PARTICLE HEATING IN SPACE AND LABORATORY PLASMAS

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Bringing Space to Down to Earth
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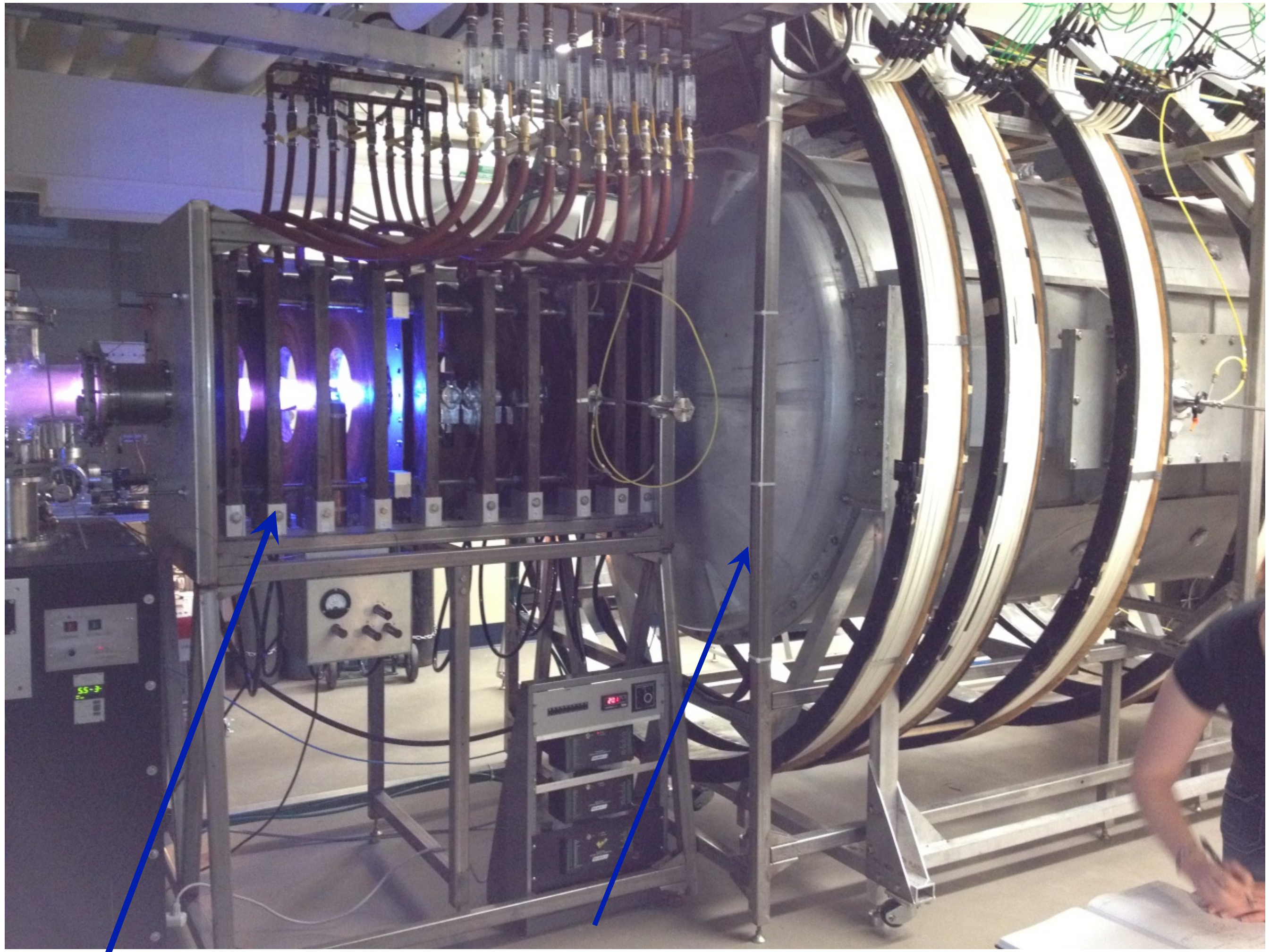
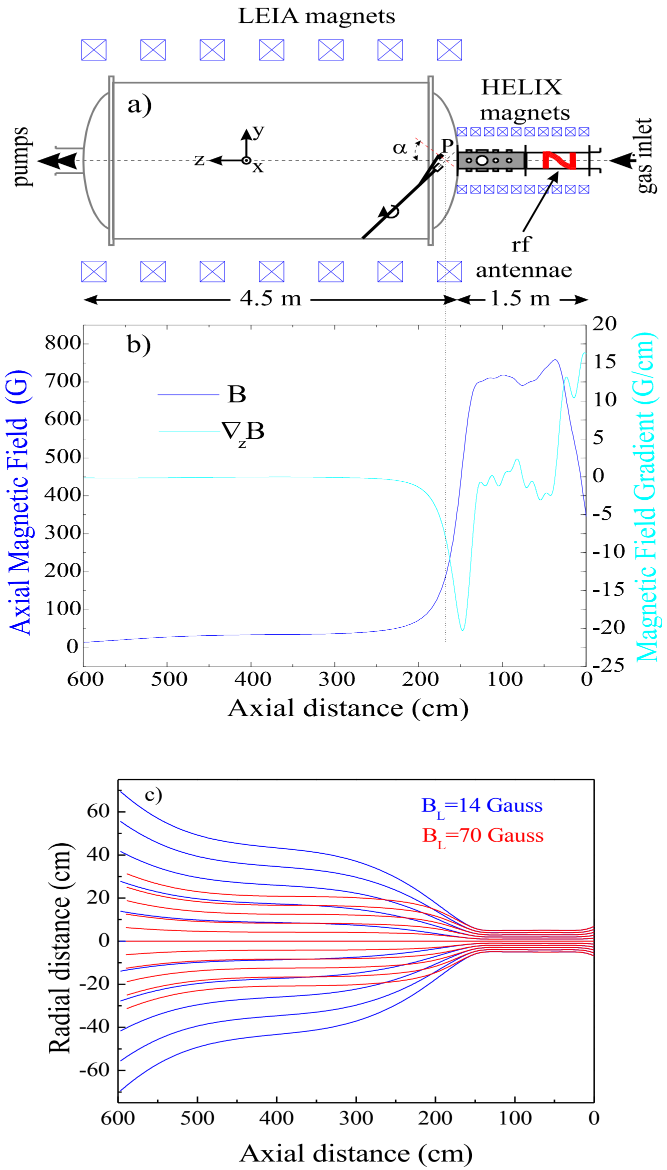
EXPERIMENTS PERFORMED IN HELIX-LEIA FACILITY



