HOW DO HEAVY IONS AFFECT TRANSPORT PROCESSES AT THE MAGNETOPAUSE?

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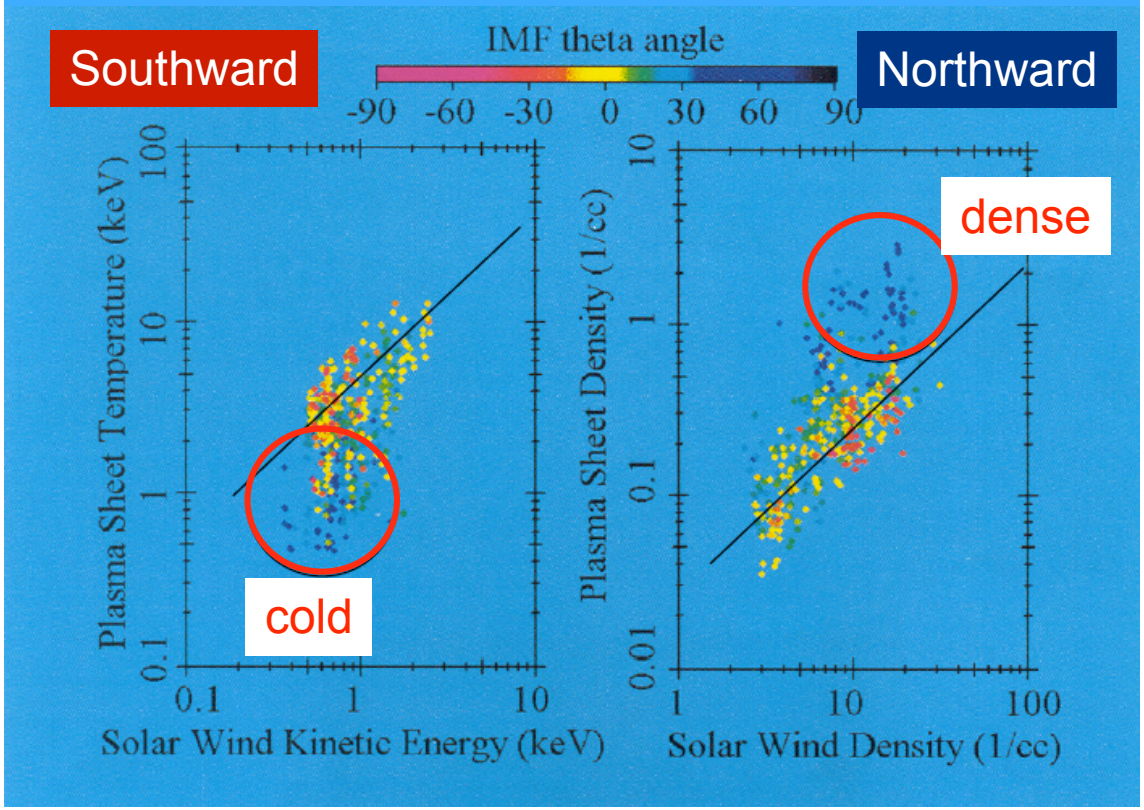
- Reconnection
- Kelvin-Helmholtz Instability
- Kinetic Alfven Wave

Magnetopause Transport

- Transport of mass, momentum, and energy across the magnetopause governs much of the dynamics of the magnetosphere

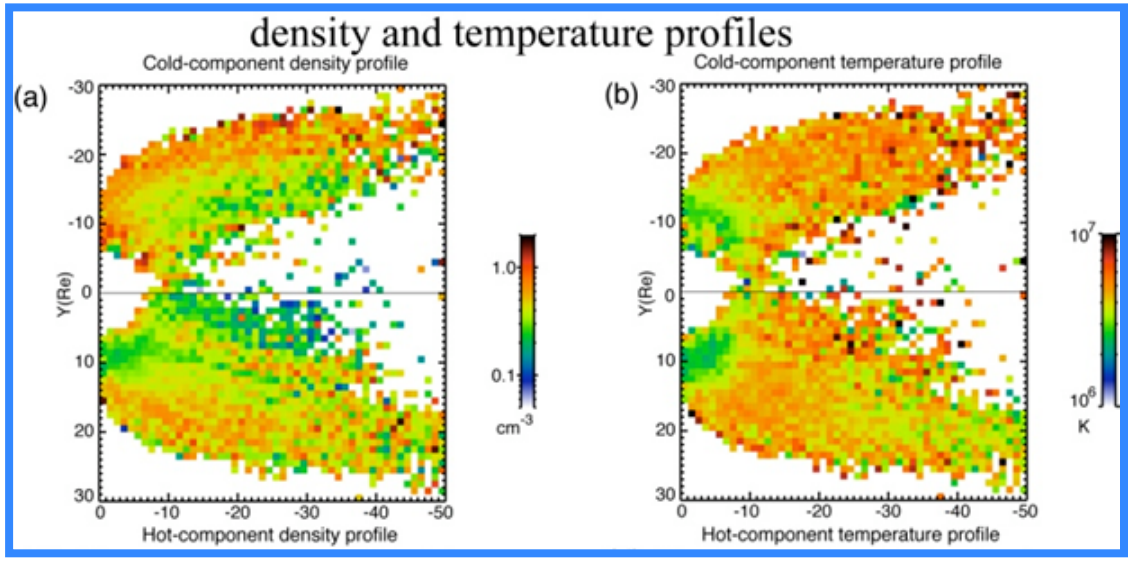
Under northward IMF, the tail plasma sheet is cold and dense



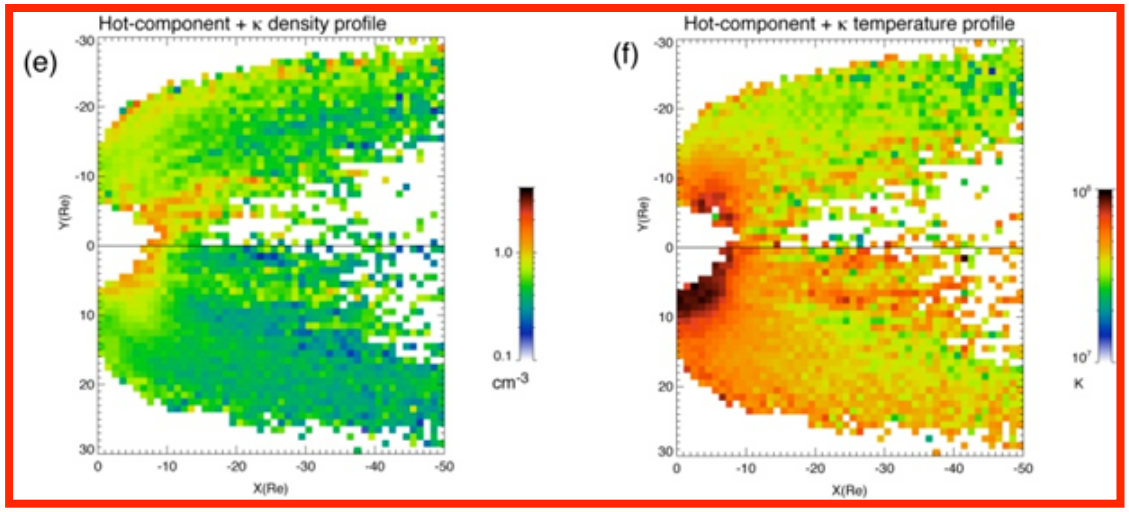
Terasawa et al., 1997

Northward IMF profiles (DMSP)

Cold plasma is dense along the flanks, hotter and denser on the dawn flank



Hot plasma shows asymmetry in temperature



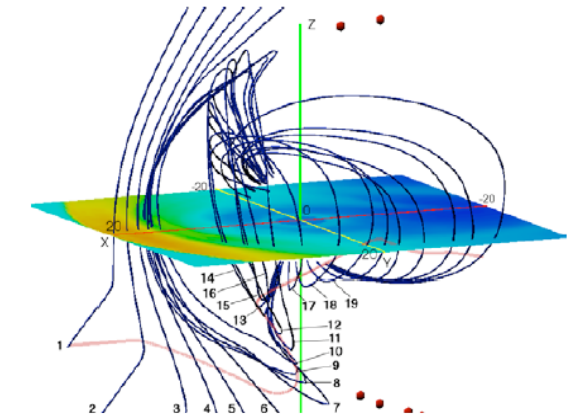
Probably the results of curvature and gradient drifts

Wing et al., 2005

Mechanisms for Magnetopause Transport

Reconnection

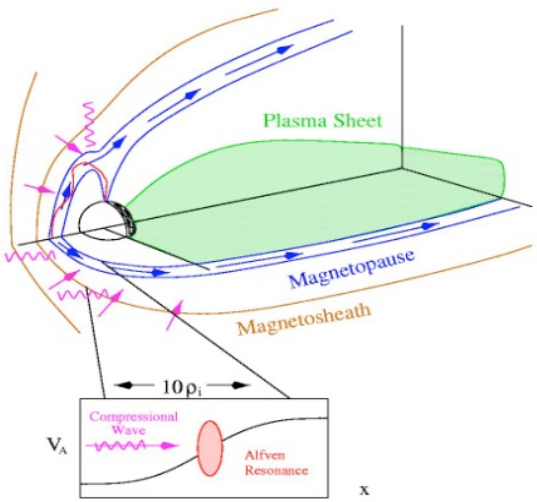
Song and Russell, 1992



Li et al., 2005

Kinetic Alfven Waves

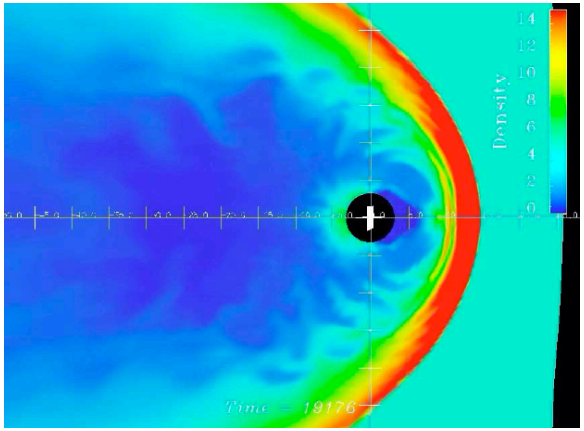
Lee et al., 1994
Johnson and Cheng, 1997



