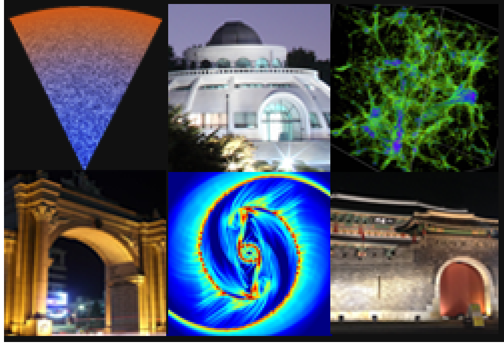

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# A study of the dynamics of the ~~3D~~ Kelvin-Helmholtz instability in a partially ionised plasma

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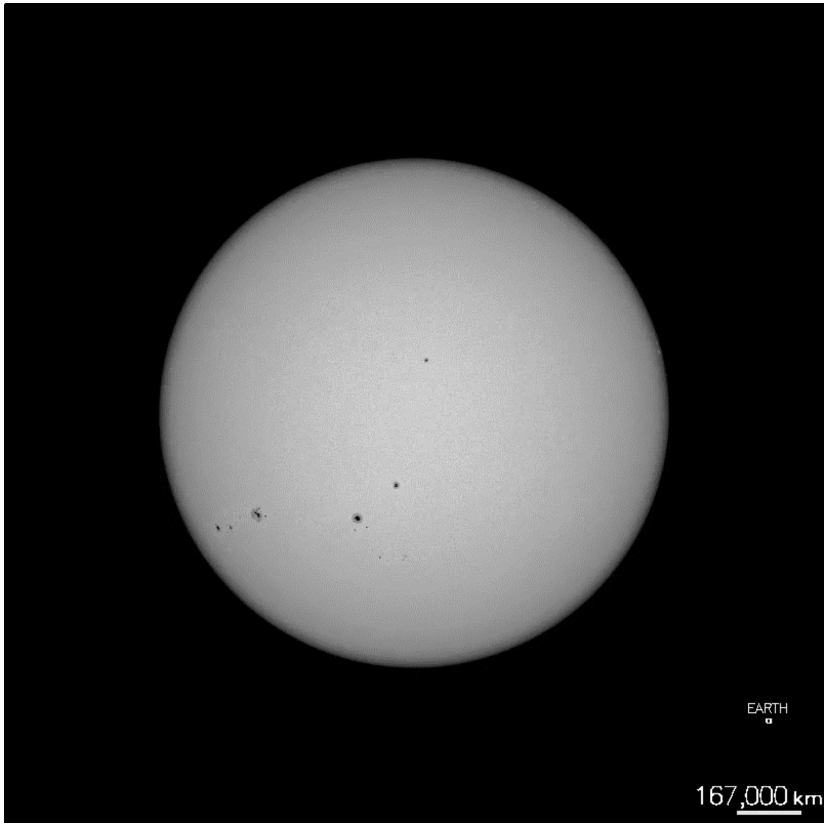
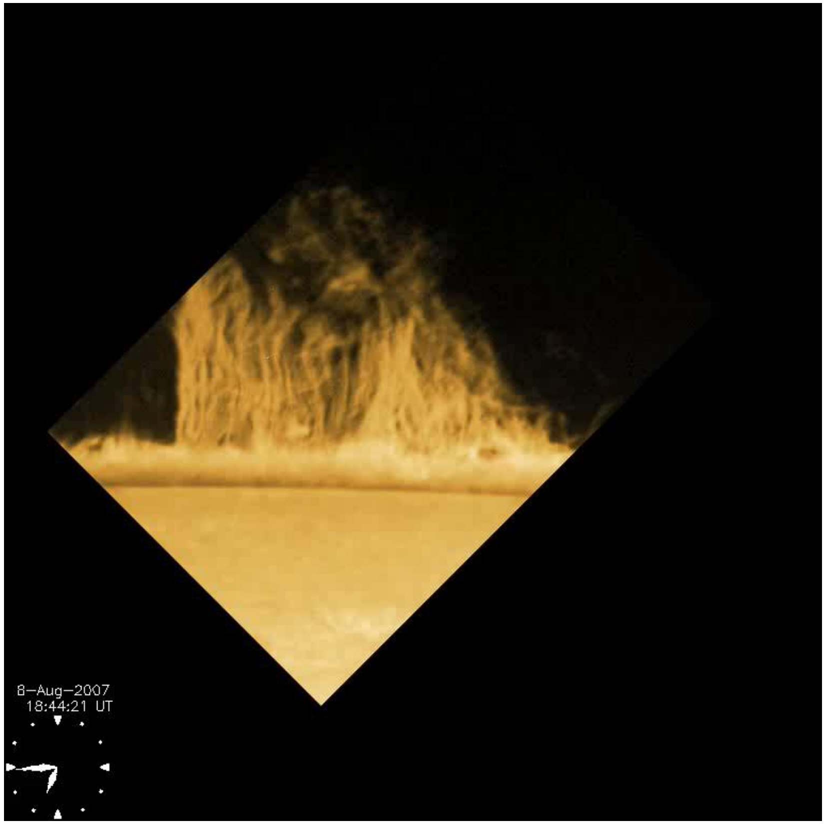
In collaboration with the (PIP) coding team, Kwasan Observatory

