Direct Evidence for Two-Fluid Effects in Molecular Clouds

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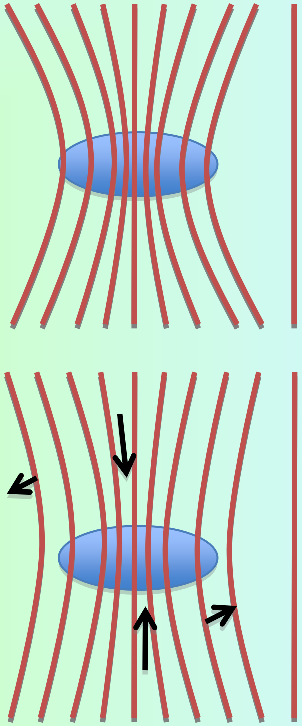
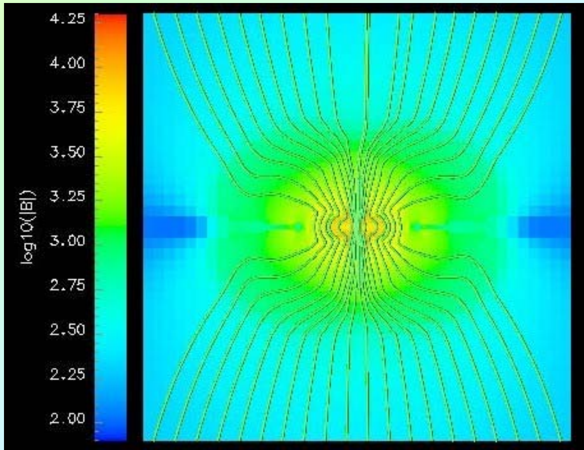
Outline

- Theoretical background on Class 0 Core Formation
  - Magnetically-regulated star formation; Fiedler & Mouschovias 1993
  - Turbulence-driven star formation; Mac Low & Klessen 2004
  - Bridging the scales; Ciolek & Basu 2006; Basu et al 2009
- New data showing that we might be tracing the dissipation (i.e. ambipolar) scales; Li & Houde 2008
- New two-fluid simulations to bridge these models; Tilley & Balsara 2010
  - Two-fluid dispersion analysis; MHD waves are damped
  - 2-fluid turbulent simulations; power spectrum of ions reduced below AD scales
  - Synthetic linewidth-size relations; agree with obs.

Magnetically-Regulated Star Formation

- Focus on the 10’s of mpc scales where prestellar cores form – need to lose **L**
- Magnetic fields coupled to ions
  - Most of material in core is neutral
  - Weak coupling – magnetic field can drift
- Magnetic fields slowly leak out of core due to ambipolar drift
- Key Challenges:
  - Why are km/s turbulent velocities observed on larger scales?
  - How do entire clouds achieve virial equilibrium?





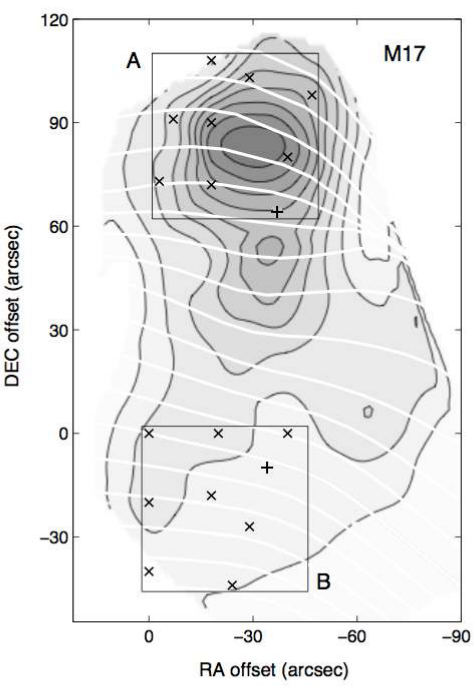
Balsara 2001

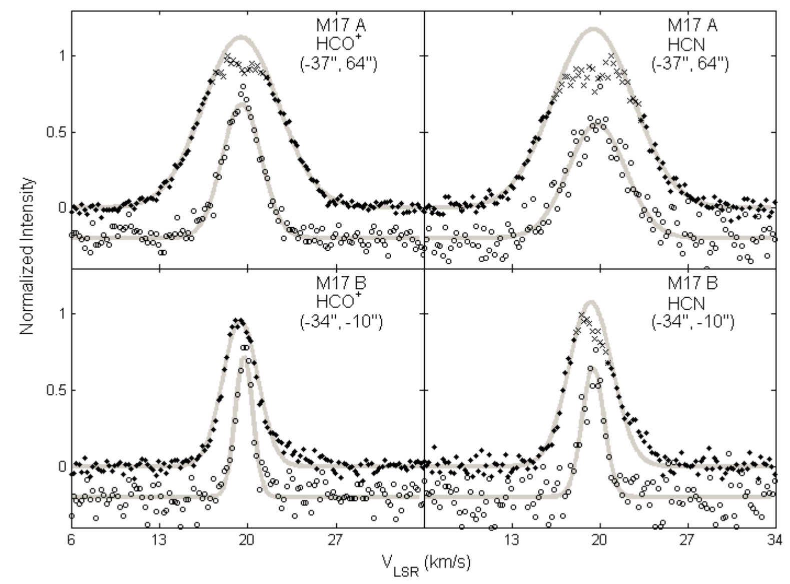
Turbulence-Driven Star Formation

- Focus on the pc scales where supersonic turbulence is observed – cores form where streams collide
- Cloud dynamics driven by internal stirring, not magnetic fields. SNR-driving; Winds; Jets
- Model requires magnetic pressure << gas pressure to form cores. Inconsistent with observations. Tilley & Pudritz 2007
- Key Challenges:
  - Evolution occurs very quickly (10^5 years)
  - How do molecular clouds survive over 10^7 years?
  - How do prestellar cores (which are observed to collapse subsonically, i.e. not on dynamical times) regulate their collapse?

