Role of parasitic instabilities in creating the turbulent corona

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Outline

Some of my thoughts on turbulence from MHD waves

Wave turbulence or parasitic instabilities

Modelling turbulence from parasitic instabilities

Some lessons from hydrodynamic Kelvin-Helmholtz instability

A case study of parasitic instability decaying MHD turbulence

A look at MHD kink waves and the Kelvin-Helmholtz instability

Thoughts on how all this may relate to solar wind turbulence

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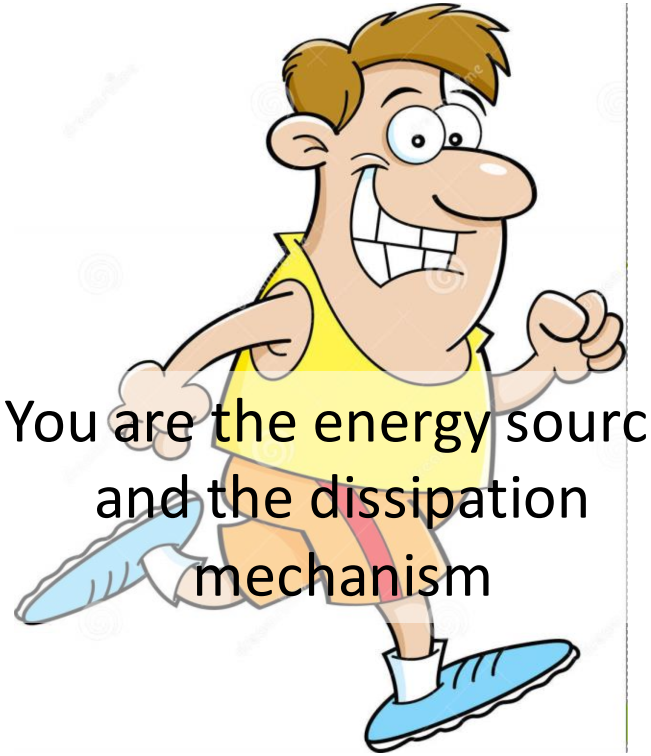
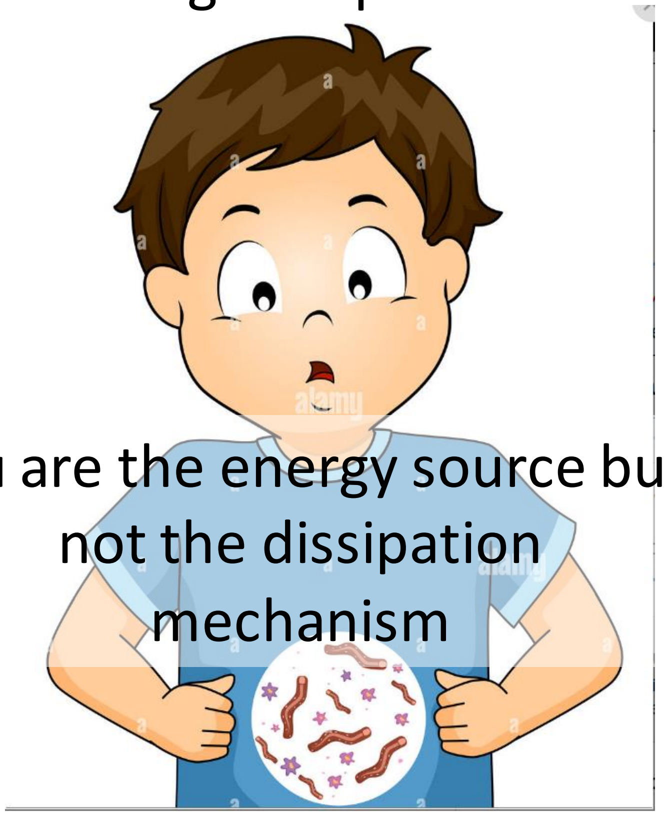
An Aside: Two possible ways to eat what you want but not gain weight

Exercise



You are the energy source and the dissipation mechanism

Ingest a parasite



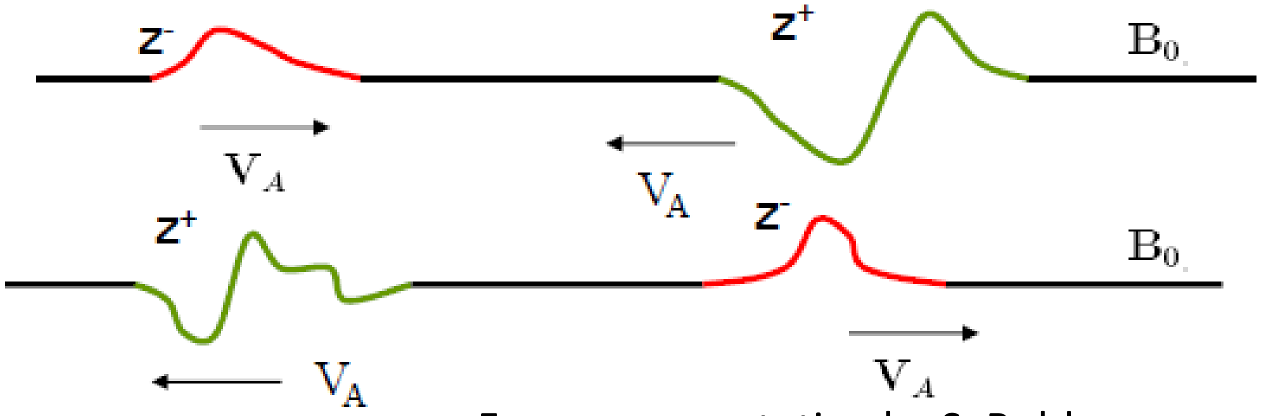
You are the energy source but not the dissipation mechanism

Though both methods will have (some) similar results, the process is very different so we’re likely to need different models

Wave turbulence in MHD

In wave turbulence the waves are the energy source and the cascade mechanism.

For example, if two nonlinear Alfven waves interact, though no energy is transferred or dissipated, the shape of the wave packet changes



From a presentation by S. Boldyrev

We can simply think of 2 regimes for this MHD turbulence:

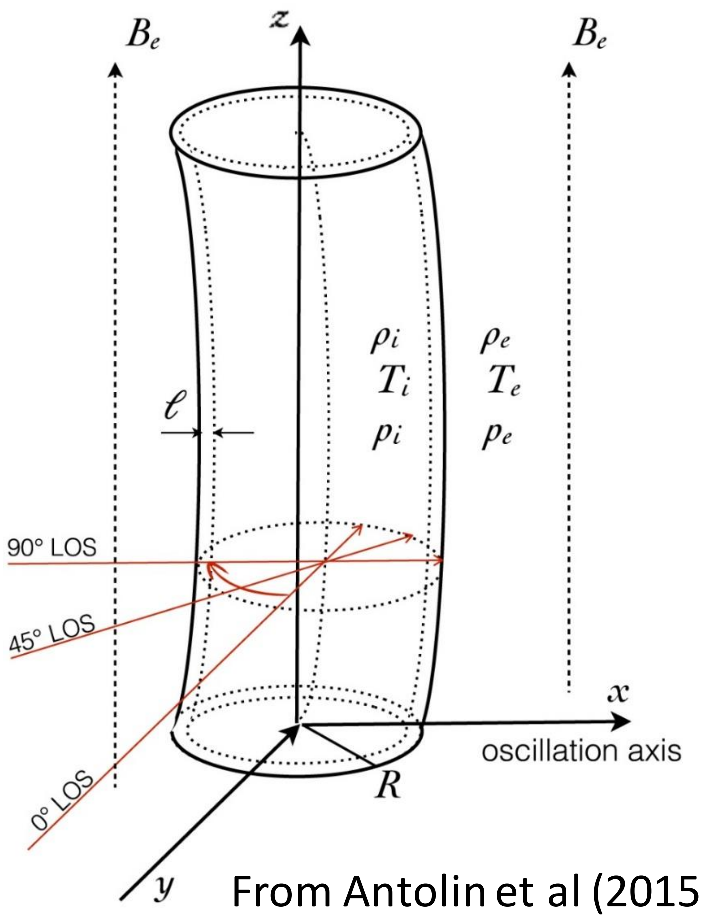
$B_0 \gg b$ and $B_0 \sim b$

These are referred to as weak and strong turbulence

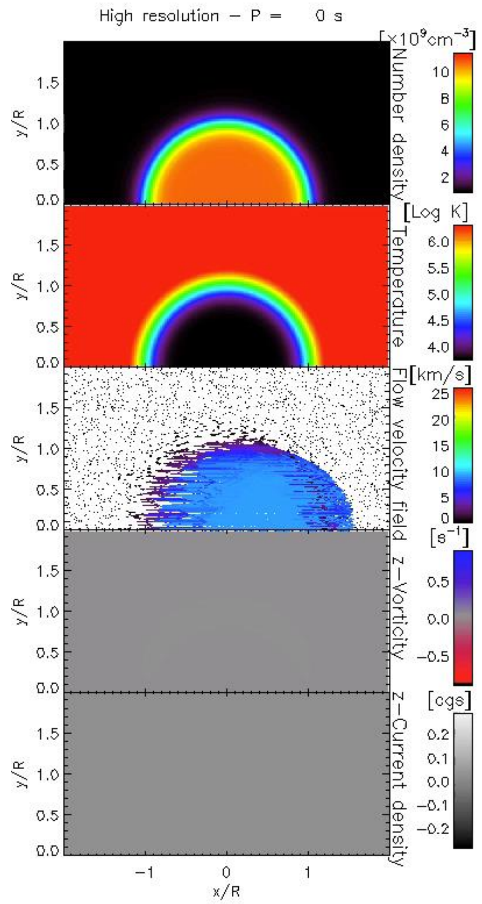
Parasitic-instability turbulence on MHD waves

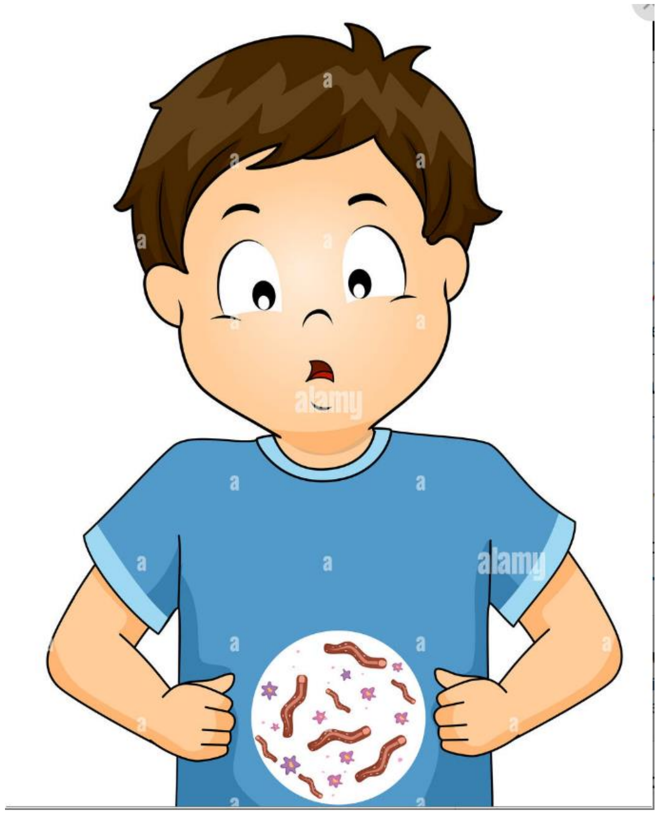
Here the waves are just the energy source, but not the mechanism for energy cascade or dissipation.

Scales that grow are not fixed by the scales of the wave itself.



