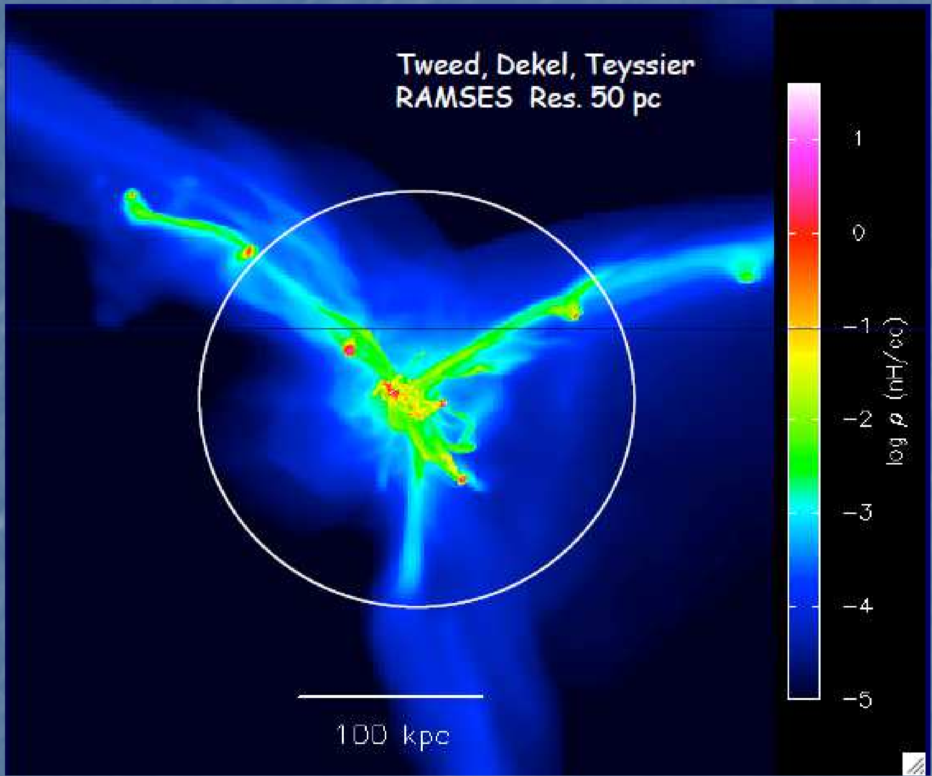
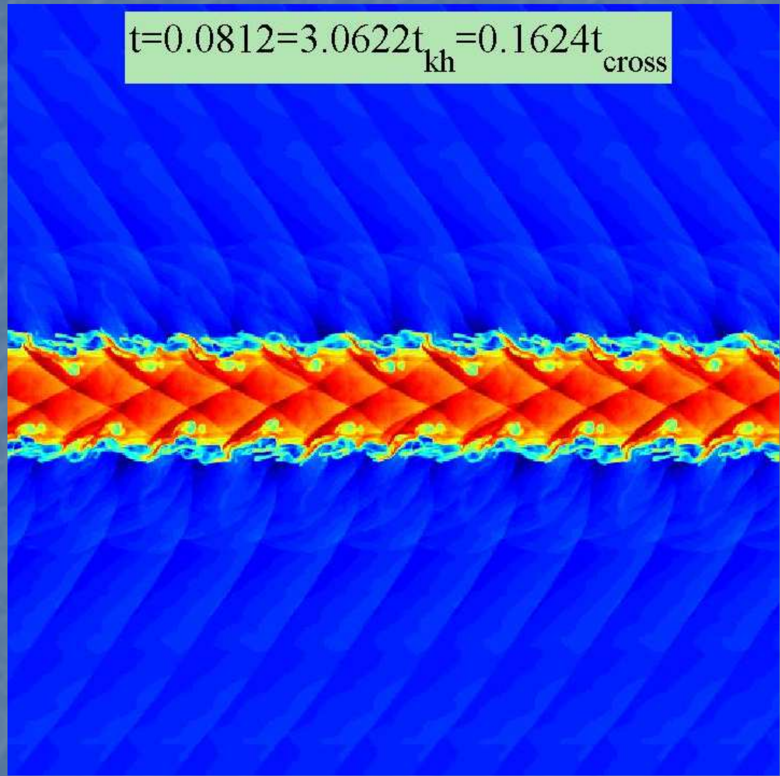
Stability of Cold Gas Streams in Hot Halos





Nir Mandelker, H.U.J.I.

