Cosmic Rays streaming instabilities :

Simulations & Experiments

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Ion Streaming Instability

- Micro-Instability (kinetic process)
- Free energy : the beam energy
- Low ω (extended MHD modes)
- Threshold instability with $\omega_{\text{max}}(k_{\text{max}})$

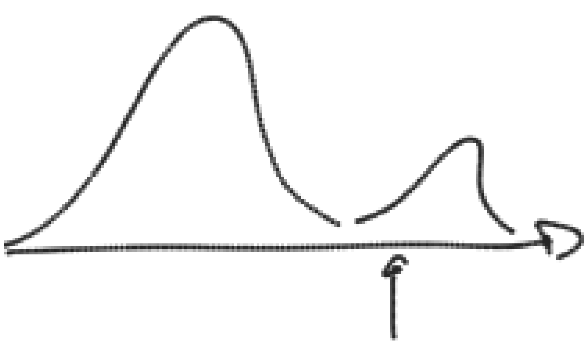
- Results in pitch-angle scattering (QL theory)
- Slowing down of the beam
- Heating of the main and/or beam
- Growth of temperature anisotropy

3 unstable modes (EM - circularly polarized) *Gary 1993*

Linearized Vlasov equation with k along B_0 field :

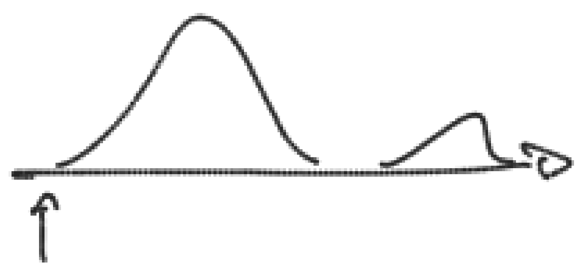
- population 1 : "main" (ISM plasma)
- population 2 : "beam" (CRs) distributions

Right-resonant



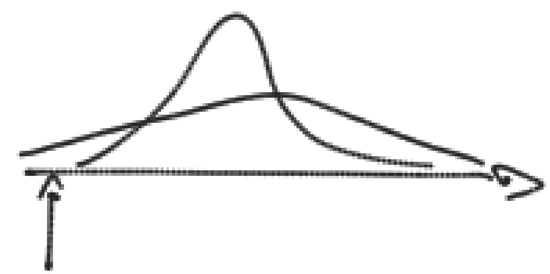
$$\frac{\omega + \Omega_p}{k_{||}}$$

Non-resonant



$$\frac{\omega - \Omega_p}{k_{||}}$$

Left-resonant



$$\frac{\omega - \Omega_p}{k_{||}}$$

Right-resonant mode *Kulsrud & Pierce 1969*

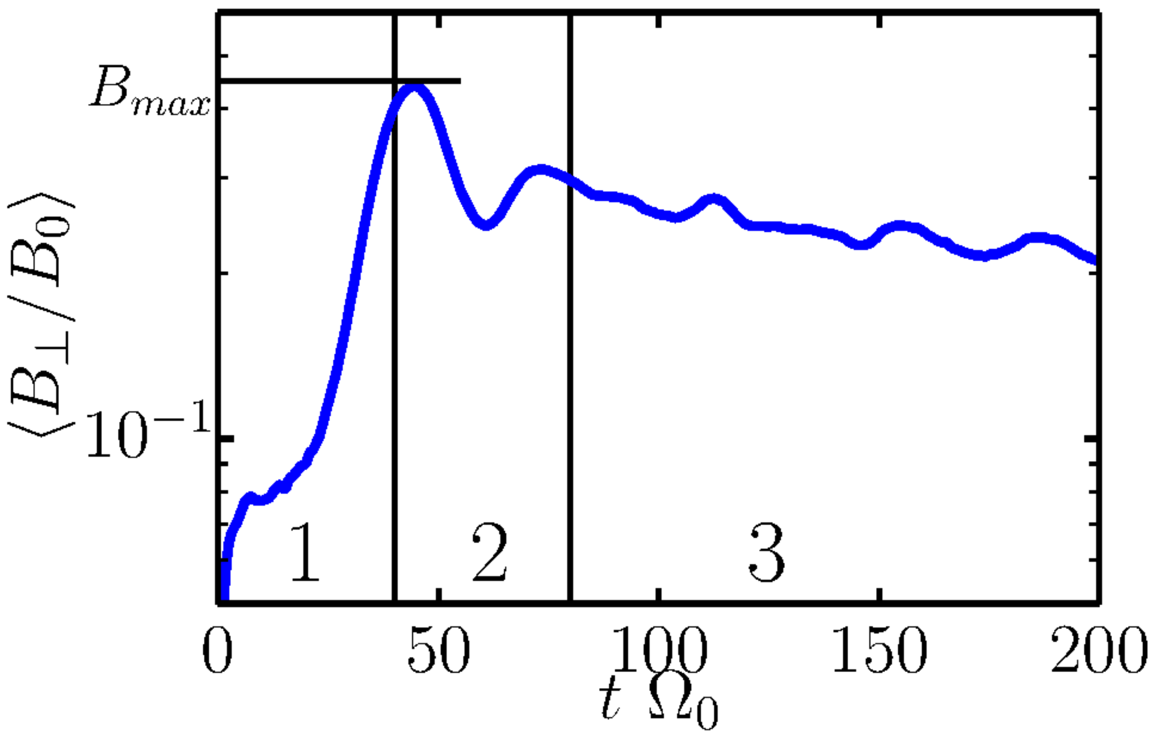
- mode with lowest thresold for cold proton beam
- Right-hand polarized (positive helicity) along $+\mathbf{V}_b$
- Most unstable mode with $\omega_r \sim \gamma$
- Growth rate in the cold limit

