Negative radiation pressure two-component field case

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Plan

1. Introduction
2. Goldstone's model
3. Conclusions

Outline

1. Introduction
   - What is the negative radiation pressure
   - Example in ϕ^4
2. Goldstone's model
3. Conclusions

Negative radiation pressure

Negative radiation pressure in *classical* field theories is a phenomenon when an object (i.e. topological defect) instead of being pushed away by radiation is being pulled toward the source of radiation.

In all cases there is some kind of mechnism which transforms part of the energy of incoming wave into another wave which carries more momentum.

Examples

- kinks in 1+1 D in ϕ^4 theory, and small modifications of ϕ^4
- oscillons (pseudobreathers) in 1+1 D, probably also in higher dimensions
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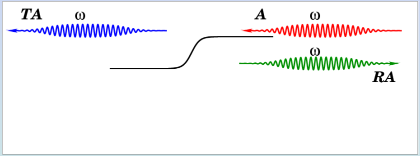
Scattering in 1+1 d:

- general scattering:
  force **pushing** the object
  $F = |R^2|A^2q^2$
- kink in ϕ^4 is transparent
- linear approximation: $F = 0$
- nonlinearity introduces waves with 2ω. They have larger momentum/energy ratio:

$$r_\omega = \sqrt{\omega^2 - 4}/\omega < r_{2\omega} = \sqrt{\omega^2 - 1}/\omega.$$

- A surplus of momentum pushes the kink **towards** the source of radiation $F \sim A^4$



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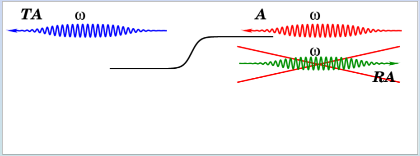

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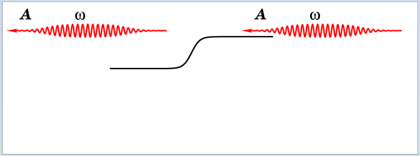

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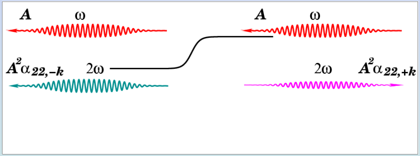

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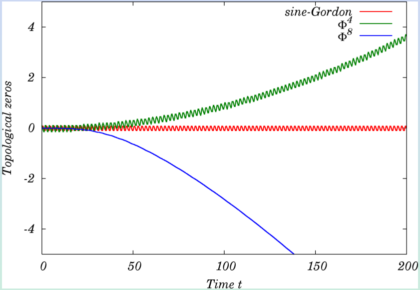

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2 Goldstone's model
- Vortex
- A toy model
- Linearization

3 Conclusions

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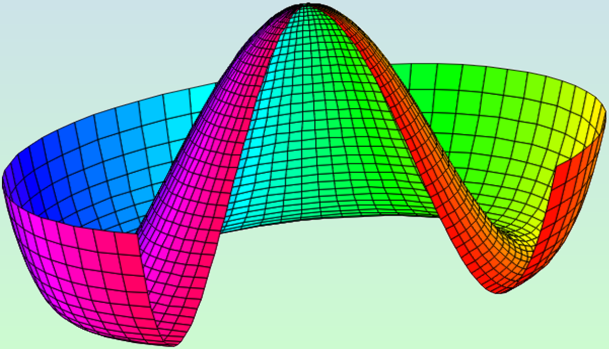
mexican hat



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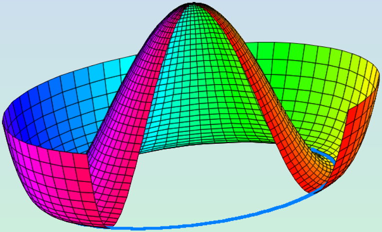

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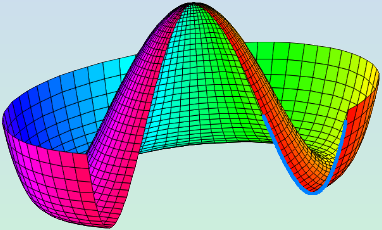

The Lagrangian leads to equation of motion

$$\ddot{\phi} - \Delta\phi + 2\phi(\phi\phi^* - 1) = 0. \tag{1}$$

As usual the static, linear (along $z-$axis) vortex solution has the form

$$\phi_s(r,\theta) = f(r)e^{iN\theta}. \tag{2}$$

This leads to an equation for profile

$$f'' + \frac{1}{r}f' - \frac{N}{r^2}f - 2f\left(f^2 - 1\right) = 0, \tag{3}$$

where $f(\infty) = 1$ (minimum of energy) and $f(0) = 0$ (smoothness of field – topological zero).