Johnson and Cheng, 1997

Kelvin-Helmholtz Instability

Otto and Fairfield, 2000



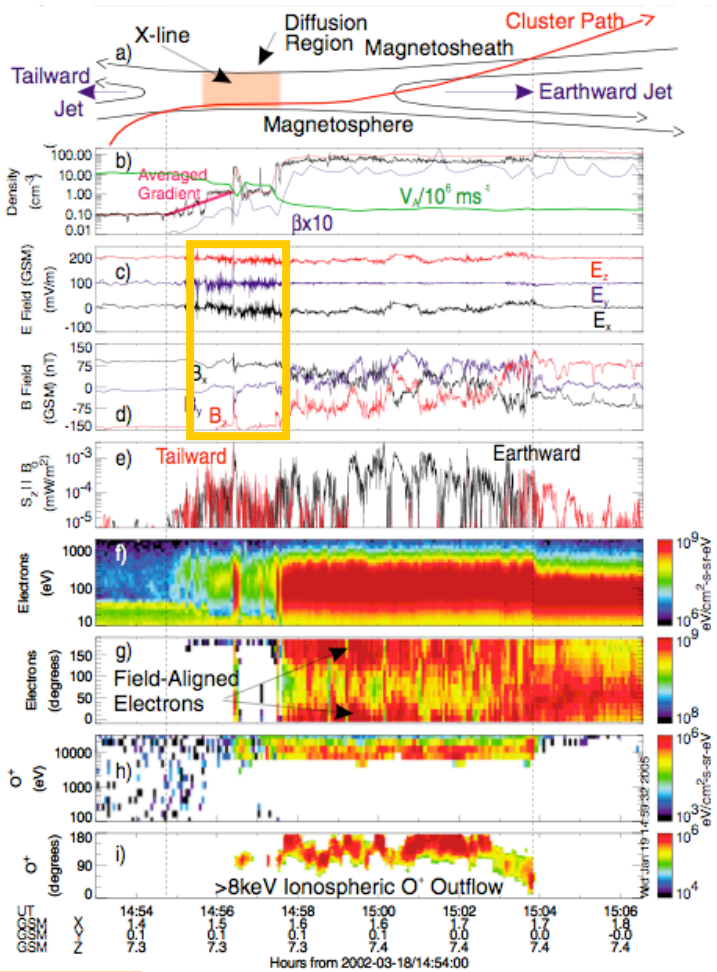
Lyon et al., 2007

Mechanisms are not Mutually Exclusive

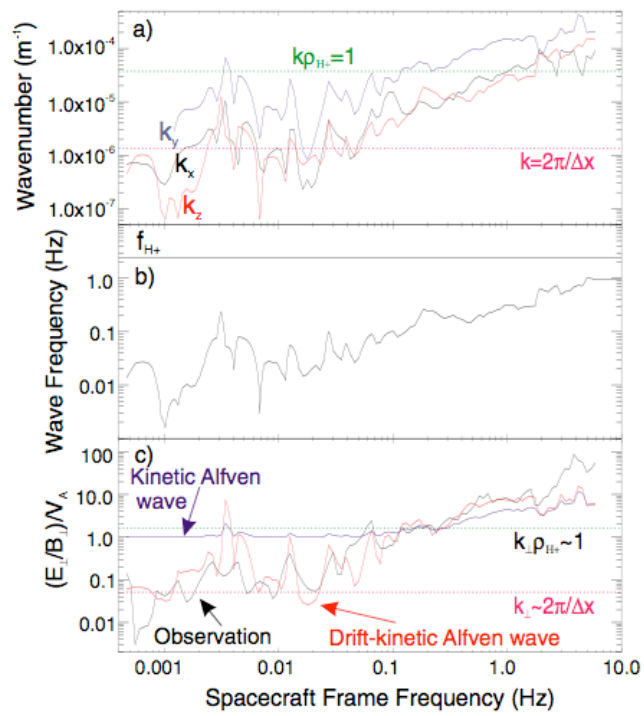
Reconnection

Kinetic Alfven Waves

Kelvin-Helmholtz Instability



Kinetic Alfven waves are associated with reconnection



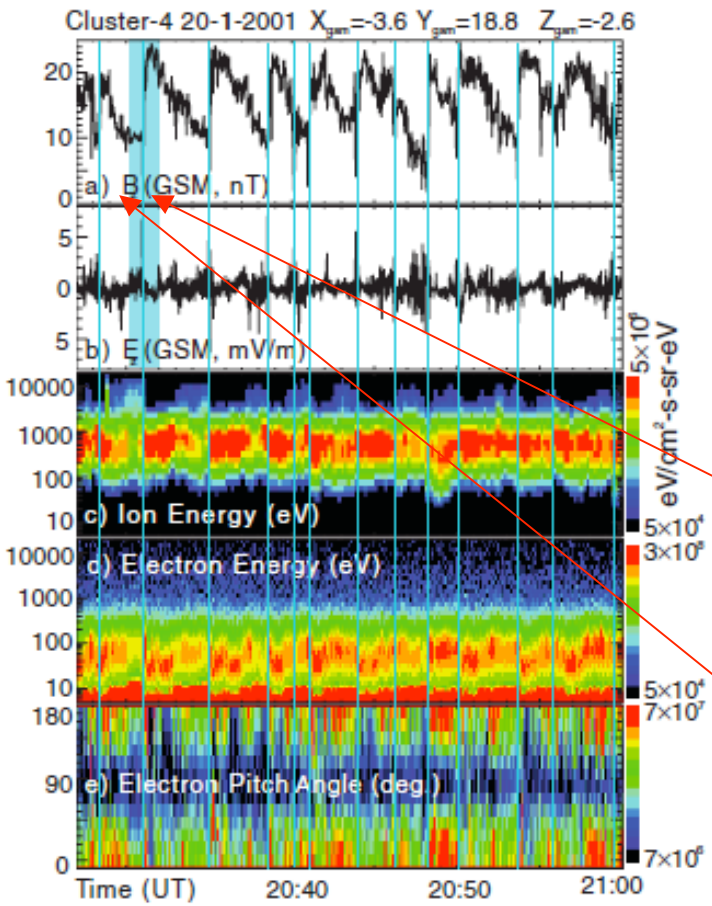
Chaston et al., 2005

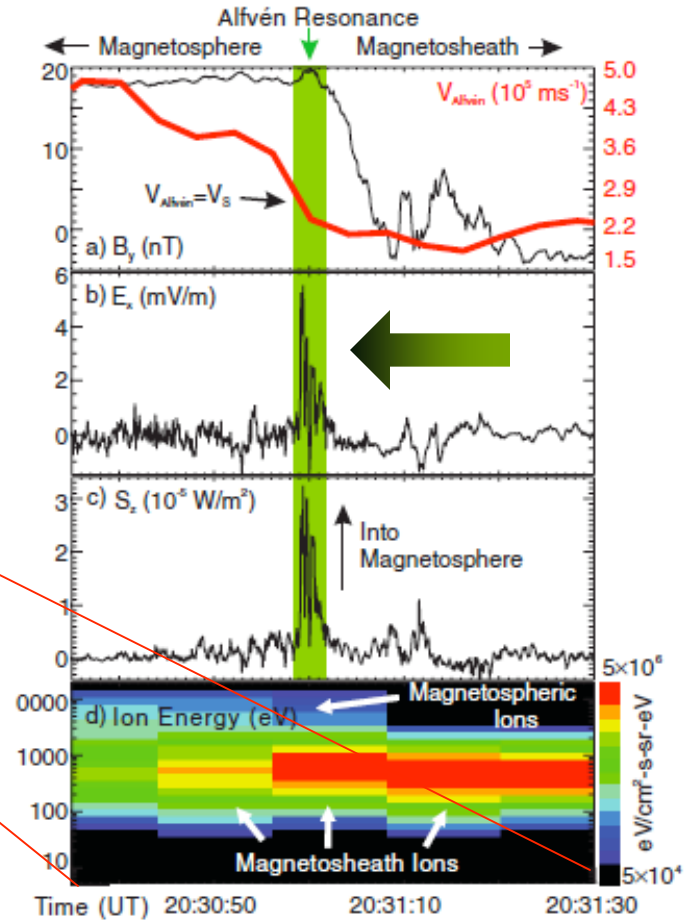
Mechanisms are not Mutually Exclusive

Reconnection

Kinetic Alfven Waves

Kelvin-Helmholtz Instability



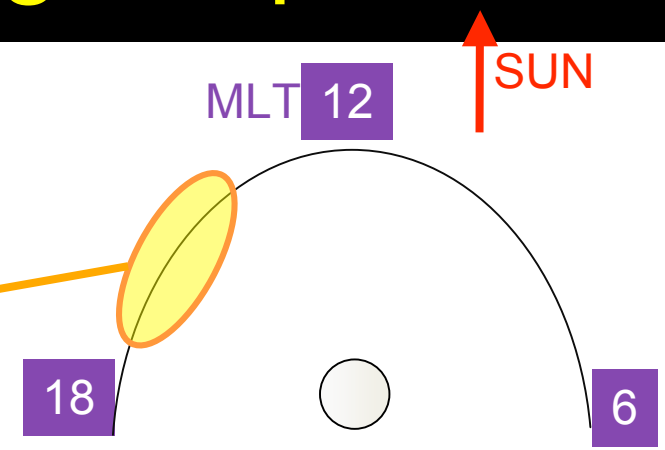


Chaston et al., 2007

Heavy Ions at the Magnetopause

	MSPBL			MSHBL		
Parameter	Dawn	Noon	Dusk	Dawn	Noon	Dusk
O^+ number density (cm^{-3})	0.014	0.021	0.053	4×10^{-3}	6×10^{-3}	0.011
O^+ mean energy (keV)	4.28	3.62	3.85	14.6	14.0	14.4
O^+ poleward velocity (km s^{-1})	57.0	66.9	52.0	88.0	162.5	119.4
O^+ normal velocity (km s^{-1})	2.4	−17.2	5.1	34.8	−16.5	15.6
Probability $P(r>1)$	0.031	0.042	0.306	[illegible]	~0	~0

Bouhram, 2005



- Heavy ions can dominate the mass content as much as 30% of the time on the dusk flank!!