Expansion Chamber

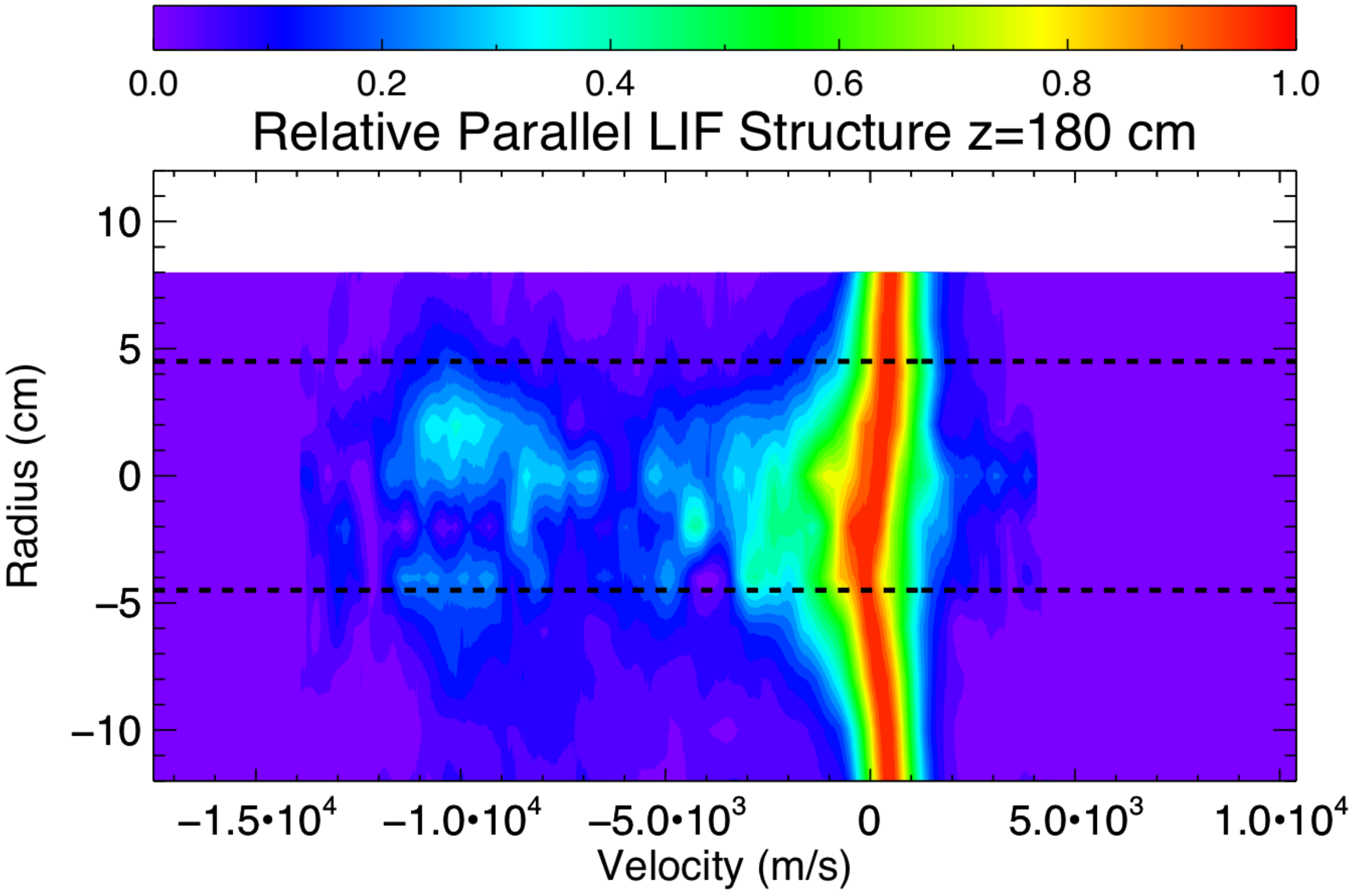
β ~ 0.01 at measurement location

Hot hELIcon eXperiment



Strong Parallel Beams in Center of Experiment

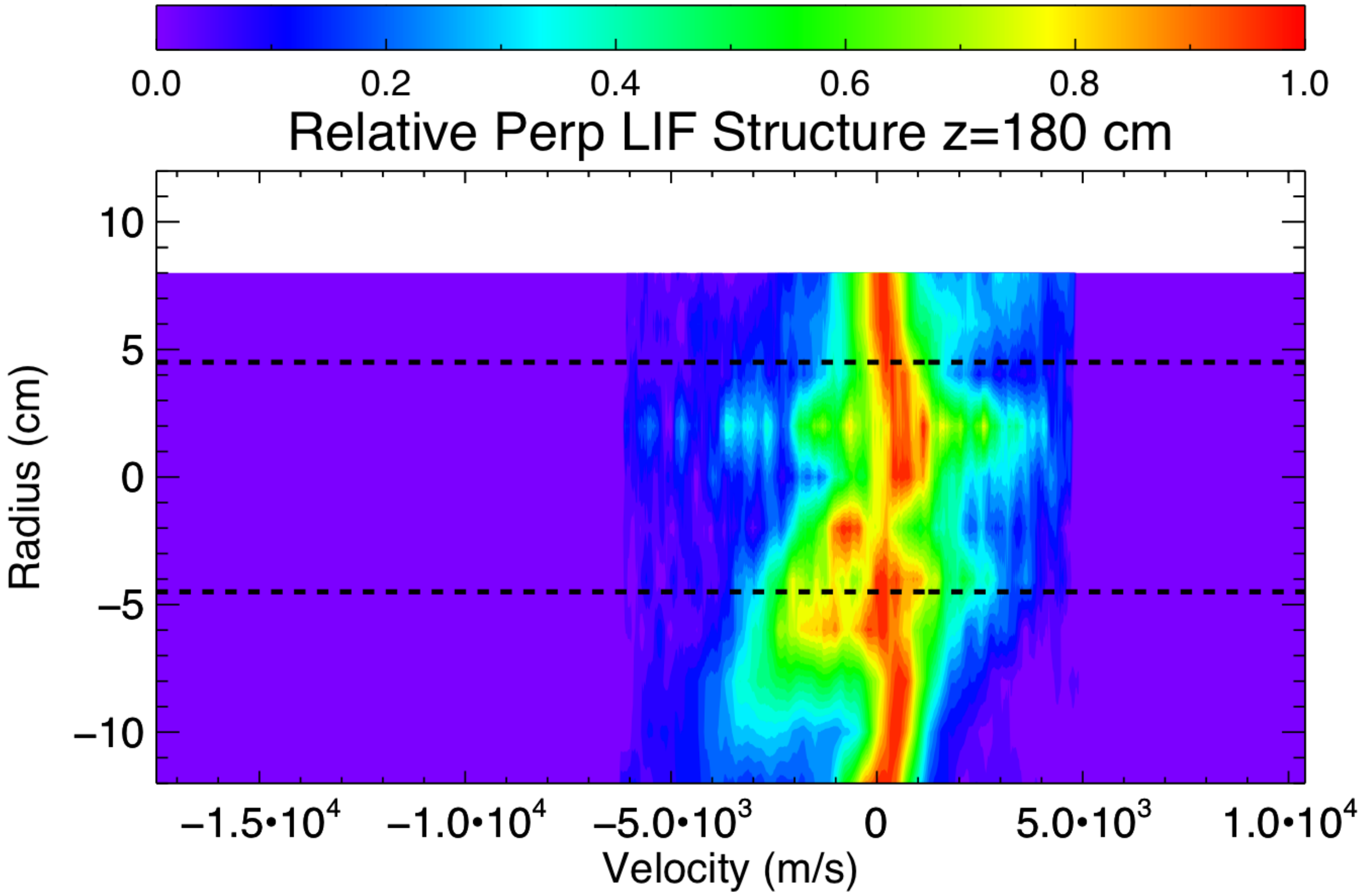
Black lines are magnetic field lines that map to a 2 cm upstream radius. The ion beam is confined to a narrow radial range even as the field expands.



Do the ions in these laboratory plasmas really have a temperature of 2 eV?

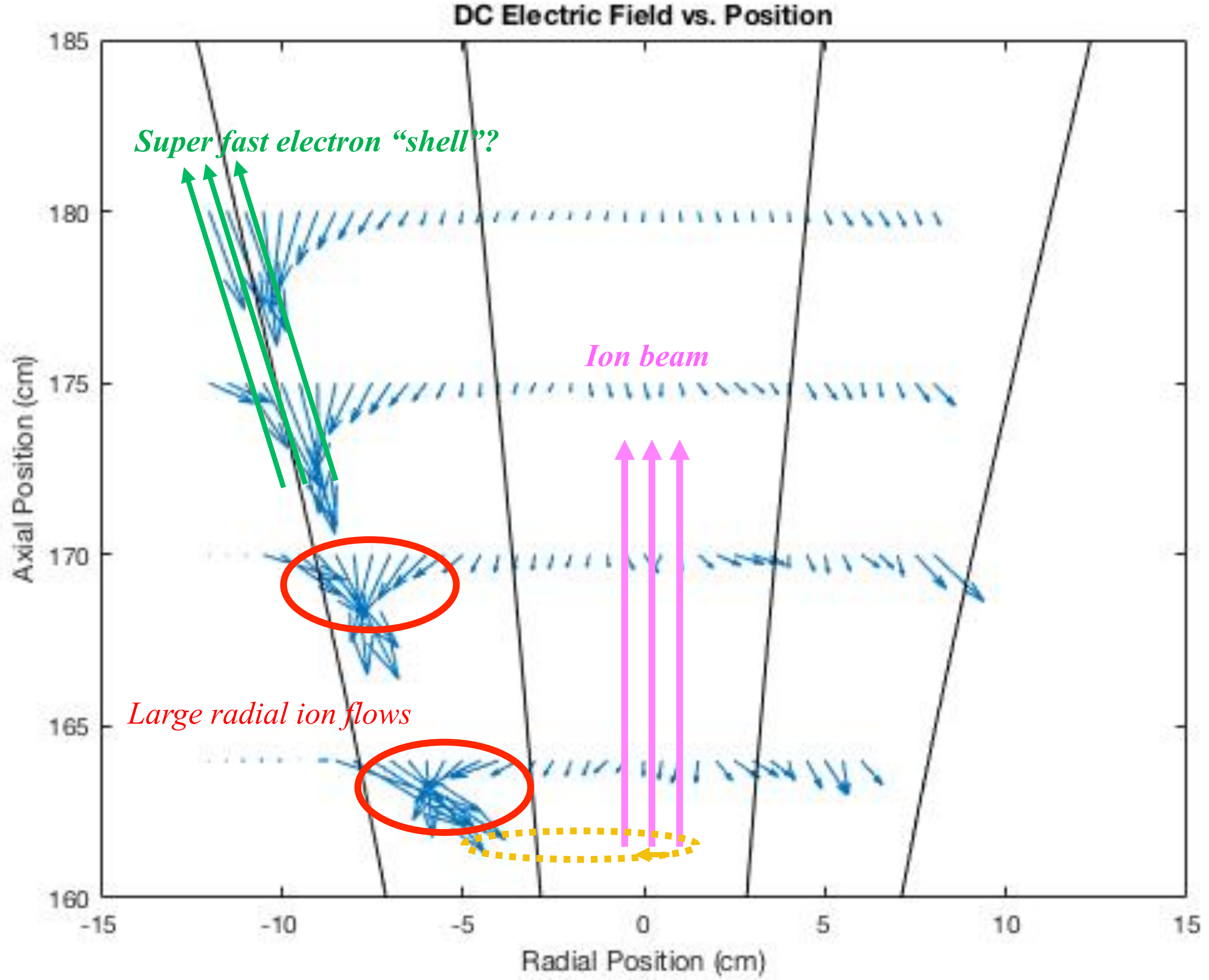
At z = 165 cm, the width of the perpendicular ion velocity distribution yields multi-eV ion temperatures. Are these real temperatures or superimposed flows in different directions?

These are collisional plasmas. How are such non-Maxwellian distributions maintained?



THE ELECTRIC FIELD HAS SIGNIFICANT RADIAL FEATURES

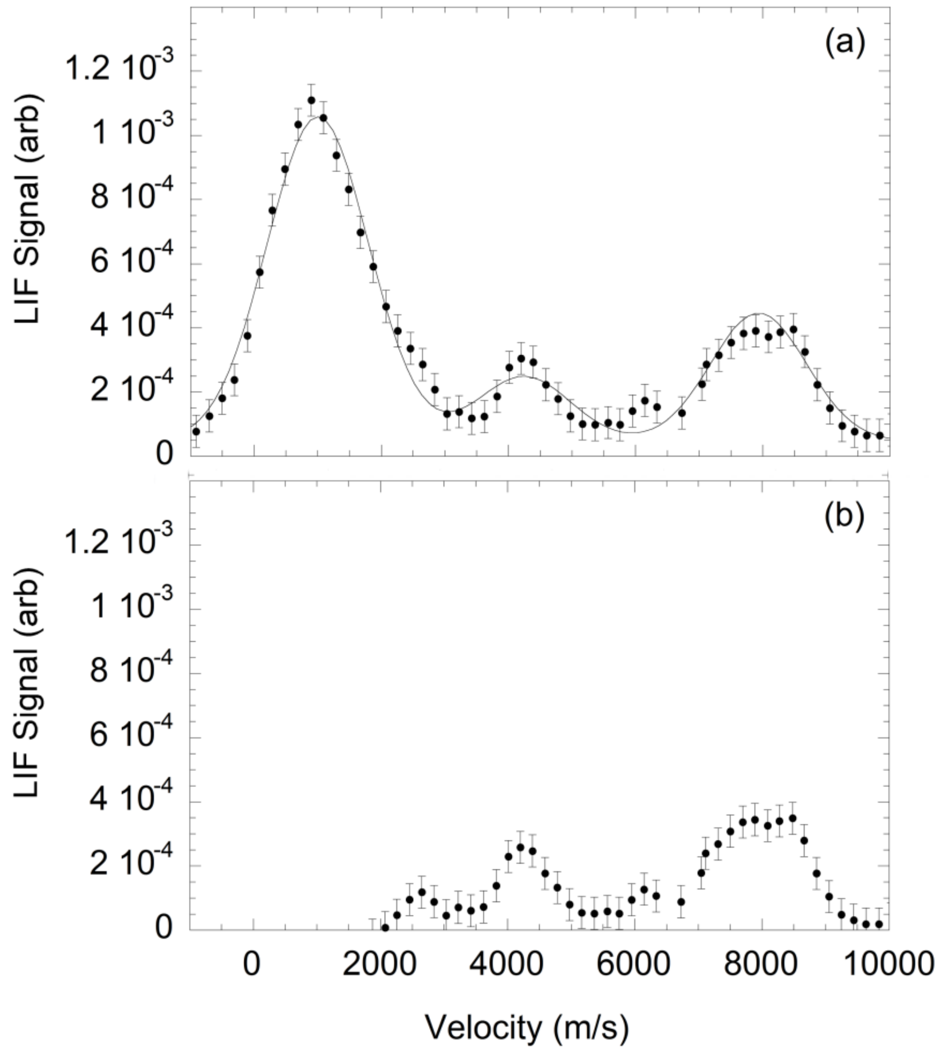
Along the axis, ions are slowed by a weak electric field. At the plasma edge, electrons are accelerated out of the source by a complex and very large electric field that maps along the expanding magnetic field. This strongly varying (with radius) electric field must create a significant charge imbalance that pulls ions out of source. Finite gyroradius effects can then combine acceleration regions.



