Anomalous Ion Heating
Status and Research Plan

Gennady Fiksel
Robert Rosner

UW Madison
Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasma

Planning meeting November 18-19, Chicago, IL

What we know

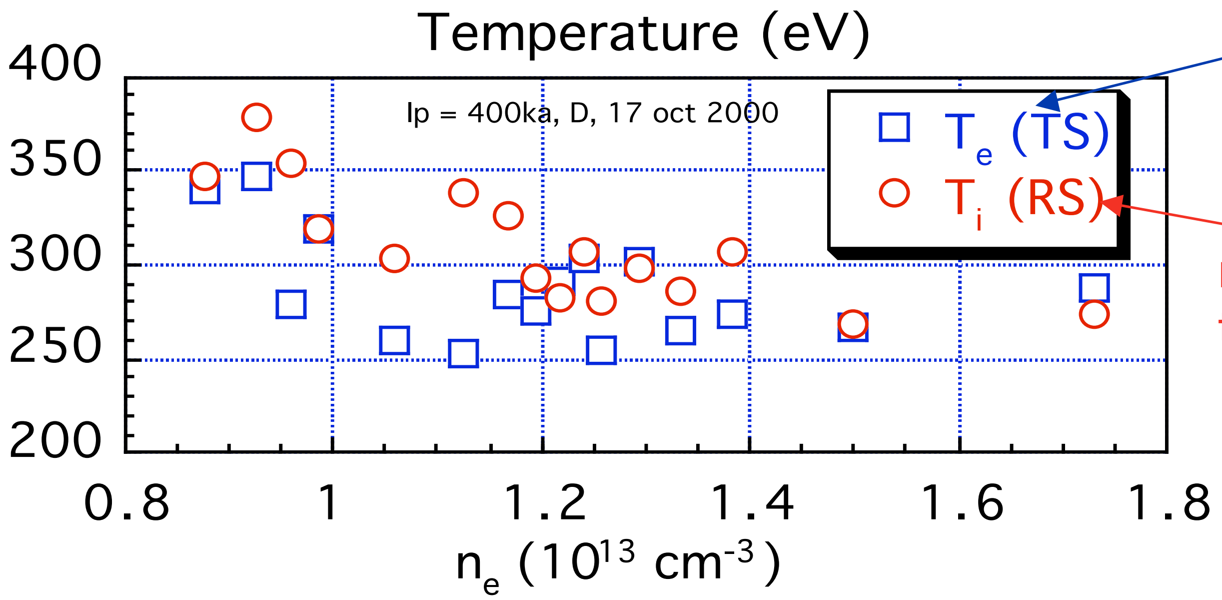
- “Anomalous” ion heating and/or acceleration is present in many laboratory and space plasmas.
- There are no reliable and experimentally proved explanations.
- There is definite correlation with magnetic reconnections and/or magnetic turbulence.
- The goal is to understand and unravel this relation.

Outline

- Experimental data
- Discussion of possible mechanisms
- Plans

Anomalous ion heating experimental results

$T_i \geq T_e$ in Ohmic discharges in MST



electron temperature

majority (H/D) ion temperature

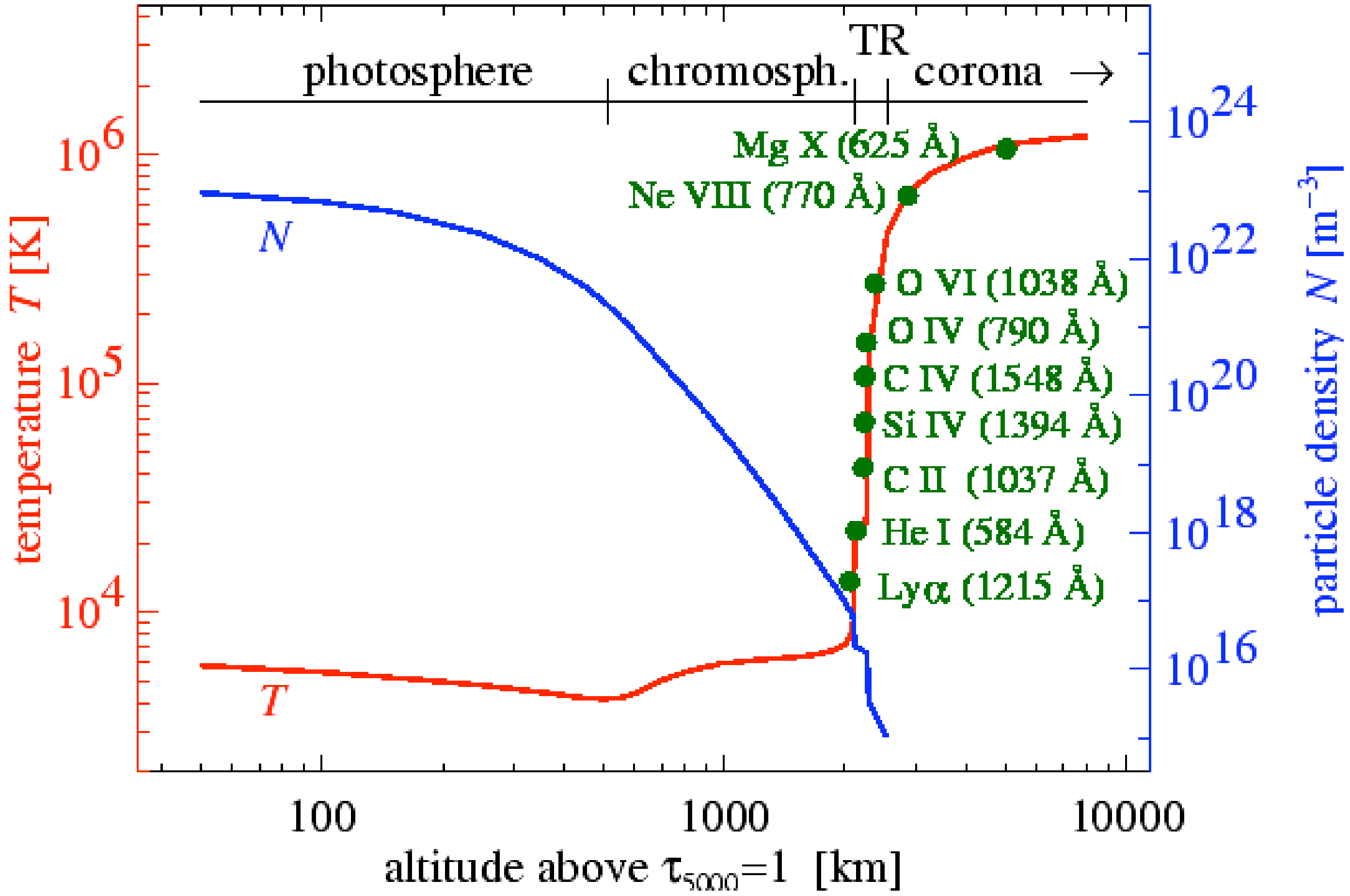
e-i collisional heating

$$Q_{\Delta} = \frac{3m_e}{m_i}\frac{nk}{\tau_e}(T_e - T_i)$$

$$\tau_e = \frac{3\sqrt{m_e}(kT_e)^{3/2}}{4\sqrt{2\pi}n\lambda e^4} = 3.44 \times 10^5 \frac{T_e^{3/2}}{n\lambda}\sec$$

