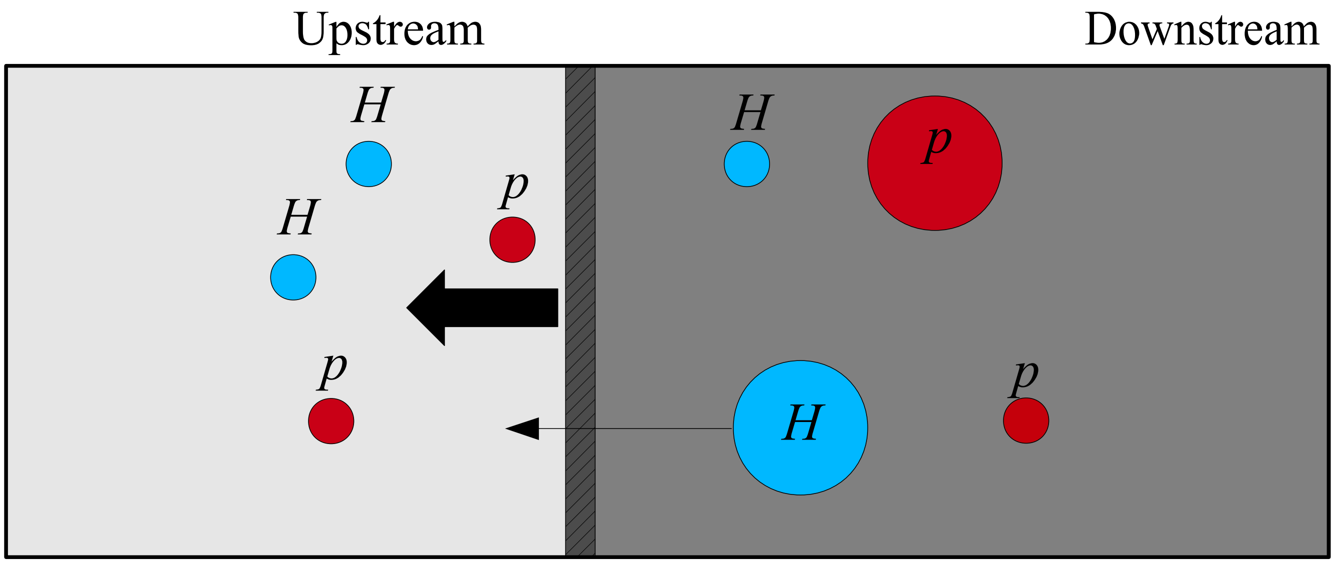
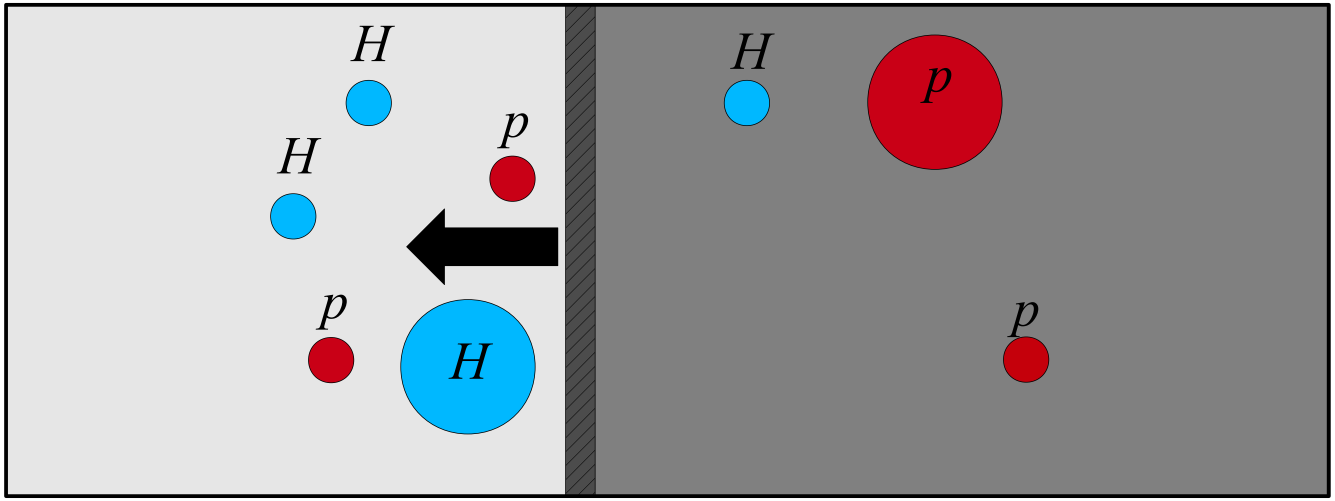