ISSUE

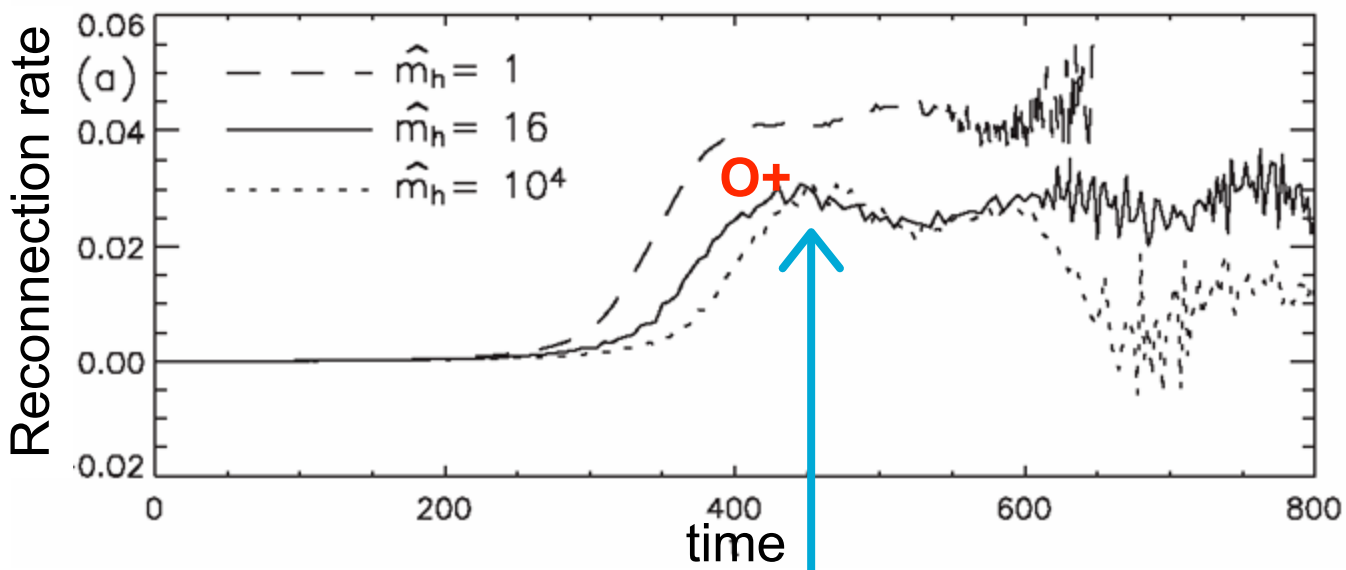
How do heavy ions affect plasma transport?

Reconnection, Kelvin-Helmholtz, Kinetic Alfven Wave

Heavy Ions and Reconnection

Proton-electron-heavy ion fluid simulation

Shay and Swizdak, 2004

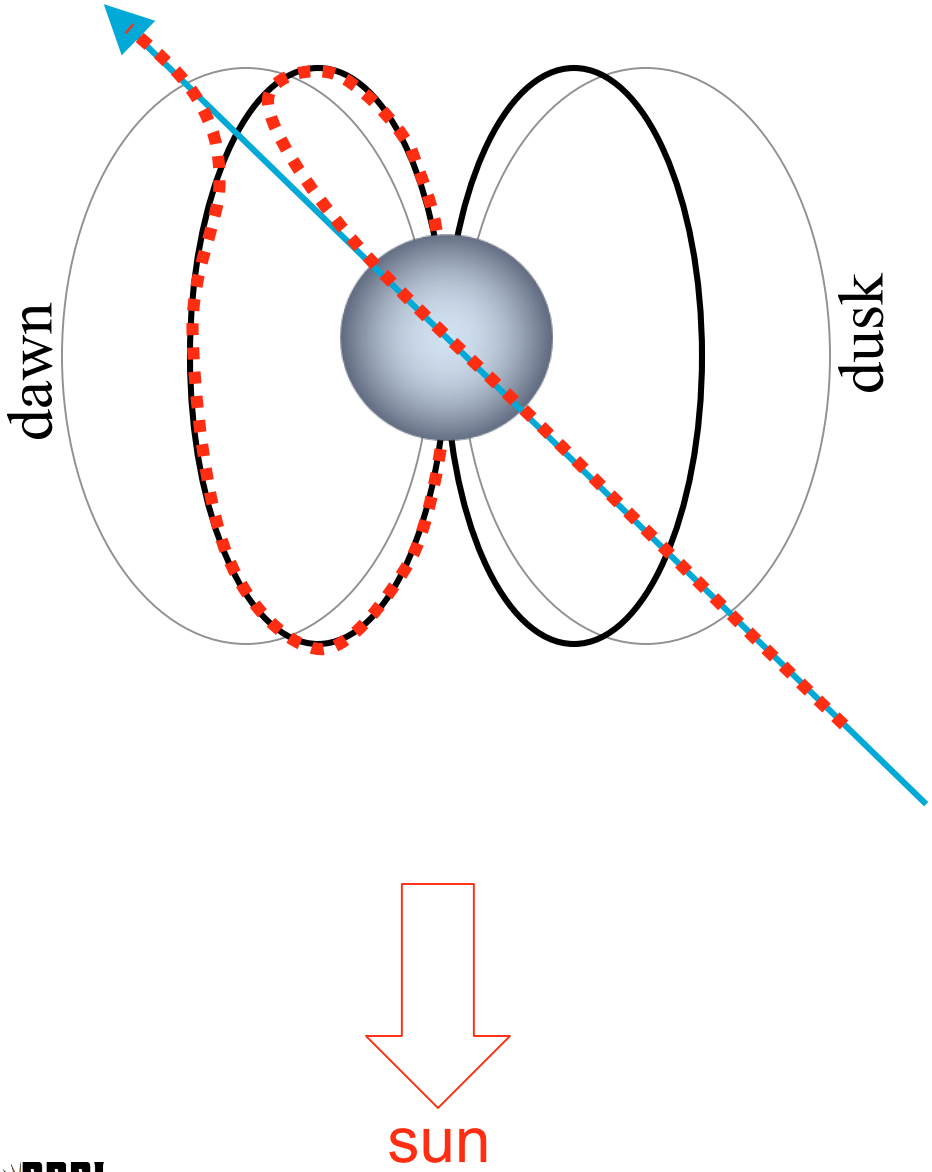


$\hat{m}_h = m_h / m_i$

Reduction of reconnection rate
(V_A is reduced)

A

Implications for Reconnection



- For configurations with **IMF B_y**
- flux transfer in steady state may be favored on the dawn flank (where there is *less oxygen*) and could lead to enhanced mass, momentum transfer on the dawn flank consistent with observations
- Single cusp reconnection could be favored ?

B

Heavy Ions and Kelvin-Helmholtz

$$(k \cdot V)^2 > \frac{(k \cdot B_{msh})^2 + (k \cdot B_{msp})^2}{4\pi\rho^*}$$

where $\rho^* = \dfrac{\rho_{msh}\rho_{msp}}{\rho_{msh} + \rho_{msp}}$

Heavy ions increase the K-H growth rate by reducing the stabilizing effect of magnetic tension

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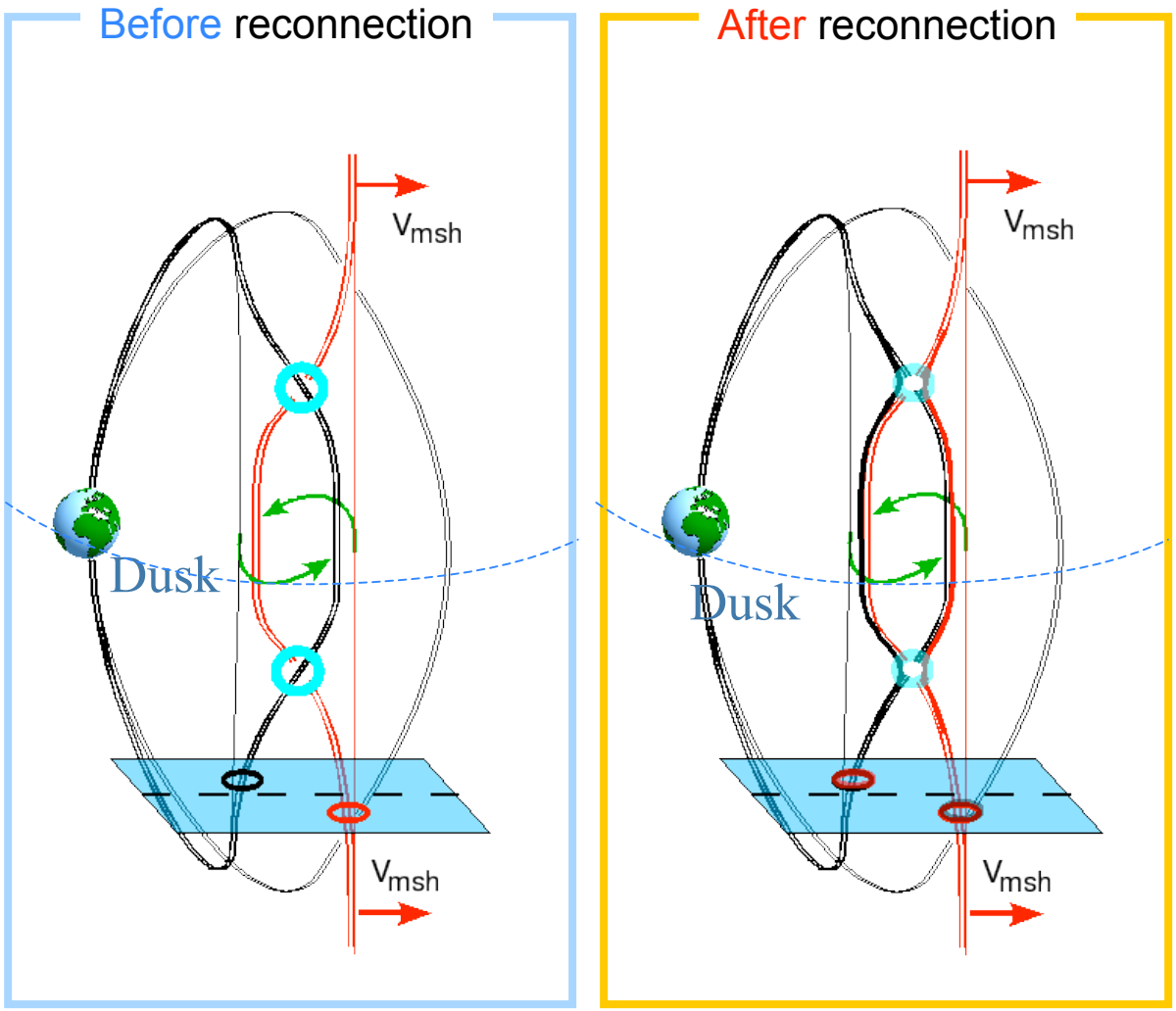
B Implications for transport resulting from reconnected flux in KH instability