Properties of the Turbulence (Small Scales)

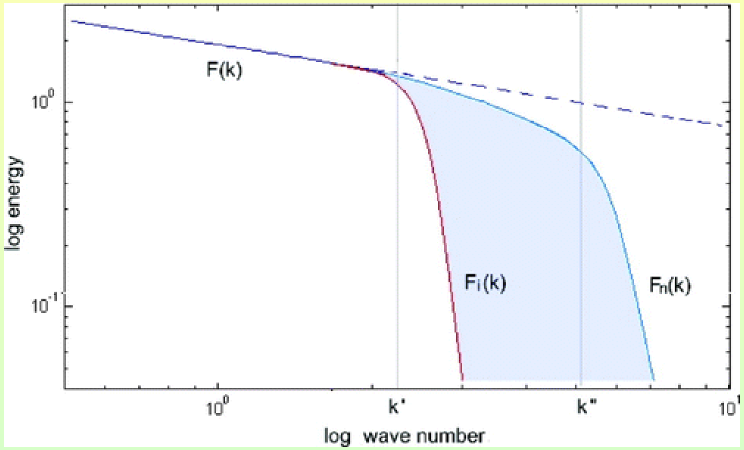
- Turbulence is expected to form an energy cascade
- Li & Houde (2008) observed that the turbulent velocity of ions (HCO^+) was smaller than that of neutral (HCN) molecules (J=4-3)
  - difference in the turbulence spectrum?
- Li et al. (2010): M17, DR21(OH), NGC 2024 show similar trends

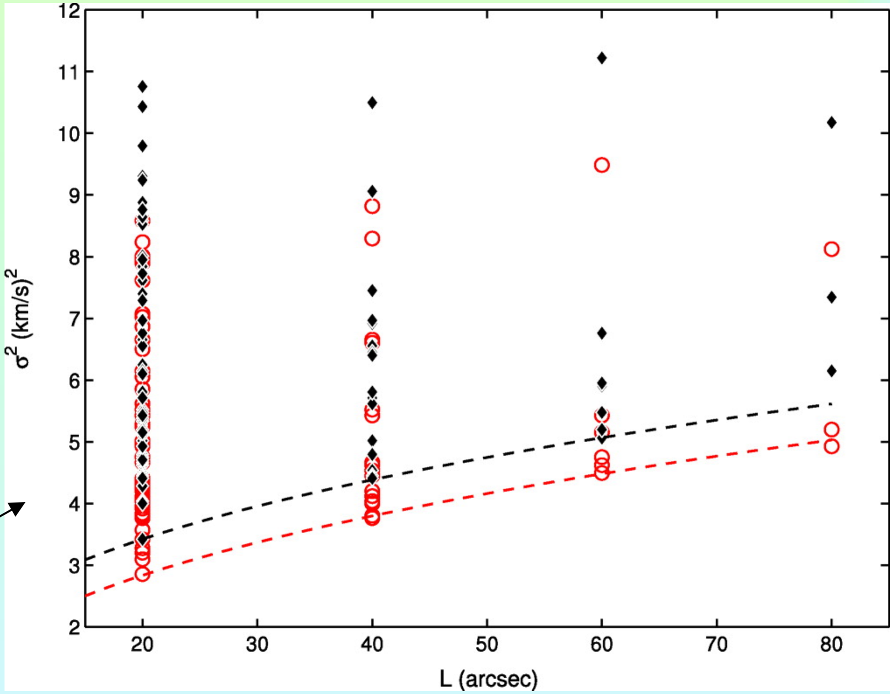




Understanding the Small Scale Results

- Ambipolar diffusion sets cutoff length for ions; not for neutrals
- Neutrals dissipate their energy on viscous scale – 5 orders smaller.
- Ions should have attenuated specta or steeper spectral slope than neutrals at (the small) ambipolar diffusion scales

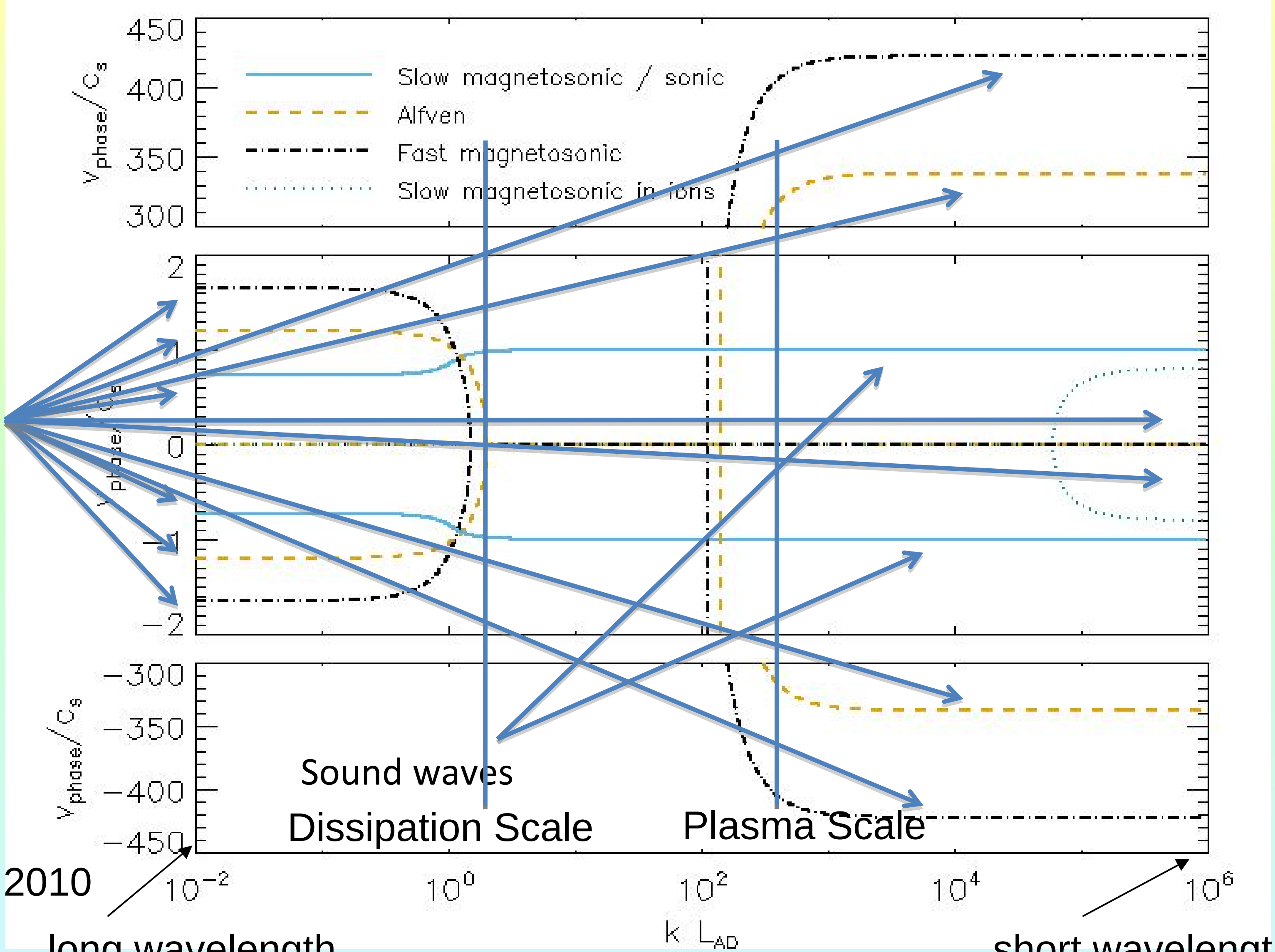




Linewidth-size relation for neutrals & ions →
Black – neutrals ; Red – ions

Wave Propagation in Partially-Ionized Systems

(Two-fluid dispersion analysis with ionization fraction 10^{-6} shown)



