Some of Francesco Ruggiero's Insights into Collective Effects

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Francesco's Qualities

- Francesco had a deep understanding of collective phenomenon
- I'll give some examples here
  - Localized impedance
  - Two-dimensional transverse Landau damping
  - Electron cloud instability
  - Space charge at high energy
- Made him a great supervisor/leader

Localized Impedance

- His thesis was my first exposure to his work
- I found it very interesting from a theoretical point of view
- Before I even met him!

Localized Impedance
Sticky Impedance Model

- Beam passes through localized object (location s)
- Induces charge distribution on object's walls
  - Based on beam distribution at s
- Effects subsequent beam arriving at location s
  - Effect is from wall charges at s

Localized Impedance
Full Vlasov Equation

- Analyze distribution at s versus turn number
- Find eigenvalues of Vlasov equation, look for instabilities
  - Fourier transform in s, integer index k
    - Observation location for distribution
    - Impedance location also
  - Equation couples mode k to mode $\bar{k}$
    - Impedance mode $k - \bar{k}$

Localized Impedance
Full Vlasov Equation

$$(\Omega - k\omega_0 - \boldsymbol{m}\cdot\boldsymbol{\omega})\Psi_{\boldsymbol{m}nk} = - i\frac{q^2N}{p}\sum_{\bar{k}} Z_{\boldsymbol{m}n;\bar{\boldsymbol{m}}\bar{n};k-\bar{k}}\Psi_{\bar{\boldsymbol{m}}\bar{n}\bar{k}}$$

$$\Psi_{\boldsymbol{m}n}(s) = \sum_k \Psi_{\boldsymbol{m}nk} e^{2\pi iks/L}$$

$$Z_{\boldsymbol{m}n;\bar{\boldsymbol{m}}\bar{n}}(s) = \sum_k Z_{\boldsymbol{m}n;\bar{\boldsymbol{m}}\bar{n};k} e^{2\pi iks/L}$$

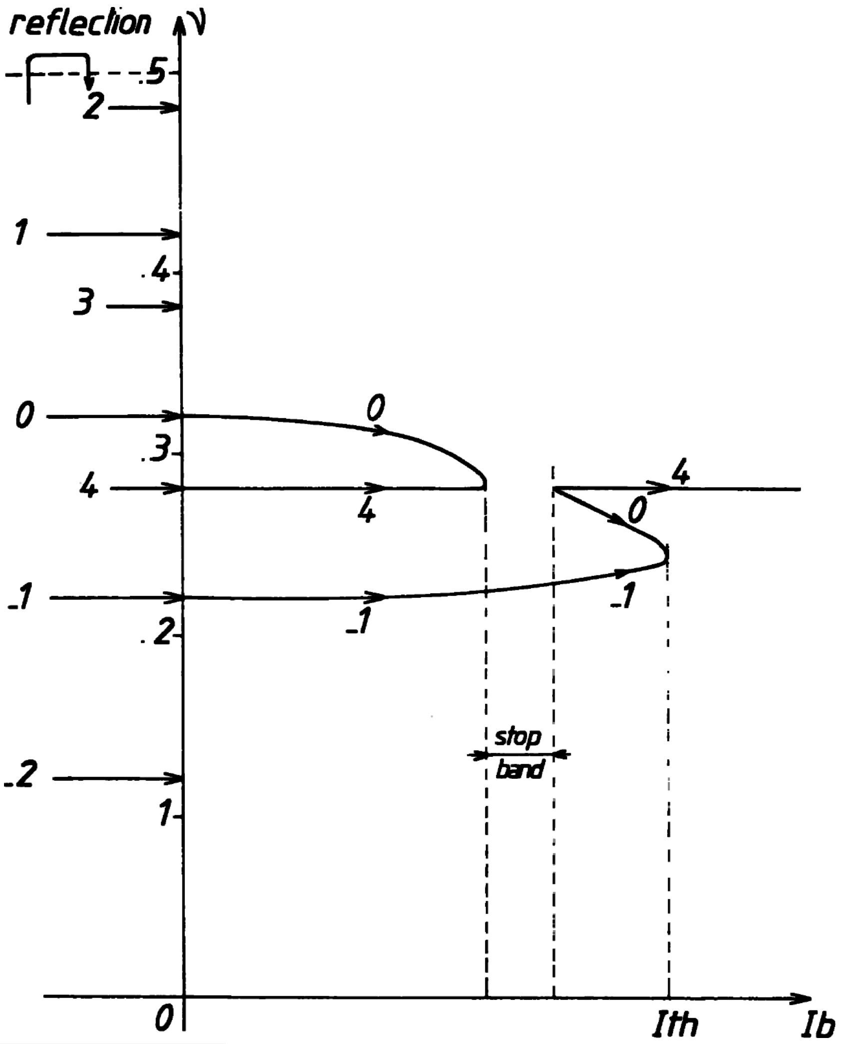
Localized Impedance Smooth Approximation

