

# Heavy Ion Heating In Coronal Mass Ejection Shocks

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# Heating in collisionless shocks

- Collisionless shock heating based on three factors:
  - $V_{\text{shock}}$ : shock speed
  - $\theta_{Bn}$ : magnetic field angle to shock normal
  - $\beta$ : ratio of thermal and magnetic pressure
- Quasi-Parallel ( $0 < \theta_{Bn} < 45$ ) vs Quasi-Perpendicular ( $45 < \theta_{Bn} < 90$ ) Shocks heat differently

# Mass proportional heating

$$kT = \frac{3}{16} mv^2$$

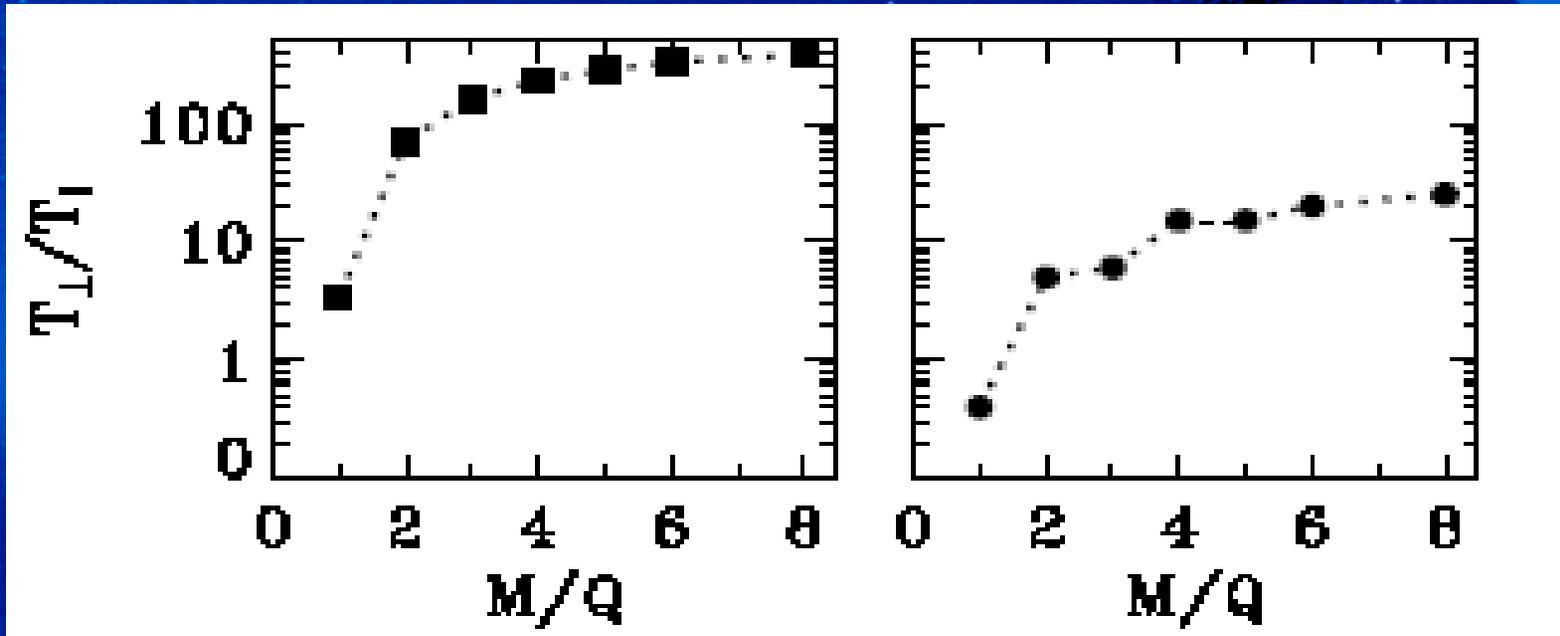
- 3/16 comes from the strong shock approximation of the RH conditions
- All ions speeds would be the same if the heating was mass proportional

# Composition of the Solar Wind

- The composition of the solar wind allows us to study many different ions
- Protons dominate
- He is the next abundant element
- O 6+ is the next most abundant

