Dynamics of millicharged dark matter in supernova remnants

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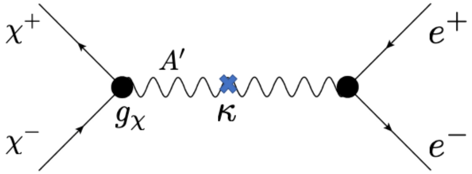
(arXiv: 2002.04625)

Millicharged Dark Matter (mDM)

Model 1: Dirac fermion DM with hypercharge $Q = Q_\chi$

Model 2: Dark fermion couples to ultralight (< 10^{-14} eV) dark photon *A'*



Effective charge $Q = \frac{\kappa g_\chi}{e}$

Motivation

- Freeze-in abundance can make up the entire DM abundance and evade current bounds.
- Direct detection from polar materials looking for sub-MeV dark matter.
- Coulomb-type scattering explains the EDGES 21-cm result nicely.
- Charged DM interact with magnetic fields in Galactic disk and supernova.
  - ➢ Can mDM gain energy from supernova?
  - ➢ An mDM cosmic ray?

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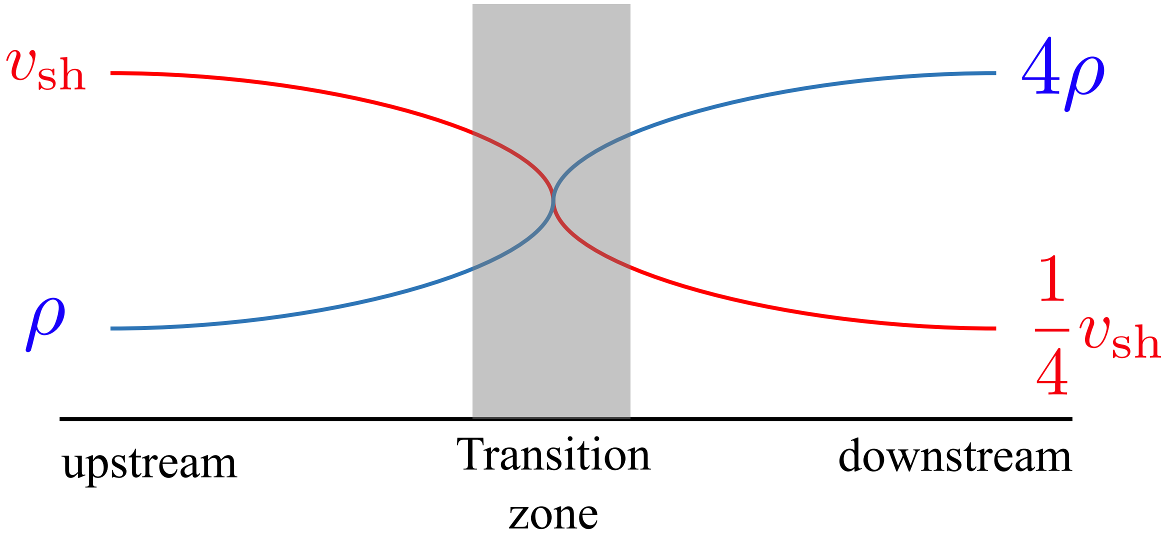
Rankine-Hugoniot condition

- Connects upstream (ahead of shock) and downstream (behind shock) states.
- Conserving *mass*, *momentum*, and *energy*.
  - Upstream bulk kinetic energy is dissipated at shock front and becomes heat.
  - Downstream flow speed $= v_{\rm sh}/4$
  - Downstream thermal speed $\sim v_{\rm sh}$



