Solitary Acoustic Wave Versus Shock Acceleration in Laser-Plasma Interactions

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The basic idea of Shock Acceleration - I

A superintense laser pulse incident on an *overdense* plasma ($\omega < \omega_p$ i.e. $n_e > n_c = m_e\omega^2/4\pi e^2$)

- heats up electrons up to high (possibly relativistic) temperatures
- pushes the laser-plasma surface at the "hole boring" velocity

$$v_{\text{hb}} = a_0 c \left(\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}\right)^{1/2} \qquad a_0 = 0.85\left(\frac{I\lambda^2}{10^{18}\ \text{W cm}^{-2}}\right)^{1/2}$$

High temperature + strong piston (hopefully) drives fast

Collisionless Shock Wave

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The basic idea of Shock Acceleration - II

According to standard theory (D. A. Tidman and N. A. Krall, *Shock Waves in Collisionless Plasmas* (Wiley/Interscience, New York, 1971), chap. 6.)

- a Collisionless Shock of velocity v_s is preceded by "reflected" ions of velocity $v_i = 2v_s$
- necessary condition for ion reflection

$$v_s > 1.6 c_s \qquad c_s = (T_e/m_e)^{1/2}$$

otherwise if $c_s < v_s < 1.6 c_s$ a non-reflecting *soliton* may exist

If $v_s \gtrsim v_{\text{hb}}$ the reflected ions have high ($>$ MeV) energy and are monochromatic (if v_s is constant); appealing and possibly dominant ion acceleration mechanism
[L.O.Silva et al, Phys. Rev. Lett. **92**, 015002 (2004)]

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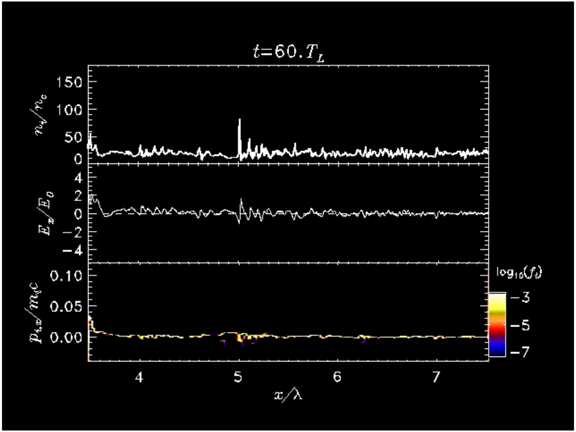
Short-pulse driven "Solitary Acoustic Wave"

1D PIC simulation: short ($\tau = 4T$), intense ($a_0 = 16$) laser pulse on an overdense ($n_e = 20n_c$), *cold* ($T_i = 0$) proton plasma slab

Short-pulse driven “Solitary Acoustic Wave”



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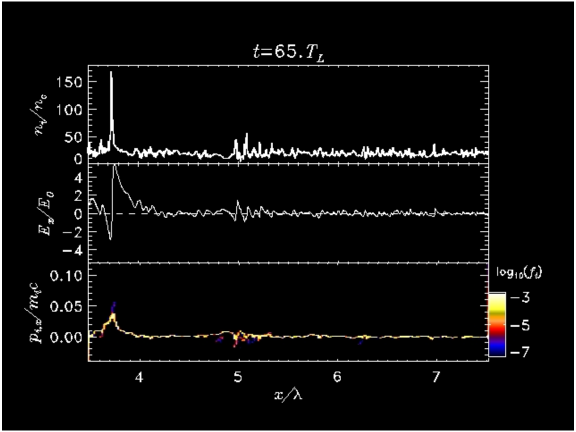

It looks like a soliton . . .

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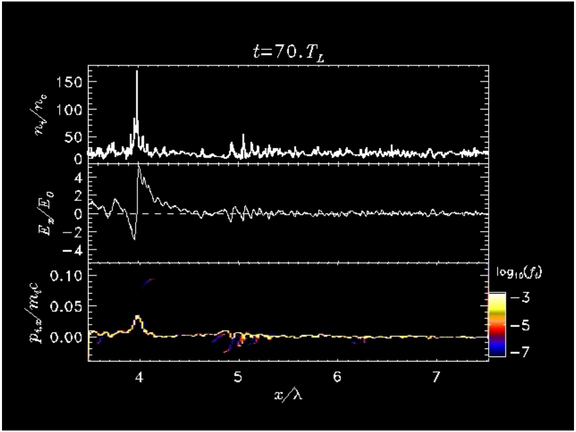

. . . but occasionally reflects a short bunch of ions!

