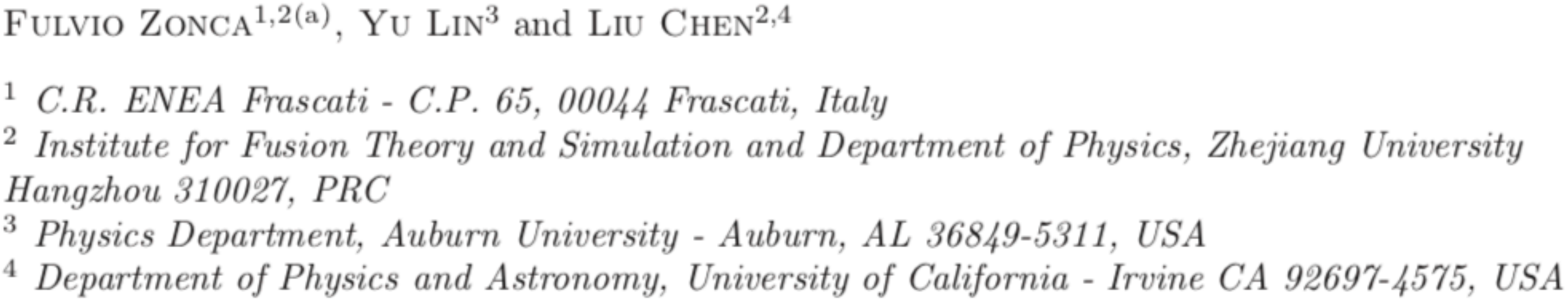
Spontaneous excitation of convective cells by kinetic Alfvén waves



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Frascati, May 13, 2019 - Meeting on
“Prospettive dell’accelerazione nei Plasmi”

EPL, 112 (2015) 65001

Convective Cells

- Kinetic Alfvén waves (KAW) and convective cells (CC) are prevalent and fundamental electromagnetic waves and structures in magnetized plasmas.
- Convective cells are structures formed in the plane perpendicular to **B**.
- Spontaneous excitation of CC by KAW has been of interest for many years due to its important implications to transport across the confining magnetic field and to the dynamics of the upper auroral ionosphere
- CC excitation by KAW can be considered as a paradigmatic example of zonal structure generation by turbulence in magnetized plasmas, and of structure formation effect on fluctuation-induced cross-field transport
- The process by which KAW may generate CC is modulational instability; that is, the reinforcement by non-linearity of the deviation from wave periodic behavior, which may lead to spectral sidebands and possibly to breaking of the periodic fluctuation into modulated pulses

Kinetic Alfvén Waves

- Kinetic Alfvén Waves (KAW) are characterize by the following dispersion relation

$$\omega^2 = k_\parallel^2 v_A^2 \left(1 + k_\perp^2 \rho_i^2 (3/4 + T_e/T_i)\right)$$

- Assuming that $\omega_{A\ell}(x) \simeq \omega_{A\ell}(x_{R\ell})(1+\kappa\zeta)$ near the resonance absorption layer, with $\zeta = x - x_{R\ell}$ and $\kappa = (d/dx_{R\ell}) \ln \omega_{A\ell}(x_{R\ell}) > 0$, one has [Hasegawa and Chen 76]

$$\left(\rho_K^2 \frac{d^2}{d\zeta^2} + \kappa\zeta\right) \delta\hat{\xi}_{x\ell} = 0 \quad .$$

$$|k_x| \cong |\omega'_{A\ell}(x) t|$$

and, thus, $|k_x| \to \infty$ as $t \to \infty$; *i.e.*, the wave function becomes singular in the asymptotic time limit.

- This indicates the break down of the ideal MHD assumption; i.e., $|k_\perp \rho_i|^2 \ll 1$. Proper treatments of microscopic ρ_i-scale SAW are what require kinetic-theory analysis.