At very low neutral pressure and large RF powers, multiple beams spontaneously appear downstream of the expansion region in HELIX-LEIA.

(a) LIF measured ivdf (circles) as a function of velocity in the expansion chamber 38 cm downstream of the plasma source. A three Maxwellian component fit (solid line) yields identical ion temperatures of ~ 0.16 eV for all three components.

(b) Same data as (a) minus the fit to the stationary background population. A very small third accelerated population appears around 2,500 m/s.

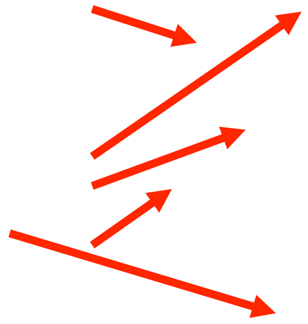


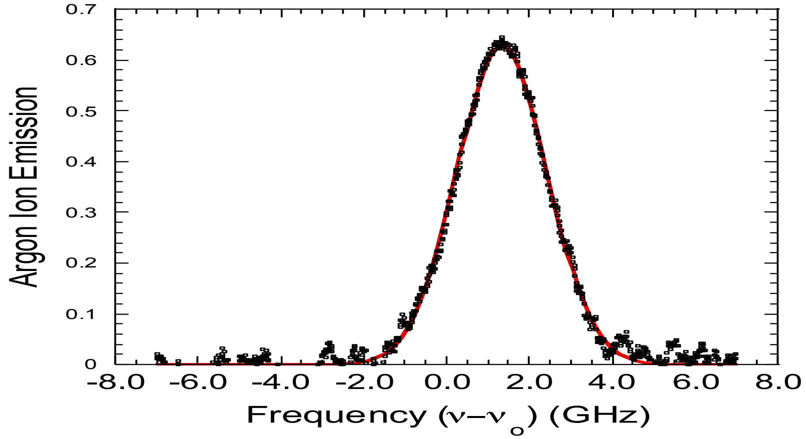
WHAT IS HEATING?

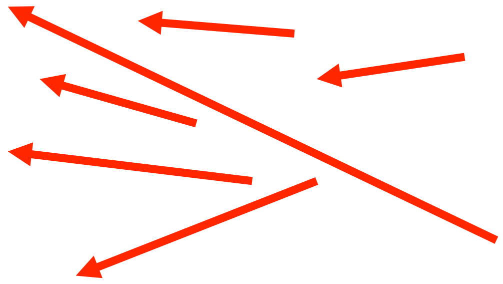
1. How do we define heating?

(a) A truly irreversible process? How can we prove that from measurements?

(b) Does it matter if what we measure to be “hot” is a superposition of flows? Does that change theoretical predictions for phenomena such as temperature anisotropy driven instabilities? Does this happen in space?







(c) Can such processes be used to our advantage in laboratory plasmas to create effective thermal anisotropies in plasmas of interest?

HELIOPHYSICS EXAMPLE OF OVERLAPPING DISTRIBUTIONS

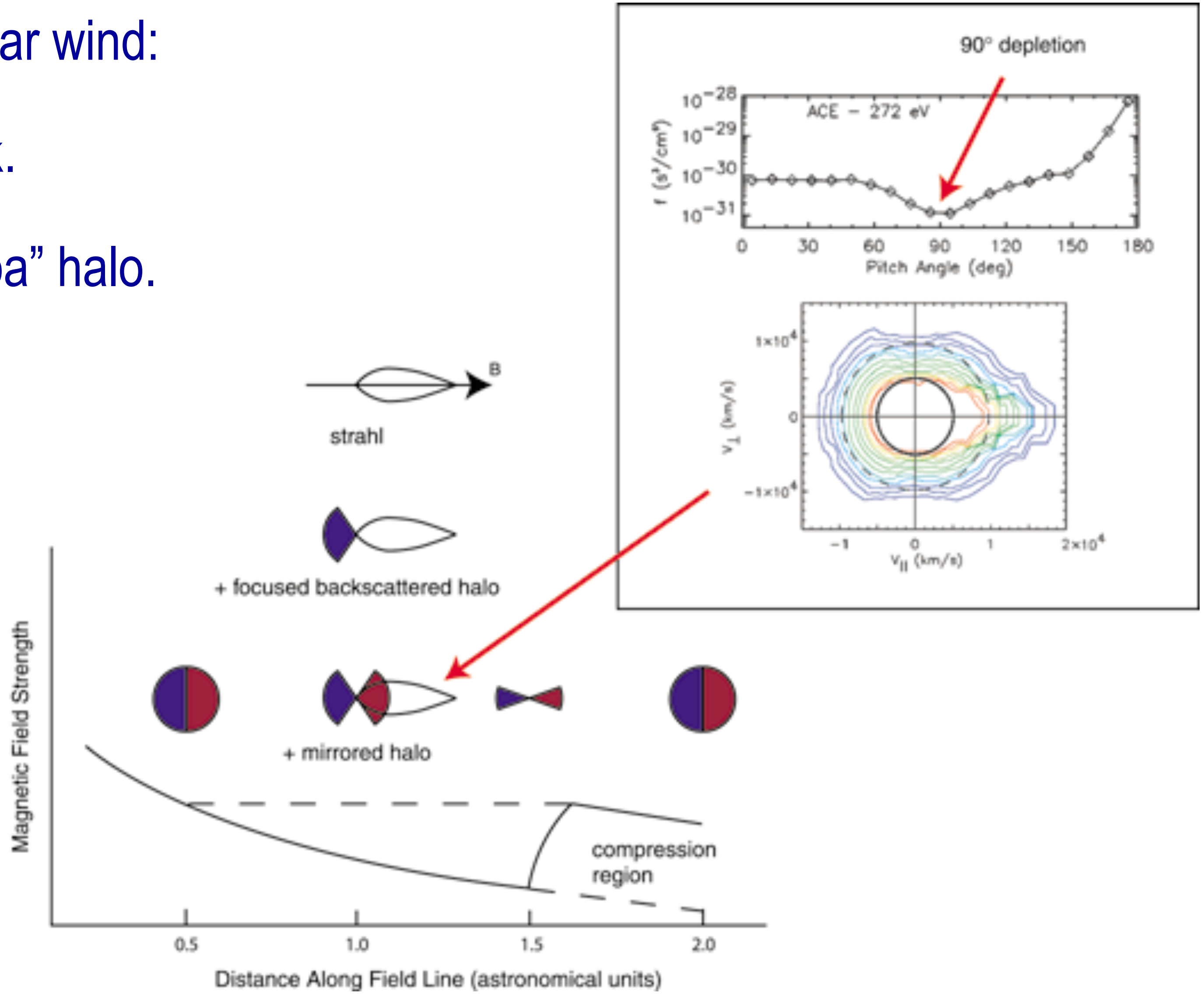
The electron distribution in the solar wind:

1. Cold, isotropic, Maxwellian bulk.

2. Energetic, fairly isotropic, “kappa” halo.

3. Very energetic beam “strahl.”

Pretty clear that three different processes are responsible for creating these three different components – probably in three different places.



ION HEATING IN LABORATORY PLASMAS

- Experiments in the 1990's [*Scime et al.*, 1992] provided the first clear association rapid and intense ion heating during magnetic reconnection in laboratory plasmas.
  - Ion heating occurred faster than any collisional timescale in the plasma.
  - Distributions went from "cold" and thermal, Maxwellian, to "hot" and thermal on the fast timescale – recent measurements suggest additional "hot" tail component also appears *Magee et al*. [2011].

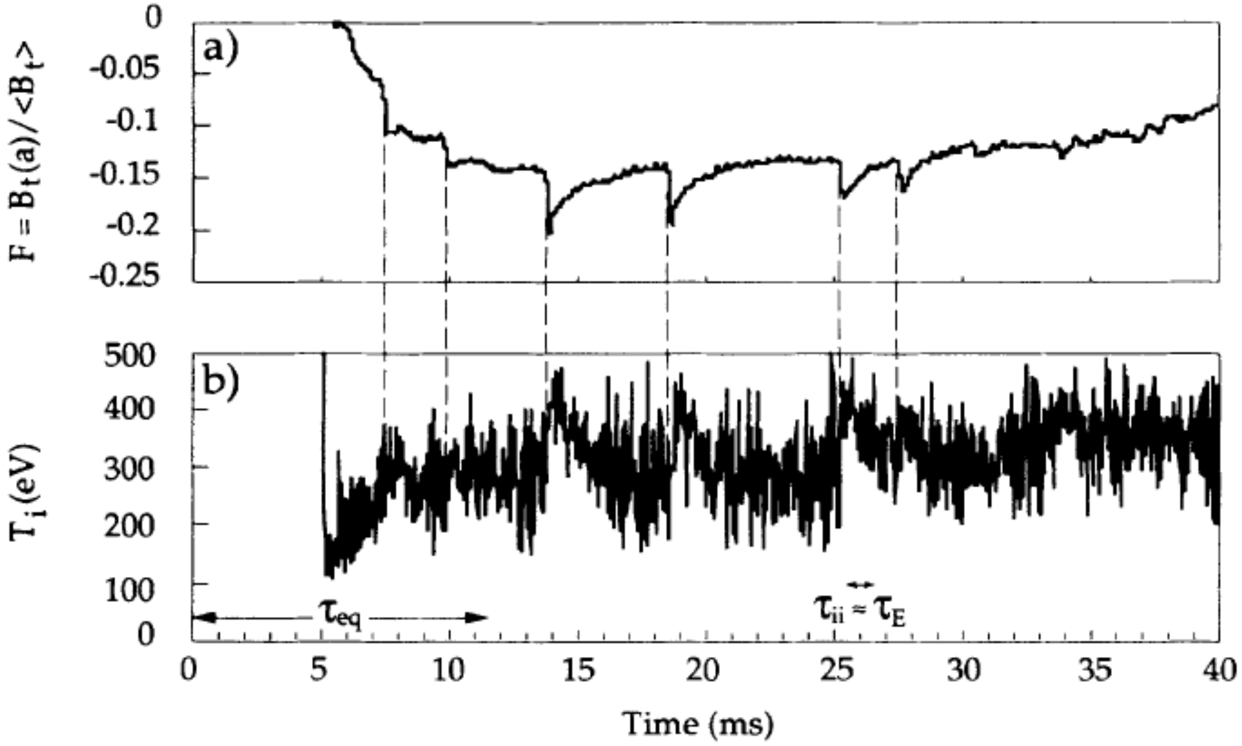


FIG. 1. (a) Reversed edge toroidal field is generated continuously and in discrete bursts. (b) Ion temperature "bursts" correlate with dynamo activity and $T_i \approx 150$ eV within 5 ms of start-up. The ion-ion collision time τ_{ii} and the ion energy confinement time τ_E are shown for reference.