From Antolin et al (2015)

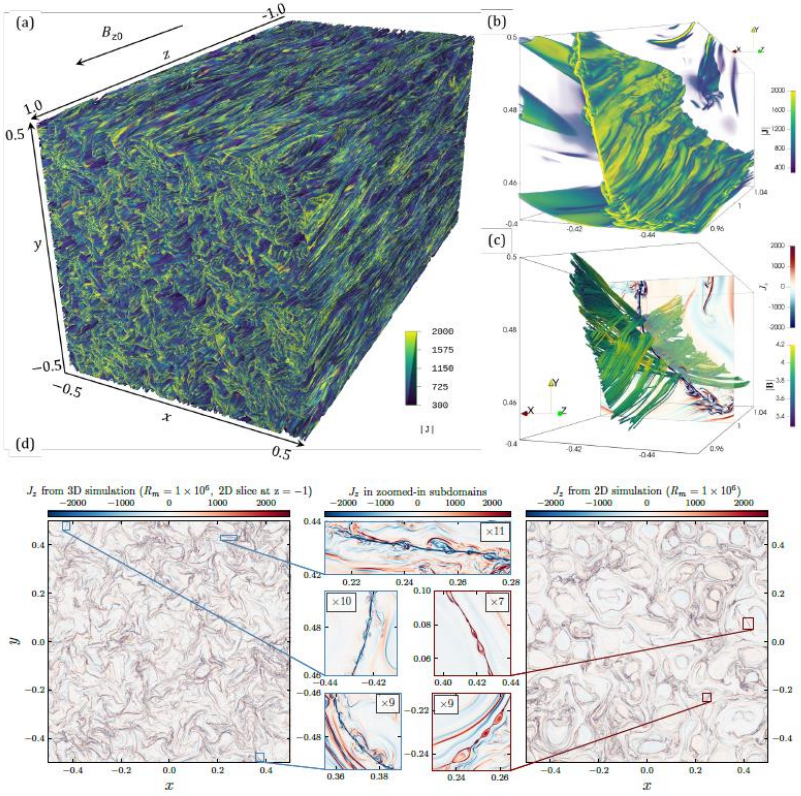




Can’t be modelled as wave-wave interaction or self-interaction of a wave

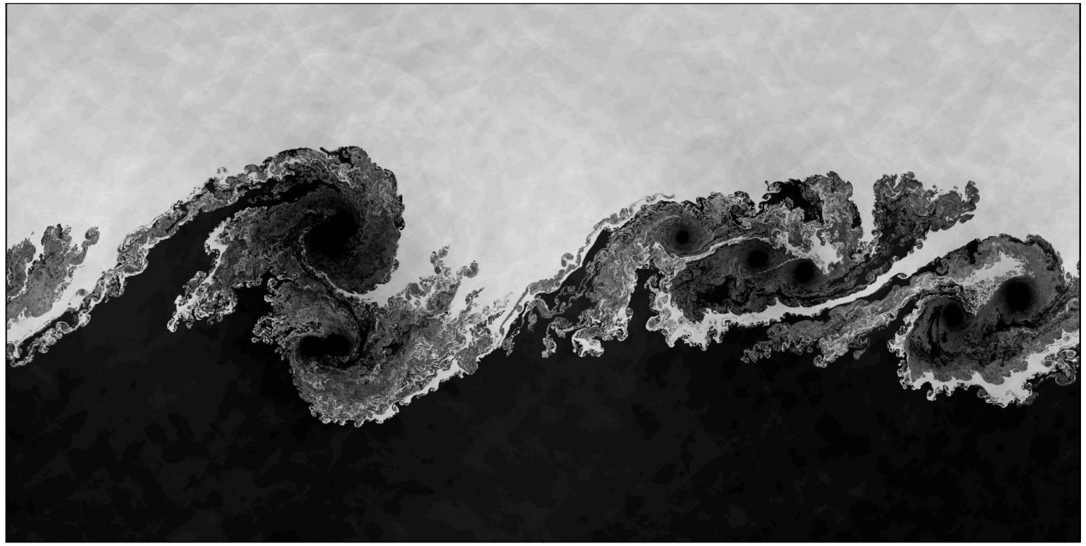
Some instabilities that can be parasitic

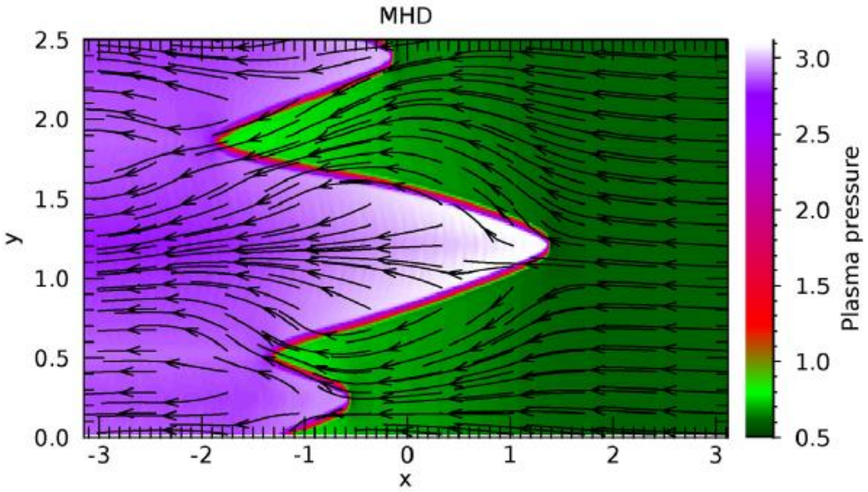
Tearing instability



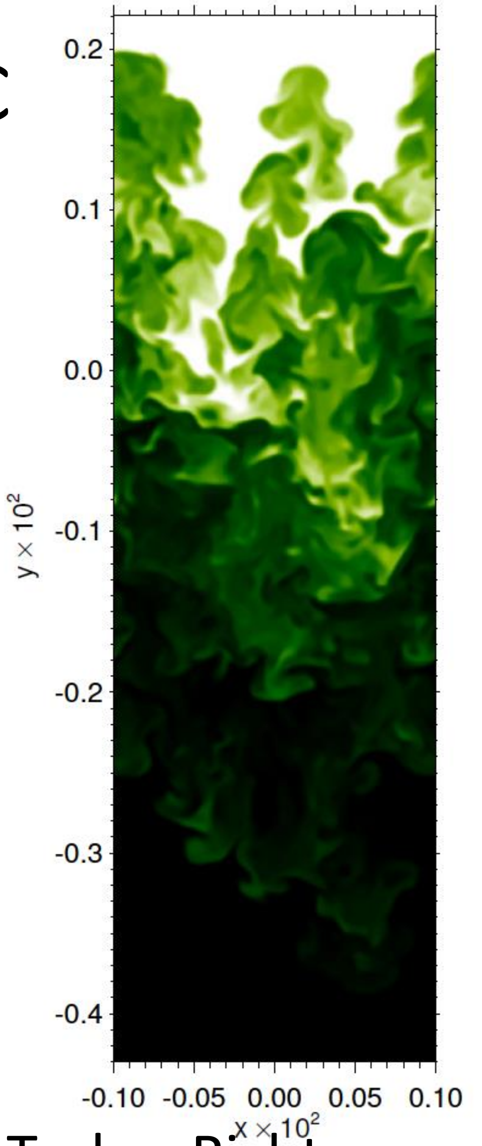
Dong et al (2022)

Kelvin-Helmholtz and other shearflow instabilities





Corrugation instability



Rayleigh-Taylor, Richtmyer-Meshkov and other baroclinic instabilities

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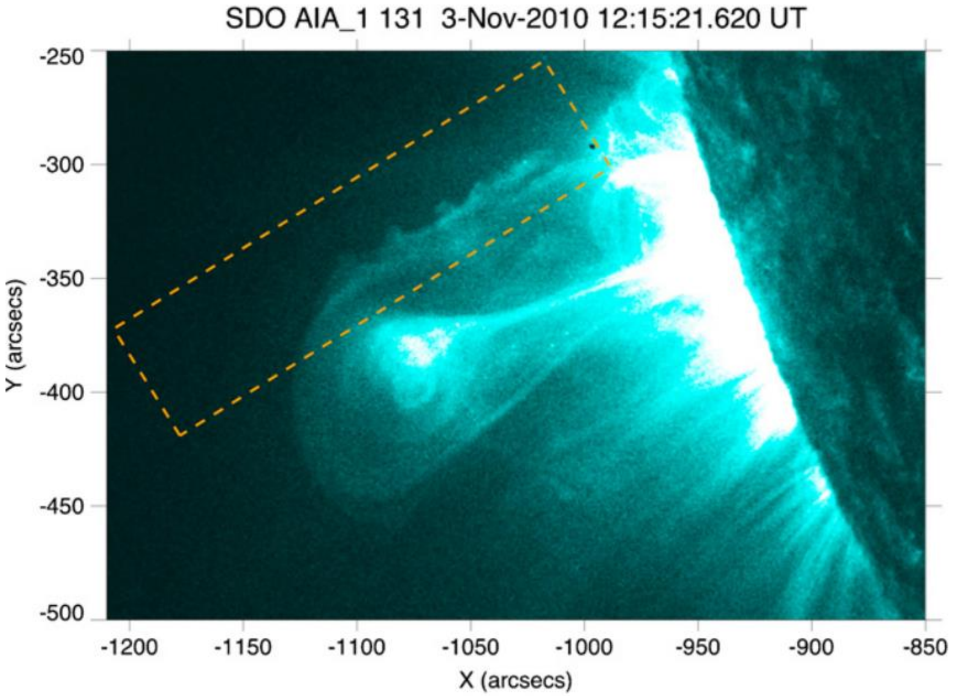
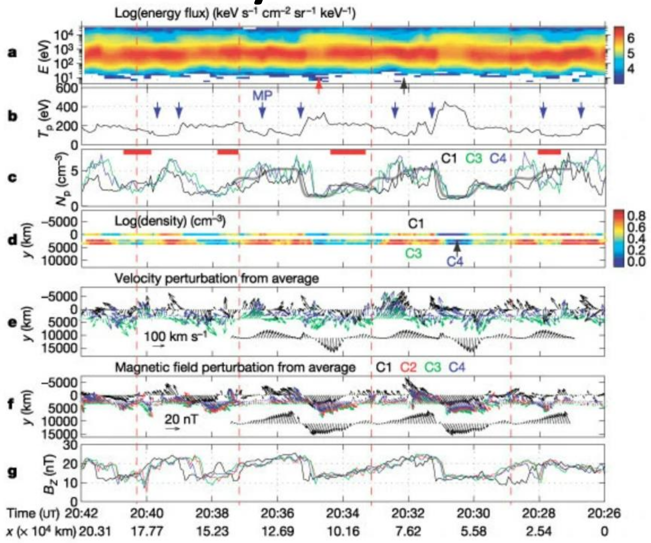
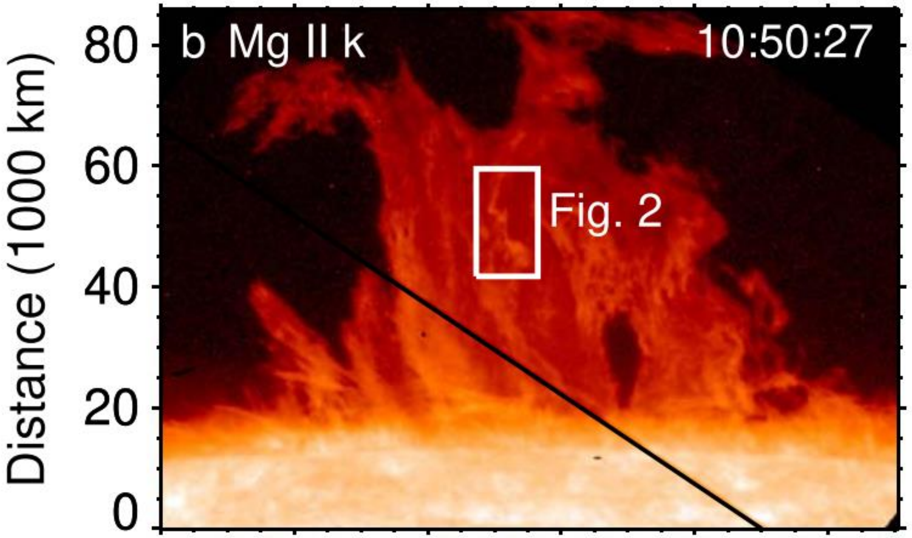
Kelvin-Helmholtz instability in the Heliosphere



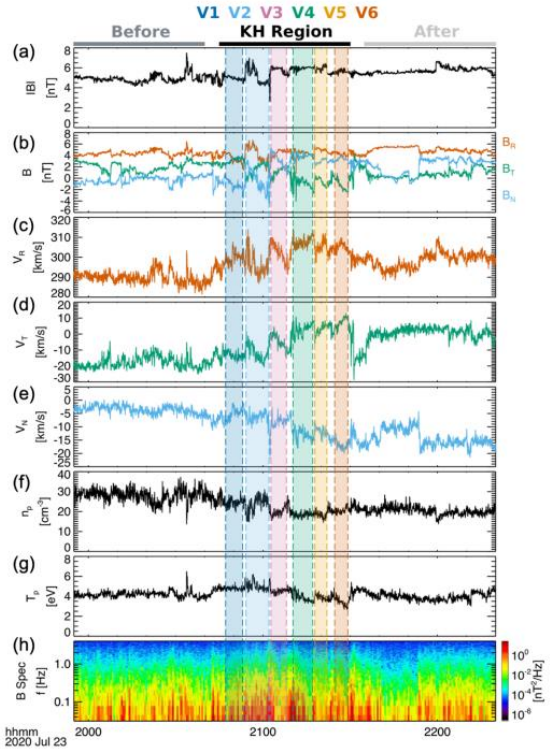
KHi on a CME flank(Foullon et al 2011)



KHi in magnetosphere (Hasegawa et al. 2004)