<u>Element</u>	<u>Abundance</u>
H	92
He	7.8
C	0.02
O	0.06
Other Heavies	0.12

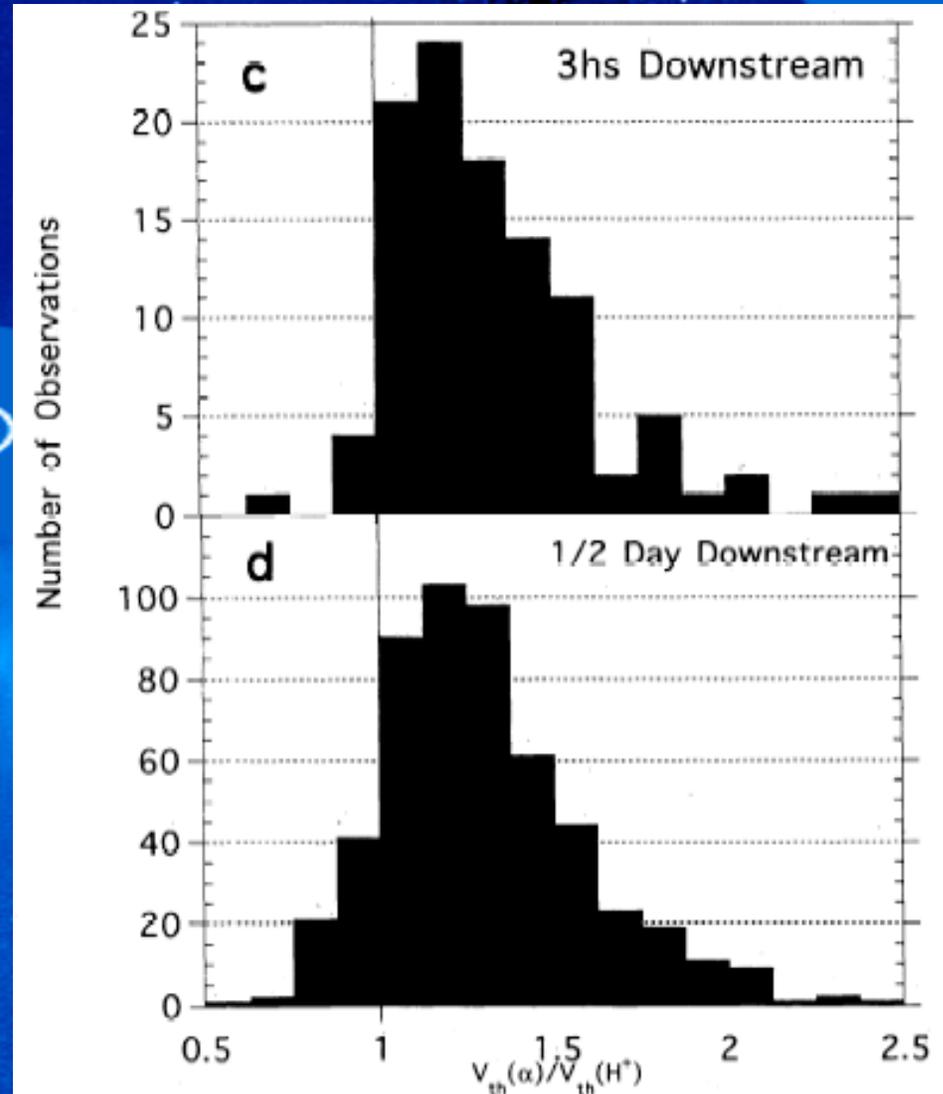
# Shock heating is strongly $M/Q$ dependent



Ratio of  $T_{dw}/T_{up}$  shows a strong dependence on the mass to charge ratio of an ion.

# CME driven shocks

- Berdichevsky et al., 1997:
  - He<sup>2+</sup>/H<sup>+</sup> observations on Ulysses
  - Most shocks produce shock heating greater than mass-proportional



