Ion-Scale Wave-Related Dissipation Processes

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First of all, note that: Ion-scale dissipation ⟷ Ion heating

Define "wave-related" for this talk:

- Does not require fully-developed propagating wavetrain for which $\omega > (\tau_{cascade})^{-1}$.
  - linear terms in governing equations for fluctuations simply correspond to linear wave-like operators, independent of relative non-linear rates. (*pace* WHM)
- Dissipation & ion heating are "volume-filling".
  - diss. processes are not localized at distinct structures, as in current sheets.

For guidance from observations, we also assume here that:

- Turbulent cascade provides the kinetic-scale energy to heat and accelerate the solar wind.

Wave-related dissipation processes:

- resonant Landau damping $\omega - k_{\|} v_{\|} = 0$

  (low parallel phase speeds can resonate with thermal ions)

- transit-time damping (compressible or mirror-mode fluctuations, moderate-to-high β)

- resonant cyclotron damping $\omega - k_{\|} v_{\|} = n\Omega_i \ (n \neq 0)$

  (requires high ω to resonate with thermal ions: ICWs or Bernstein waves)

- NL stochastic dissipation [Chen et al. 01; Johnson & Cheng 01; White et al. 02; Voitenko & Goossens 04; Chandran et al. 10]

  (requires finite-amplitude fluctuations at high $k_{\perp}$)

Ion heating in corona and solar wind is observed to act primarily to

- increase $T_\perp$
- heat heavy ions $>$ protons (T_i to mass-proportional or more)

Increasing $T_\perp$ (at ~ constant B_o) $\longrightarrow$ increasing ion magnetic moment.

This immediately eliminates gyrokinetic treatments for accurate models of the dissipative cascade.

(Fundamental assumption of GK is conservation of mag. moment)

Furthermore:

- ~~Landau damping~~
- ~~transit-time damping~~

yields parallel heating only

For perpendicular ion heating:

- resonant cyclotron damping –
  high ω allows non-adiabaticity in time

and/or

- NL stochastic dissipation –
  high $k_\perp$ allows non-adiabaticity as ions gyrate through spatial variations

♦ Turbulent dissipation may be dominated by one of these processes (or by current sheets) or may involve a combination of them.

♦ Dissipation processes in the low-β corona need not be the same as those in the moderate-to-high β solar wind.

Turbulent cascade is anisotropic:

- Resonant cyclotron damping requires nonlinear coupling of quasi-2D power into high-frequency waves ($\omega \sim \Omega_i$).

maybe through: fast mode $\rightarrow$ ICWs [Chandran 05, Cranmer & vBall. 12]

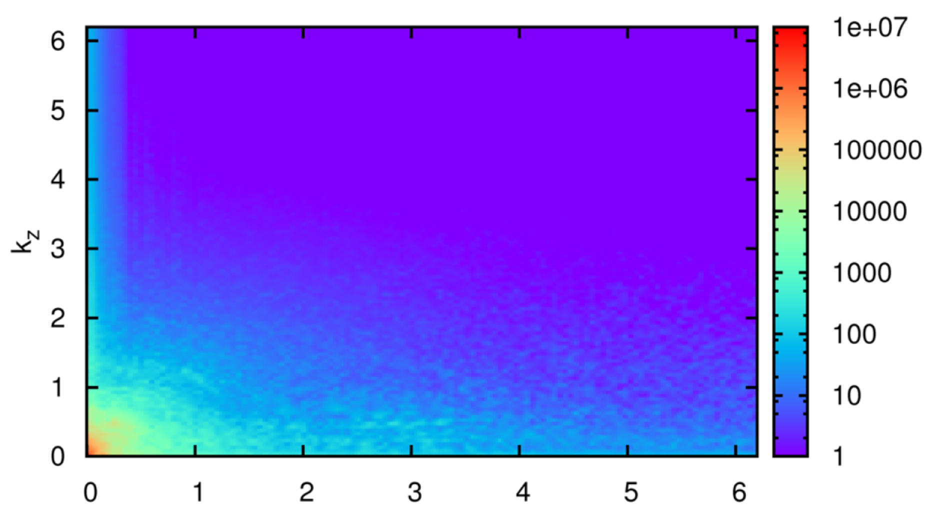
fast mode $\rightarrow$ Bernstein waves [Markovskii et al. 10]

KAWs $\rightarrow$ Bernstein waves [Podesta 12]

- Or, perhaps through a direct parallel cascade

low $k_{||}$ $\rightarrow$ high $k_{||}$ [Yoon 07]

- Hybrid simulations also find parallel ICW power can be produced by primarily perpendicular cascade [Verscharen et al. 12]