Supernova collisionless shock

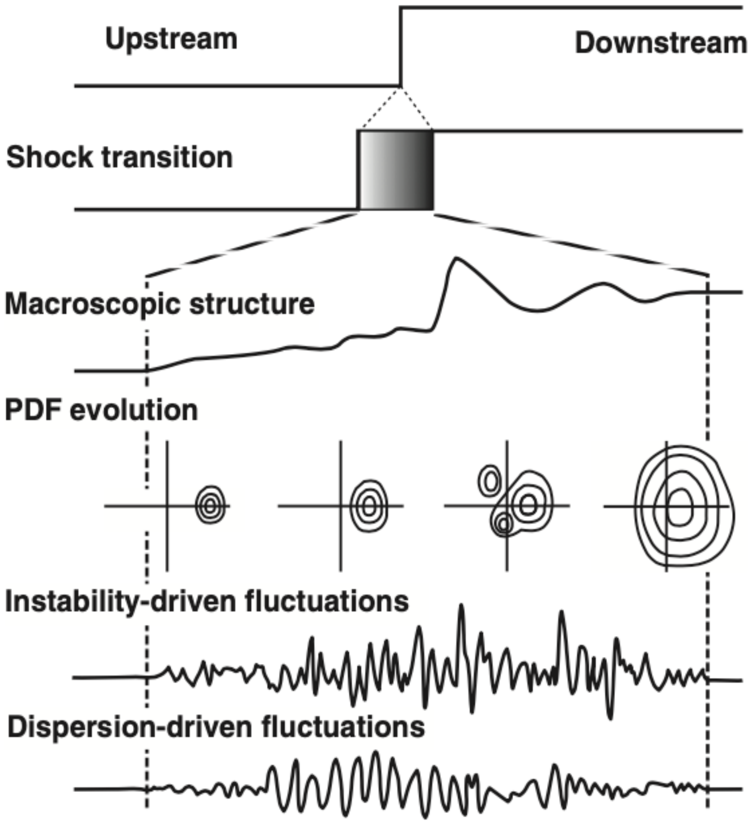
1. Shock is linked to the increase of entropy. Upstream bulk kinetic energy is dissipated to heat at the shock zone.
    - Collisional: fluid viscosity (e.g., sonic boom)
    - Collisionless: plasma instability (e.g., astro shocks)

2. Collisionless shock dissipates upstream bulk kinetic energy to heat through *wave-particle* interaction.
    - ➢ Fluctuations comes from counter-streaming ion instability.

3. The thickness of shock: several proton Larmor radius.

$$r_{L\chi} \sim \frac{m_\chi}{Q_\chi} \gg r_{\mathrm{L,proton}}$$

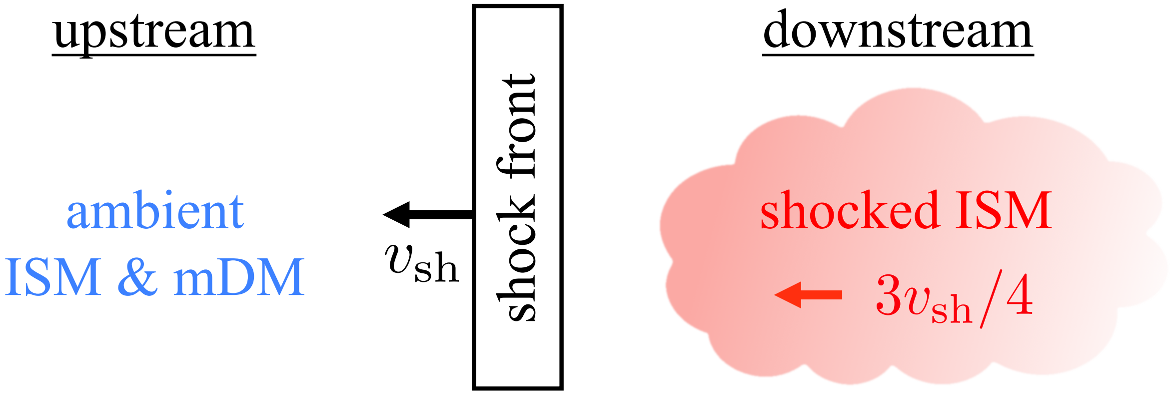
No interaction to mDM at shock front!