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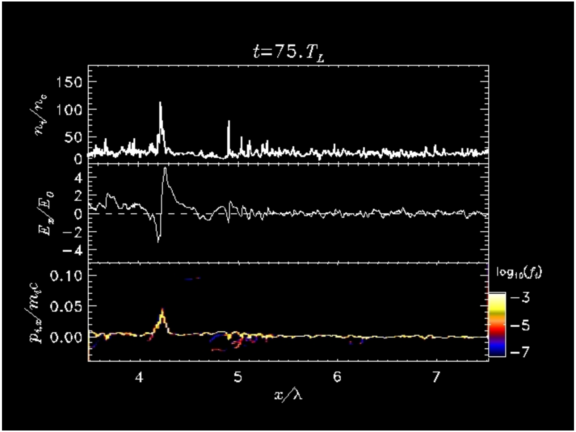

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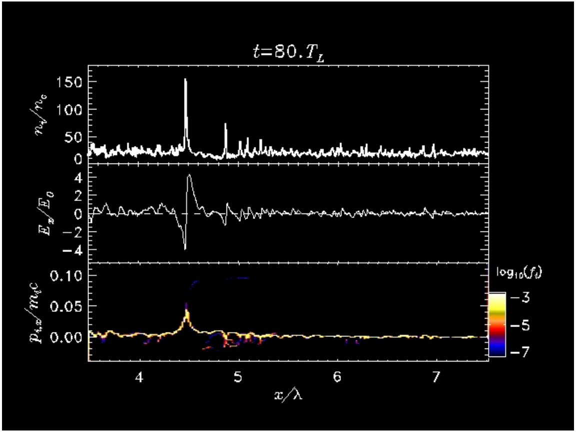

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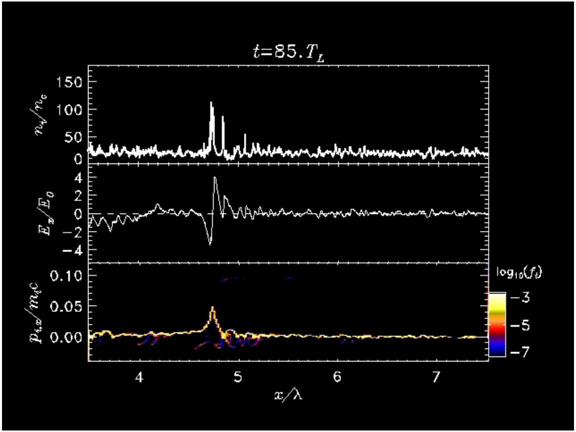

Acceleration is “pulsed”, solitary wave almost stays unchanged

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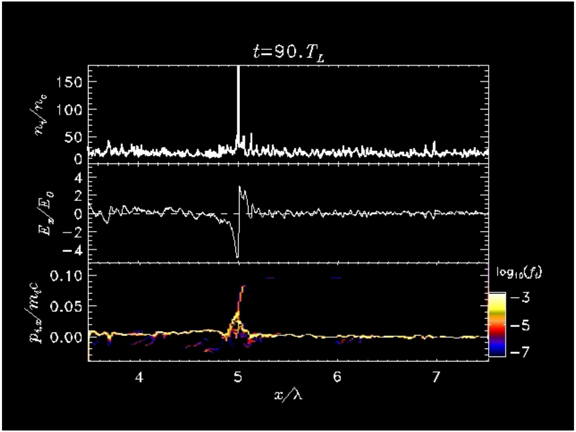