- General solutions are written in terms of Airy functions and have the following form away from the SAW resonant absorption layer

$$\delta\hat{\xi}_{x\ell} = \frac{\delta\hat{\xi}_{x\ell 0}}{\kappa\zeta} \qquad \zeta < 0 \ , \qquad \text{SAW}$$

$$\begin{aligned}\delta\hat{\xi}_{x\ell} &= \frac{\delta\hat{\xi}_{x\ell 0}}{\kappa\zeta} - \frac{\pi^{1/2}\delta\hat{\xi}_{x\ell 0}}{(\kappa\rho_K)^{2/3}}\left(\frac{\rho_K^{2/3}}{\kappa^{1/3}\zeta}\right)^{1/4} \qquad \text{SAW} \oplus \text{KAW} \\ &\quad \times \exp\left\{ i\left[\frac{2}{3}\left(\frac{\kappa^{1/3}\zeta}{\rho_K^{2/3}}\right)^{3/2} + \frac{\pi}{4}\right]\right\} \qquad \zeta > 0 \ .\end{aligned}$$

- One important feature of KAW is that it possesses a significant component of parallel electric field.

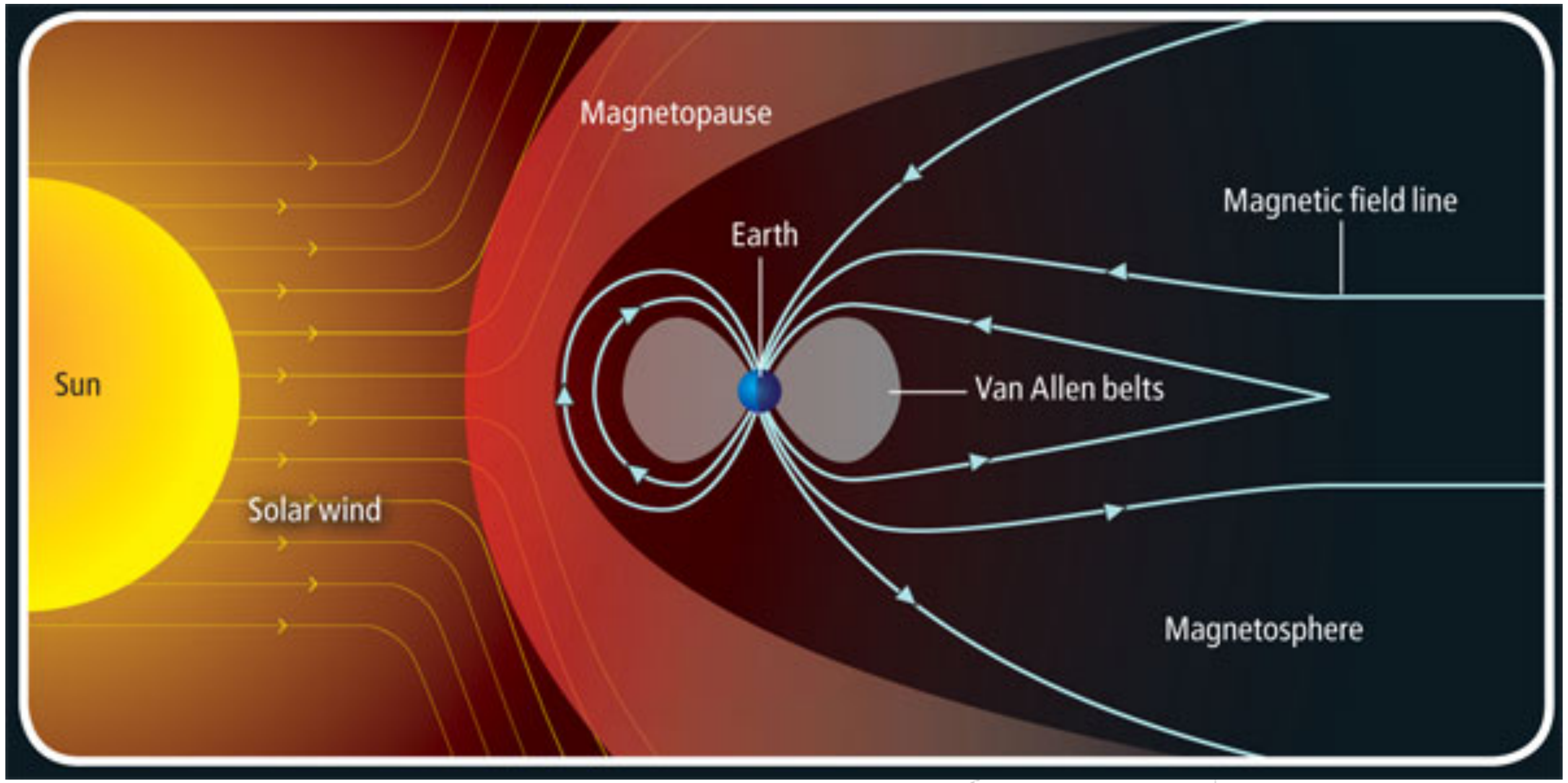
$$\tau = T_e/T_i \ ; \ b_k = k_\perp^2 \rho_i^2$$

