How Electron Beam Drives Cyclic Langmuir Collapse and Coherent Radio Emission

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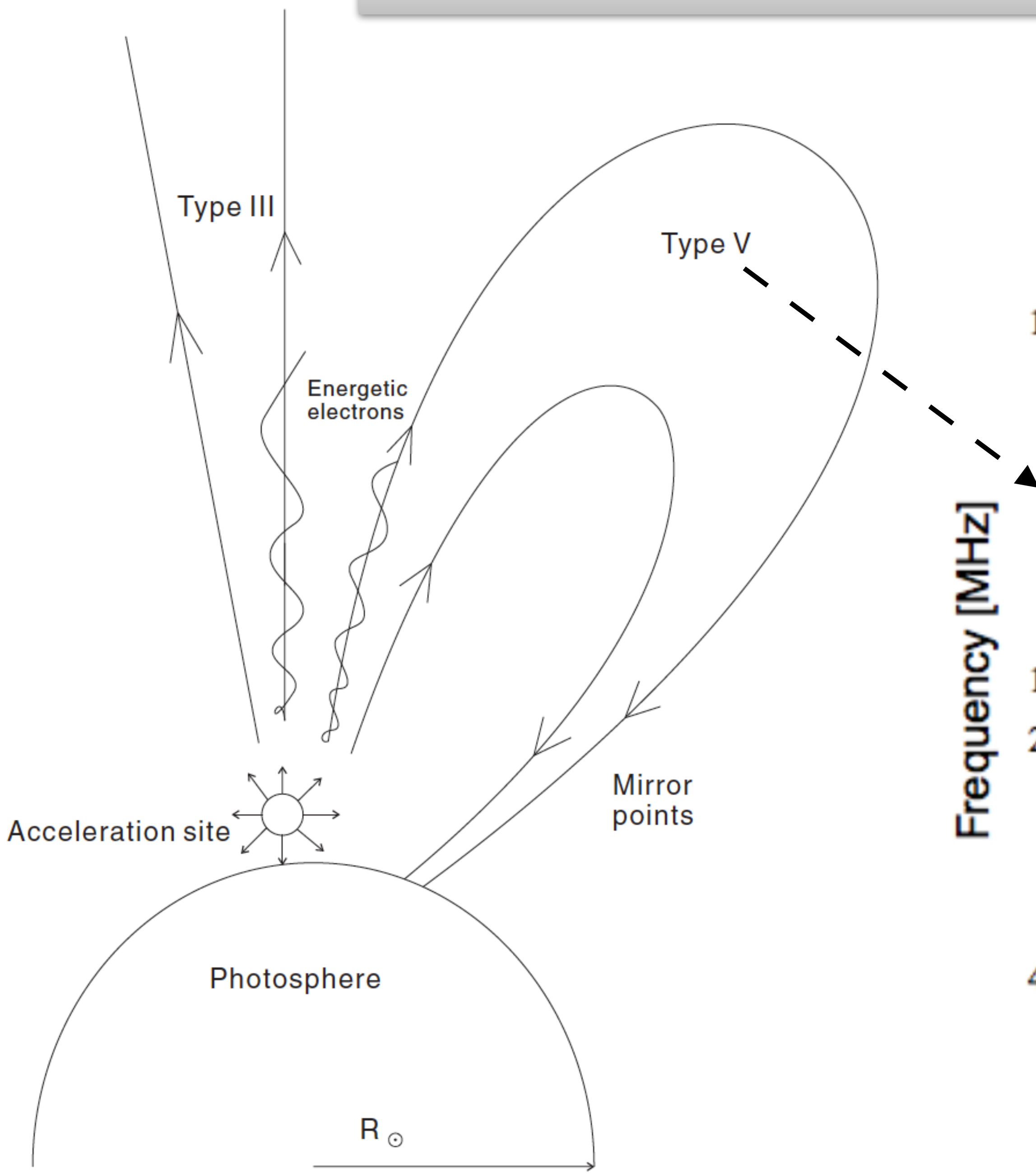
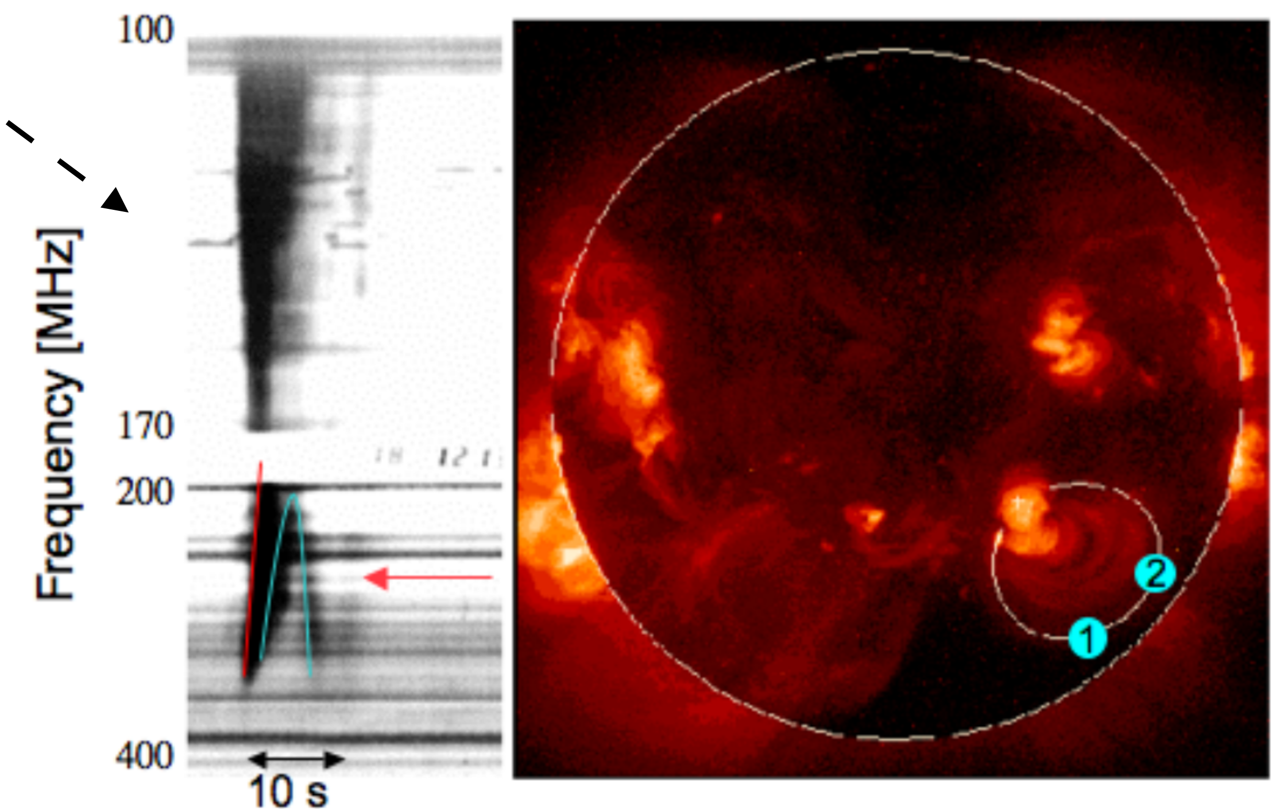
Electron Beams in Space