• Collisionless shocks heats up only ions

• Charge exchange can occur before ionization is completed because $\sigma_{ce} > \sigma_{ion}$ → a new population of hot hydrogen arises

• Hot hydrogen atoms can recross the shock and transfer momentum and energy upstream → formation of a *neutral precursor*

# Basic physics of Balmer shocks

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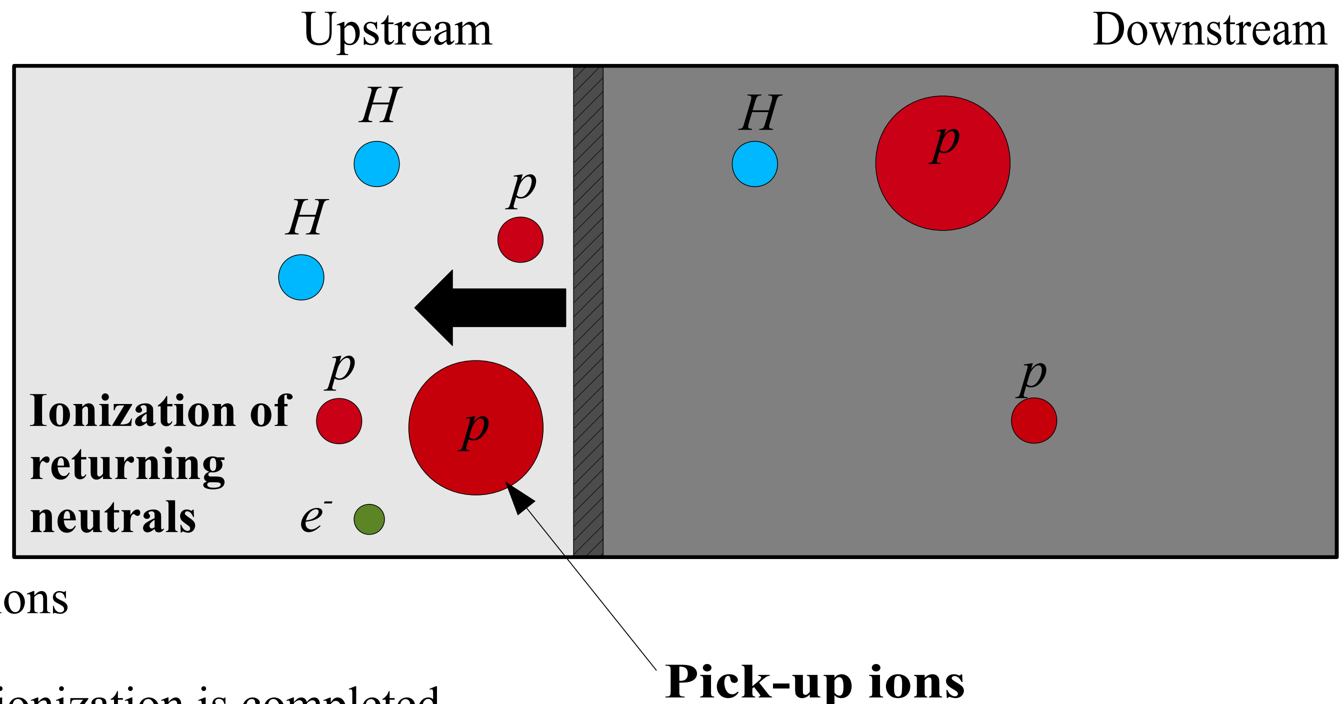