$$\frac{\gamma}{\Omega_p} = \left(\frac{n_b}{2n_T}\right)^{1/3}$$

- $k_{\mathrm{max}} = o(c/\omega_p)^{-1}$: asymptotically goes to whistler mode
- Beam protons are resonating :
  - pitch-angle diffusion of beam protons (QL theory)
  - heating of protons from main & beam

Right-resonant mode

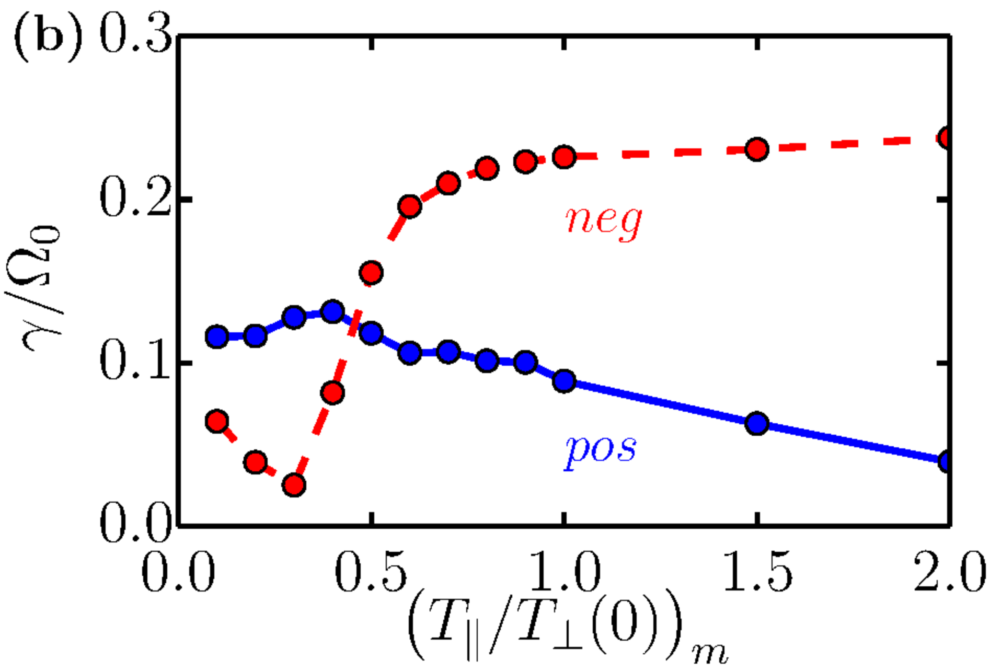
- 3 phases : growth, saturation (overshoot) & relaxation



$\longrightarrow$ Effects of magnetic fluctuations ?