Vortices with winding number N larger than 1 are unstable so we assume $N = 1$. It is quite easy to obtain an asymptotic form of f for large values of r:

$$f(r \to \infty) = 1 - \frac{1}{4}r^{-2} - \frac{9}{32}r^{-4} - \frac{161}{128}r^{-6} - \frac{24661}{2048}r^{-8} + \mathcal{O}(r^{-10}). \tag{4}$$

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How do vortices interact with radiation?

- Goldstone's mode pushes the vortex

$$\phi(x, y = L, t) = (f(r) + iA\cos(\omega t))e^{i\theta}$$

- amplitude mode pulls the vortex (NRP)

$$\phi(x, y = L, t) = (f(r) + A\cos(\omega t))e^{i\theta}$$

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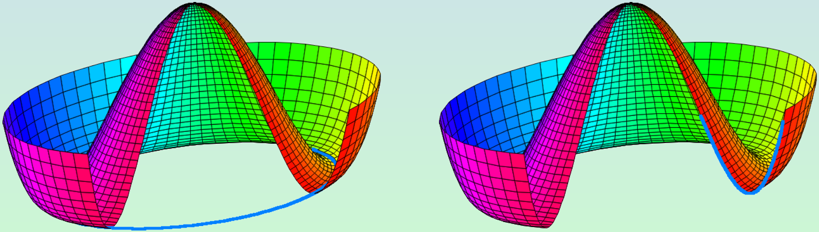

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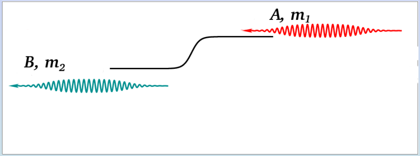

From energy conservation law we get:

$$\frac{1}{2}A^2\omega k_1 = \frac{1}{2}B^2\omega k_2 \Rightarrow B^2 = \frac{k_1}{k_2}A^2$$

where $k_i^2 = \omega^2 - m_i^2$. The force acting on the kink is equal to:

$$F = -\frac{1}{2}A^2k_1^2 + \frac{1}{2}B^2k_2^2 = \frac{1}{2}A^2k_1(k_2 - k_1).$$

If $k_2 > k_1$ (or other words: $m_2 < m_1$) the force pushes the kink against the wave and we have another example of the NRP.

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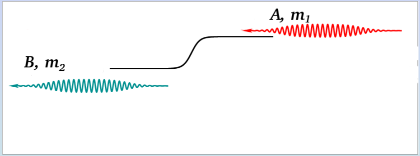

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Example 1

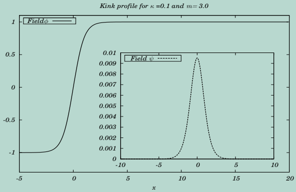
- A toy model of two interacting fields:

$$\mathcal{L} = \mathcal{L}_{\phi^4} + \frac{1}{2}\left(\psi_t^2 - \psi_x^2 - m^2\psi^2\right) + \mathcal{L}_{int}$$

where

$$\mathcal{L}_{int} = \frac{1}{2}\kappa(\phi^2 - 1)\psi.$$

$m_\phi = 2.$



Example 1 cont.

We consider scattering of the ψ over the kink.
In limit for small coupling constant κ and small amplitudes A we obtain that

$$
\begin{aligned}
R_{\psi\psi} &= 0 \\
R_{\psi\phi}(q,k) &= \frac{\pi\left(3k^2-q^2-4\right)}{4q\sqrt{(q^2+1)(q^2+4)}\,\sinh\left(\frac{q+k}{2}\pi\right)} \\
T_{\psi\phi}(q,k) &= R_{\psi\phi}(-q,k)
\end{aligned}
$$

where $k=\sqrt{\omega^2-m^2}$ and $q=\sqrt{\omega^2-4}$ are wave numbers of ψ and ϕ fields respectivily.
Note that our approximation fails when $k\approx q$ that is when $m\approx 2$.
Using Noether theorem we can calculate energy and momentum balance.
From that we can obtain the force acting on the kink.

Exaple 1 cont.

$$F = \frac{1}{2}A^2 q\left(T^2(q-k) - R^2(q+k)\right)$$

Note that when $q < k$ *i.e.* $m < 2$ the force is always negative (or at most zero) whatever the coefficients R and T are.

When $m > 2$ the direction in which the kink accelerate can be determined only after substitution the values of R and T.

The negative radiation pressure appears when

$$T^2 > \frac{q+k}{q-k}R^2.$$

This inequality can be rewritten (when $R \neq 0$) as

$$\frac{\sinh\frac{q-k}{2}\pi}{\sinh\frac{q+k}{2}\pi} > \frac{q+k}{q-k}$$

which is true for all $q > k > 0$. The force vanishes only when $R = 0$ that is when $\omega^2 = \frac{3m^2}{2}$.

