What can Pickup Ions tell us about Solar Wind Turbulence?

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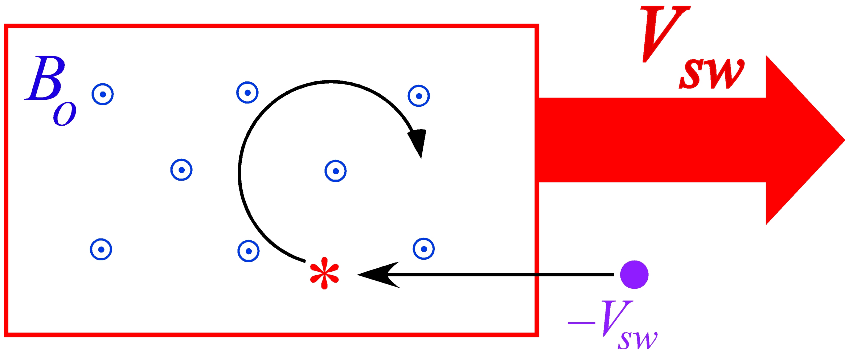
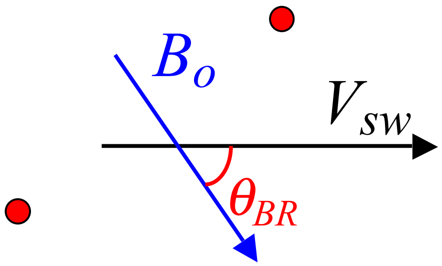
- Overview of Pickup Ions (protons) in the solar wind
- Isotropization and wave generation
- Observations of pickup proton-generated waves
- Turbulent effects and heating of the outer solar wind
- “Dominant turbulence” model and its consequences
- Summary and conclusions

Interstellar pickup protons in the solar wind



- Interstellar neutral hydrogen with small inflow $\upsilon \sim 26$ km/s
- Ionized in supersonic solar wind (charge exchange + photoionization)
- New ions $\upsilon \sim -V_{sw}$ in solar wind frame, gyrate about *B*-field



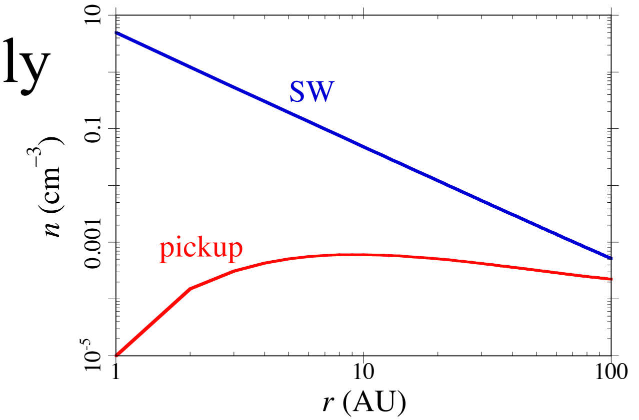
→ Unstable ring distribution with thermal speed $\upsilon_{th} \sim V_{sw}$

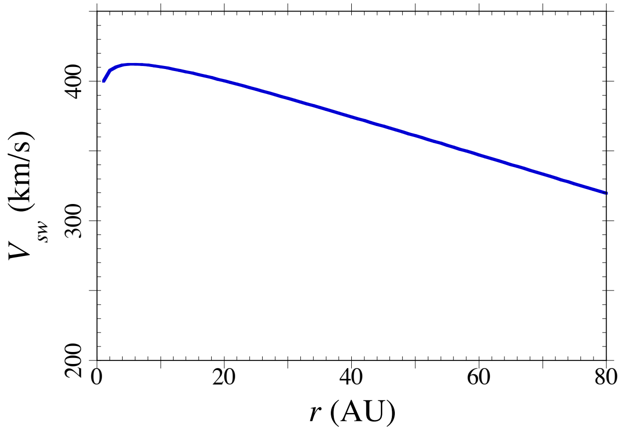
- Ring generates waves and scatters toward isotropy

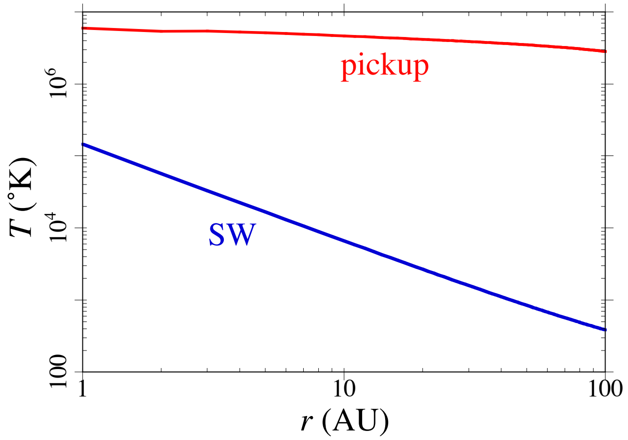
→ thermal SW core + hot pickup proton shell + waves.

Interstellar pickup ions accumulate continually as solar wind plasma flows outward:

- Relative density reaches ~ 20% at termination shock distances.
- Mass & momentum loading slow the SW.
- Total plasma temp. increases with *r*.
- Deceleration plus increase in plasma β reduces SW Mach number, weakens termination shock.







These pickup protons are observed at *Ulysses*, *Cassini*, and *New Horizons*

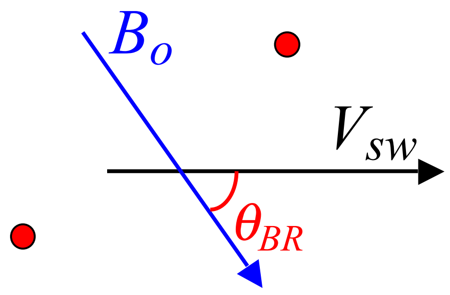
SW deceleration and effects at termination shock are also observed.