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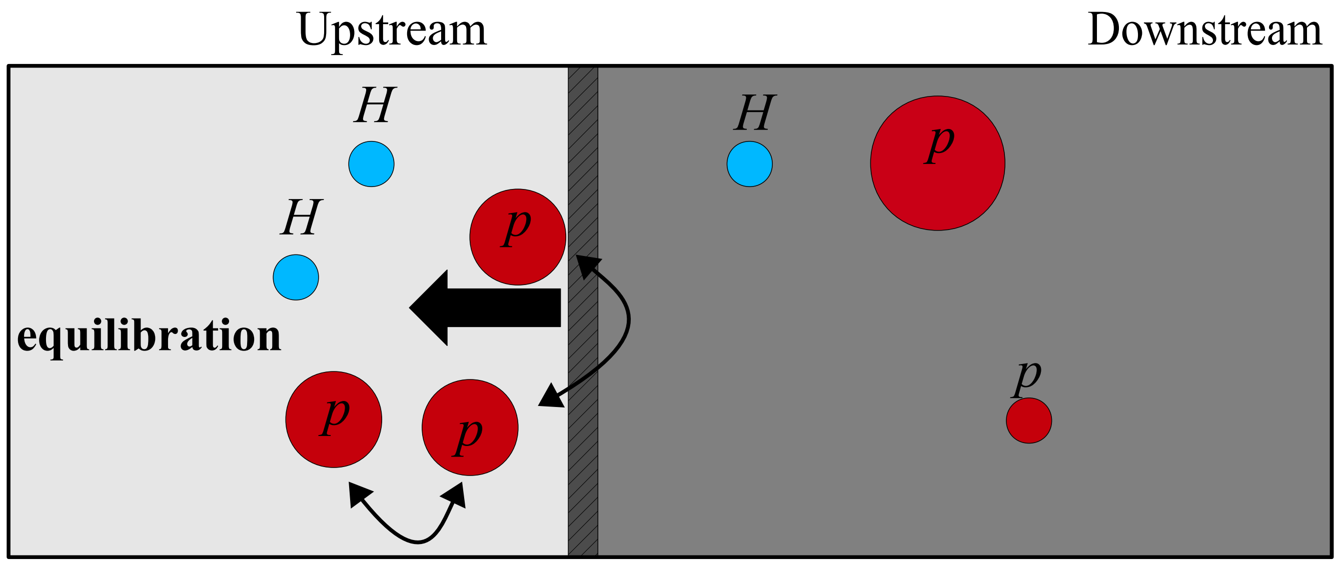


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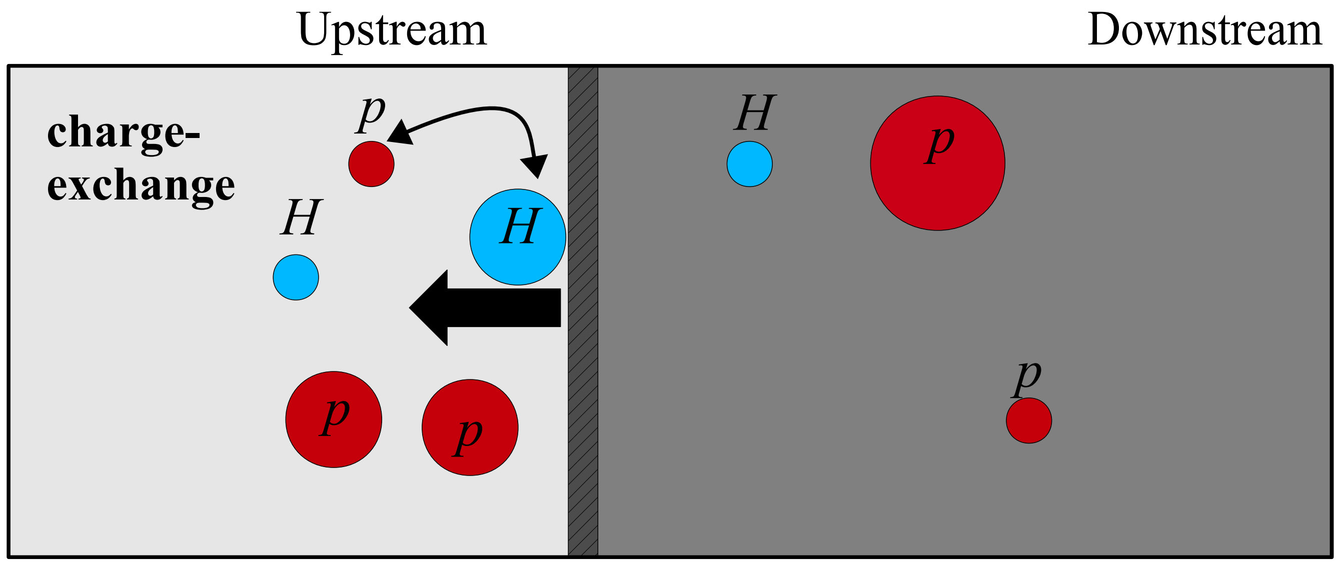