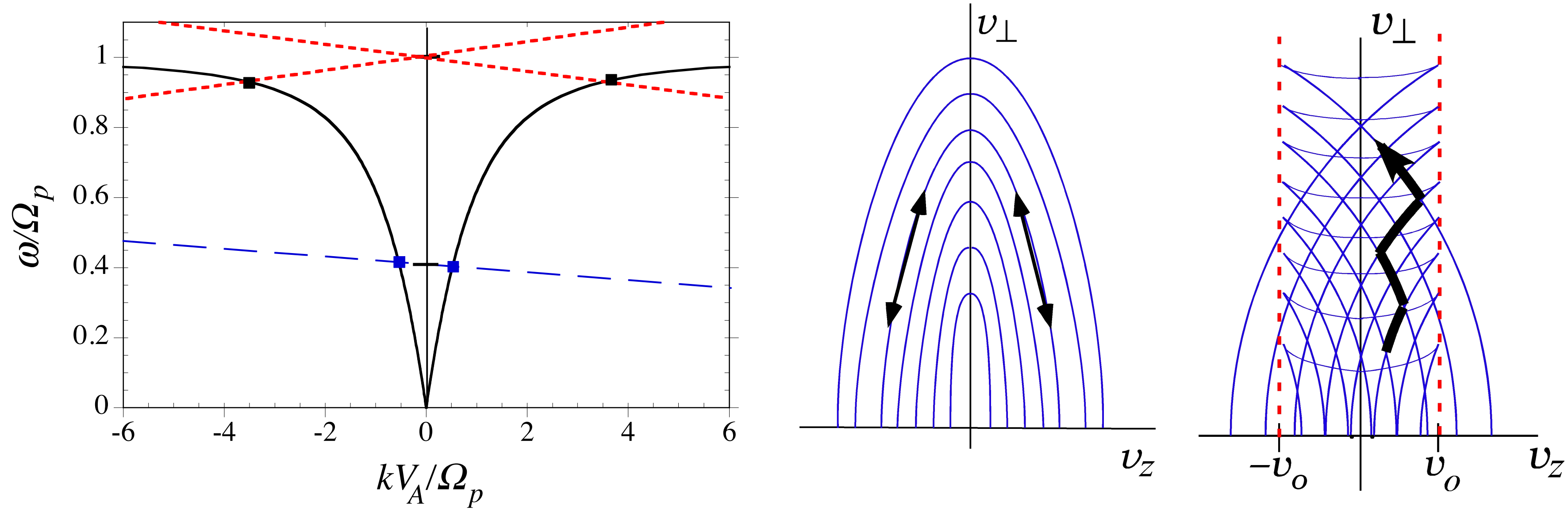
QL theory gives detailed description of cyclotron interaction,
depending on wave intensities and the dispersion relation.

ICWs: $\omega(k) - k\, v_z = \Omega_i$

resonance condition

protons

heavy ions



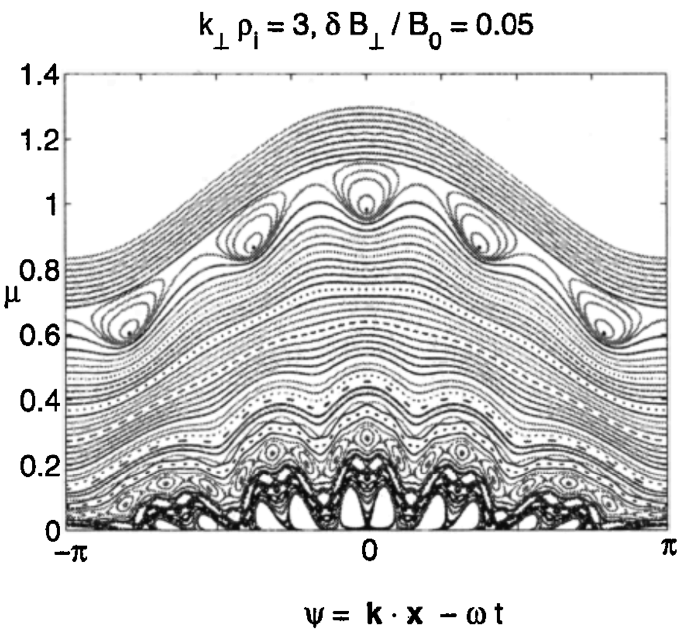
- Low-β protons resonate with only one wave at a time.
- Proton resonant surfaces do not overlap:

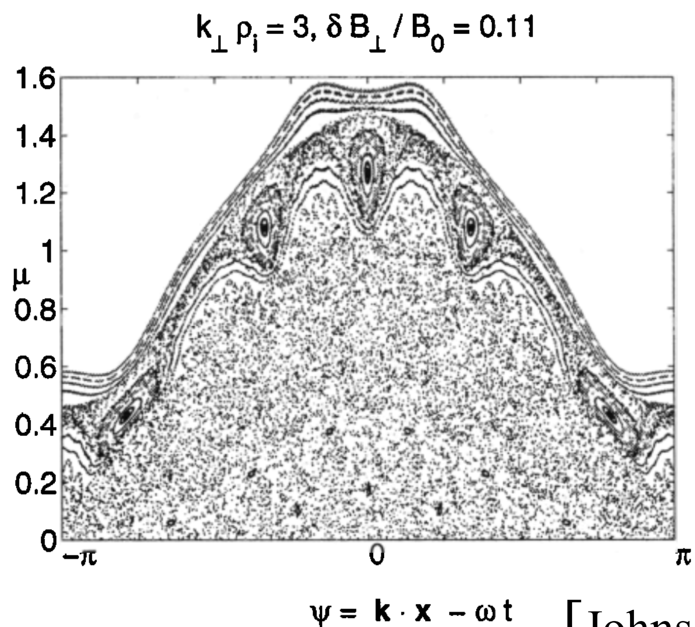
  → Absorption of parallel wave energy is limited.
- Heavy ions can have multiple resonances

  → Preferential perpendicular heating.

- NL stochastic dissipation simply requires the cascading fluctuations to be strong enough at ion gyroradius scales to disrupt the ion gyromotion, yielding non-periodic behavior:

$$\frac{\delta v_{turb}\left[k_\perp = \rho_i^{-1}\right]}{v_\perp} \gtrsim 0.1 - 0.3 \qquad \text{[Chandran et al. 10]}$$





[Johnson & Cheng 01]

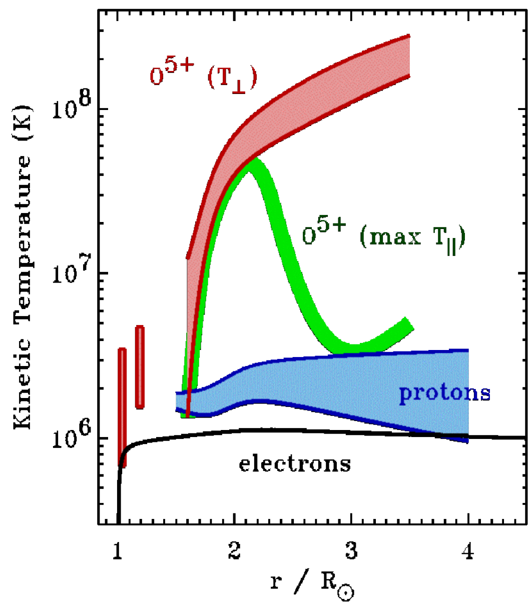
- Chaotic orbits will give diffusion in $v_\perp$ $\rightarrow$ heating
- This mechanism also predicts pref. heating of heavy ions from the larger δv_{turb} in cascade spectrum at heavy ion gyroradii.

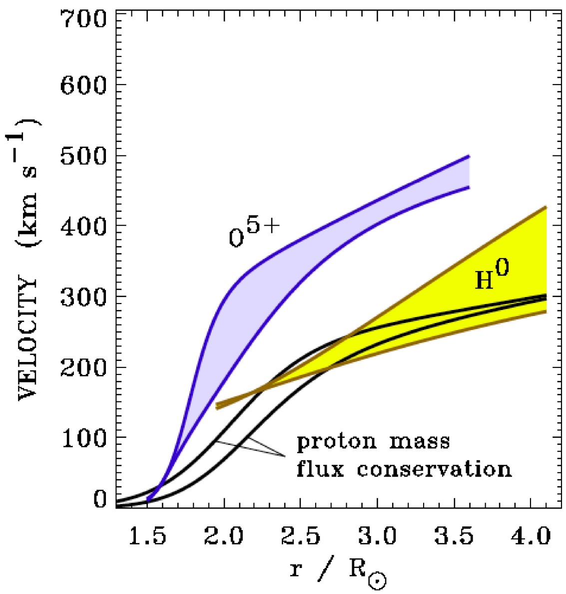
To identify the operative dissipation mechanism(s),

we move to the observations.

Coronal observations are clear, but not definitive:

- UVCS measures line broadening and Doppler dimming of several ions, but we have no information on the properties of the turbulence there.