# Partially (Weakly) ionized plasma in solar physics

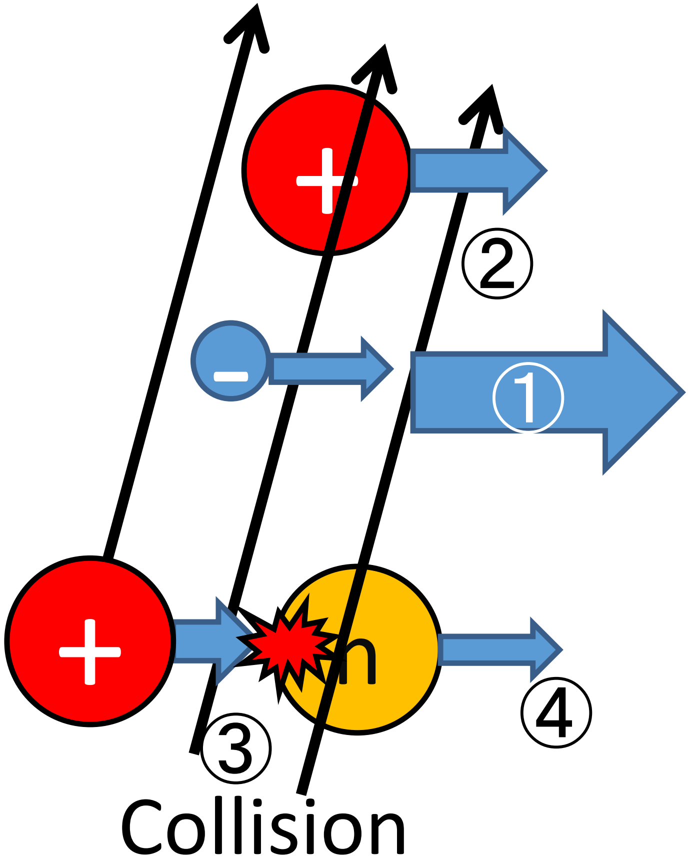


The solar photosphere (turbulence & convection). Ionisation fraction $\xi_p \sim 10^{-4} - 10^{-6}$



The solar chromosphere and prominences (waves, reconnection, instabilities and turbulence). Ionisation fraction $\xi_p \sim 10^{-1} - 10^{-3}$

# How are neutrals coupled to magnetic fields



① Movement of magnetic field

② together with charged particles

③ Charged particles collide with neutrals

④ Neutrals move in the same direction as the charged particles

Perfect coupling $v_{in/ni} = \infty$

strong coupling $v_{in/ni} \gg \nu_{DYN}$

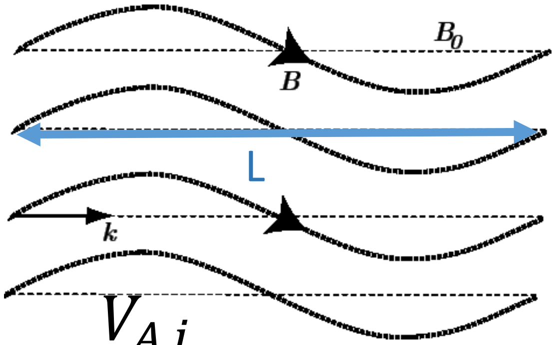
marginal coupling $v_{in/ni} \sim \nu_{DYN}$

weak coupling $v_{in/ni} \ll \nu_{DYN}$

no coupling $v_{in/ni} = 0$

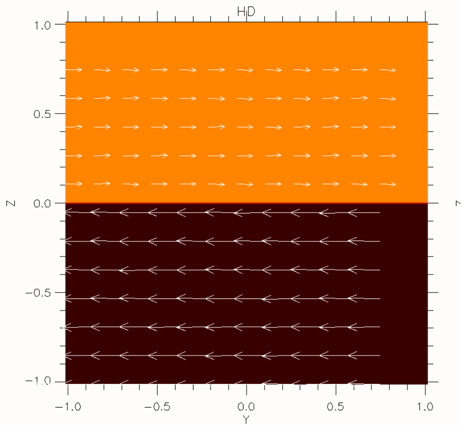
# ‘Dynamic time’ vs ‘Collision time’