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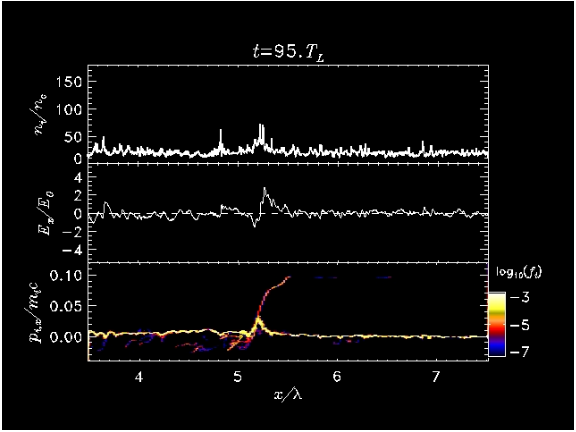

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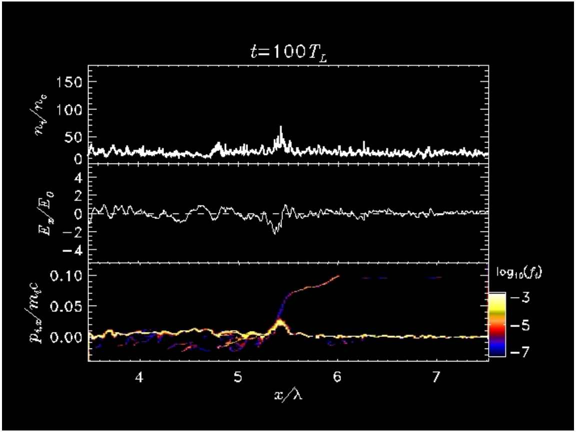

Eventually a long-lasting “shock-like” reflection occurs . . .

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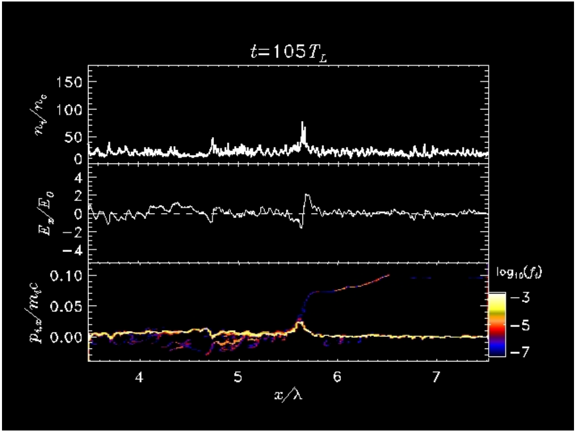

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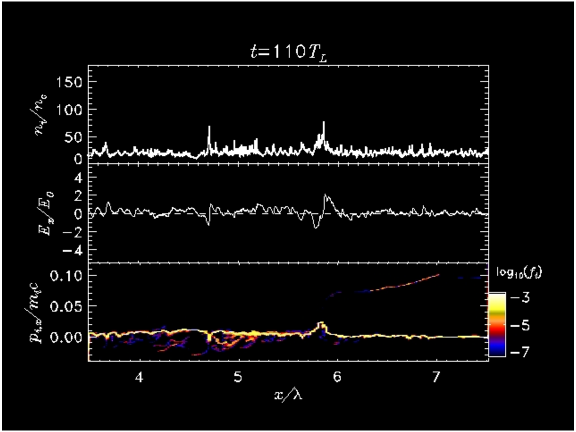
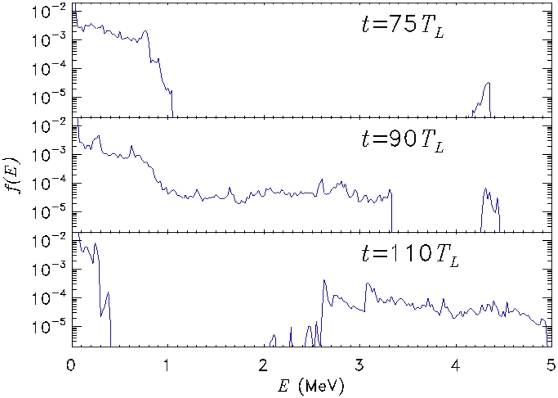


. . . and the solitary wave damps out

Evolution of ion spectrum



Monoenergetic peak smears out as the solitary wave damps (reflection from a moving, slowing down wall)