Non-resonant mode *Bell 2003*

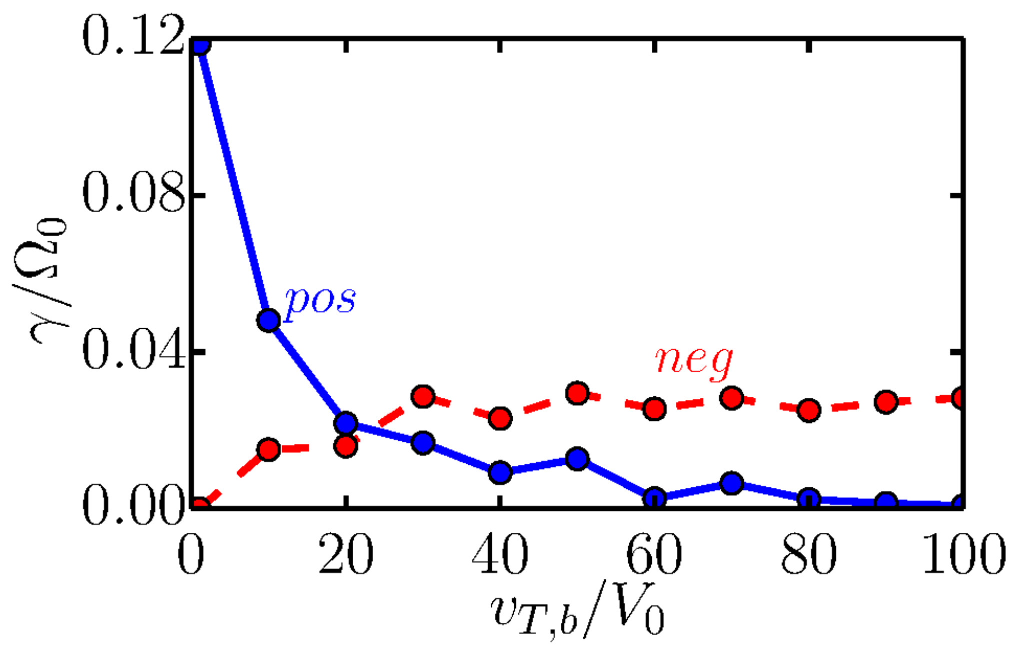
- This is a fluid-like mode (close to firehose mode)
- Needs a dense/fast beam



$\longrightarrow$ Can dominate the R-resonant mode : $\dfrac{\gamma}{\Omega_p} = \dfrac{n_b}{2n_T}\dfrac{v_b}{v_A}$