- Electron beams are common in space which are associated with the acceleration processes in magnetic reconnection, shock waves or ….
- Electron beams from stellar-like flares, magnetosphere of planets,black hole, supernova, pulsar et al.
- *Electron beams can produce plasma coherent emission with electron plasma frequency. In solar corona, the frequency is in radio band.*

Solar Radio Bursts and Observations of Electron Beams in Corona (from 1946-)

Wild et al. 1963, Annu. Rev. Astro. Astrophysics

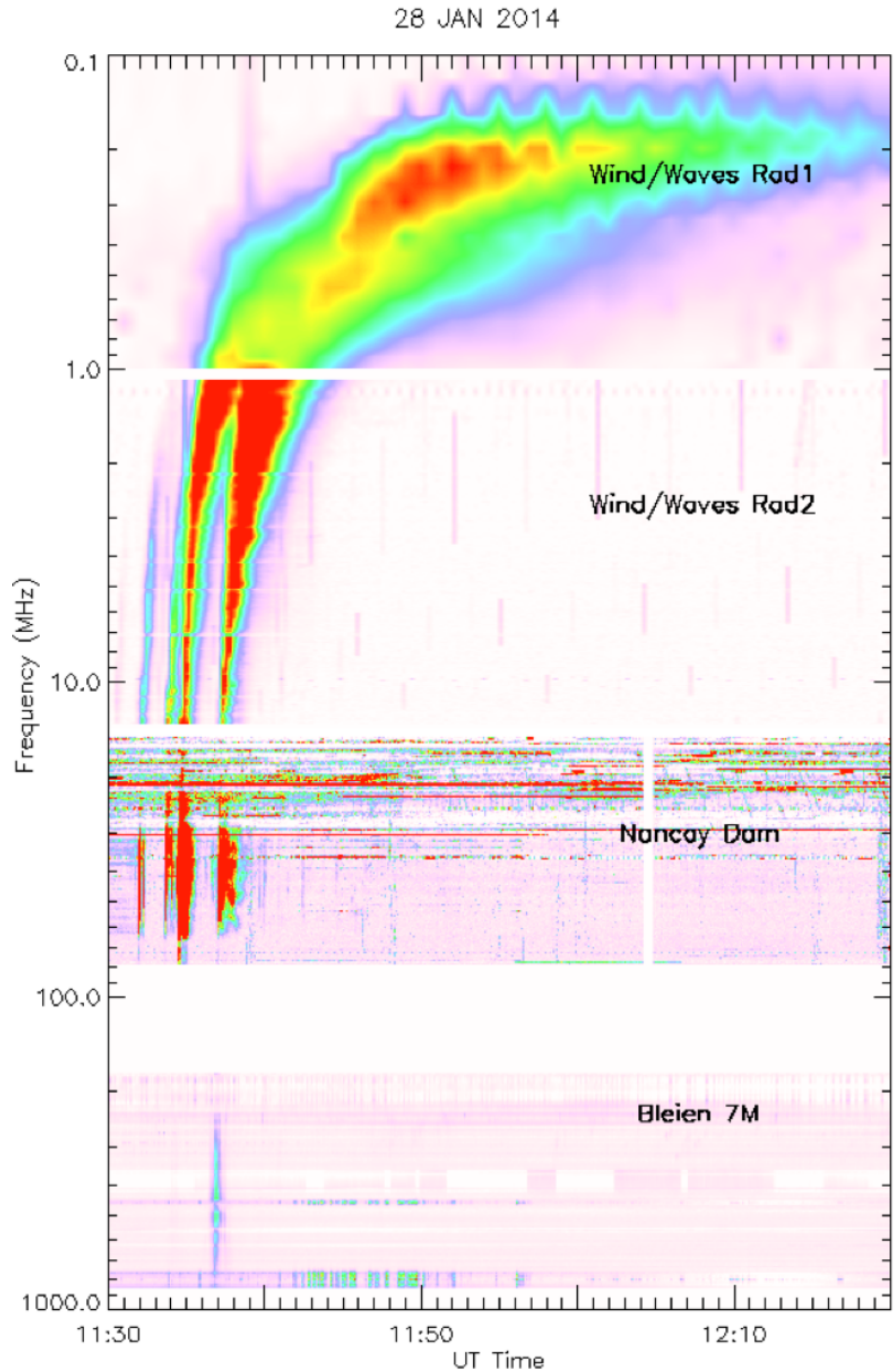




$$\omega_{pe} \propto \sqrt{n}$$

From Tang et. al.

- Type III burst tracks the electron beam as it travels through the decreasing plasma density of the solar corona and solar wind.



From a talk by H. Reid.

Electron Beams and Radio Bursts

- Ginzburg & Zhelezniakov in 1959 proposed electron beam produces solar radio bursts.
- Solar radio bursts are coherent plasma emission. The effective brightness temperature

$$T_{eff} >> 10^6 K$$

Sturrock's Dilemma 1964

- Electron beam generates coherent emission through electron two-stream instability (ETSI).
- Saturation time of ETSI ~ $1/\omega_{pe}$
- In corona: $1/\omega_{pe} \sim 10^{-8}s$
- Coronal radio burst (Type V): ~ 1-10ms.
- Type III~1s to tens minutes
- **How to reconcile the saturation time and emission time?**

Previous Models
Progress and Problems

- **Progress:**
- realization of coherent plasma emission is produced through **disparate wave coupling (or modulation)** (Sagdeev, 1969, book) between Langmuir wave and Ion acoustic wave.