Burgess & Scholer 2015

Plasma instabilities from mDM

- A relative velocity between shocked interstellar medium (ISM) and unshocked mDM can excited plasma waves.
- Plasma waves backscatter on mDM from wave-particle interaction.
- mDM particles are isotropized in the shocked ISM frame. The shocked gas *sweeps up* DM.



upstream

ambient
ISM & mDM

v_{sh}

shock front

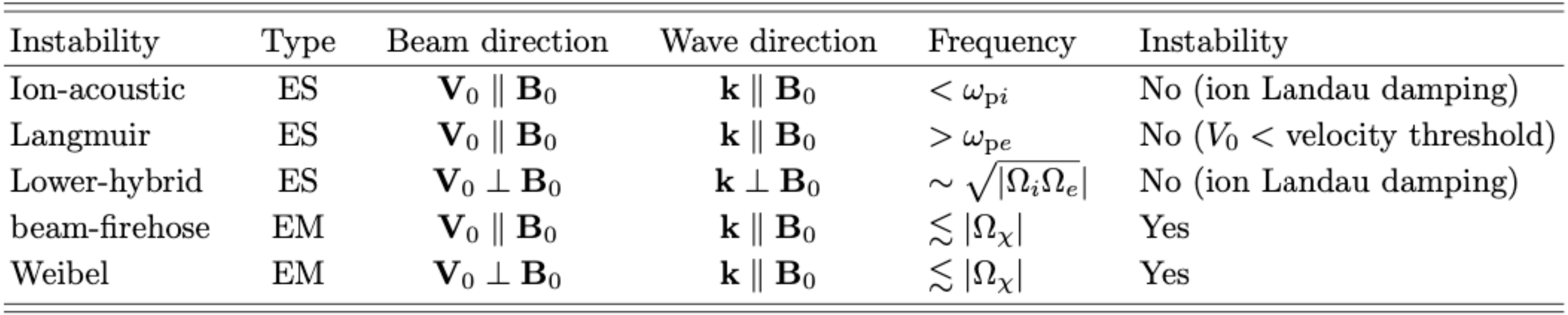
downstream

shocked ISM

$3v_{\mathrm{sh}}/4$

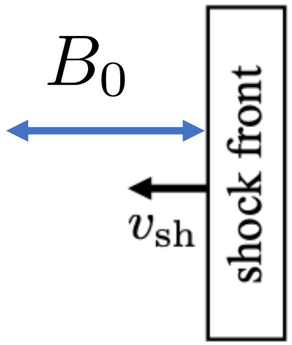
(Milky Way frame)

Zoo of plasma: choose representative plasma instabilities

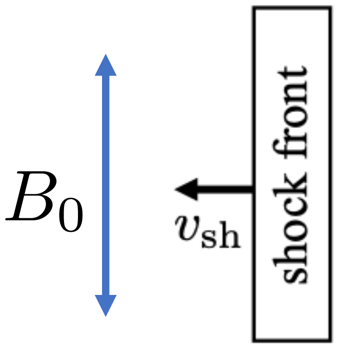


Instability	Type	Beam direction	Wave direction	Frequency	Instability
Ion-acoustic	ES	$\mathbf{V}_0 \parallel \mathbf{B}_0$	$\mathbf{k} \parallel \mathbf{B}_0$	$< \omega_{\mathrm{p}i}$	No (ion Landau damping)
Langmuir	ES	$\mathbf{V}_0 \parallel \mathbf{B}_0$	$\mathbf{k} \parallel \mathbf{B}_0$	$> \omega_{\mathrm{pe}}$	No ($V_0 <$ velocity threshold)
Lower-hybrid	ES	$\mathbf{V}_0 \perp \mathbf{B}_0$	$\mathbf{k} \perp \mathbf{B}_0$	$\sim \sqrt{\lvert \Omega_i \Omega_e \rvert}$	No (ion Landau damping)
beam-firehose	EM	$\mathbf{V}_0 \parallel \mathbf{B}_0$	$\mathbf{k} \parallel \mathbf{B}_0$	$\lesssim \lvert \Omega_\chi \rvert$	Yes
Weibel	EM	$\mathbf{V}_0 \perp \mathbf{B}_0$	$\mathbf{k} \parallel \mathbf{B}_0$	$\lesssim \lvert \Omega_\chi \rvert$	Yes

