Hydrodynamic Instabilities
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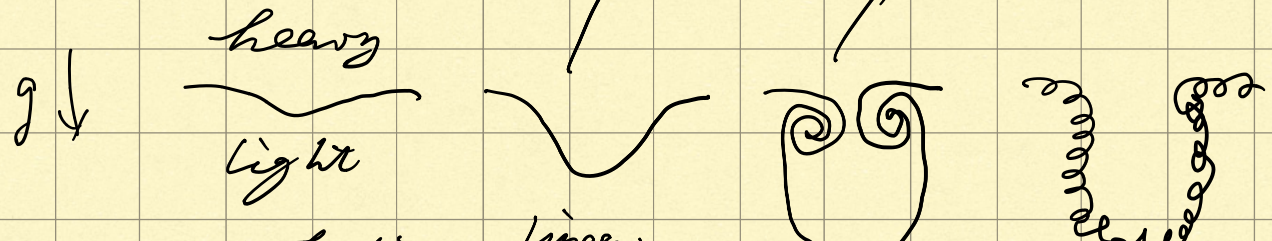
(1) RTI   scale free   hits to another scale



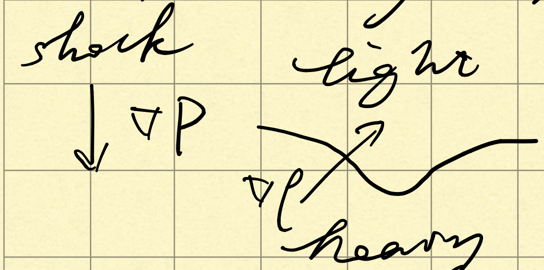
perturbation   linear   non-linear   fully-mixed

{ growth rate
{ fastest growing mode

turbulence   simulation   turbulence

saturation: ~ t damp

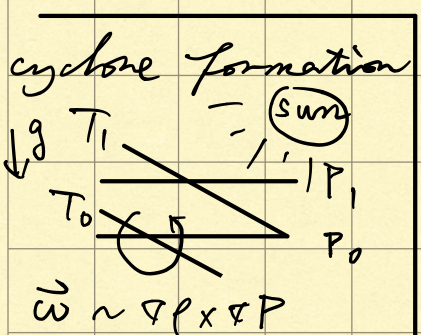
Richtmyer-Meshkov Instability



$\vec{\omega} \equiv \nabla \times \vec{v}$

$$\frac{\partial \omega}{\partial t} = -(v\cdot\nabla)\omega + (\omega\cdot\nabla)v - \omega(\nabla\cdot v) + \frac{1}{\rho^2}\nabla\rho\times\nabla\left(P+\frac{B^2}{8\pi}\right) - \frac{1}{\rho^2}\nabla\rho\times\frac{(B\cdot\nabla)B}{4\pi}$$

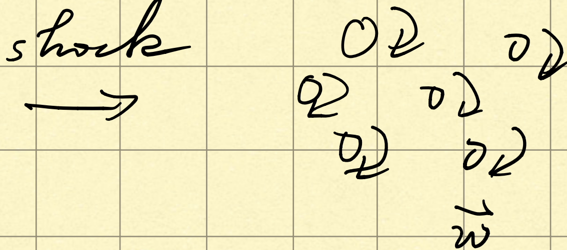
stretching, compression; baroclinic vorticity; magnetic tension



$$\frac{\partial B}{\partial t} = -(v\cdot\nabla)B + (B\cdot\nabla)v - B(\nabla\cdot v)$$