Return to the wave-particle interaction which scatters the pickup protons to isotropy.

For V_A/V_{sw} small, dominant process is the quasilinear resonant cyclotron interaction with parallel-propagating waves. [Wu & Davidson 72, Lee & Ip 87]

Newly ionized protons form an unstable ring-beam in SW frame.

$$v_\perp = V_{sw} \sin \theta_{BR}$$
$$v_\parallel = V_{sw} \cos \theta_{BR}$$



Pitch-angle scatter toward isotropy

$\hookrightarrow$ lose energy in plasma frame

$\hookrightarrow$ energy goes into waves.

These waves should peak at the

spacecraft-frame gyrofrequency:

- cyclotron resonance condition

$$\omega(k) - k\,\upsilon_{\|} = \Omega$$

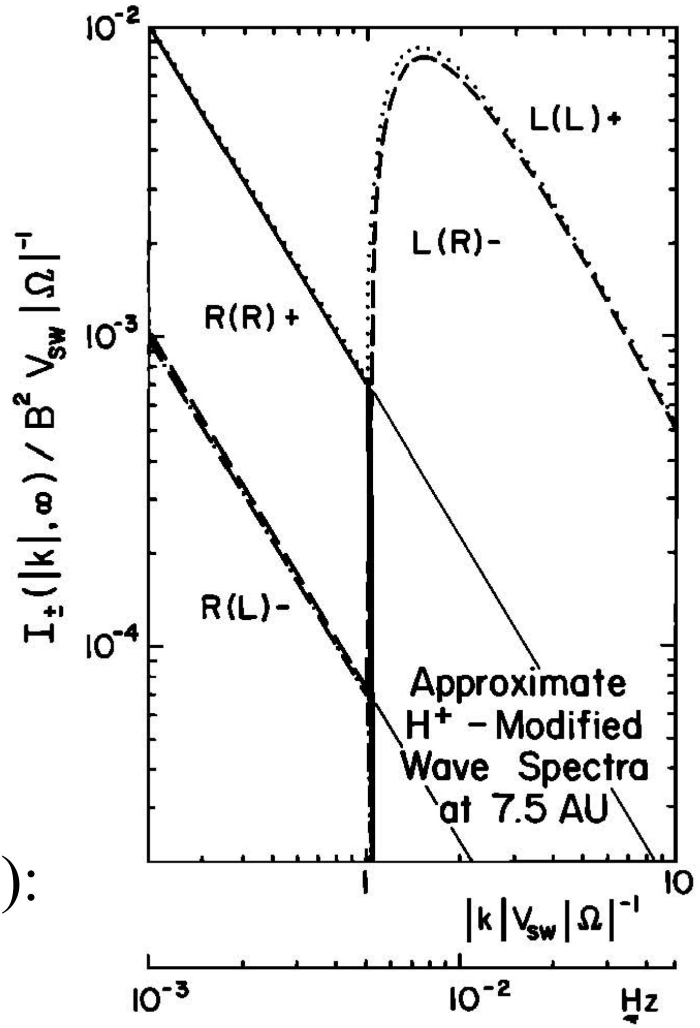
- initial ring in SW frame

$$\upsilon_{\|} = V_{sw}\cos\theta_{BR}$$

gives $k_{res} \sim \Omega/(V_{sw}\cos\theta_{BR})$

- Doppler shift to s/c frame (Taylor approx):

$$\omega_{sc} = \mathbf{k} \bullet \mathbf{V}_{sw} = k_{res} V_{sw}\cos\theta_{BR} = \Omega$$



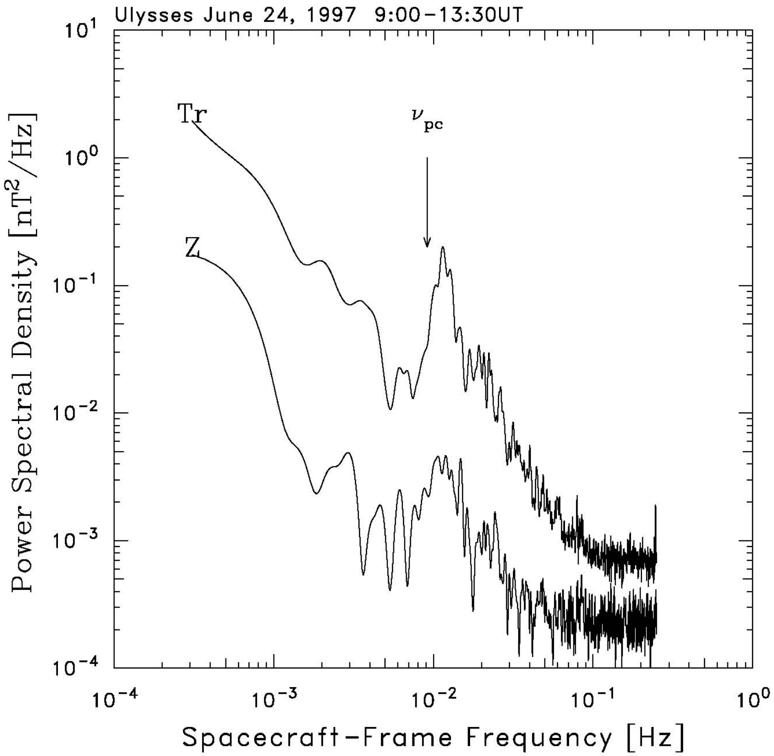
Lee & Ip [87] predicted substantial spectral enhancements

in SW beyond 5 AU, due to these waves.