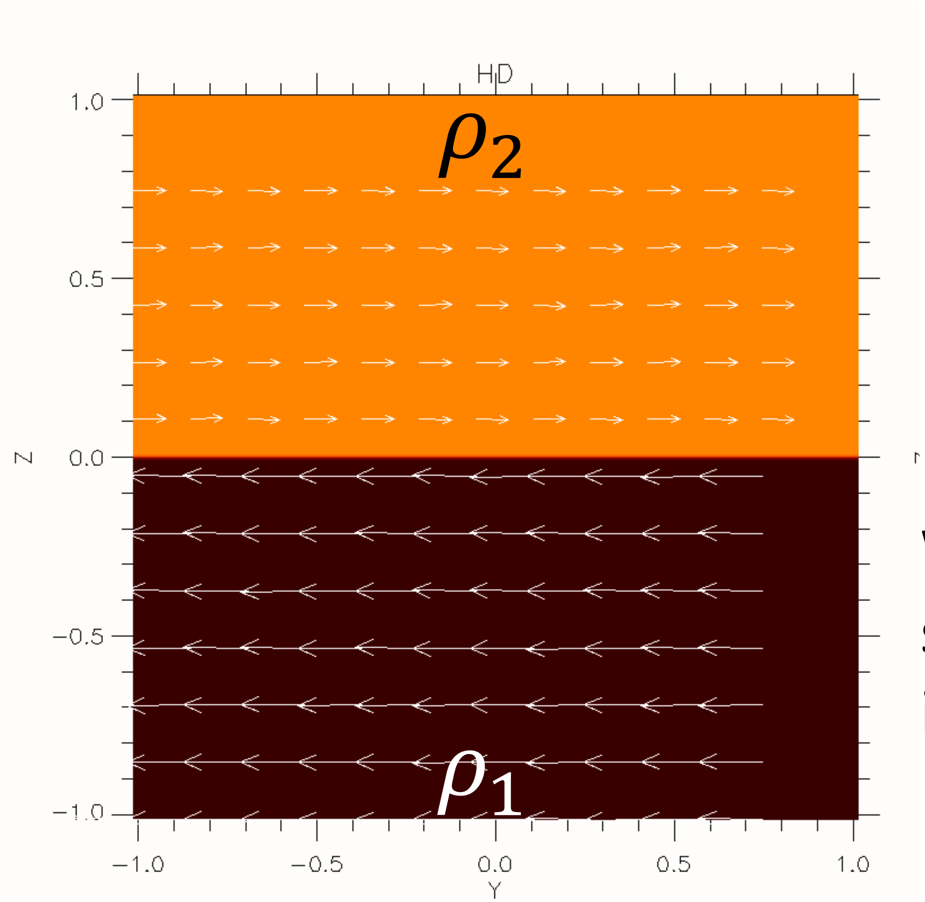


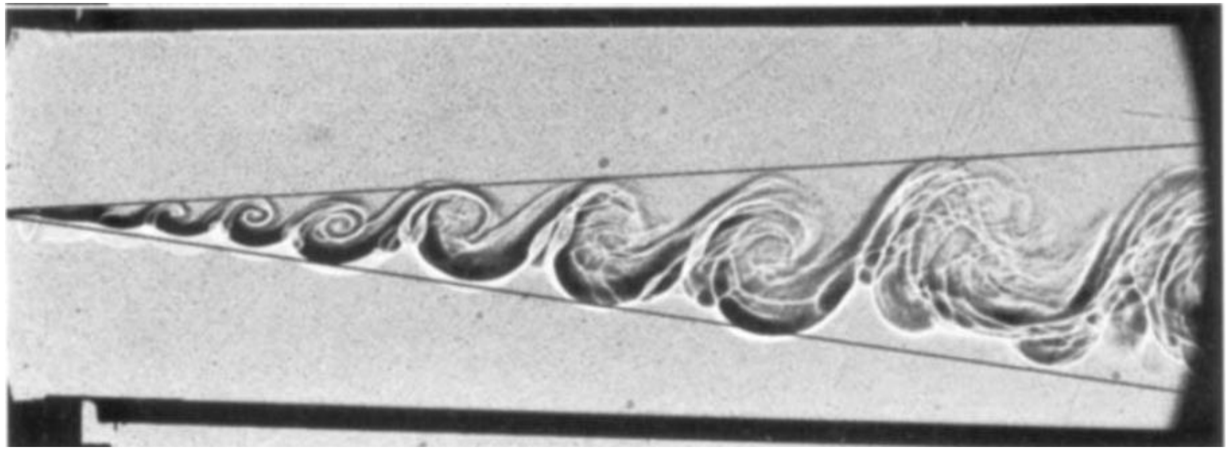
In solar prominences (Hillier & Polito 2018)



KHi in the solar wind (Kieokaew et al. 2021)

Nonlinear KHi mixing – Lessons from hydrodynamics





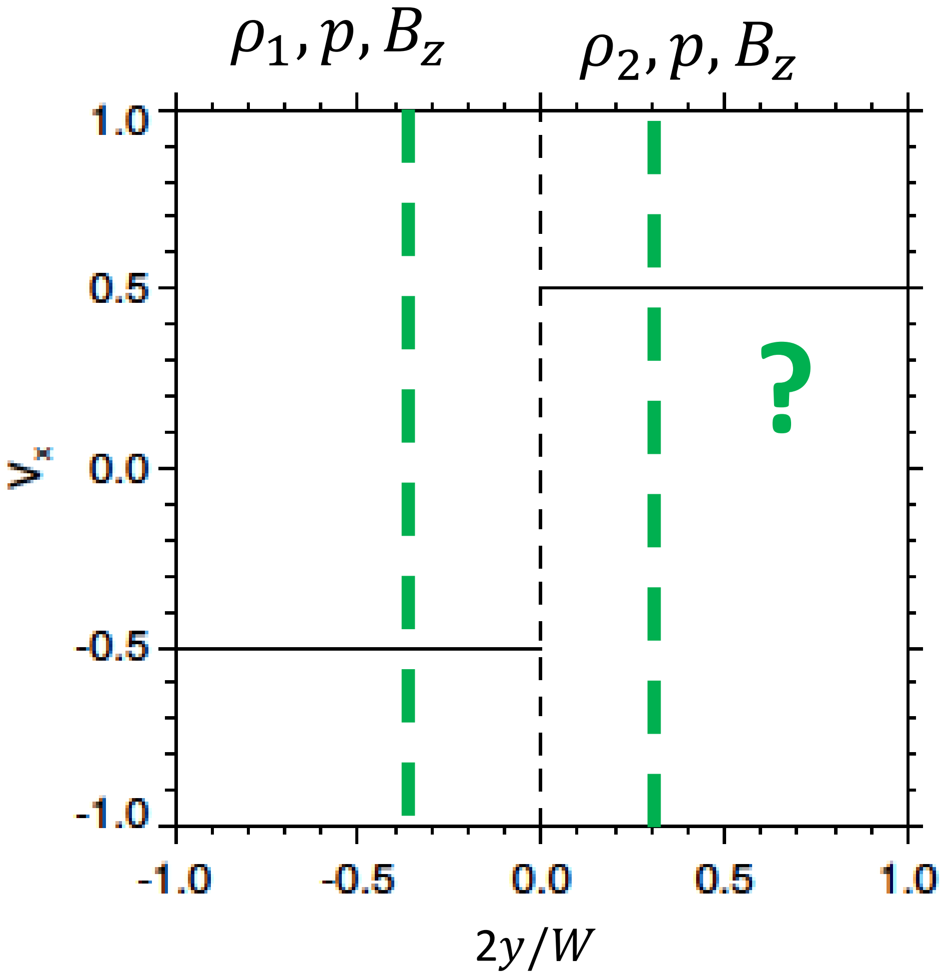
Self-similar mixing layer growth from experiments (Brown & Roshko 1974)

We know from hydrodynamic experiments and simulations that the nonlinear development of the KHi is a self-similar evolution (e.g. Winant and Browand 1974) with the mixing layer thickening as:

$$W \propto C(\rho_1, \rho_2)\Delta V t$$

Different C values have been found. For example ~0.18 for quasi 2D dynamics (Brown & Roshko 1974) to ~0.11 in 3D simulations (Baltzer & Livescu 2020). But these change with density contrast!

My basic turbulence model (in the self-similar frame)



Note I only care about the large scale response to the turbulence, so don't have any detailed model of the turbulence itself

We look at the nonlinear behavior a shear-layer with uniform quantities in each layer (a very simplified model to look at the problem).

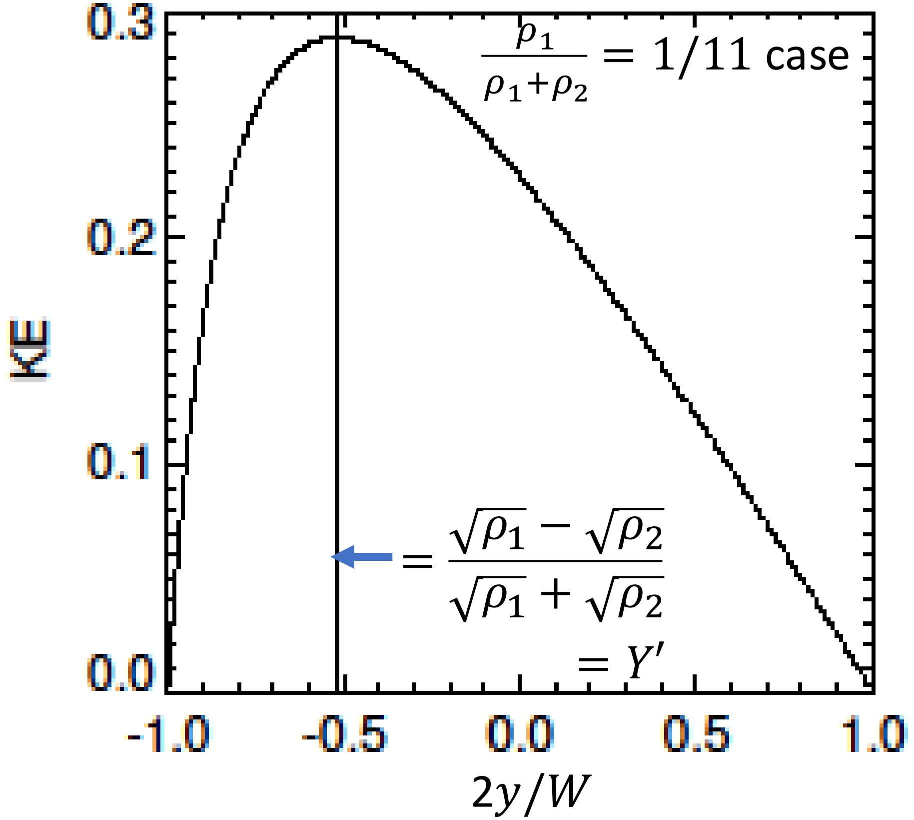
Here we assume that the shear layer does become turbulent.

The first question we have to answer is: where is the mixing layer placed?

Calculating characteristic quantities

The key parameter we have to optimize for the layer position is the free energy available to drive the turbulence.

Basic concept is that turbulence is hungry for energy so works to extract as much as it can

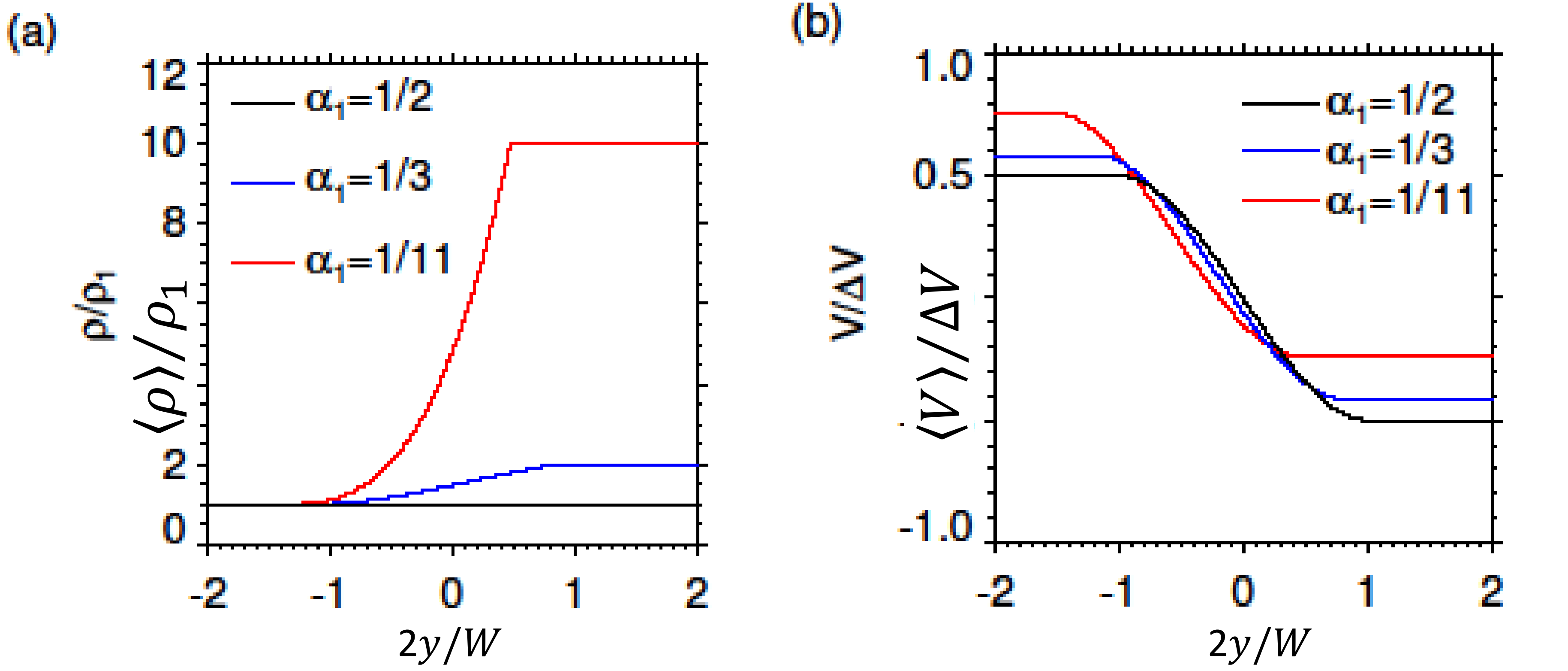


Once the layer positions is know, conservation laws give characteristic values of physical quantities in the mixing layer.