- No coupling between different k if effective impedance independent of s
  - Effective impedance: transverse weighted by β
  - Still coupling between
    - Internal bunch modes
    - Multibunch modes
- Usually assume uniform effective impedance

Localized Impedance
Single Impedance

- Francesco looked at a different limit
- All impedance in one location
- Only fractional tunes can be relevant
- All k above are strongly coupled
- Instead use a basis localized at a point s

Localized Impedance Mode Coupling



- Mode coupling between non-adjacent mode numbers
- Coupling typically weak
  - “Stop band”, then stable again
- Final instability between $m = 0$ and $m = -1$

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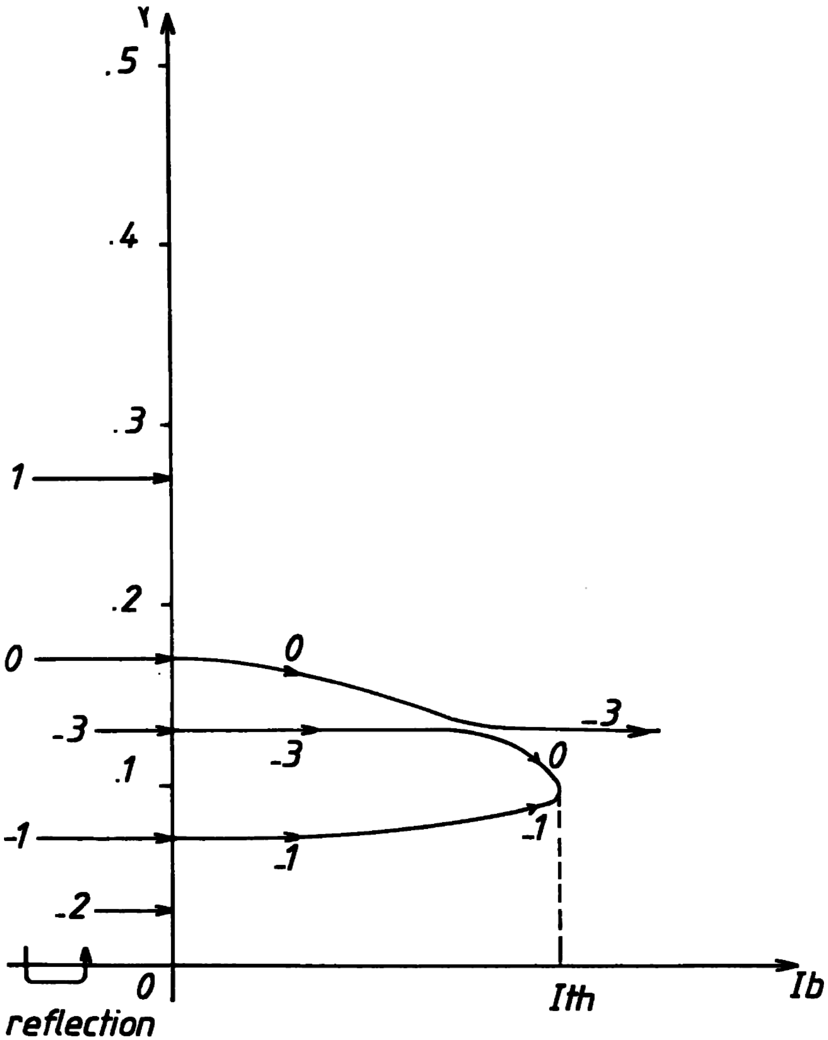
Localized Impedance Mode Parity