These waves are observed, but only sporadically.

[E. Smith et al. 94, Murphy et al. 95, Joyce et al. 13]

→ Why aren't these waves always present?



Long-standing puzzle, until recent work, mostly by UNH undergrads, provided a solution.

[Cannon et al., *ApJ*, 2014a,b]

- First, expanded the *Ulysses* data set to > 500 cases.

Then, we consider relevant time scales:

growth of wave enhancements ↔ spectral transport of
wave energy by turbulence

Note that instability growth rate,

$\gamma \gg dE_W/dt$ "wave accumulation" rate,

where $dE_W/dt \sim$ ionization rate × neutral H density

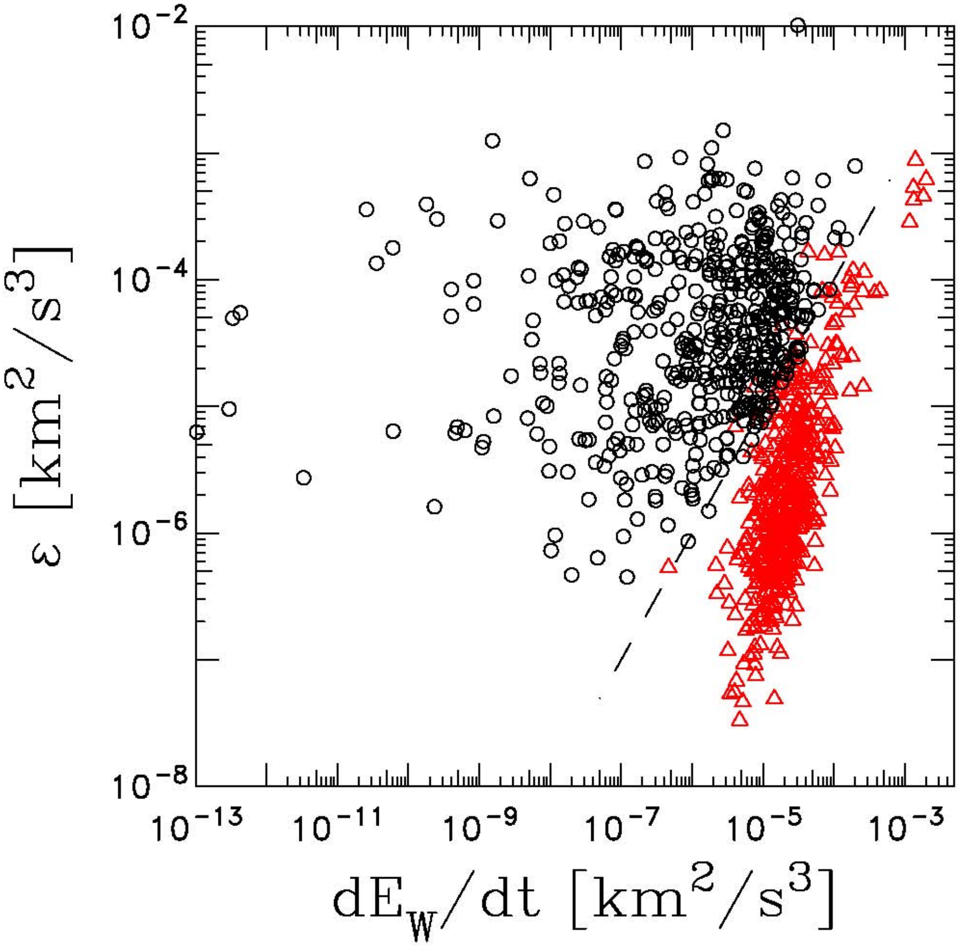
- Accumulation of wave power is controlled by

  $dE_W/dt \longrightarrow$ a function of measurable SW parameters

- Dispersal of wave energy by spectral transport is given by

  Kolmogorov cascade rate $$\varepsilon = \frac{f^{5/2}}{V_{sw}\, N_p^{\;3/2}}\, I(f)^{3/2}$$

Cannon et al. [14b] compared these rates for the observed wave events (red) and for an equivalent number of "non-events" (black) from adjacent time periods.



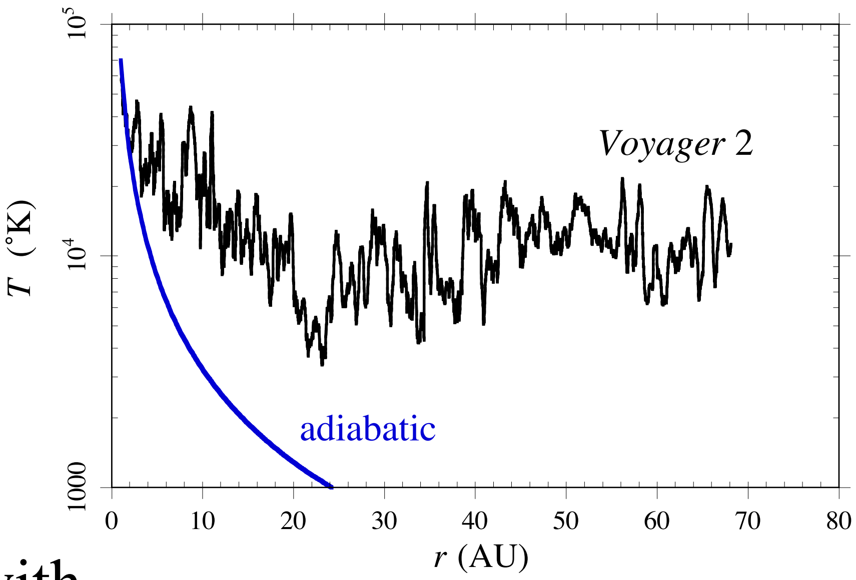
Pickup ion waves are seen when the cascade rate is smaller than the accumulation rate.