What if "heating" is just lots of beams?

Drake et al., [2009] showed that test ions can gain considerable energy through "pickup ion" acceleration in the reconnection exhaust.

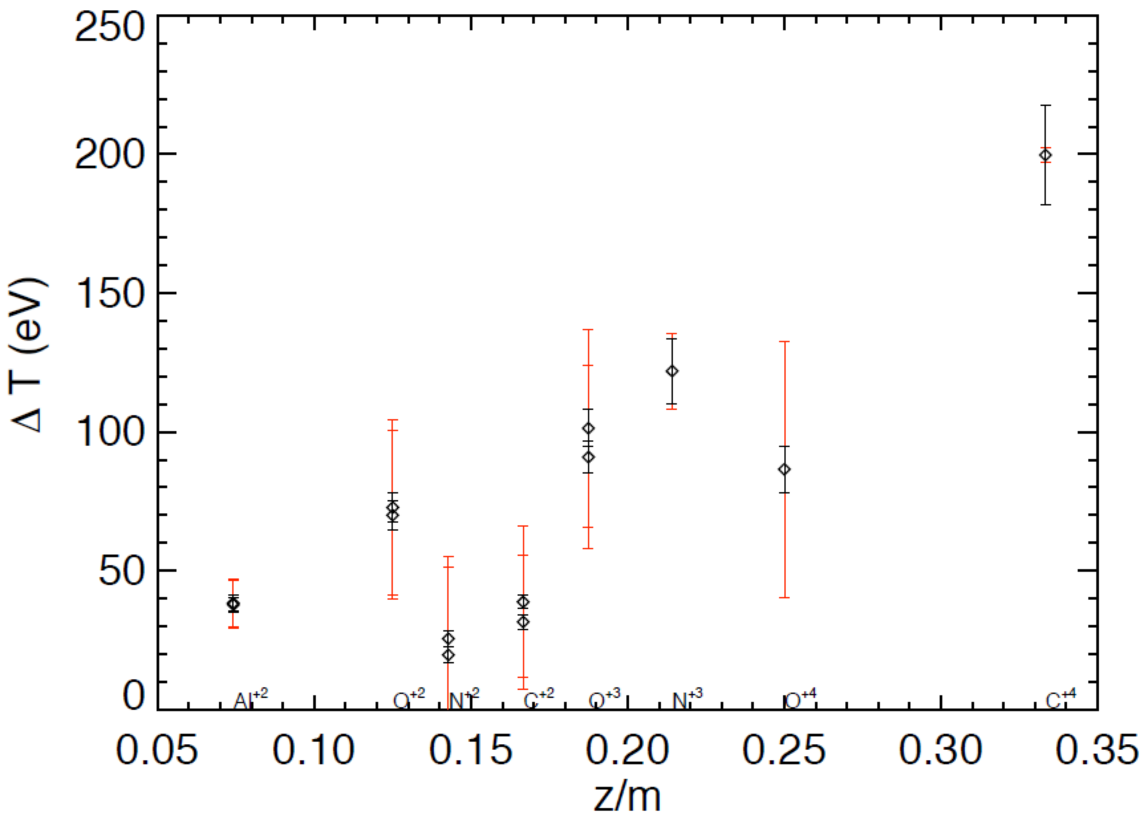
Assuming that the bulk ions experience simple and reversible acceleration in lots of discrete electric fields, the rate of ion energization (heating) should depend solely on the energy gained by ions falling through the electric fields across the exhaust:

$$\Delta\left(m\mathrm{v}^2/2\right)/\Delta t \approx \sqrt{dq^3E^3/2m}$$

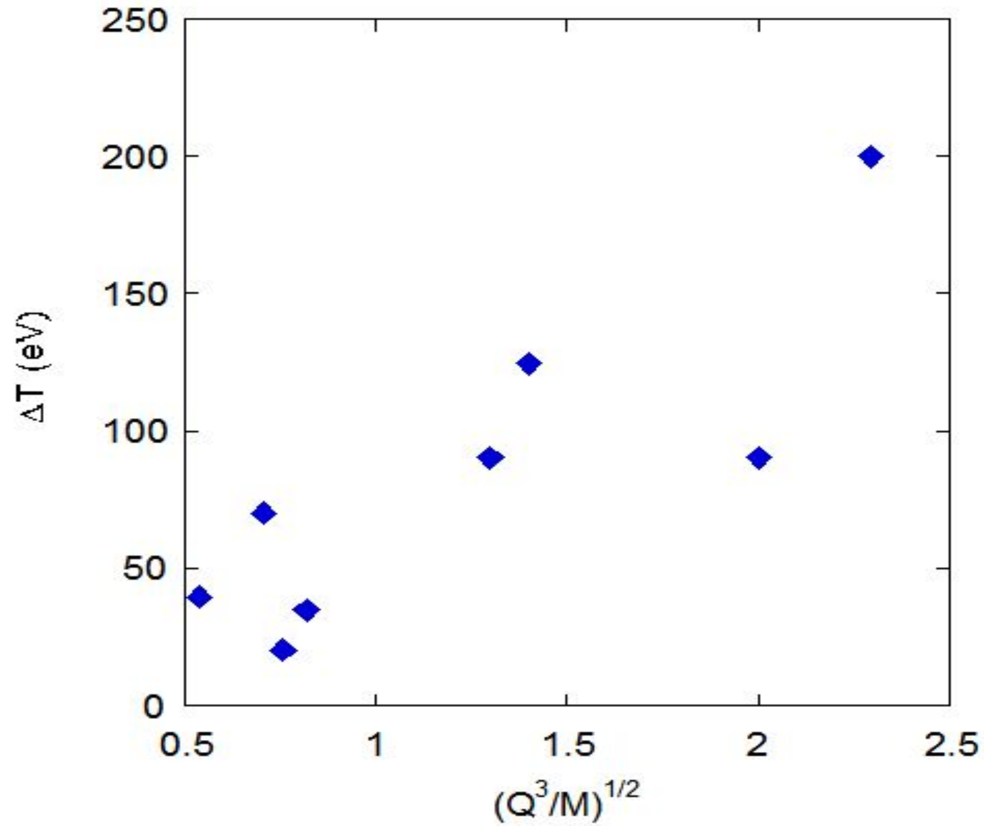
where E is the electric field in the DL of thickness d and the heating rate is determined by the transit time of the ions. The energization rate of ions of different charge-to-mass (q/m) ratios should scale as $(q^3/m)^{1/2}$ and be independent of the magnitude of the magnetic fluctuation amplitude.

The "thermal" distribution shape arises from many randomly oriented electric field structures and is thus a reversible process.

RE-ANALYSIS OF MADISON SYMMETRIC TORUS CHARGE AND MASS DEPENDENT RECONNECTION ION HEATING DATA IS ENCOURAGING BUT EQUIVOCAL.



Net energy gain during reconnection event [*Santhosh Kumar et al.*, 2013]



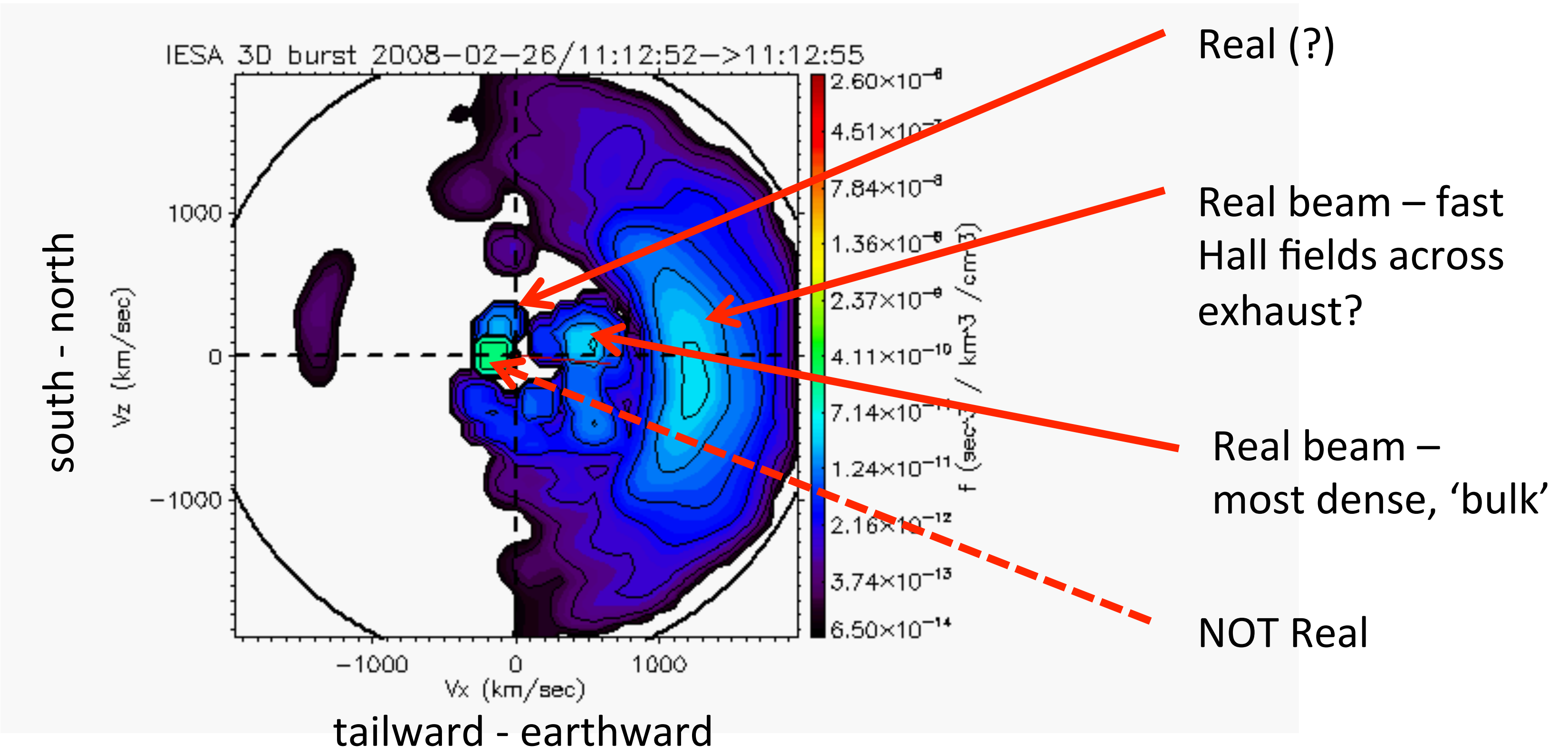
Same data ordered by "random electric field acceleration" scaling

Ion beams in magnetic reconnection exhausts

Plasma instrument from the THEMIS spacecraft.