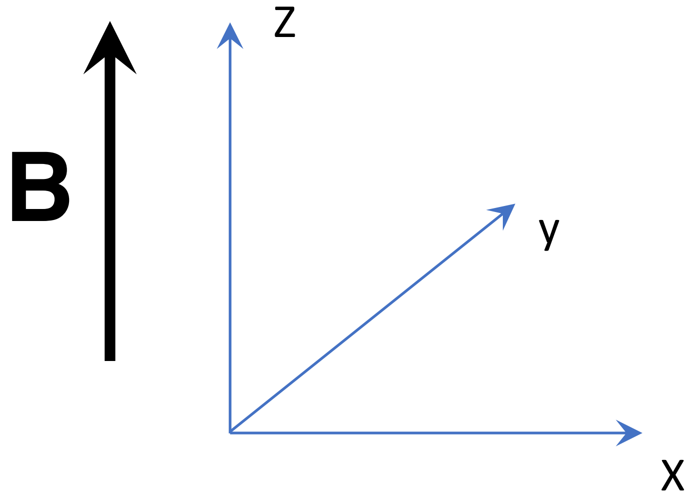
$$\omega_k^2 = k_\parallel^2 v_A^2 \frac{b_k \sigma_k}{(1-\Gamma_k)} \qquad \delta E_{\parallel k} = i k_\parallel \tau (1-\Gamma_k)\delta\phi_k \qquad \Gamma_k = e^{-b_k} I_0(b_k)$$