- Weak ETSI models: Papadopoulos et al; M. Goldman et al, Robinson et al, … (Robinson, Rev. Mod. Phys., 1997) which all focus on interplanetary Type III burst

$$n_{beam}/n_{background} << 1, 10^{-6}$$

- **Problems:**
- Recent in-situ observations of solar flares near acceleration source region found

$$n_{beam}/n_{corona} < 1$$

- Ion acoustic wave is heavily damped in the nearly isothermal plasma of solar corona.

Langmuir Collapse and Emission

(Zakharov, V. E. 1972)

Kolmogorov turbulence
Energy inject from large scale, gradually cascades to small scale through three-wave couplings and stops due to landau damping

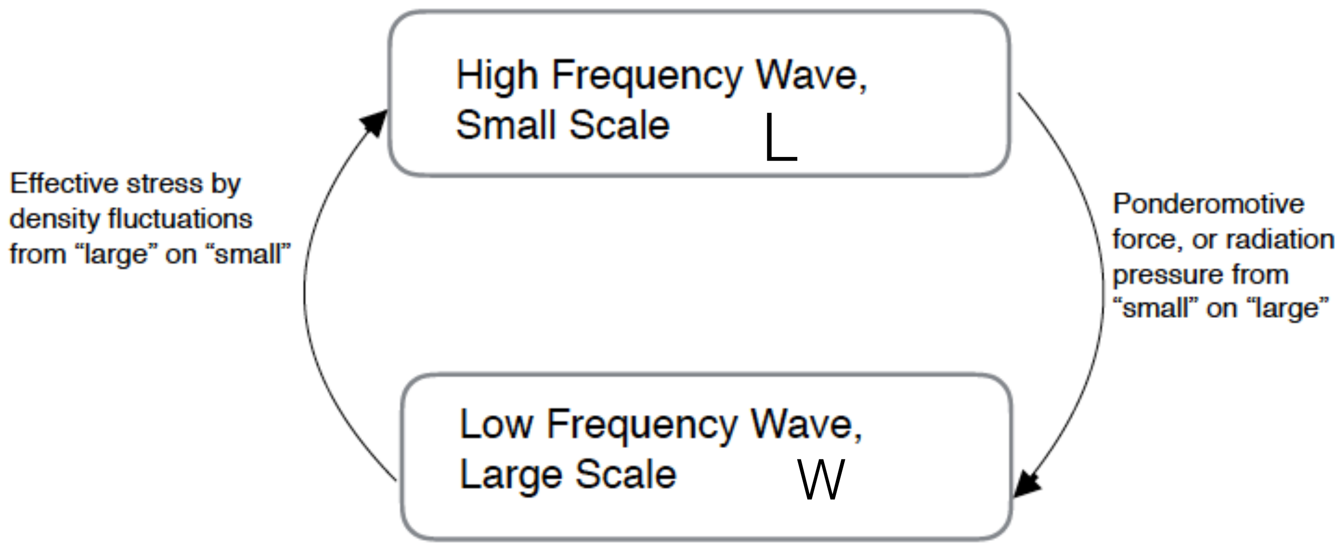
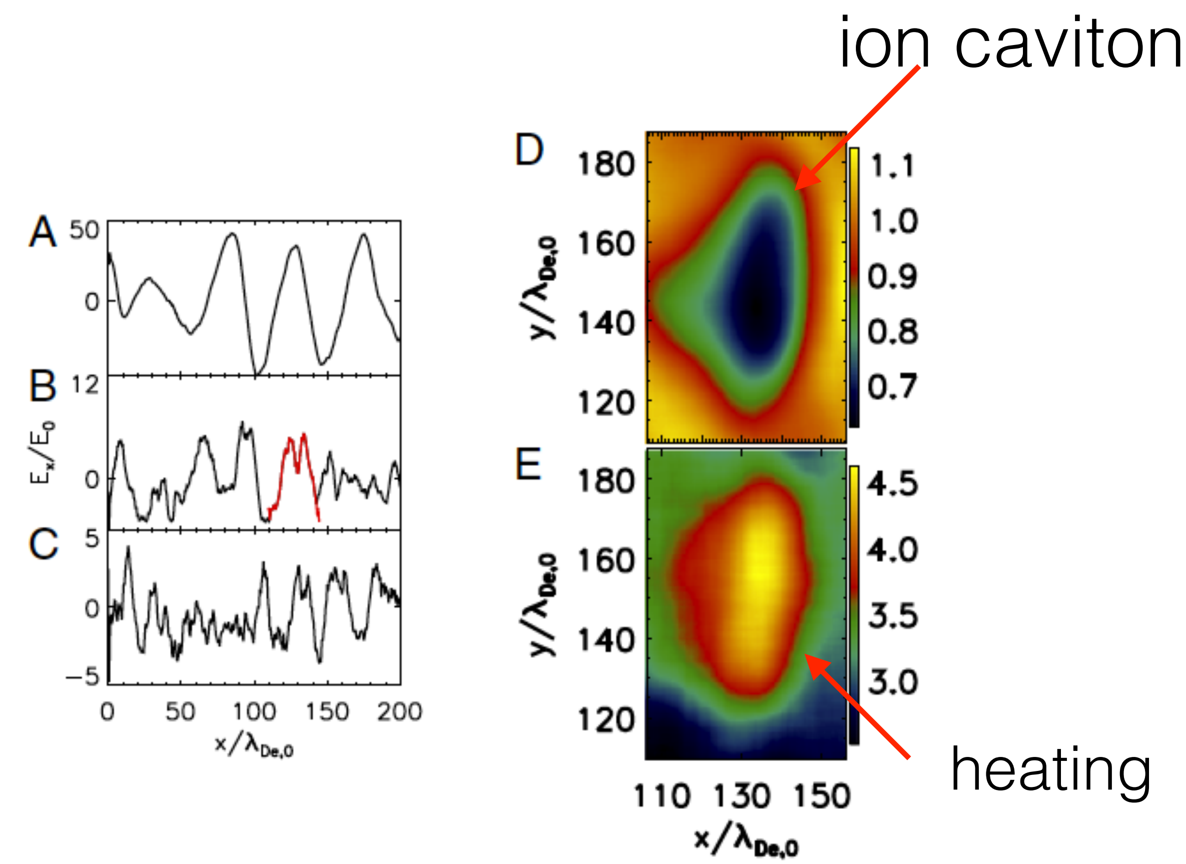


Fig. 2. Interaction of disparate scale wave coupling.