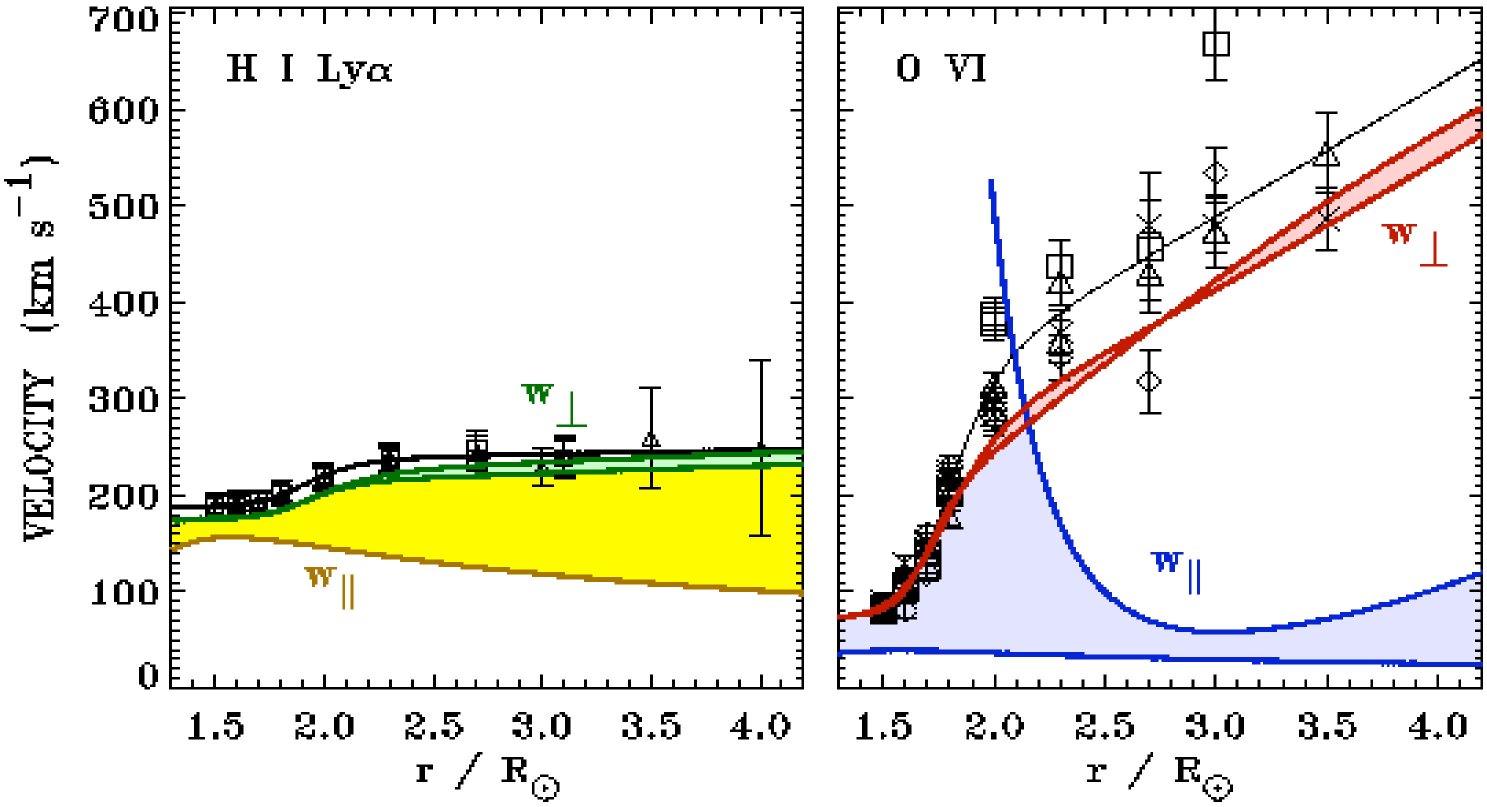
requires $T_i < T_e$

Strong heating of protons and especially heavy ions in solar corona



Heating is M and Z dependent

High flow velocities ; ion heating is anisotropic



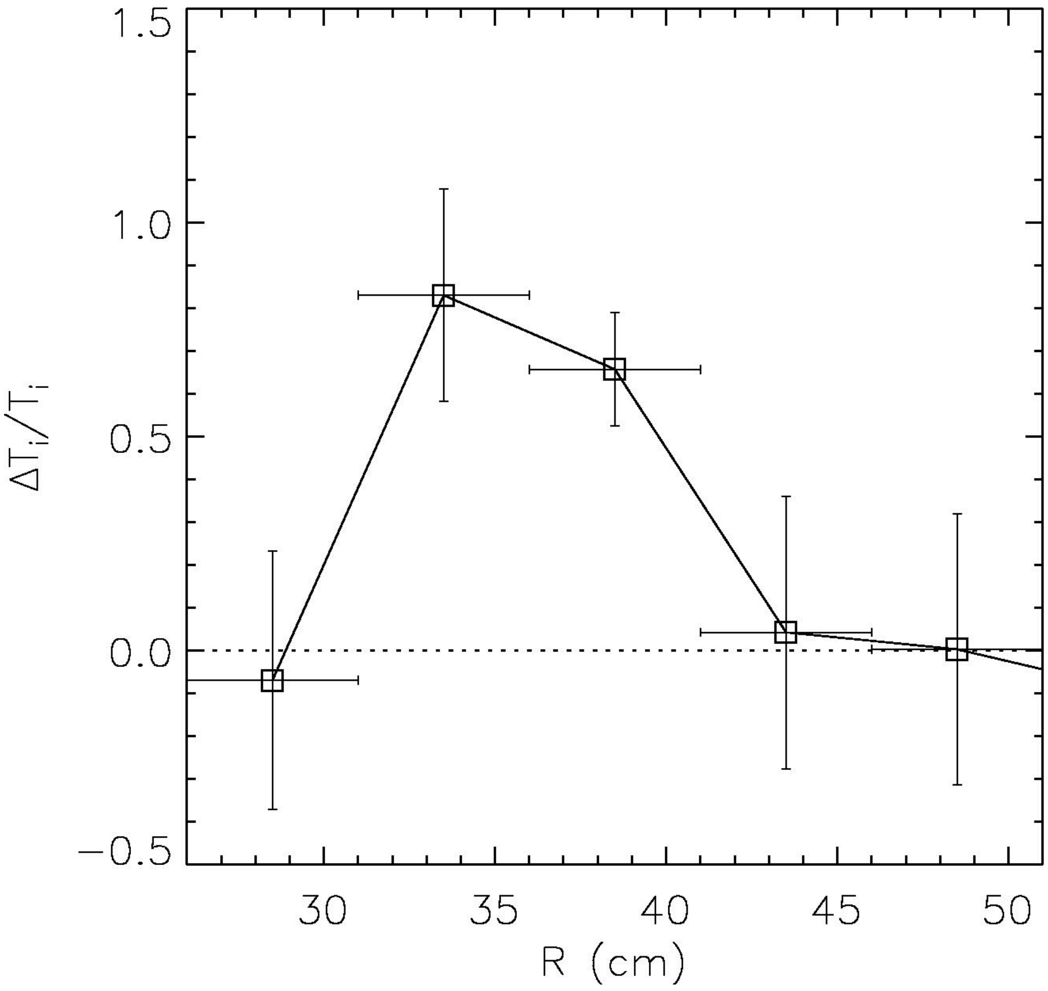
From: Cranmer et al.,

ApJ, **511**, 481 (1998)