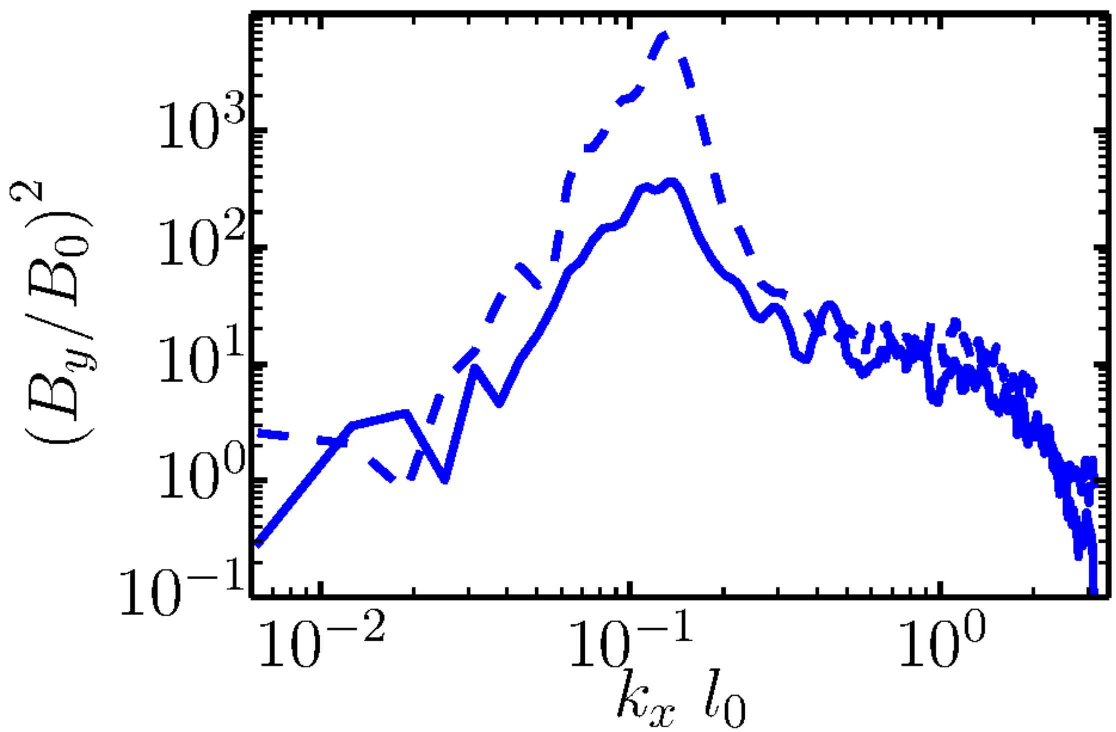
Left-resonant mode

Needs a very hot beam...



- Negative helicity, along $+\mathbf{V}_b$
- Proton beam resonating

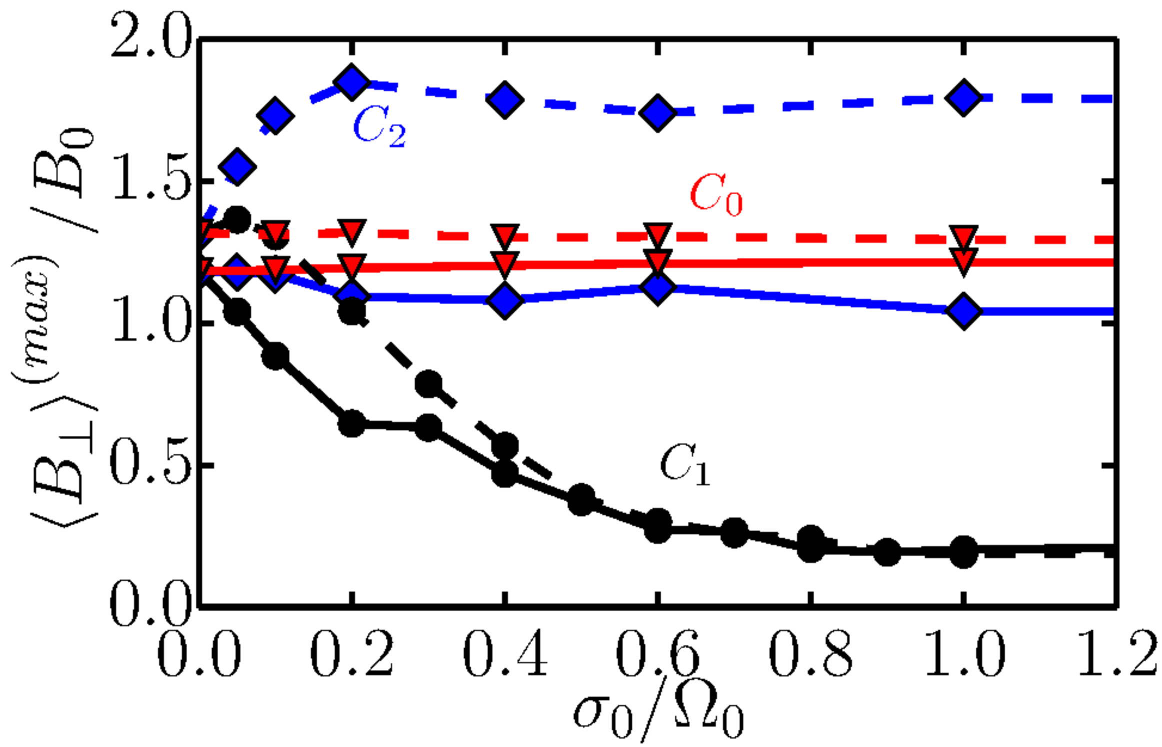
Effects of collisions



- Collisions do not modify the instability features
- Can slow down the beam and ease energy transfers