# CME shock study

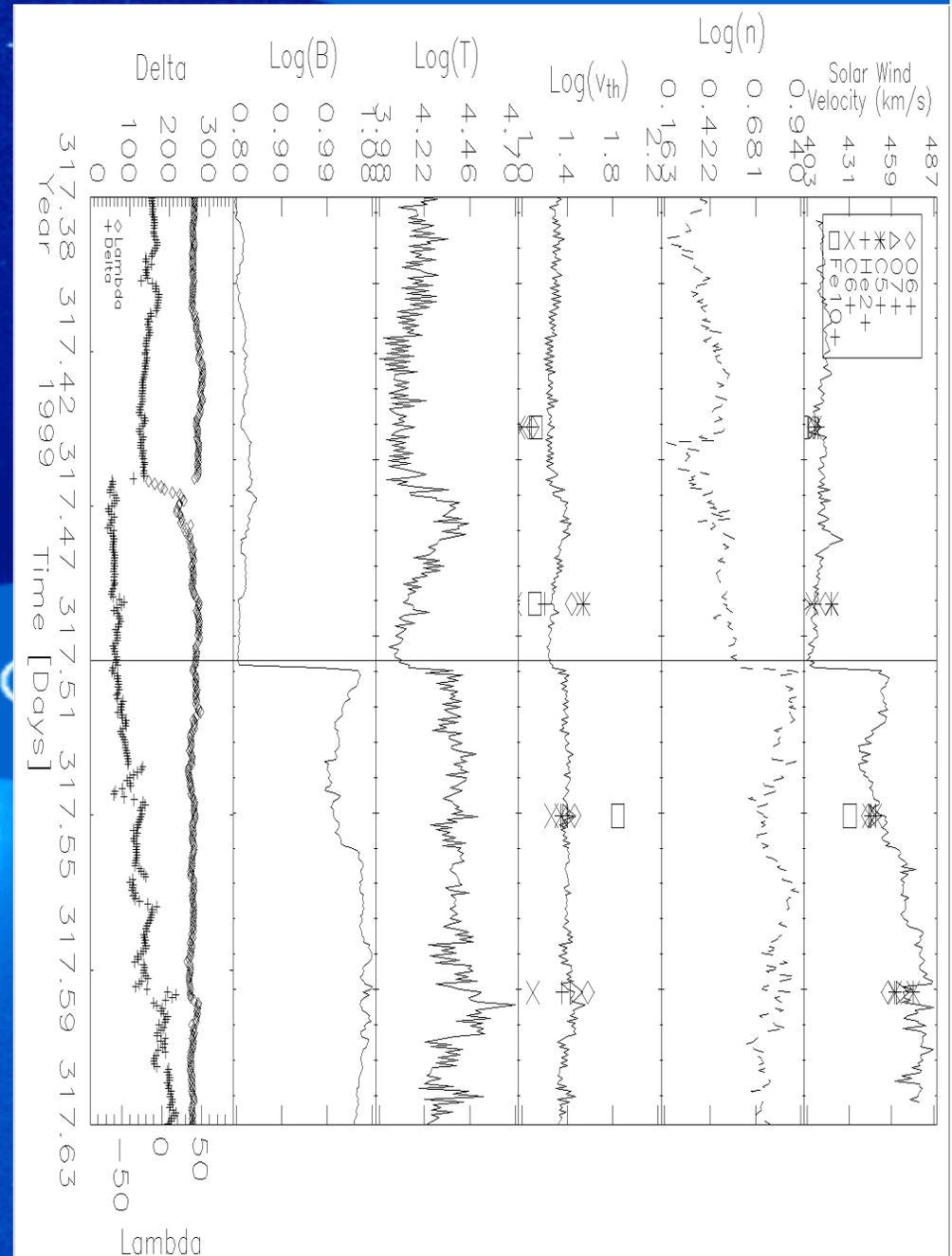
Total Number of Shocks	21
Quasi-Perpendicular	17
Quasi-Parallel	4
Mach Number	1.1-5.9
Beta	0.01-1.4

Plasma data courtesy of SWICS, SWEPPAM, MAG.

Shock properties characterized by C. Smith, UNH.

# Shock analysis

- Data were taken with the ACE satellite
  - magnetic angle
  - magnetic field strength
  - temperature
  - thermal velocities
- Heavy elements are analyzed at time-resolution of 1 hour.
- 12 minute interval that includes shock is skipped.
- $M/Q = 1, \dots, 5.6$