Downstream of a reconnection event, multiple ion beams observed.

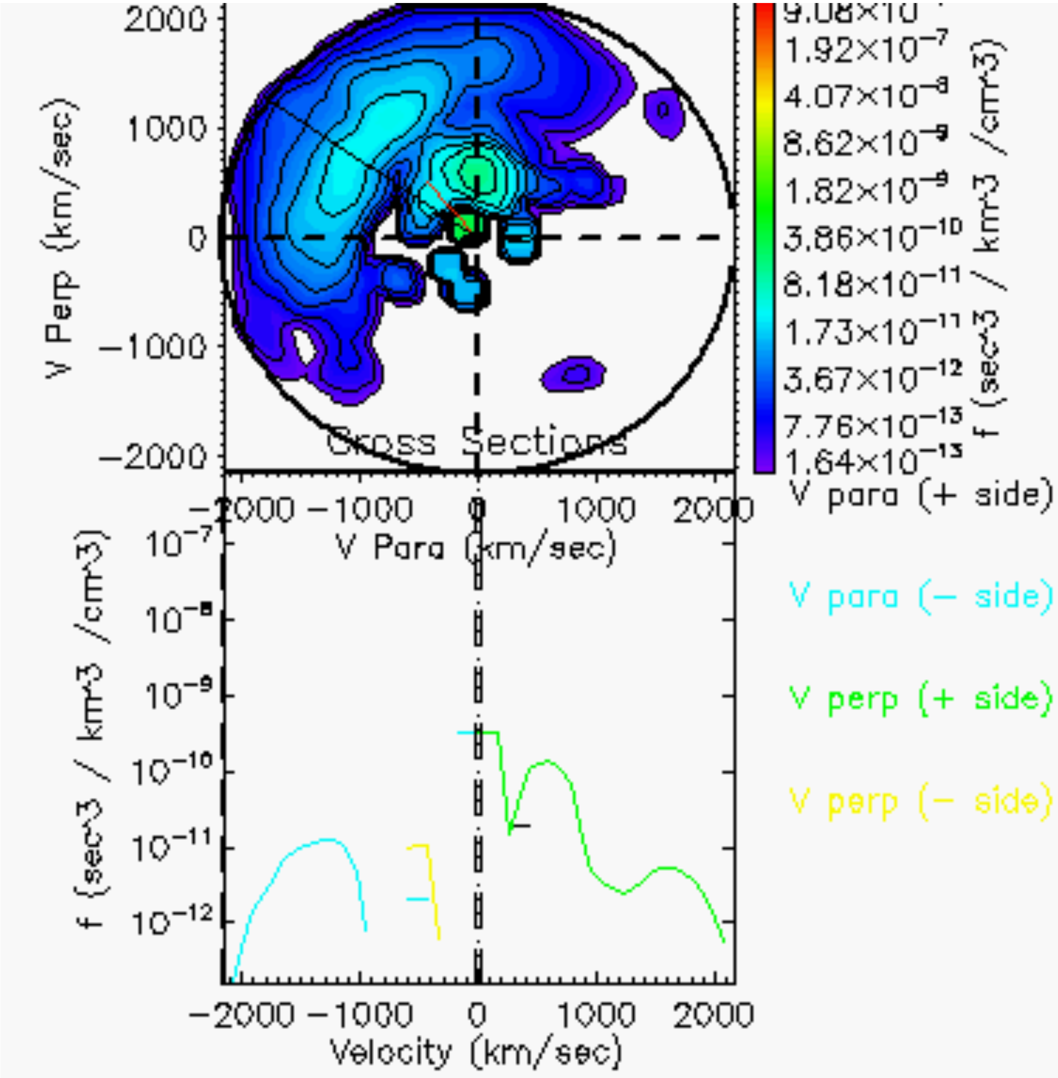
Ion distribution at 11:12:55



Coordinate system is in GSM – so v_x is Earthward/tailward, v_z is north/south

This is a cut through the distribution. There is no integration in the *y* direction (out of page)

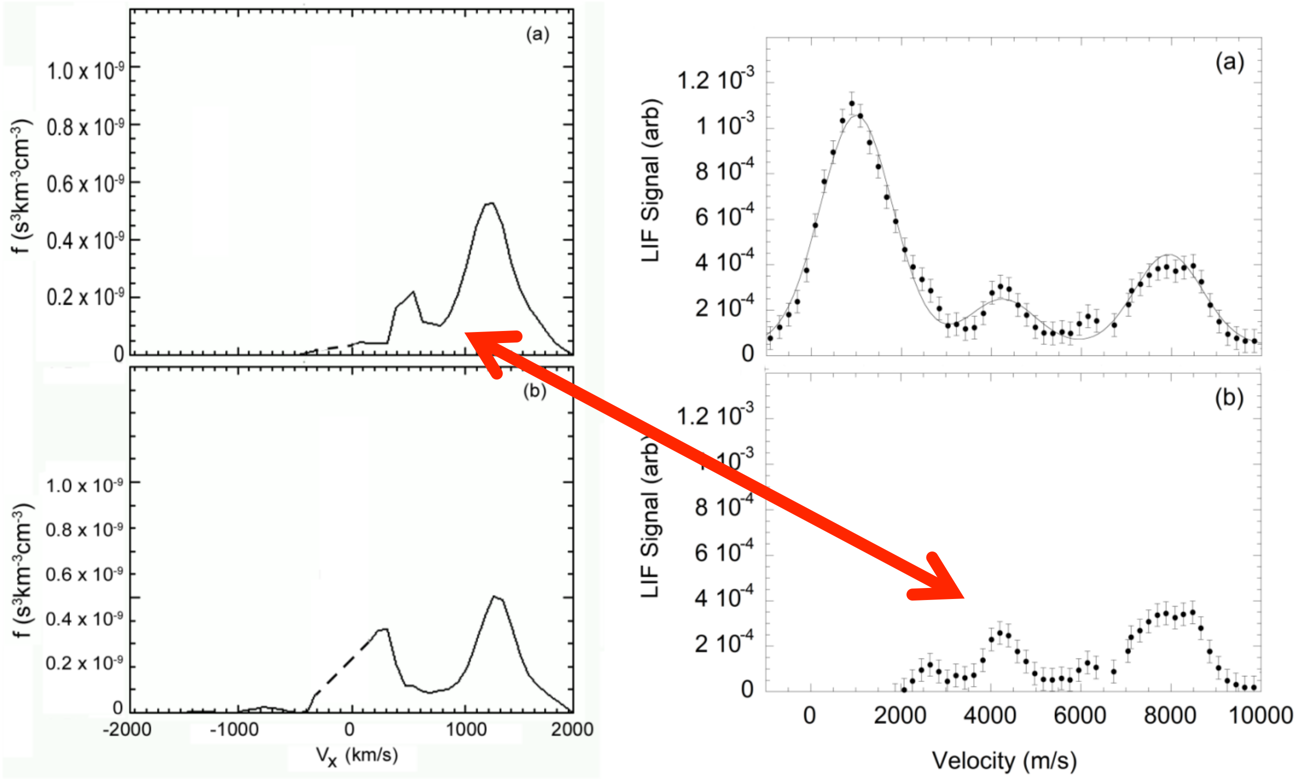
ION BEAMS IN MAGNETIC RECONNECTION EXHAUSTS



- Are the ion beams a unique signature of magnetic reconnection?
- How many ion beams should appear in the exhaust?

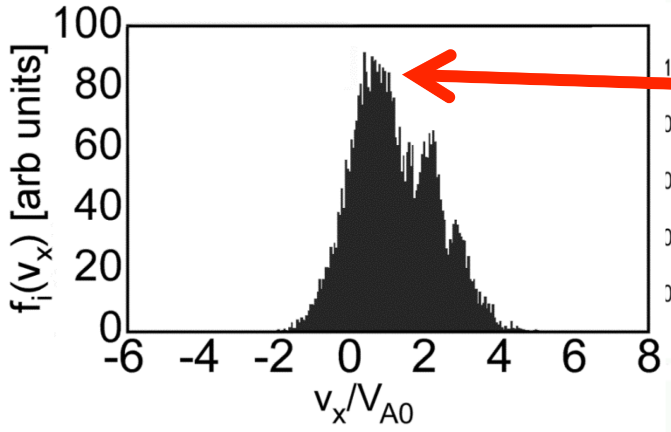
Ion beams in magnetic reconnection exhausts look surprisingly similar to those seen in laboratory plasmas.

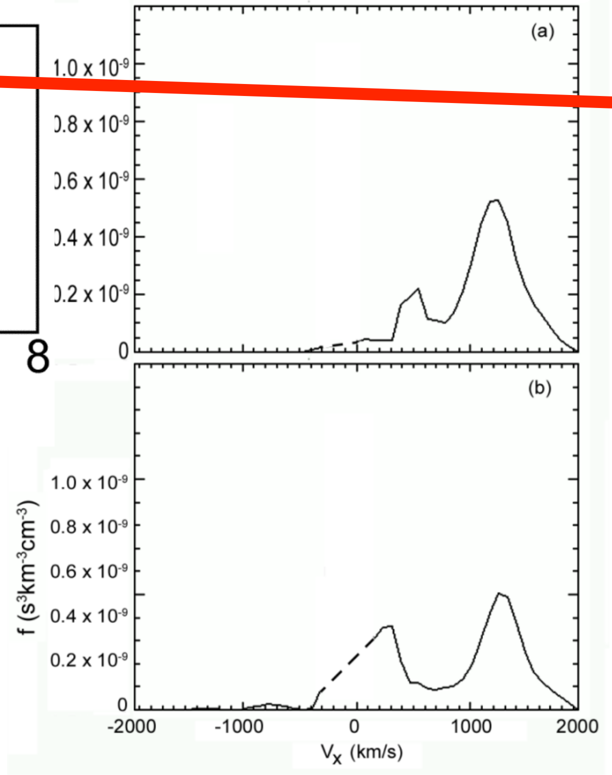
- Laboratory ivdfs look remarkably similar to THEMIS 1D cuts.
- (a) The ivdf for a bursty bulk flow event on 26 Feb 2008 at 11:12:52 and three seconds later at (b) 11:12:55.
- A large background signal in the measurement at zero velocity due to photoemission and spacecraft charging has been deleted from the THEMIS data.