Parallel shock



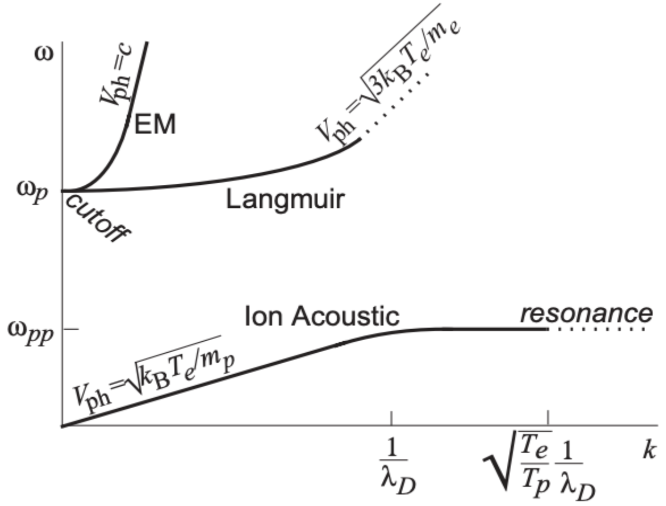
Perpendicular shock



Electrostatic waves and instabilities: suffer Landau damping

- Ion acoustic wave: a sound wave of ions, $\mathbf{B}_0 \parallel v_{\rm sh}$
- Langmuir wave: fast electron oscillation, $\mathbf{B}_0 \parallel v_{\rm sh}$
- Lower hybrid wave: ion oscillation across **B** field, $\mathbf{B}_0 \perp v_{\rm sh}$

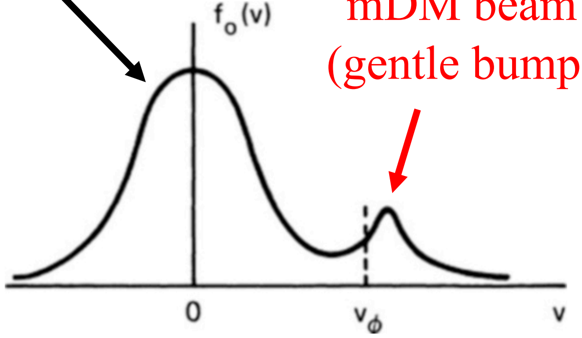
1. Small Q_χ/m_χ, effectively low-density plasma
2. mDM beam speed ~ proton thermal speed ~ $v_{\rm sh}$



Blandford and Thorne 2017

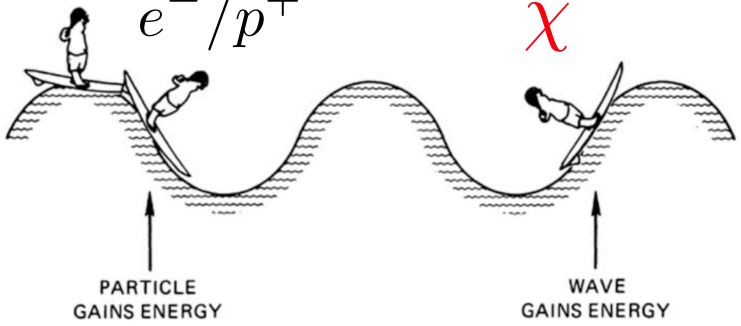
Proton/electron plasma

mDM beam (gentle bump)