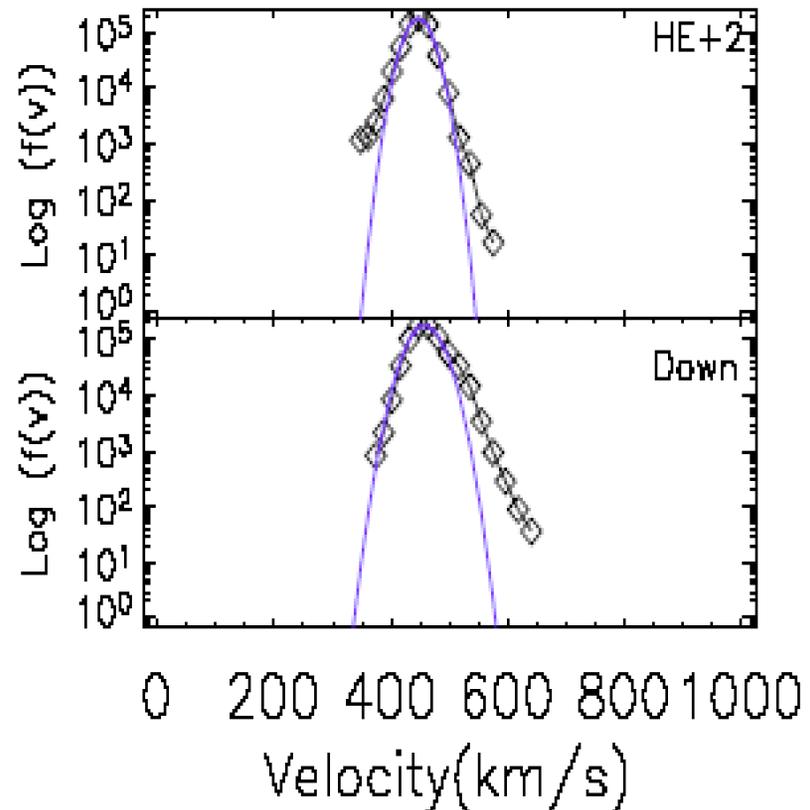


# Selection criteria

- Selection of shocks: During 1 hour interval
  - $\_B/B < 20\%$
  - $\_T/T < 20\%$
- Thermal speed are obtained from distribution functions.
- Moments calculates by Gaussian fits.

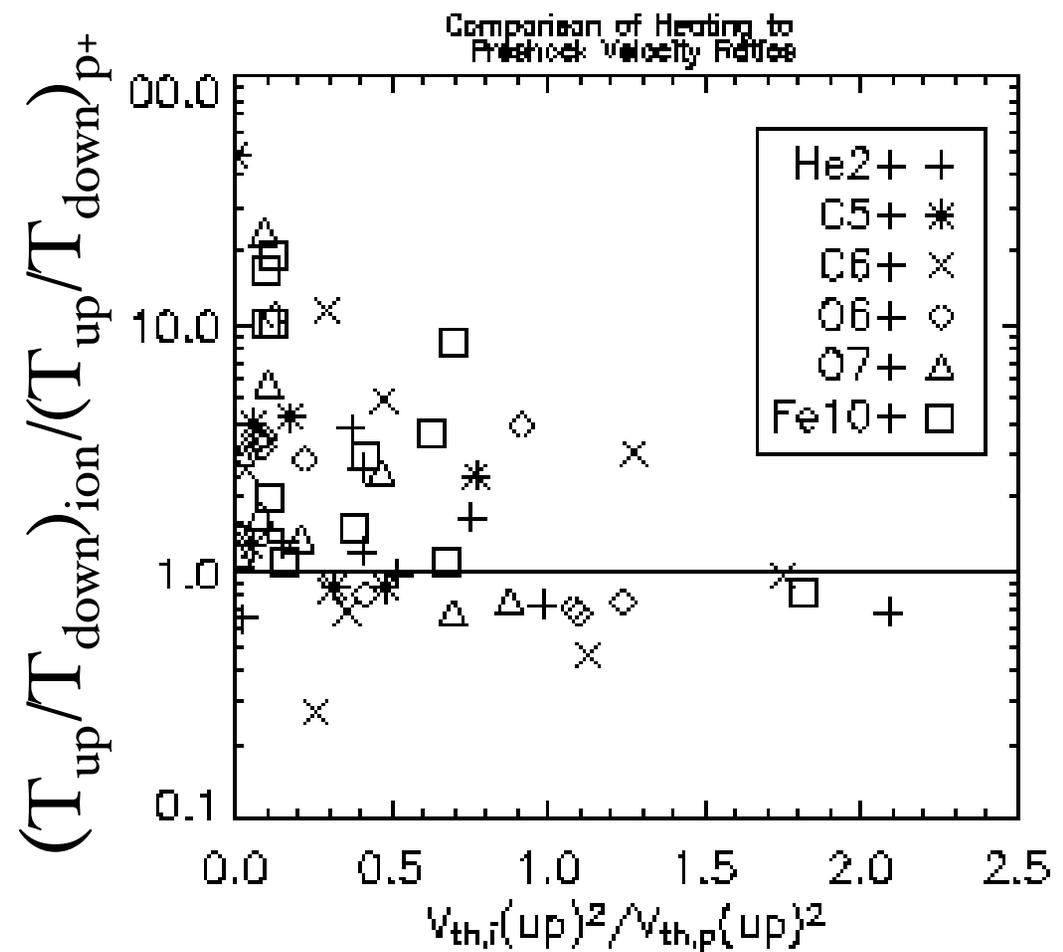
# Heavy ions

- Non-Maxwellian velocity distribution functions appear in 75% of the cases.
- The suprathermal tail appears after the shock



# Perpendicular shocks: effect of initial conditions

- Ions do not start in thermal equilibrium.
- More “thermalized” ions get more energy.