Fast Magnetosonic Waves

Slow Magnetosonic Waves

Alfvén Waves

Sound waves

Dissipation Scale

Plasma Scale

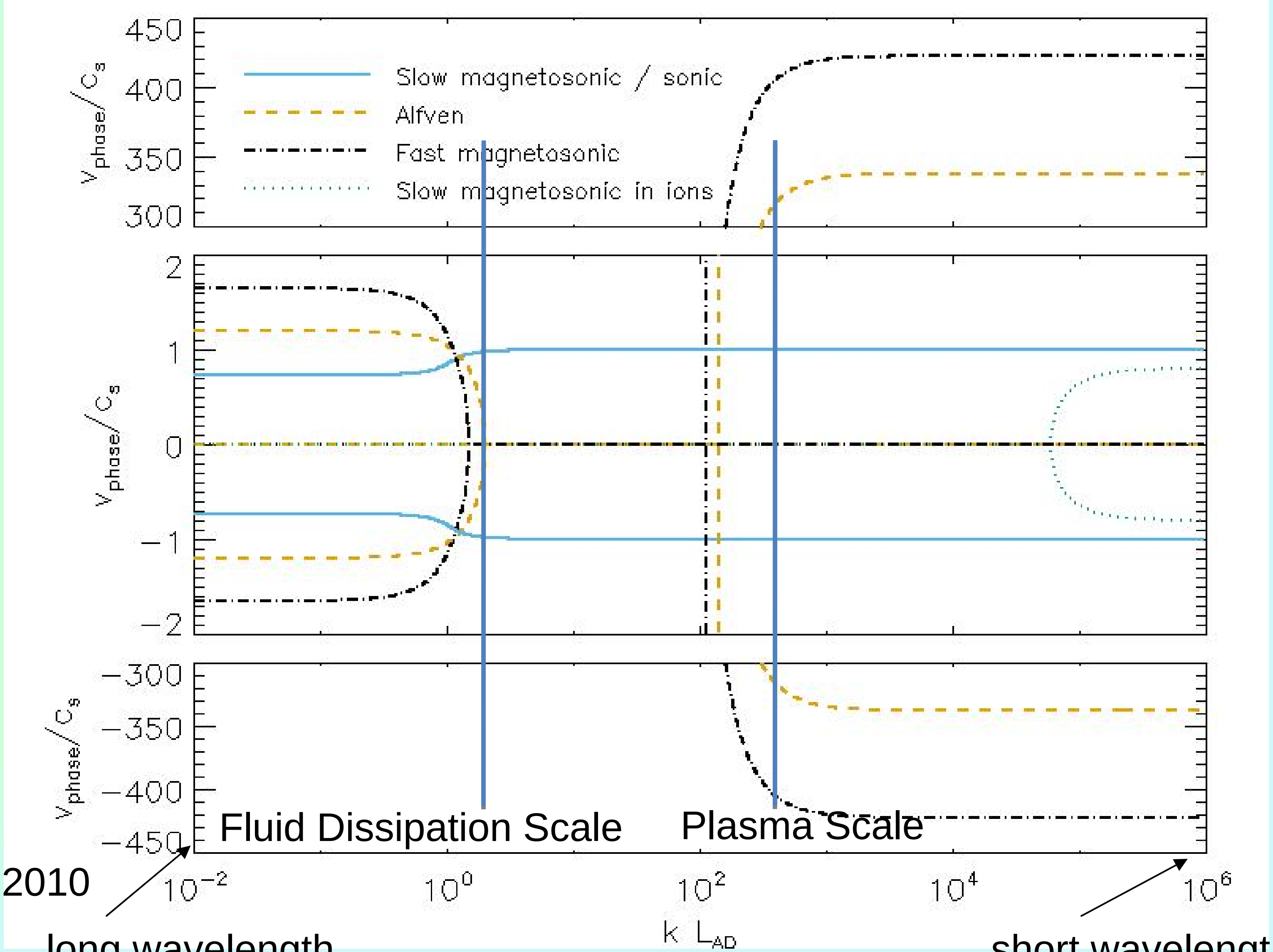
long wavelength

short wavelength

Balsara 1996
Tilley & Balsara 2010

Wave Propagation in Partially-Ionized Systems

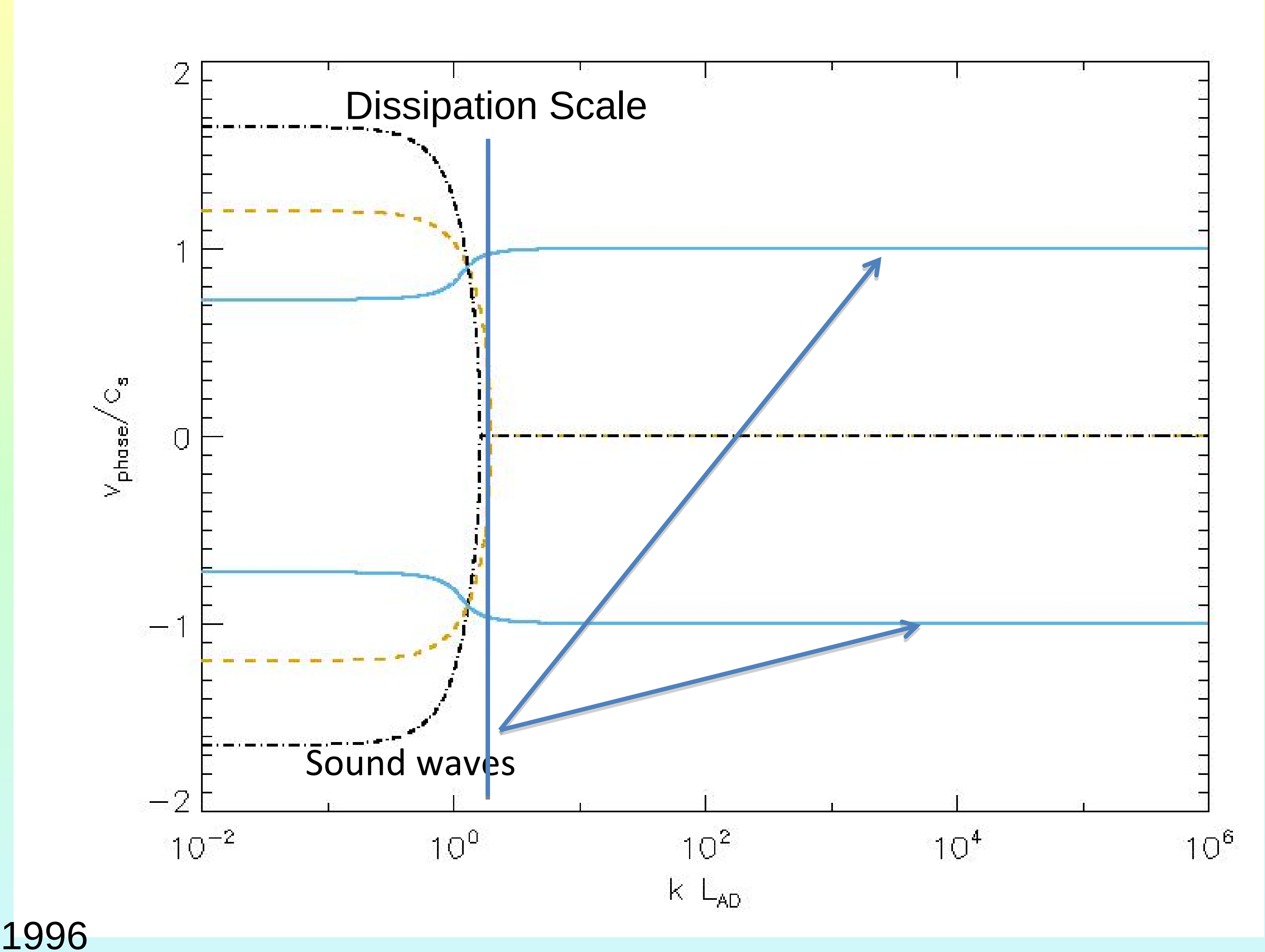
(Two-fluid dispersion analysis with ionization fraction 10^{-6} shown)