Our understanding and (supposed) lesson learned

- For *cold* ions a a genuine shock wave can't form (can't "pick up" a fraction of "resonant" ions for the reflected trail)
- A solitary wave can reflect ions as short-duration, small-number, monoenergetic bunches, otherwise damps attempting to reflect *all* background ions

Hint: the ion distribution plays an important part

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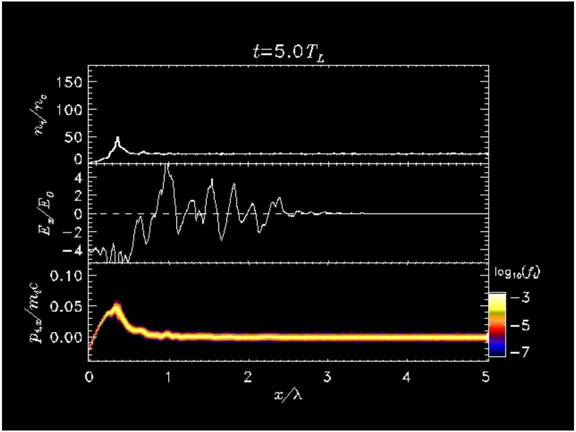
Hot ions: steady ion reflection

Same 1D PIC simulation, but now $T_i = 5$ keV

Hot ions: steady ion reflection



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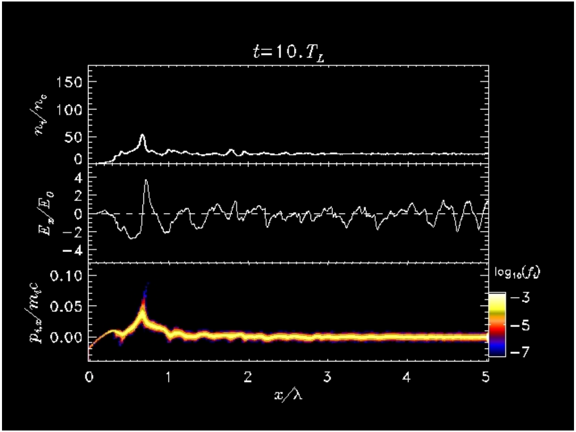

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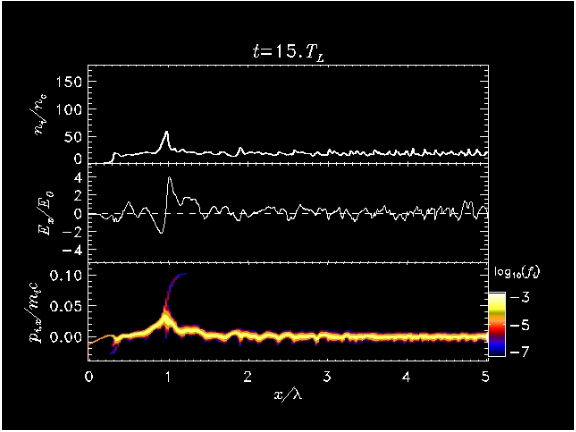

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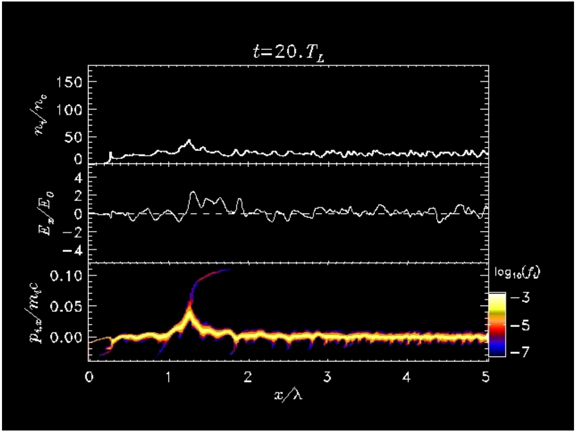

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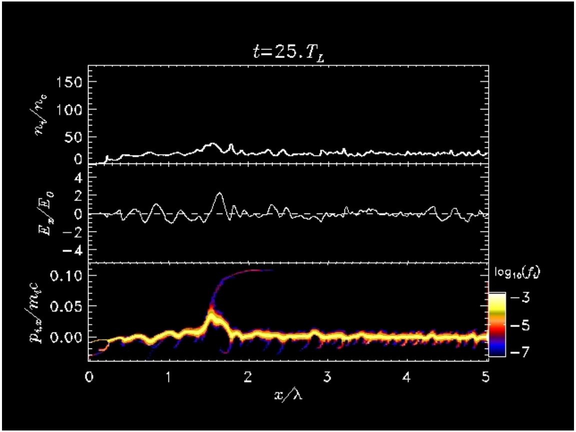

It looks like a shock which steadily reflects ions . . .