Note the large anisotropy: $T_{O\perp}/T_{O\parallel} \geq 10$

Enhanced Ion Heating in MRX
Measured Locally at Reconnection Region

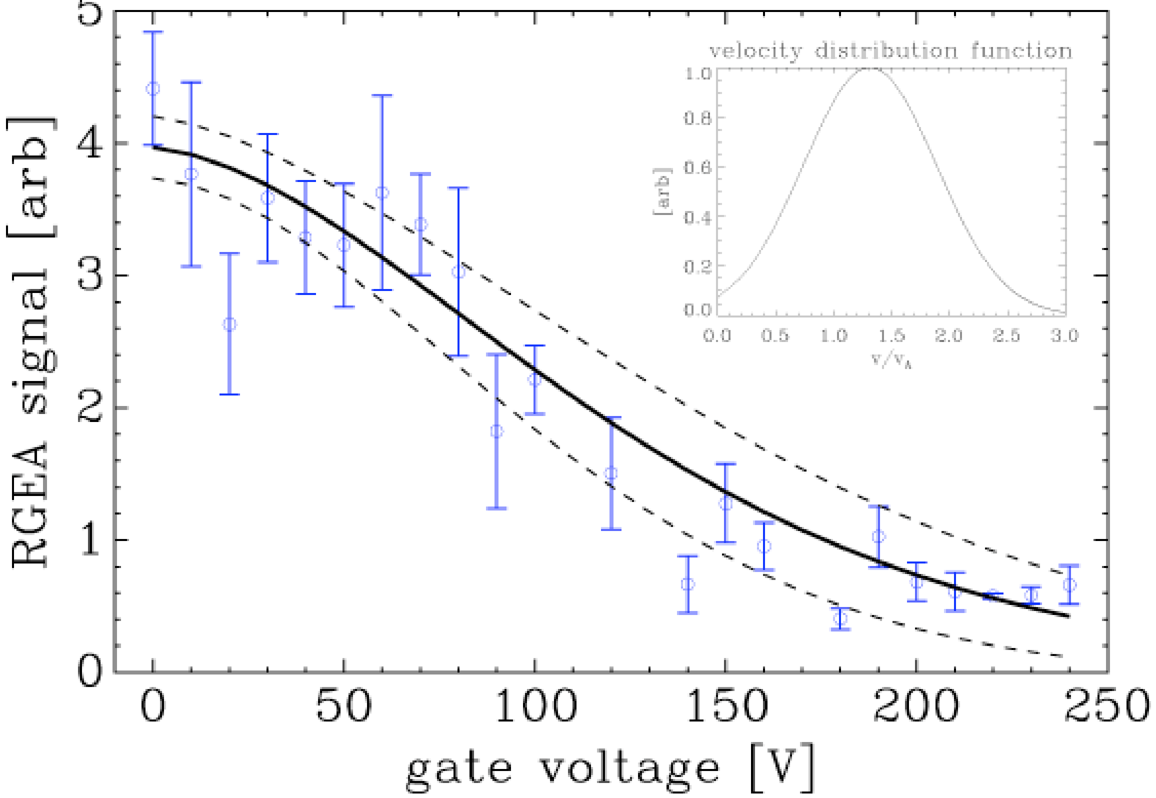
(Hsu et al. ‘00)



Alfvenic flows and ion heating in SSX

C. Cothran
M. Brown

Ion energy distribution measured with electrostatic analyzers



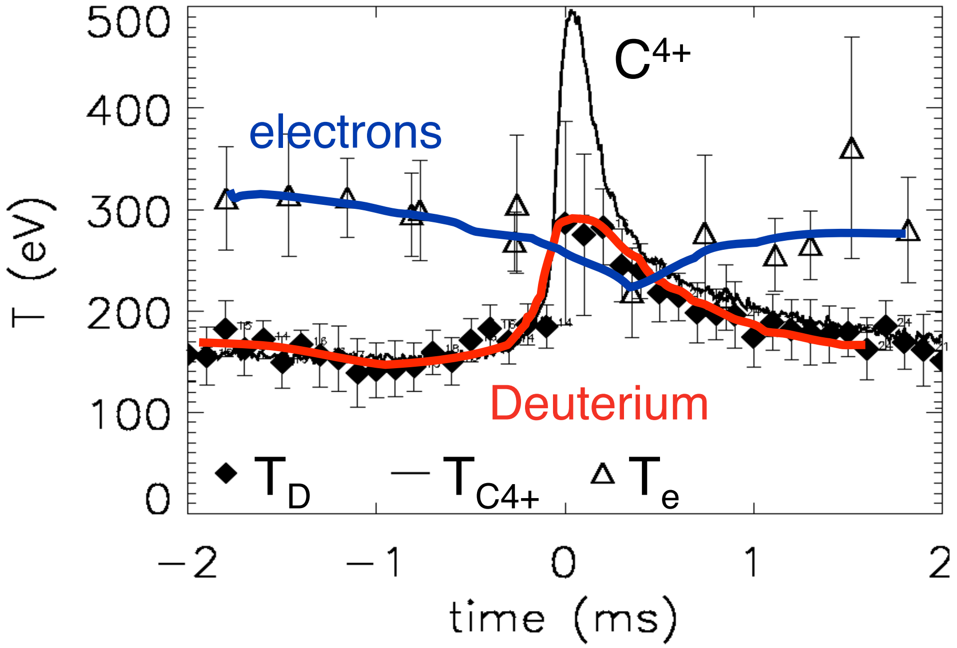
Fit to a thermal distribution with drift:
T=33±11eV and V=86±20eV

Strong ion heating in MST during reconnection events

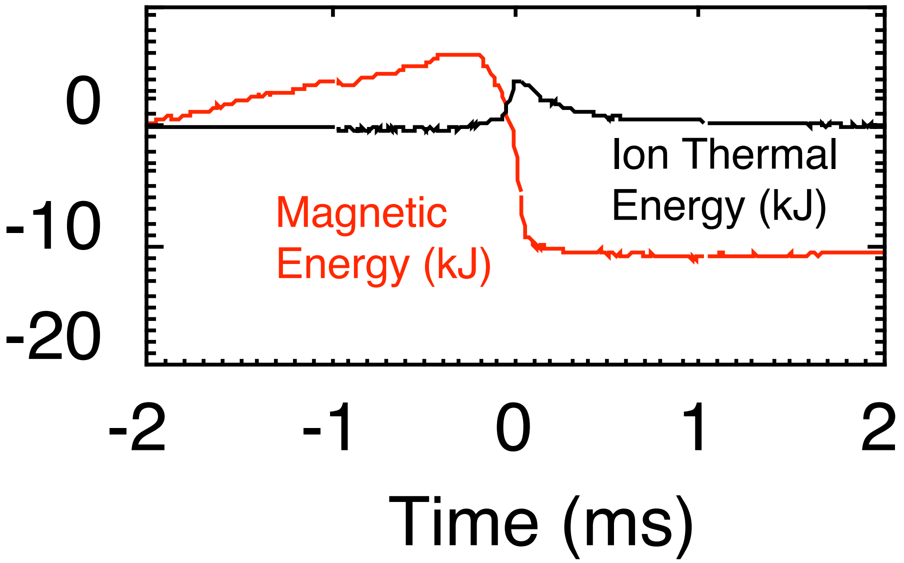
CMSO

More about reconnections later

Both impurities and majority components are rapidly heated. Stronger heating of heavy ions.