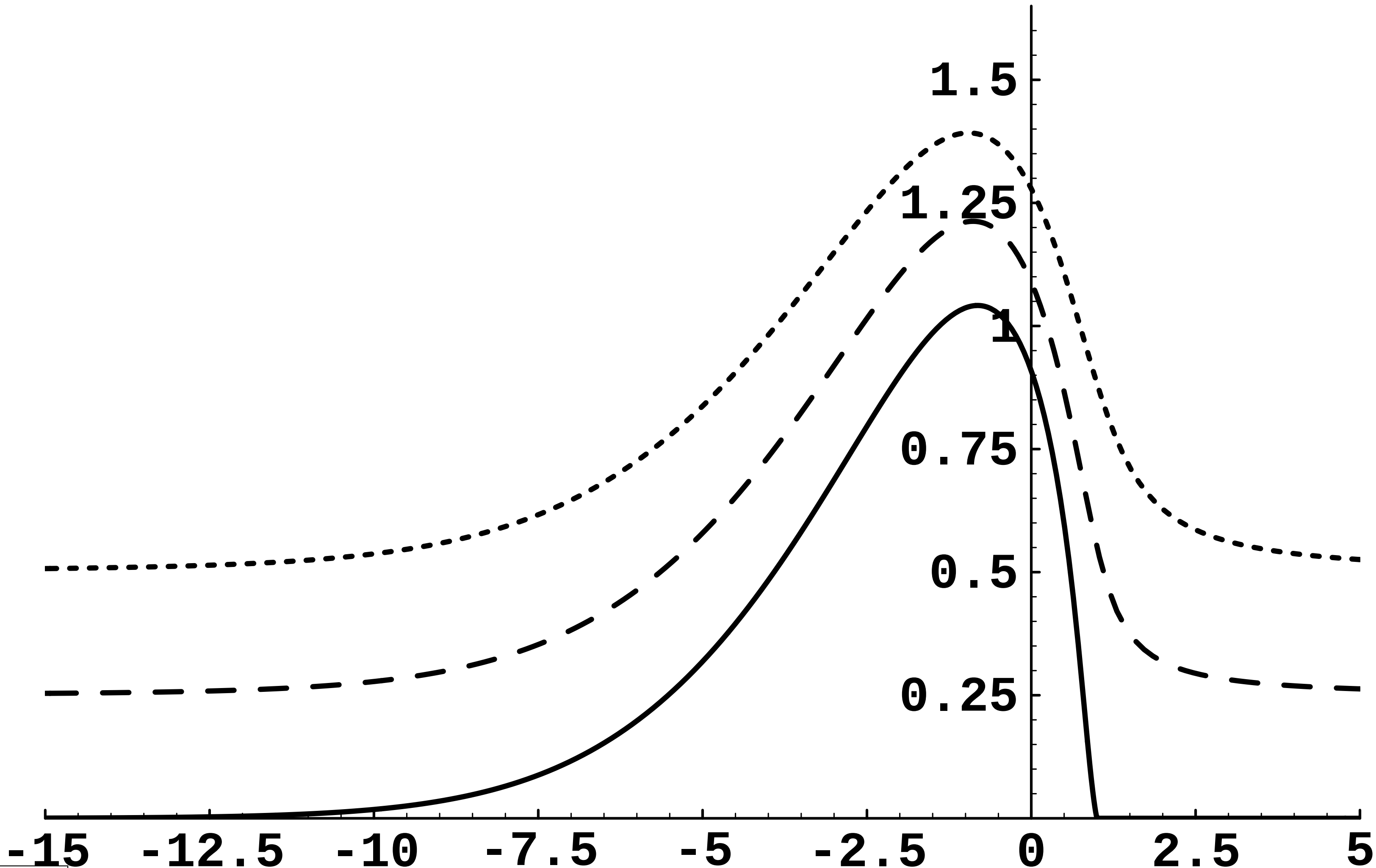


- Some modes don't give stop band
- Reason: "parity" of low-current eigenmodes
- Different parity than main modes!
  - $+\omega_y + m\omega_s$ coupled with $-\omega_y + \bar{m}\omega_s$
  - This always strongest

Two-Dimensional Landau Damping
Introduction to Landau Damping

- Tune depends on oscillation amplitude
- Finite beam size, spread in frequencies
- Oscillation involving entire beam will decohere
  - If frequency within beam frequency spread
- Stability diagram
  - Complex oscillation frequency within boundary, stabilized
  - Boundary expresses tune range in beam