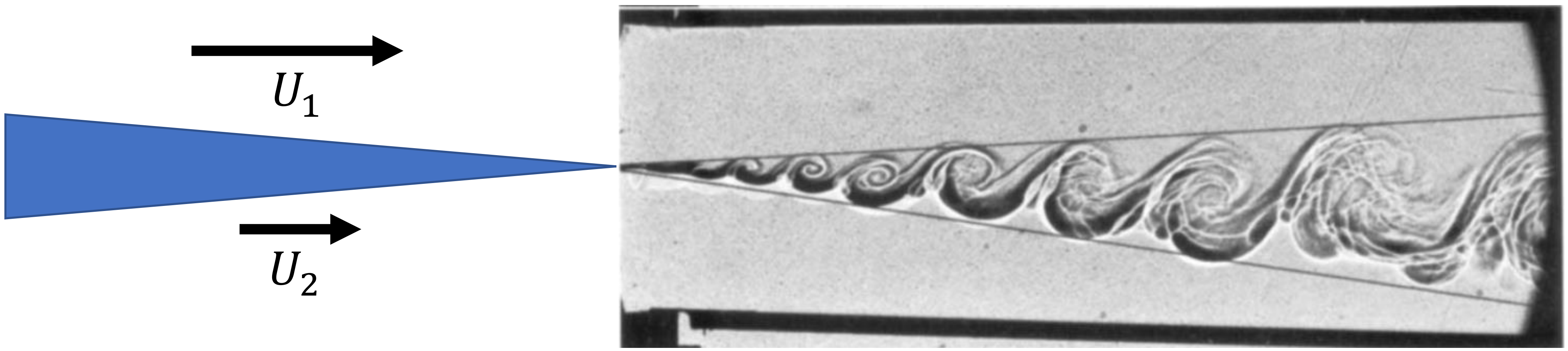
$\rho_{mix} = \sqrt{\rho_1 \rho_2}$, $\qquad T_{mix} = \sqrt{T_1 T_2}$.

Modelling the ⟨ ⟩ distribution

Beyond the characteristic quantities of the layers, it is also possible to create approximate distributions for the x-z averages of the physical quantities (again through conservation laws and maximizing the energy extracted from the flow with some conditions)



Self-similar mixing model



Self-similar mixing layer growth from experiments (Brown & Roshko 1974)

The model I have just described predicts that the RMS of the fluctuating velocity component scales as

$$V_{\mathrm{RMS}} = \frac{1}{\sqrt{2}} \frac{(\rho_1 \rho_2)^{1/4}}{\sqrt{\rho_1} + \sqrt{\rho_2}} \Delta V$$

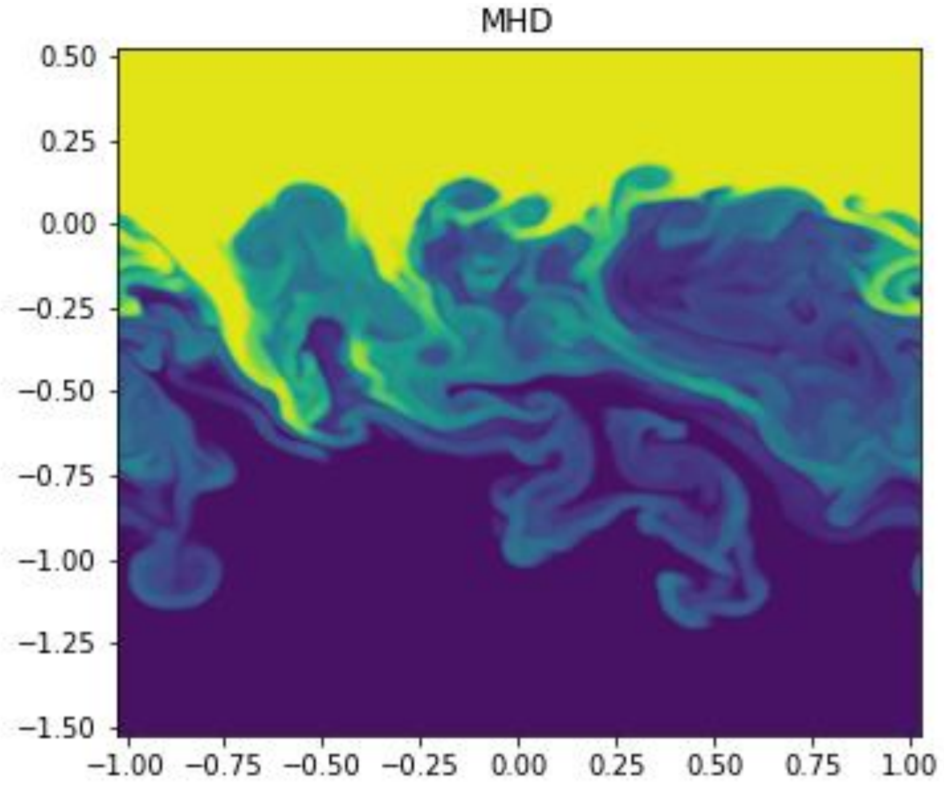
Using this we can (through dimensional analysis) update our self-similar model for the mixing layer width

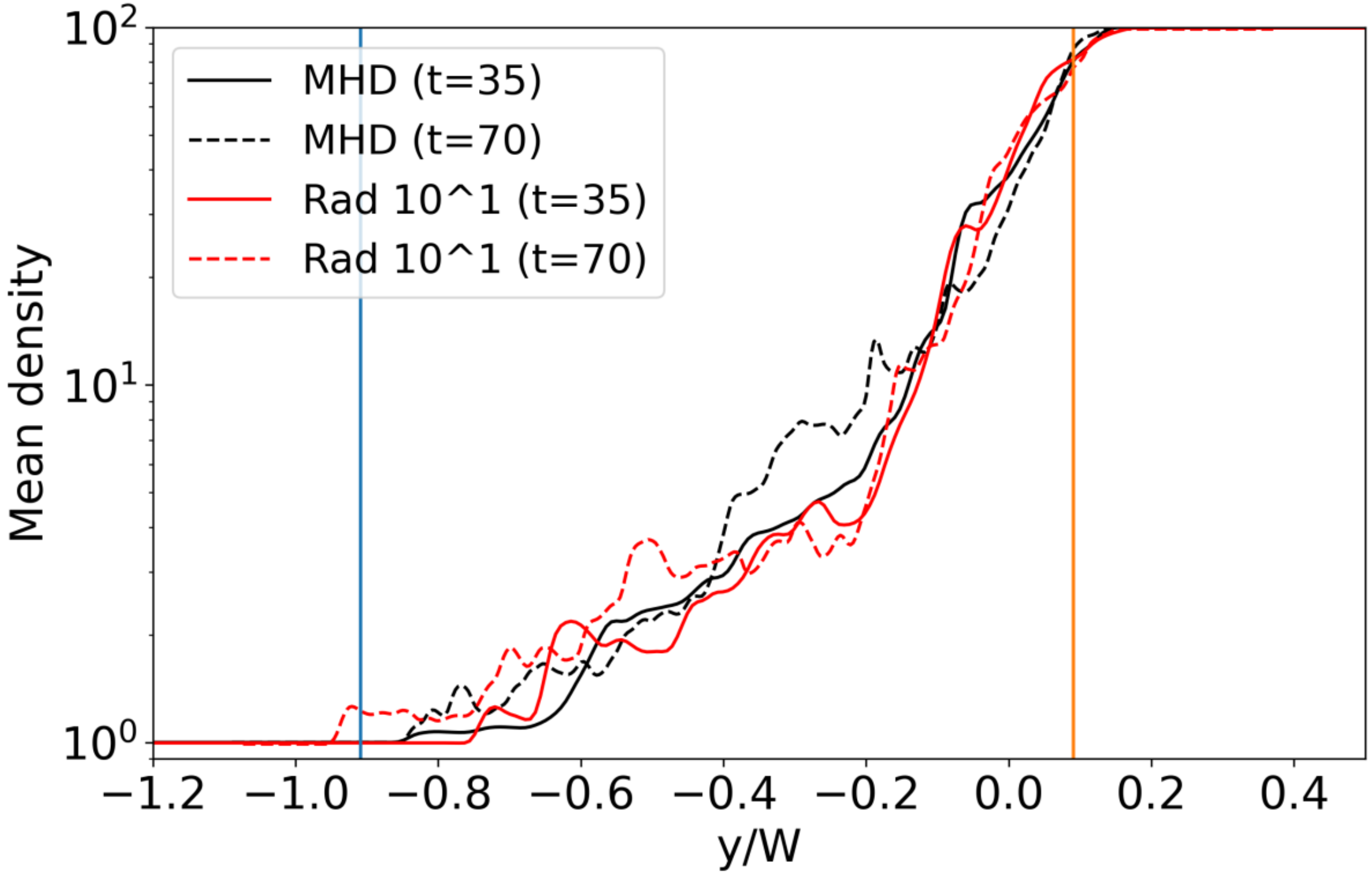
$$W = \frac{C_1}{\sqrt{2}} \frac{(\rho_1 \rho_2)^{1/4}}{\sqrt{\rho_1} + \sqrt{\rho_2}} \Delta V t,$$

So does my mixing model work?

Mixing layer for 2D, span-wise magnetic field, super-sonic, low-beta mixing layer. Mixing layer bounds are nicely modelled using $C_1 = 0.5$

Density





Also successful in reproducing internal structure of 3D MHD mixing layer (Hillier and Arregui 2019)

What are the fundamentals of these processes

Driven by instabilities, so this always requires inhomogeneities (in density, pressure, velocity, magnetic field). These may be created by other turbulence or exist already in the background

The turbulence that develops is a nonlinear process that does not get fixed at particular scales by linear instability physics, but can grow and decay in both scale and intensity with time.

Self-similar evolution is a characteristic of this process.

Big question is: does this self-similar mixing process work in more complex systems (e.g. oscillating loops)