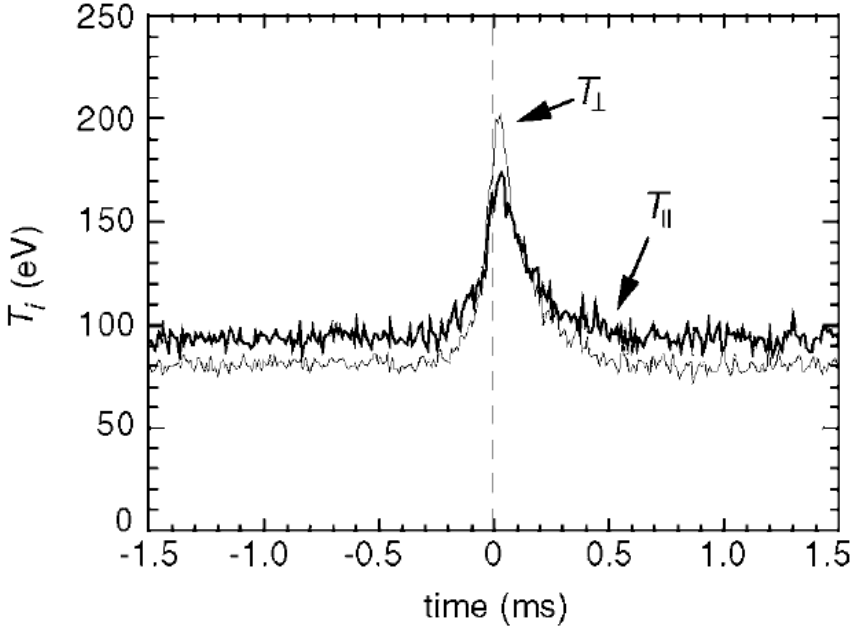


Changes in the thermal energy are large and comparable to the released equilibrium magnetic energy.

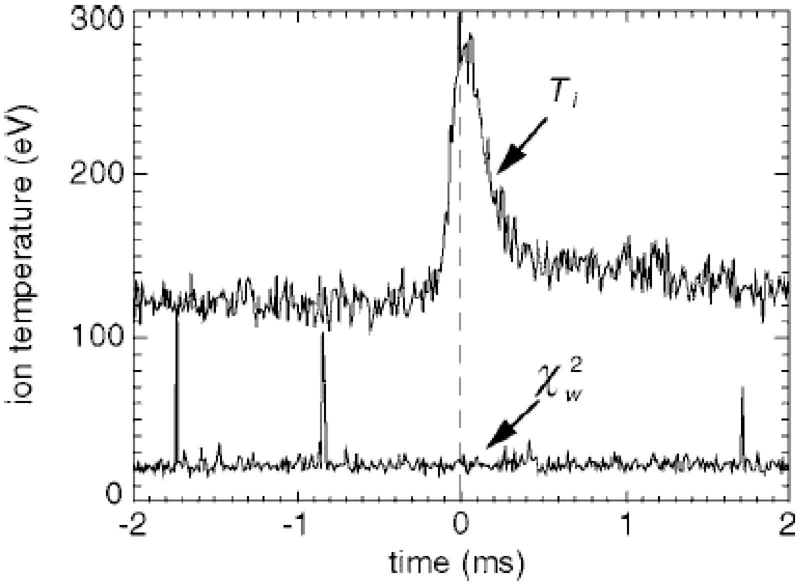


Reconnection heating on MST is almost isotropic. No alfvenic flows. Distribution function remains Maxwellian

$T_{||} \approx T_{\perp}$



Distribution function remains Maxwellian through reconnection



Comparison of ion heating

	MST	MRX	SSX	Solar Wind
$T_{\parallel} / T_{\perp}$	1	?	?	>0.1
Maxwellian	Yes	?	?	?
V_{flow}/V_A	0	?	1	0.1-0.3
T_Z/T_p	>1	?	?	>> 1

In extra-solar astrophysics, the issue is a bit different …

- For so-called "underluminous" AGNs, predicted energy release from accreted mass does not agree with observed luminosity from accreting systems
- There are two (astrophysical) solutions
  - **Ions and electrons do not couple**
    - **Electrons cool rapidly**
    - **Ions cannot lose heat energy, remain hot**: ADAF
  - The observed mass accretion rate is not correct
    - Accretion luminosity only due to (small) fraction of matter that actually accretes
    - Some (large) fraction of the accretion flow ultimately escapes in the form of a wind or jet: **ADIOS**

Ion heating and magnetic turbulence

Typical numbers for MST

$$n_i = 10^{19}\ \mathrm{m}^{-3}$$

$$T_i = 200\ \mathrm{eV}$$

$$\tau_i = 1\ \mathrm{ms} \qquad \tau_e = 10\ \mu\mathrm{s}$$

$$\Delta T_i = 200\ \mathrm{eV}$$ (more for impurities than for majority)

