# Collision Dynamics of Boson Stars

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## Equation/Method

We present the results from a **numerical** investigation of dynamics of the **head-on** collision of the boson stars. Our basic motivation is to study the **two-body problem in GR** with a simpler form of matter fields. With the boson stars being represented by the massive complex scalar field, $\psi$, we solve the **Einstein-Klein-Gordon** (EKG) equations (in axisymmetry) to simulate the dynamics of $\psi$ and the spacetime metric.

Initial data is set up by superimposing two single boson star initial data separated along the $z$ axis. Single boson star initial data is in turn set up as a "ground" state solution assuming spherical symmetry and an ansatz, $\psi(t,r) = \phi_0(r)e^{-i\omega t}$ where $\phi_0$ and $\omega$ become the eigenfunction and eigenvalue of an eigenvalue problem that will provide initial data. Two colliding boson stars are initially boosted towards each other with the linear momentum parameter, $P_0$ so that $\psi(t,r)$ is multiplied by the factor $e^{iP_0 z}$.

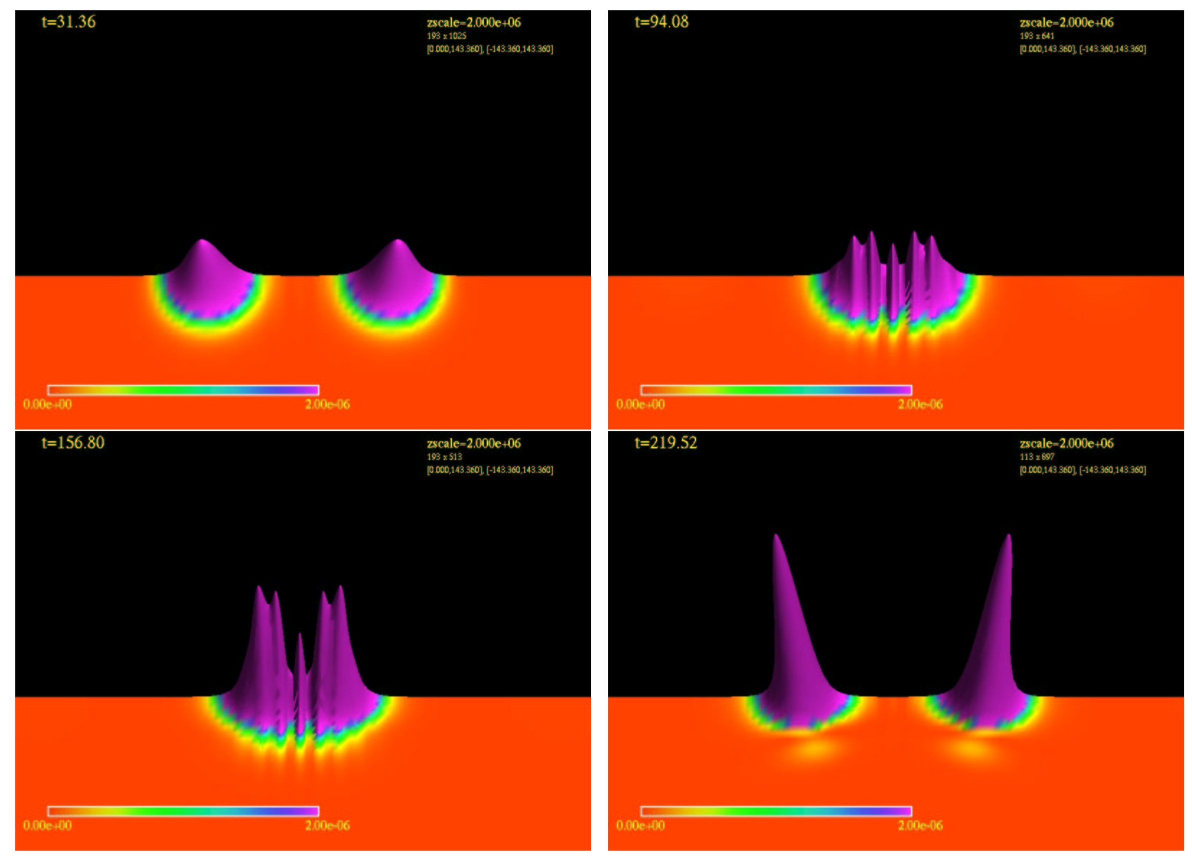
Once the initial data is set up, time evolutions of $\psi$ and all the geometric variables are computed using an Adaptive Mesh Refinement (AMR) code, `graxi_ad`. `graxi_ad` solves the Einstein(-Klein-Gordon) equations in axisymmetry and is based on Berger-and-Oliger AMR scheme.