IGM@50, June 08, 2015

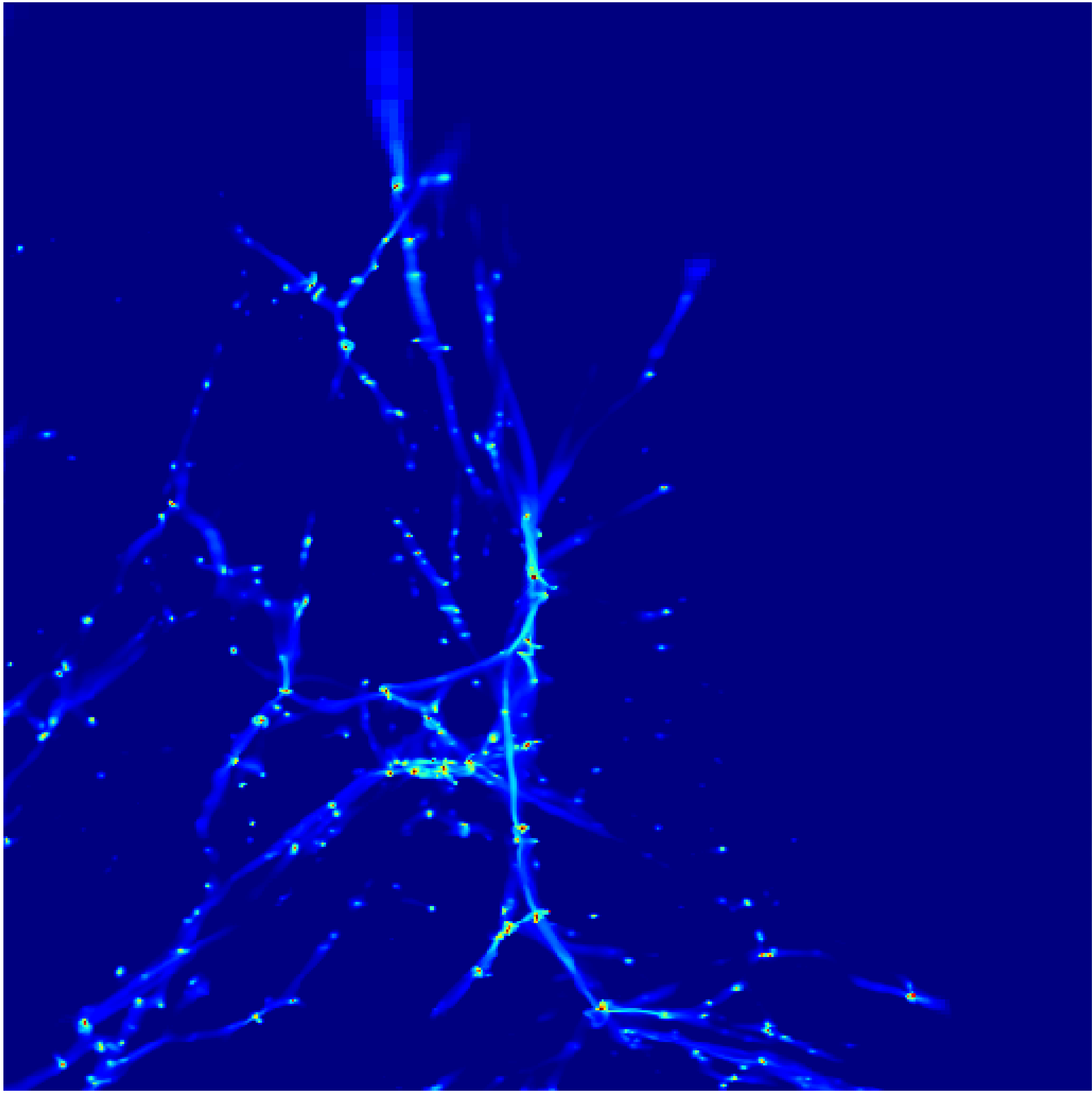
Collaborators

Dan Padnos, Yuval Birnboim, Avishai Dekel

Andi Burkert, Mark Krumholz, John Forbes

The Plan for Today

- Cosmological context (Thanks Avishai!)
- Linear Theory (or everything you wanted to know about Kelvin-Helmholtz instability and were afraid to ask)
- Preliminary Simulations