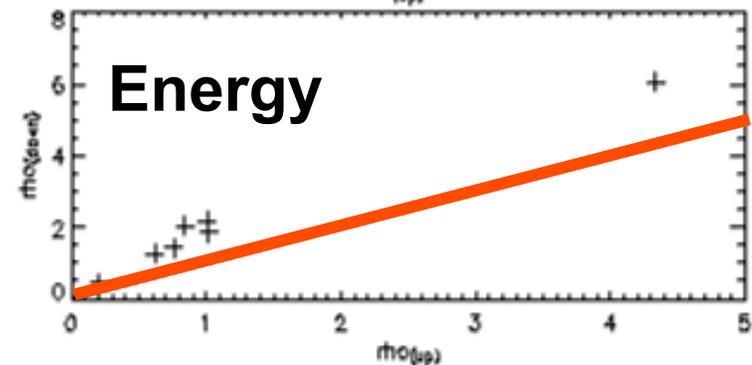
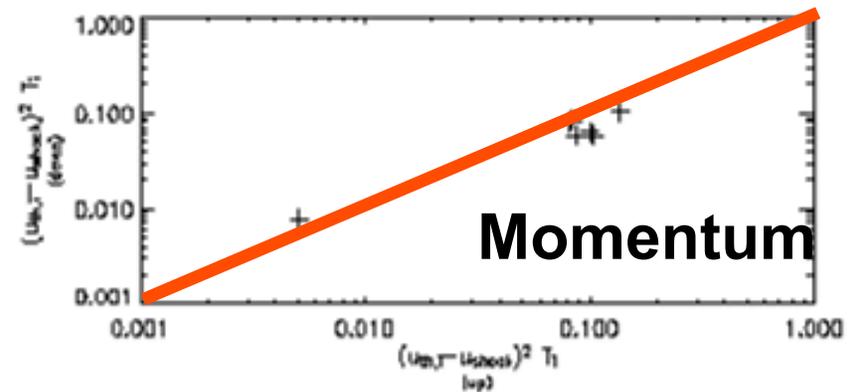
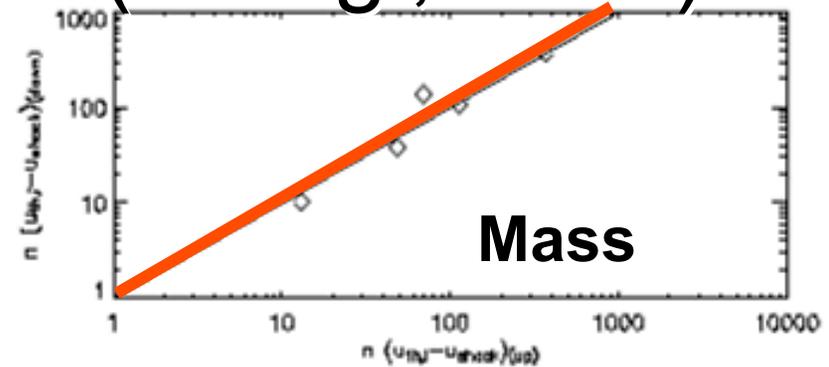