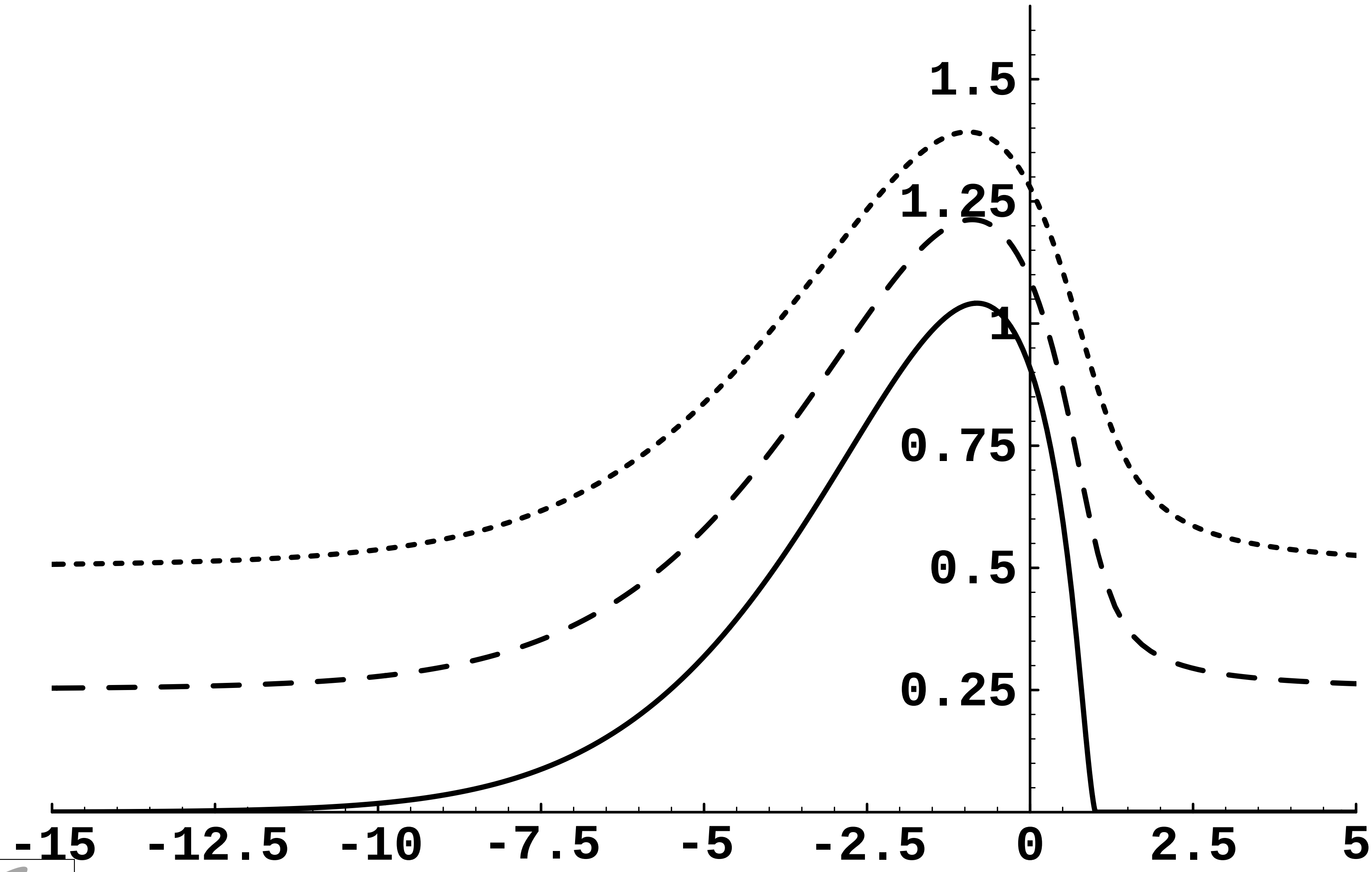
Two-Dimensional Landau Damping Tune Spread in One Dimensions