Otherwise, the turbulence distributes the wave energy over the inertial range before it can accumulate to observable levels.

Thus, our QL expectations are valid, once turbulence is included.

This is good, because turbulence driven by pickup proton isotropization is needed to explain observations farther out.

- *Voyager* instruments only measure SW ion core - can't detect PUIs.



Observed core temperature:

- $r \lesssim 20$ AU $-$ heating consistent with stream-stream interactions and shocks.
- $r > 20$ AU $-$ streams merge and weaken.

$\longrightarrow$ Core is still heated: must be due to pickup process.

$\longrightarrow$ No collisions: must be due to fields (turbulence)

Pickup isotropization generates waves

→ wave input drives turbulent cascade

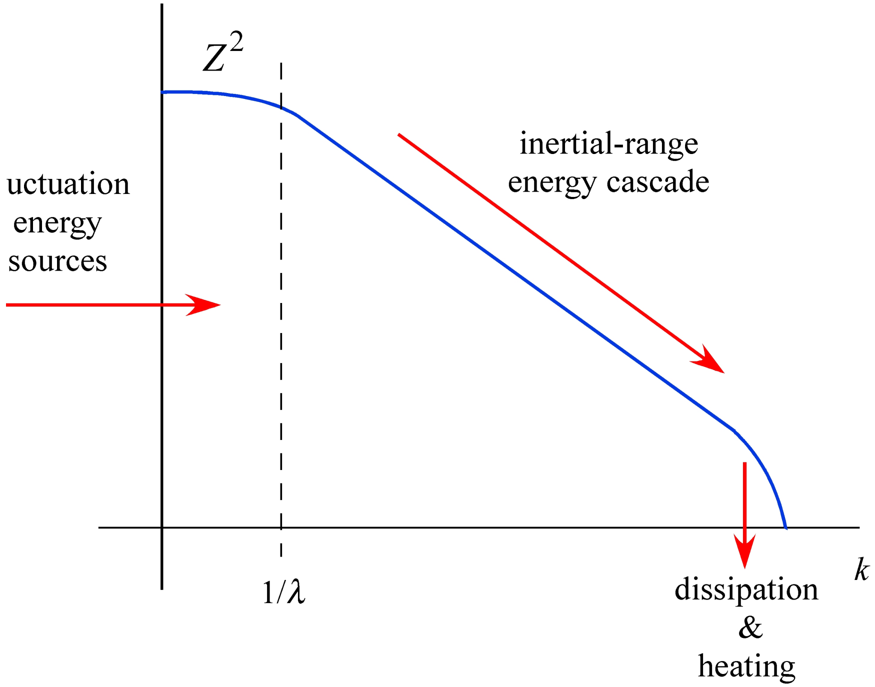
→ turbulent dissipation heats core protons

[Zank et al. 96; Williams et al., 98; Matthaeus et al., 99; C. Smith et al., 01]

- Cascade is described with a phenomenological turbulence model

[Matthaeus, Zhou, Zank, Smith, Oughton, Breech,...]

In simplest form, turbulent effects described by 2 quantities:



- $Z^2(r) = <\delta v^2> + <\delta b^2>/4\pi\rho$

  total fluctuation energy,

  dominated by large scales

- λ outer scale of inertial range

  (~ correlation length)

- Energy evolves as SW expands
- Dissipation ~ Z^3/λ heats core

Equations are non-linear, but first order. Take inner BC at 1 AU.

- In steady state (to within coefficients of order 1):

$$\frac{dZ^2}{dr} = \underset{\substack{\text{expansion}\\ +\ \text{shear}}}{-\frac{Z^2}{r}} \underset{\substack{\text{Kolmogorov}\\ \text{dissipation}}}{-\frac{Z^3}{\lambda V_{sw}}} \underset{\substack{\text{pickup proton}\\ \text{driving}}}{+\frac{Q}{V_{sw}}}$$

$$\frac{d\lambda}{dr} = -\frac{Z^2}{r} + \frac{Z}{V_{sw}} - \frac{\lambda Q}{V_{sw} Z^2} \, ; \qquad Q = \zeta \frac{{V_{sw}}^2}{n_{sw}} \frac{dN}{dt}$$

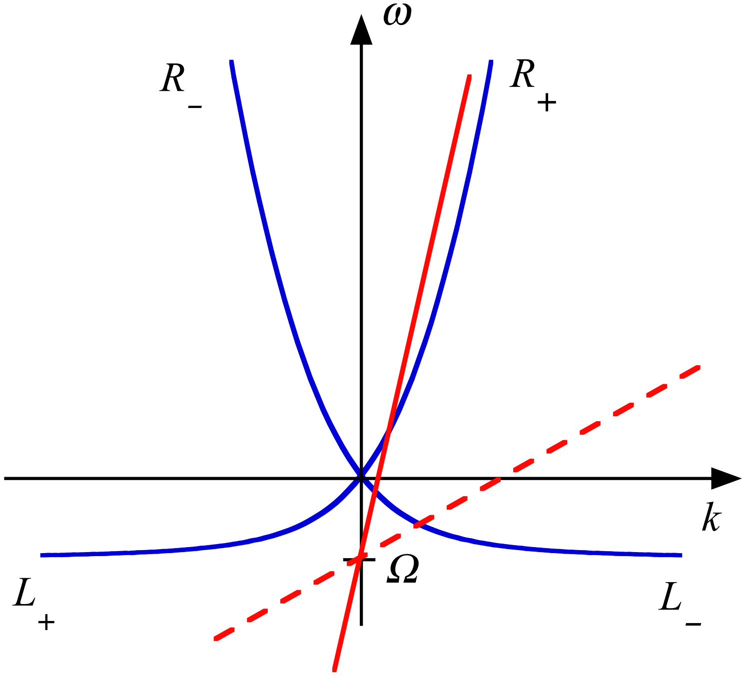
- Subsidiary equation yields solar wind core temperature

$$\frac{dT}{dr} = \underset{\substack{\text{adiabatic}\\ \text{cooling}}}{-\frac{4T}{3r}} \underset{\substack{\text{dissipative}\\ \text{heating}}}{-\frac{m}{3k_B}\frac{Z^3}{\lambda V_{sw}}}$$