# Parallel shocks (Buergi, 1985)

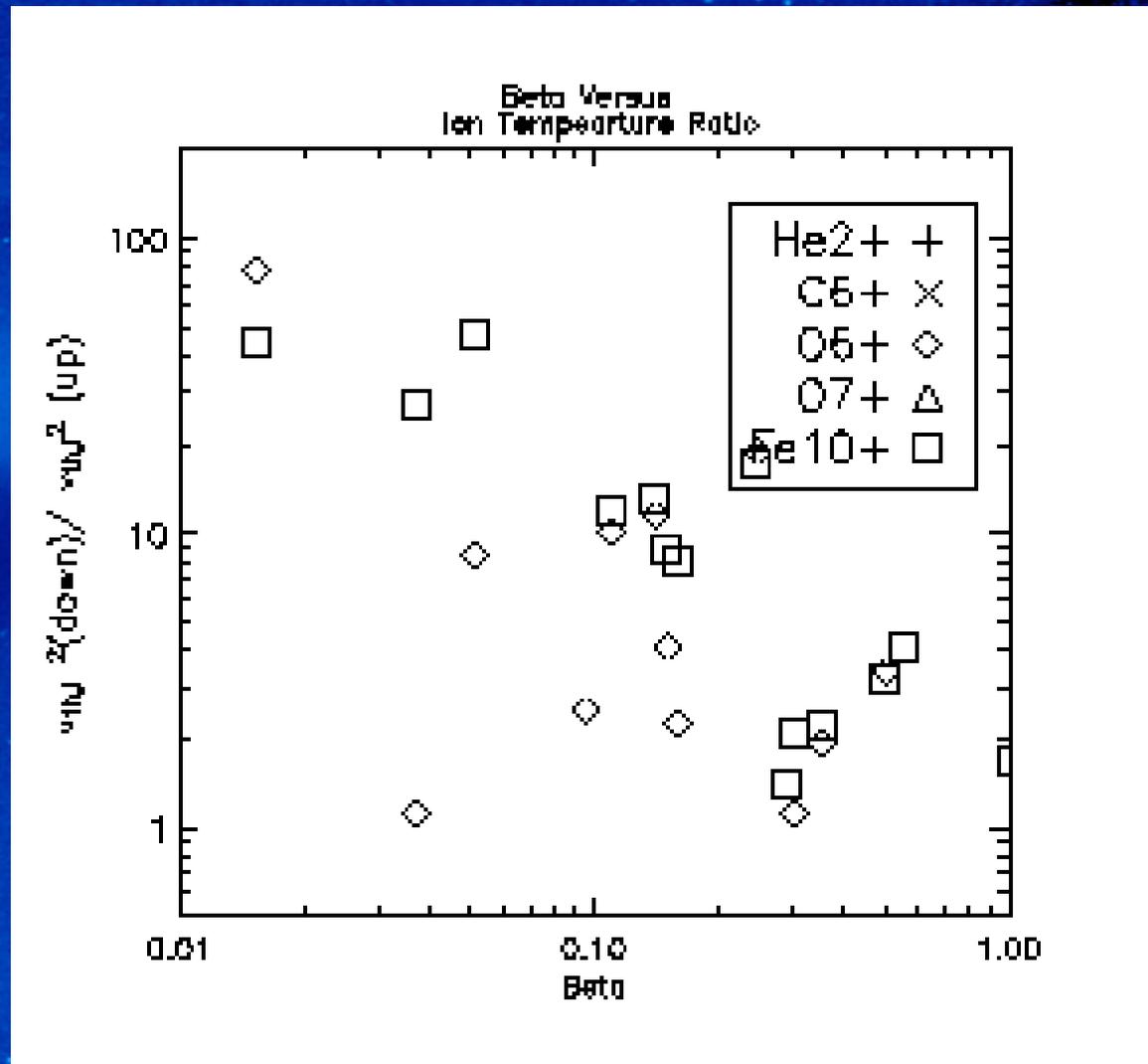
- 3 species, electrons, protons and heavy ions

## Ion jump conditions

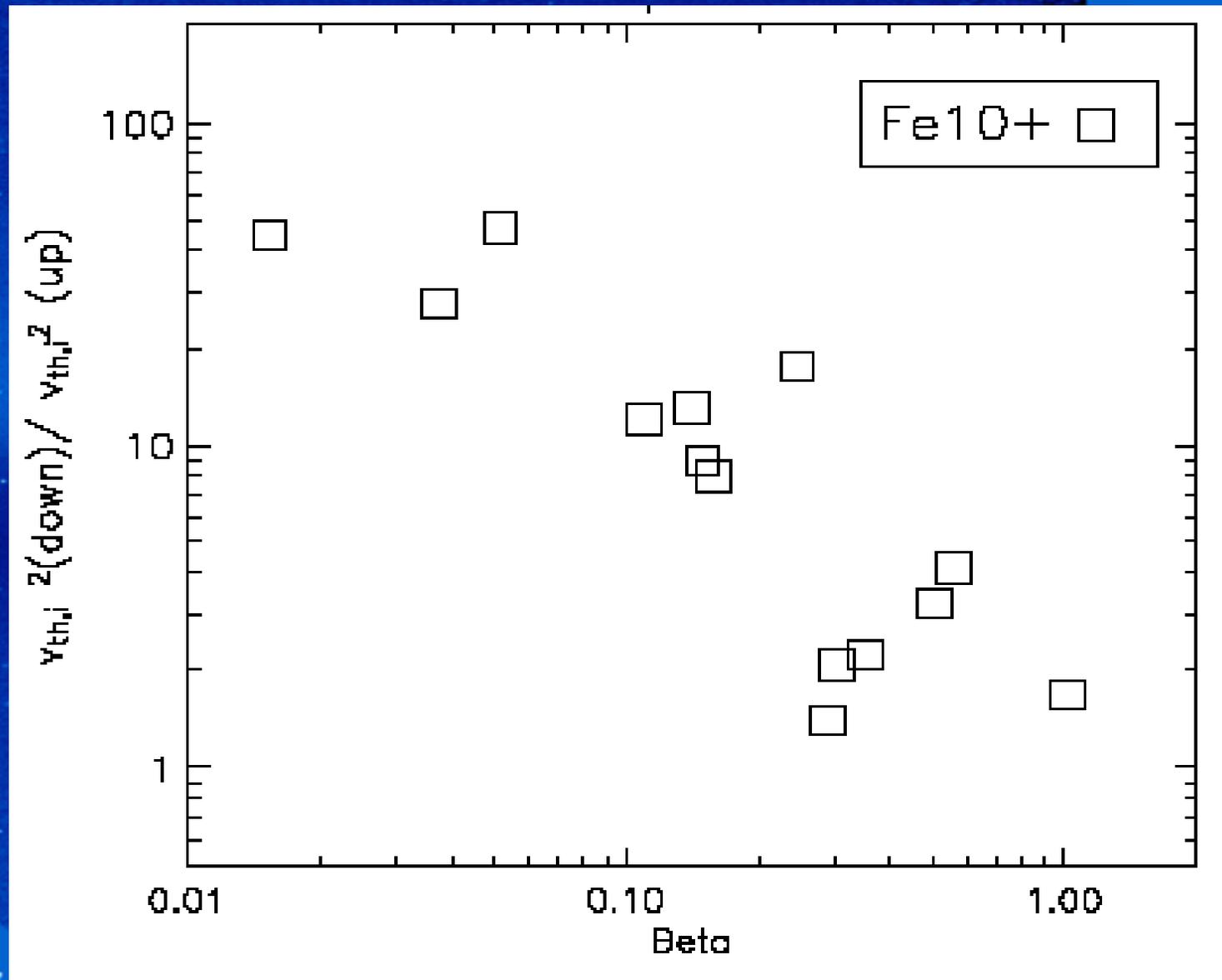
- $[n_i u_i] = 0$
- $[u_i^2 T_{i,\parallel}] = 0$
- $[0.5 m_i u_i^2 + 3/2 k T_{i,\parallel}] = 0$
- More energy transferred than theory predicts