## Alfven waves



$$\frac{V_{A,i}}{L} \text{ VS } \nu_{in/ni}$$

## Instabilities



$$\omega = f(V, C_S, V_A, L, \ldots) \text{ VS } \nu_{in/ni}$$

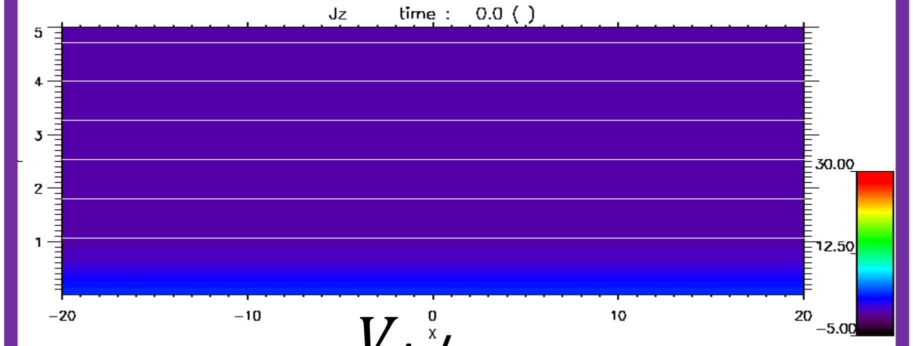
## Turbulence

Dimensional arguments give:

$$\left(\frac{\epsilon}{L^2}\right)^{1/3} \text{ VS } \nu_{in/ni}$$

(Like a partially ionized plasma Kolmogorov lengthscale)

## Reconnection



$$v_{REC} \sim {}^{V_A}/_{L} \text{ VS } \nu_{in/ni}$$

# “And the mountains flowed before the Lord”

Judge 5.5

c.f. Deborah number associated with polymeric fluids

$$De = {}^{t_{RELAX}}/_{t_{OBS}}$$

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In solar physics (and astrophysics in general), we are interested in a huge range of temporal and spatial scales. We cannot only think of our “mountains” as “solid” or “fluid”

# The (PIP) code

New code to study partially ionized plasma developed at Kyoto University

3D HD and 3D MHD conservative equations solved coupled by collisons (both fluids taken as ideal gases)

$$\frac{\partial \rho_n}{\partial t} + \nabla\cdot(\rho_n \mathbf{v}_n) = 0$$

$$\frac{\partial}{\partial t}(\rho_n\mathbf{v}_n) + \nabla\cdot(\rho_n\mathbf{v}_n\mathbf{v}_n + P_n\mathbf{I}) = -\underline{a_c\rho_n\rho_p(\mathbf{v}_n-\mathbf{v}_p)}$$

$$\frac{\partial e_n}{\partial t} + \nabla\cdot\left(\mathbf{v}_n(e_n+P_n)\right) = \underline{a_c\rho_n\rho_p\left(\frac{1}{2}(v_p^2 - v_n^2) + 3R_g(T_p - T_n)\right)}$$

$$\frac{\partial\rho_p}{\partial t}+\nabla\cdot(\rho_p\mathbf{v}_p)=0$$

$$\frac{\partial}{\partial t}(\rho_p\mathbf{v}_p)+\nabla\cdot\left(\rho_p\mathbf{v}_p\mathbf{v}_p+\left(P_p+\frac{\mathbf{B}^2}{8\pi}\right)\mathbf{I}-\frac{\mathbf{BB}}{4\pi}\right) = \underline{a_c\rho_n\rho_p(\mathbf{v}_n-\mathbf{v}_p)}$$

$$\frac{\partial e_p}{\partial t}+\nabla\cdot\left(\mathbf{v}_p(e_p+P_p)+\frac{E\times B}{4\pi}\right) = \underline{a_c\rho_n\rho_p\left(\frac{1}{2}(\mathbf{v}_p^2-\mathbf{v}_n^2)+3R_g(T_p-T_n)\right)}$$

$$\frac{\partial\mathbf{B}}{\partial t}+\nabla\times\left(-\mathbf{v}_p\times\mathbf{B}+\eta\nabla\times\mathbf{B}\right)=0$$

Schemes: Fourth-order central difference (eg Vogler et al 2005) and HLL type (e.g. Miyoshi & Kusano 2005)

MPI parallelized (no complications from collision terms)

# Solving for the collision terms

$$\frac{\partial \rho \mathbf{v}}{\partial t} \sim -\upsilon \rho \mathbf{V}_D$$

Two problems are associated with solving this equation:

1) This equation is very stiff, meaning that the safety factor for the CFL condition has to be annoyingly small
2) When simulating a whole stellar atmosphere, where densities can vary by many orders of magnitude, there will be regions with very high collision frequency that we need to make simulatable