e^-/p^+

χ



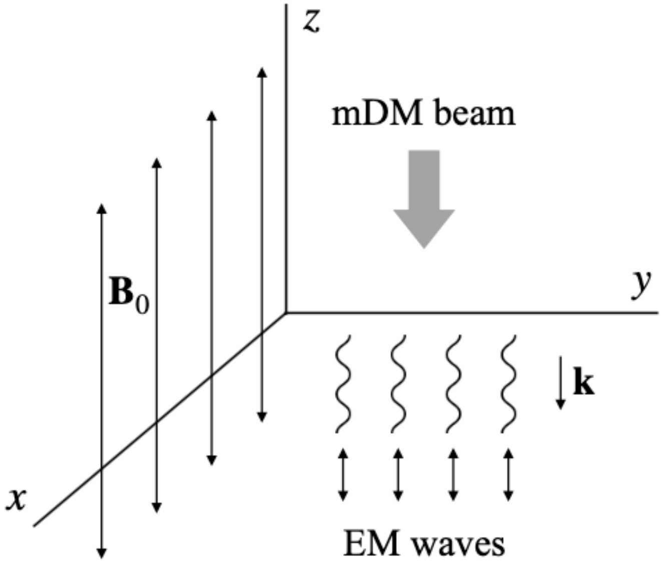
Francis Chen 1984

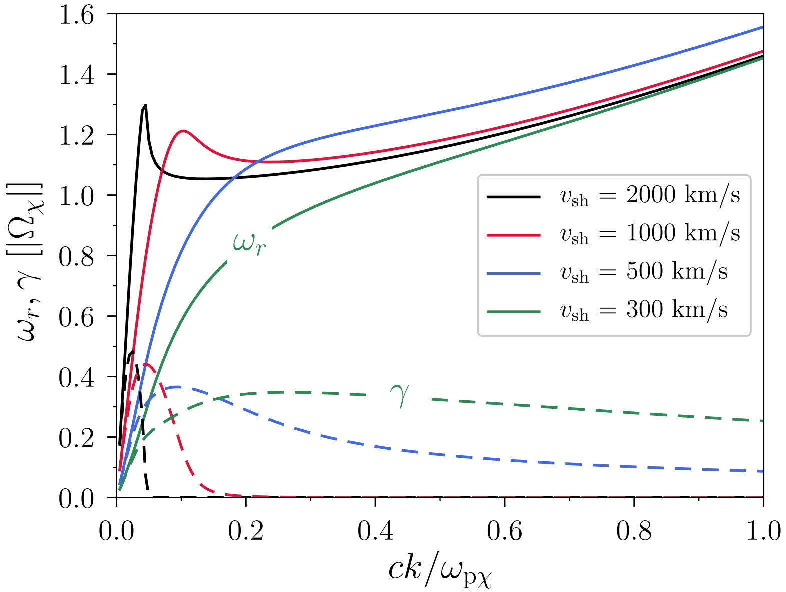
EM wave: firehose instability in parallel shock

Dispersion relation $$0 = D^{\pm}(k,\omega) = c^2k^2 - \omega^2 - \sum_{j=i^+,e^-} \omega_{\mathrm{p}j}^2 \left(\frac{\omega}{kv_{\mathrm{th},j}}\right) Z(\xi_j) - \sum_{s=\chi^+,\chi^-} \omega_{\mathrm{p}s}^2 \left(\frac{\omega - kV_0}{kv_{\mathrm{th},\chi}}\right) Z(\xi_s)$$

(main plasma) (Doppler shifted mDM)

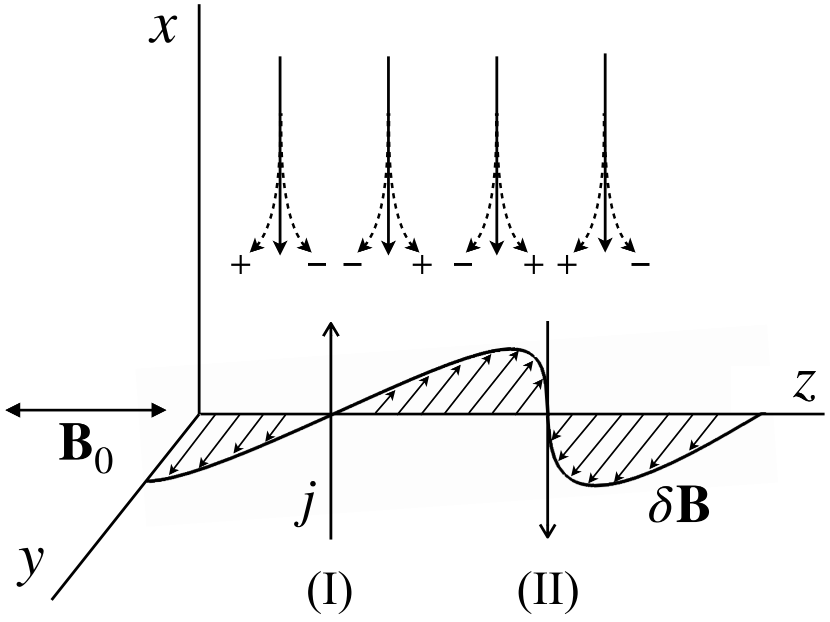
Solve $\omega = \omega_r + i\gamma$. Positive γ means a growing instability mode.