$$\Delta t \sim 200\ \mu\mathrm{sec}$$

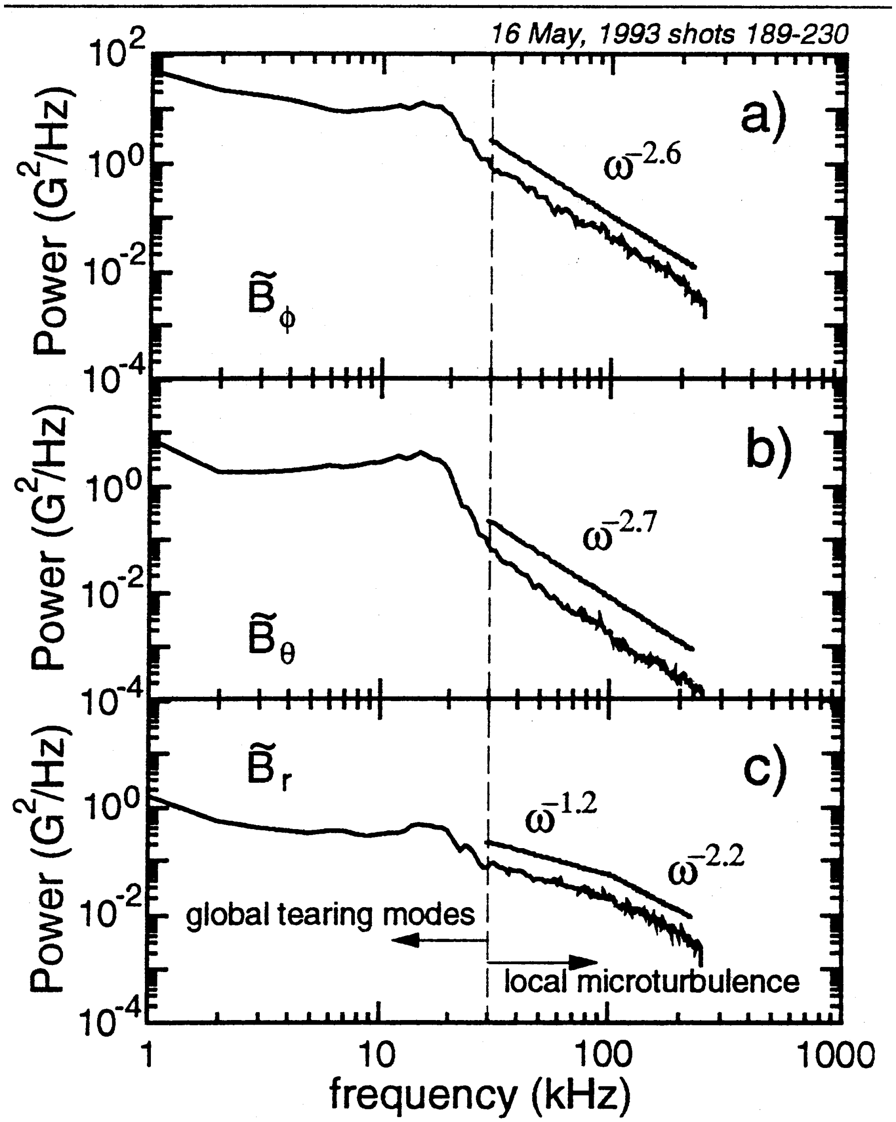
$$\frac{3}{2} k n T_i V = 4 kJ$$

Energy released via redistribution of equilibrium magnetic field 10 kJ

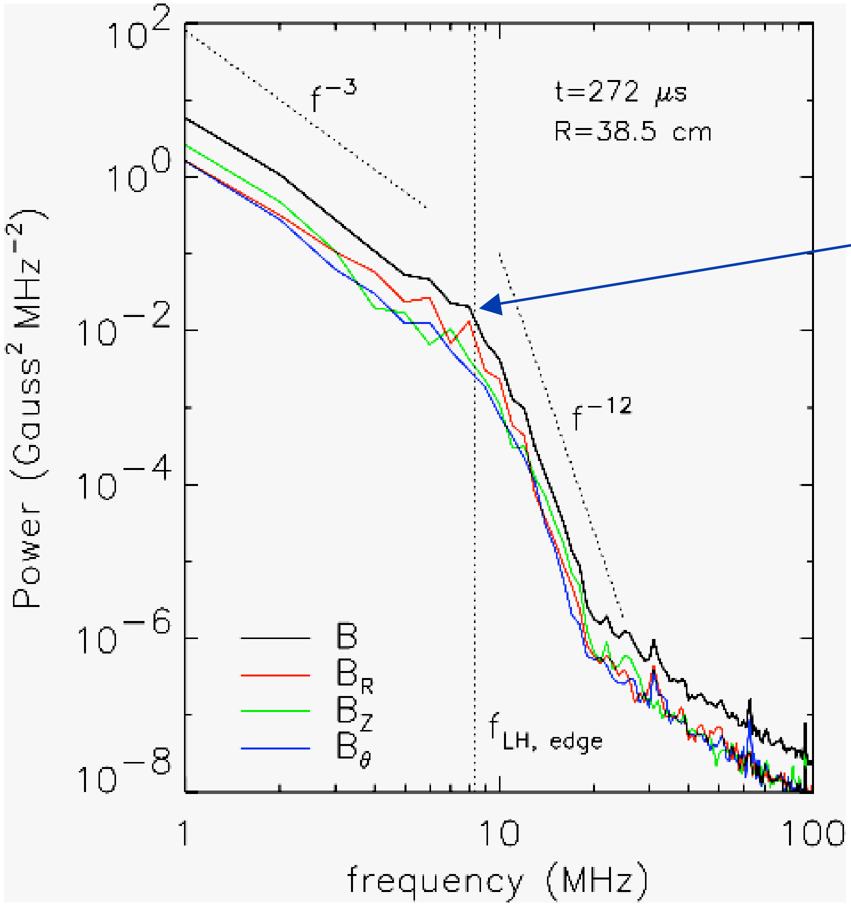
$$P_i = \frac{\frac{3}{2} k n_i \Delta T_i}{\Delta t} = 2\ \mathrm{MW/m}^3$$

How is the energy delivered and absorbed into the ions?

Broad spectra of magnetic fluctuations on MST

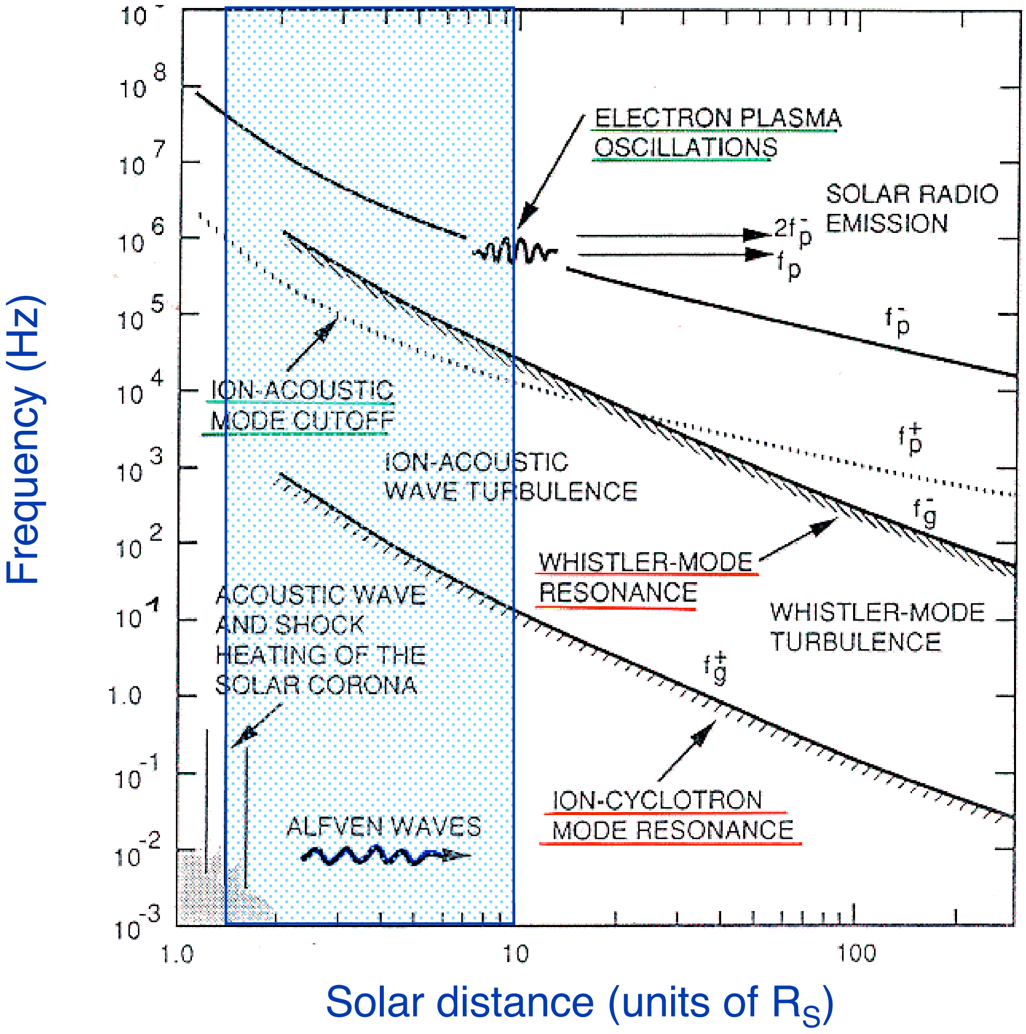


Power spectra of magnetic turbulence on MRX



Possible indication of power absorption by LH?