But for strong coupling it is easy to show that

$$V_D(t) = V_D(t_0)\exp(-\alpha \rho_{TOT} t)$$

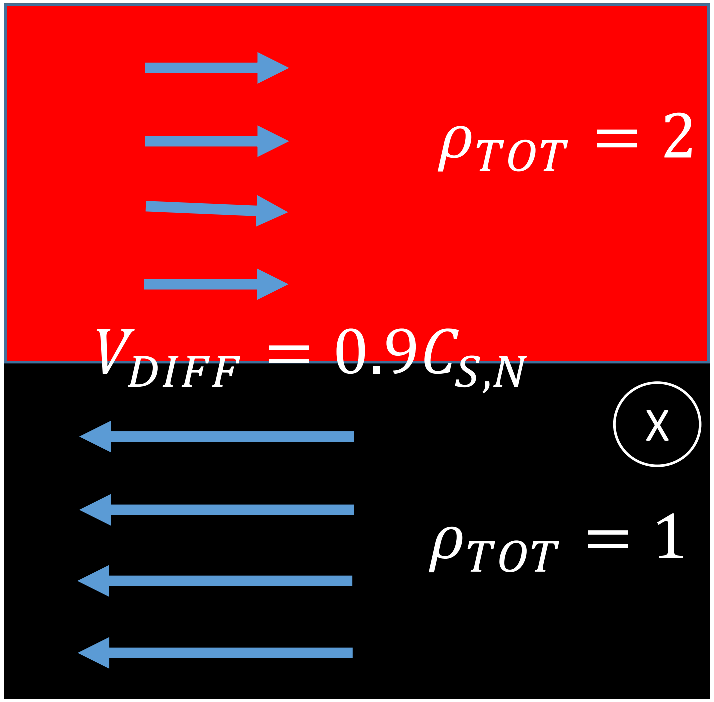
Which allows for an analytic solution to be give for the integration at timescales below the dynamic timescale

# The Magnetic Kelvin-Helmholtz instability in partially ionised plasma

Fundamental instability of astrophysical plasma.

Partially ionized effects have been investigated in molecular clouds (Jones & Downes 2012) and solar prominences (Diaz et al 2012)