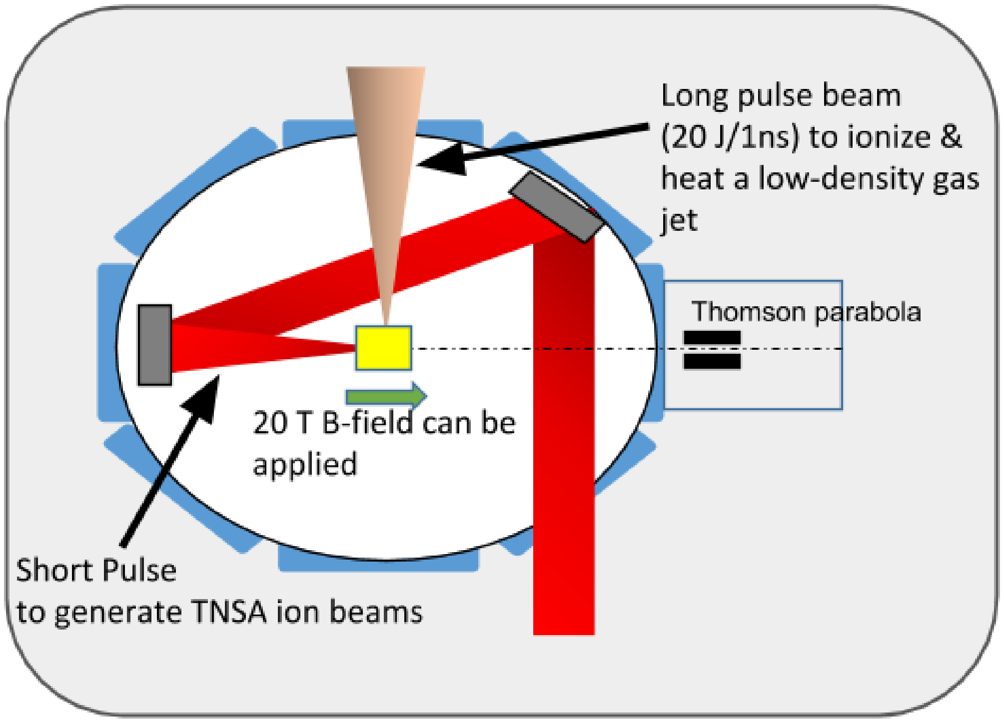
Effects of collisions

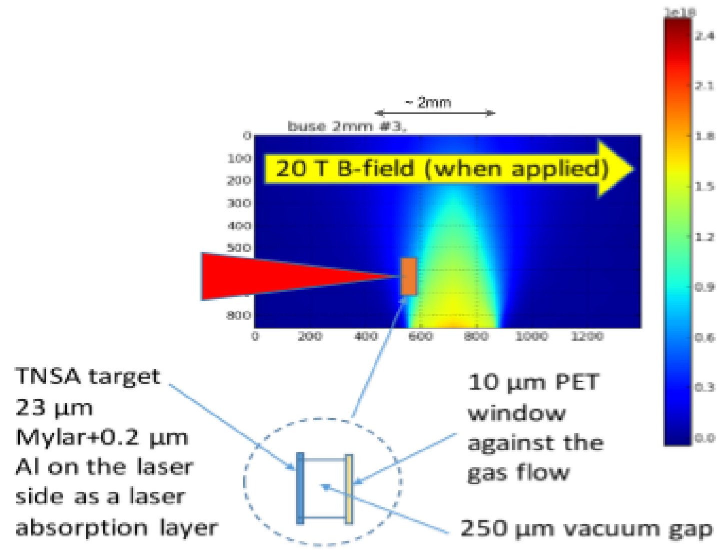
For a mixed case : R-resonant & non-resonant



$\rightarrow$ Growth of δB depends on the colliding particles

Experimental Set-up





- Magnetic field from external coils (LNCMI)
- Gas/plasma produced by the nano laser
- Beam produced by the pico laser (TNSA)

Experimental features

- Gas or Plasma of the “main” :
  - pre-ionized by the pico laser & e^- from the beam
  - ionization rate $\sim 10^{-2} - 10^{-3}$
  - can be ionized by the nano laser (inverse Bremsstrahlung)

- Proton beam by TNSA mechanism :
  - large energy dispersion
  - spectral shape can eventually be modified

$\rightarrow n_b/n_m$ vary with distance from beam to gas : 10^{-1} 10^{-4}

$\rightarrow v_b$ vary with the pico intensity (up to 10MeV)

Comparison of parameters

Parameters	HEDP	ISM
Magnetic field (T)	20	3×10^{-10}
main density (m^{-3})	10^{22} - 10^{25}	10^{3} - 10^{4}
beam density (m^{-3})	10^{19} - 10^{21}	10^{-4}
main temperature (ev)	10 - 50	10^{4} - 10^{5}
beam temperature (MeV)	0.1 - 10	1 - 100
mean free path (m)	10^{-2}	
Beta parameter (main)	$10^{-3} - 1$	1
Beta parameter (beam)	$10^{-2} - 1$	1
Ion gyroperiod (s)	5×10^{-10}	3×10^{1}
Proton skin depth (m)	7×10^{-5}	7×10^{6}
Alfvén speed ($m.s^{-1}$)	2×10^{5}	2×10^{5}