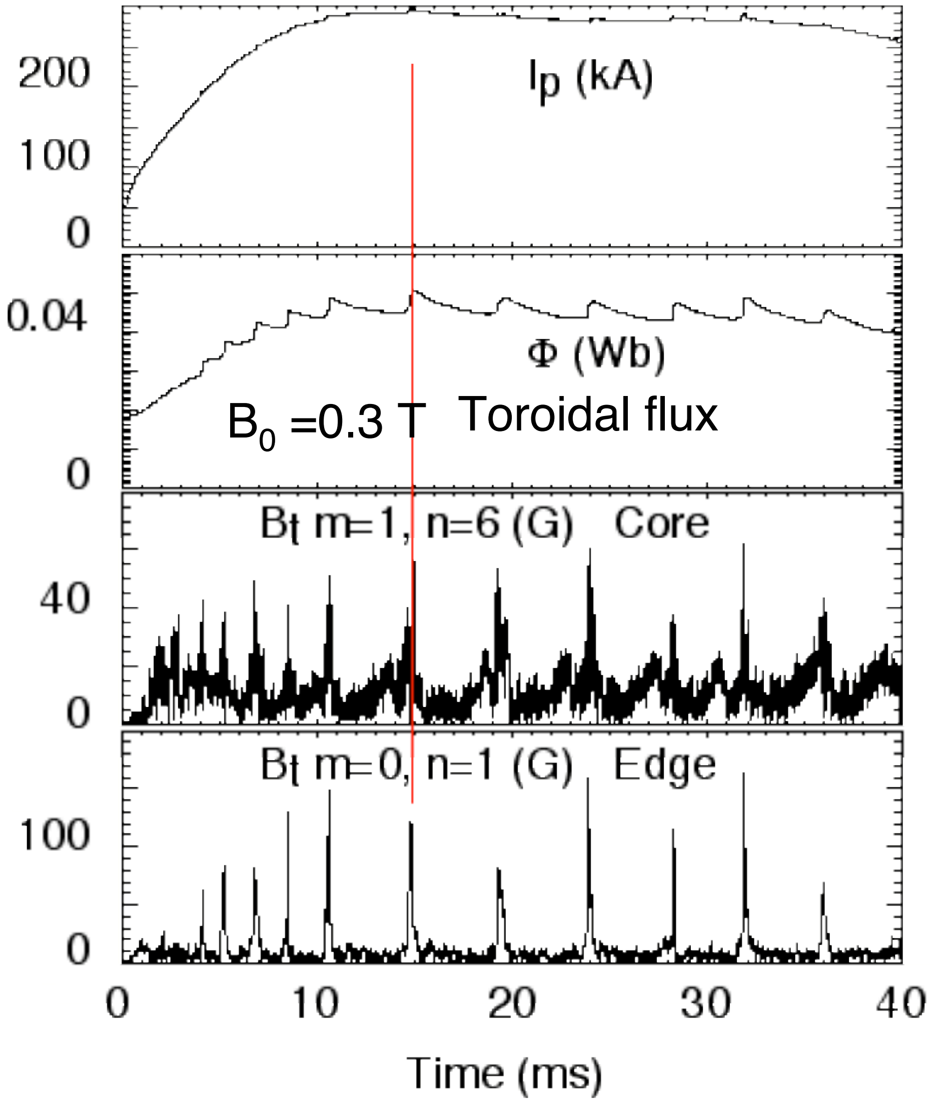
Solar turblence



Wave frequencies vary extremely widely in the outflowing solar wind

(from Gurnett 1978)

Two flavors: continuous fluctuations and discrete events



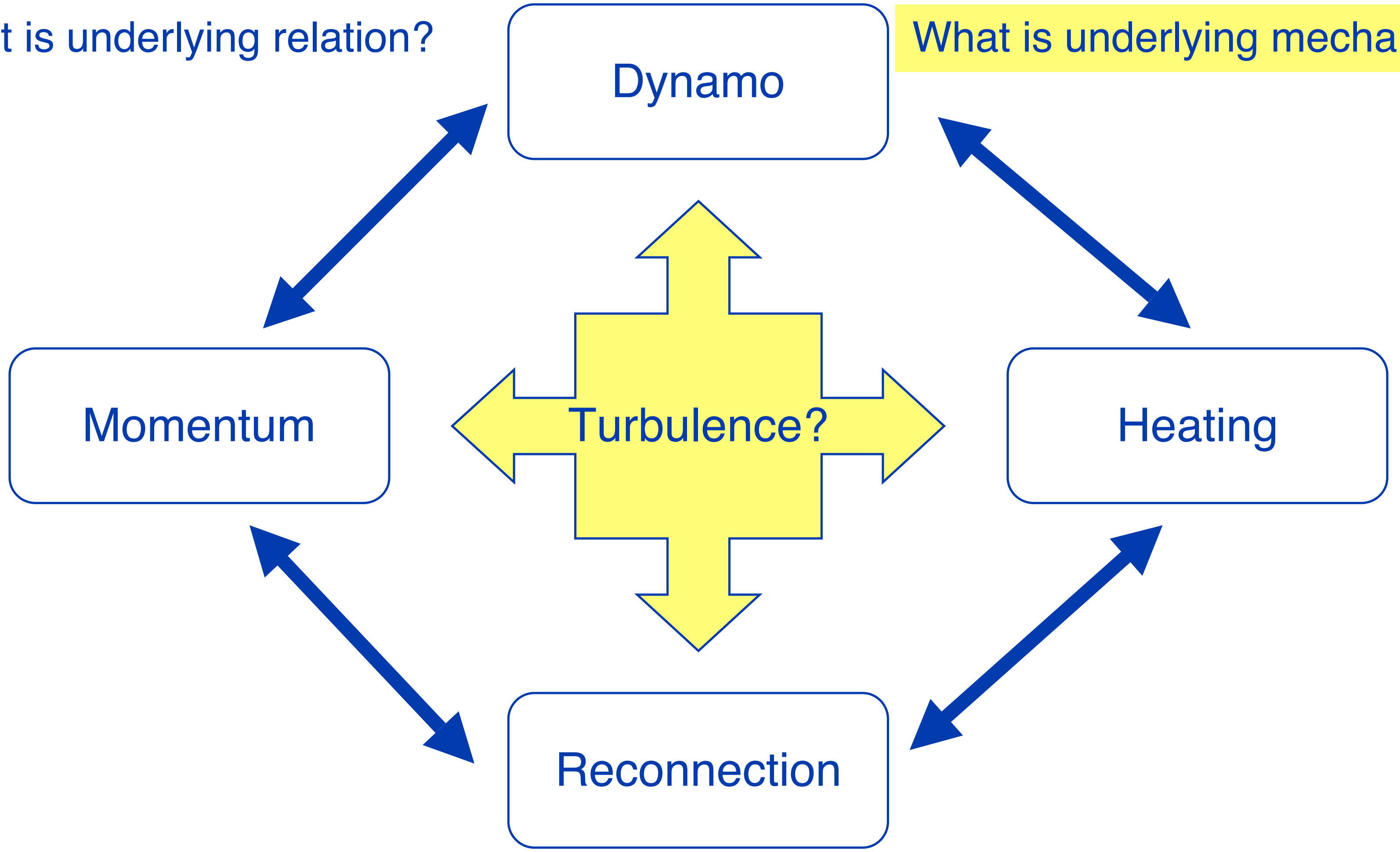
Flux generation

Fluctuation amplitude increases.