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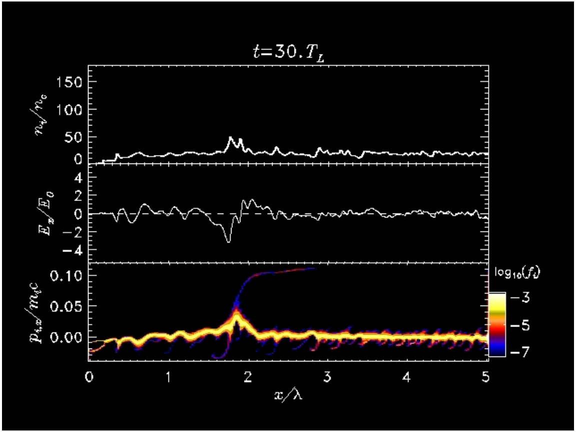

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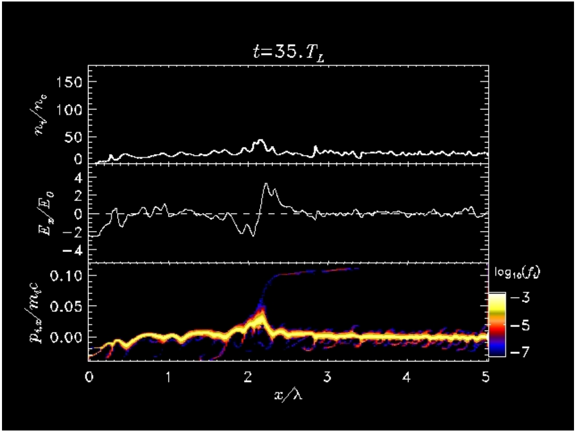

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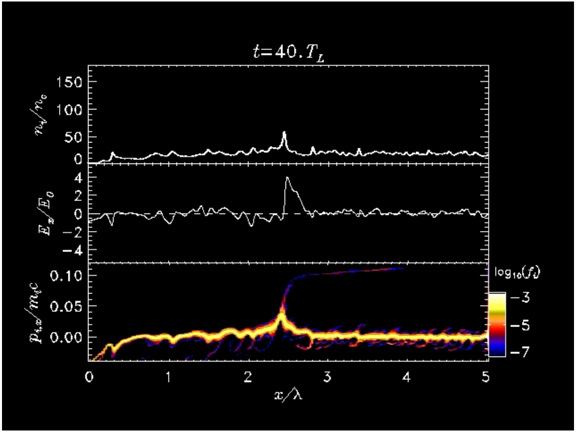

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...slowing down in time a bit and broadening the spectrum

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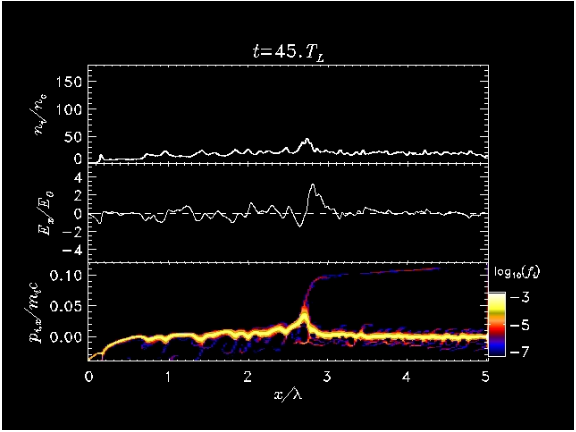