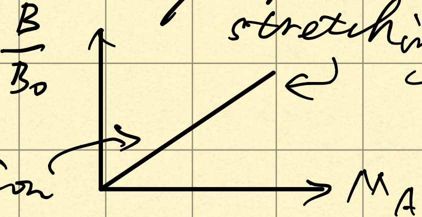
stretching compression

cloud-shock instability



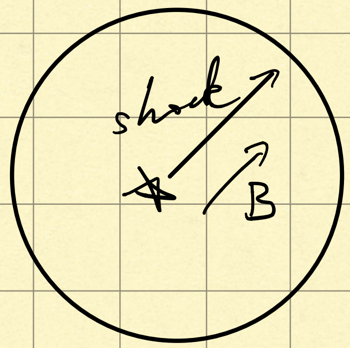
magnetic field amplification

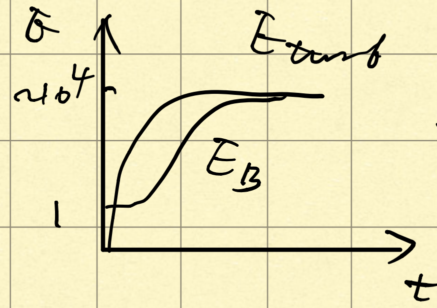
$$\frac{B}{B_0} \propto M_A$$



SNR

$M_A \sim M \sim 10^2$, $\frac{B}{B_0} \sim 10^2$

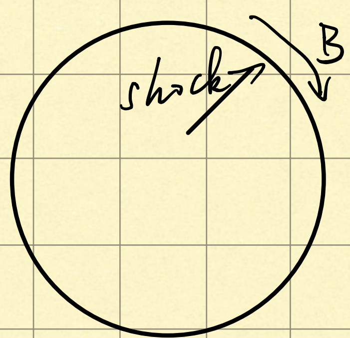


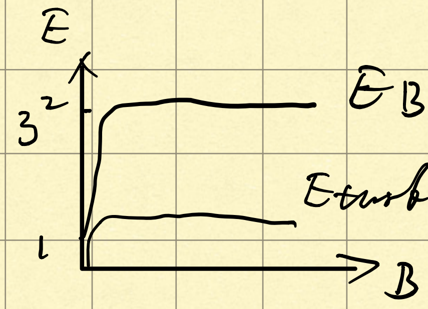


B amplified by **stretching** (turb dynamo)

saturation: $E_B \sim E_{turb}$

Cluster outskirts

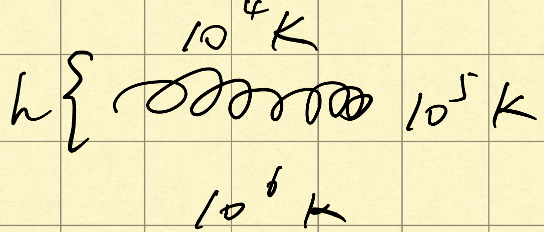




$M_A \gtrsim M \sim 3$ $\frac{B}{B_0} \gtrsim 3$

turbulence suppressed by B tension amplified by **compression**

② KH I + cooling: turbulent mixing layer (TML)



$T_{mix} \sim \sqrt{T_c T_h}$

if: $\frac{h}{v_{turb}} \sim t_{cool}$

then $h \sim v_{turb} t_{cool} \sim v_{shear} \cdot t_{cool}$

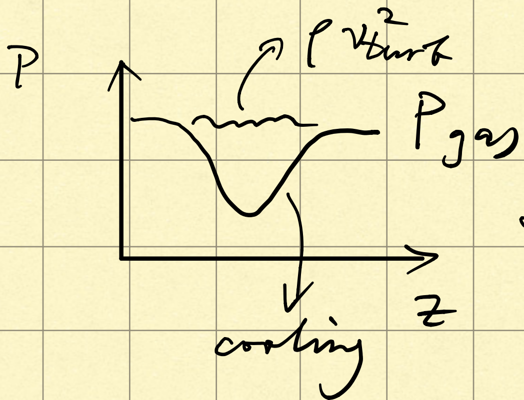
$$\Rightarrow N_{OVI} \sim \underbrace{f_{OVI} \cdot f_0 \cdot Z \cdot n}_{n_{OVI}} \cdot \underbrace{v_{shear} \cdot t_{cool}}_{h}$$

since $t_{cool} \propto (Z \cdot n)^{-1}$

theory: $\begin{cases} N_{OVI} \propto Z^0 \\ N_{OVI} \propto t_{cool} \end{cases}$ simulation: $\begin{cases} N_{OVI} \propto Z^1 \\ N_{OVI} \propto t_{cool}^{1/2} \end{cases}$