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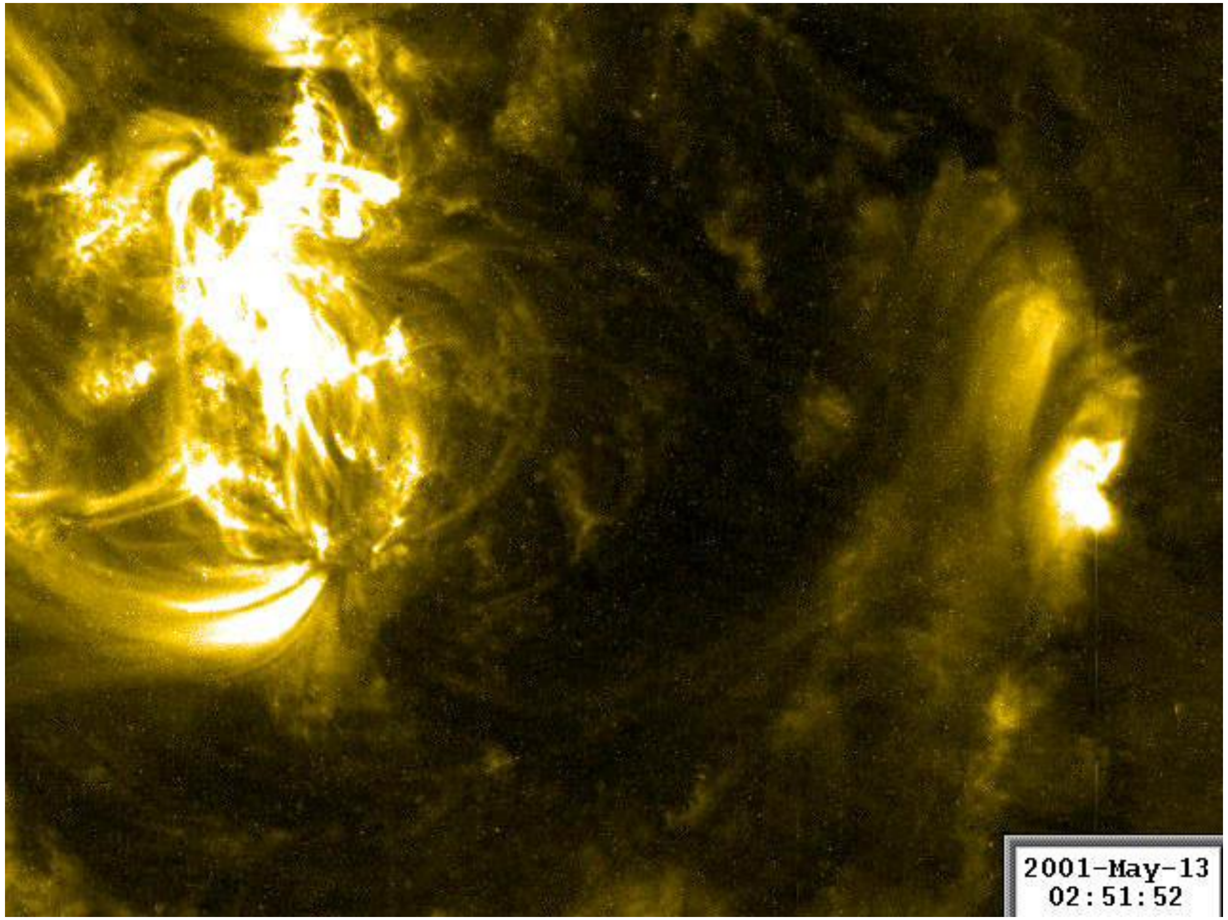
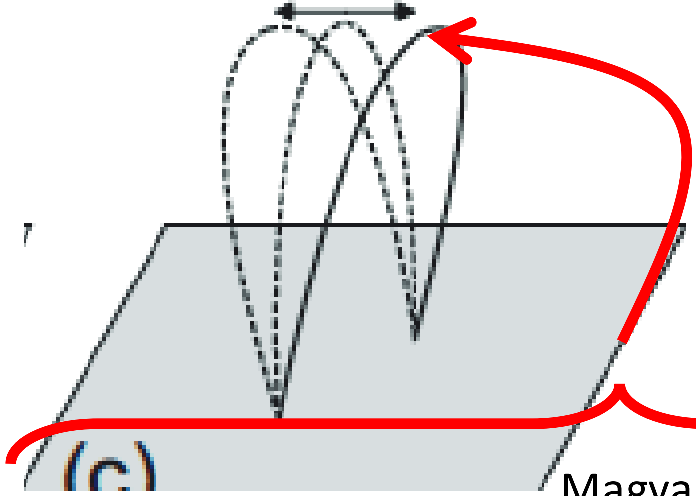
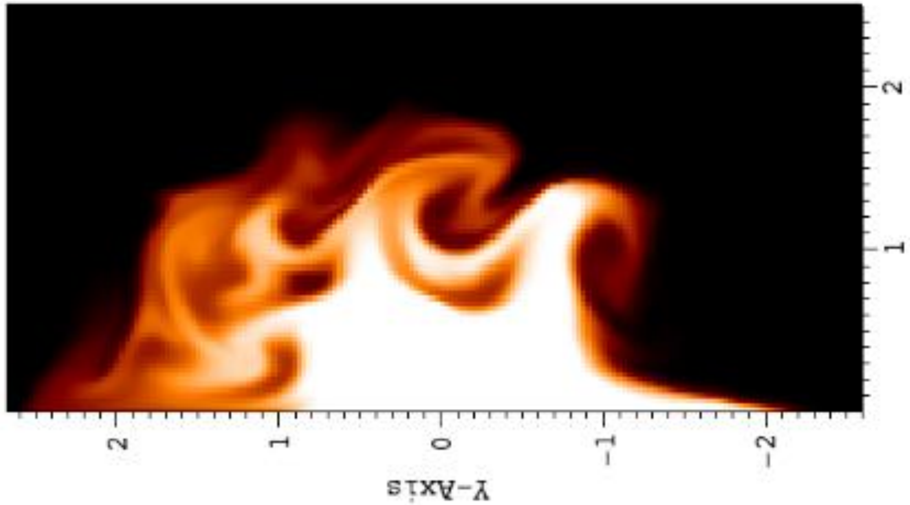
Kink waves and the Kelvin-Helmholtz instability





Instability creates turbulence at apex

Magyar et al 2016



Interest in these oscillations as the decay profile is used to infer information on the coronal magnetic field, and they could be contributing to the heating of the corona

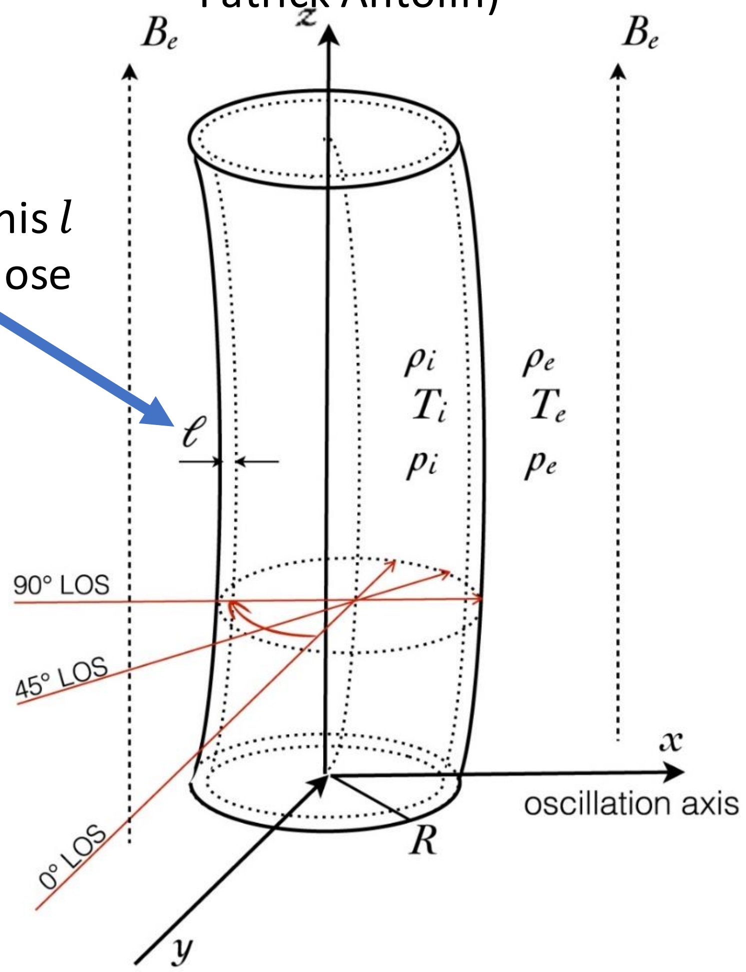
Self-similarity in wave-excited Kelvin-Helmholtz instability

Problem setup (stolen from Patrick Antolin)

Hypothesis

MHD-wave-driven Kelvin-Helmholtz turbulence can also have a self-similar evolution with turbulent layer growing $\propto t$ (until the whole system has reached the limits of its turbulence development)

I take this l to be close to 0

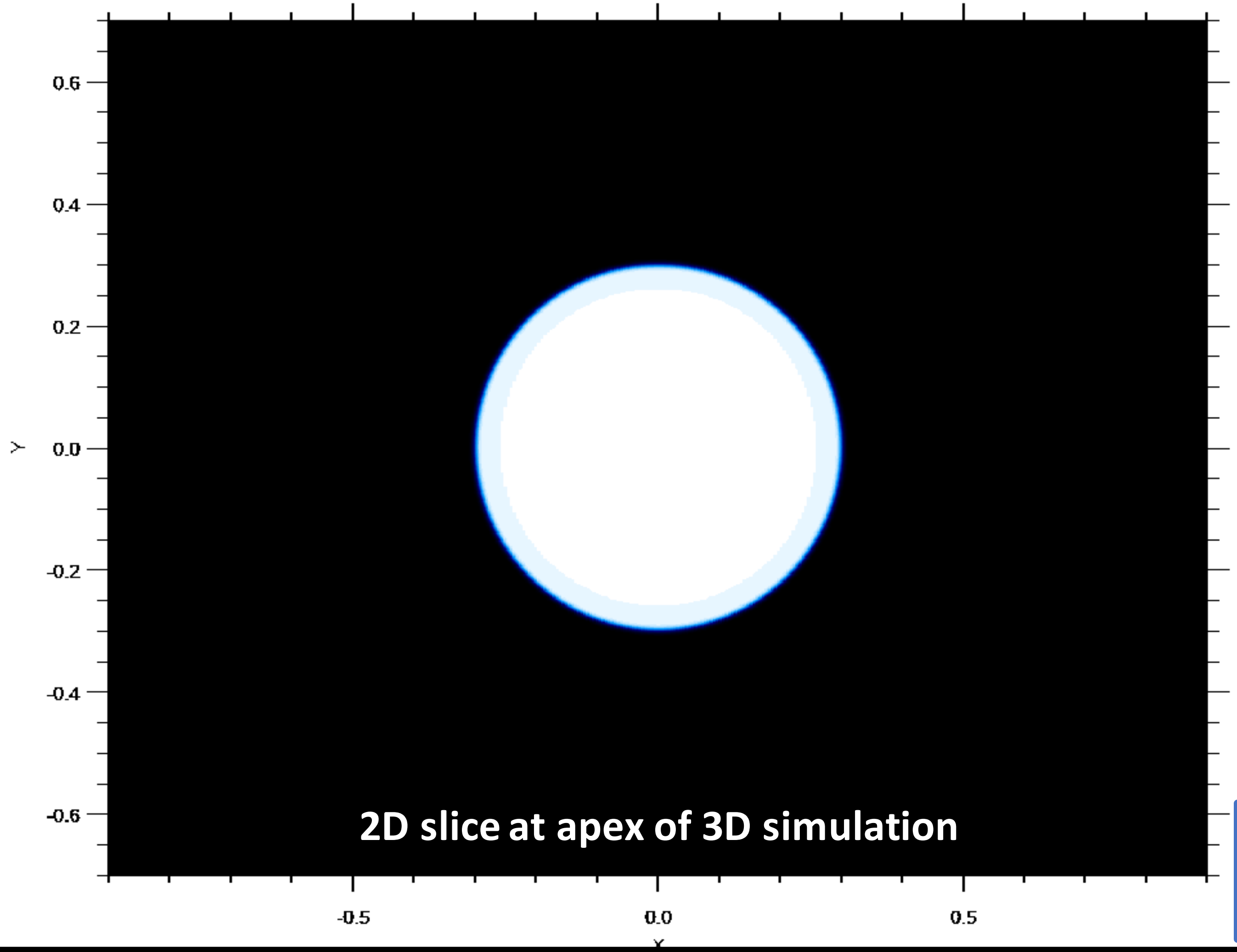


For my experiment I will look at kink waves in a flux tube

Lots of other good work in this field by many authors including Howson+ (2017), Magyar+ (2016), Terradas+ (2008) & (2018), Antolin+ (2014), (2016), (2017) & (2018)

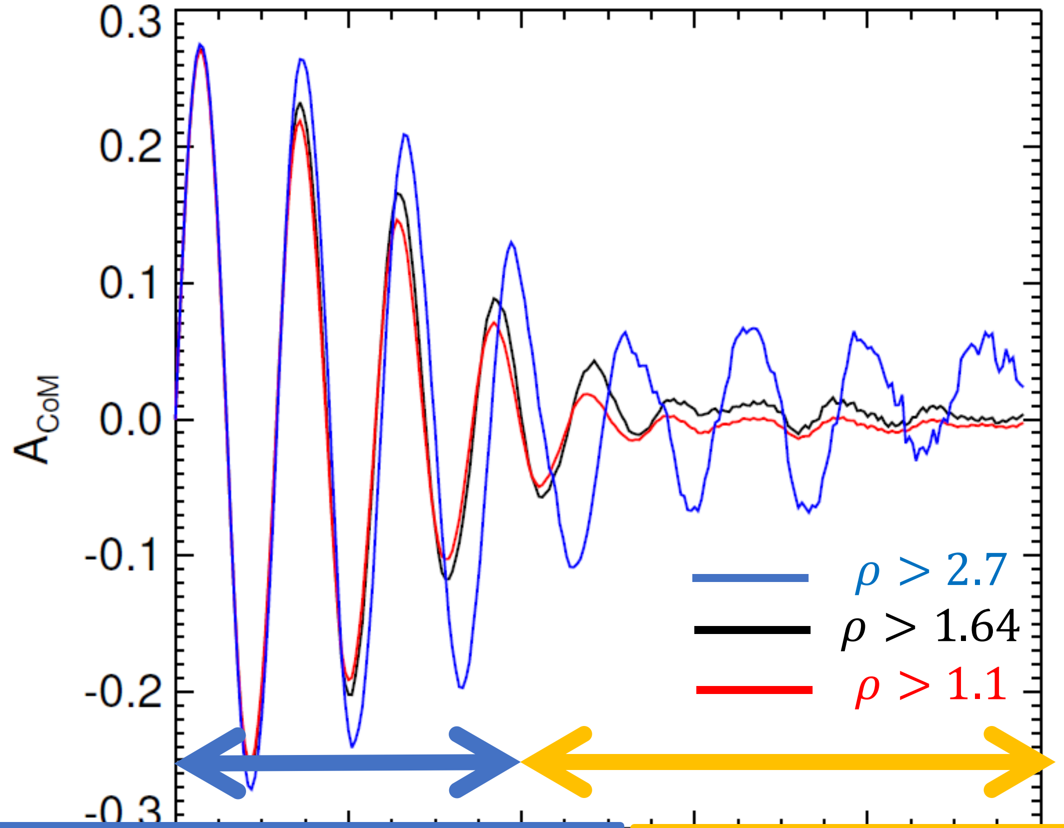
Development of Kelvin-Helmholtz turbulence