Langmuir wave
Low frequency wave

inverse energy transport →

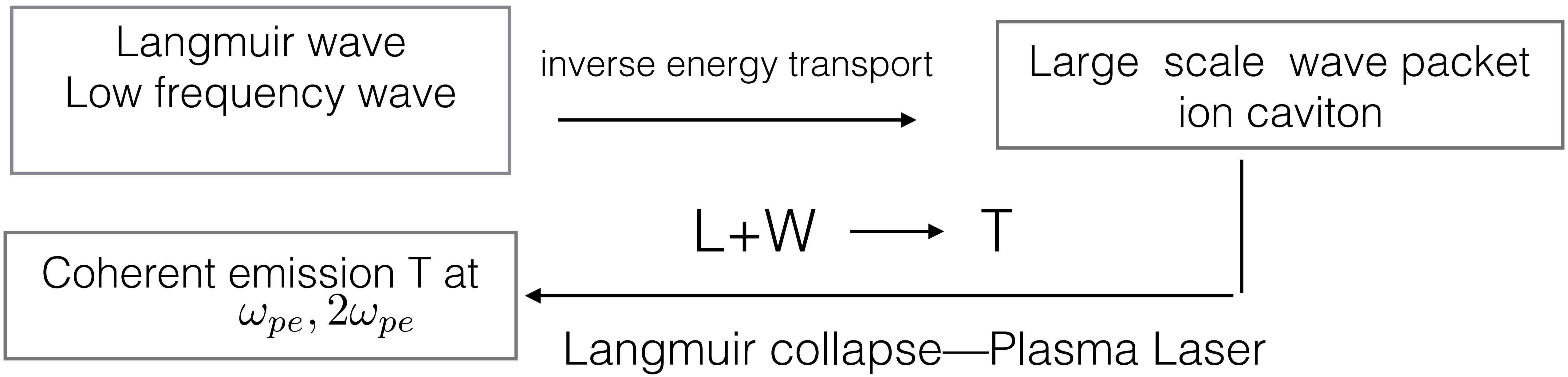
Large scale wave packet
ion caviton

L+W ⟶ T

Langmuir collapse—Plasma Laser

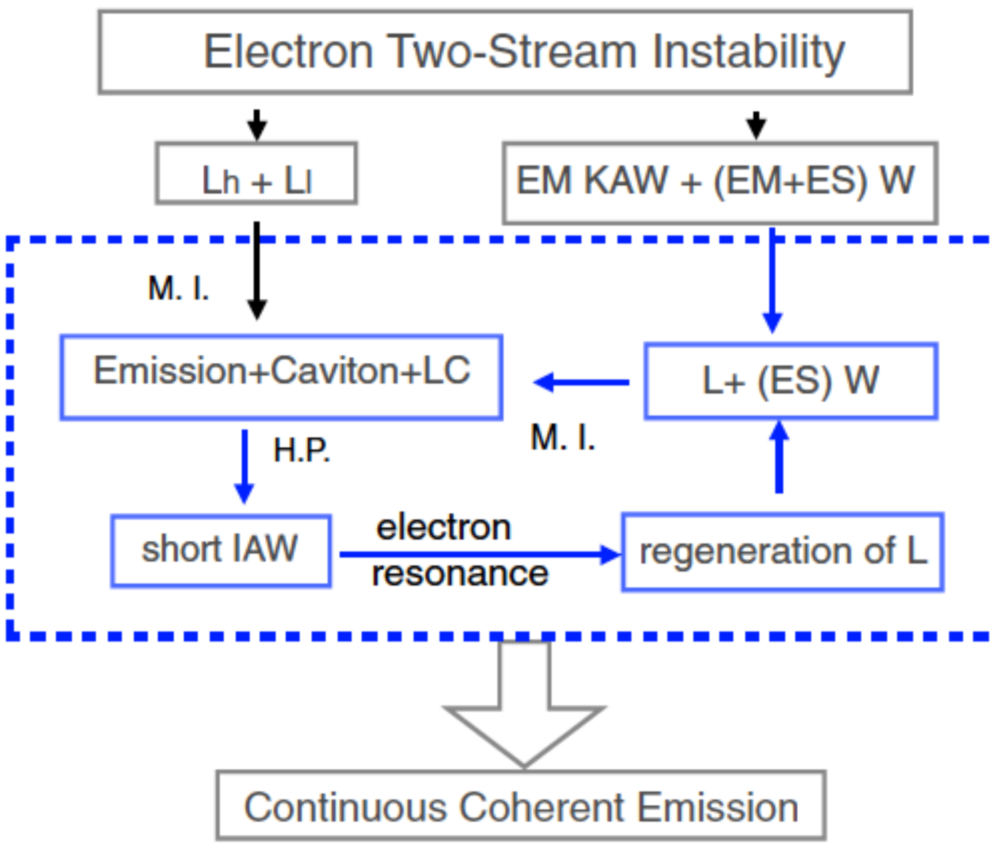
Coherent emission T at
$\omega_{pe}, 2\omega_{pe}$

How to Produce Continuous Coherent Emission Through Langmuir Collapse



Repeating this process—Feedback of Langmuir collapse regenerates Langmuir wave and inverse energy cascade