Balsara 1996
Tilley & Balsara 2010

Turbulence with Single-Fluid Ambipolar Diffusion

(dispersion analysis of two-fluid with heavy ion approximation also done)



Dissipation Scale

Sound waves

from Balsara 1996

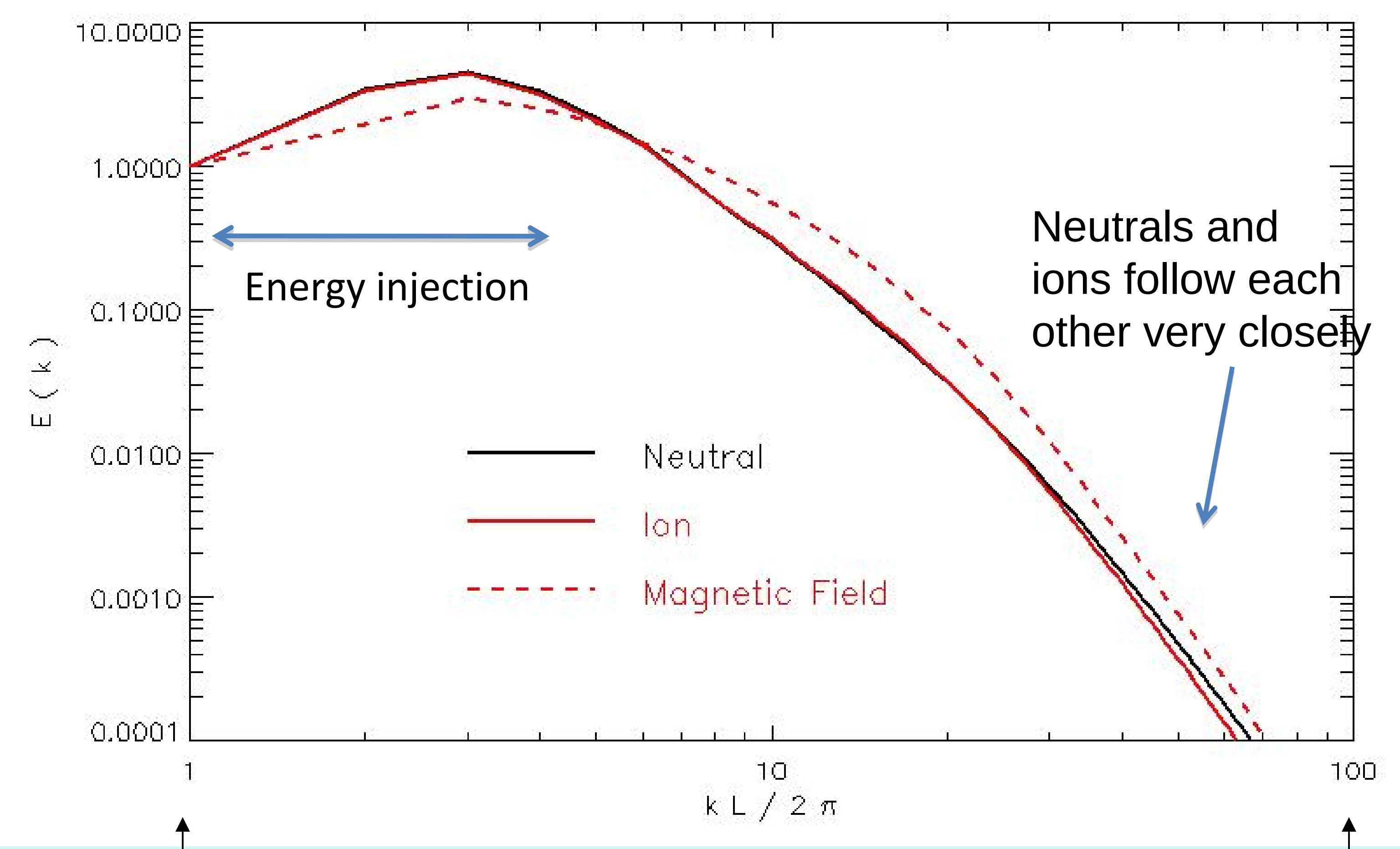
Our Simulations of Two-Fluid Turbulence

- RIEMANN code
- Compare ionization fractions from 10^{-2} to 10^{-6}
- Continually driven by adding a spectrum of kinetic energy at large wavelengths
- Alfven speed in ions needs to be resolved – makes timesteps v. small & simulations v. challenging

- Big Question: Is there a difference in the character of the turbulence at and beneath the dissipation scale? How does it reflect on measurements that are made at larger scales?

Energy Spectrum – Well-Ionized (10^{-2})

(Energies normalized at $k=2\pi/L$; all waves survive)