We look at damping of centre-of-mass motions of a kink wave (density ratio 3:1) for a very-thin boundary tube (initial kick at 20% of sound speed)



2D slice at apex of 3D simulation

Centre of mass position for different ρ thresholds

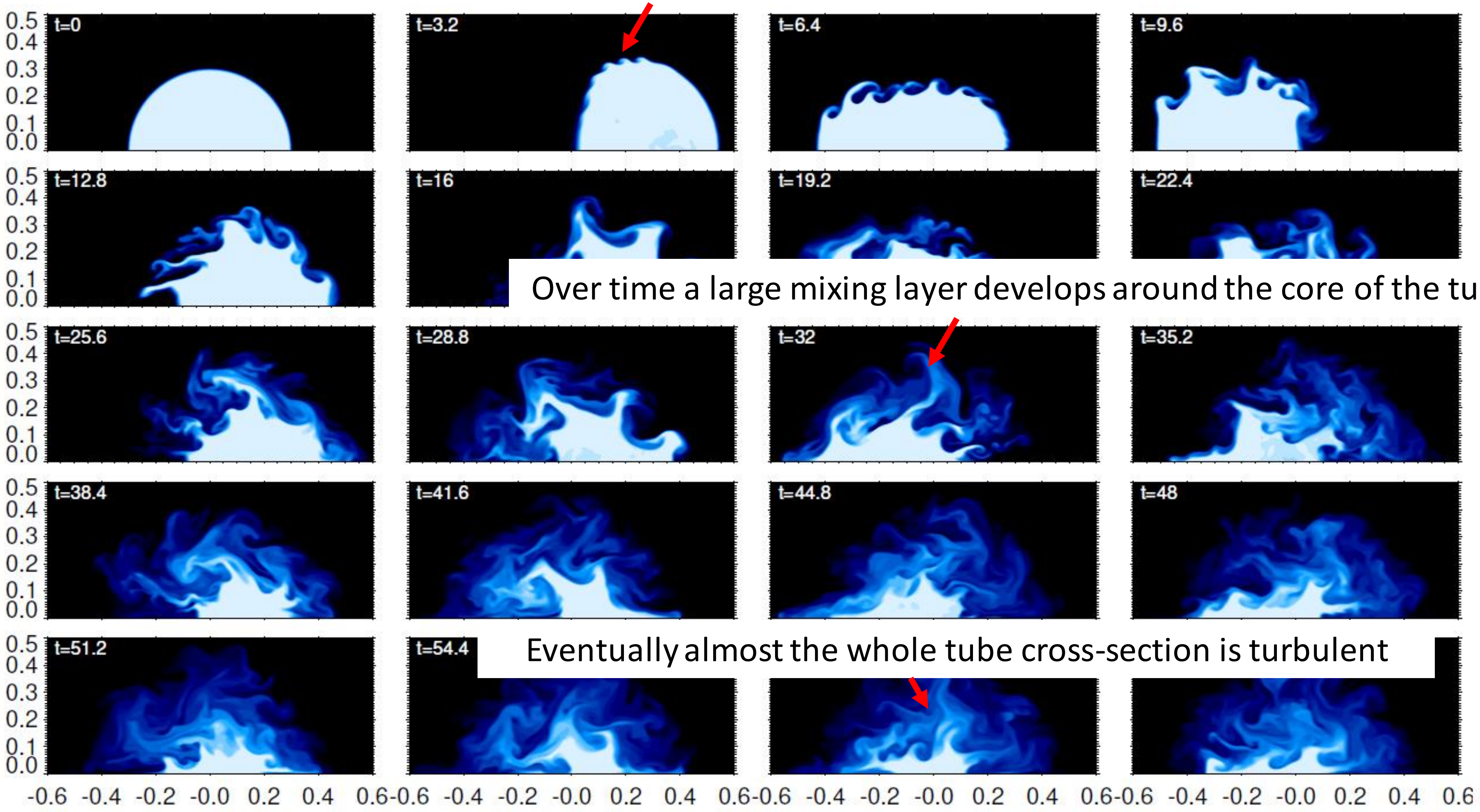


Coherent oscillations of core drive instability dynamics

Motions dominated by turbulence

Snapshots of density evolution

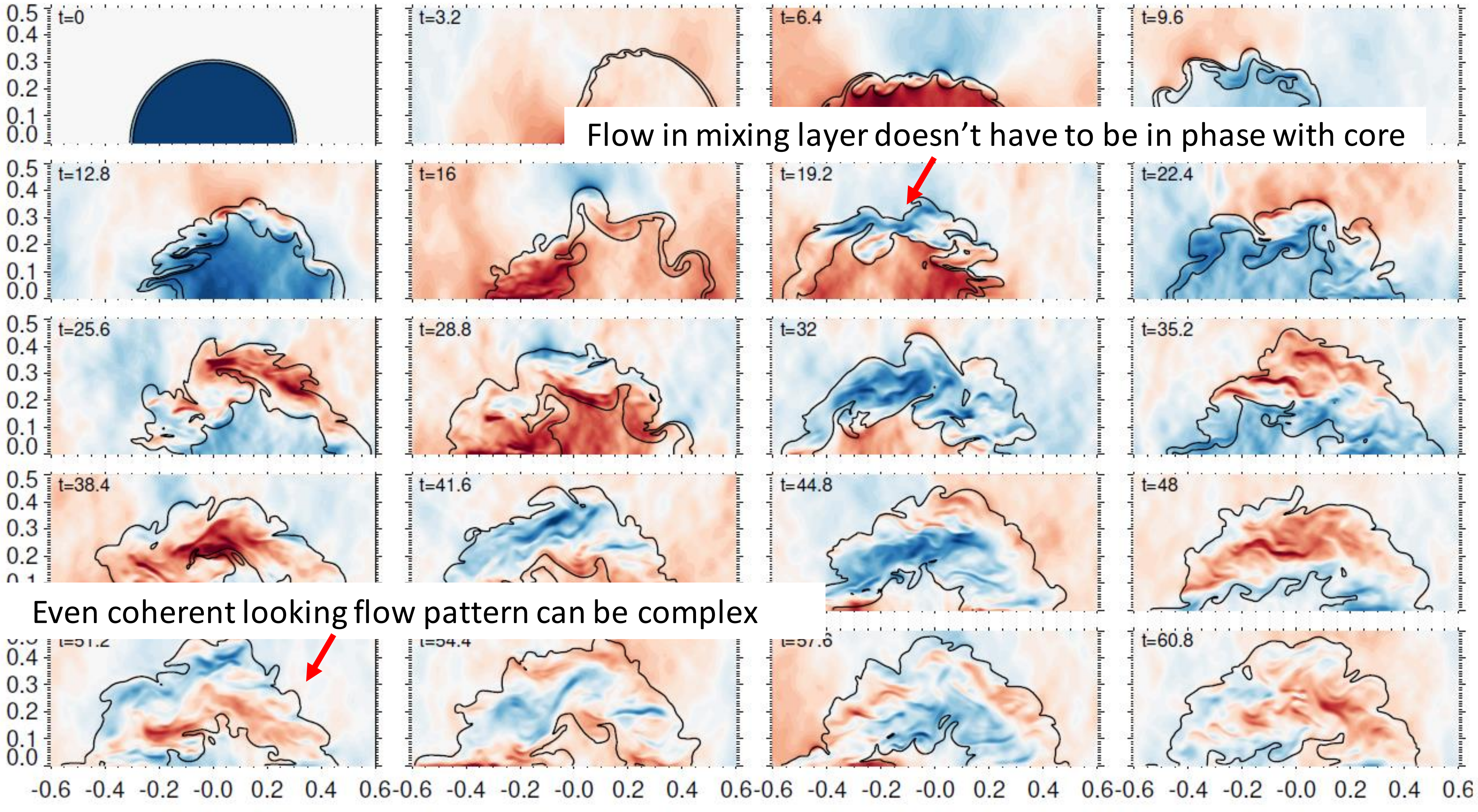
Growth of instability at small scales (not m=2 mode)



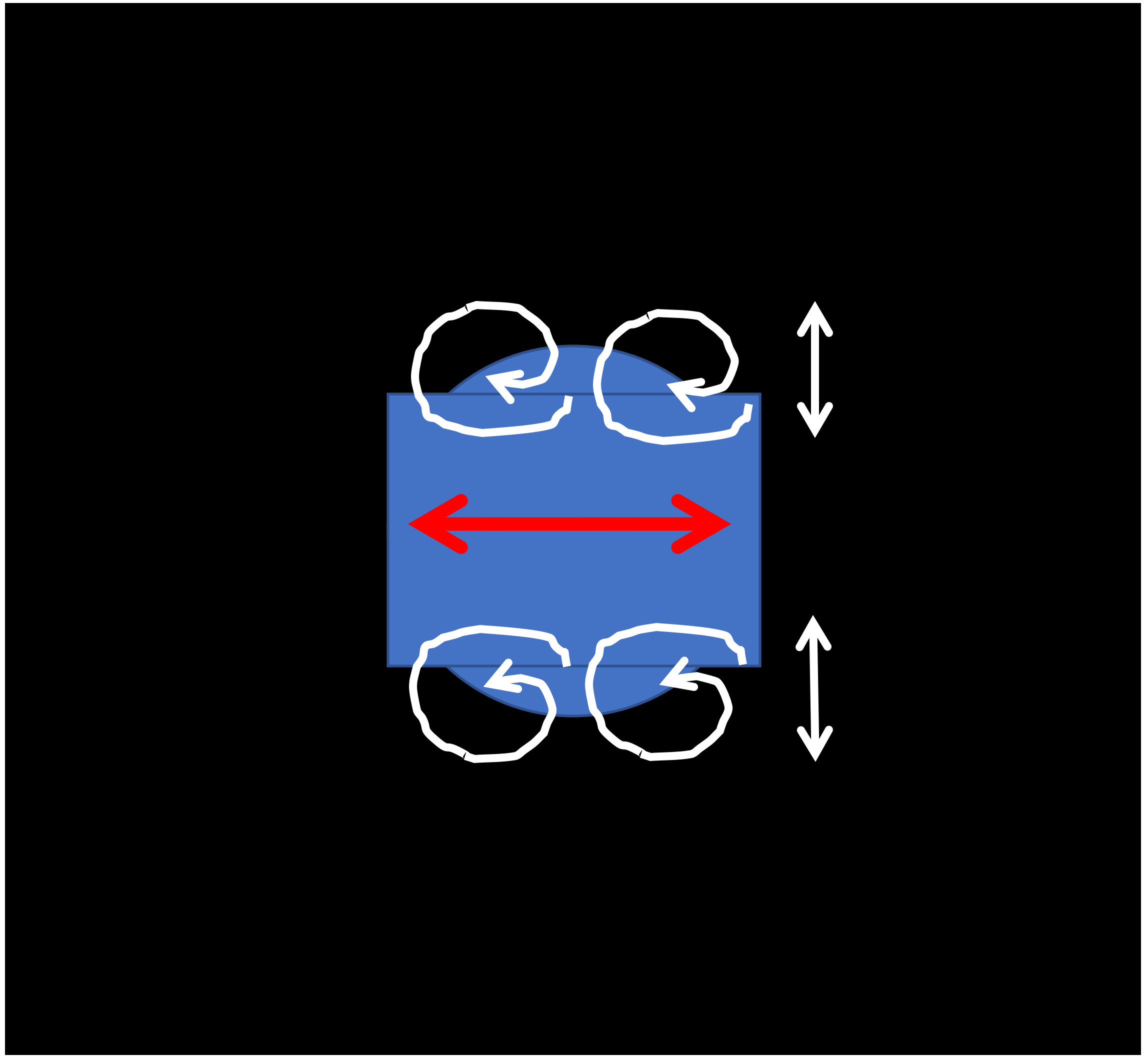
Over time a large mixing layer develops around the core of the tube