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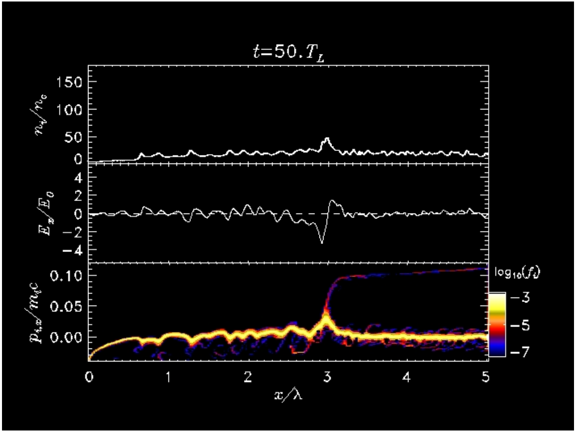

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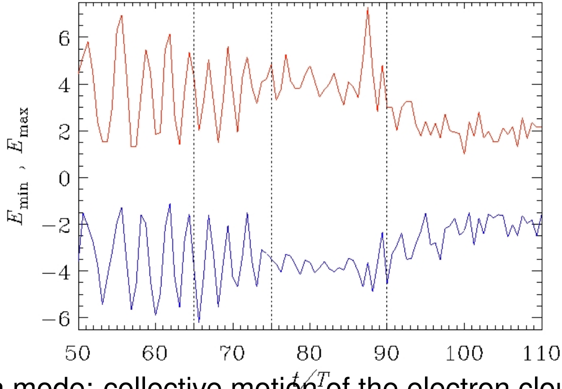
Oscillations of the solitary wave field

Red: max$(E_x) > 0$ Blue: min$(E_x) > 0$

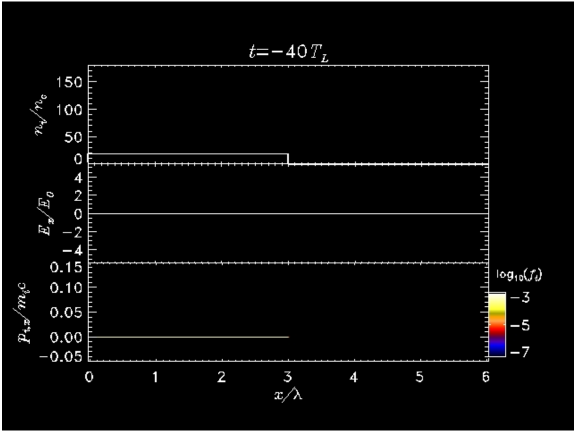


Oscillation mode: collective motion of the electron cloud across the ion density spike

Solitary wave breaking in expanding sheath

Shorter slab: solitary wave reaches rear side sheath

Solitary wave breaking in expanding sheath



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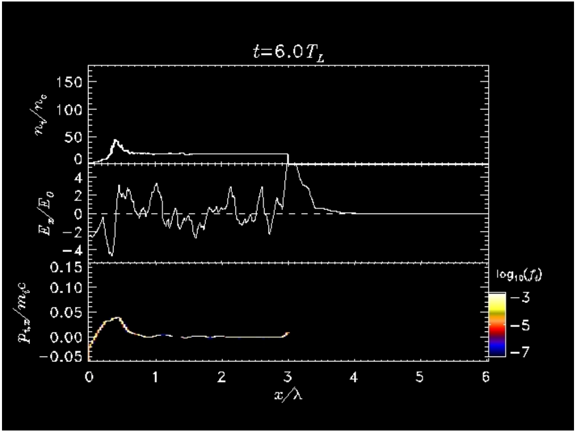

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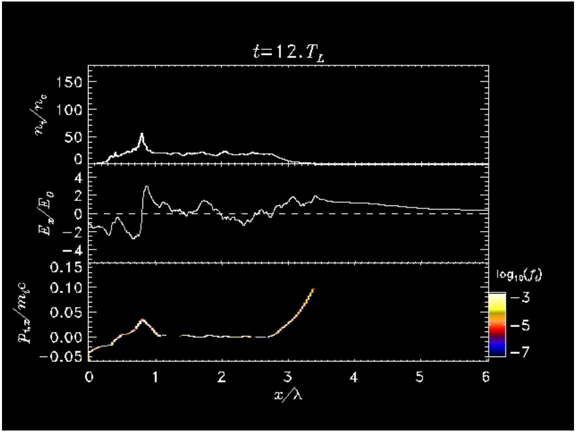