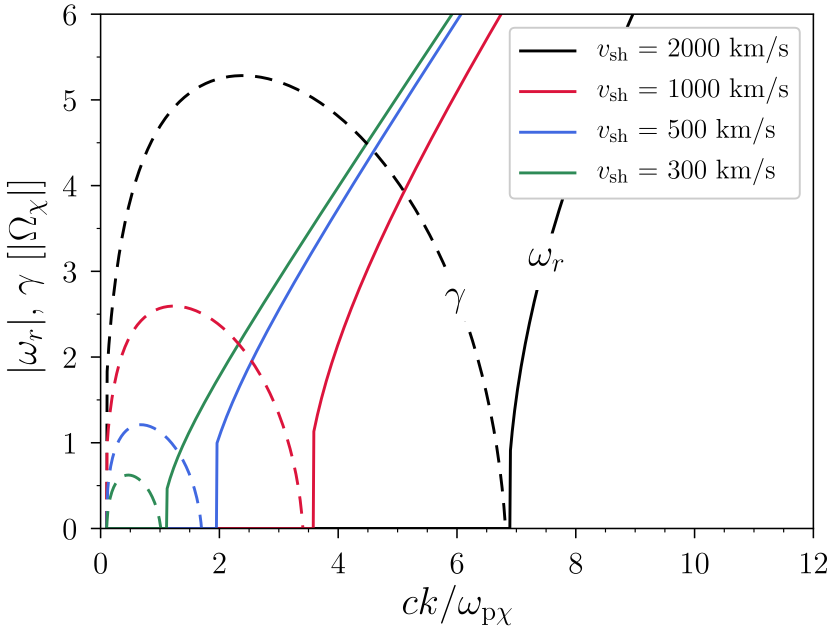




EM wave: Weibel instability in perpendicular shock

Dispersion relation $$0 = D^{\pm} = c^2k^2 - \omega^2 - \sum_{j=i^+,e^-} \omega_{\mathrm{p}j}^2 \left(\frac{\omega}{kv_{\mathrm{th},j}}\right) Z\left(\xi_j\right) - \sum_{s=\chi^+,\chi^-} \omega_{\mathrm{p}s}^2 \left[\left(\frac{\omega}{kv_{\mathrm{th},\chi}}\right) Z\left(\xi_s\right) + \left(\frac{V_0}{v_{\mathrm{th},\chi}}\right)^2 \left(1 + \xi_s Z\left(\xi_s\right)\right)\right]$$





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Saturation of instability

1. mDM beam is isotropized in the downstream plasma in one instability timescale. Then we say instability is saturated

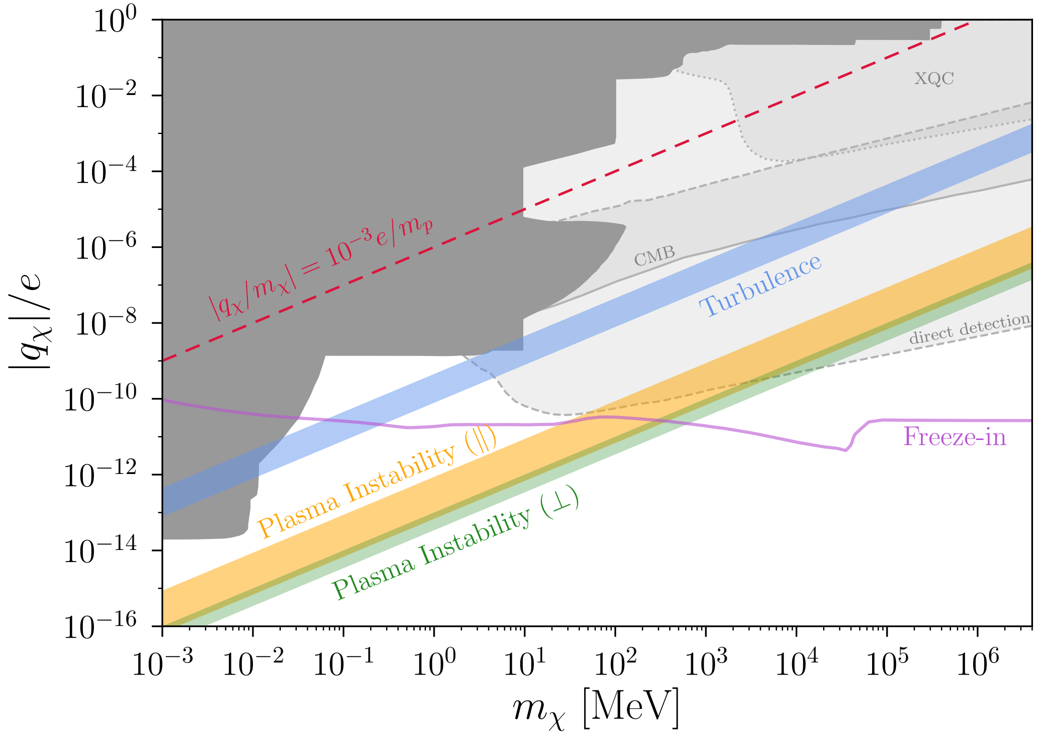
$$\text{instability time} \sim 1/\gamma \sim 1/\Omega_\chi$$