Dynamo, reconnection, momentum transport, ion heating happened at the same time

What is underlying relation?

What is underlying mechanism?



Dynamo

Momentum

Turbulence?

Heating

Reconnection

Possible mechanisms

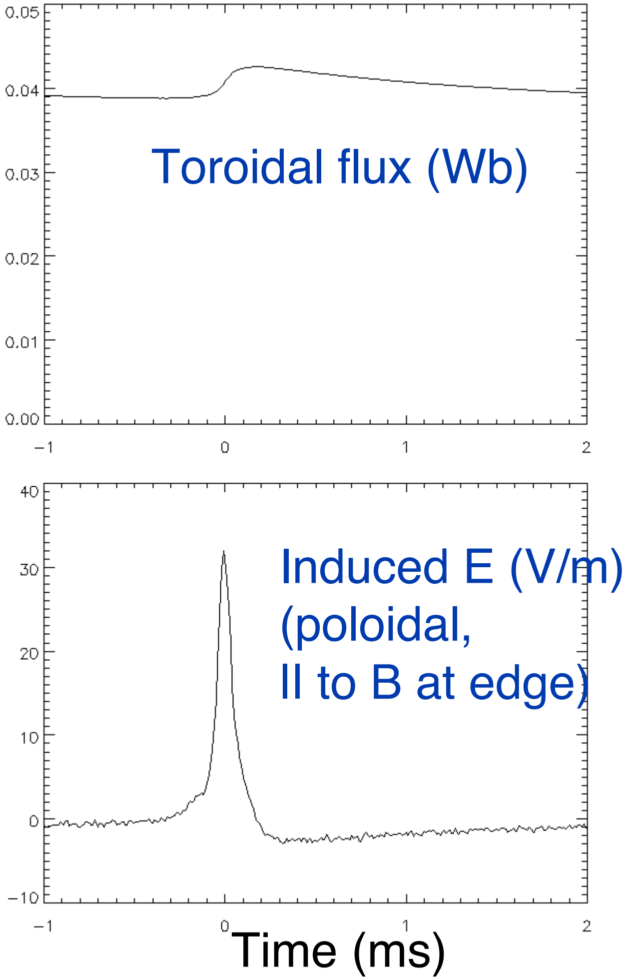
Approach:
limit the number of candidates
and concentrate efforts

Questions to ask

- What is the free energy source?
- How does the energy cascades in time, space, and frequency from the energy source to the ions?
- What is the absorption mechanism? What fluctuation are responsible for ion accelerating and heating?
- Does it agree with experiments? Enough power? Isotropy? Flows? Z, M dependence?

Acceleration by mean electric field

Reconnection generates electric field



For a free ion:

$$E_{\parallel} = 30\ V/m,\ M = 2,\ \Delta t = 200\ \mu s$$

$$E_{kin} = \frac{1}{2}\frac{e^2}{M_i} E_{\parallel}^2 \Delta t^2 \ = \ 900 \text{ eV}$$

Not so in e/i plasma:

Electric force is balanced by friction against electrons

$$E = J/\sigma = e n_e u_e / \sigma$$

$$\tau_e = \frac{3\sqrt{m_e}(kT_e)^{3/2}}{4\sqrt{2\pi} n_e \lambda e^4} = 10\ \mu s$$

Balance is reached fast, on the electron collision time scale

$$E_{kin} = \frac{1}{2(1.96)^2}\frac{e^2}{M_i} E_{\parallel}^2 \tau_e^2 = 0.5 \text{ eV}$$

Nevertheless, mean electric field acceleration is possible

- When another sink for electron momentum is present:
  - magnetic trapping
  - friction with impurities and neutrals
  - electron momentum scattering by fluctuations
  - electron momentum scattering by stochastic magnetic field
- If accelerated, how is the energy dissipated? Must be very fast and efficient dissipation mechanism.

Low and intermediate frequencies : ion viscous heating due to tearing modes

Braginskii equations for 2-fluid MHD:

$$\frac{3}{2}n_i\frac{dkT_i}{dt}+p_i\nabla\cdot\mathbf{v}=-\nabla\cdot\mathbf{q_i}-\boxed{\pi:\nabla\mathbf{v}}+\mathbf{Q}$$

adiabatic heating

losses

viscous heating

e-i collisions

Potentially strong mechanism for heating in MST

Large parallel viscosity $\eta_0 = 0.96 nkT_i\tau_i$

$$P_{visc} \sim \eta_0 \left(\frac{dv_i}{dx_i}\right)^2 \sim \eta_0 (kv)^2$$

For typical tearing modes in MST

$n = 10^{19}\ \mathrm{m}^{-3}$

$T_i = 300\ \mathrm{eV}$

$\tau_i = 1\ \mathrm{ms}$

$k = 1\ \mathrm{m}^{-1}$

$v = 3\times 10^3\ \mathrm{m/s}$

⇒

$\eta_0 = 0.5\ \mathrm{J/m^3 \cdot s}$

$P_{visc} = 4.5\ \mathrm{MW/m^3}$

High power, inherently isotropic mechanism
But ion mfp is too long - questions of applicability
Modify for weakly collisional plasma