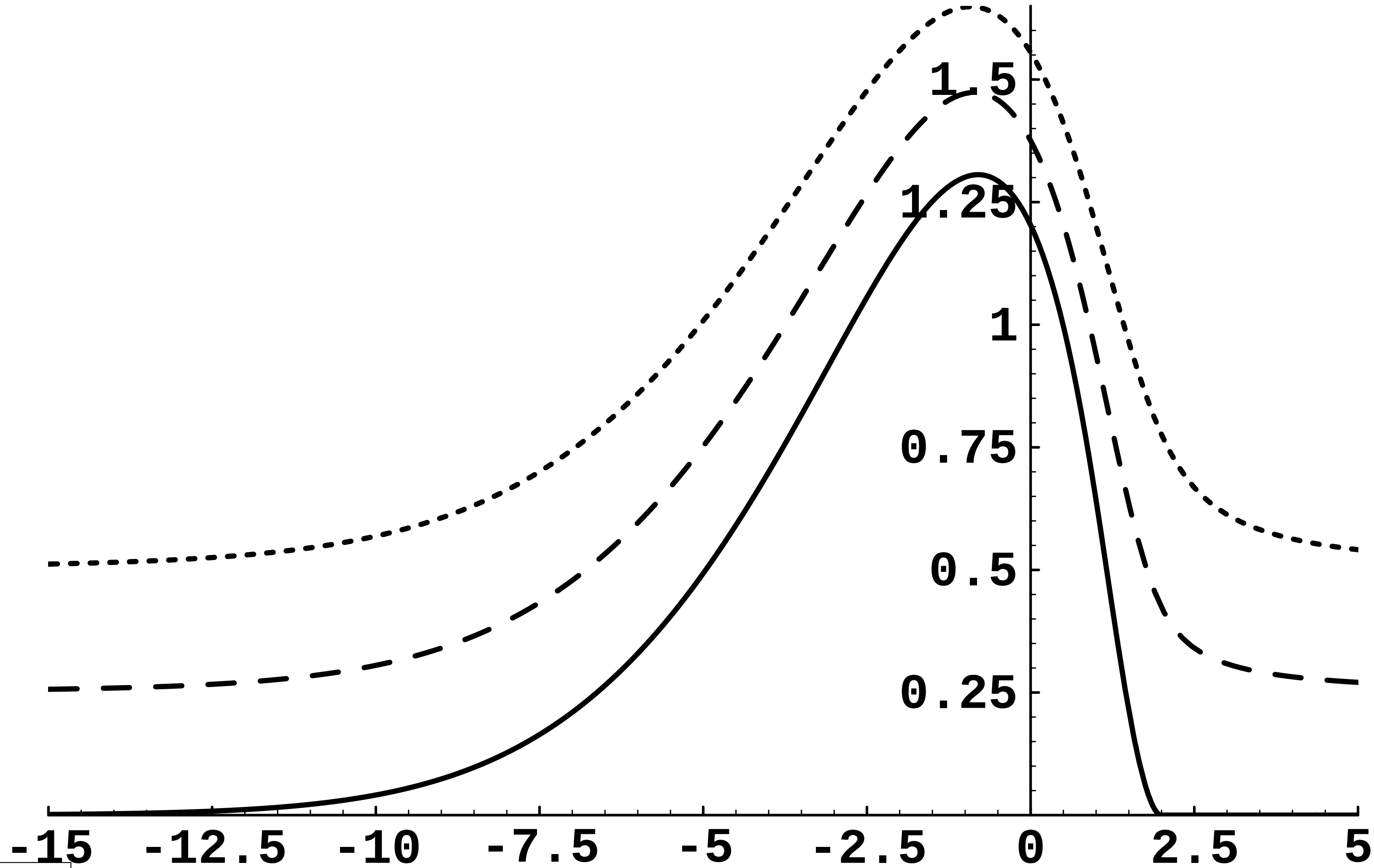
Two-Dimensional Landau Damping

- LHC: little radiation damping
  - Landau damping important damping mechanism
- Landau damping caused by tune spread with amplitude
- Betatron tune spreads in two directions
- Calculation had only been done in one direction