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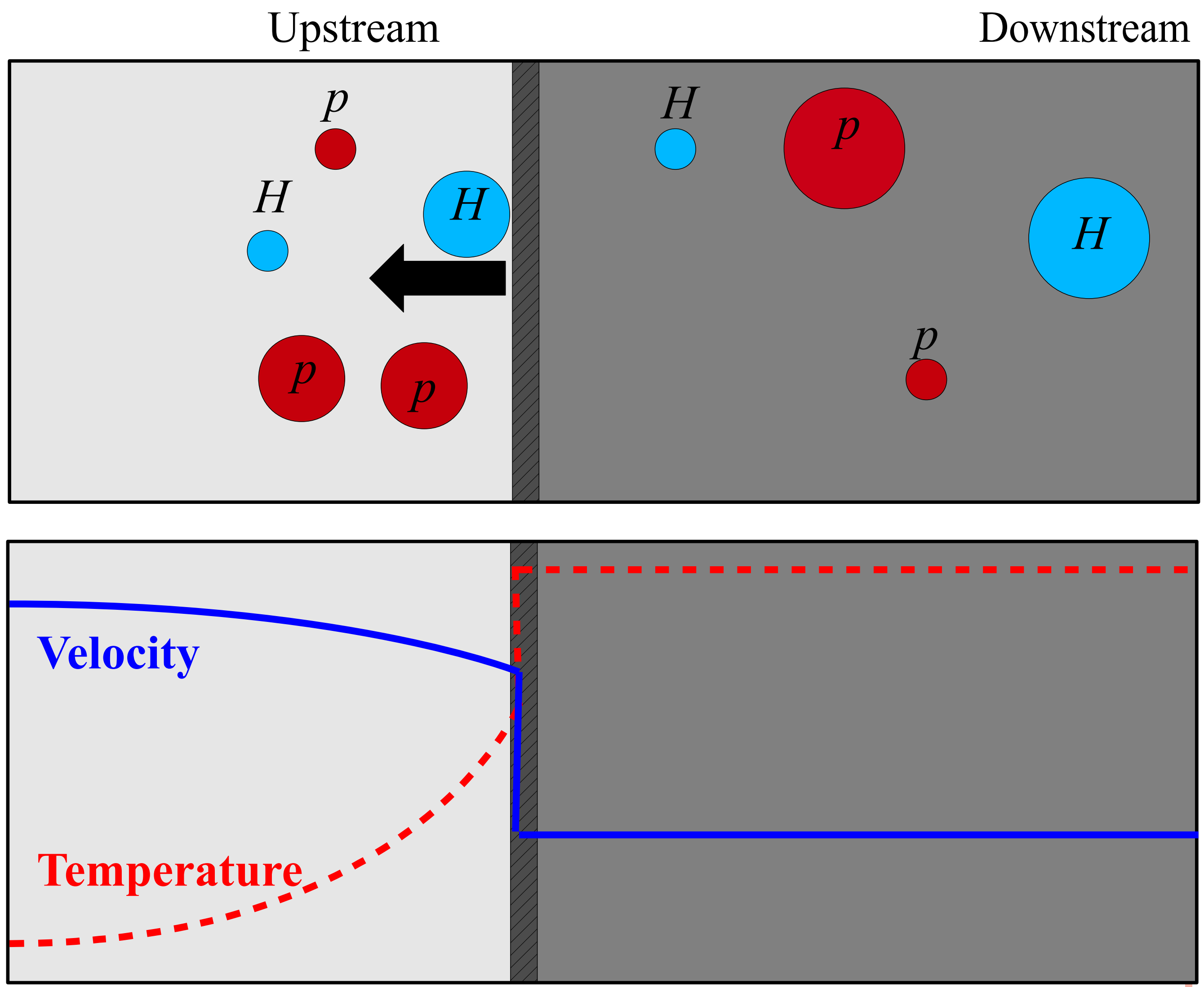
• Hot hydrogen atoms can recross the shock and transfer momentum and energy upstream → formation of a *neutral precursor*

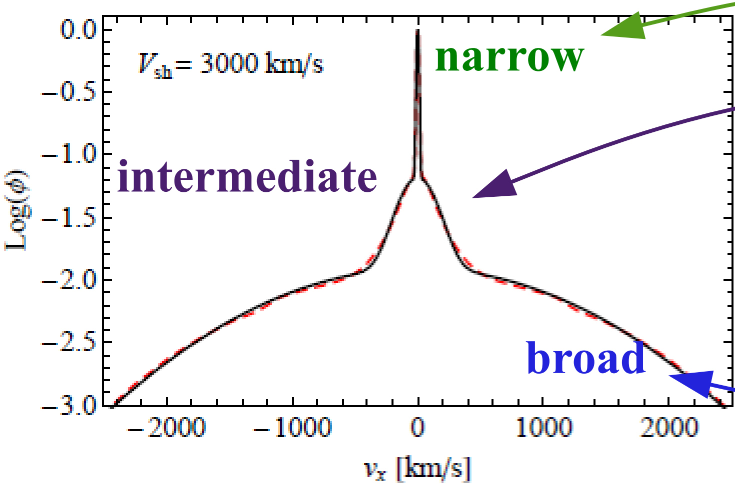
• Charge-exchange with protons in the precursor generates a third population of warm hydrogen