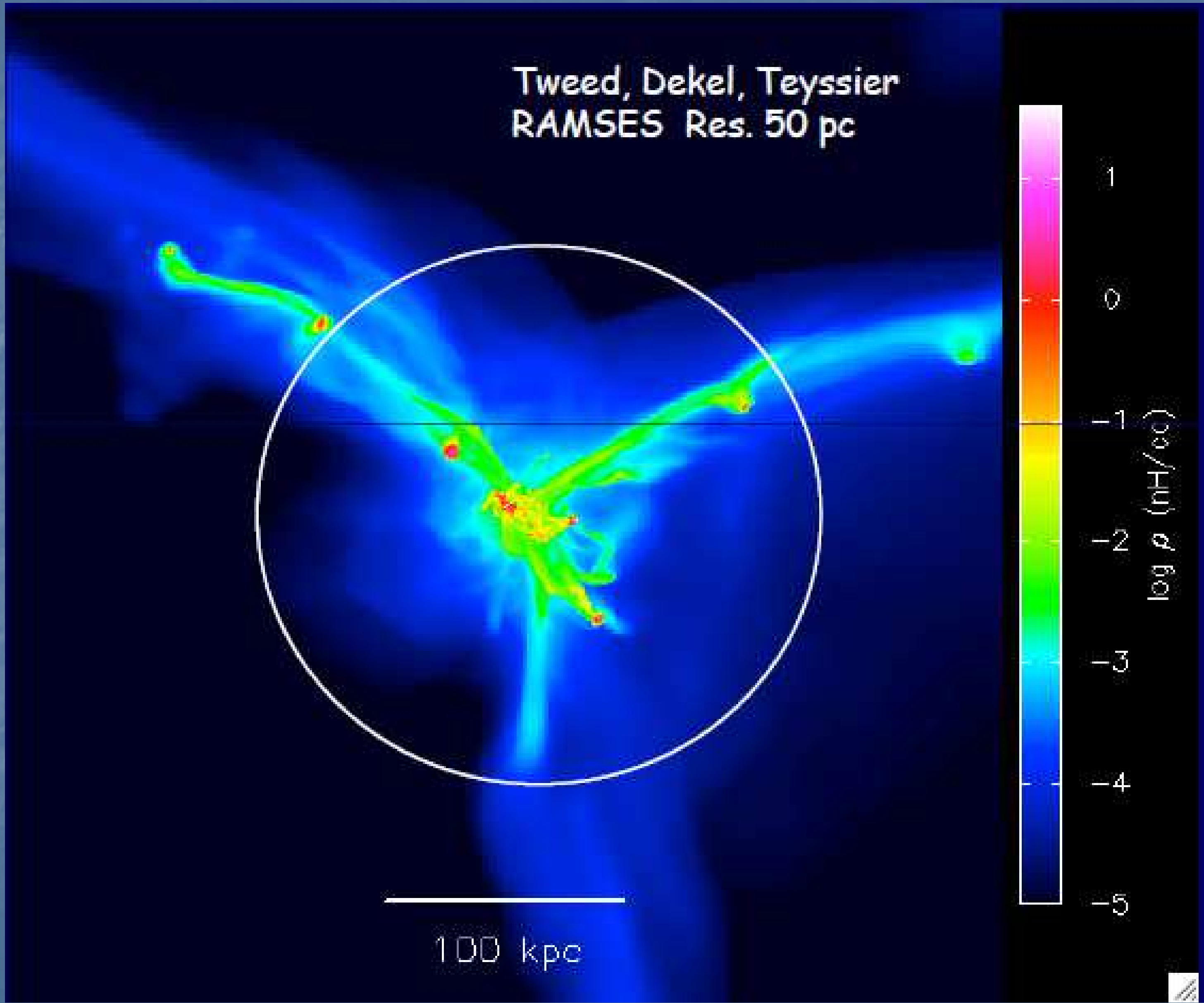


Cosmic-web Streams feed galaxies: mergers and a smoother component

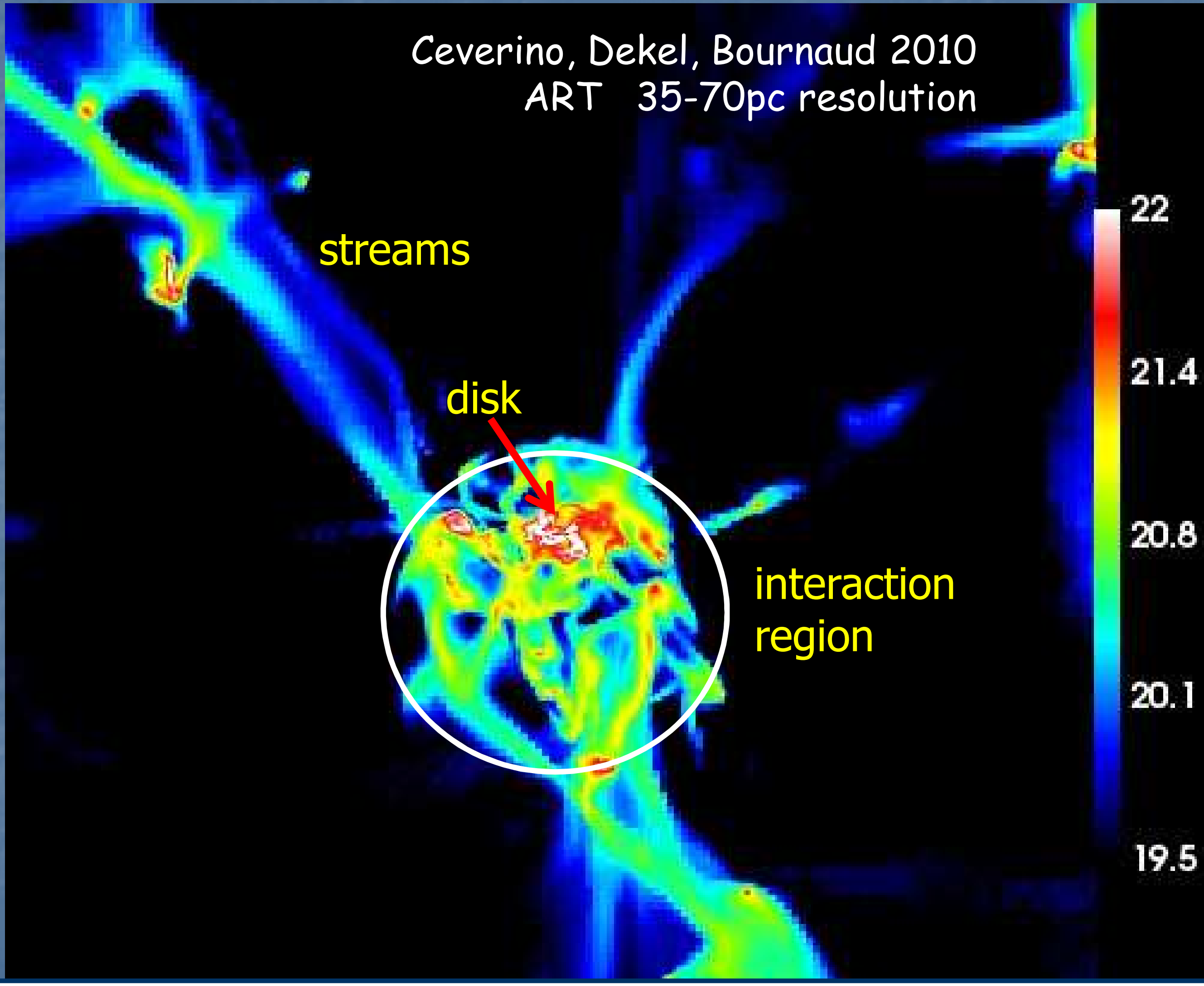
AMR RAMSES
Teyssier, Dekel

box size 300 kpc
resolution 30 pc
z ~ 5.0 – 2.5

Streams feeding a high redshift galaxy



The "Messy" Region



In massive halos, streams may breakup due to shocks, hydro and thermal instabilities, collisions between streams and clumps, heating.

Main Question

Do the streams breakup before they reach the galaxy?

Study growth of various instabilities:

Hydrodynamical: Kelvin-Helmholz instability of dense super-sonic jet in hot medium

Thermal: Clumping due to runaway cooling (seeded by KH eddies?)

Gravitational (external): Rayleigh-Taylor instabilities

Gravitational (self): Local Jeans collapse (seeded by KH eddies?)