# Scaling with plasma beta

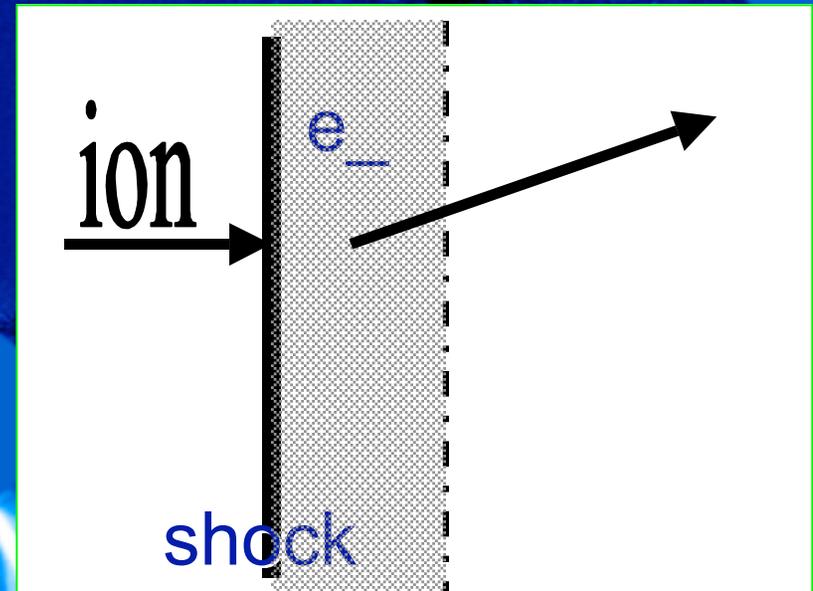


# Fe plot



# Heating mechanism at the CME shock front

- From bow shock studies by Fuselier and Schmidt (1997)
- Protons assumed to be dominate
- Heavy ions are treated as a test particle
- Protons create a potential as they slow down over the shock
- This potential causes the heavies to speed up to conserve energy