→ Need to define ζ from details of wave-particle interaction.

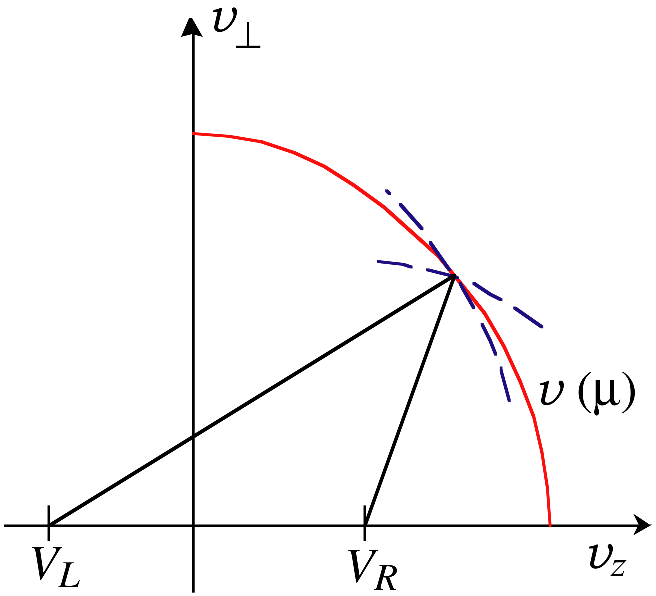
- Quasi-perpendicular waves do not scatter suprathermal particles.
- Take resonant interaction with parallel-propagating waves

cyclotron resonance



$$\omega(k) - k\,v_{\parallel} = -\Omega$$

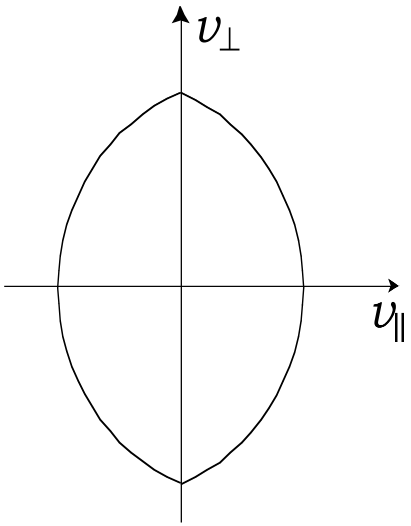
resonant scattering



particles conserve their energy in the wave frame

- Waves which scatter protons to $\begin{Bmatrix}\text{greater}\\ \text{lesser}\end{Bmatrix}$ energy will $\begin{Bmatrix}\text{damp}\\ \text{grow}\end{Bmatrix}$.
- Proton ring scattering to isotropy will damp $R_\pm$ and generate $L_\pm$.

When only interaction is with $L_{\pm}$, get a bispherical pickup shell,



[Galeev & Sagdeev 88; Johnstone et al. 91]

$$\zeta \sim V_A/V_{sw}$$

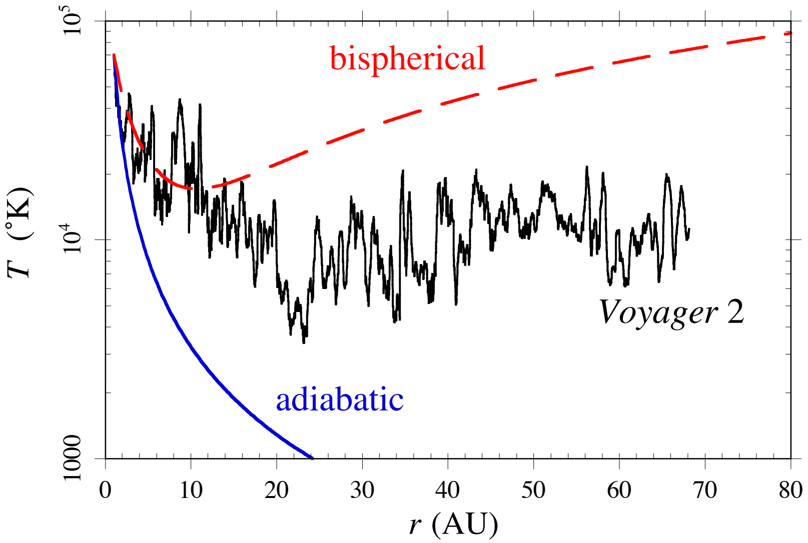
Energy lost by ring in scattering to bispherical shell

↳ energy input to turbulence.

BUT

Bispherical assumption gives

too much heating.