External shocks: Richtmyer-Meshkov instabilities in feedback induced shocks

Typical numbers

Stream temperature: $T_s \sim 10^4 - 10^5\ K$

Surrounding temperature: $T_b \sim T_v \geq 10^6\ K\ \ (\mathrm{M_h} \geq 10^{12} M_{\odot})$

Pressure equilibrium: $P_b \simeq P_s$

Density contrast: $\delta \equiv \frac{\rho_s}{\rho_b} \simeq 10 - 100$

Stream velocity: $V \simeq V_v \sim \sqrt{\frac{K_B T_{vir}}{m}} \sim C_b$

Mach number: $\mathrm{M} \equiv \frac{V}{C_b} \sim 1 - 1.5$

Stream radius: $\mathrm{R_s} < 10\ kpc \sim 0.1\ R_v$

Size ratio: $\alpha \equiv \frac{R_s}{R_{vir}} \sim 0.01 - 0.1$

KHI in Planar Geometry

Standard Hydrodynamic Equations

$$\frac{D\rho}{Dt} + \rho\,\vec{\nabla}\cdot\vec{v} = 0$$

$$\rho\frac{D\vec{v}}{Dt} + \vec{\nabla}P = 0$$

$$\frac{DP}{Dt} - c^2\frac{D\rho}{Dt} = 0$$

Unperturbed Solution

$$\rho_0 = \rho_0(z)$$

$$\vec{v}_0 = v_0(z)\,\hat{x}$$

$$P_0 = const$$

Linear Perturbations

$$\rho_1,\ \vec{v}_1,\ P_1$$

$$f_1 = f_1(z)\exp\left[i\left(k_x x + k_y y - \omega t\right)\right]$$

$$\vec{k}\cdot\vec{v}_0 = \cos(\phi)$$

Eigenmodes of the Problem

$\rho_1, \vec{v}_1$ as a function of $\{P_1,\ (\rho_0,\ \vec{v}_0,\ c_0)\,,\ (\omega,\ k)\}$

4 algebraic equations

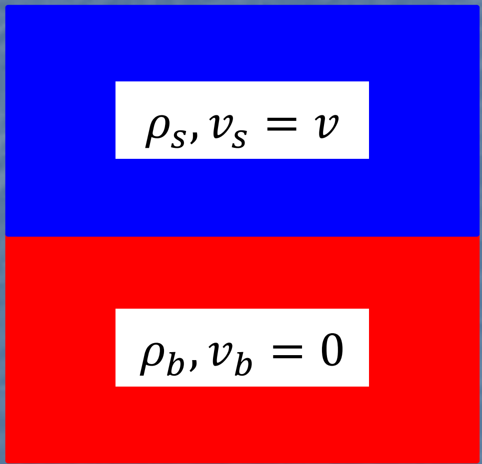
$$P_1'' - \left[\frac{2v_0'}{v_0 - \frac{\omega}{k_x}} + \frac{\rho_0'}{\rho_0}\right]P_1' - k^2\left[1 - \left(\frac{k_x}{k}\right)^2\left(\frac{v_0 - \frac{\omega}{k_x}}{c}\right)^2\right]P_1 = 0$$

1 ODE

Eigenmode equation

(1) Incompressible Sheet, KKHI

Kindergardener's



Incompressible : $c_s, c_b \to \infty$

$$t_{KH} = \frac{1+\delta}{2\pi\sqrt{\delta}} \left(\frac{\lambda}{v}\right)$$

$$\lambda \simeq R_s \simeq 0.01 R_v, \qquad v \simeq V_v, \qquad \delta \simeq 100$$

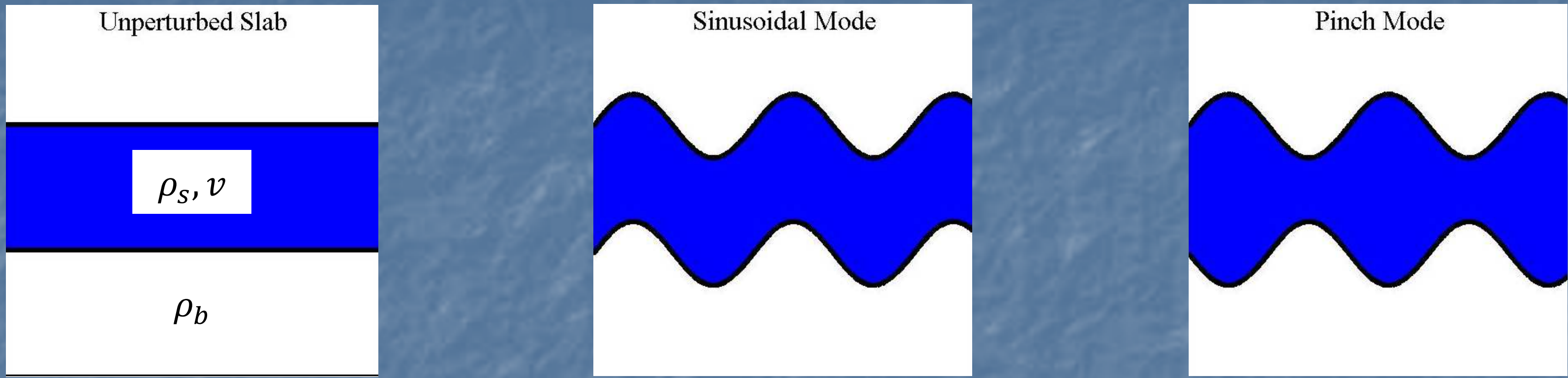
$$t_v \simeq 60 t_{KH}$$

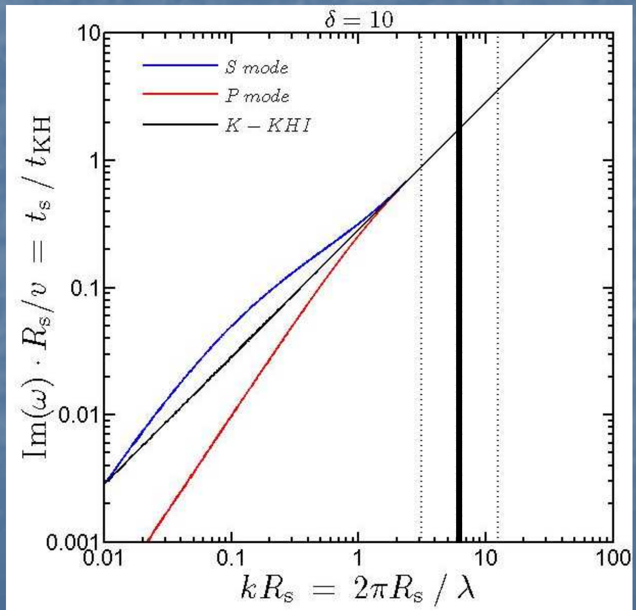
Stream Unstable!