All simulations on a 500x500 grid



**The simulation setup**

Ionisation fraction $\xi_i = 0.5$

$\beta = 0.3$

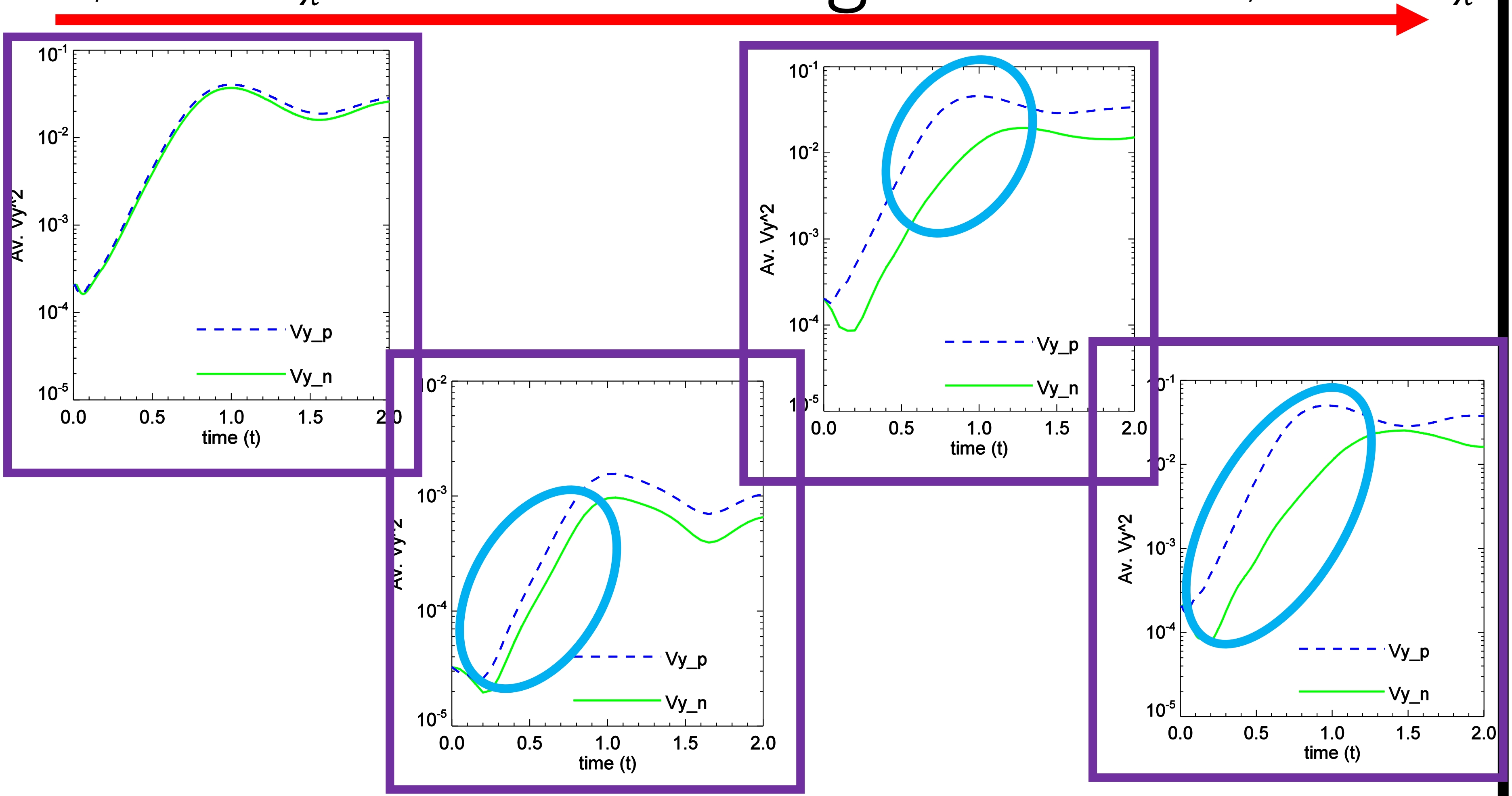
Magnetic field along line of sight