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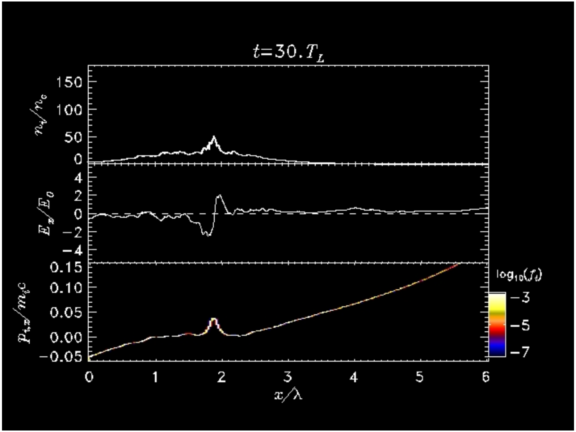

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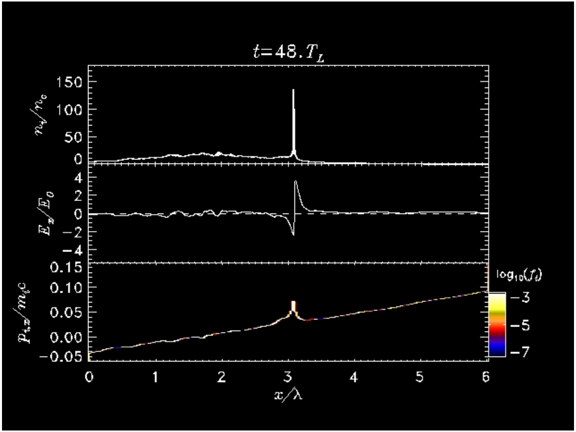

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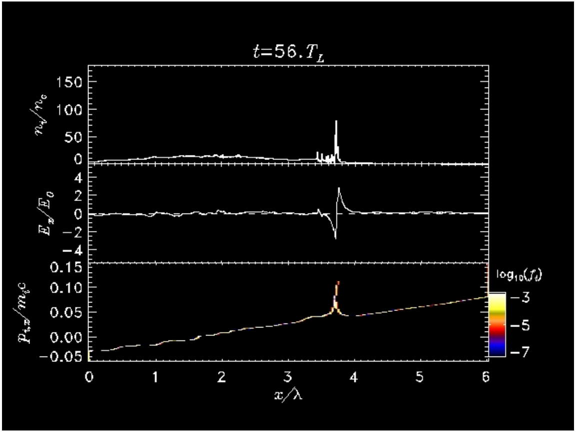

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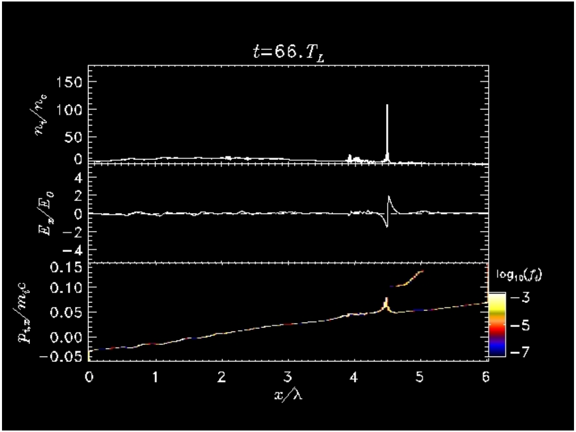

Wave breaks at “resonant” point

[see also Zhidkov et al, Phys. Rev. Lett. **89**, 215002 (2002)]

Conclusions (preliminary)

- Short-pulse, superintense laser interaction with overdense plasmas may generate collisionless shocks, solitons, or something "hybrid": a solitary wave with pulsed reflection of ions
- The initial ion distribution plays an important part
- Monoenergeticity might be at odd with efficiency: large numbers of reflected ions lead to wave loading and *slowing* down

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