Energy injection

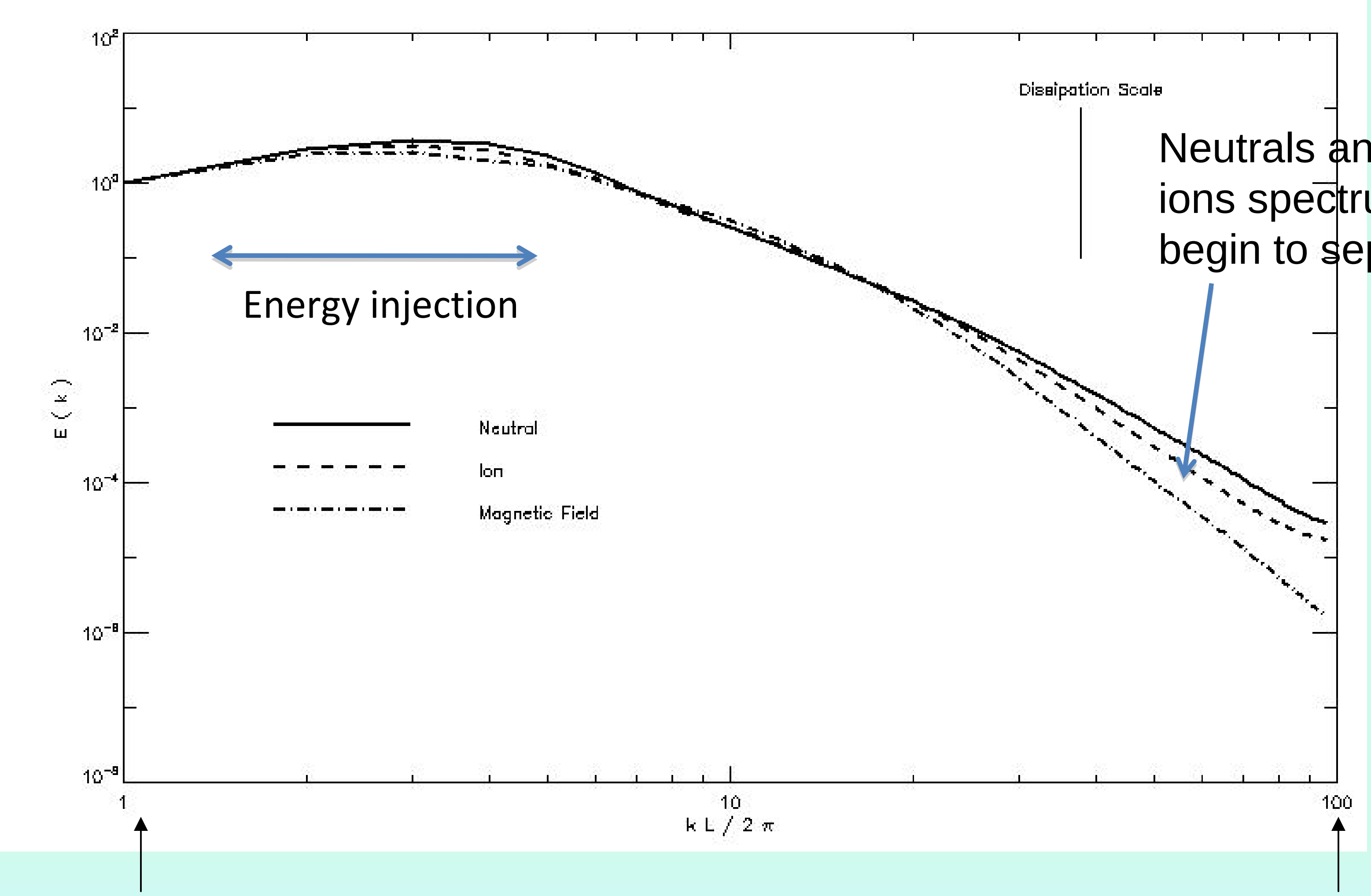
Neutrals and ions follow each other very closely

long wavelength

short wavelength

Energy Spectrum – Less Ionized (10^{-3})

(Alfven & fast magnetosonic waves drop out in the ionized fluid below dissipation scale)



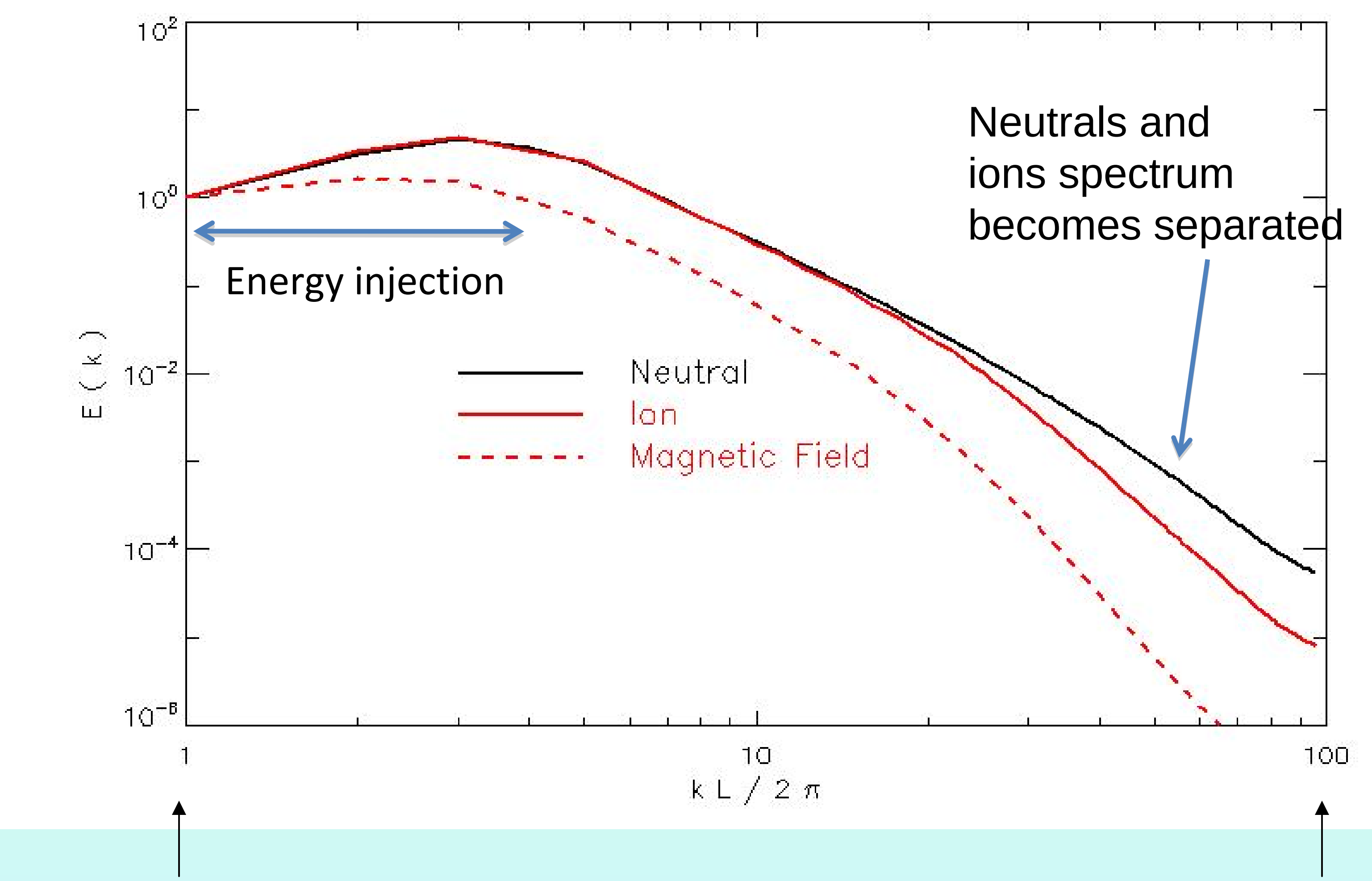
Energy injection

Neutrals and ions spectrum begin to separate

long wavelength

short wavelength

Energy Spectrum – Poorly Ionized (10^{-5})