- So he did it for two dimensions!

Two-Dimensional Landau Damping Tune Spread in One Dimensions



Two-Dimensional Landau Damping Tune Spreads in Same Direction



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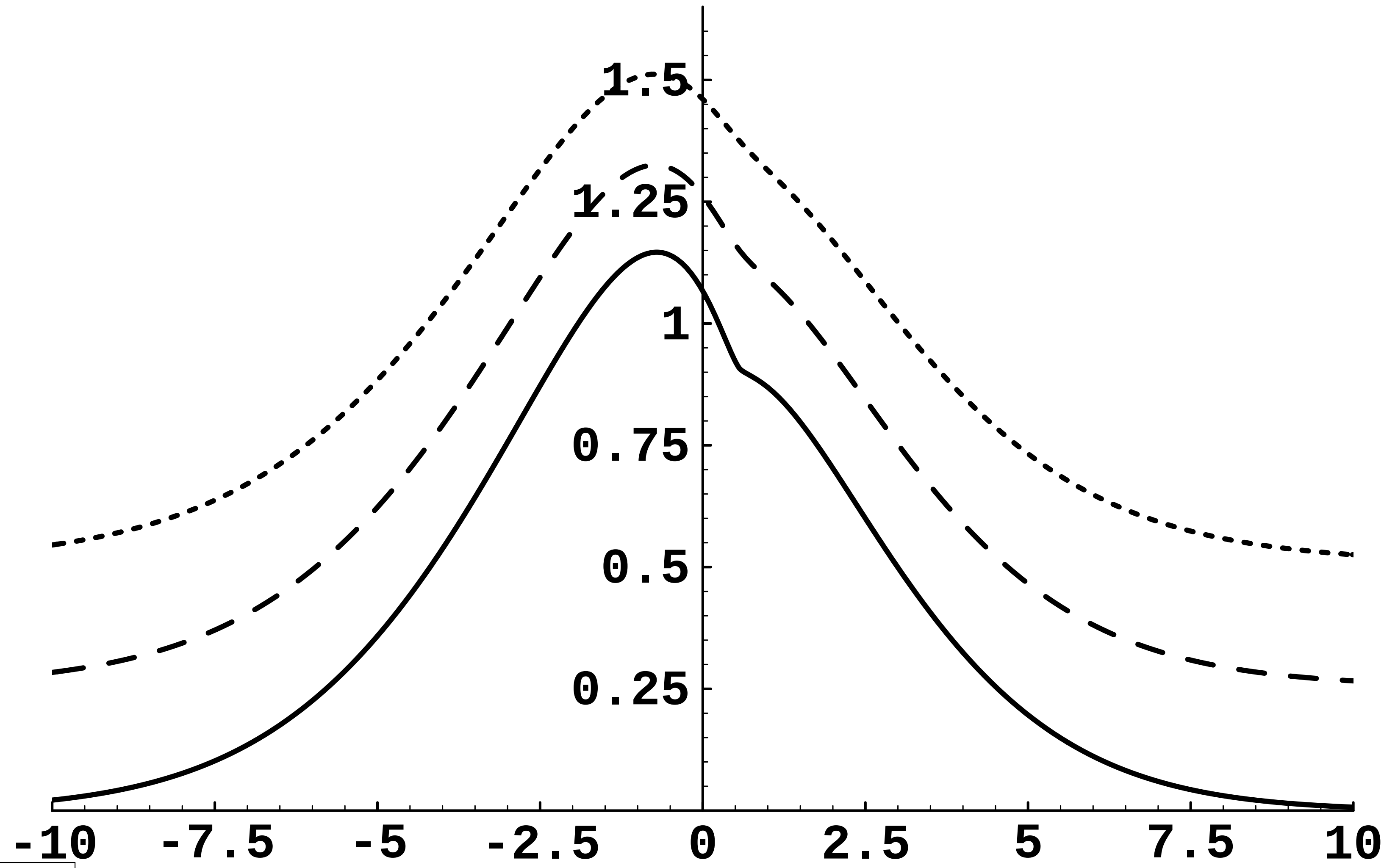
Two-Dimensional Landau Damping Tune Spreads in Opposite Directions