Cyclic Langmuir Collapse and Continuous Coherent Emission



Short IAW
short wavelength ion acoustic wave
frequency: ω_{pi}

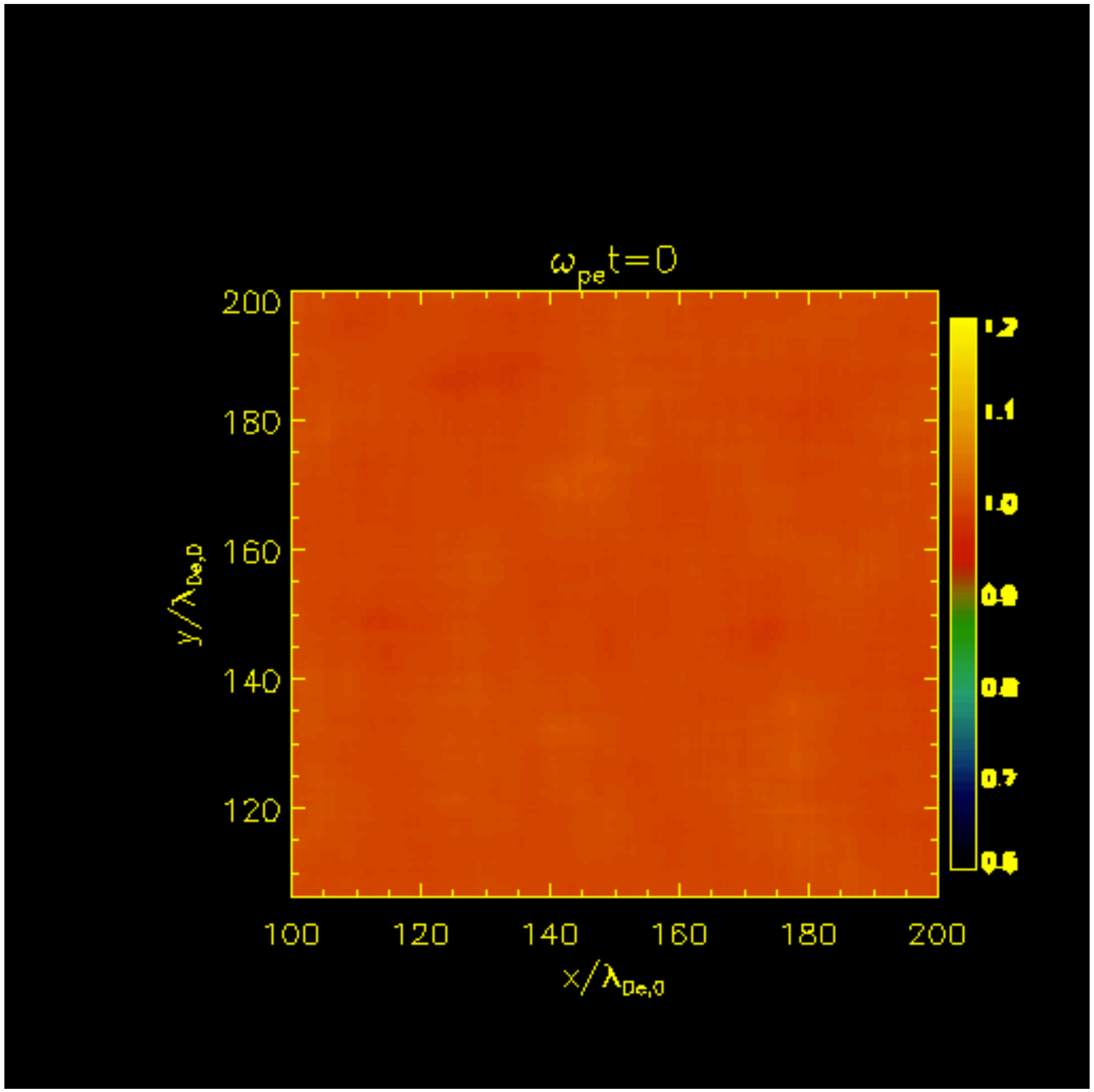
For short-wavelength IAWs with $k\lambda_{De} \approx 1$ in a
$T_i \approx T_e$, the dispersion relation becomes

$$\omega^2 \approx \omega_{pi}^2 \frac{1+\sqrt{3T_i/T_e}}{4} + \sqrt{\frac{3T_e}{T_i}} k^2 v_{ti}^2,$$

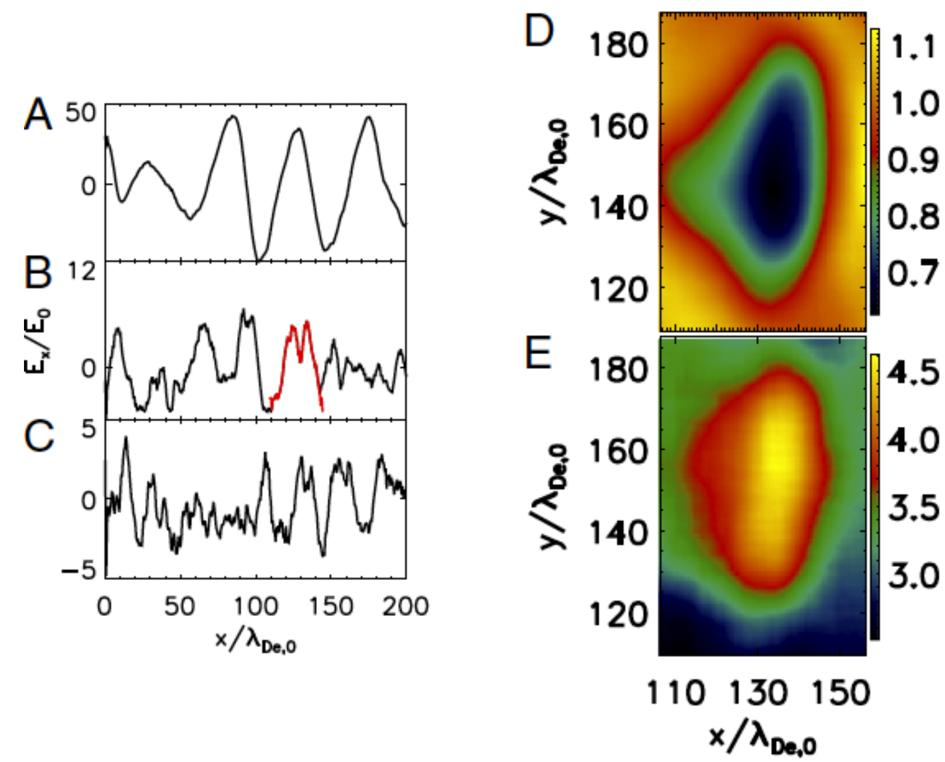
box) that produces coherent emission continuously. H.P., high pressure; L, Langmuir wave; L_h, Langmuir wave with higher frequency produced by the background electrons; L_l, Langmuir wave with lower frequency produced by the trapped electrons in solitary waves; M.I., modulational instability; *W*, Whistler wave.