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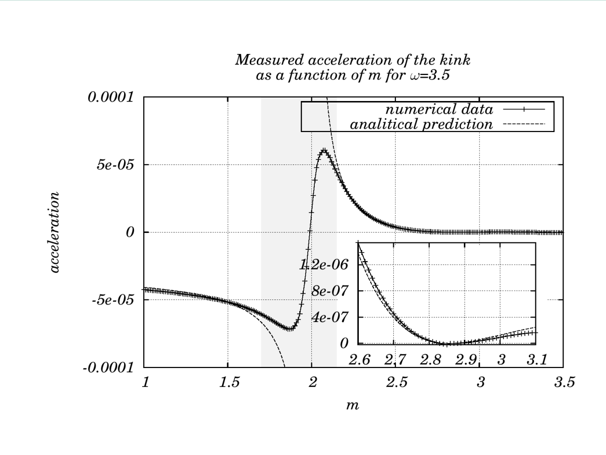

Further examples

- Vortices in Goldstone's mode:
  NRP for scattering amplitude wave
- Abelian Higgs model vortices:
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To the static vortex we add a small, cylindrically-symmetric perturbation $\phi = \phi_s + \delta\phi$. The appropriate equation has the form:

$$\delta\ddot{\phi} - \Delta\delta\phi + 2(2f^2 - 1)\delta\phi + 2f^2 \mathrm{e}^{2\mathrm{i}N\theta}\delta\phi^* = 0. \tag{5}$$

One can seek the solution of the form:

$$\delta\phi = \sum_{m=-\infty}^{\infty} \mathrm{e}^{\mathrm{i}(N+m)\theta}\left(\mathrm{e}^{\mathrm{i}\omega t} s_m^+ + \mathrm{e}^{-\mathrm{i}\omega t} s_m^-\right). \tag{6}$$

The equations for $s_m^\pm$ can be obtained by plugging (6) into (5) and changing the summing variables from m to $-m$ in some terms:

$$\begin{bmatrix} \mathbf{D}_m & 2f^2 \\ 2f^2 & \mathbf{D}_{-m} \end{bmatrix} \begin{bmatrix} s_m^+ \\ s_{-m}^{-*} \end{bmatrix} = \omega^2 \begin{bmatrix} s_m^+ \\ s_{-m}^{-*} \end{bmatrix} =: \mathbf{L} \begin{bmatrix} s_m^+ \\ s_{-m}^{-*} \end{bmatrix}, \tag{7}$$

where

$$\mathbf{D}_m := -\partial_{rr} - \frac{1}{r}\partial_r + \frac{(N+m)^2}{r^2} + 2(2f^2 - 1). \tag{8}$$

It is more convenient to introduce the following variables:

$$\begin{bmatrix} a_m \\ g_m \end{bmatrix} := \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} s_m^{+} \\ s_{-m}^{-*} \end{bmatrix}. \tag{9}$$

The equation for new functions is simply

$$\begin{bmatrix} \mathbf{D}_a & \frac{2Nm}{r^2} \\ \frac{2Nm}{r^2} & \mathbf{D}_g \end{bmatrix}\begin{bmatrix} a_m \\ g_m \end{bmatrix} = \omega^2 \begin{bmatrix} a_m \\ g_m \end{bmatrix}, \tag{10}$$

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$$\mathbf{D}_g = -\partial_{rr} - \frac{1}{r}\partial_r + \frac{N^2+m^2}{r^2} + 2(f^2-1). \tag{11b}$$

The physical interpretation is now more clear. a_m describes a field which far away from the vortex core looks like a field with mass $m_a^2 = 4$ and g_m describes a massless field (the Goldstone's mode).

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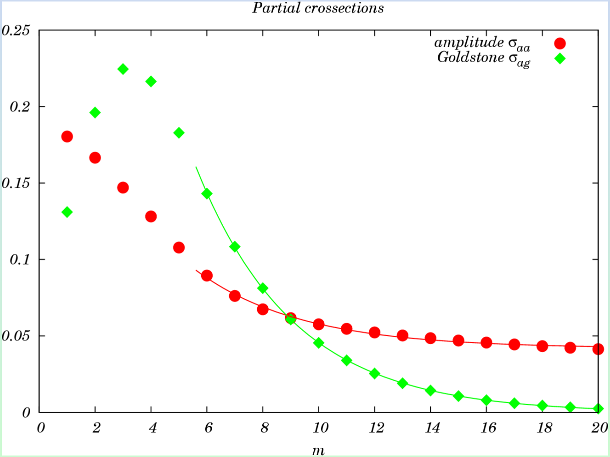
Crossections for $\omega = 3.0$ for different positive values of m together with fitted functions (for large r) of type $f(x) = A + B\mathrm{e}^{-Cm}$.