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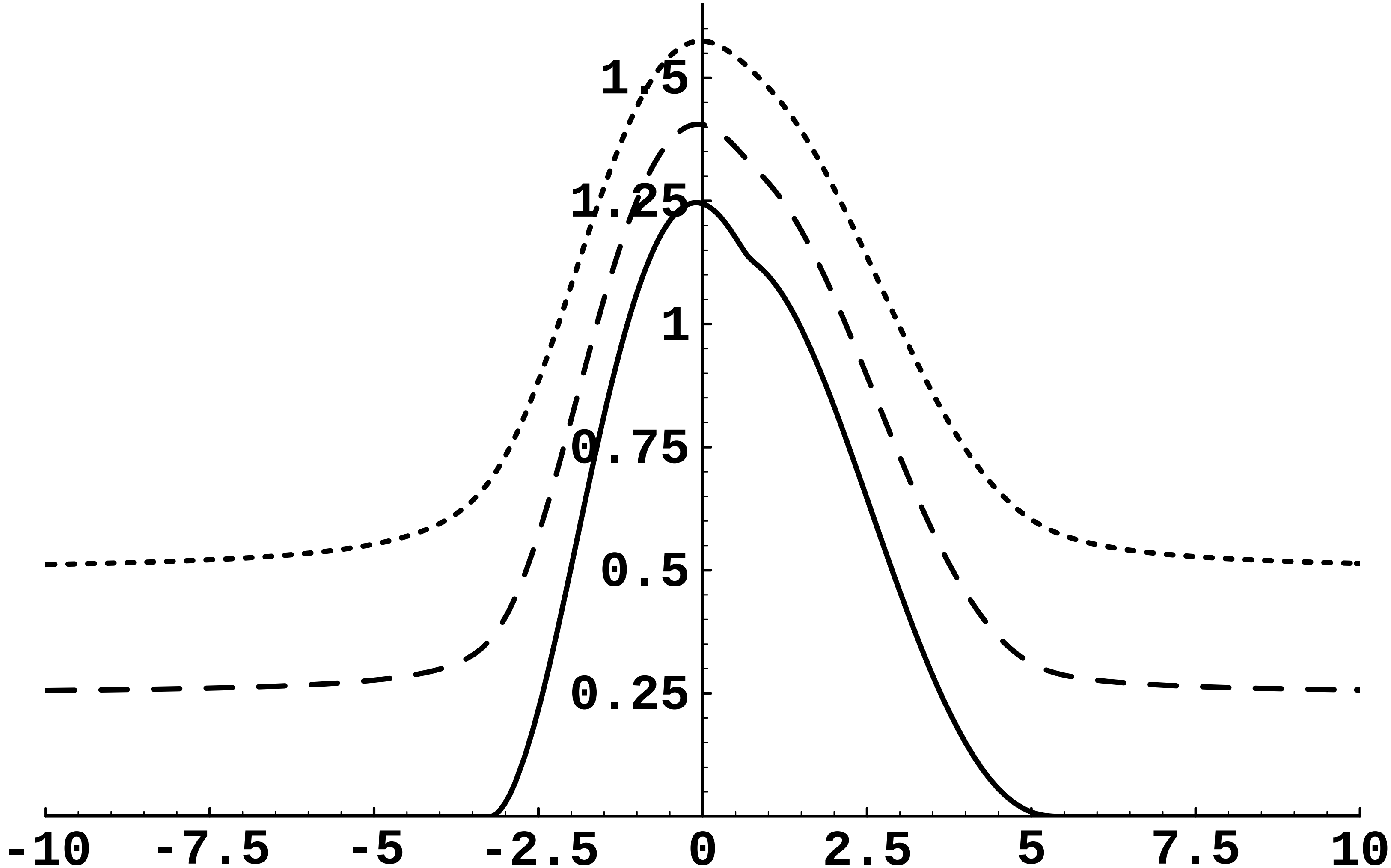
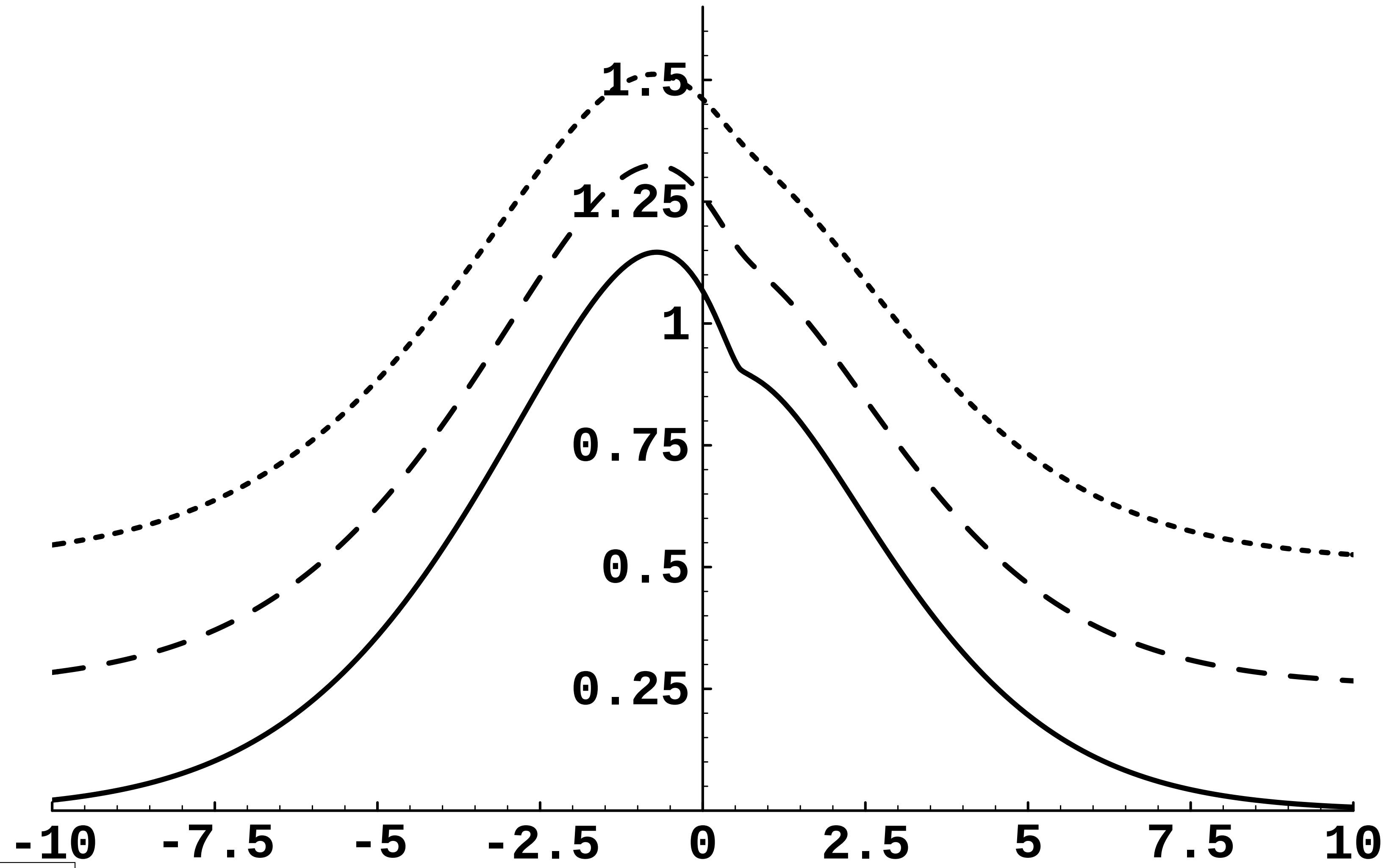
Two-Dimensional Landau Damping Effects