- *Che, Goldstein, Diamond, and Sagdeev, Proceedings of National Academy of Sciences of the United States of America, 2017*

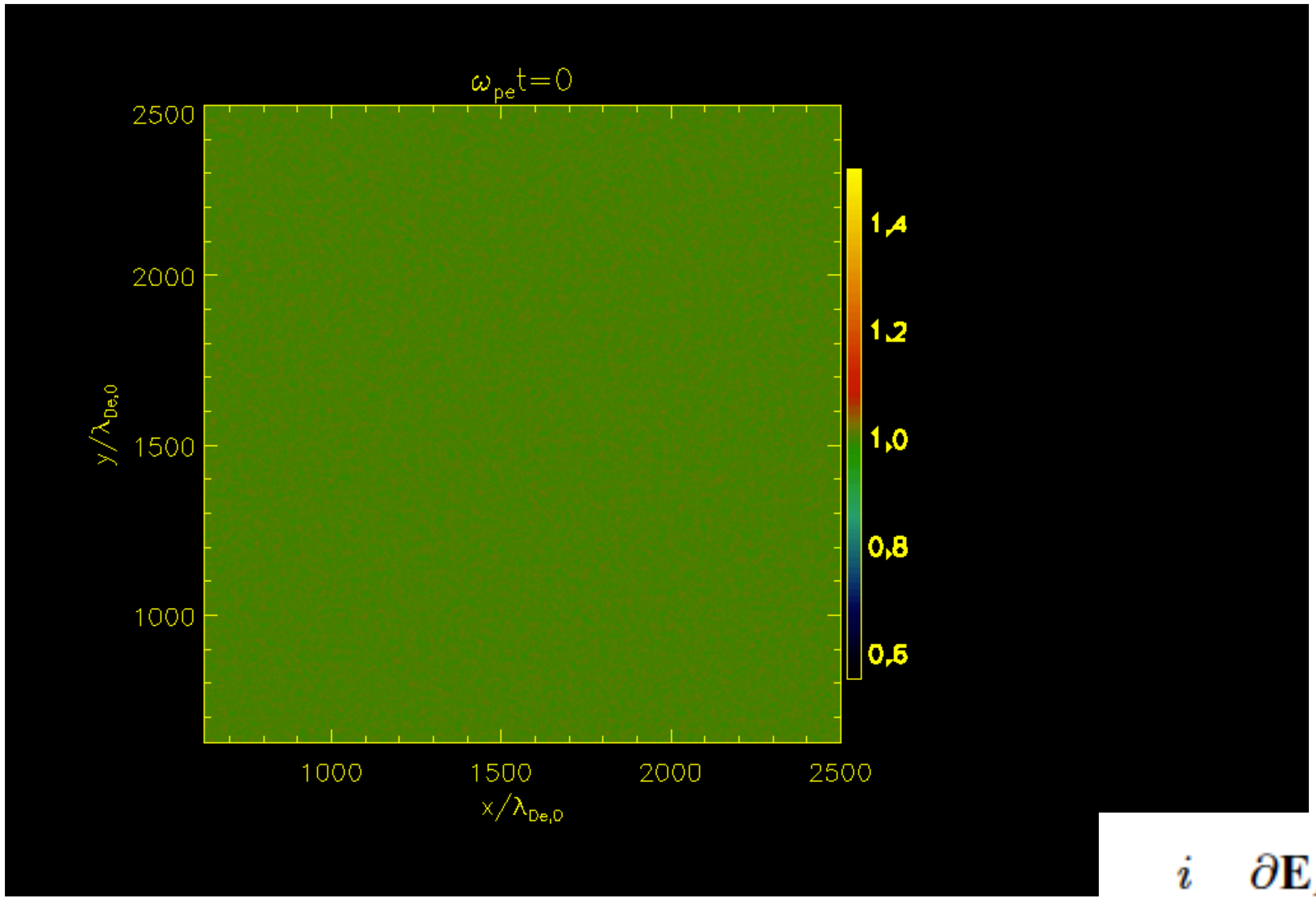
The formation of ion caviton caused by Langmuir collapse during Nonlinear ETSI



$$L_h + L_l -> T$$



Repeating Langmuir Collapse and Repeating Formation of Ion Cavitons



Attention to the changing of directions of the cavitons propagation:

Emission changes from

$$L_h + L_l -> T(\sim 2\omega_{pe})$$

to $$L + W -> T(\omega_{pe})$$

W: Whistler wave

Governing equations:

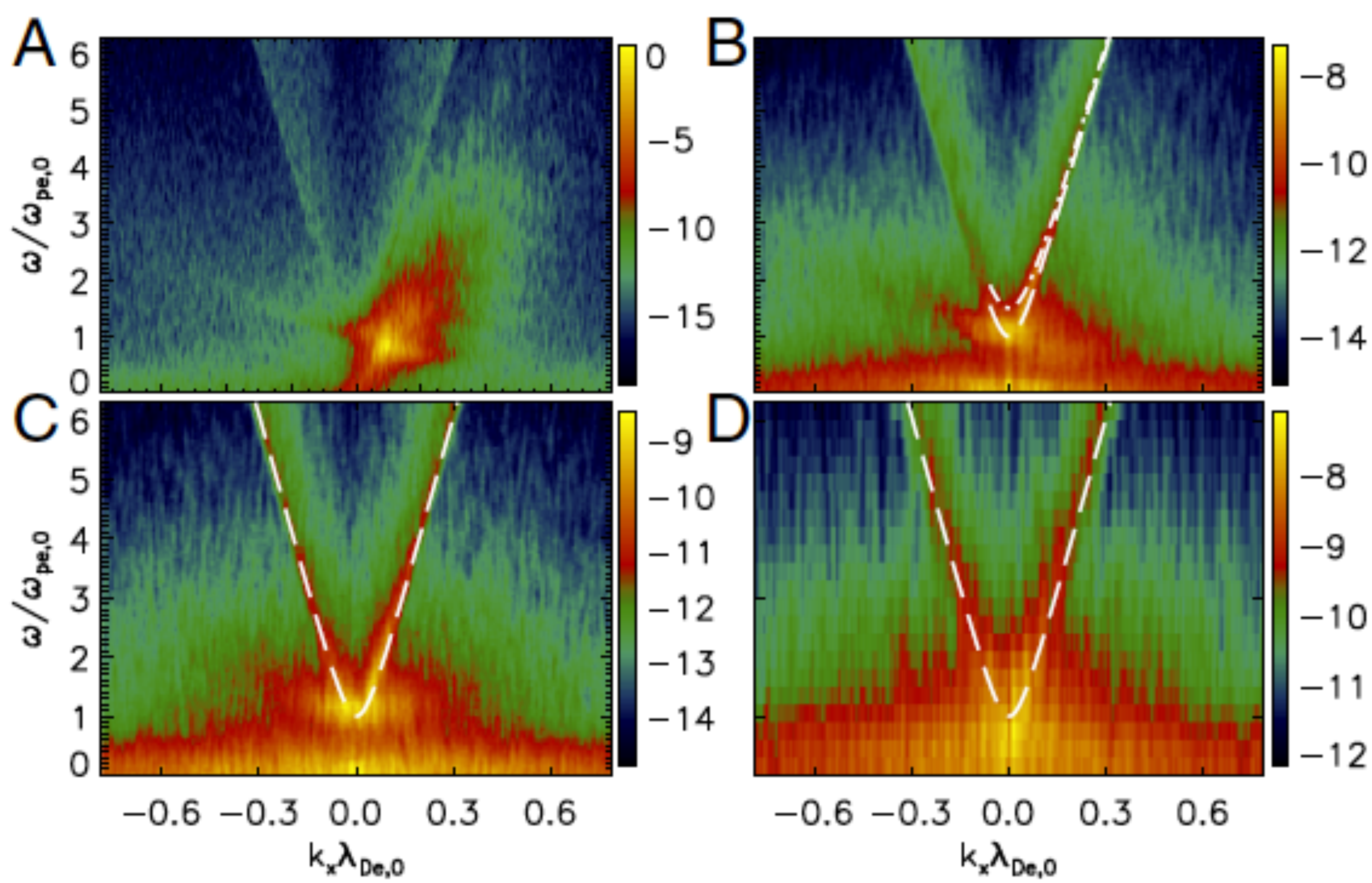
$$\frac{i}{\omega_{pe,0}}\frac{\partial \mathbf{E}_L}{\partial t} + \frac{\gamma v_{te}^2}{4\omega_{pe,0}^2}\nabla^2 \mathbf{E_L} - \frac{\delta n_s}{2n_0}\mathbf{E}_L = \frac{\delta n_{s,new}}{2n_0}\mathbf{E}_L$$

$$= -\frac{\omega_{pe}}{12}\sum_k \frac{|\delta n_s^k|^2}{n_0^2 k^2 \lambda_{De}^2}\left(1 + i\frac{2}{3}\frac{\gamma_k}{\omega_{pe} k^2 \lambda_{De}^2}\right)\mathbf{E}_L,$$

$$\frac{\partial^2}{\partial t^2}\frac{\delta n_s}{n_0} - c_s^2 \nabla^2 \frac{\delta n_s}{n_0} - M = \nabla^2 \frac{\phi_{\mathrm{pm}}}{n_0 m_i},$$

Emission lasts 5 orders of magnitude longer than the linear saturation time of ETSI

ω_{pe}^{-1}



$10^5\omega_{pe}^{-1}$

Comparison to Observations

Table 1. Model predictions and observational evidence

Model predictions	Observations	Refs.
In the solar corona, emission duration	Coronal type J and U radio bursts	(3, 4, 31)
$\approx 10^5 \omega_{pe}^{-1} \approx 1 - 10$ ms	Weak coronal type III radio bursts	
Langmuir waves and whistler waves	Interplanetary type III radio bursts	(16, 32, 33)
Langmuire collapse and short wavelength IAW	Interplanetary type III radio bursts	(15, 34, 35)

Nanoflares and the Origin of Electron Halo and Kinetic Turbulence of Solar Wind

- Observations of weak coronal radio bursts are associated with Nanoflares which can accelerate electrons to KeV (Saint-Hilaire et al, Apj, 2012).

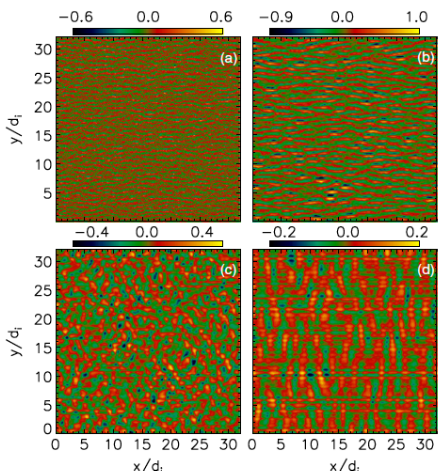
- New observations found the origin of solar wind is associated with nanoflares (Feldman, JGR, 2015) .

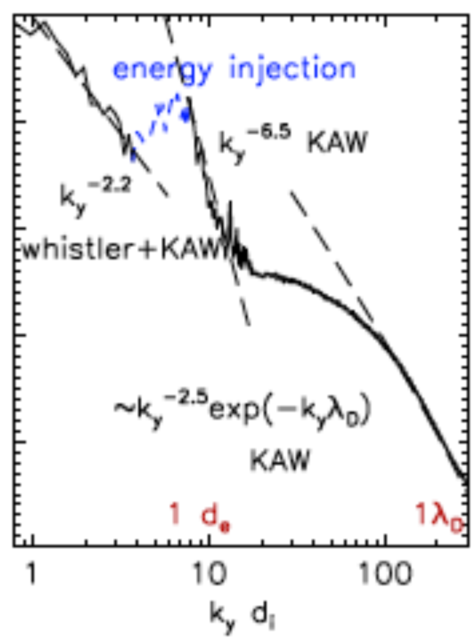
- KeV electron beams can produce electron halo, kinetic Alfven wave and whistler wave turbulence observed in the solar wind (Che et al, PRL, 2014, ApjL, 2014).