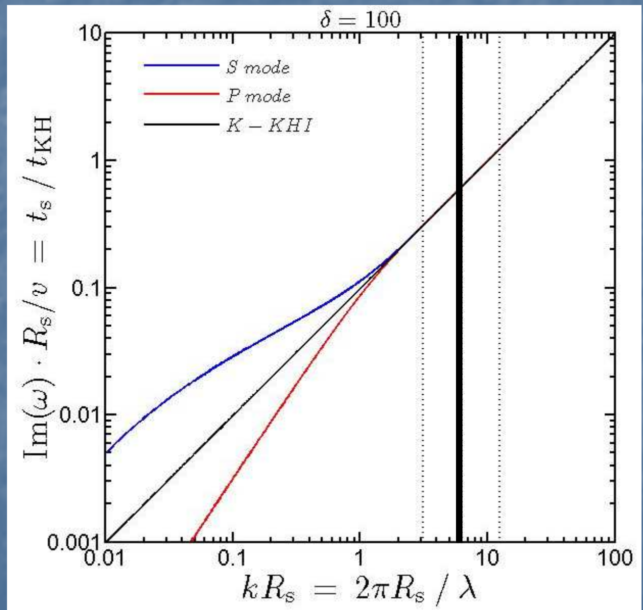
<u>Two complications:</u>

1. Geometry
2. Compressibility

(2) Incompressible Slab





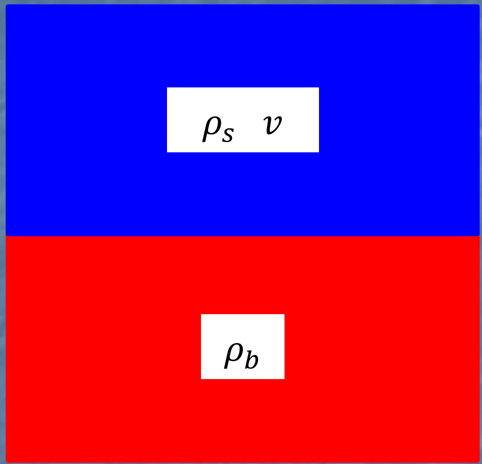


$\lambda \simeq R_s \simeq 0.01 R_v \quad v \simeq V_v$
$\delta \simeq 100$

$t_v \simeq 60 t_{KH}$

Stream Unstable!

(3) Compressible Sheet



Compressible: $\frac{c_b}{c_s} = \sqrt{\delta}$

$\mathrm{M} \equiv \frac{v}{c_b}$

$\delta \simeq 100 \quad M = 1.0$

Stream Unstable

$\delta \simeq 100 \quad M = 1.5$

Stream Stable

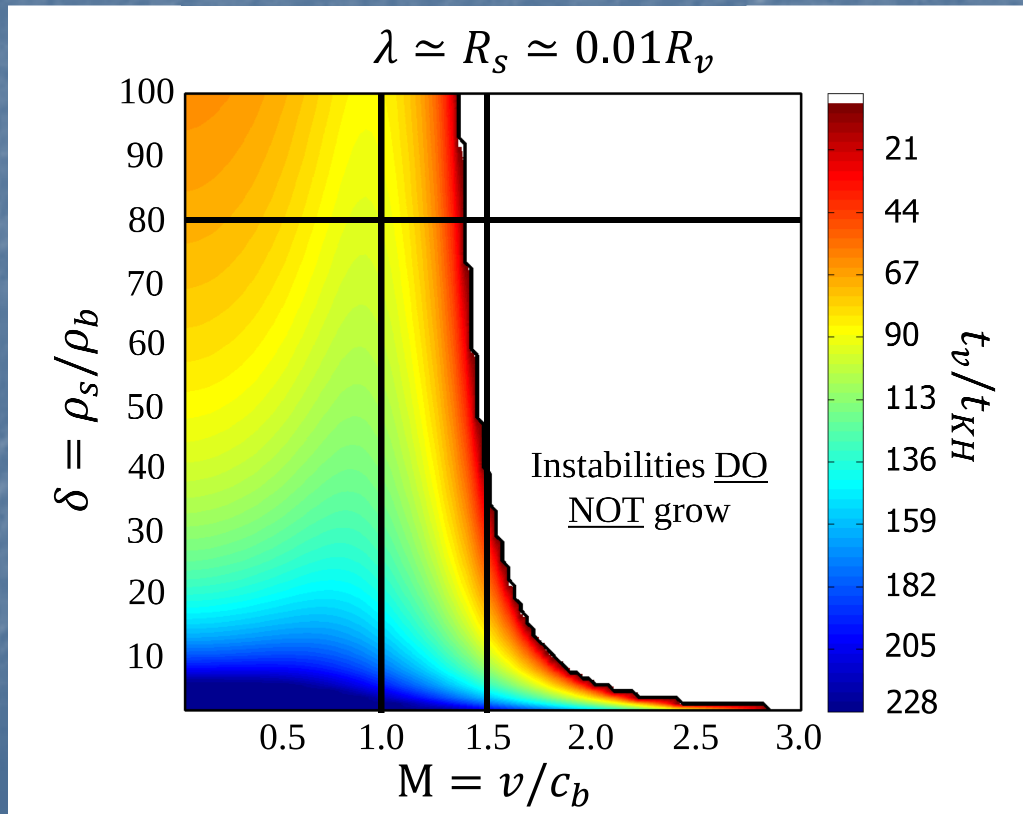
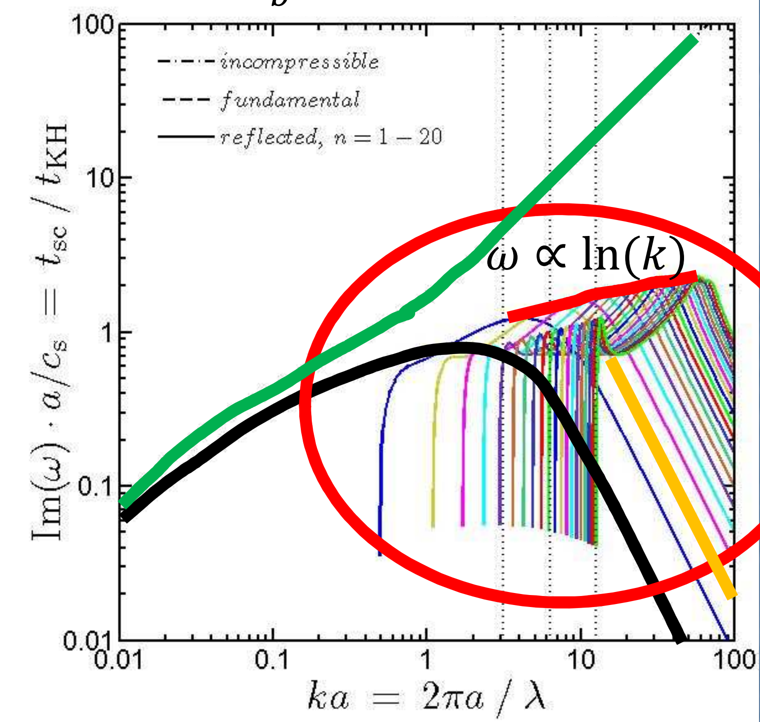