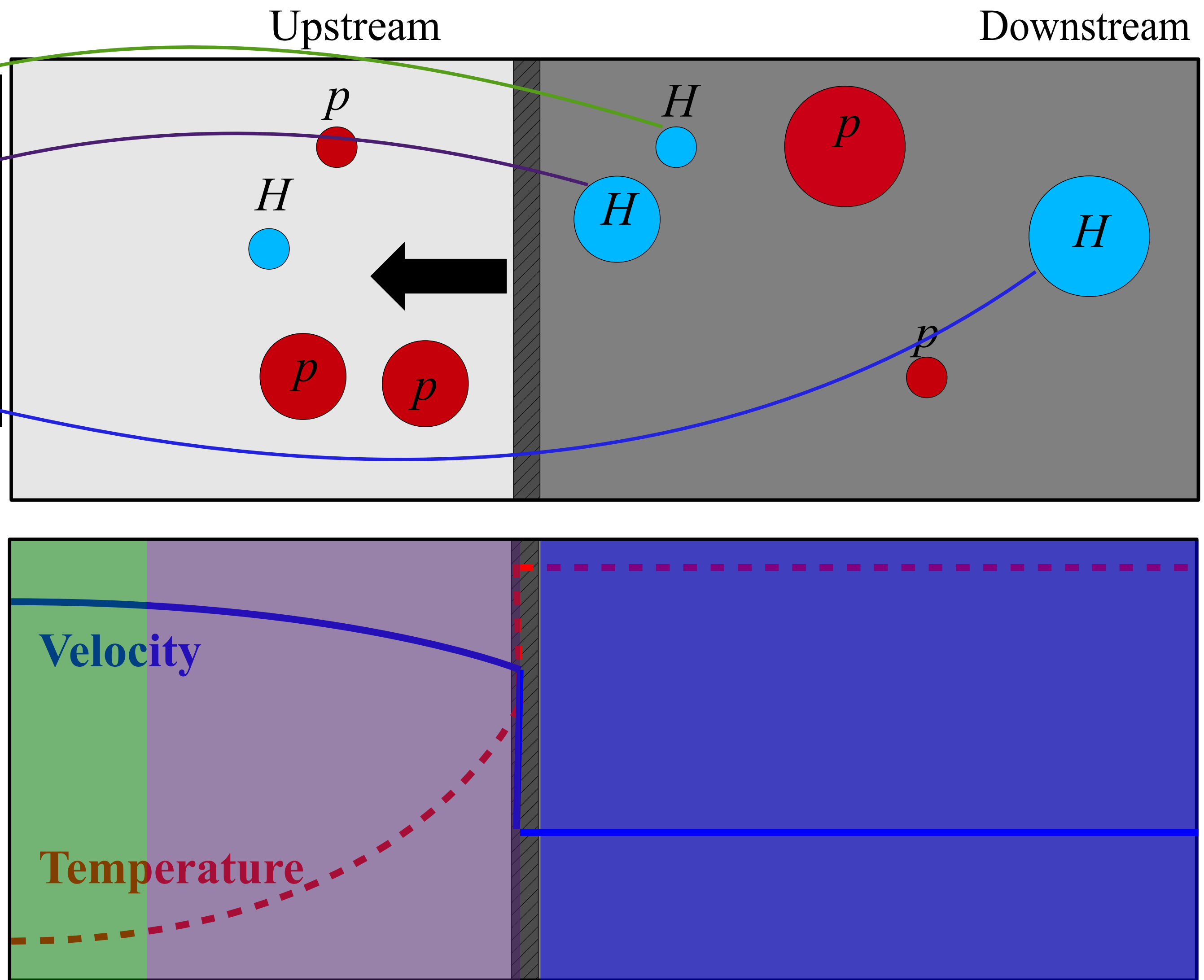
# Basic physics of Balmer shocks




**Formation of a *neutral-induced* precursor**

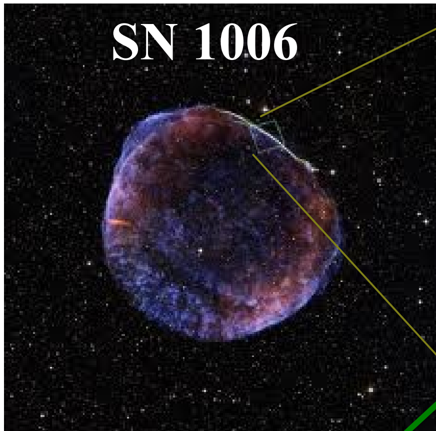
# Basic physics of Balmer shocks

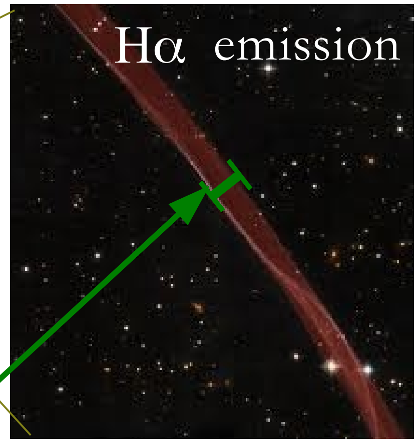


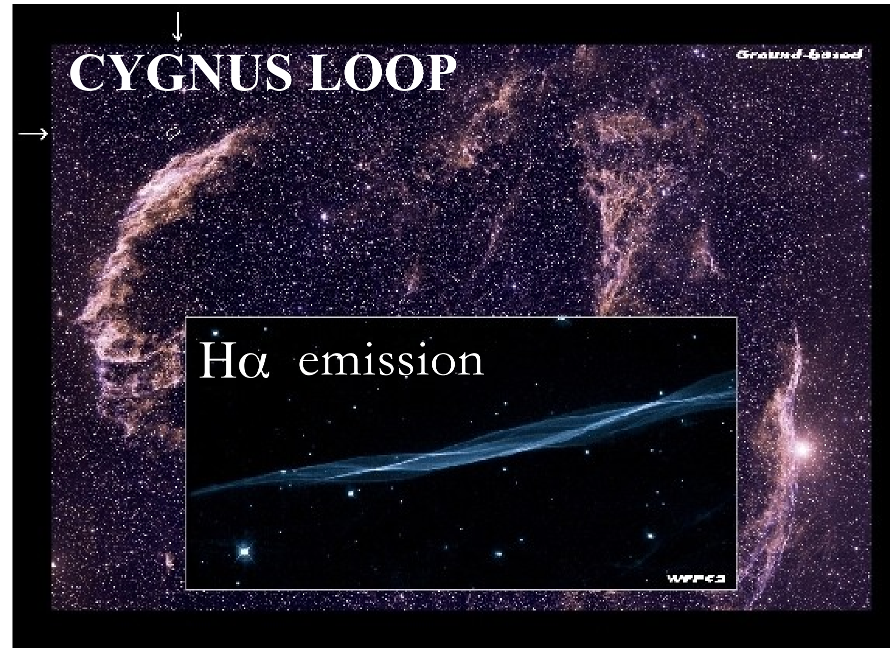