Energy injection

Neutrals and ions spectrum becomes separated

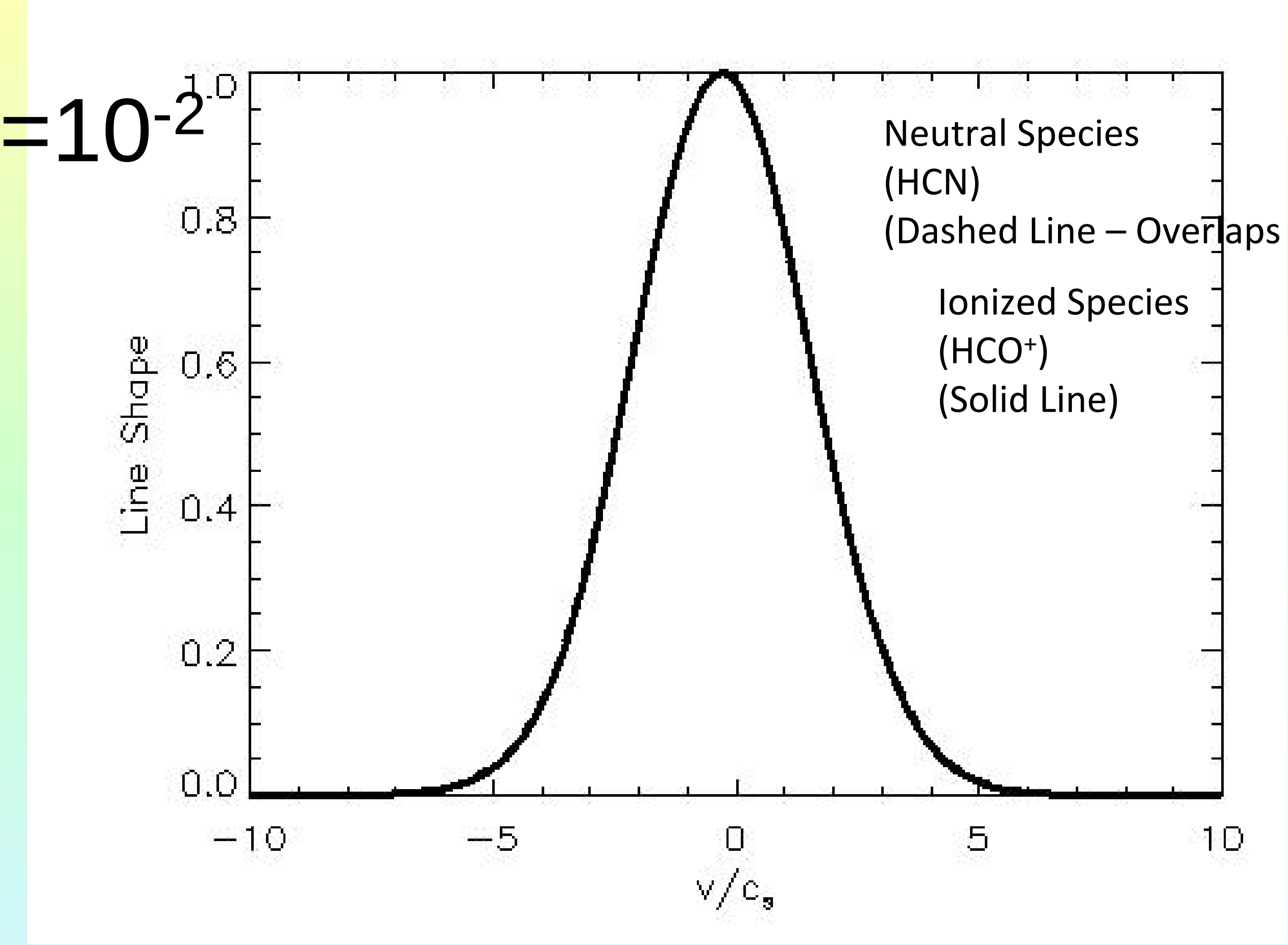
long wavelength

short wavelength

Line Widths of Neutral and Ionized Species

(Synthetic Line Profiles)

$\xi = 10^{-2}$



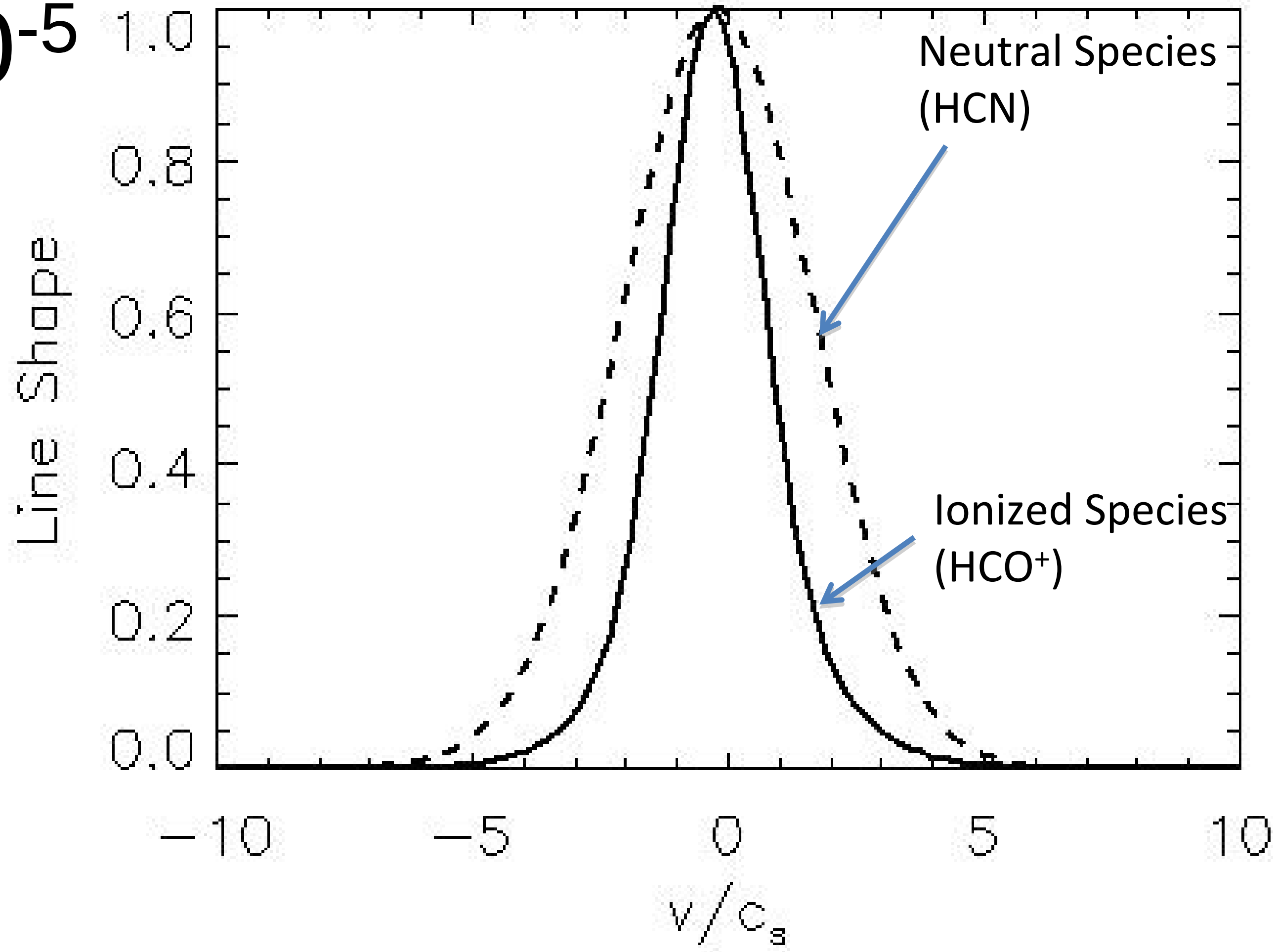
Neutral Species
(HCN)
(Dashed Line – Overlaps with solid)