## Results

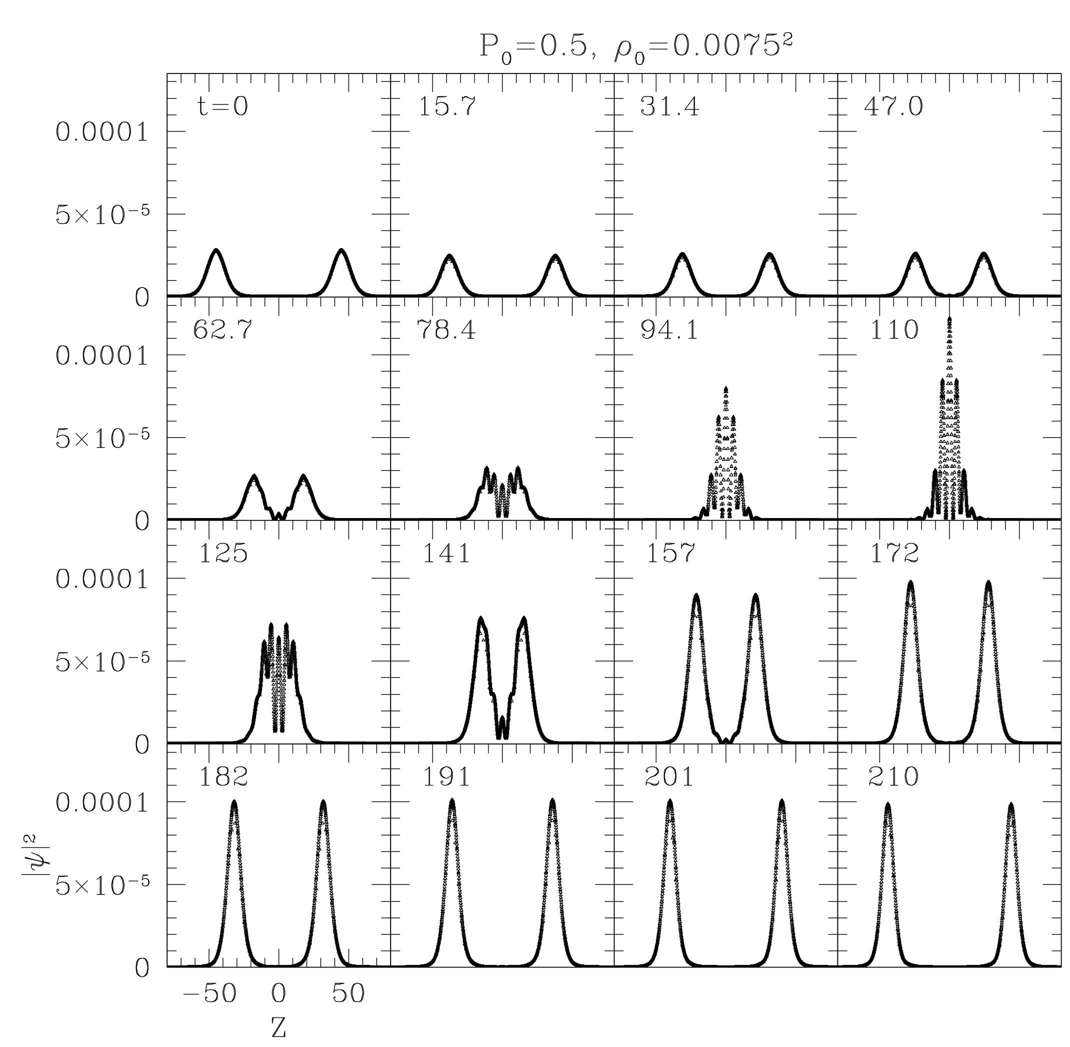
Limiting our study to the situations where gravity **is** strong but black holes do **not** form, the study of head-on collisions of the boson stars reveals two regimes with the very different dynamical properties: solitonic and merging regimes.