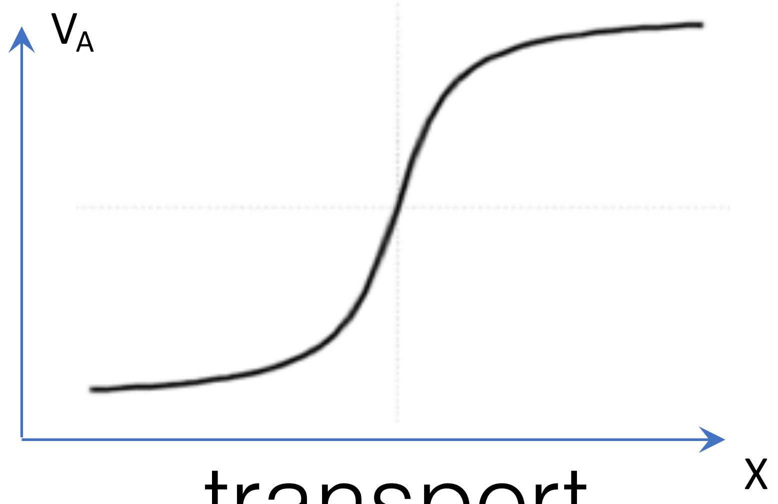
$$\sigma_k = 1 + \tau(1-\Gamma_k)$$

Frequency can be comparable to ion cyclotron

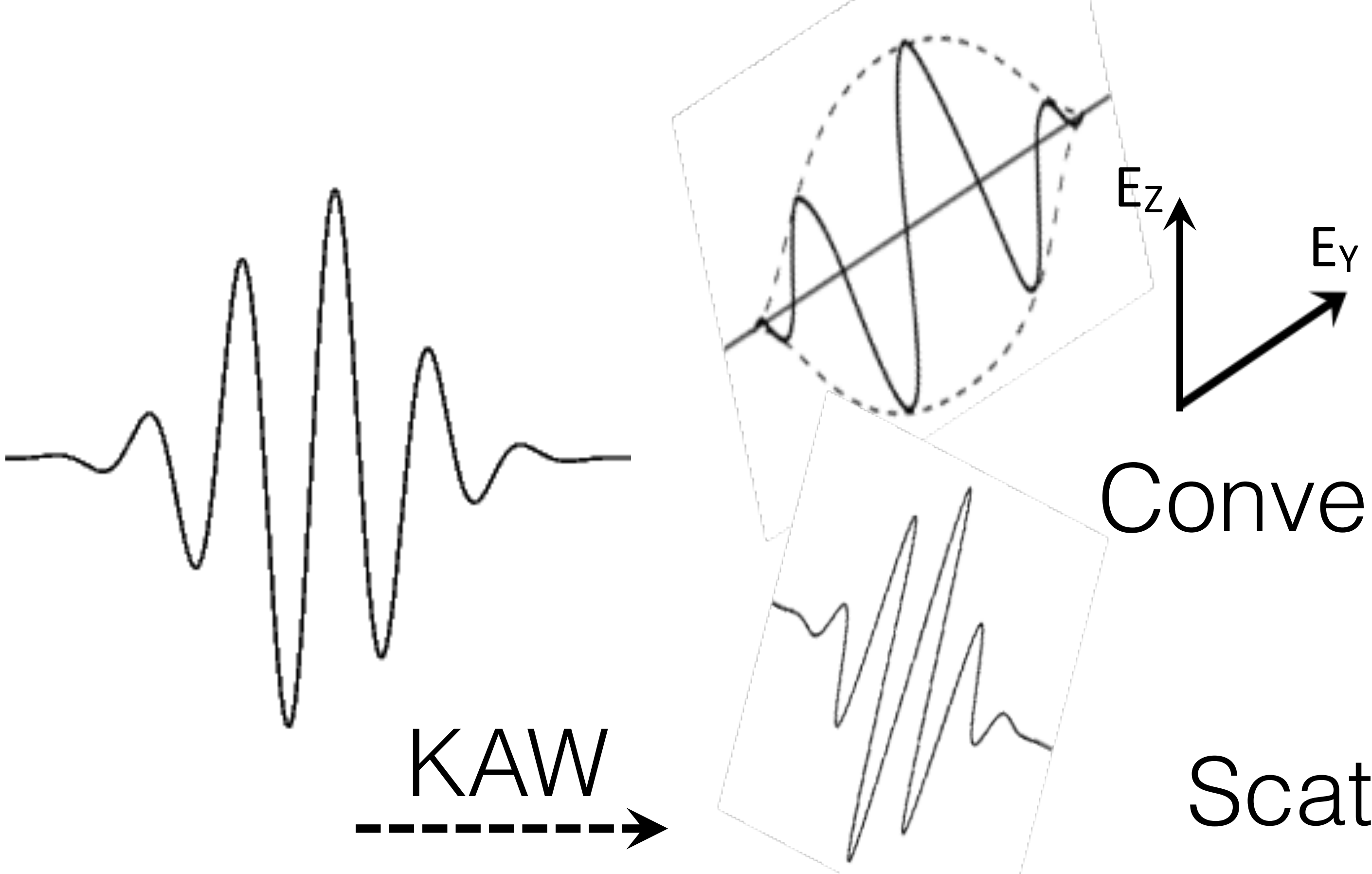
Modulational Instability







transport



Convective Cell

KAW

Scattered KAW

- Modulational instability: threshold process triggered above critical amplitude of mother KAW ==> well described by analytical theory in excellent agreement with numerical simulations