Most cases $\upsilon_{in} = 100$

# Linear Regime

$v_{in/ni} \gg {}^{V_{DIFF}}/_{\lambda}$

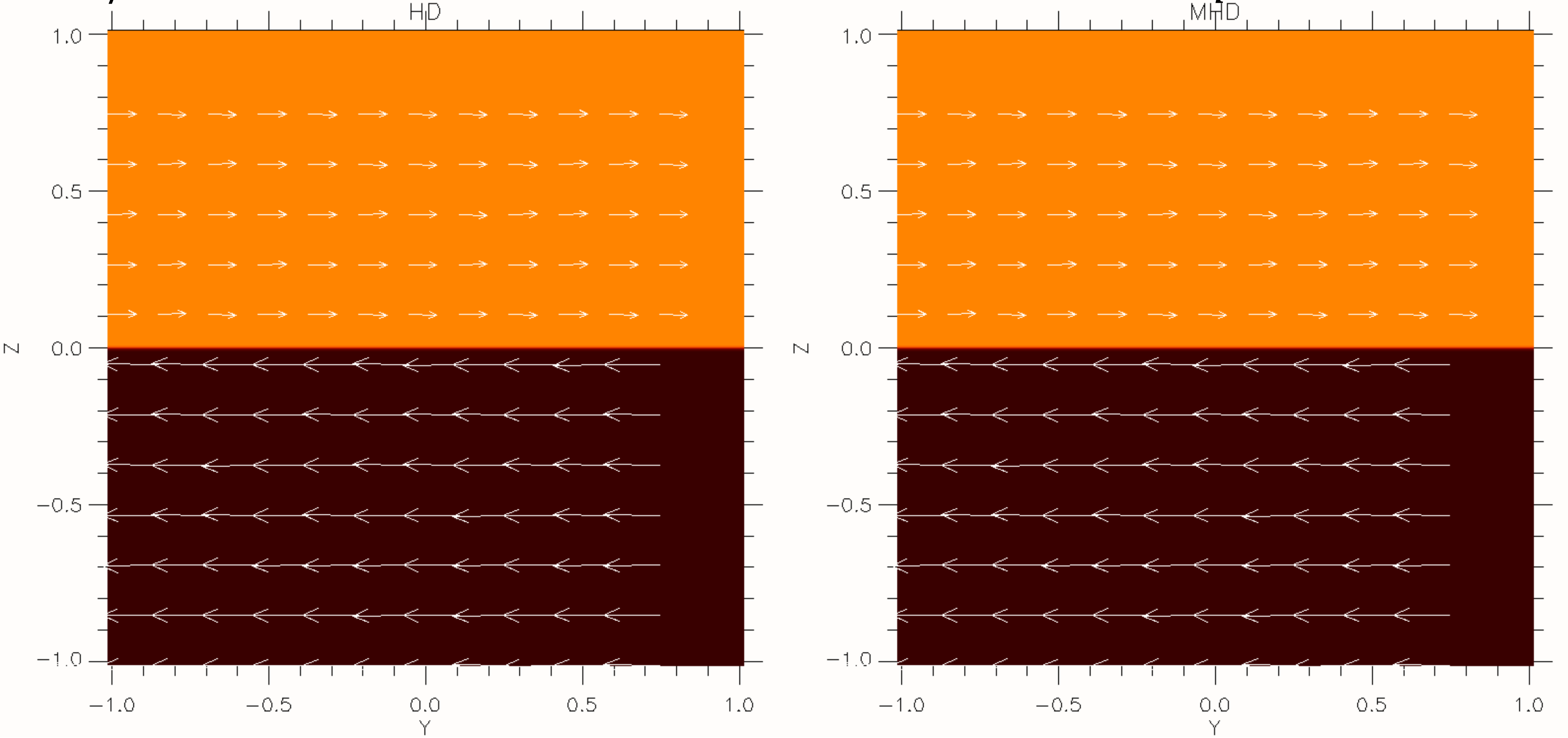
$v_{in/ni} \ll {}^{V_{DIFF}}/_{\lambda}$