**Solitonic Collision**: Here, the head-on collision of two boson stars that are initially boosted towards each other does **not** result in a merger. Instead, rather remarkably, they propagate without spreading before and after the collision. The boson stars "survive" the collision and simply "pass through" each other. boson stars behave as **solitons**. This solitonic collisions also exhibit **interference** patterns on $\psi$ as well as on spacetime geometry **while** the two boson stars are interacting with each other. This interference pattern manifest an internal structure of the boson star, which is **hidden** in its isolated state, but is revealed **during** an interaction with another boson star. In the solitonic collisions, total ADM mass, $M_{adm}$, is conserved with less than 0.5% error, which implies that no gravitational energy is radiated during the solitonic collision.

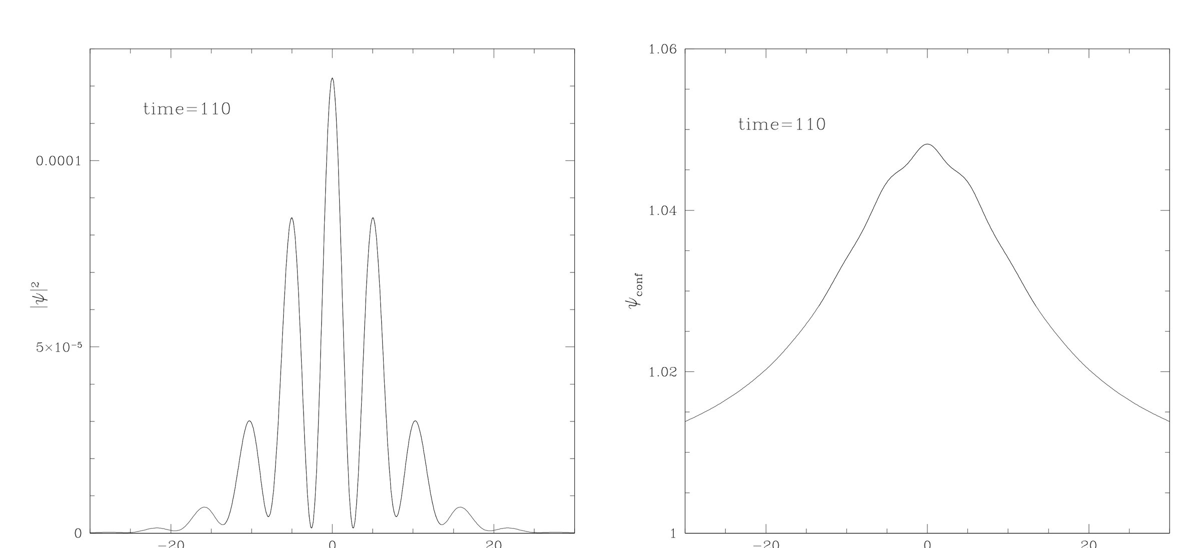
The following figures provide an example for the solitonic collision. The central density of the stars at the initial time ($t = 0$) is $\rho_0 = \phi_0^2 = 0.0075^2$ and the initial boost parameter is $P_0 = 0.5$ (speed of light corresponds to $P_0 = 1$). The 2D plots of $|\psi|^2(\rho,z)$ for 4 different times:




Time evolution of $|\psi|^2(\rho = 0,z)$ (along the axis of collision) is shown below. An interference pattern develops, around $t \sim 60 - 150$ during which two boson stars are in a temporarily merged state. After the collision, the interference pattern completely disappears.