**Formation of a *neutral-induced* precursor**

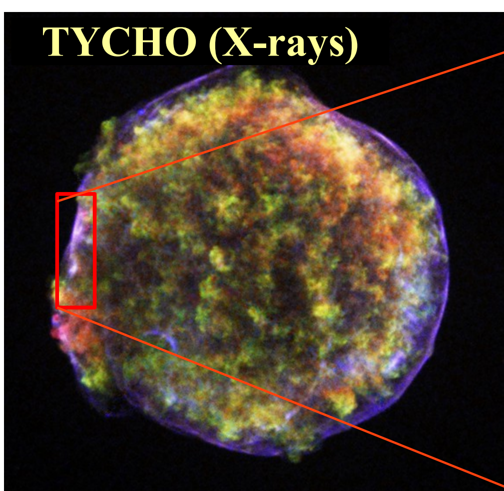
# Balmer-Dominated Shocks



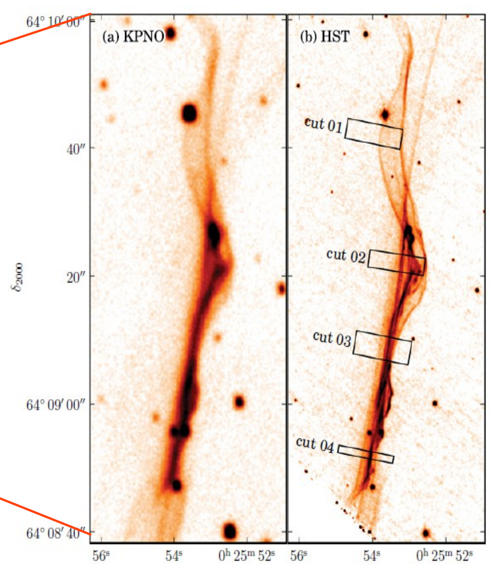




Thickness ~ 10" → $3 \cdot 10^{17}$ cm
Hα resolution ~ 0.7" → $2 \cdot 10^{16}$ cm