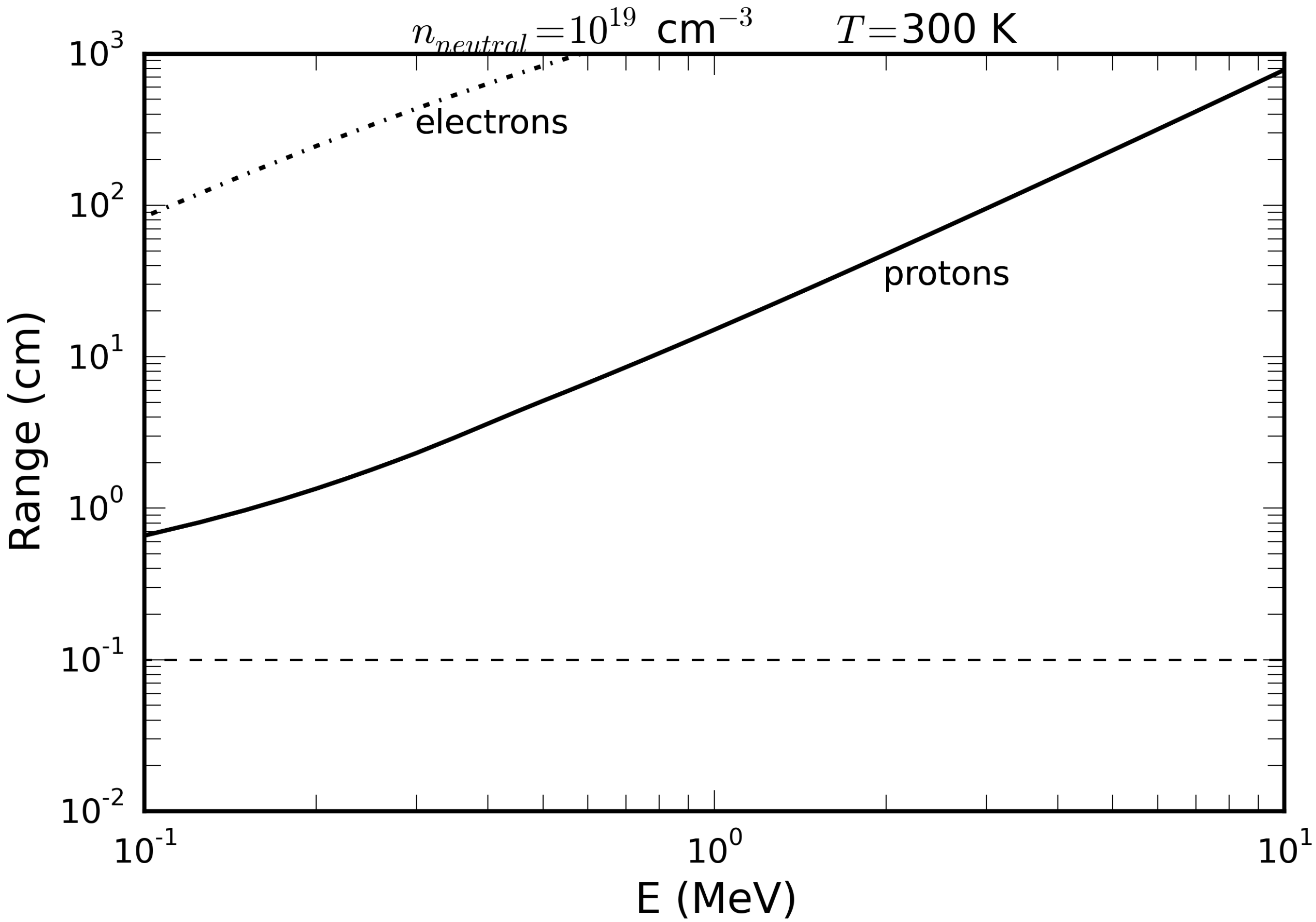
Most unstable mode : non-resonant ?