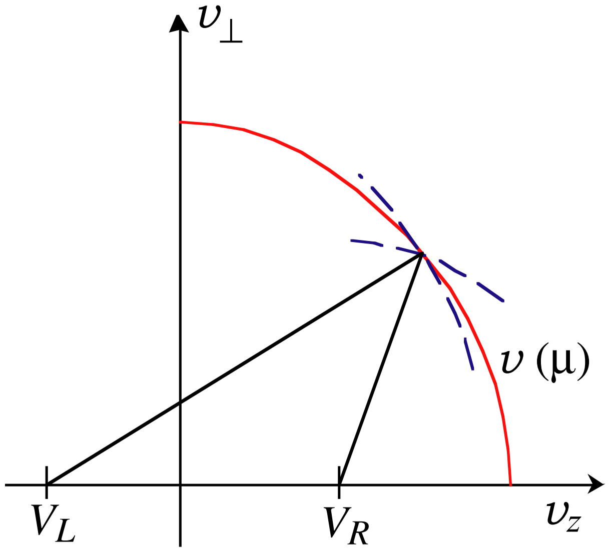
“Dominant turbulence” assumptions: [Isenberg et al. 03; Isenberg 05]

- Note that incremental pickup rate is small ($\tau \sim$ several months)
- Turbulent interactions have lots of time to

  replenish the fast-mode waves damped by new pickup protons.

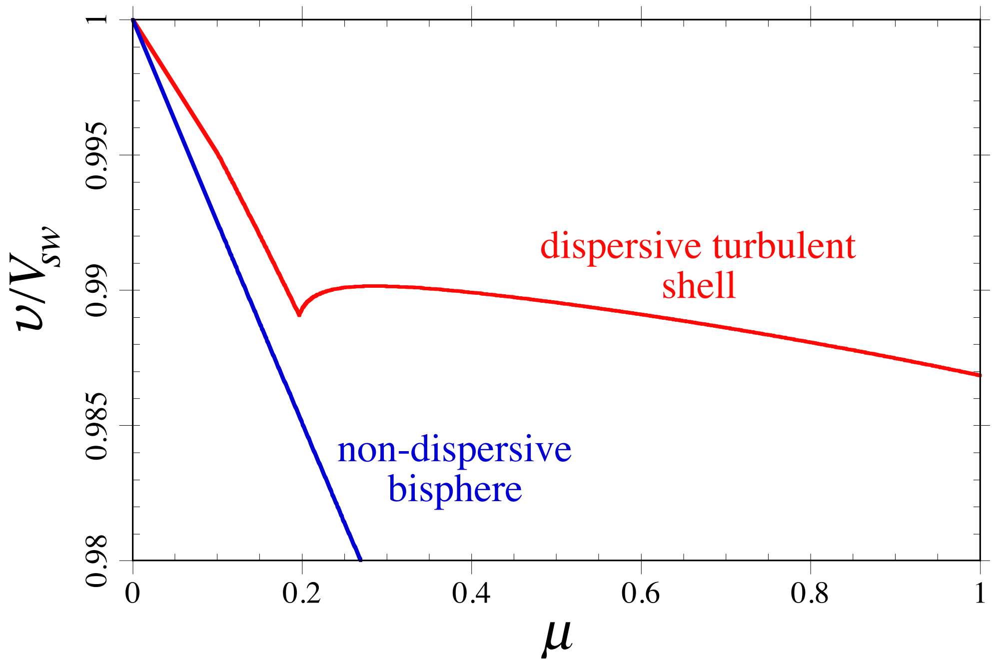
  ↳ Assume all parallel modes equal, with $I \sim k^{-5/3}$.

Shell shape $\upsilon(\mu)$ now given by simultaneous scattering from all resonant modes, weighted by their intensities at resonance.



$$\frac{d\upsilon}{d\mu} = \frac{D_{\mu\upsilon}}{D_{\mu\mu}} = \frac{\sum_j V_j \frac{I_j(k_r)}{\left|\mu\upsilon - W_j\right|}\left(1-\frac{\mu V_j}{\upsilon}\right)}{\sum_j \frac{I_j(k_r)}{\left|\mu\upsilon - W_j\right|}\left(1-\frac{\mu V_j}{\upsilon}\right)^2}$$

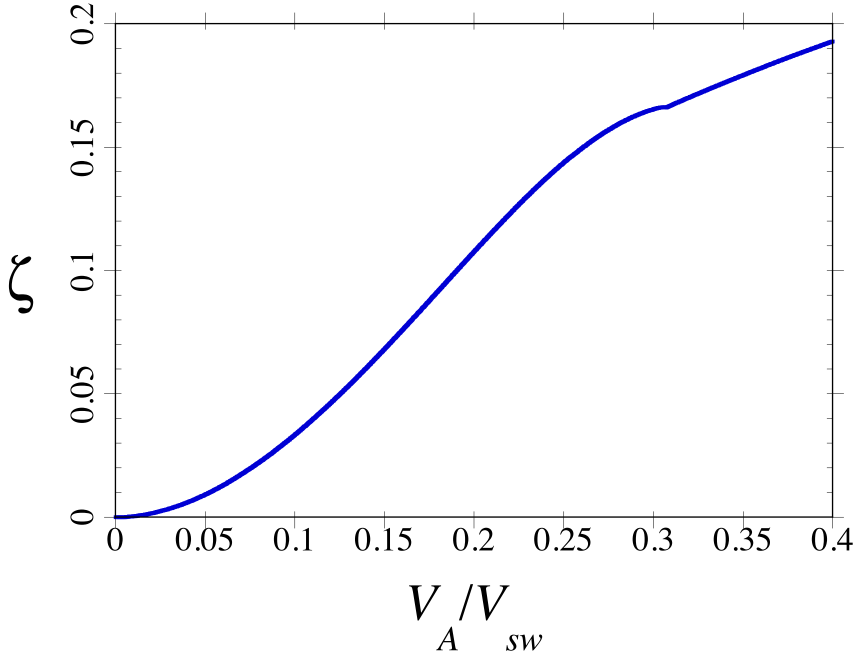
For $V_A/V_{sw} = 0.075$:



Revised $\zeta(V_A/V_{sw})$

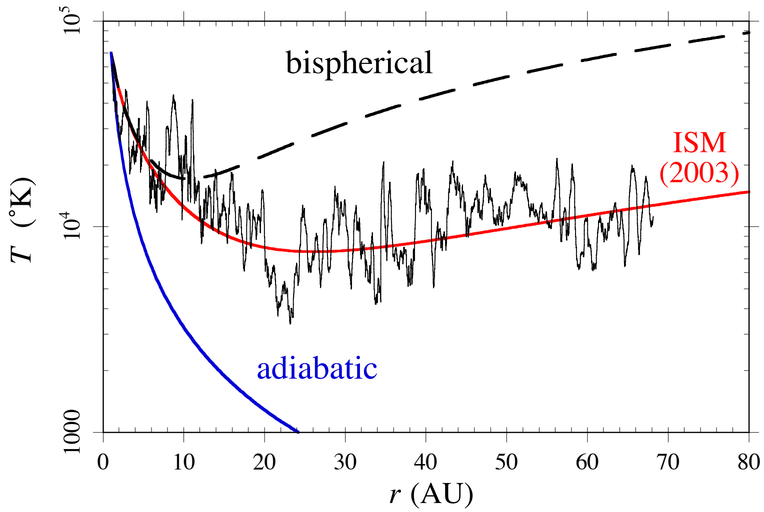
corresponding to

new shell shapes:



Now, steady-state solution gives good agreement with *Voyager* 2 temperature measurements.

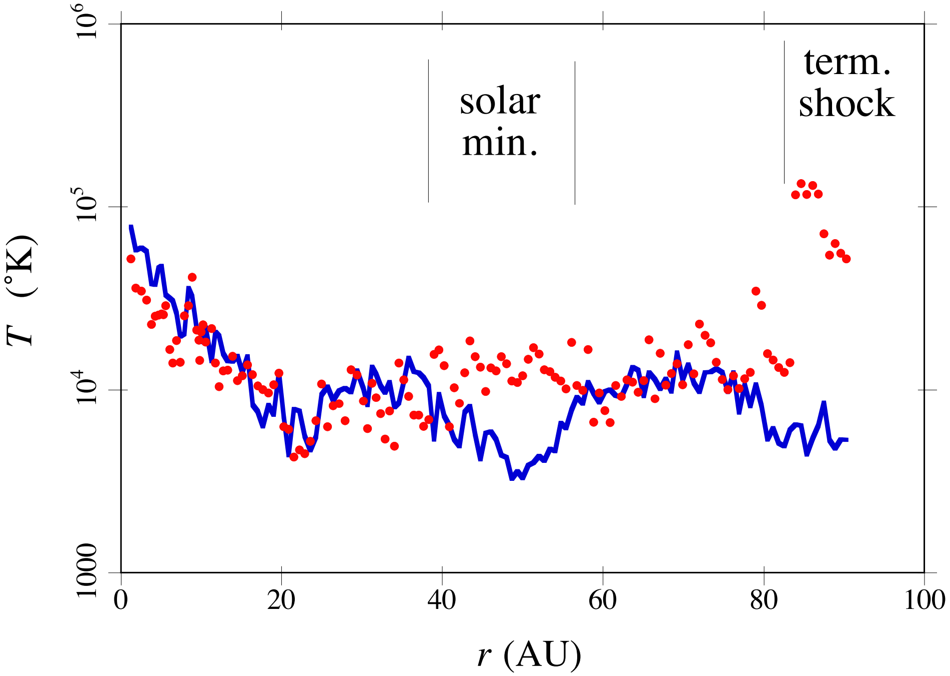
[Isenberg, Smith & Matthaeus 2003]



"Time-dependent" does even better:

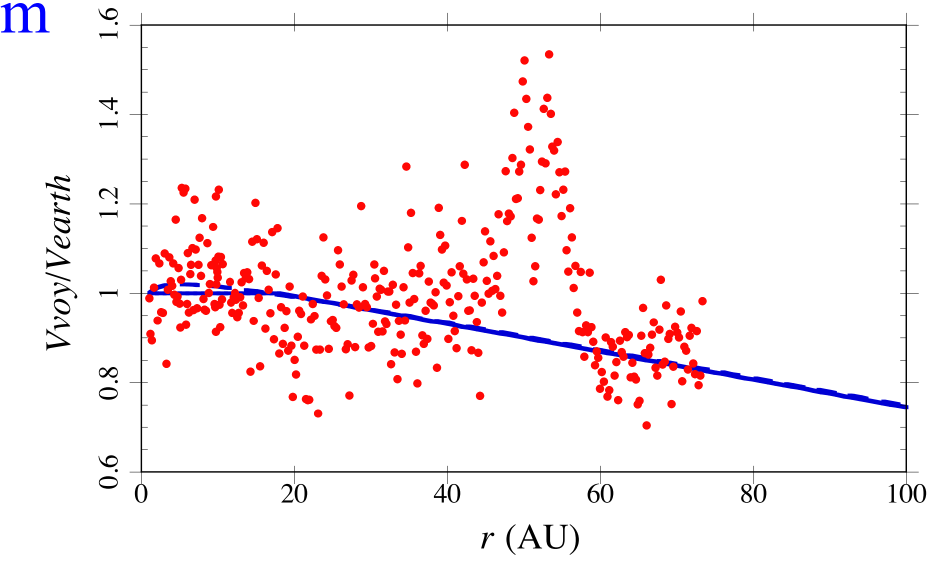
Back-propagate Voyager times to 1 AU, then solve equations outward using observed SW conditions as BCs.