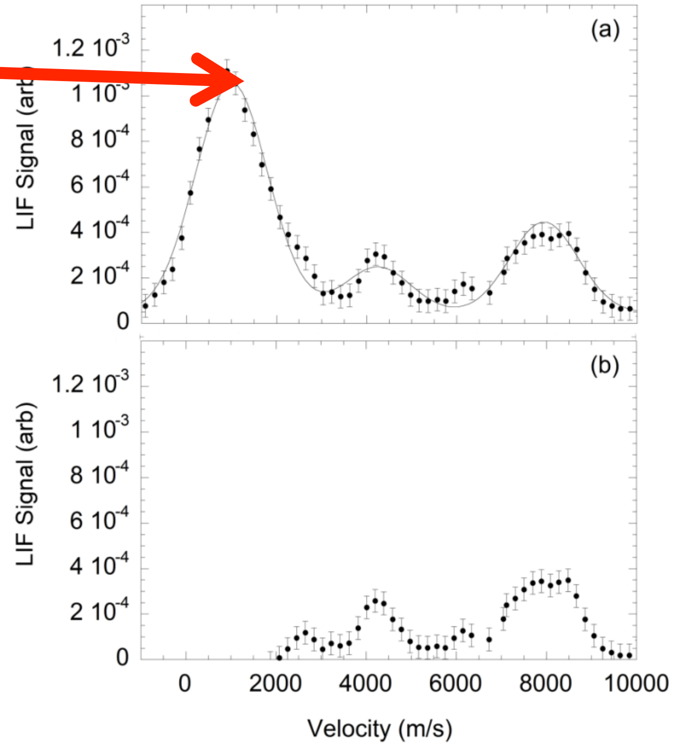


Computational models, space data, and lab ion beam measurements all have similar features

- Simulation ivdfs look remarkably similar to THEMIS 1D cuts and the laboratory measurements.







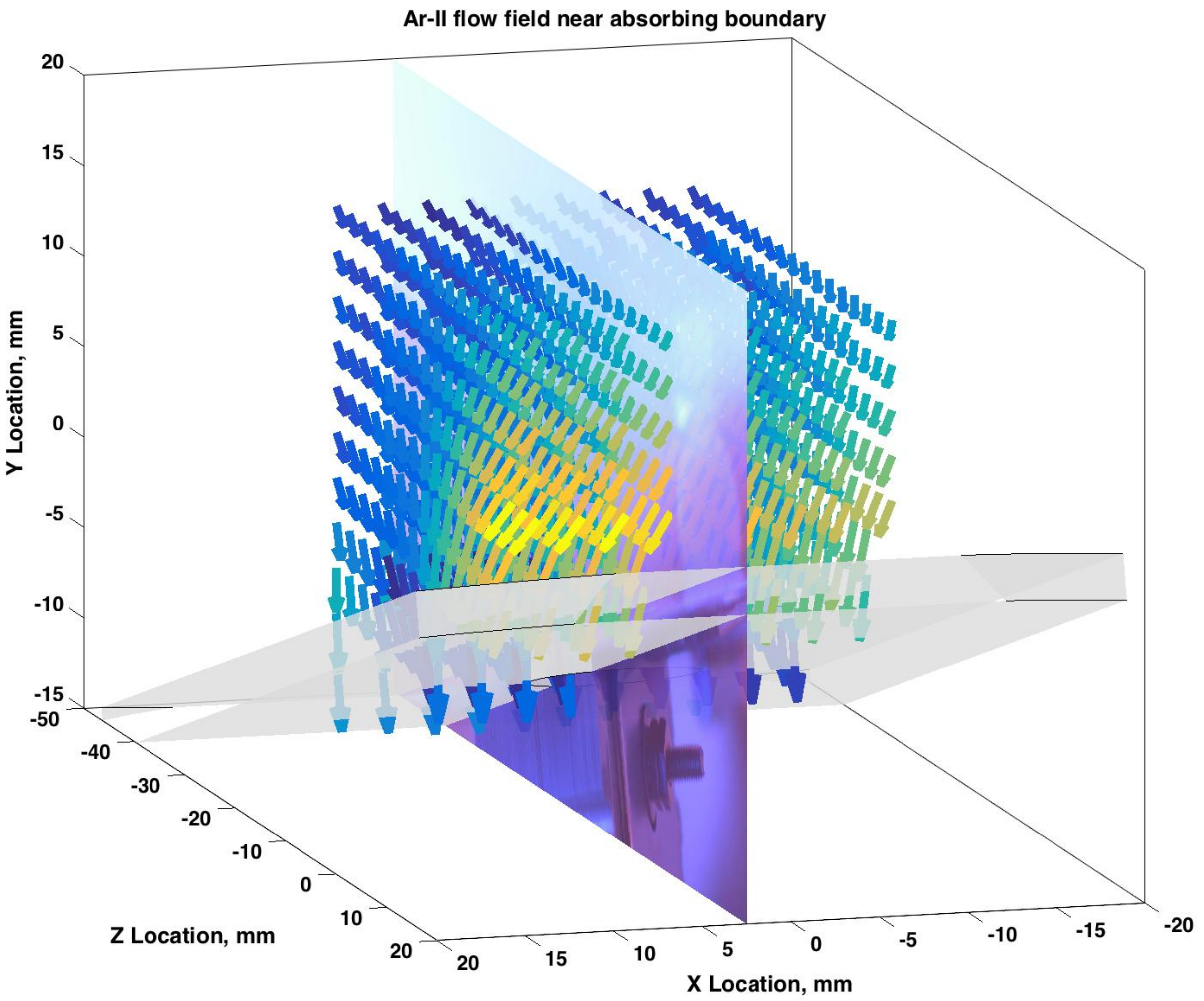
2.5D PIC simulation with a large guide field . The computational domain size is L_x x L_y = 40 d_i x 20 d_i where $d_i = c/\omega_{pi}$. Periodic boundary conditions in x and perfect electric conductor boundaries at y = 0 and $y = L_y$. The simulation starts with a classic Harris sheet of high density particles surrounded by background particles with a density an order of magnitude lower. The distribution is obtained 20 ion inertial lengths downstream of the reconnection site.

OPEN SCIENCE QUESTION 1: PROCESSES AND TOOLS.

1. How do we define

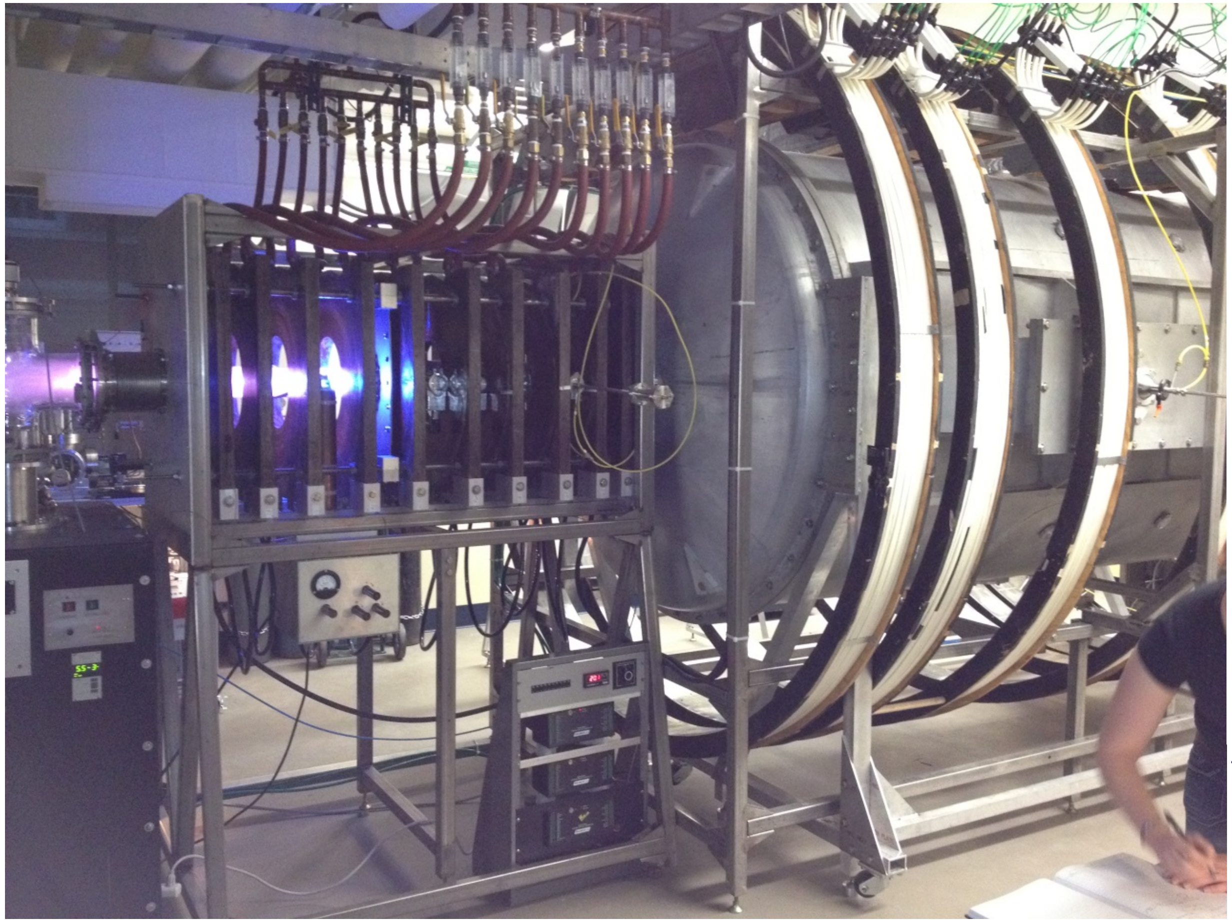
2. Does the instabili
   collisions becau
   couple together