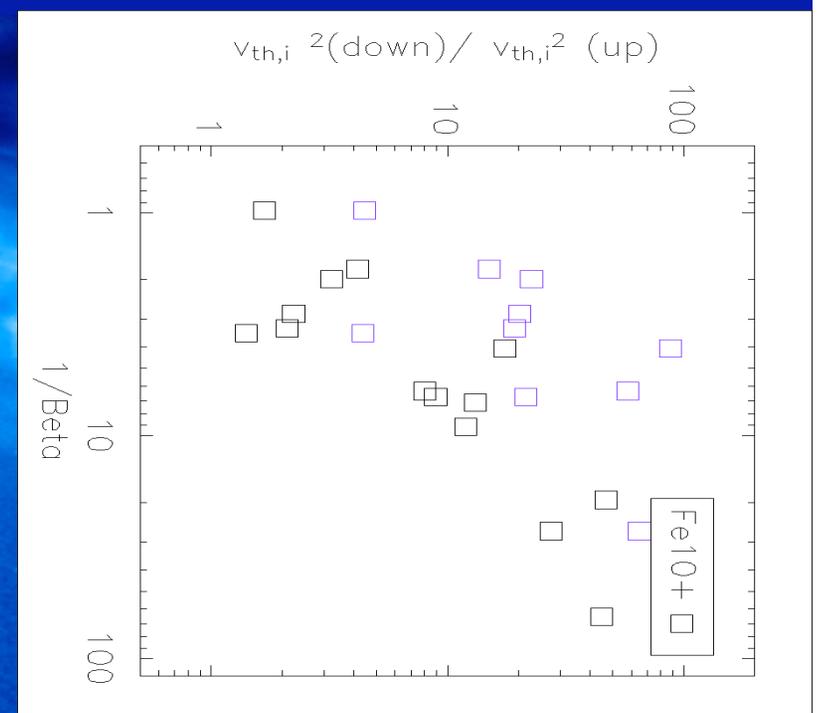


$$v_{i,2} = v_{p,1} \sqrt{\frac{(\alpha-1)+c^2}{\alpha}}$$

# Heating mechanism at the CME shock front (continued)

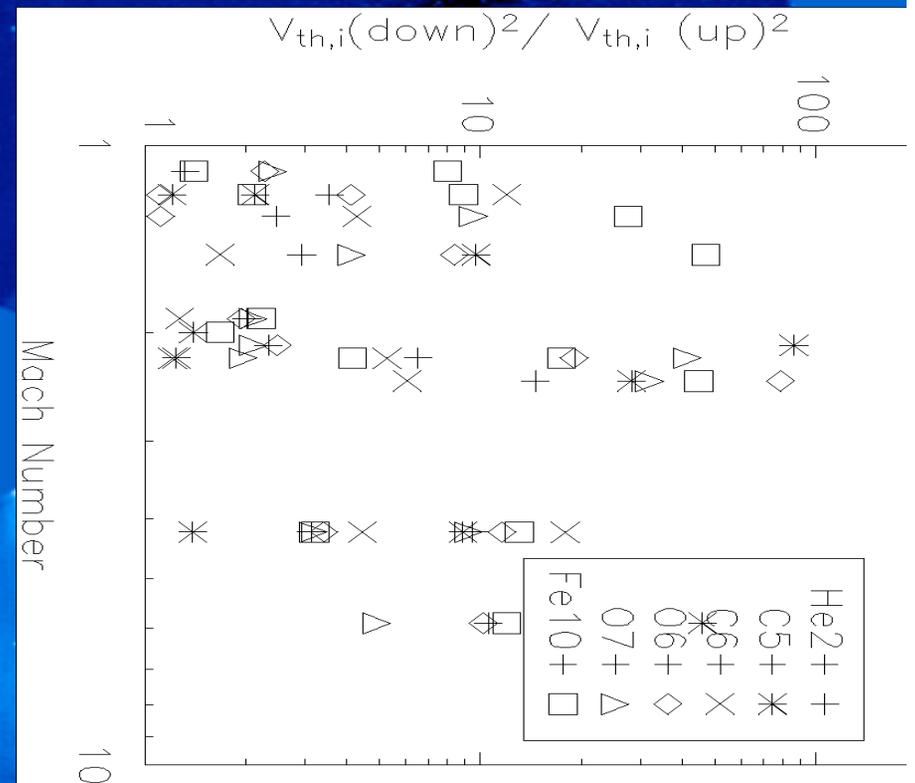
- Relating to  $\beta$
- Using the data for Fe 10+ in black and purple is the predicted value using the above equation

$$\frac{v_{i,2}^2}{v_{i,1}^2} = \frac{M_A^2 2kT(\alpha - 1) + c^2}{v_{i,1}^2 m_p \beta \alpha}$$



# Dependence of heating on shock properties ?

- Shock Alfvénic Mach Number: No observed dependence
- Important Dependences
  - Shock angle
  - Upstream (proton) plasma  $\beta$



# Summary for heavy ion heating

- CME Shock heating has a strong  $M/Q$  dependence.
- Perpendicular shocks impart a larger fraction of energy to heavies.
- The heating rate does not depend on Mach number, but upstream proton  $\beta$
- We need models to interpret these data. Obviously, heavies are sensitive to kinetic effects.
- $\beta$  trends can be applied to other astrophysical shocks to predict magnetic field