For strong coupling, the instability grows in the two fluids together. As coupling gets weaker a lag develops, and the fluids eventually develop their own growth rates (consistent with linear theory of Soler et al. 2012)

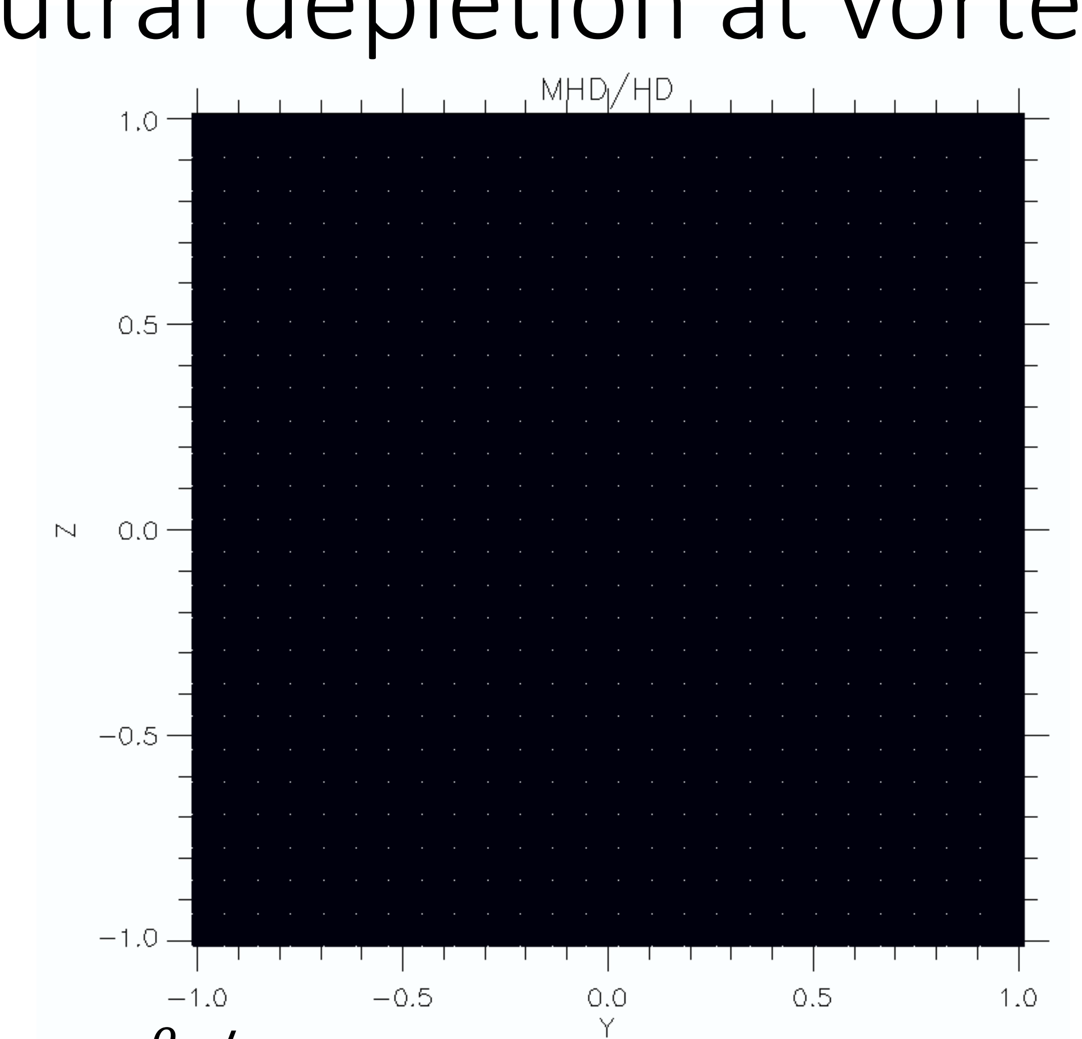
# The nonlinear PIP KH

$v_{in/ni} = 100$ $\rho_n$ $\rho_p$



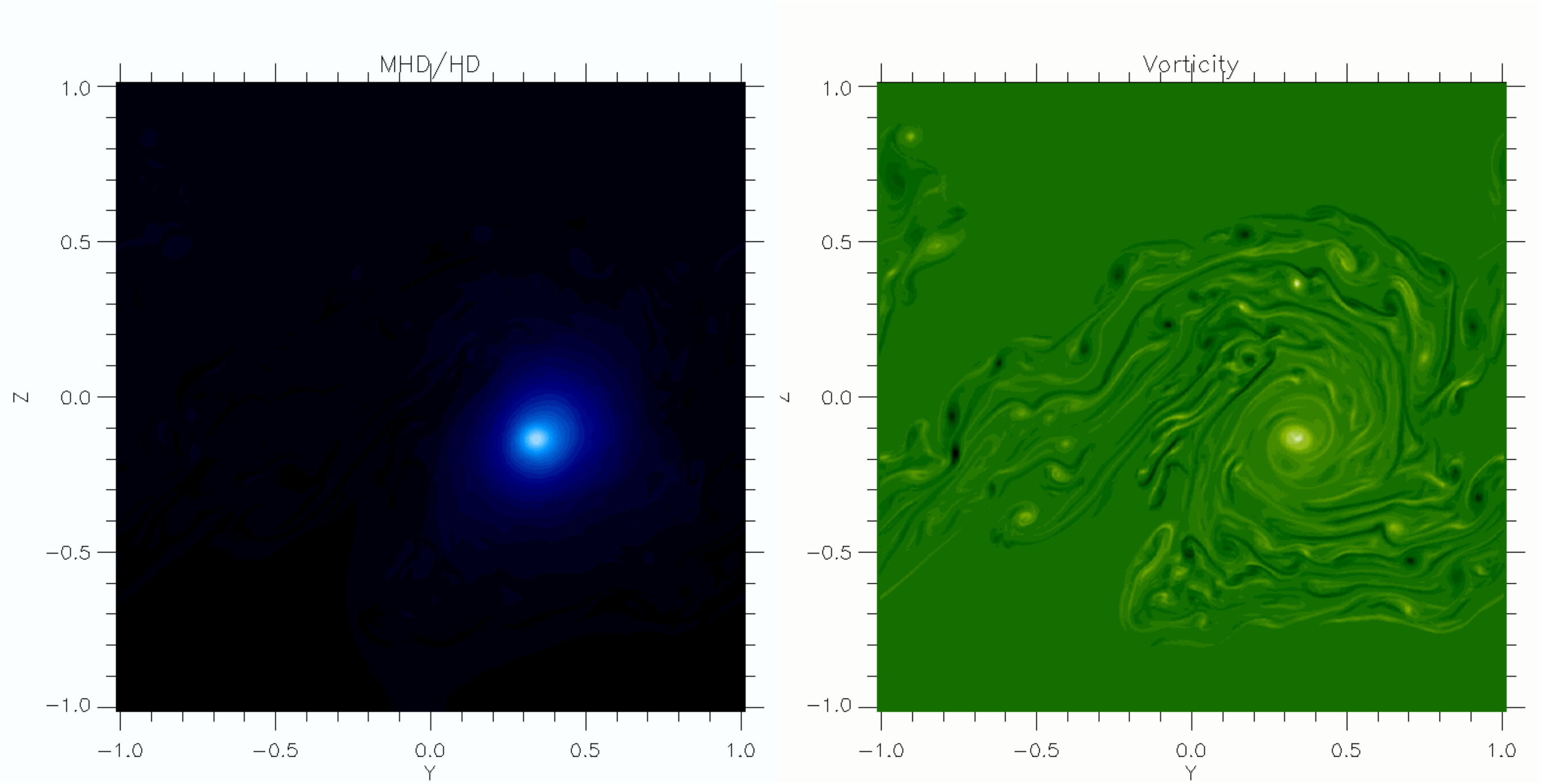
Movie shows $\rho_n$ and $\rho_p$ with the arrows showing velocity vectors for each fluid. Though the similar dynamics develop, the density distributions show stark differences in the centre of the vortex