Figure by Dan Padnos

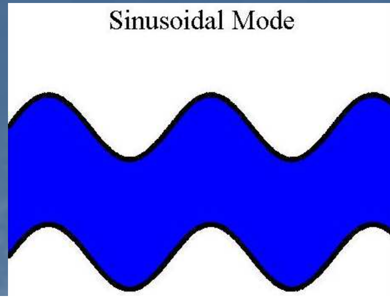
(4) Compressible Slab

$M_b = 1.5 \quad \delta = 100$

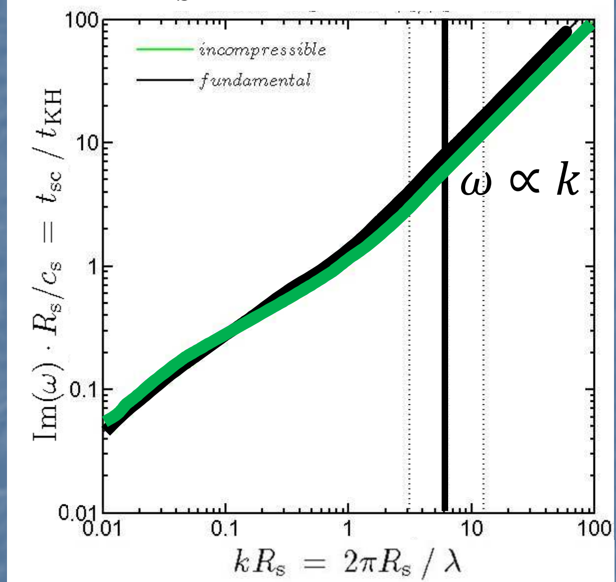


Each mode decays as $\lambda \to 0$ since sheet is stable

Beware: Non-linear coupling of modes?



$M_b = 1.0 \quad \delta = 100$



Fundamental Mode: Any values of M_b and δ and all wavelengths

$\lambda \simeq R_s \simeq 0.01 R_v$ $\quad t_v \simeq 60 t_{KH}$

Reflected Modes: Only when

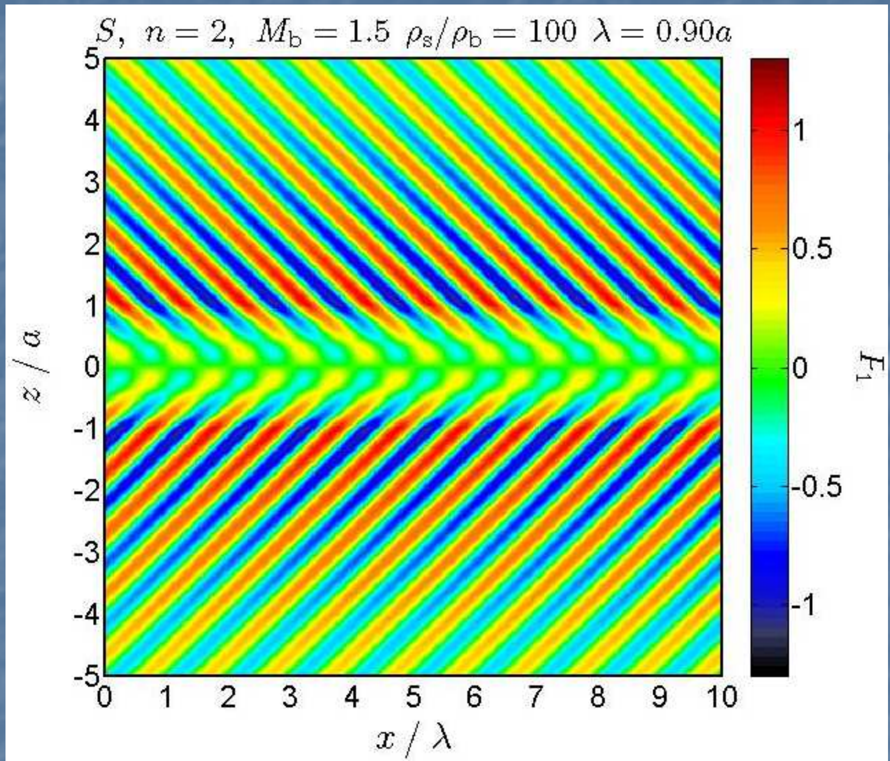
$\mathbf{v} > \mathbf{c_b} + \mathbf{c_s}$

