

possible applications:

KHI in ~~gas~~<sup>SAS</sup> streams (feeding high- $z$  gal.)

- Mandelker + 16, 17. ~~prep.~~
- Padmanabhan + 18
- Anup + 19. ~~prep.~~

$$M_h \gtrsim 10^{12} M_\odot \geq 222.$$

Agenda

(1) Linear KHI

(2) Non-linear KHI

(3) Beyond Adiabatics

$$\text{Pressure Eq.} \Rightarrow \frac{P_s}{P_b} = \frac{T_b}{T_s}$$

$$\delta \equiv \frac{P_s}{P_b} \sim \frac{T_b}{T_s} \sim 100 \quad (10-100)$$

$$M_b = \frac{V_s}{C_b} \sim 1 \quad (0.5-2)$$

$$M_s = \frac{V_s}{C_s} \sim \delta^{\frac{1}{2}} M_b \sim 10 \quad (5-20) \gg 1$$

$\uparrow$   
 $C_s \sim T_s^{-\frac{1}{2}}$

Questions:

(1) Stable? Q. Streams: stable/unstable?

(2) Disruption in halo? Q. Thickness of surviving stream?

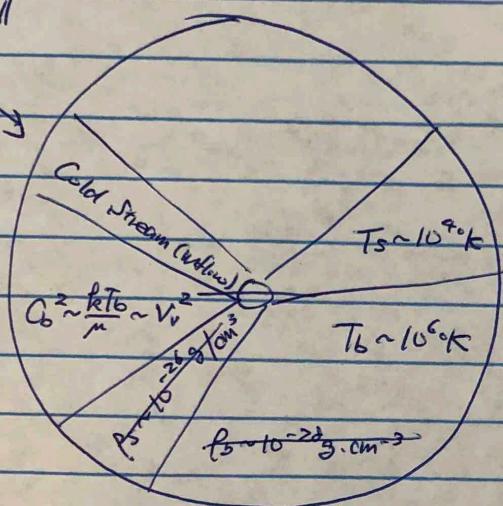
vote!

(3) Gas deposited in CGM?

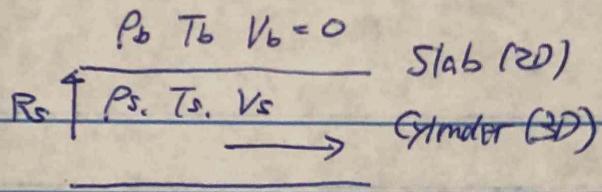
(4) Emissed cooling radiation from dissipation?

Cosmological infall

$$V_s \sim \left( \frac{GM}{Rv} \right)^{\frac{1}{2}} \sim V_v$$



3 timescales



$$t_{sc} = \frac{2R_s}{c_s} \quad \dots \text{stream sound crossing time}$$

$$t_{KH} = w_I^{-1}(\lambda, M_b, \delta)$$

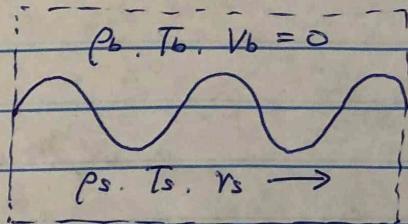
↑  
Imag. comp. of pert wavelength  
dispersion rel.

$$t_v = \frac{R_v}{V_s} \quad \dots \text{vortex crossing time}$$

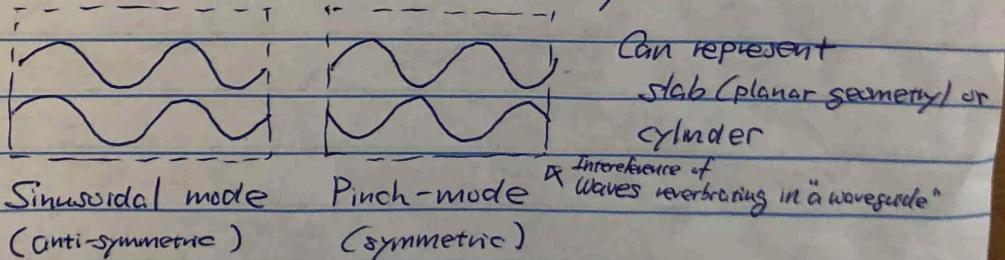
Stream unstable if  $\frac{t_v}{t_{KH}} \gg 1$ .

Nature of instabilities set by  $\frac{t_{sc}}{t_{KH}}$

(1) if  $t_{KH} < t_{sc}$ , 1-boundary instability. (Surface mode)



(2) if  $t_{KH} > t_{sc}$ , 2-boundary instability (Body mode)



Slab: 2 symmetry modes  $\Rightarrow S\text{-mode} \rightarrow P\text{-mode}$

Cylinder: infinitely many symmetry modes defined by the azimuthal wavenumber ( $m$ )  $\Rightarrow \lambda_\phi = \frac{2\pi R_s}{m}, m = 0, 1, 2, \dots$

Incompressible Sheet :  $C_s, C_b \rightarrow \infty$

$$t_{KH} = \omega_I^{-1} = \frac{1+f}{2\pi\sqrt{\delta}} \left( \frac{2}{V_s} \right)$$

Typical stream :

$$\lambda \sim R_s \sim 0.01 R_v$$

$$V_s \sim V_v, \delta \sim 100$$

$$t_v \sim 60 t_{KH}$$

Stream unstable?