In the cold limit :

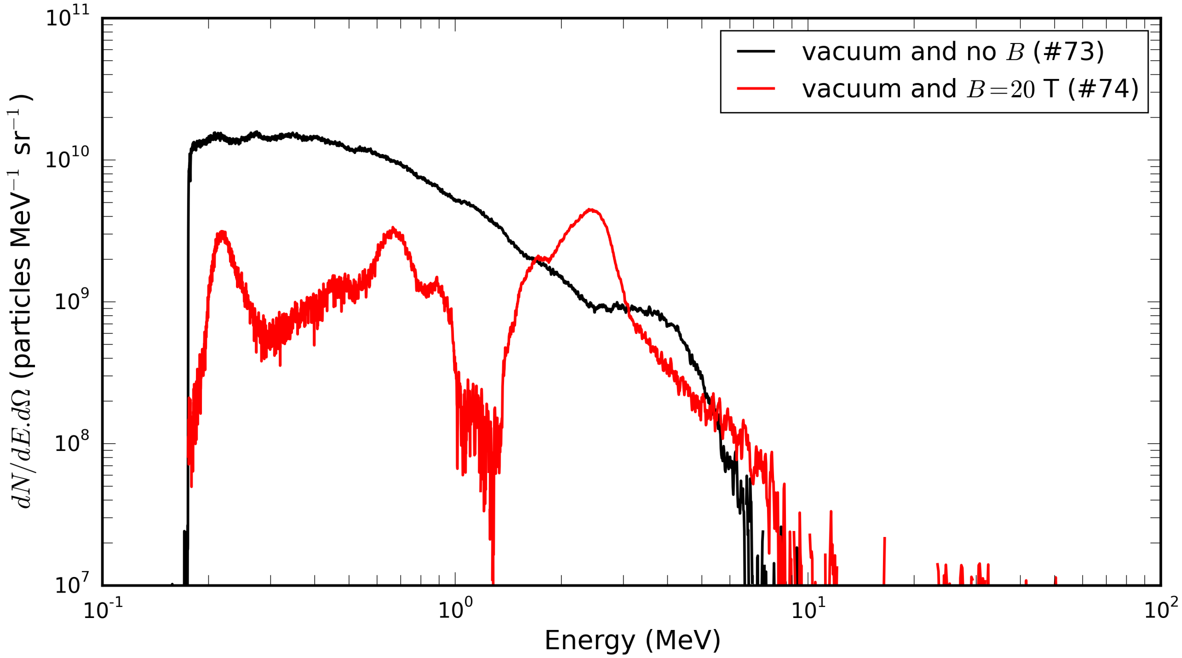
$$\frac{\gamma_{RR}}{\gamma_{NR}} = 2 \left(\frac{m_m}{m_b} \frac{n_m}{n_b} \right)^{2/3} \frac{v_A}{v_b} = 1 - 25$$

- mean free path > system size
- $v_b \sim 3 v_A$
- total time of experiment : up to 50 gyroperiods