Otto, 2007

Competing Effects

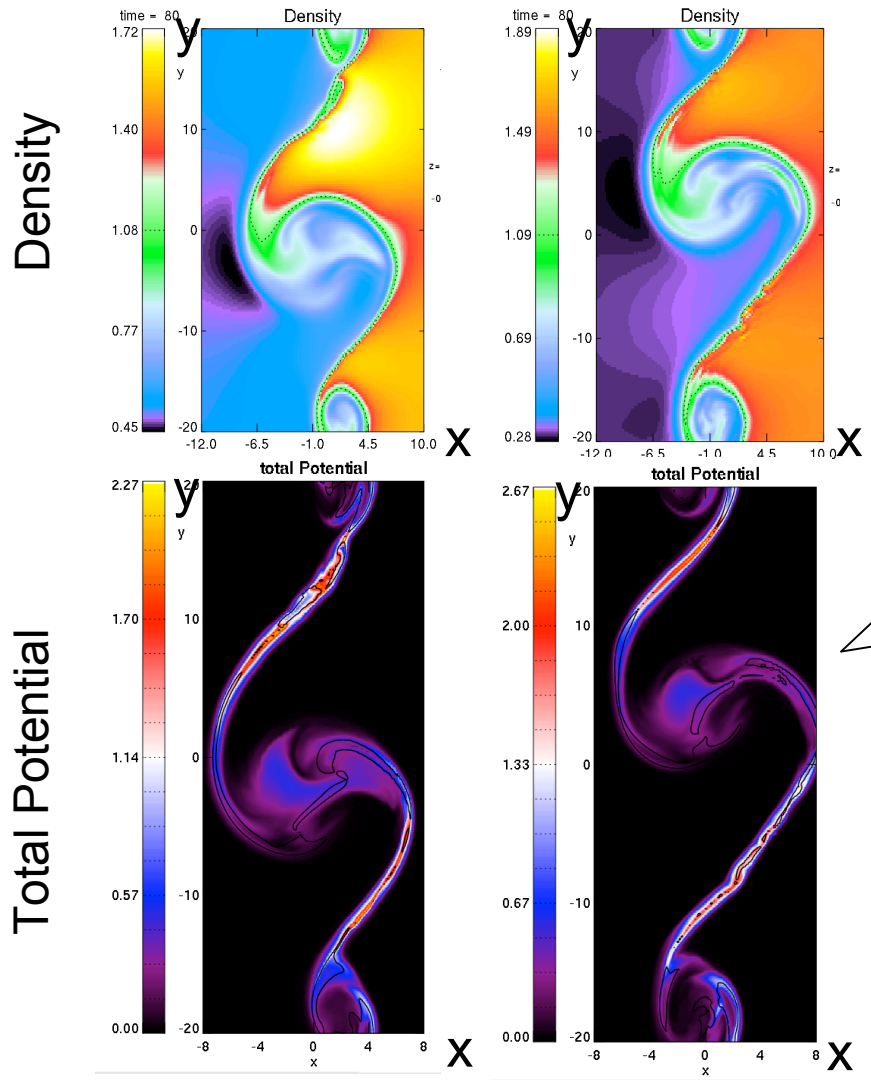
- Increased KH growth
- Reduction in V_A

Question:

Does flux transfer depend more on the interchange of flux (vortex size/growth rate) or on the reduction of V_A ?

B Implications for transport resulting from reconnected flux in KH instability

$\rho_{sphere}/\rho_{sheath}$: 1:3 1:5



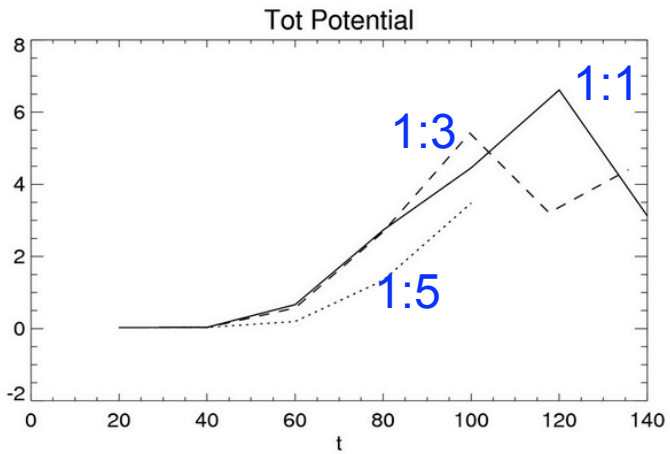
Small magnetic shear : 10°

- When vortices form, the reconnection rate adjusts to reconnect the interchanged flux

Integrated potential is a measure of the reconnection rate and is roughly the same

B Implications for transport resulting from reconnected flux in KH instability

$\rho_{sphere}/\rho_{sheath}$



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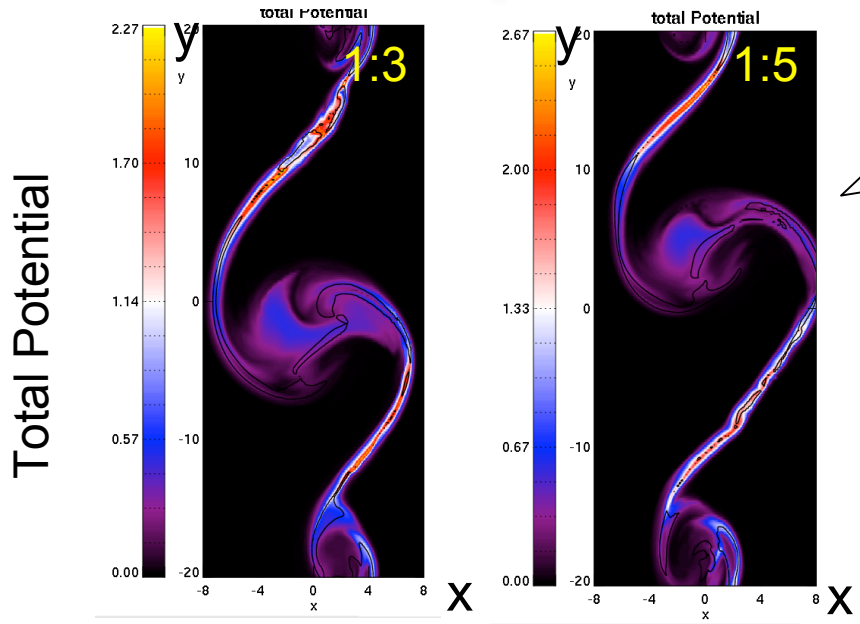

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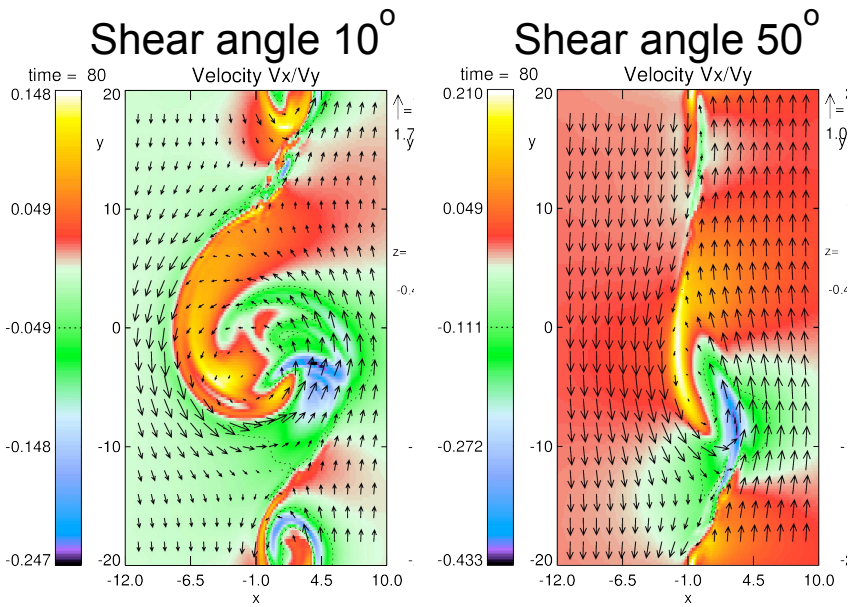