Two Complications :

(1) Geometry : Sheet / Slab / Cylinder

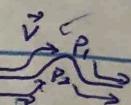
$$(2) Compressibility : \frac{C_b^2}{C_s^2} = \frac{P_s}{P_b} = \delta \quad M_b \sim \frac{V_s}{C_b}$$

$$\Rightarrow \text{unstable if } M_b < M_{crit} = (1 + \delta^{-\frac{1}{3}})^{\frac{3}{2}} \quad \left. \begin{array}{l} \delta = 1 \\ \delta \rightarrow \infty \end{array} \right\}$$

Linear Dispersion Relation :

(1) Sheet  $\rightarrow$  stable if  $M_b > M_{crit}$

(1D)  $\rightarrow$  unstable if  $M_b < M_{crit}$

Bernoulli's principle :   
 $\Rightarrow p_{pert.} \text{ grows!}$   
 Flow can't react & destroy s. perturb.

(2) Slab  $\Rightarrow$  always unstable for all  $M_b$

(2D)  $S^{surface}$ -mode : unstable for  $M_b < M_{crit}$

$B^{body}$ -mode : "  $M_b \gtrsim M_{crit} \quad @ \lambda < \lambda_{crit, n}$

(3) Cylinder  $\Rightarrow$   $S$ -mode is always unstable b/c  $V_s \cdot k = V_s$  (2D)

$V_s \cdot k < V_s$  (3D)  
double infinite seq. of unstable modes for large  $m$

Similar to Slab, except  $(n, m)$  for  $\lambda \approx R_s$

$t_{KH, cyl} < t_{KH, slab}$

for  $\lambda \approx R_s$

In all cases & most of the parameter space,

$$\boxed{\frac{t_v}{t_{KH}} \gg 1} \Rightarrow KH \text{ highly non-linear?}$$

## Non-linear KHI in 3D

Surface mode  $\Rightarrow$  turbulent mixing layer

KH eddies at interface  
penetrate into either medium

$$h(t) = \alpha V_s t \quad \alpha \approx 0.1 \quad \text{dimensionless growth rate.}$$

$t$  only valid length scale!

$\Rightarrow$  creates turbulent mixing zone  
that grows by the meter of  
adjacent eddies

$$\frac{h_b}{h_s} = \sqrt{\delta} \quad h_b + h_s = h = \alpha V_s t$$

(inverse cascade)

$\Rightarrow$  expands into both fluids

$$\Rightarrow \begin{cases} h_s = \frac{1}{1+\sqrt{\delta}} \alpha V_s t \\ h_b = \frac{\sqrt{\delta}}{1+\sqrt{\delta}} \alpha V_s t \end{cases}$$

Stream Disruption when  $h_s \sim R_s \uparrow \Rightarrow t_{\text{disrupt.}} \neq \frac{\sqrt{R_s}}{\alpha V_s}$

$\frac{R_s \text{ max}}{R_v} \sim (0.5 - 5)\%$

Since  $t_{\text{dis}} \propto R_s$ ,  $\frac{t_{\text{dis}}}{t_{\text{vir}}} \propto \frac{R_s}{R_v}$   
There exists a max. ratio  $\frac{R_s \text{ max}}{R_v}$  s.t.  
for  $R > R_s \text{ max}$ ,  $t_{\text{dis}} > t_{\text{vir}}$  Stream survives  
 $R < R_s \text{ max}$ ,  $t_{\text{dis}} < t_{\text{vir}}$  Stream disrupts

Stream Deceleration when  $h_b \sim 2R_s$

$\Rightarrow$  Drag force:  $\dot{V}_s(t)$

$\Rightarrow$  Mass entrainment:  $\frac{\dot{m}}{m} = -\frac{\dot{V}_s}{V_s}$  (momentum conservation)

$\Rightarrow$  Energy dissipation:  $\frac{\dot{E}_{\text{kin}}}{E_{\text{kin}}} = \frac{\dot{m}}{m} + 2 \frac{\dot{V}_s}{V_s} = \frac{\dot{V}_s}{V_s}$

$\Rightarrow$  For cold streams,  $(10 - 50)\%$  of the grav. pot. energy  
gained by falling down the potential well from  $R_v$  to  
 $0.1 R_v$  is dissipated by KHI:  $\Delta E_{\text{KHI}} = (10 - 50)\% E_{\text{stream}}$

$\Rightarrow L_y \propto \text{blobs}$  (if this energy is radiated away  
as  $L_y \propto$ )

Next steps:

(I)  $\vec{B}$  & thermal conduction can stabilize surface modes  
↳ Berlock + 19

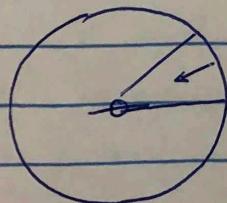
(II) Self-gravity: streams unstable if  $M_L > M_{L, \text{crit}} = \frac{2C_0^2}{G} \rho$   
↳ Aung + 19 (isothermal)

$t_{\text{ff}} \sim 0.6 \frac{r}{v_s} \frac{\rho_s}{0.1} \text{ Ms}^{-1}$  ... collapse time  $\sim$  half of inflow time  
 $M > M_{\text{crit}}(M_b, \delta) \Rightarrow$  stream fragmentation + clump formation in the halo.  
 $M < M_{\text{crit}}(M_b, \delta) \Rightarrow$  KHI disruption

(III) Cooling: important if  $t_{\text{cool, mix}} < t_{\text{disrupt}}$

- delays disruption  $\Rightarrow$  cooling flow onto streams
- mass entrainment  $\uparrow$   $\Rightarrow$  mix. layer expands out into bkg.
- stream deceleration  $\uparrow$
- energy dissipation & radiation  $\uparrow$

(IV) Gravitational potentials of halo & filament



e.g., Coriolis effect in the density stratified medium.