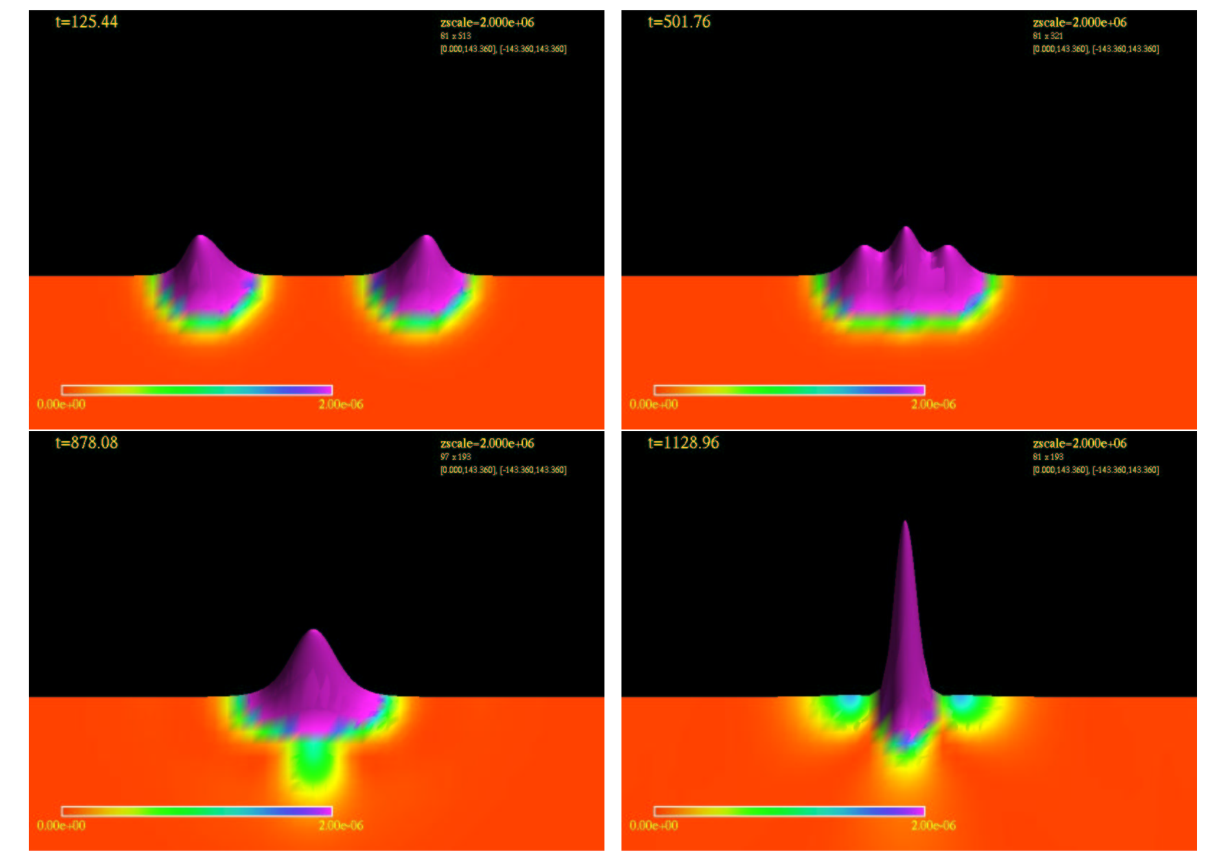



The following figures provide a close-up view of the interference. Figure in the left is $\psi(\rho = 0,z)$ at $t = 110$ and the one in the right is conformal factor of the spatial metric, $\psi_{conf}$ at $t = 110$.