Large magnetic shear

↓

More stabilization

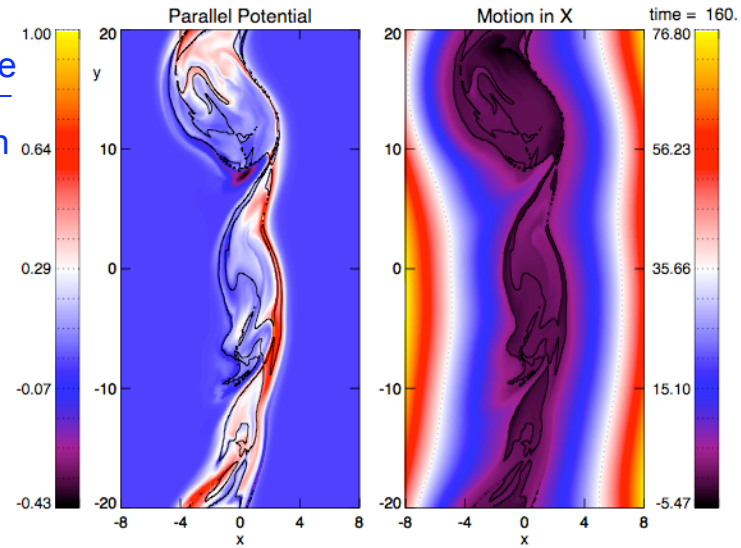
↓

Growth rate (→ vortex size) will be larger with heavy ions

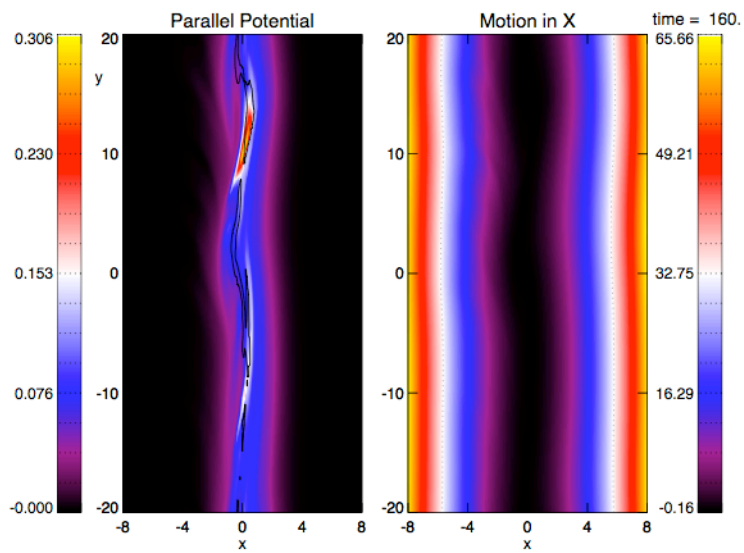
B Implications for transport resulting from reconnected flux in KH instability

$\frac{\rho_{sphere}}{\rho_{sheath}}$

1/3



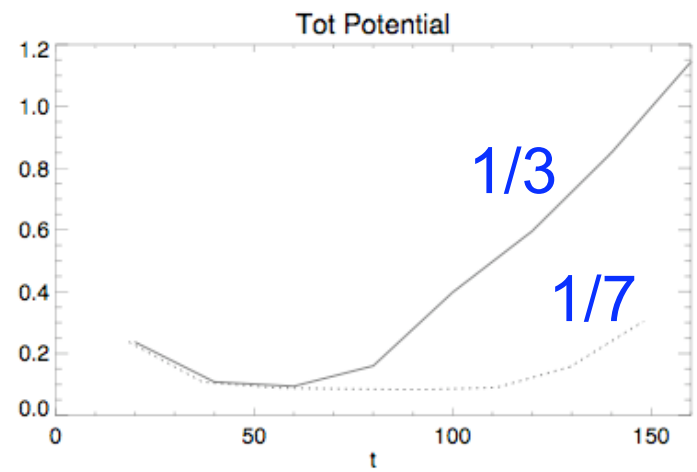
1/7



Large magnetic shear : 70°

Growth rate (→ vortex size) is larger for heavy ions

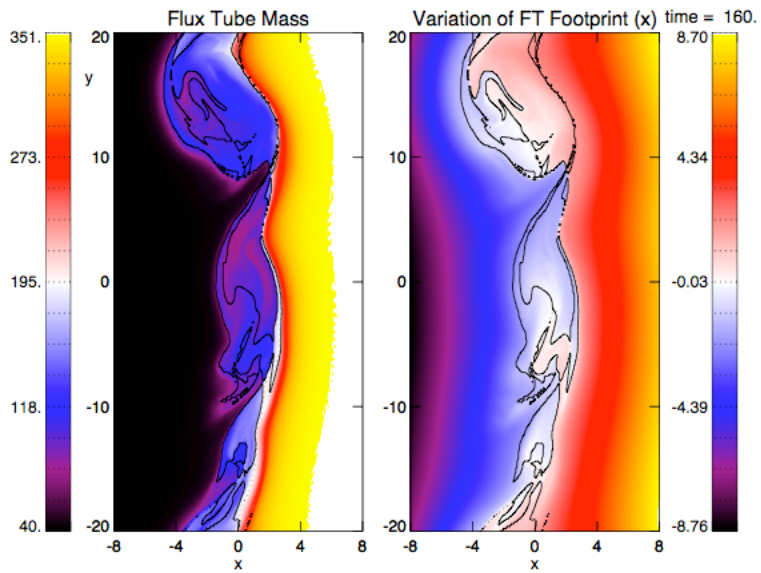
Reconnection rate larger for heavy ion case because much more flux interchange



B Implications for transport resulting from reconnected flux in KH instability

$\frac{\rho_{sphere}}{\rho_{sheath}}$

1/3



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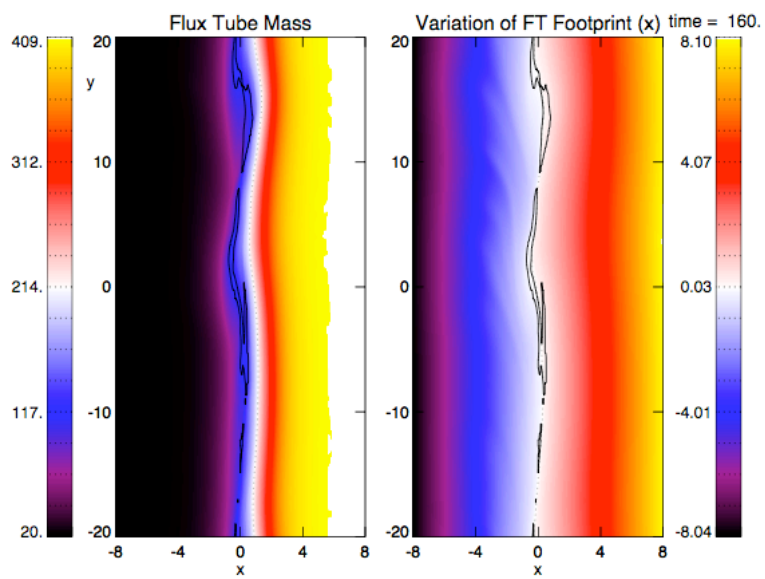
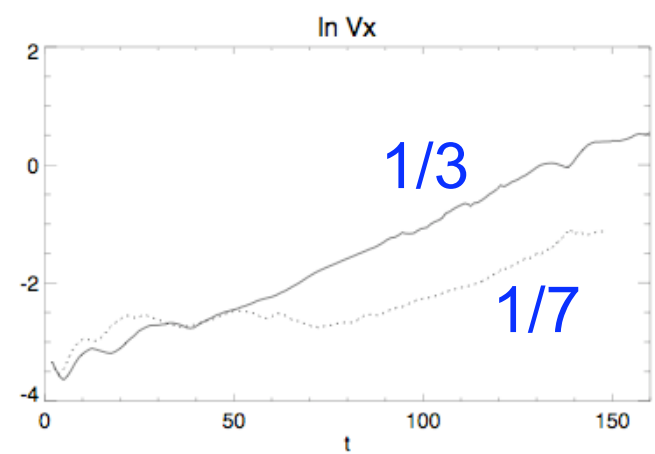
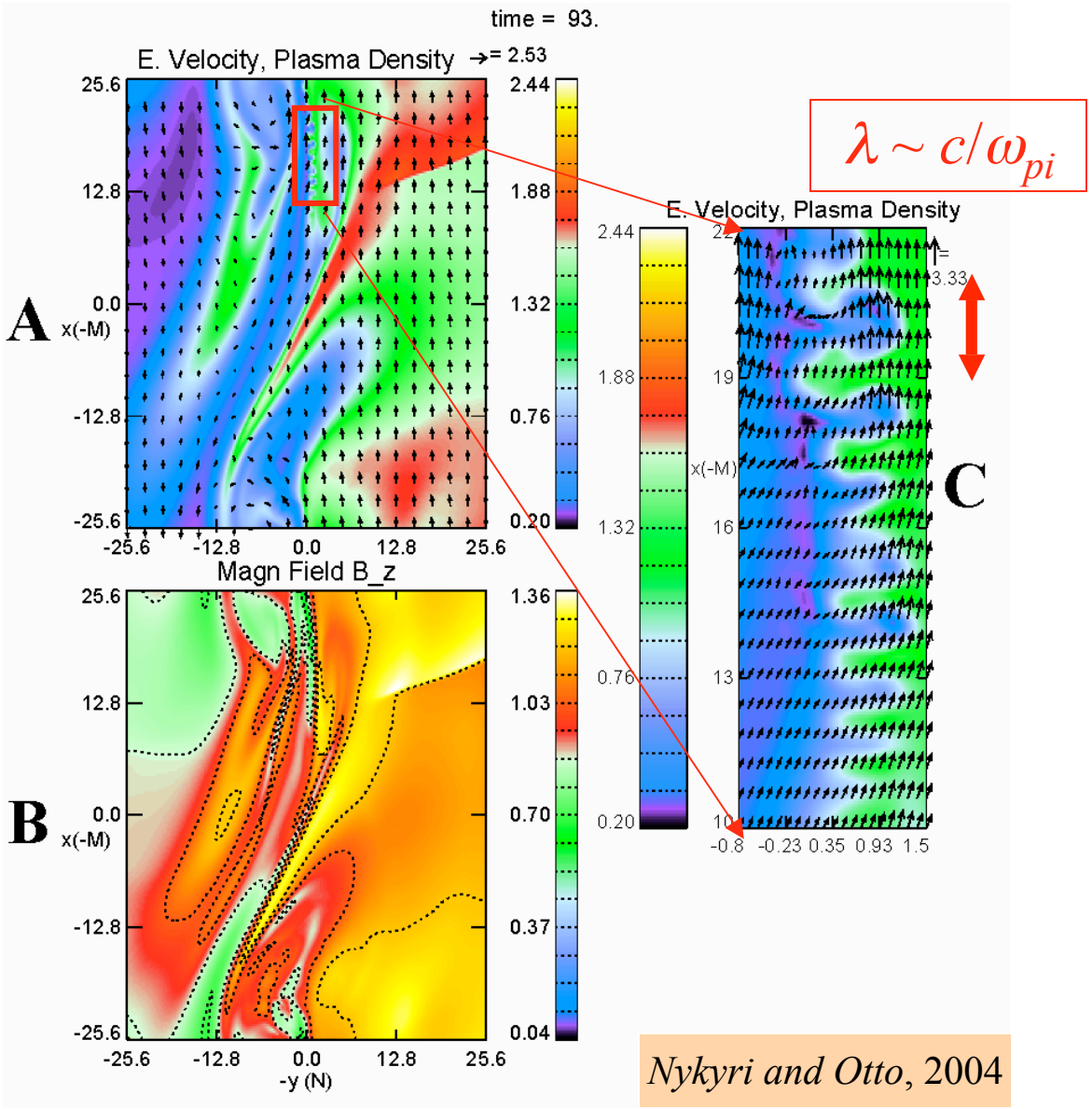