Critical wavelengths

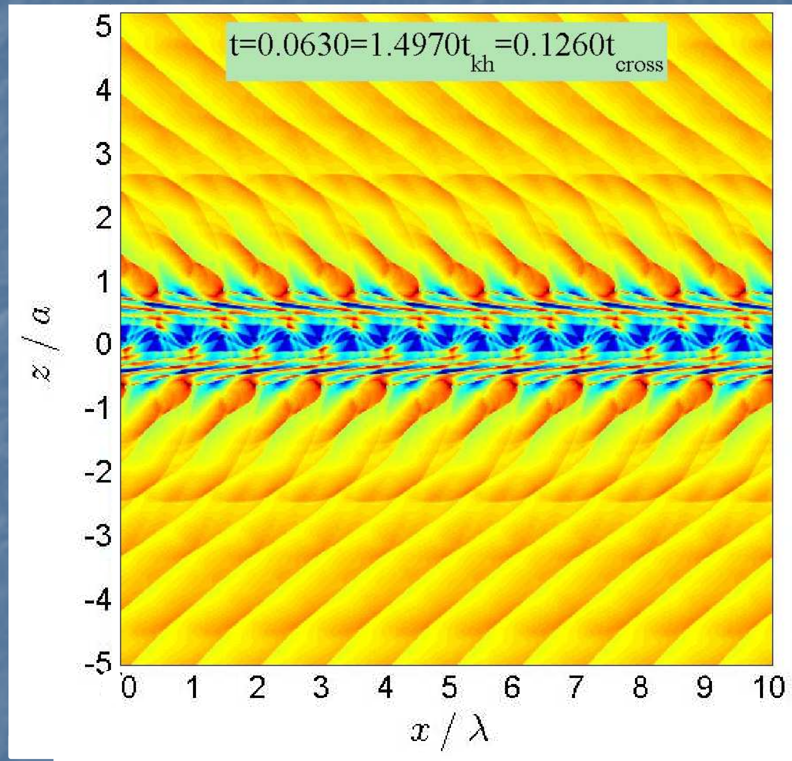
$\lambda \simeq R_s \simeq 0.01 R_v$ $\quad t_v \simeq 10 t_{KH}$

$\lambda \simeq R_s \simeq 0.1 R_v$ $\quad t_v \simeq t_{KH}$

Reflected mode at Resonance



Analytic



Simulation (RAMSES)

Pressure waves are reflected off the jet boundary

Constructive interference at resonance

Propagation angle $\sin(\theta) \simeq \frac{1}{M_b}$

(5) Compressible Cylinder

See also (e.g.) Birkinshaw 1984; Payne & Cohn 1985; Hardee & Norman 1988; Bodo + 1994
Analysis of hot jets in cold backgrounds

- Axisymmetric modes nearly identical to (P) modes in slab
- Additional non-axisymmetric modes have comparable growth rates. Additional coupling?