Ionized Species
(HCO^+)
(Solid Line)

Line Widths of Neutral and Ionized Species

(Synthetic Line Profiles)

$\xi = 10^{-5}$



Neutral Species (HCN)

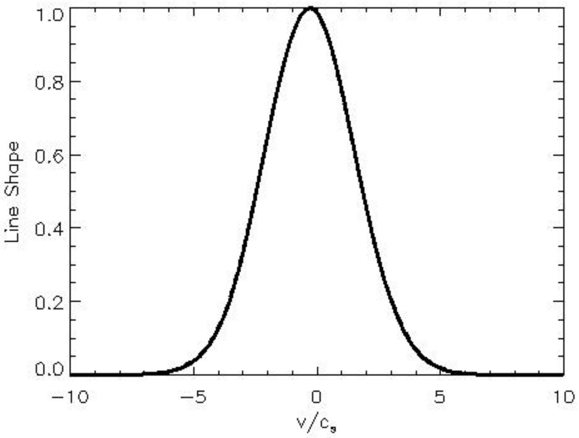
Ionized Species (HCO^+)

Tilley & Balsara 2010

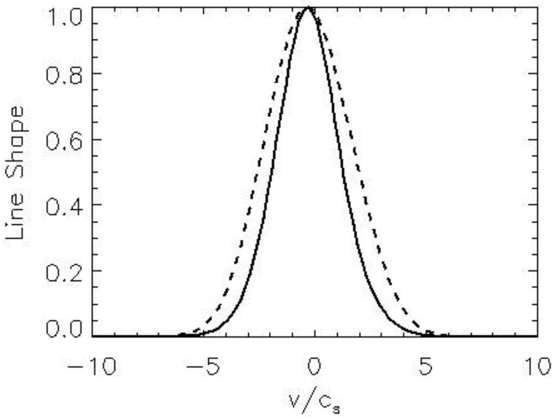
Comparison at Different Ionizations

Difference between ion and neutral linewidths increases at smaller ionization fractions