Eventually almost the whole tube cross-section is turbulent

Vx velocity field



Modelling of stage 1: development of the turbulence



Firstly, to help with modelling, we treat the tube cross-section as a rectangle

The turbulent layer thickness (h) is predicted to grow (following a self-similar evolution) as

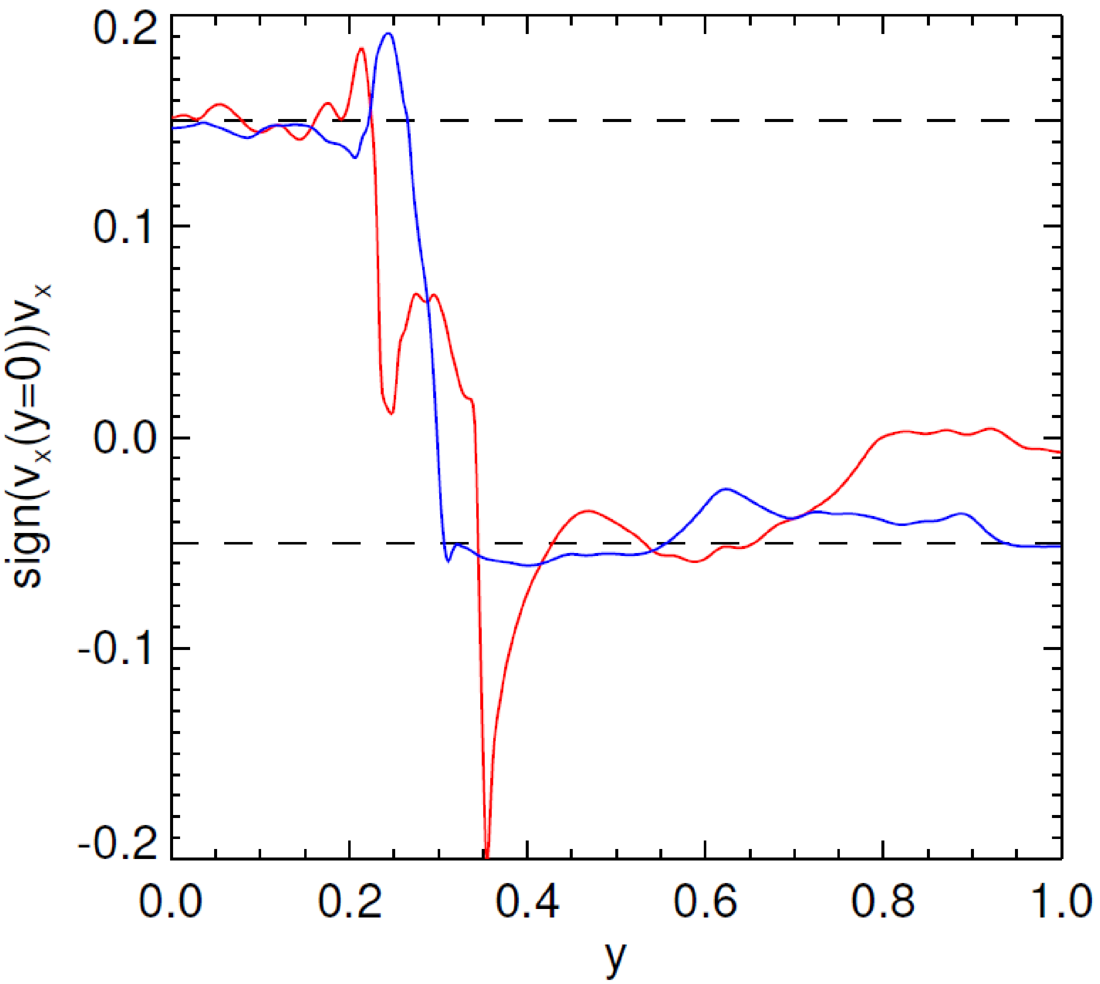
$$h = C_1 \sqrt{\frac{1}{2}\frac{(\rho_i \rho_e)^{1/4}}{\sqrt{\rho_i}+\sqrt{\rho_e}}} \Delta V t$$

To match with hydrodynamic experiments we C_1 to be in the range 0.3 to 0.5.

Shift of mixing layer to low density side taken as predicted by Hillier and Arregui (2019).

Citations: Hillier and Arregui (2019); Hillier, Van Doorsselare & Karampelas (2020); Brown and Roshko (1974); Hillier, Arregui & Matumoto (in prep); Hillier, Snow & Arregui (submitted to MNRAS)

Determining ΔV from the simulation

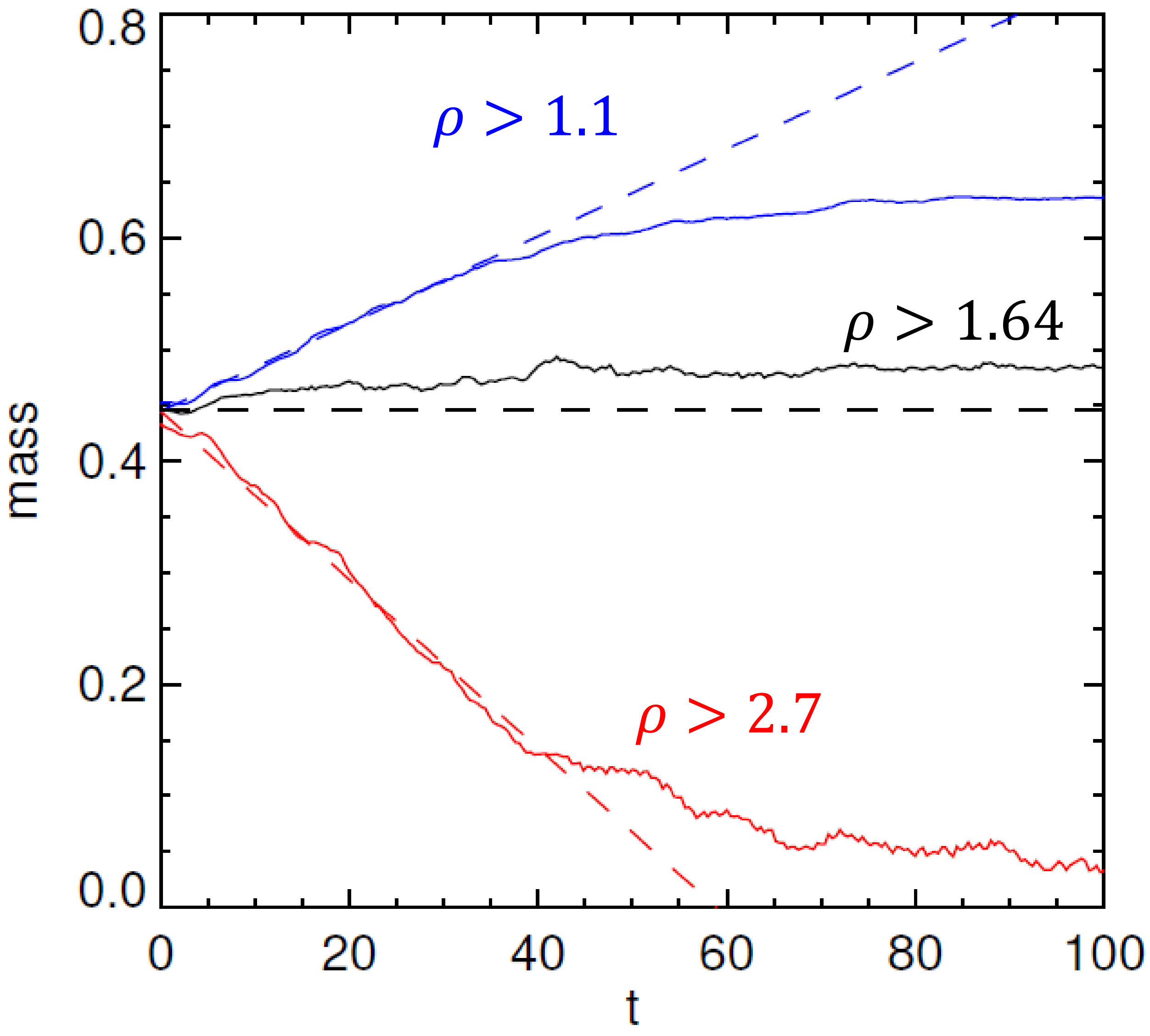


$$h = C_1 \sqrt{\frac{1}{2} \frac{(\rho_i \rho_e)^{1/4}}{\sqrt{\rho_i} + \sqrt{\rho_e}}} \Delta V t$$

It is difficult to know beforehand what the velocity jump will be as I just kick the system in a pretty crude way. So I have to see how my velocity shear settles down.

Looking at two peaks for the velocity amplitude, I get an instantaneous ΔV of 0.2, but then this oscillates so I multiply by $1/\sqrt{2}$ (as I care about the RMS turbulent velocity).

Mass evolution as a benchmark for the model



The simplest prediction to test of the mixing layer model is to investigate the evolution of mass above a given density threshold at the apex

This is given by

$$m = m_0 + 2R\Delta m h(t)$$

with Δm directly predicted by the model of Hillier and Arregui (2019).

Looking at three different density thresholds this model clearly predicts (dashed lines) the initial mass evolution (solid lines) for $C_1 = 0.3$.

Model predicts its own failure at late times as core has negative mass for **t>45**. This change in dynamics is also seen.

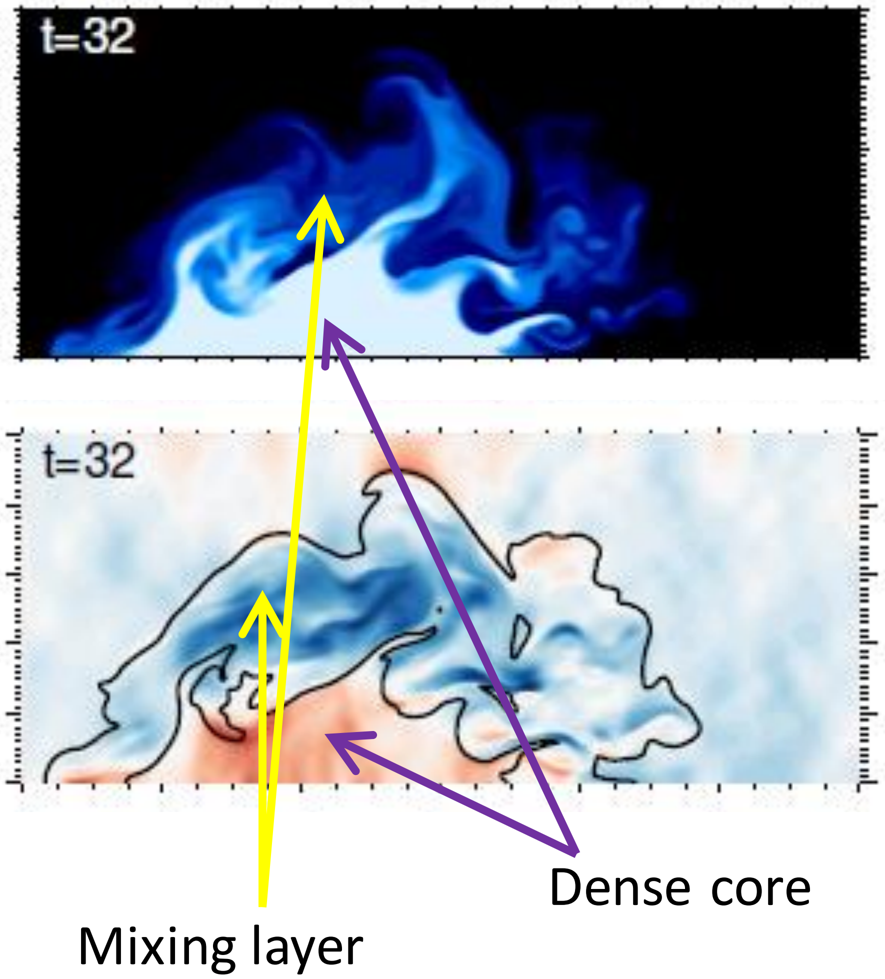
Predictions for the momentum evolution

Momentum is more complex to deal with as the sign changes with time.