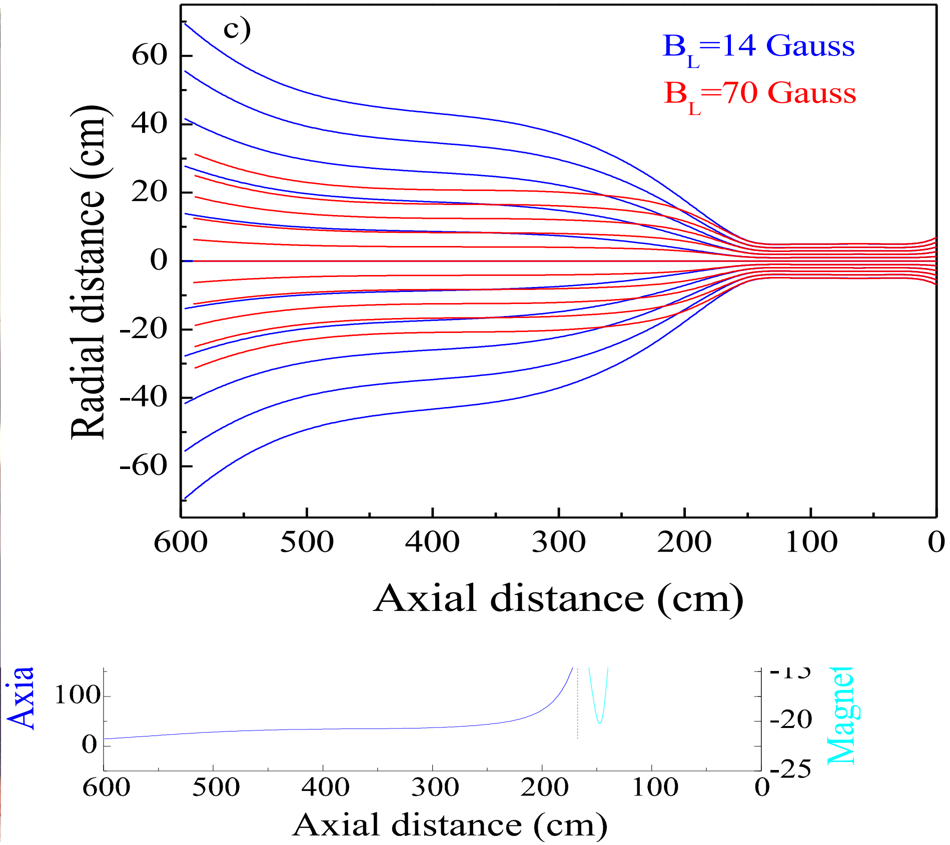
3. When we measur
   distribution in co



Open science question 2: processes and tools.

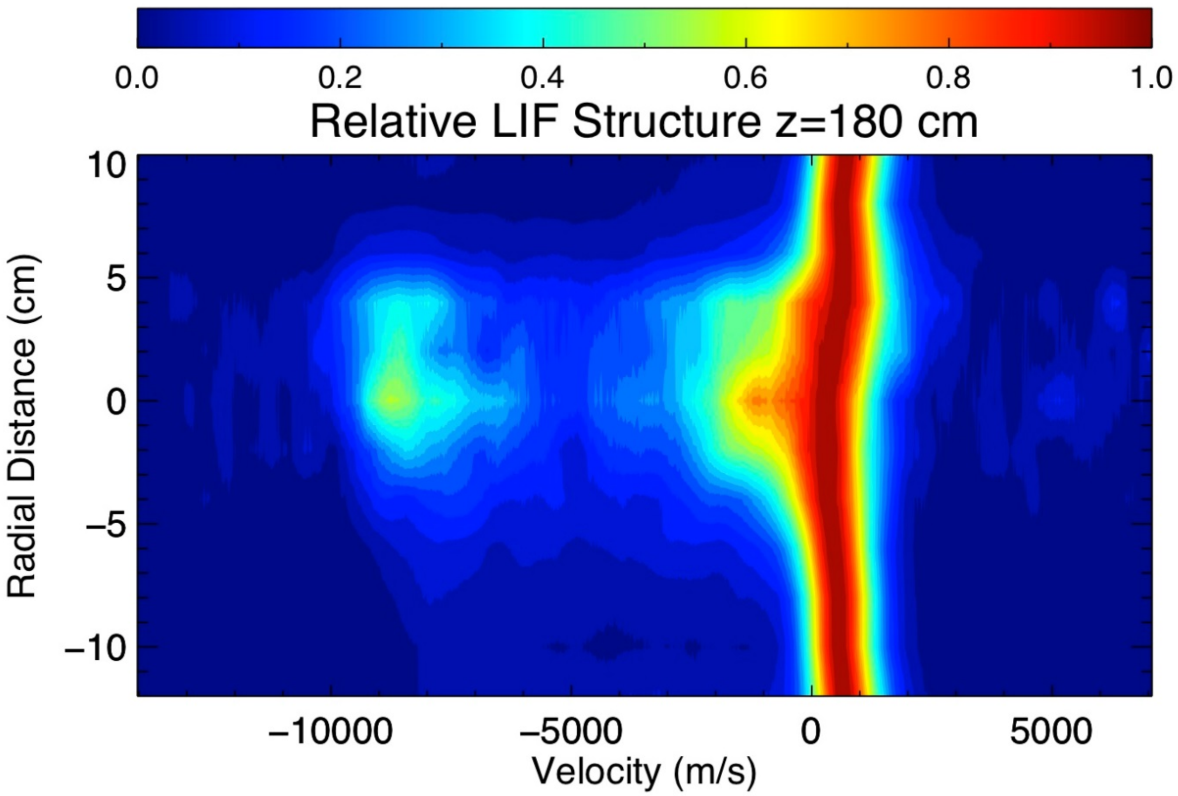
1. The role of collisions in determining the strength of electric fields in auroral zone relevant laboratory experiments – beam slowing due to charge exchange or does the physics change?