2. Saturation length be smaller than supernova shock size:

$$L_{\rm sat} \sim v_{\rm sh}/\gamma_\chi < R_{\rm SN}$$

But another issue is shock expands….

Adiabatic decompression!



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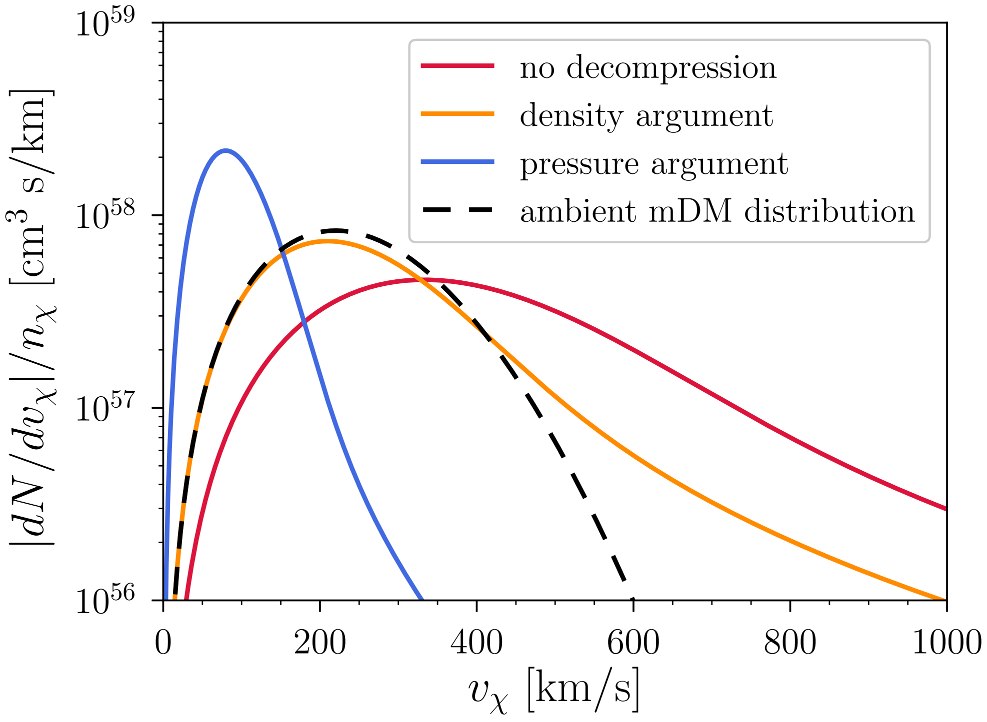
Adiabatic decompression

- mDM scatters on plasma waves as the shock remnants expands
  a) Density argument: when shocked ISM density equals ambient ISM density, decompression stops
  b) Pressure argument: when shocked ISM pressure equals ambient ISM pressure, decompression stops

Adiabatic decompression cools mDM back to ambient DM thermal distribution, or even colder!



Conclusion

- mDM interacts with shocked hot electron/proton plasma through plasma instabilities. It is a wave-particle interaction.

- The same plasma effect also adiabatically decompresses downstream mDM. The final mDM velocity distribution returns to ~ ambient mDM distribution, or even colder!

- Plasma physics plays important role to dark cosmic ray formation.