Large magnetic shear : 70°

Growth rate (→ vortex size) is larger for heavy ions and more mass transfer



B Heavy Ions and Kelvin-Helmholtz



Nykyri and Otto, 2004

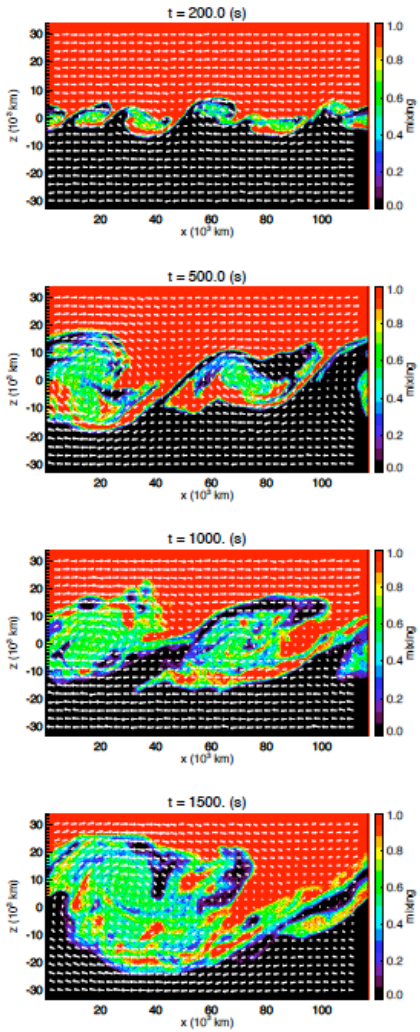
Dissipation/ secondary instability at the ion inertial length –

may inhibit vortex formation and affect mixing on kinetic scales

$$\lambda \sim c/\omega_{pi} \sim m_i^{1/2}$$

Oxygen : $\lambda_O \sim 4\lambda_i$

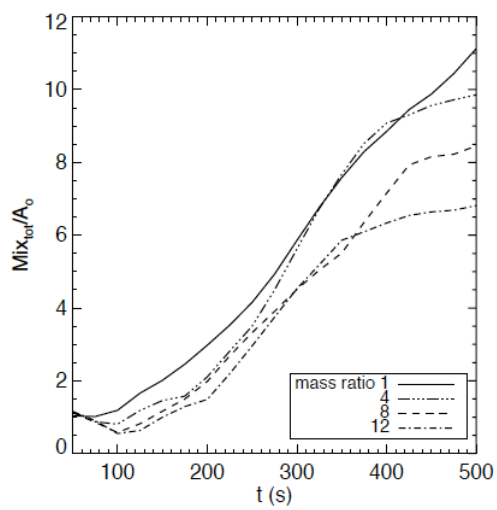
B Heavy Ions and Kelvin-Helmholtz

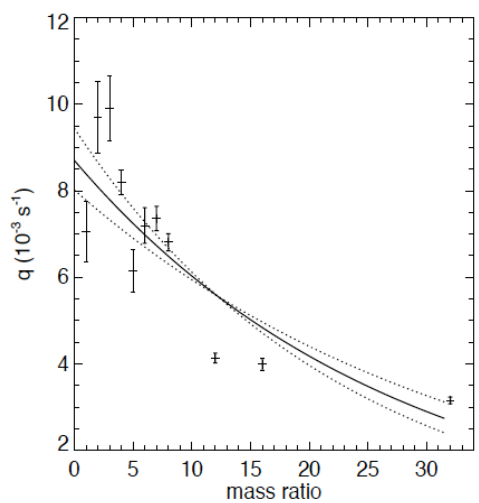


Delamere et al., 2010

Hybrid Simulations:

Dissipation/secondary instability at the ion inertial length – ***inhibits vortex formation and affect mixing on kinetic scales***





B

Implications for KH

- Reconnection rate is determined more by the line-tying condition (forcing) rather than the Alfven speed
- Effect of Magnetic Shear & Heavy Ions
  - Small shear →
    - Not as much stabilization from heavy ions
    - Not much difference in transport
  - Large shear →
    - More stabilization so KH instability is faster for large mass density (favoring the dusk flank)
    - Expect increased rate of flux transfer
    - More transport and thicker boundary layer
- Perhaps nonlinear stabilization occurs at smaller amplitude on the dusk flank leading to less transport from mixing??

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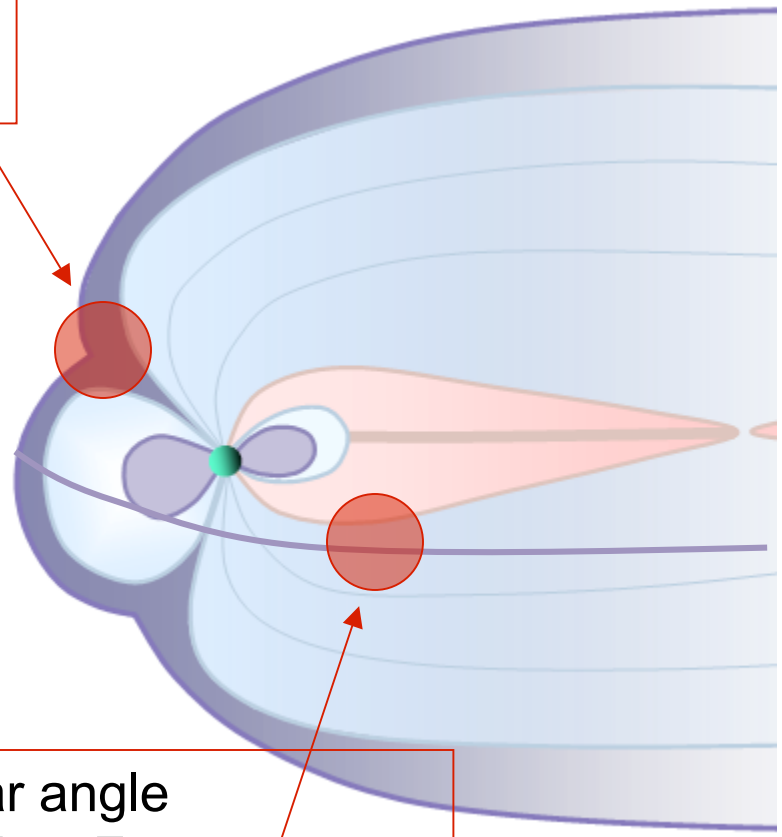
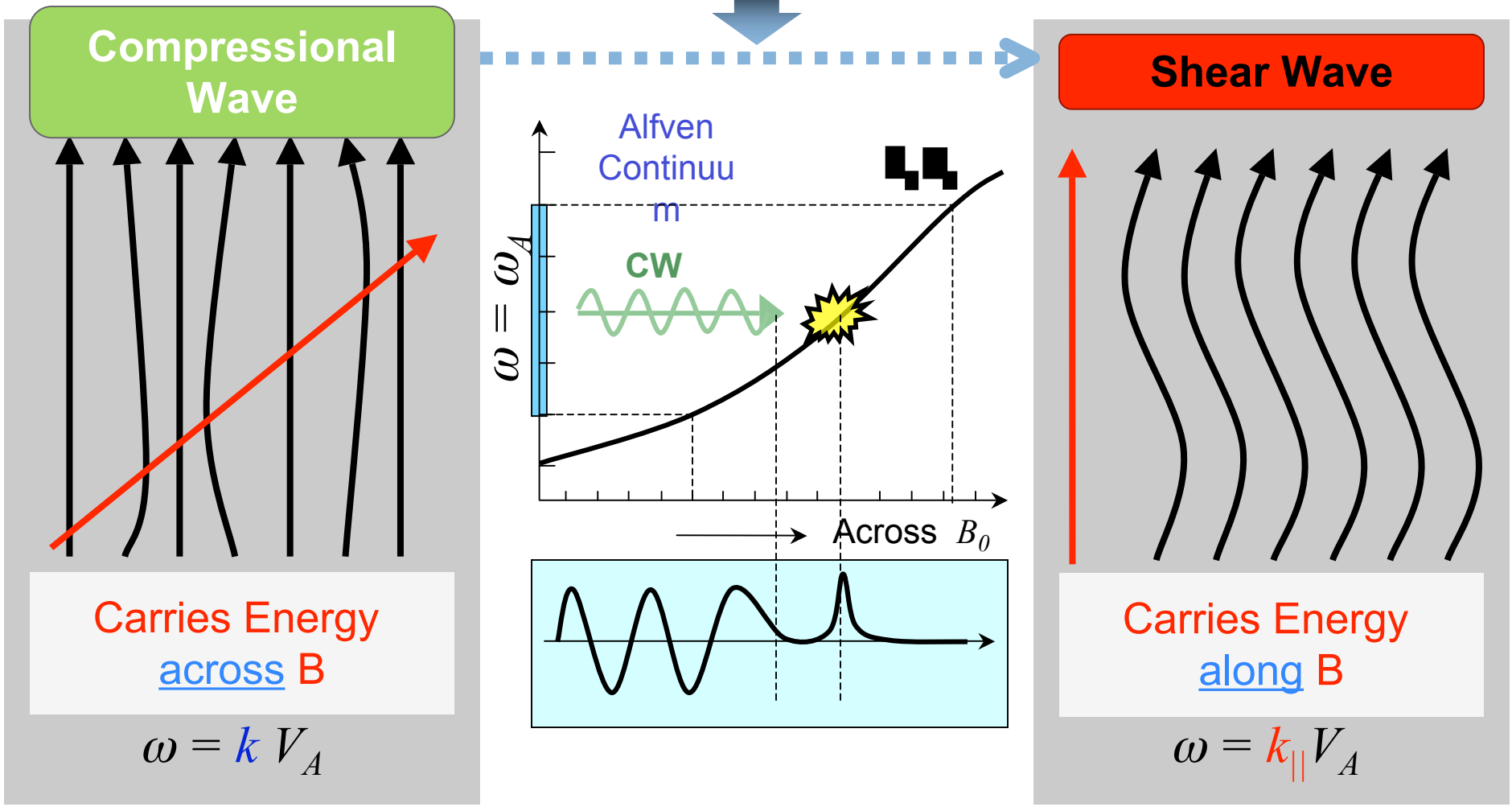
Implications for KH