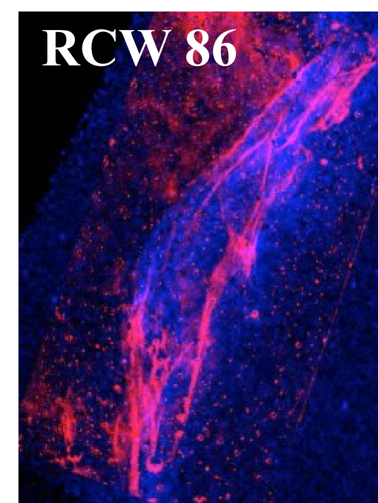


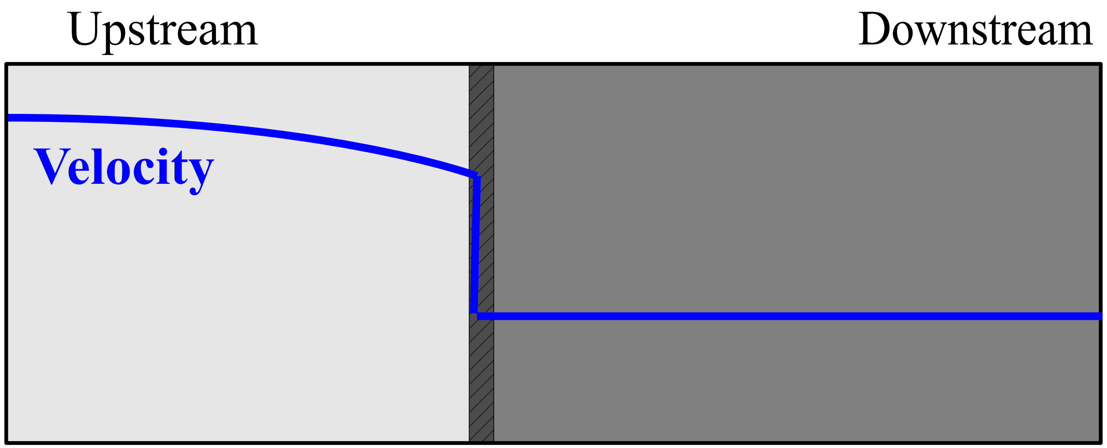

**Hα emission**







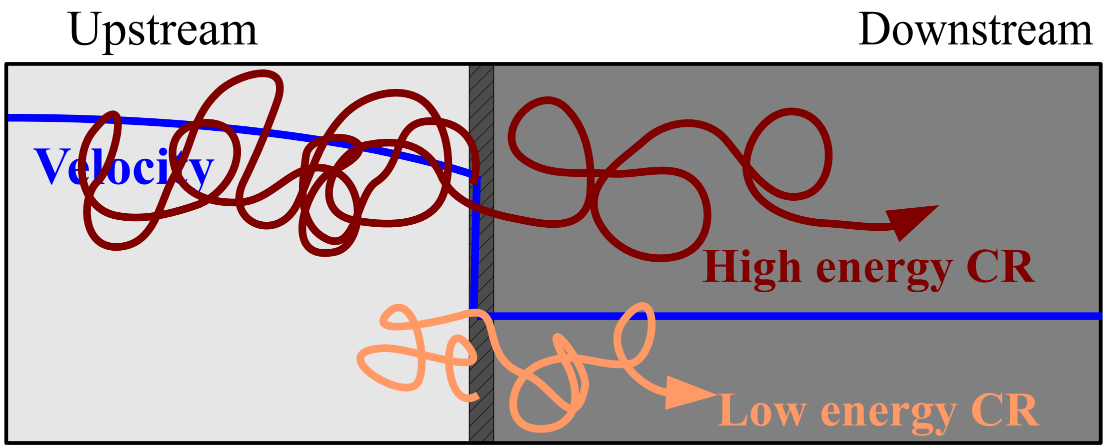
# CR acceleration in presence of neutrals: test-particle regime



# CR acceleration in presence of neutrals: test-particle regime

The compression ratio is a function of particle energy:

$$r(E) = \frac{u_1(E)}{u_2(E)}$$




[Blasi, G.M., Bandiera, Amato & Caprioli 2012, *ApJ* 755, 121]