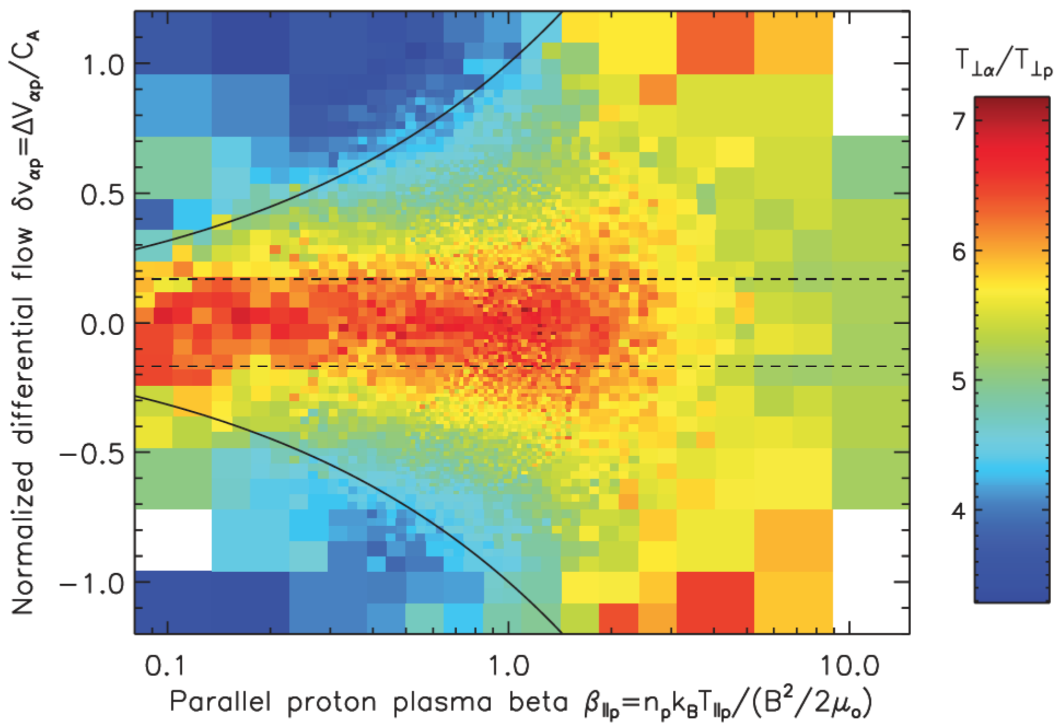


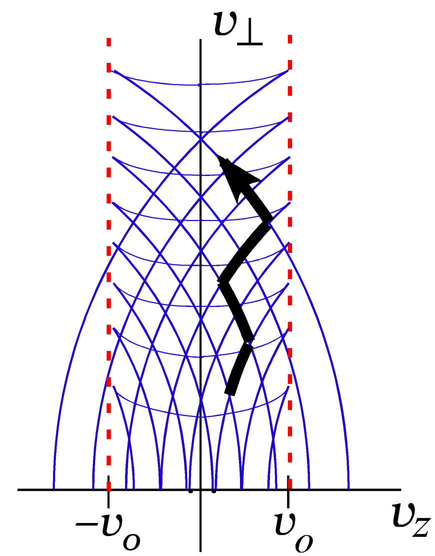
[Kohl et al. 98]

- Plausible solar wind models using either cyclotron-resonant heating or nonlinear stochastic heating can be constructed.

At 1 AU, recent analysis by Kasper et al. [13] may be very important.

- More than 16 years of WIND/SWE data with low collisional age:





→ More efficient heating of alphas at low differential speed.

- Could be evidence of cyclotron-resonant Fermi mechanism.
- NL stochastic mechanism may also be able to explain these features.
- We need observation/theory comparisons for individual events.

Conclusions

- Turbulent dissipation necessarily causes particle heating.

- If collisionless turbulent dissipation is responsible for the
  observed ion heating in the corona and solar wind,
  it must operate primarily to increase ion magnetic moment,
  and to yield more heating of heavy ions than of protons.

- Gyrokinetic treatments require mag. moment conservation and so
  prohibit the dominant channel for ion-scale dissipation.

- Similarly, dissipation mechanisms which primarily
  increase ion $T_{||}$ cannot be important for
  dissipation of ion-scale turbulence.

- Remaining "wave-related" processes are:
    - cyclotron-resonant dissipation of turbulently-generated ICWs or Bernstein waves.
    - nonlinear stochastic disruption of gyro-orbits by cascading $\perp$ disturbances.
- Dominant dissipation process need not be the same for all heliospheric conditions.
- Ultimately, the issue of collisionless ion-scale dissipation will likely be resolved by detailed comparisons of model predictions with in-situ spacecraft observations.