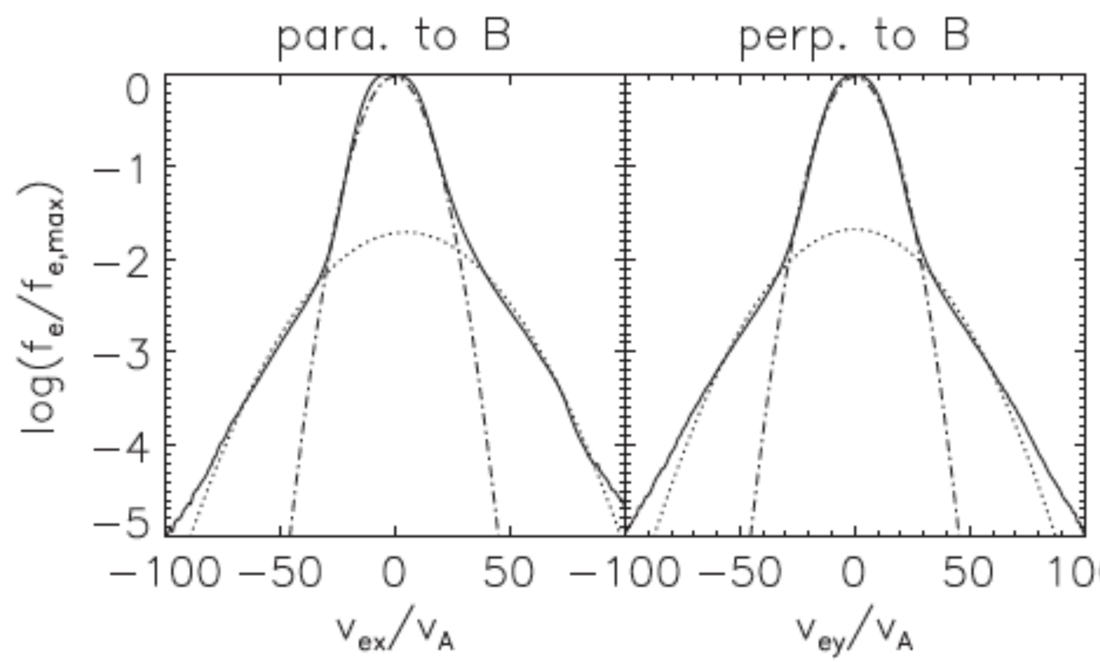
- Electron halo is found to be associated with the anomalous electron heat flux in the solar wind (Bale, ApjL, 2013).

Kinetic Turbulence in the solar wind

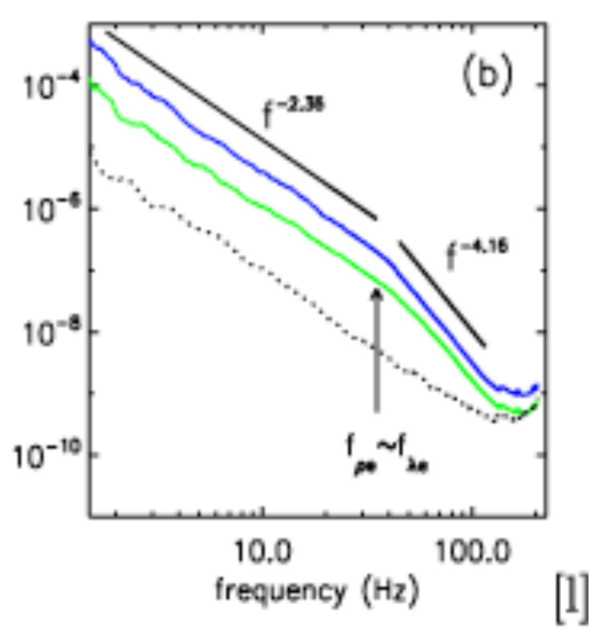
simulation, Che et al, PRL, ApjL, 2014



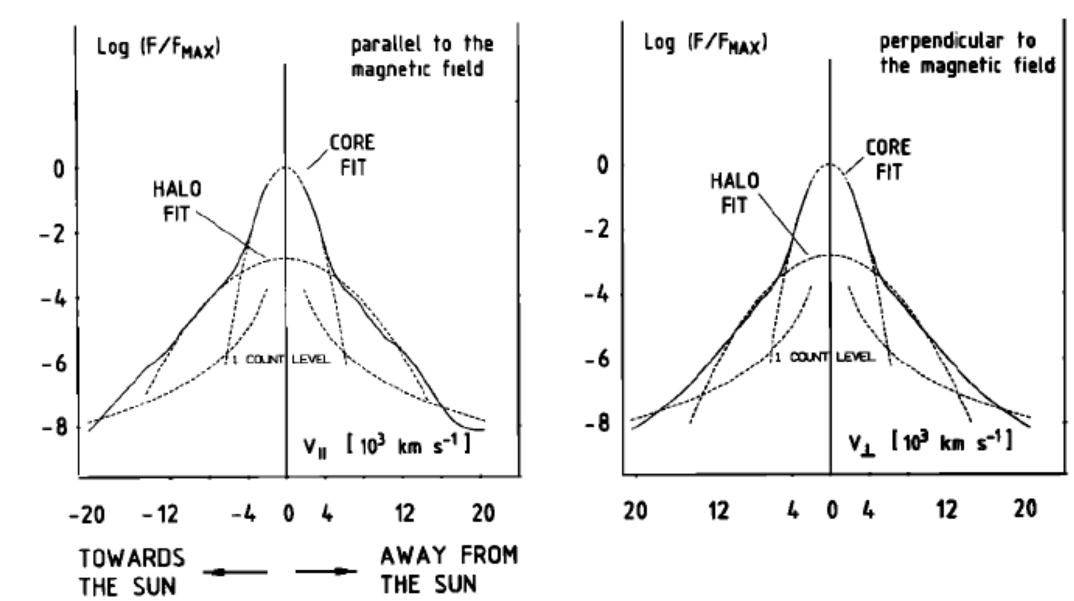




observation, Pilipp et. al, JGR, 1987



Sahraoui et al., 2009, PRL



Broad Applications

- The track of radio bursts and other band radiations can explore the acceleration mechanism of solar flares.

- Electron Beams are common in the solar corona. The nonlinear evolution of ETSI unifies the origin of electron halo, kinetic turbulence and nanoflare radio bursts. SPP and SO can investigate these topics.

- MMS in-situ observations of electron beams in magnetosphere can provide direct evidence on the emission mechanism (we are working on an event).

- Energetic electrons in radiation belt…