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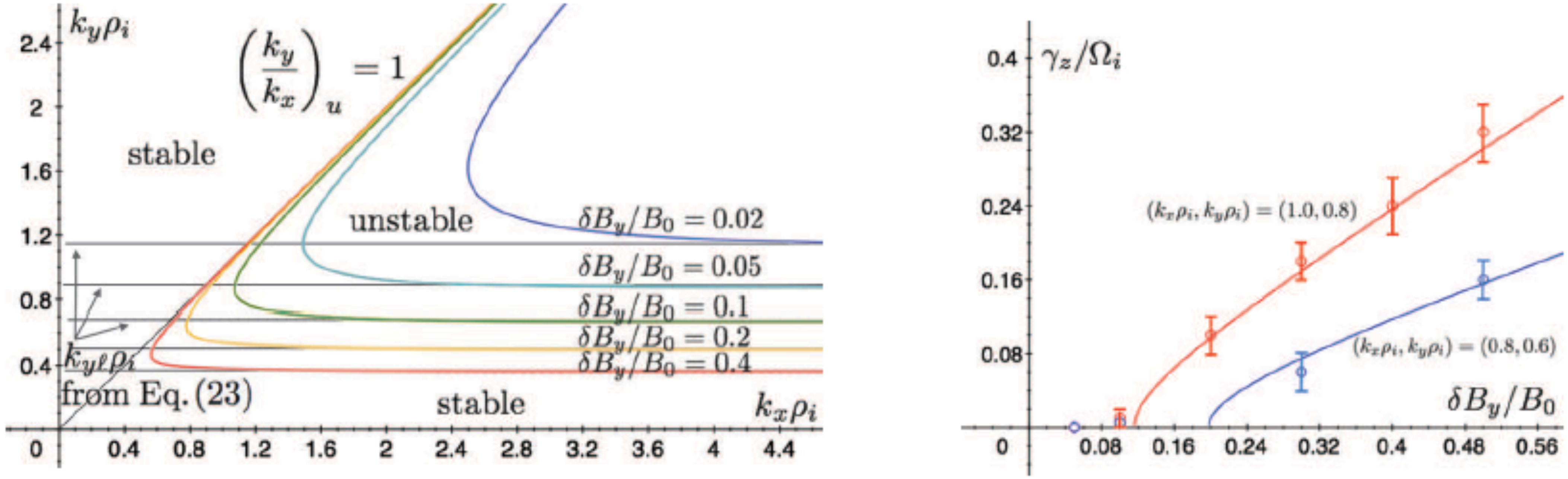

Fig. 1: (Colour online) Left: marginal stability curves in the $(k_x\rho_i, k_y\rho_i)$-plane for fixed $k_{\parallel 0}\rho_i = 0.02$, $\tau = 1$ and $\beta_e = \beta_i = 0.2$ and different values of $\delta B_y/B_0$. Right: modulational instability growth rate (continuous line), including finite $\gamma_z/\omega_0 \sim \mathcal{O}(1)$, *vs.* $\delta B_y/B_0$ is compared with hybrid simulation results (open circles) for $(k_x\rho_i, k_y\rho_i) = (0.8, 0.6)$ (blue) and $(k_x\rho_i, k_y\rho_i) = (1.0, 0.8)$ (red).

- Rich nonlinear kinetic processes with practical applications for space and laboratory plasmas: implication on vortex/current filament formation
  - require full nonlinear kinetic description (kinetic ions and gyrokinetic electrons) ==> GeFi model [Chen&Lin]
  - international collaboration with USA and China

Nonlinear Plasma Acceleration

- Proof of principle study: work in progress
    - 1D (cylindrical) magnetized plasma configuration (θ-pinch)
    - Non-uniformity in the radial direction
    - Modulational instability near magnetic axis (Larmor radius)
    - Issues arising:
        - n, B and coupled power scaling of inductive parallel E
        - fine tuning of width (Larmor radius) of convective cell size
        - impact of radial particle transport

- Collaboration network: USA (Auburn, Irvine) and China (Hangzhou, Hefei)
    - GeFi model formulation in terms of fields (rather than potentials)
        - Nonuniformity (1D first; then 2D toroidal)
        - Gauge invariant/relativistic