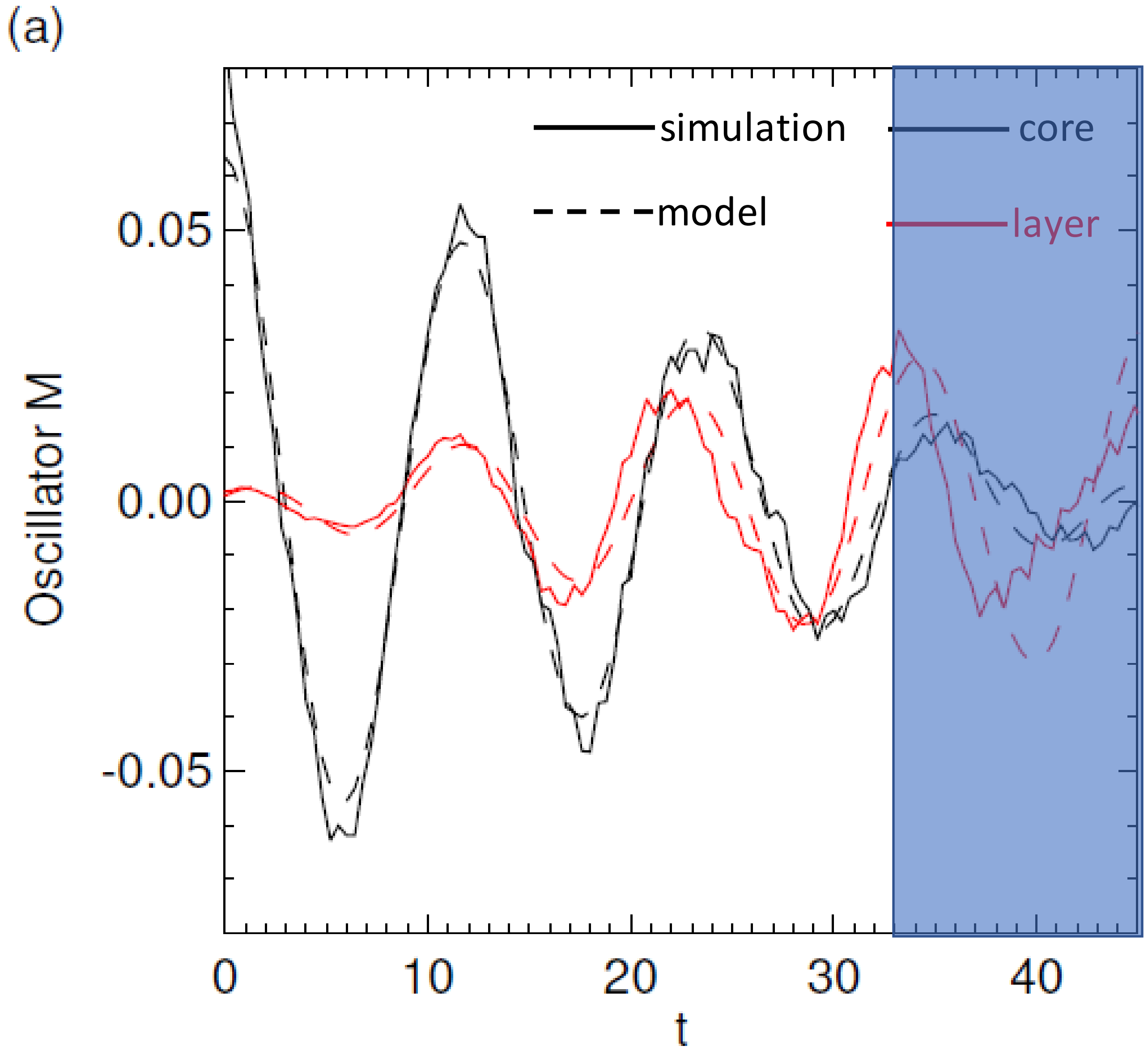
For the dense core we already know it is oscillating with the kink frequency, so we just assume that is continues, and that the momentum extraction process has the same frequency.

For the mixing layer, there is a continuum of natural oscillatory frequencies, but we treat all of these as being coupled by the turbulence so we have one characteristic frequency given by the mean density $\left(\sqrt{\rho_1 \rho_2}\right)$. But the momentum is injected into the layer at the kink frequency.

To model this we use forced linear oscillators.



Predictions for the momentum evolution



We model this layer as two forced linear oscillators of the form

$$\frac{dM_L}{dt} = -\omega_A^2 I_L - \dot{F}_L \cos(\omega_{KINK} t)$$

And

$$\frac{dM_C}{dt} = -\omega_{KINK}^2 I_C - \dot{F}_C \cos(\omega_{KINK} t)$$

where $\dot{F}$ is the forcing (predicted from Hillier and Arregui 2019) and I is the time integral of the momentum.

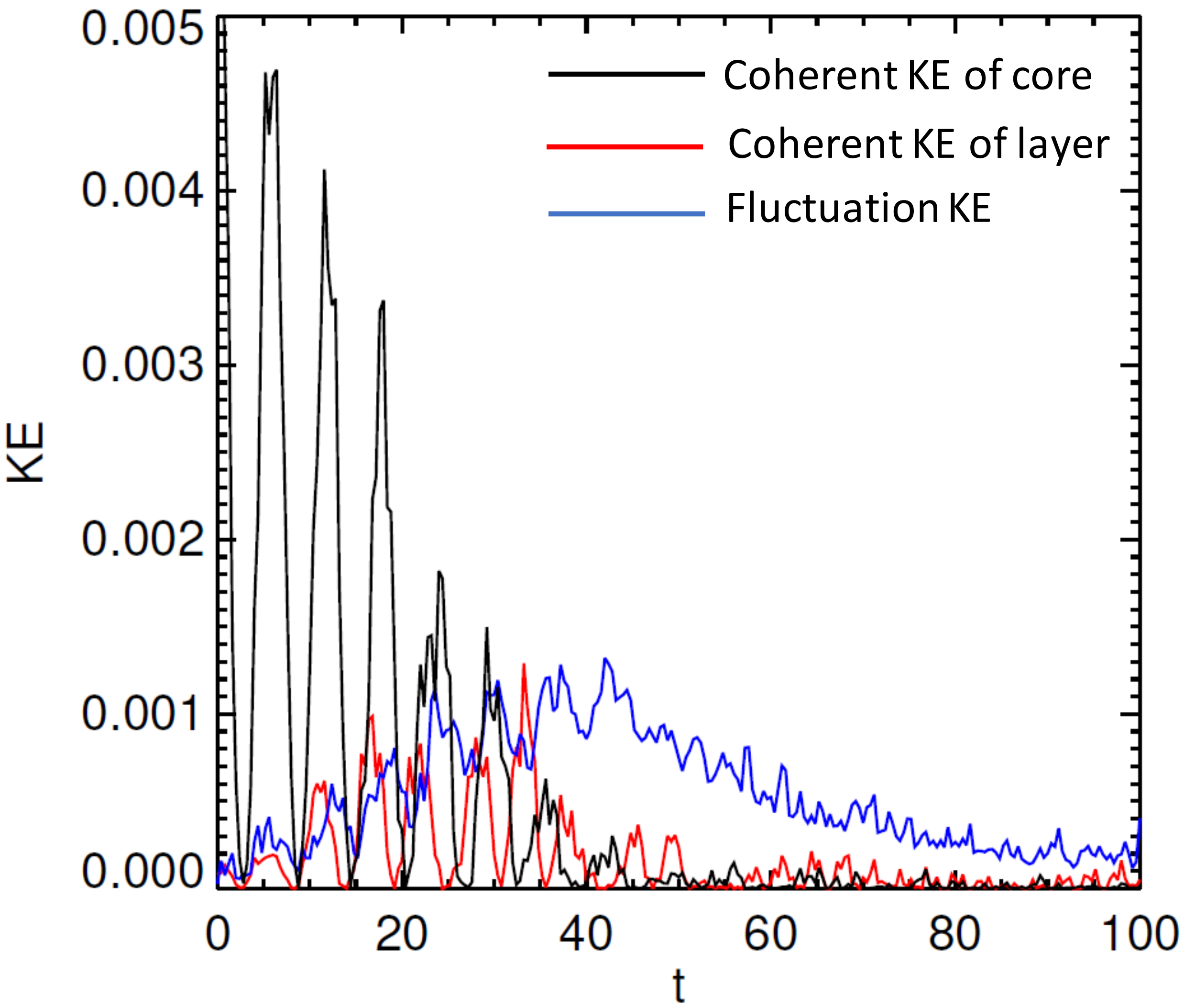
This can be used to get a model for damping (which is neither exponential decay or Tom's model)

Transition to a predominantly turbulent state (and its subsequent decay)

The initial stage of the model extracts energy from coherent motions and turns it into turbulence.

Unsurprisingly at late times most of the energy is held in turbulent fluctuation and not in coherent wave motions.

The energy held by this turbulence decays over time.



Modelling the decaying turbulence

Starting with transport of turbulent energy, e.g.

$$\frac{dE_{\rm turb}}{dt} = \mathbf{v}\cdot\nabla E_{\rm turb}$$

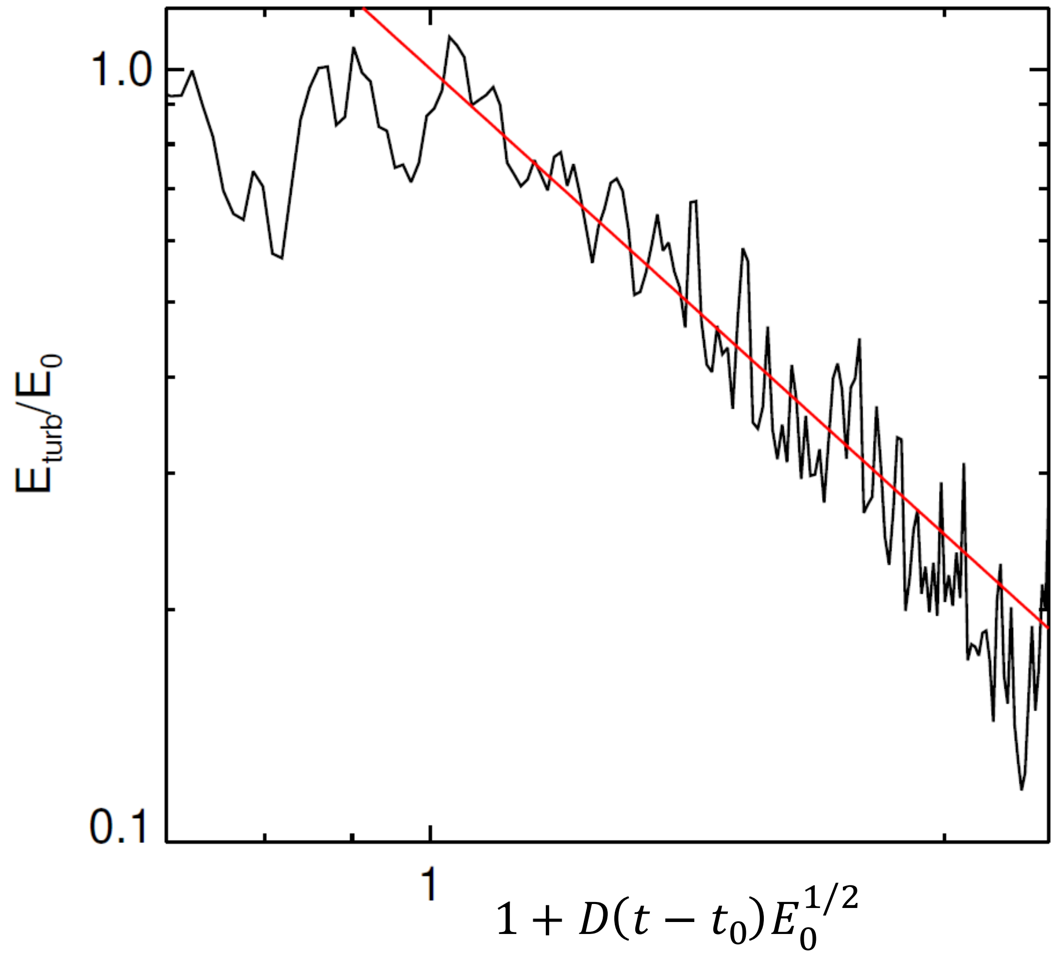
Following the simple model of Taylor (193?) if we assume the largest scale of the turbulence doesn't vary as it decays we get

$$\frac{dE_{\rm turb}}{dt} = \mathbf{v}\cdot\nabla E_{\rm turb} \approx C\frac{u_{\rm RMS}}{L}E_{\rm turb}.$$

This has the solution

$$E_{\rm turb} = \frac{1}{(D(t-t_0)+E(t_0)^{-1/2})^2}$$

With $D = 0.3 \times \sqrt{\frac{2}{A\sqrt{\rho_1\rho_2}}}\frac{1}{2.7L}$



Key points

- Two dynamic phases showing self-similar growth of turbulent layer and then decaying turbulence.
- Both can be understood using relatively simple (hydrodynamic) models of KHi turbulence and decaying turbulence, we can understand both the evolution of the turbulent layer and important impacts on the coherent motions of the system
- It is possible to calculate relatively tight bounds for heating rates, and get a velocity amplitude damping profile for the wave (this is nothing like exponential damping).

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Where might this be relevant for this workshop

- Because of the inhomogeneities (either existing already or created by wave turbulence), there is huge potential for parasitic instabilities (and the turbulent transport they create to appear in the solar wind)

- The heliospheric current sheet, boundaries between slow and fast wind, etc could be regions where parasitic instabilities play a key role in solar wind turbulence. Potentially they are even more prevalent.

An alternative to the Uniturbulence phemenology

- Tom gave a really nice introduction into the uniturbulence model he proposes, but I have a question: What if there is also a little bit of background noise in the system?
- Are there any parasitic instabilities (maybe baroclinic instabilities) that grow?