[C. Smith et al. 2007]

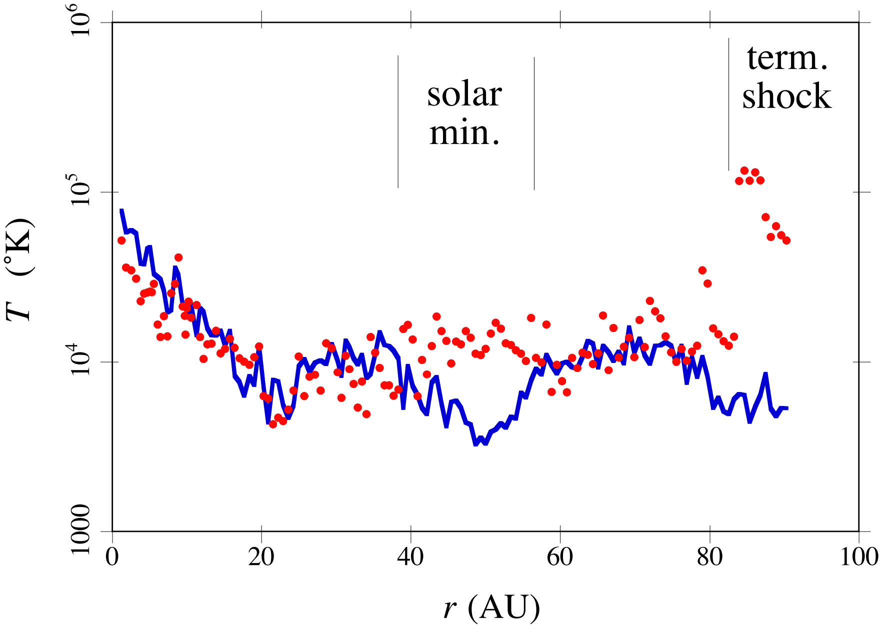


Discrepancy during solar minimum is due to:

- high heliolatitude of Voyager
- latitude-dependent SW.



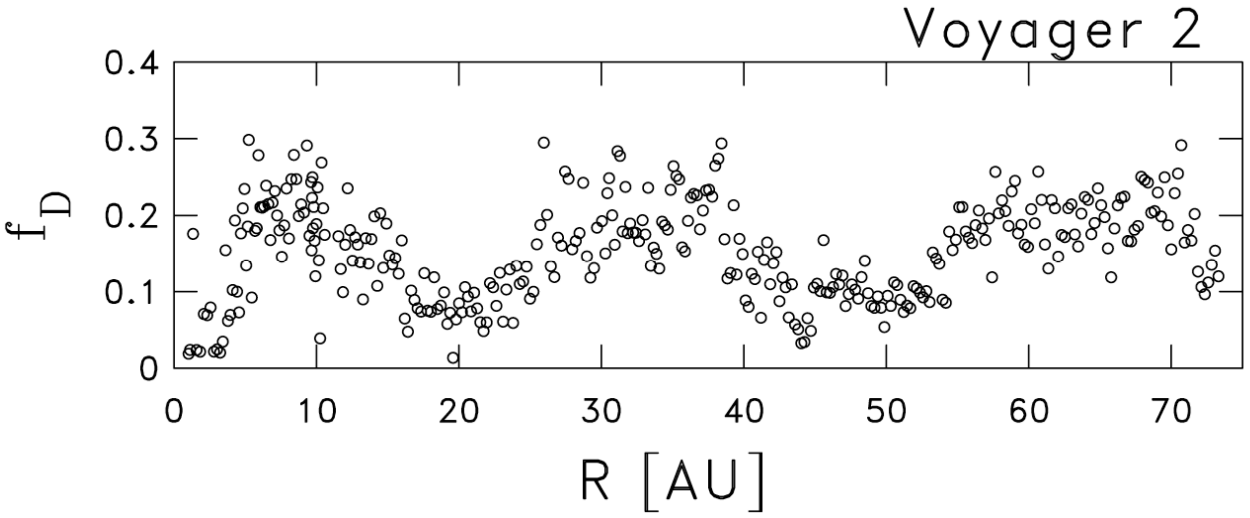
SW conditions at Earth do not correspond with those at Voyager at this time.



Unfortunately, many models of this turbulent heating in the outer SW prefer to use a constant "fudge factor" in place of ζ to set their pickup proton heating rates:

$$\zeta = f_D \frac{V_A}{V_{sw}} \qquad\qquad Q = f_D \frac{V_A V_{sw}}{n_{sw}} \frac{dN}{dt}$$

But f_D has no theoretical foundation and is also not likely to be constant [C. Smith et al. 2007]:



What does all this mean for solar wind turbulence?

Evidence is that:

- ion-cyclotron waves ($L_\pm$) are generated by pickup proton isotropization.
- solar wind turbulence ~ 5 AU disperses this wave power, folding it into the inertial range spectrum.
- beyond ~ 20 AU, SW turbulence is driven by these fluctuations, resulting in observed core heating.

- However, to get the observed energy right, we need to assume that quasi-parallel $R_\pm$ waves are actively maintained despite the continual damping by isotropization of new pickup protons.

We conclude that, in addition to the usual cascade to higher $k_\perp$,
SW turbulence must bring about the conversion
of quasi-parallel ion-cyclotron and fast-mode waves

$$L_\pm \leftrightarrow R_\pm ,$$

either directly or indirectly.

This turbulent equilibration of quasi-parallel waves
needs to be theoretically understood and
incorporated into models of collisionless turbulence.