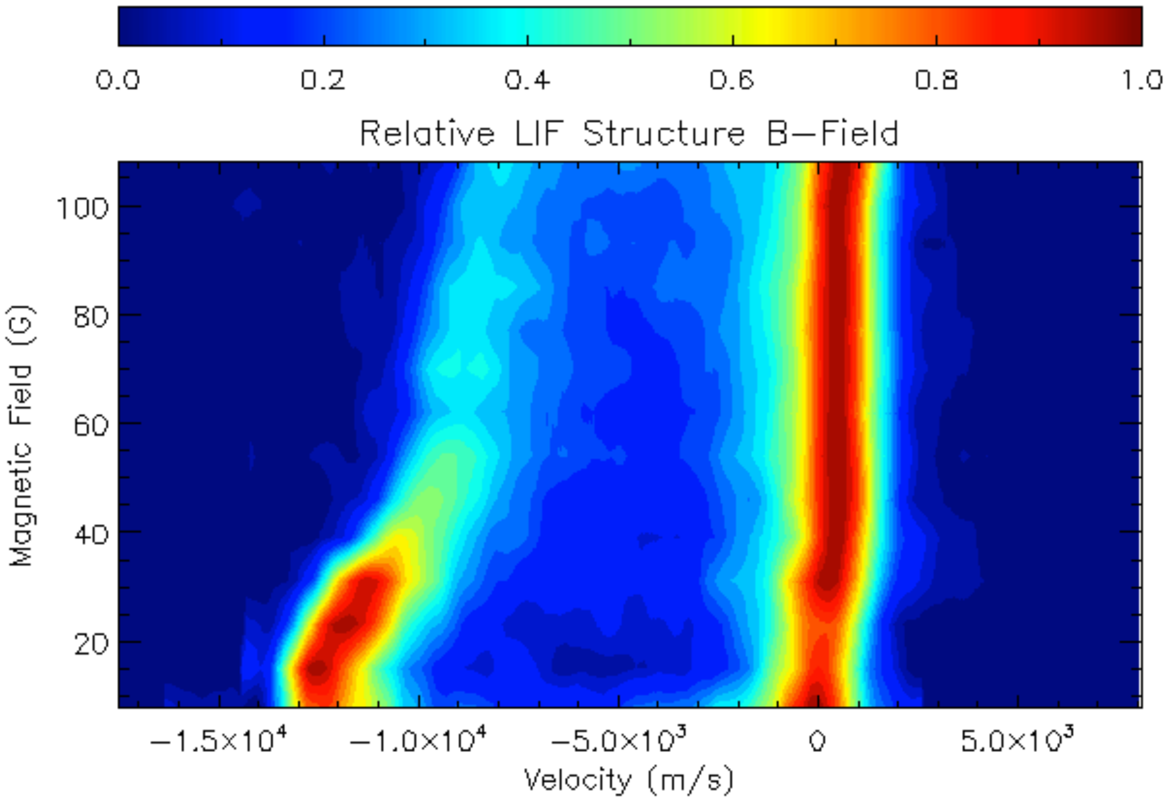


IVDF MEASUREMENTS SHOW LOCALIZED ION BEAM

Ion beam confined to central core of plasma

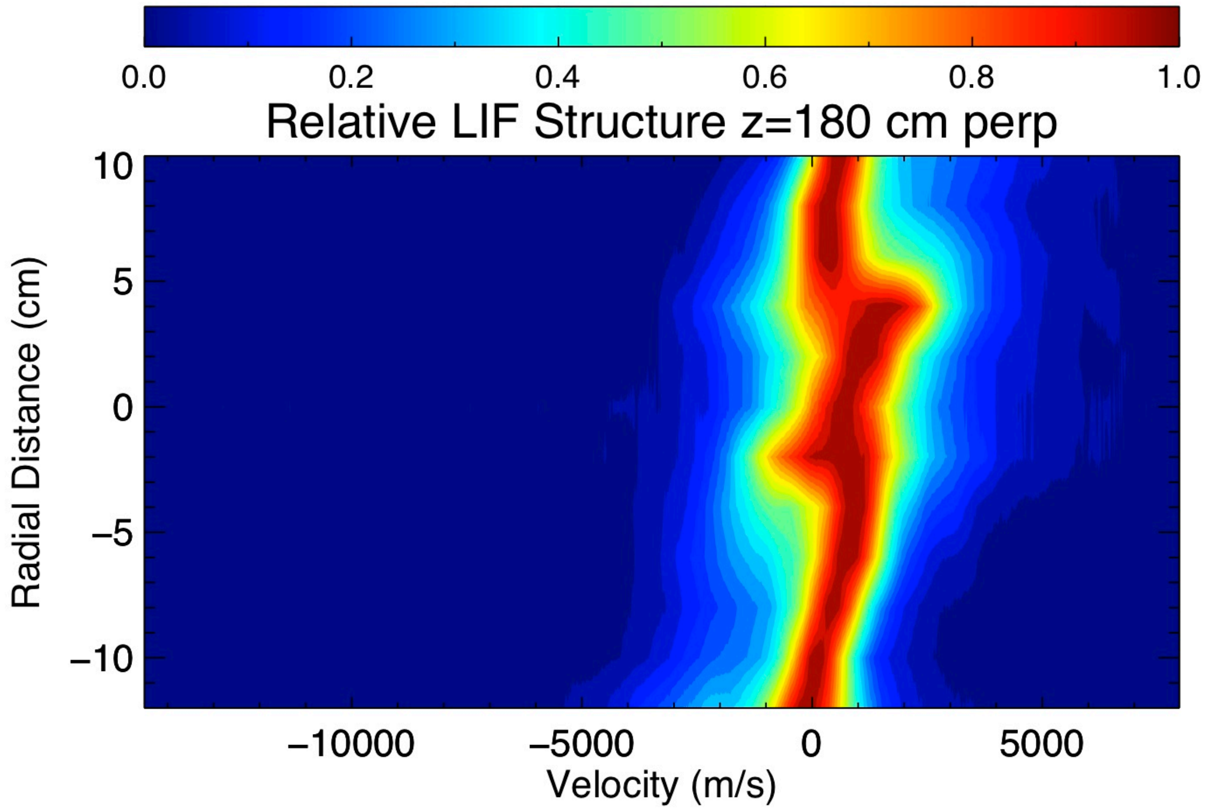


Beam slows with decreasing mirror ratio

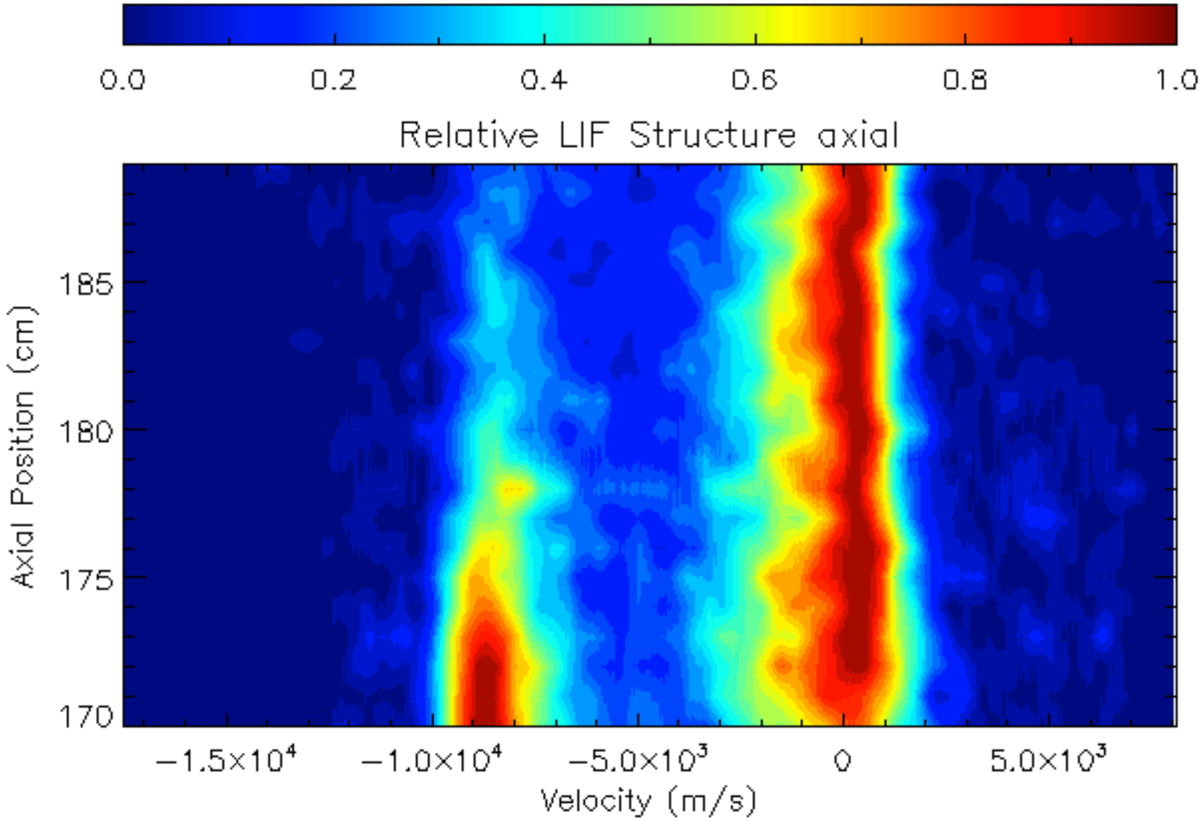


Parallel beam appears in projection, constant in z

Perpendicular IVDF shows projected beam but no spreading

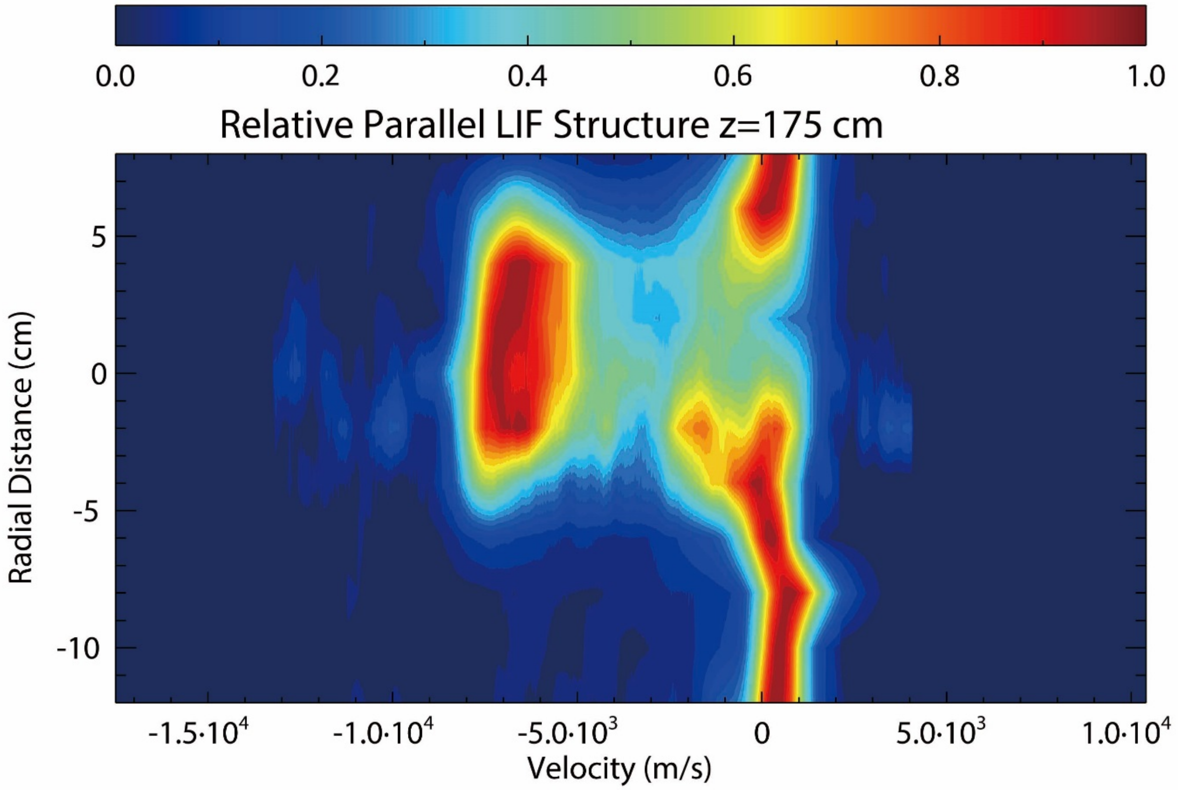


Parallel beam speed unchanged along axis.

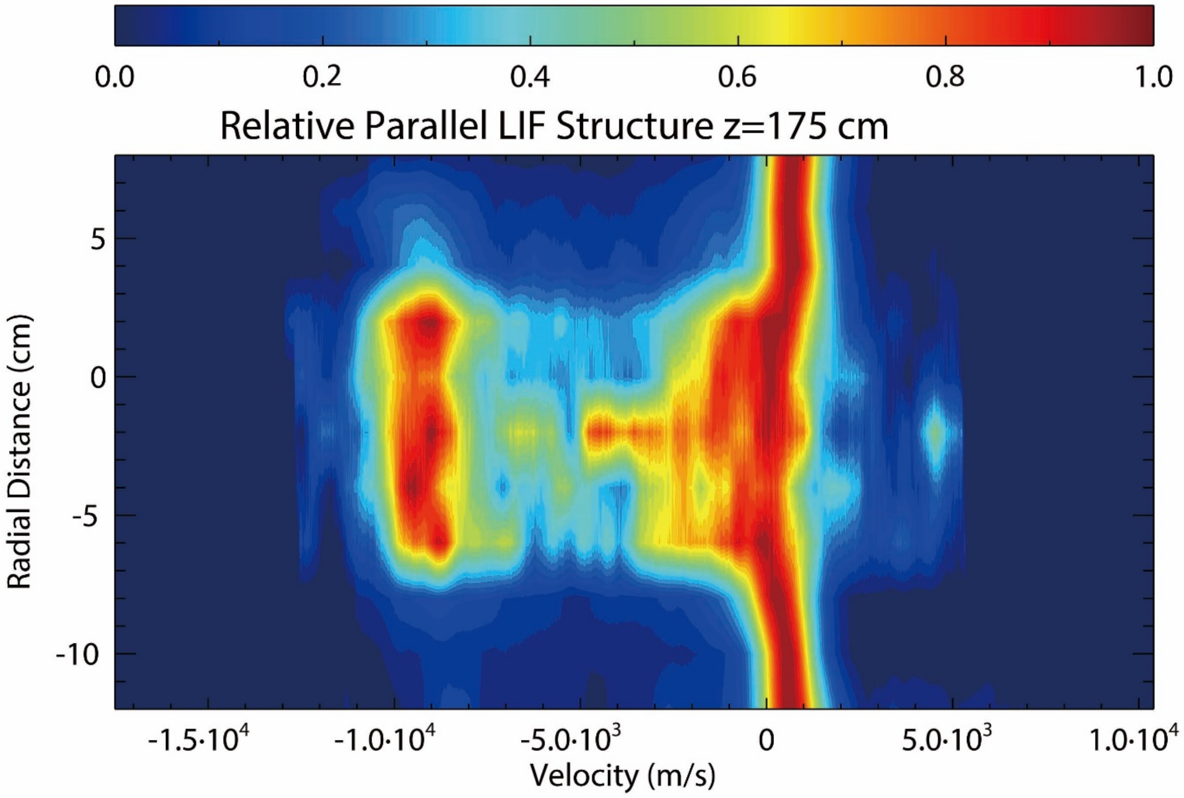


Yet lower pressure yields faster beam

$P_{LEIA} = 7.6 \times 10^{-5}$ Torr



$P_{LEIA} = 3.5 \times 10^{-5}$ Torr



PARTING THOUGHTS

- Space plasma measurements are getting faster with better time resolution to see faster phenomena and sometimes with better spatial coverage. Impulsive phenomena are likely to create overlapping distributions in distant measurement locations – how should such measurements be interpreted?
- Can laboratory experiments give us insight into how such distributions form and their likely signatures?
- Can theory/computation help us understand the interaction timescales for such complex velocity distributions?
- What is the best way to define the "temperature" of a plasma?