- For Goldstone's mode the values are:
  $$\begin{array}{rrcl} A_g = & -0.00028 & \pm & 0.00016 \\ B_g = & 0.7982 & \pm & 0.0059 \\ C_g = & 0.2856 & \pm & 0.0012 \end{array}$$
  A_g should be positive (all$\sigma > 0$) so $A_g = 0$ with accuracy better than 3 three digits. Exponentially decaying crossections are very common.
- For amplitude mode the values are:
  $$\begin{array}{rrcl} A_g = & 0.04187 & \pm & 0.00077 \\ B_g = & 0.226 & \pm & 0.022 \\ C_g = & 0.265 & \pm & 0.016 \end{array}$$
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$$M_R = M_0 + \pi \log R,$$

where M_0 is finite and $R \gg 1$ is a radius within which we integrate energy density.
If the vortex would accelerate with finite acceleration the total crossection should also diverge as

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$$\sigma_{aa}^2 \sim \log R \sim \log m$$

which implies

$$\sigma_{aa}(m) = \frac{A_3}{\sqrt{m}}$$

which also gives a nice fit ($A_3 = 0.1991 \pm 0.0034$).

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- We expected $\sigma_{ag} > \sigma_{aa}$ in order to explain NRP and we obtained finite σ_{ag} and infinite σ_{aa}.
- Even if the topological zero was accelerating towards the source of radiation the scattering for the whole field implies the radiation pressure is **positive**.
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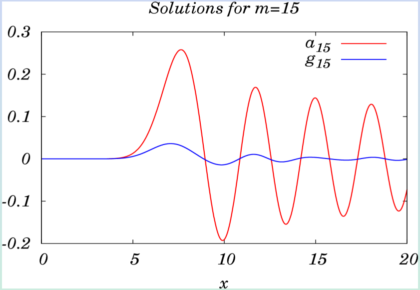
- The first zero of is always larger than $r_0 > m/k$.
- For small distances *R* from the vortex core only small values of $m \lesssim 2kR$ needs to be consider.



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Field inside a small tube can undergo a NRP, however further away from the core the positive RP emerge. This causes a **stress** between the vortex core and its asymptotic cloud.

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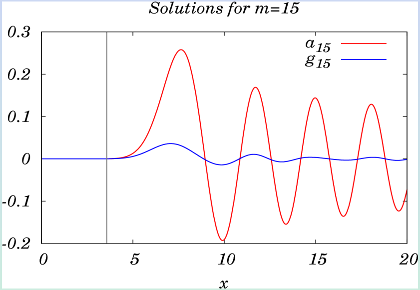

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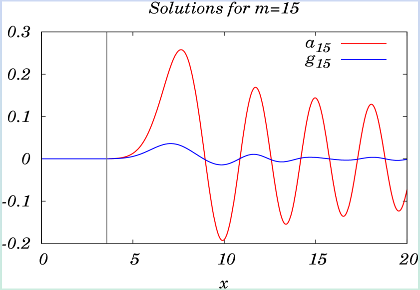

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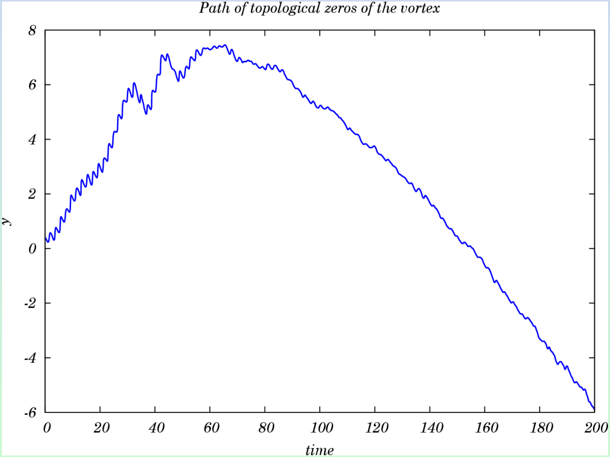
Path of the topological zero of the vortex. First the vortex is accelerating towards the radiation. Then the rest of the field drags the vortex core.



Outline

1 Introduction

2 Goldstone's model

3 Conclusions

- Due to the difference in masses between massless Goldstone's mode and massive amplitude mode **the core** of the vortex undergoes NRP when is hit with amplitude wave. $F \sim A^2$ unlike in ϕ^4 model where $F \sim A^2$.
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- a stress is created which finally drags the vortex
- Abelian Higgs model vortices are much more compact objects (often dubbed the *local* vortices). There is a true NRP (needs more calculations).

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- Acts as effective attractive interaction between a defect and perturbation or excited defects. Instead of $F \sim \mathrm{e}^{-aR}$ we have $F \sim R^{-D}$.
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