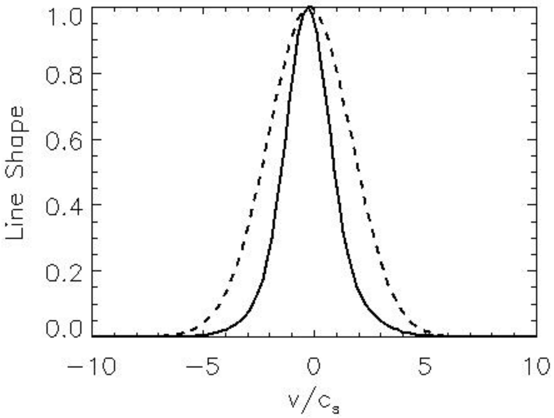
$\xi = 10^{-2}$



$\xi = 10^{-4}$

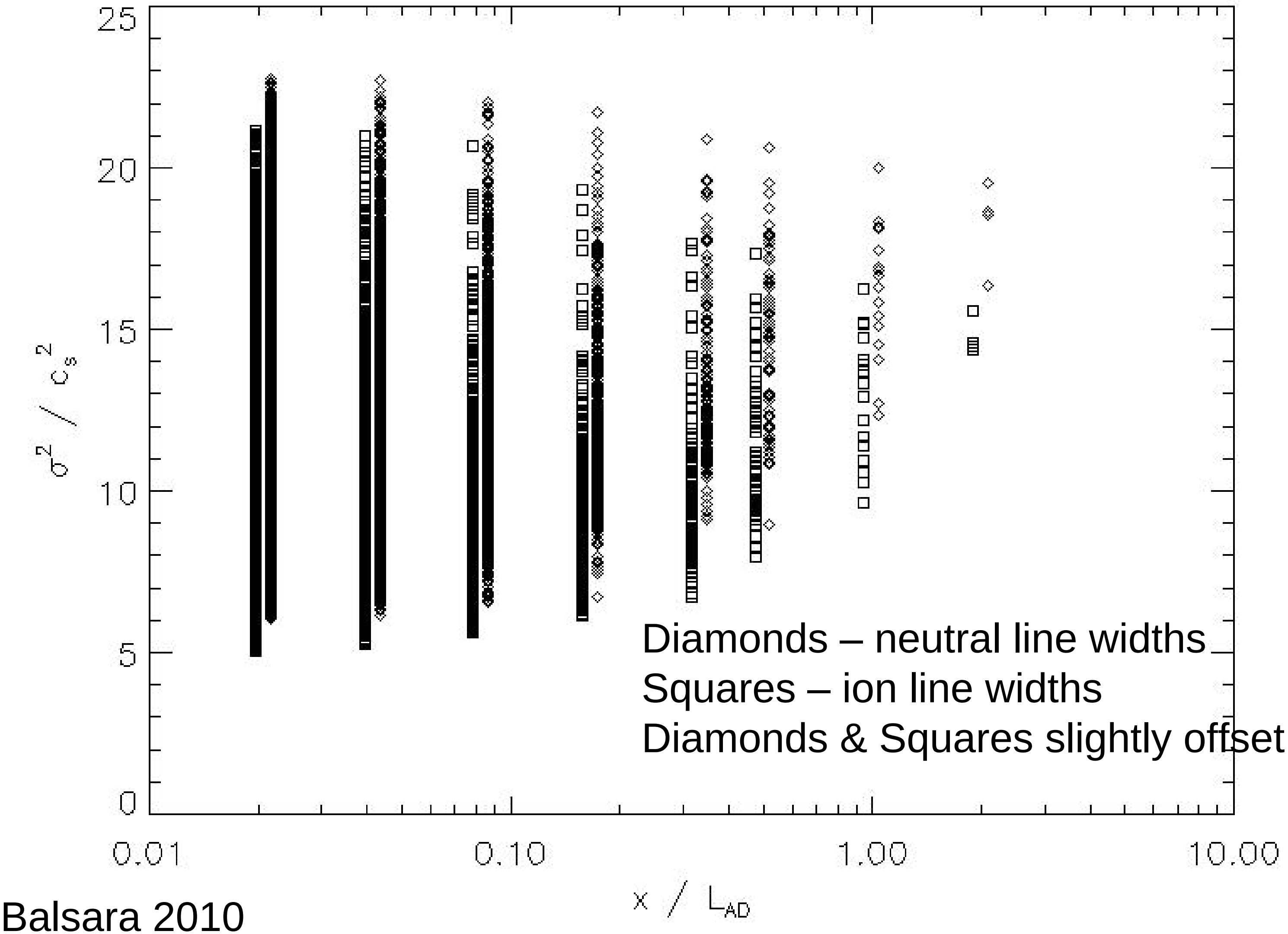


$\xi = 10^{-5}$



Tilley & Balsara 2010

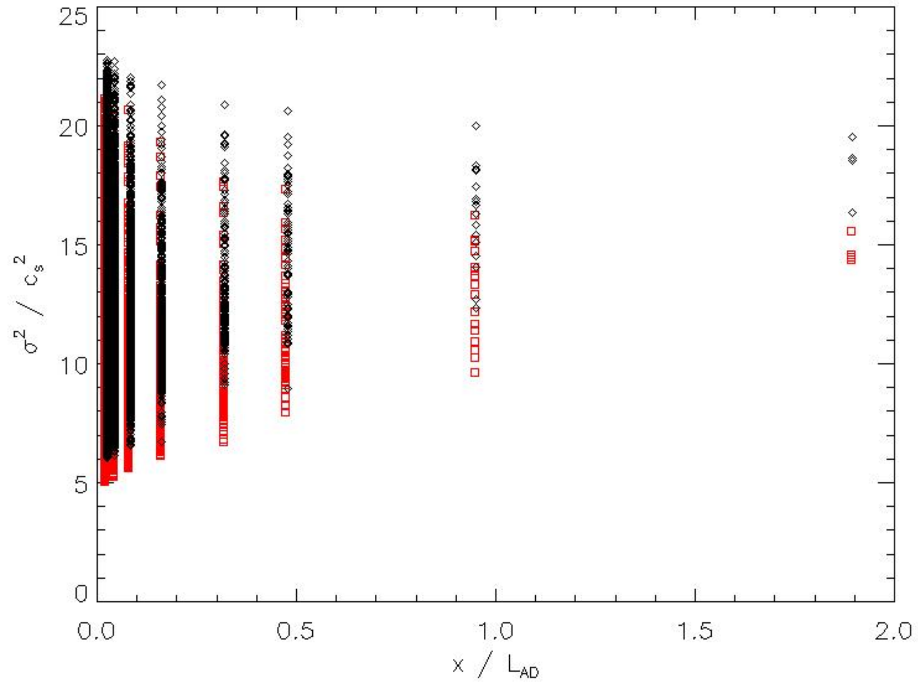
Linewidth-Size Relation from Simulations



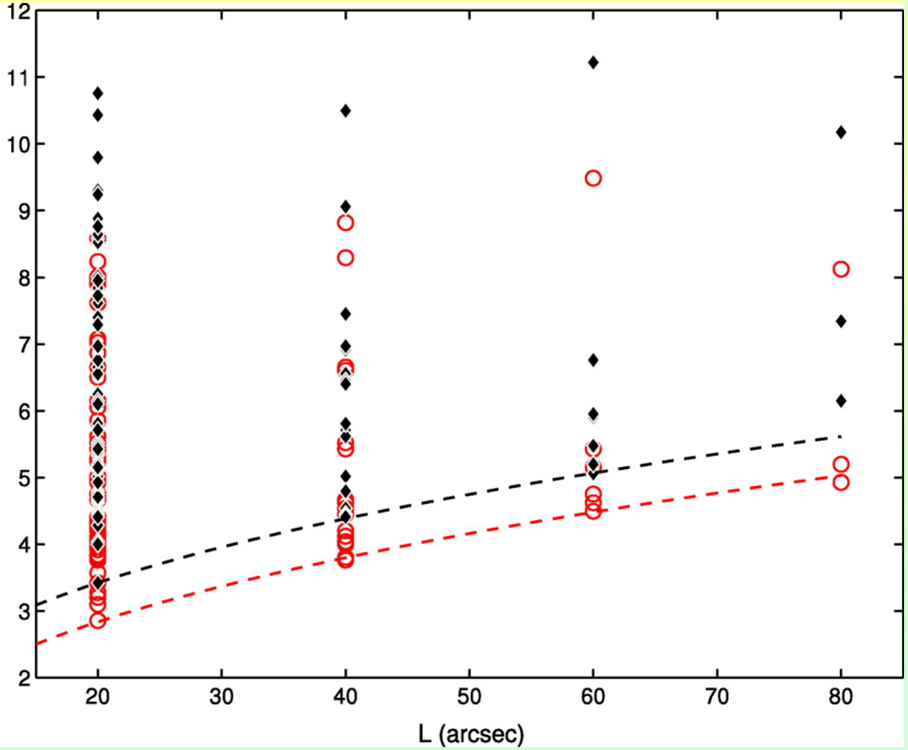
Diamonds – neutral line widths
Squares – ion line widths
Diamonds & Squares slightly offset

Tilley & Balsara 2010

Comparing the Linewidth-Size Relations



Our simulation results



Measured line widths (Li & Houde 2008)
(Note that the dissipation scale is at
~0.01 pc, or about 1 arcsec in this figure

Black – neutrals ; Red – ions for both plots

Summary

- Problem in star formation -- reconcile presence of strong turbulence and strong magnetic fields
- Gravitational collapse requires a mechanism that allows magnetic fields to disengage from the collapsing flow ➔ Large, 3D, two-fluid simulations give us a way to reconcile vigorous turbulence on large scales with quiescent collapse on small scales.
- Two-fluid ambipolar drift has quantifiable effects on the turbulent line widths that are measured. ➔ Observable handle on the ambipolar diffusion scale
- Dispersion analysis ➔ Alfven & m-sonic waves damped
- Turbulent spectra ➔ Lower power in ions than neutrals
- Linewidth-size relation ➔ We have simulations to back up the observations & their interpretation

- New computational tools have been constructed that allow us to bridge the gap between the turbulently regulated models and the magnetically regulated models

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