# CR acceleration in presence of neutrals: test-particle regime

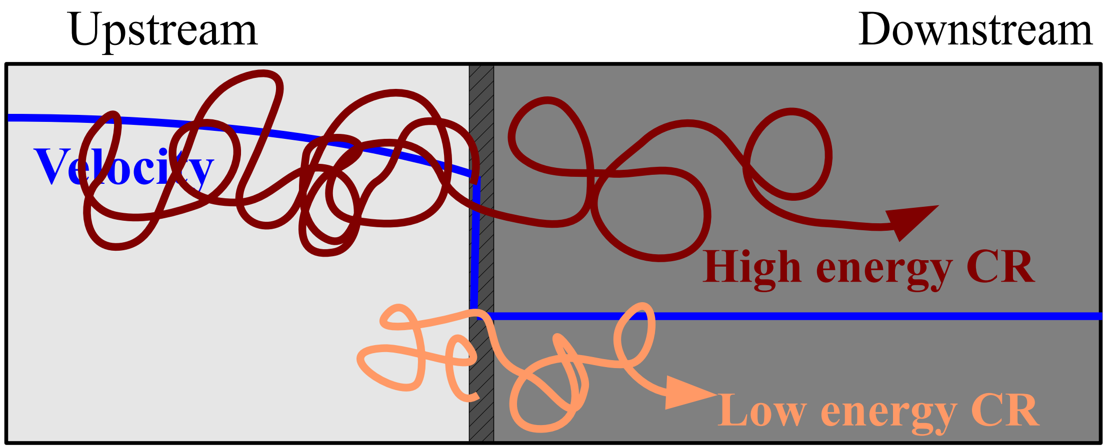
The compression ratio is a function of particle energy:

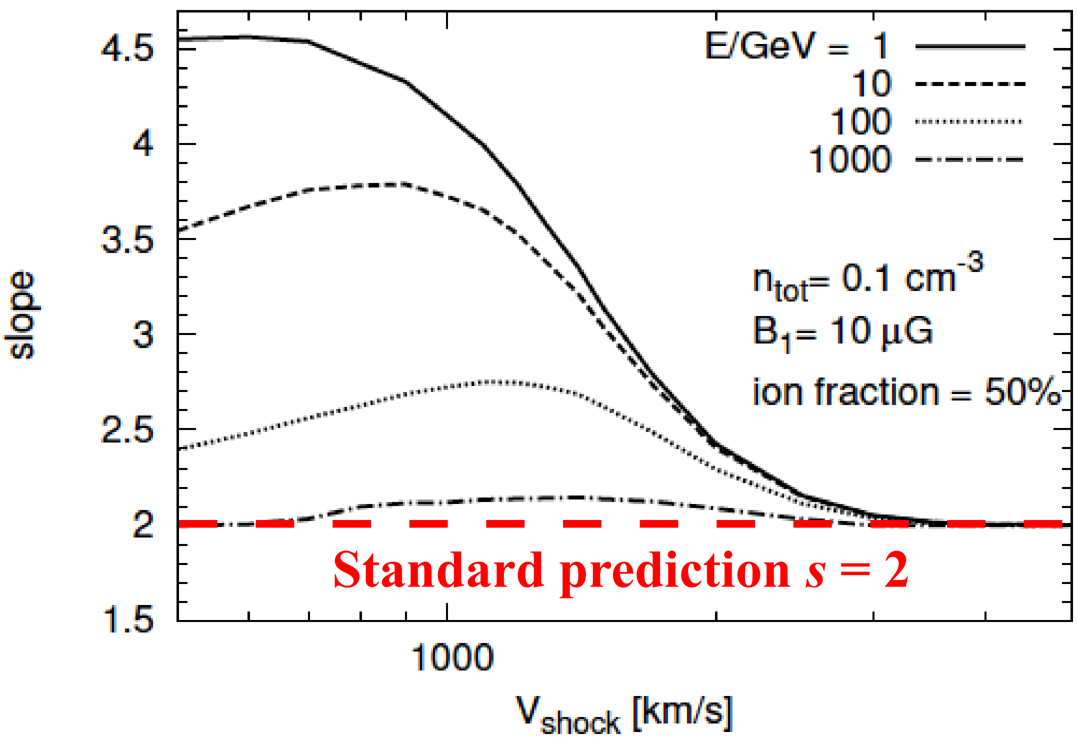
$$r(E) = \frac{u_1(E)}{u_2(E)}$$

Slope of CR spectrum

$$s(E) = \frac{r+2}{r-1}$$

→ For $V_{sh} < 3000$ km/s and large neutral fraction the CR spectrum can be very steep




[Blasi, G.M., Bandiera, Amato & Caprioli 2012, *ApJ* 755, 121]

# Conclusions

## Penetration of CRs into diffuse clouds

**Using a kinetic stationary analytical model we showed that**

- Losses inside the cloud
  - → density gradient outside the cloud
    - → generation of Alfvén waves
      - → shielding effect for CR with $E$ < 10-100 MeV

## Acceleration by shocks propagating through a cloud with neutral H

**Large fraction (>10%) of neutral hydrogen can change the shock structure.**

- Formation of a neutral-induced precursor
  - → Steeper spectra of accelerated particles for $E$ < 1 TeV and for $V_{sh}$ < 3000 km/s