Reconnection rate
: decreases



Large shear angle
KH instability : Faster
Increased rate of flux transfer
More transport

c Compressional Waves Mode Convert at the Alfven Resonance

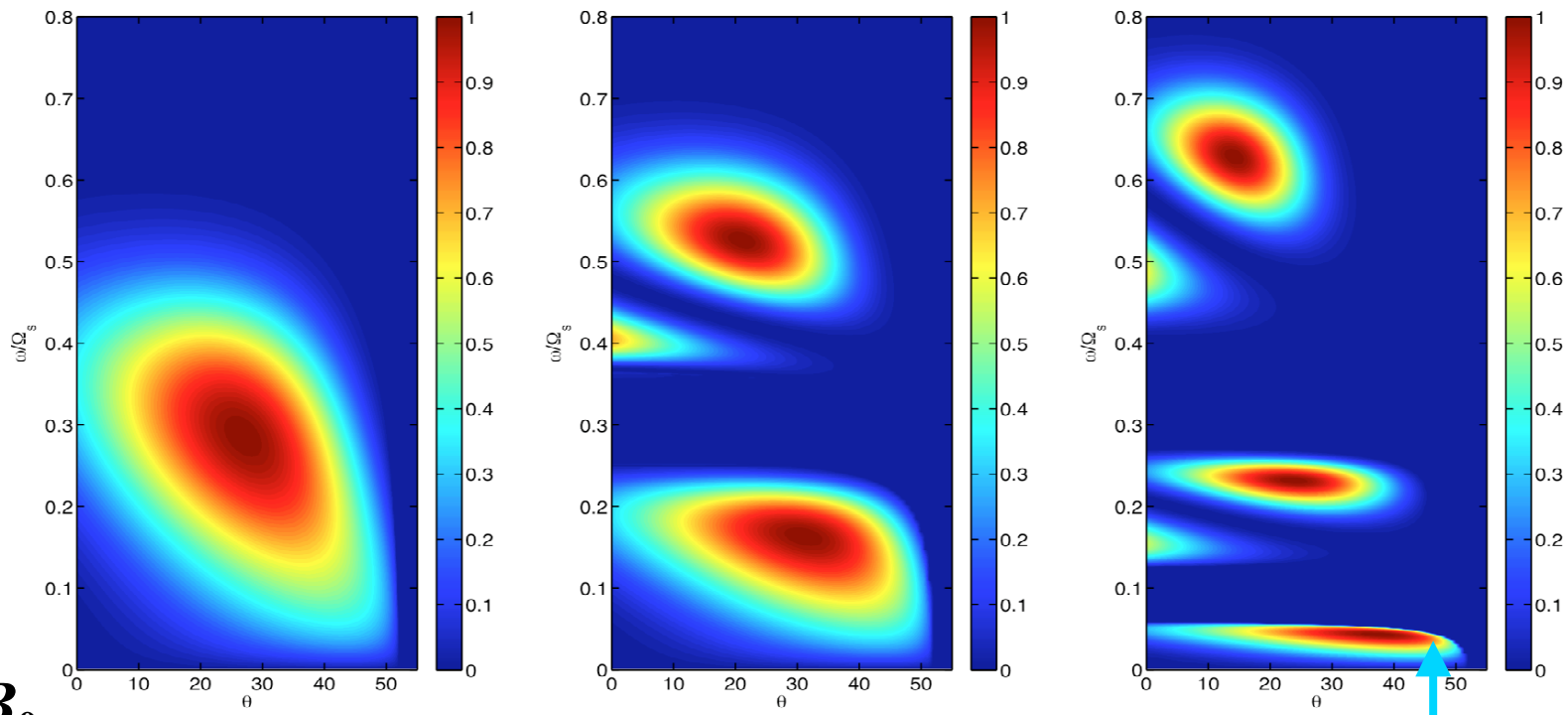


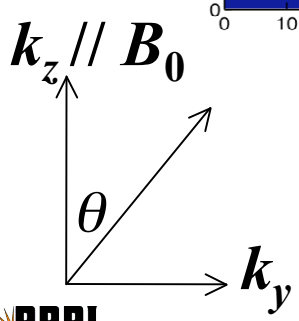
c Efficiency of Mode Conversion is Enhanced at Low Frequency by Heavy Ions

H^+ = 100%

H^+ = 90%
He^+ = 10%

H^+ = 80%
He^+ = 10%
O^+ = 10%

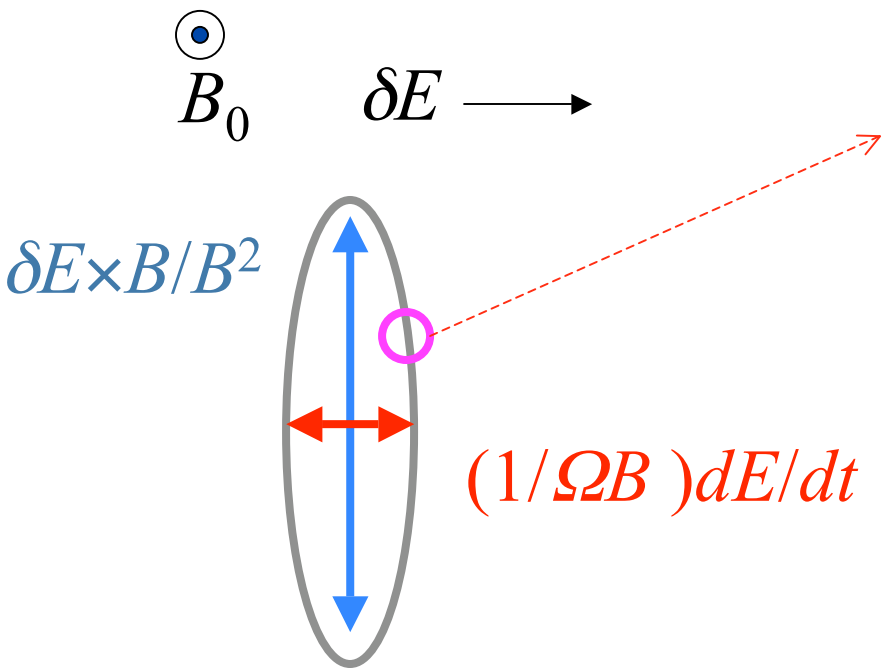




Normalized to f_{ci} at resonance

At MP~25 mHz (Pc3 range)