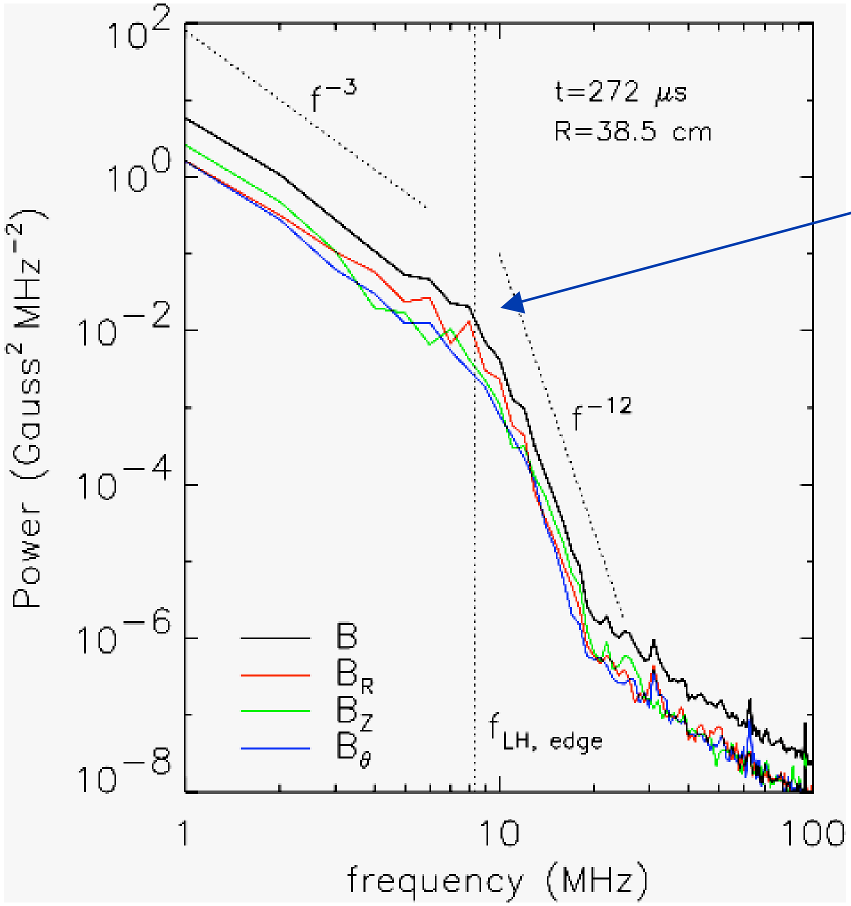
Ion cyclotron heating

- Leading candidate for solar corona heating
- Preferential perpendicular heating
- Solar wind can be explained by acceleration of high-$v_{\square}$ ions down the magnetic hill.

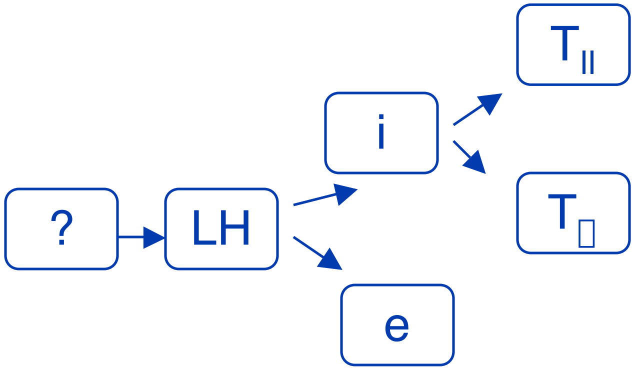
Caveats:

- Dissipation is predicted for fluctuation with high $k_{\square}$ but do they have large amplitude $\square \approx \square_{ci}$?
- Amplitude seems to be too small for MST but more careful evaluation is needed.

Low hybrid waves in MRX



Possible indication of energy dissipation?



Experimental plans

MST diagnostic set

Existing diagnostics

- CHERS - active Doppler spectroscopy. Ion impurities temperature and flow. Good spatial (few cm) and temporal (10 usec) resolution.
- RS - Rutherford scattering diagnostic - majority ion temperature. Spatial and temporal resolution is somewhat below than that of CHERS.
- NPA - Neutral particle analyzers - majority ions temperature, good time resolution but chord averaged spatially.
- IDS - passive Ion Doppler Spectroscopy - chord averaged ion impurities temperature and flow

New acquisitions or modifications

- DNB - longer pulse, higher energy
- Modified insertable probe for local ion Doppler spectroscopy
- New probe for local measurements of ion energy deposition $\langle J_i E \rangle$
- Mach probe for local ion flow measurements
- New high resolution, high frequency magnetic fluctuation probes

MST experimental plans

- Detailed accounting of ion energy balance
  - Modeling and measuring of magnetic field energy profile.
  - Spatially and time resolved measurements of ion temperature
  - Electron collisional heating
  - Measurements of CX losses
  - Modeling of ion transport
- Correlation with magnetic fluctuations, contribution from different modes.
- Ion flow and isotropy of ion heating, dependence on plasma collisionality.
- Z/M phenomenology of ion heating.
- Acceleration and heating by externally generated inductive low frequency mean electric field.
- Local measurements of ion energy deposition $<J_i E>$
- Local measurements of ion flow and evaluation of ion viscous heating.
- Study of heating of test “cold” ions injected by a pellet injector
- Study of heating (or cooling) of test “hot” ions from energetic neutral beam. Transport of fast ion in stochastic magnetic field.

MRX experimental plans

- To characterize ion heating and electron heating during reconnection process as a function of various parameters and boundary conditions: (a) collisionality, (b) strength of guide field, (c) “push” versus “pull” reconnection geometry, (d) driving MHD force etc
- To correlate ion and electron heating with classical processes, such as electron-ion collisions and viscous stresses
- To correlate ion and electron heating with wave activities, including newly measured high-frequency measured fluctuations

Diagnostics and tools

- Local ion flow and temperature diagnostics (IDSP, energy analyzer)
- Global ion flow and temperature diagnostics (line-integrated measurements)
- Local fluctuations measurements by probes (B-dot and electrostatic)

Solar corona studies

- **Line shift** by Doppler effect
    - Bulk motion along line of sight
- **Line broadening/spectral line shapes**
    - p, ion, e- velocity distributions along line of sight, departures from Maxwellians
- **Collisionally-excited line intensities/ratios**
    - Abundances, ionization state; electron density & temperature
- **Thomson scattering** (of solar photospheric light by coronal e^-)
    - Measure electron density as function of solar distance
- **Resonant scattering** via Ly □, ...
    - Measure wind speed in plane of sky, as f‘n of solar distance, by resonant scattering intensity data with electron density data from Thomson scattering (`Doppler dimming‘)
- **Broadband X-ray photometric imaging**
    - Spatially-resolved plasma density/pressure/temperature
- **Hanle effect/EUV spectropolarimetry**
    - Magnetic field strength

SSX plans

Study role, mechanisms for flow in FRC-like equilibrium

Measure flows more accurately:

- ion doppler spectroscopy (D. Craig consulting)
- single shot measurement of T_i, v_i histories (1 μs resolution)

Theory: Key issues and approach

- Issues
  - Ion acceleration in electric field: Effects of multi-component plasma, magnetic trapping, runaways, stochastic magnetic field.
  - Fast dissipation of ion flow kinetic energy -viscous vs. collisionless.
  - Viscous heating by compressional tearing modes:
  - Ion heating by tearing modes in weakly collisional plasma. Application of kinetic calculated dielectric tensor to tearing modes.
  - Alfven cascade: does it work, and if so, how?
  - Reconnection and ion heating.
- Approach
  - Directly benefit from other participating groups of the Center - understanding ion heating is closely coupled to better understanding of reconnection processes, dynamo and flow generation, and turbulence studies, in particular the energy cascading and dissipation.
  - Key simulation tool: 2-fluid numerical simulations, i.e., NIMROD, FLASH. Non-linear tearing modes with viscosity. Anisotropic viscosity?

Theory and simulations (from MRX)

- Calculate heating rates due to wave activities by using quasilinear theories in 2 fluid models
- Calculate heating rates due to wave activities by using simple nonlinear theories taking into account of wave-particle interactions
- Calculate heating rates based on 3D 2-fluid simulation of reconnection
- Calculate heating rates based on 3D PIC simulation of reconnection
- Two-fluid simulation of reconnection (FLASH, NIMROD)
- PIC simulation of reconnection (collaboration with Drake, Li, et al)

Cross-fertilization

- Design and fabrication of diagnostics - probes, Doppler spectrometer...
- Using the same diagnostics in different machines
- Using other facilities?