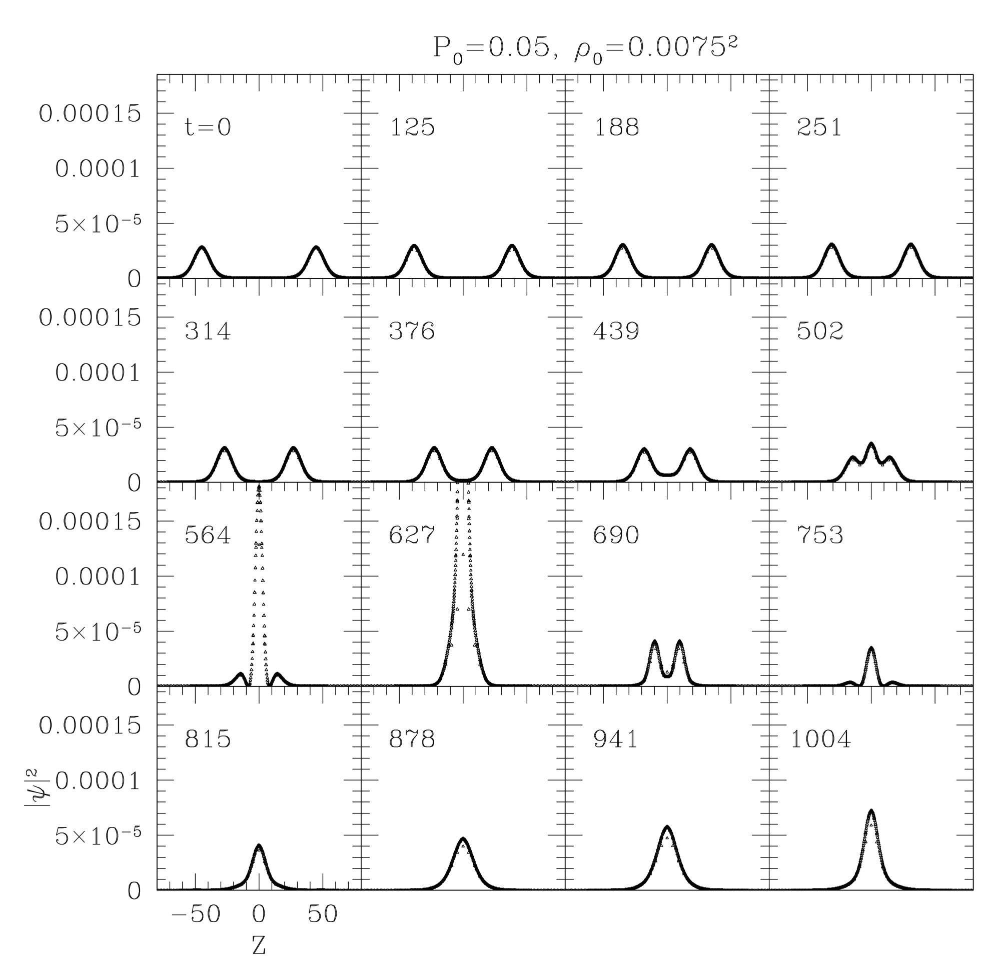


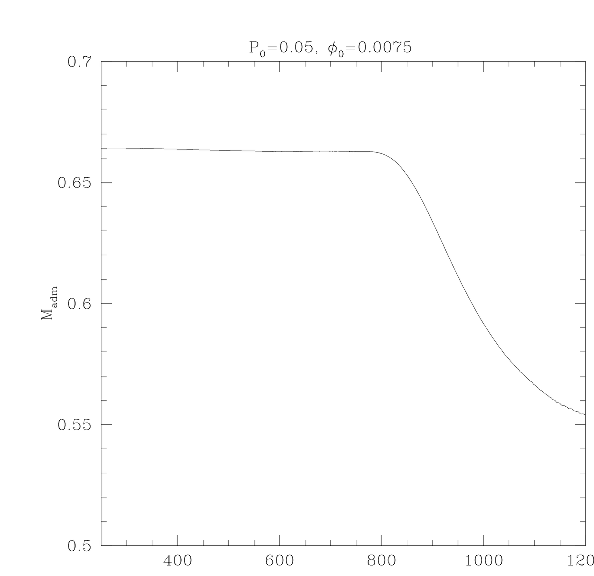

**Merging Collision**: Here, two boson stars interact with each other, but rather than showing solitonic behavior, **merge** to become a single boson star.

The following figures provide an example of the merging collision. The initial central density of the stars is $\rho_0 = \phi_0^2 = 0.0075^2$ and given the initial boost parameter, $P_0 = 0.05$, the boson stars propagate without spreading as in solitonic collisions before the collision. However, instead of showing a solitonic behavior, two starts merge into a single star after the collision ($t \geq\sim 800$). The 2D plots of $|\psi|^2(\rho,z)$ for 4 different times:




Merger process involves the gravitational energy that is radiated away during the collision. The ADM mass integral, $M_{adm}$, integrated around the central region where the merged boson star is located (see below) shows that $M_{adm}$ decreases significanly during the merger. Time evolution of $|\psi|^2(\rho = 0,z)$ along the axis of collision and $M_{adm}$ as a function of time are shown:




## Discussions

The two-regime picture presented here can be understood in terms of competition between kinetic energy and gravitational potential energy. Solitonic collision occurs when the initial boost parameter, $P_0$, (i.e. kinetic energy) is large whereas merging collision occurs when $P_0$ is small. In the solitonic collision, the kinetic energy drives the dynamics and the boson stars can escape the influence of gravity. But, with a small initial velocity as in merging collision, the kinetic energy of the stars is not large enough to overcome gravity of the merged system. Further analysis is currently underway.