c Threshold for ion heating is reduced for heavy ions moving in a KAW

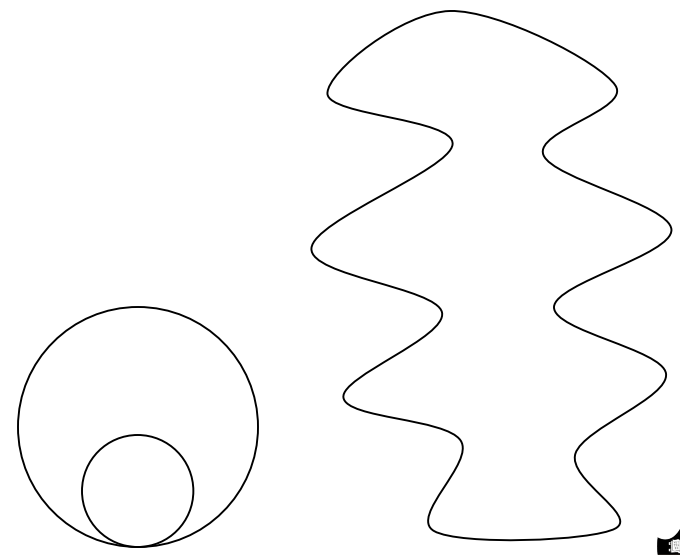


Gyromotion

$$\ddot{\xi} = \sin(\kappa\xi - \nu t) - \xi$$

$$\kappa = k_y E/(\Omega B)$$

$$\nu = \omega/\Omega$$



$$\frac{dv}{dt} = \frac{q}{m}E + v \times \Omega$$

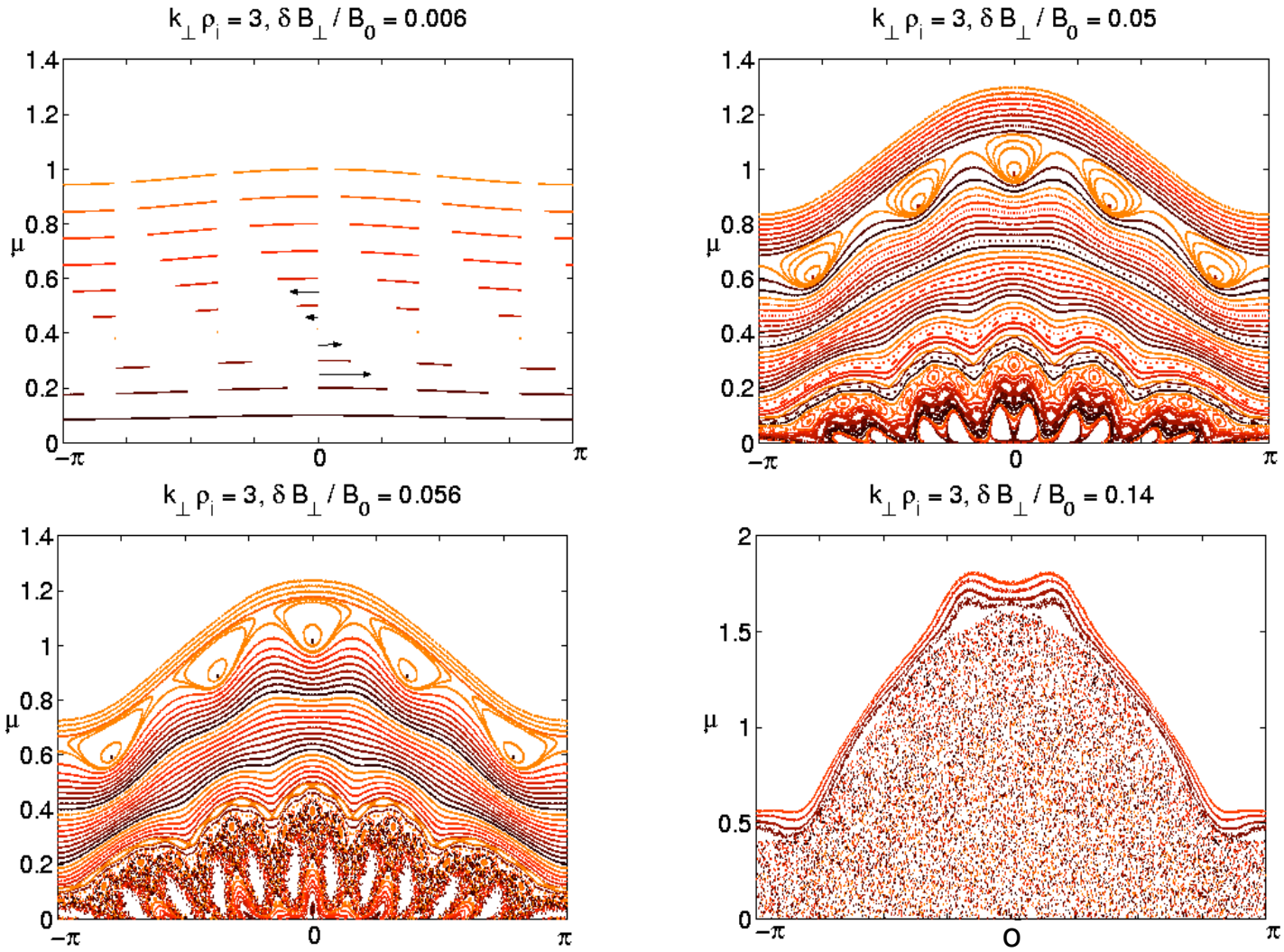
Stochastic Threshold is Reduced for Heavy Ions

$\omega = \Omega / 5$

Poincare sections

μ

μ



$\psi = k \cdot x - \omega t$

$\psi = k \cdot x - \omega t$

[Johnson and Cheng, 2001]

Stochastic Threshold is Reduced for Heavy Ions

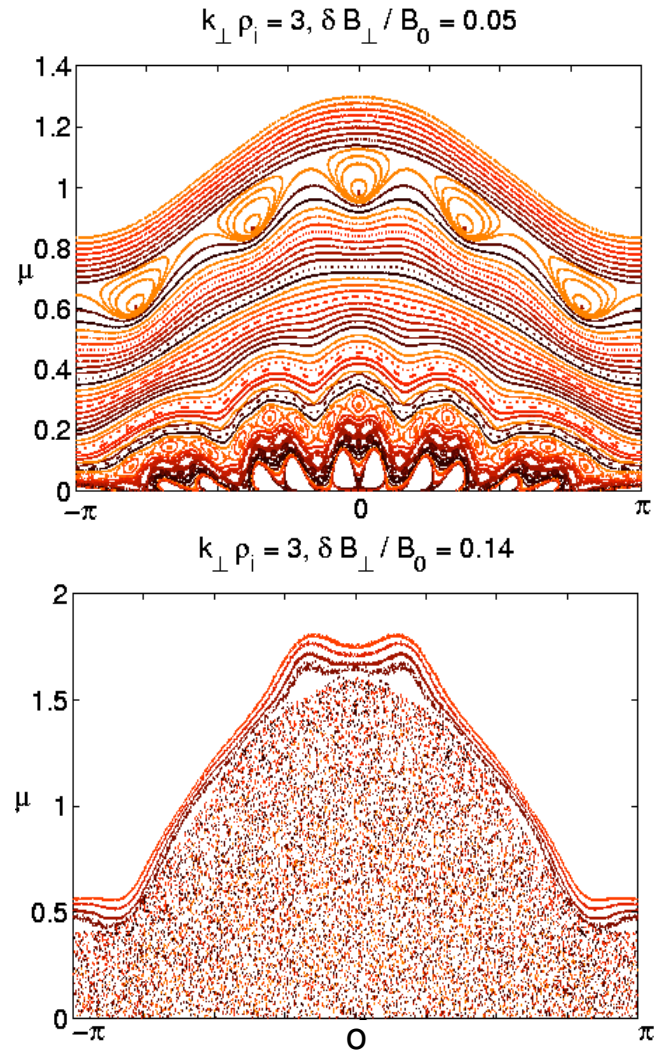
$\omega = \Omega / 5$

Threshold

$k_y x_p = k_y E_y / (B\Omega) \sim 1$

➔ $E_y \sim 1 / m$

Enhanced heating of heavy ions relative to protons



$\psi = k \cdot x - \omega t$

[Johnson and Cheng, 2001]

c Mass dependence Quasilinear Transport

$qE_{\parallel}$ force

$$D_{HM} \sim \pi \frac{k_y^2 \psi^2}{|k_z| B_0^2} f_{i,res} \sim \pi \frac{k_y^2 E_z^2}{k_z^2 |k_z| B_0^2} f_{i,res}$$

$D_{HM} \sim 2\times10^9 m^2/s$

$qV_D \times \delta B_{\perp}$

$$D_{V_d \times \delta B_{\perp}} \sim \pi \frac{k_y^2 \phi^2 \omega_d^2}{|k_z| B_0^2 \omega^2} f_{i,res} \sim \frac{k_y^2 v_i^2}{\omega^2} \left(\frac{\rho_i}{L_B}\right)^2 \left|\frac{\phi}{\psi}\right|^2 D_{HM}$$

$D > 100 D_{HM}$

$-\mu \nabla \delta B$ force

$$D_{\mu \nabla \delta B} \sim 2\pi k_y^2 \rho_i^2 \frac{v_i^2}{|k_z|} \left|\frac{\delta B_{\parallel}}{B_0}\right|^2 f_{i,res} \sim 2 \left|\frac{\delta B_{\parallel}}{B_0}\right|^2 \left|\frac{T}{e\psi}\right|^2 D_{HM}$$

$D > 100 D_{HM}$

$$\psi, \delta B_{//} \propto \rho_{mass}$$

$$f_o \sim e^{-\frac{7\sim16}{\beta}} \qquad f_H \sim e^{-\frac{1}{\beta}}$$

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Implications for KAWs

- Enhanced Wave absorption
  - Low frequency spectrum mode converts more efficiently if there are heavy ions
  - Enhanced efficiency leads to enhanced transport
- Enhanced heating of heavy ions relative to protons
- Enhanced diffusion of light ions and reduced diffusion of heavy ions

- *Transport should be enhanced on the dusk and dawn (not quite as much) flanks but the wave source may be on the dawn flank.* **???**

Summary

- Heavy ions are abundant at the magnetopause
- Increased reconnection at dawn could lead to increased entry and a dawn-dusk asymmetry
- When there is more magnetic shear, K-H should be favored on the dusk flank where it is most often reported, and momentum transport may be enhanced by heavy ions. For small shear, differences in transport may not be as signficant.
- Low frequency, compressional wave energy is more efficiently captured when there are heavy ions, and the ions are more efficiently heated