The Importance of Eigenmodes

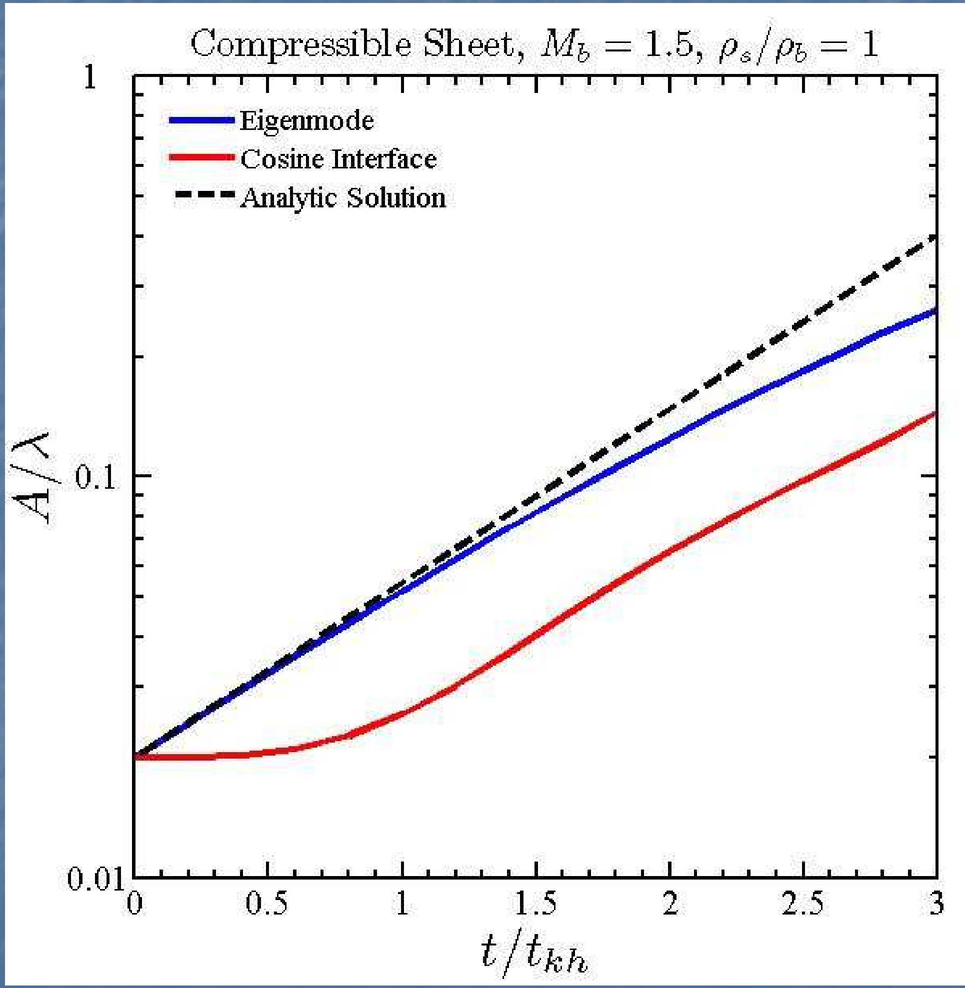


Figure by Dan Padnos

Eigenmodes **<u>DO NOT</u>** span all possible initial conditions

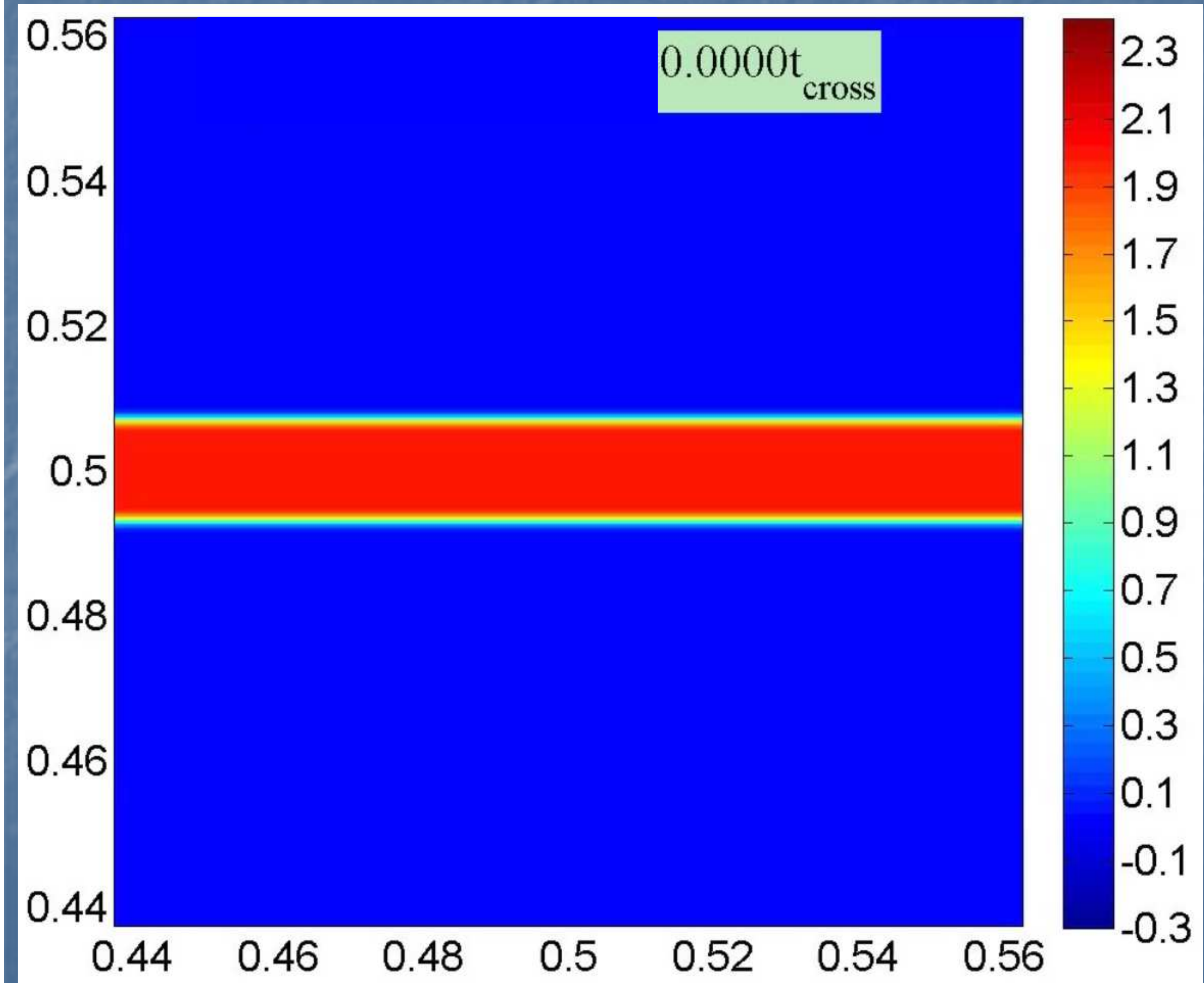
When comparing growth rate in simulations to linear theory, **<u>MUST</u>** use eigenmode perturbations

<u>Random IC must either:</u>

- Decay into eigenmodes + additional waves
- Go non-linear first

$M = 1.5\ \delta_\rho = 100\ R_v = 80\lambda = 160R_s$

(non-eigenmode)



$t_{cross} = t_v$

Summary and Outlook

First step in systematic study of instabilities in cold, supersonic streams penetrating hot halo

Conclusions

KHI – more complicated than you thought! (Not for kindergardeners)

Reflected modes dominate instability of supersonic jet

Cold flows in virial halos: Parameters are right at the boundary between two phases of instability – fast and slow

Immediate term:

Quantitative analysis of non-linear evolution with simulations

Stream disruption, mass flux / energy / momentum decrease

Eigenmode vs non-eigenmode ICs

Medium to long term:

Add cooling, gravity (convection, magnetic fields...) and study other instabilities

THANK YOU!!