- Tune shifts in same direction
  - Larger instabilities damped
- Tune shifts in opposite direction
  - Real mode shifts in both directions allowed
  - Interesting with modest space charge
- Expected Gaussian tails to be truncated
  - Francesco worked out model with cuts at 3σ
  - Later we worked out arbitrary cuts

Two-Dimensional Landau Damping Distribution with Truncated Tails



Two-Dimensional Landau Damping Gaussian Distribution



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The LHC Electron Cloud “Crash Program”

- At the time there was skepticism about electron cloud
- He looked at others calculations, saw its potential importance for LHC
- He vigorously led a program to address it

Electron Cloud: Head Load

- Head load in magnets was important
- Energy transfer beam to electron cloud
- He guessed that this could be approximated analytically
  - Assuming known initial distribution
- Analytic computation told us we needed more simulation steps during beam passage
  - Electrons trapped in beam field

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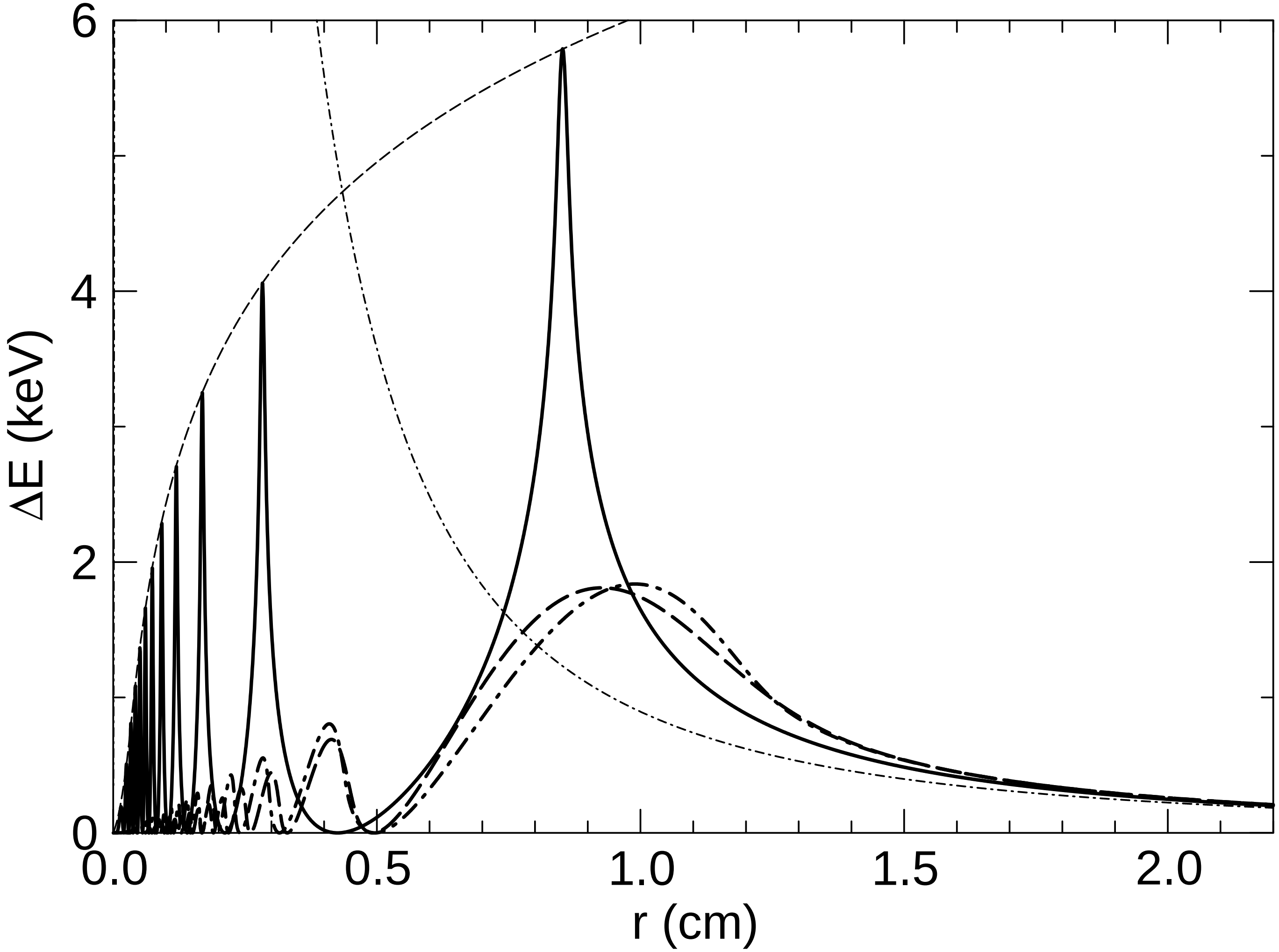
Electron Cloud Energy Gain



Space Charge and Impedance

- Questioned whether space charge should treated just as impedance
  - Different: beam itself, not wall, mediates
- Important for LHC: large coherent tune shift favorable for Landau damping (opposes inductance)
- Induces large incoherent tune spread
  - Tune shift with amplitude—Landau damping?

Conclusion

- Francesco understood deeply collective phenomenon
- Went beyond simple repetition of previous work
- Encouraged those around him to do so also
  - Gave us many great ideas
- Produced many interesting results
- A great friend and colleague