Collisionality of the beam

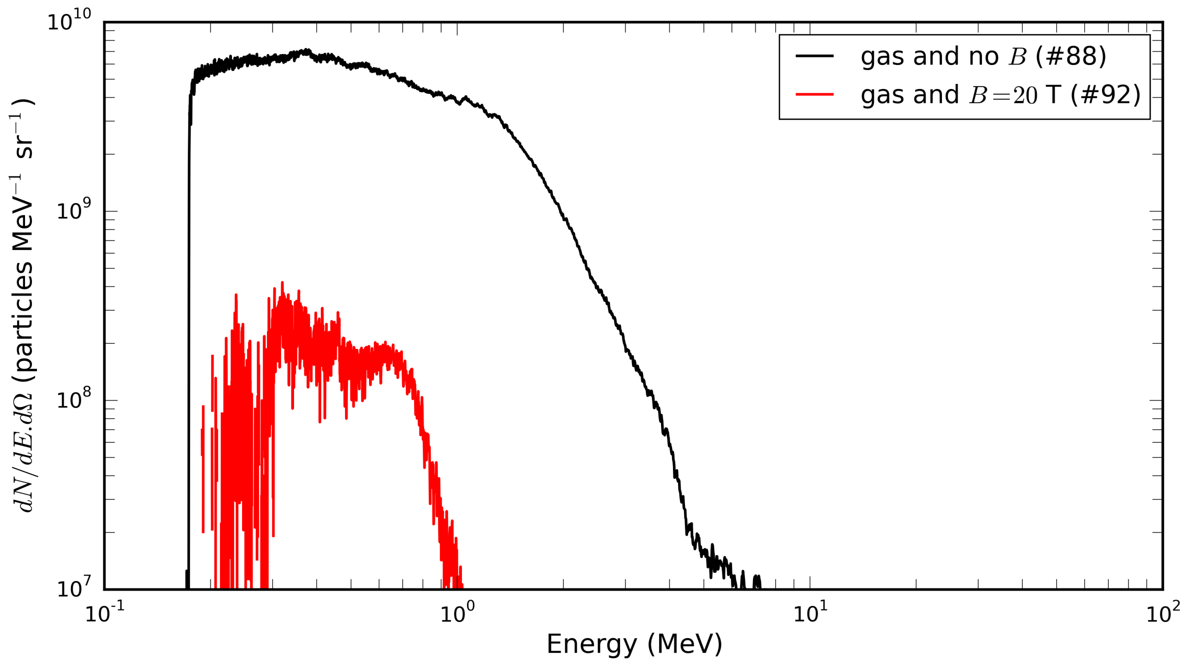


Proton beam in magnetized vacuum



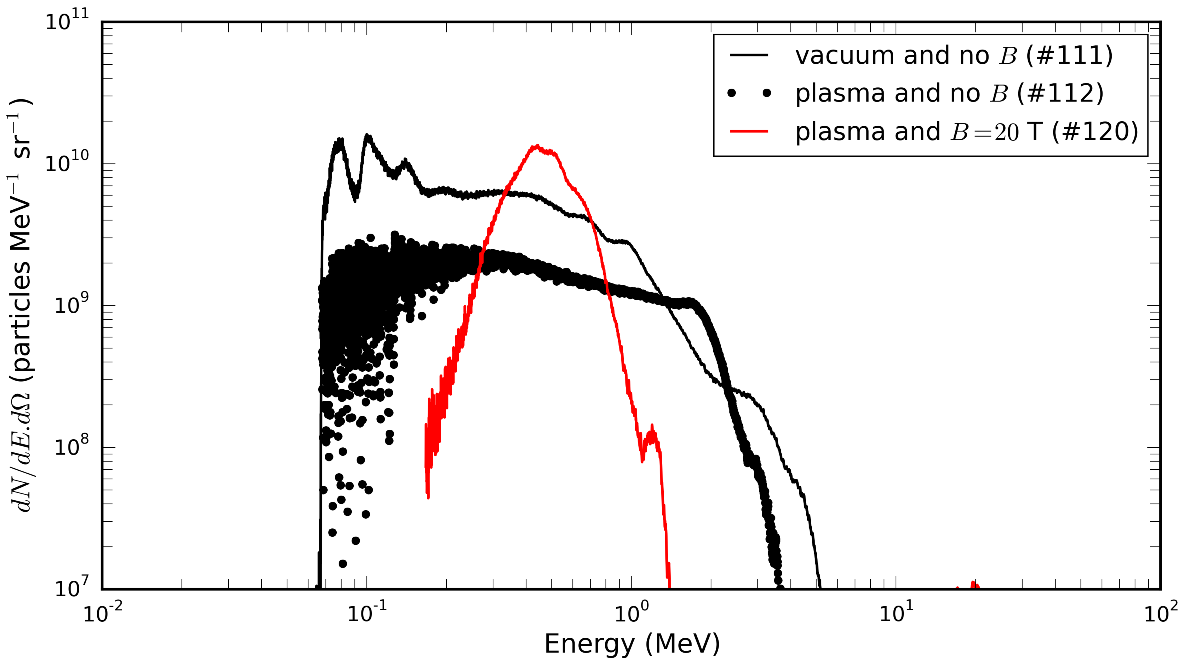
- Energy cutoffs : Thomson parabola & pico intensity
- With B : effects of hot magnetized e^{-}

Proton beam in magnetized gas



- Without B : no interraction with neutral gas
- With B : ionization of background for instability ?

Proton beam in magnetized plasma



- Without B : interraction with the plasma ?
- With B : same cutoff & clear bunching

Concluding remarks

- EM ion streaming instabilities : 3 modes
- Kinetic structure of ionized ISM & CR are to be clarified
- Effects of collisions are numerically importants
- Role in growing δB & slowing down/heating the beam
- Lab experiments are promizing (add diagnostics)
- Need simulations to decifer data from experiment