# Neutral depletion at vortex centre



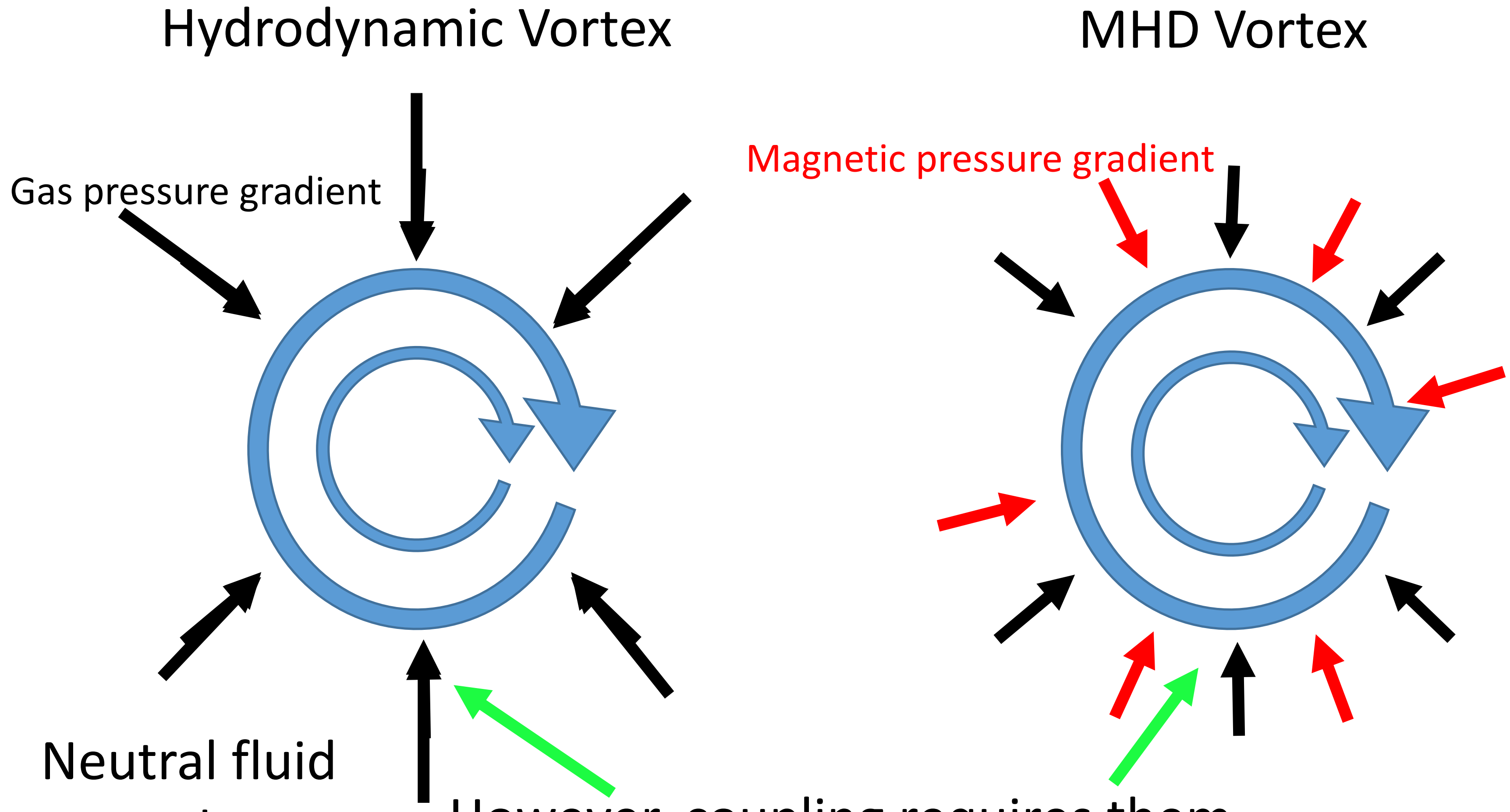
Movie shows ${}^{\rho_p}/_{\rho_n}$ with the arrows showing drift velocity $\mathbf{V}_D = \mathbf{v}_i - \mathbf{v}_n$. Strong regions of neutral depletion form in the vortex centre

# Neutral depletion at vortex centre



$^{\rho_p}/_{\rho_n}$ (left) and vorticity (right). This highlights that though there are many vortices, only the long-lived vortex shows significant depletion

# Ion-neutral centrifuge



Neutral fluid can no longer be contained!

However, coupling requires them to have the same temperature

# Summary

- The (PIP) code is progressing well and ready for use in scientific research. Work is still in progress to improve its usage on supercomputers
- Application to the Kelvin-Helmholtz instability shows that ion-neutral centrifuges are formed in the KH vortex (neutral dust can undergo a similar process c.f. Hendrix and Keppens 2014)
- Inverse cascade (mainly a 2D effect?) can transport the non-ideal effects to be important at ‘ideal’ length/timescales (as suggest by Jones and Downes 2012)