reason: $v_{turb} \neq v_{shear}$, $v_{turb} \neq$ const

instead $v_{turb} \sim v_z$ positively related to t_{cool}



$P_{gas} + \rho v_{turb}^2 \sim$ constant

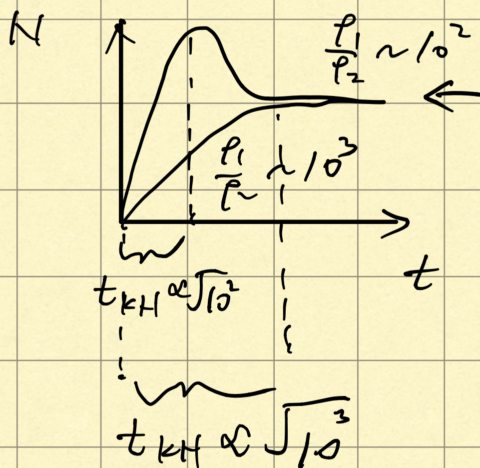
faster cooling → quicker hot gas entrainment & larger v_{turb}

Saturation: cooling ~ hot gas influx

$$\Sigma_L \sim n^2 \Lambda h \sim P_{hot} \cdot v_z$$

$$\Rightarrow h \sim \frac{\Sigma_L}{n^2 \Lambda} \sim v_z \cdot t_{cool}, \quad v_z \propto t_{cool}^{-1/2}$$

$h \propto N_{OVI}$, CIV, SiIV $\propto t_{cool}^{1/2}$, not t_{cool}^{1}



For TML, growth time is determined by KHI, while saturation level determined by cooling

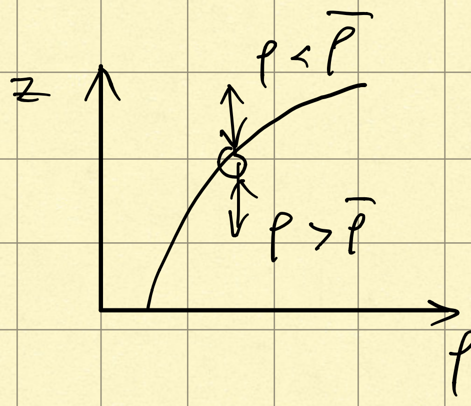
③ TI + B fields

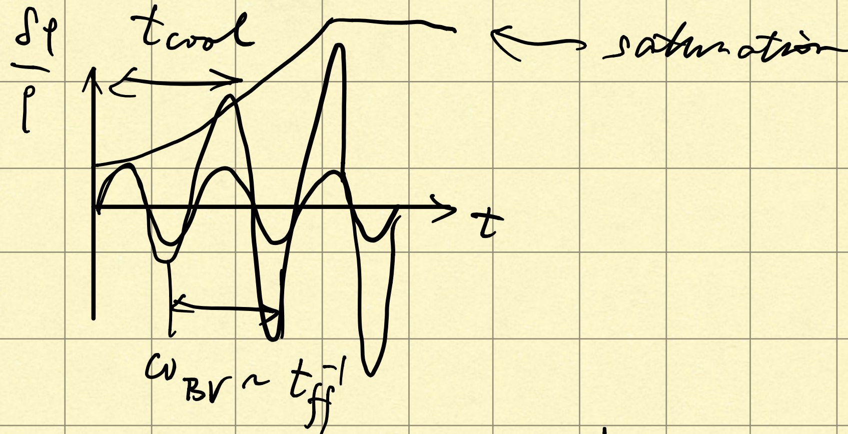
$\partial \mathcal{L} / \partial T < 0$ growth timescale: t_{cool}

in gravitationally stratified medium:

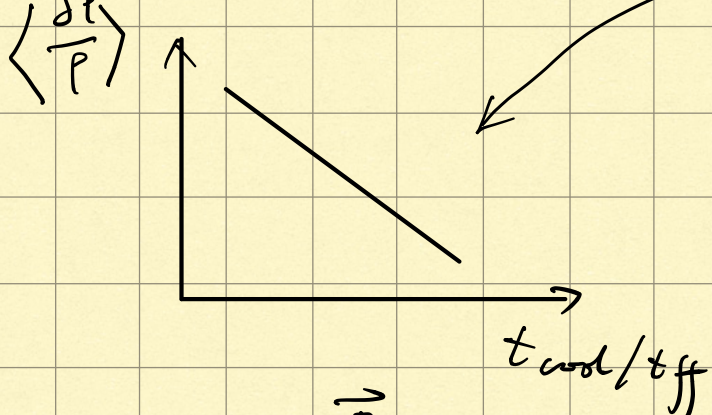
saturation: $t_{cool} \sim t_{grow} \sim t_{damp} \sim \frac{1}{k v_{turb}}$

v_{turb} ← gravity waves driven by buoyancy

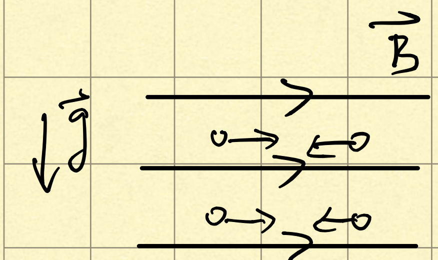


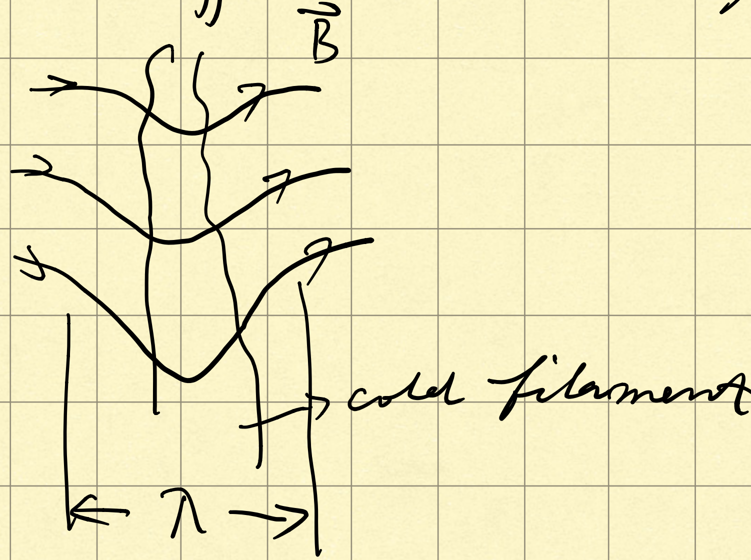


saturation gives: $\frac{\delta\rho}{\rho} \sim \left(\frac{t_{cool}}{t_{ff}}\right)^{-1}$



B tension → suppress buoyant oscillation
→ more thermally unstable
→ more multiphase gas





B tension ~ gravity

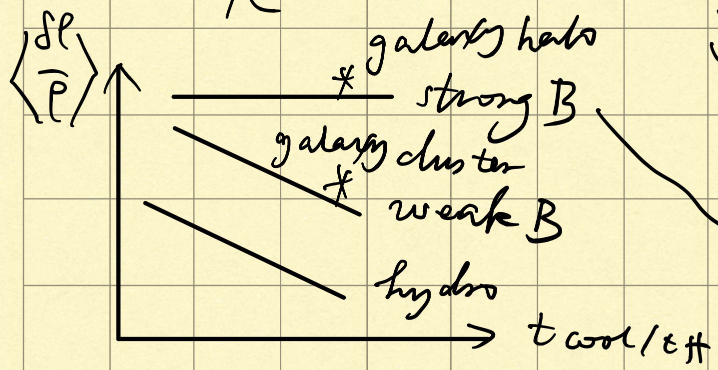
$$\frac{B^2}{\lambda} \sim \delta\rho \cdot g$$

Alfven crossing ~ cooling

$$\frac{\lambda}{v_A} \sim t_{cool}$$

$\Downarrow$

$$\frac{\delta\rho}{\rho} \sim \left(\frac{t_{cool}}{t_{ff}}\right)^{-1} \beta^{-1/2}, \quad \beta \equiv \frac{E_{gas}}{E_B}$$



$v_A t_{cool} \gtrsim R_{halo}$, all modes are thermally unstable!