On the relevance of scalar fields in the new LIGO era

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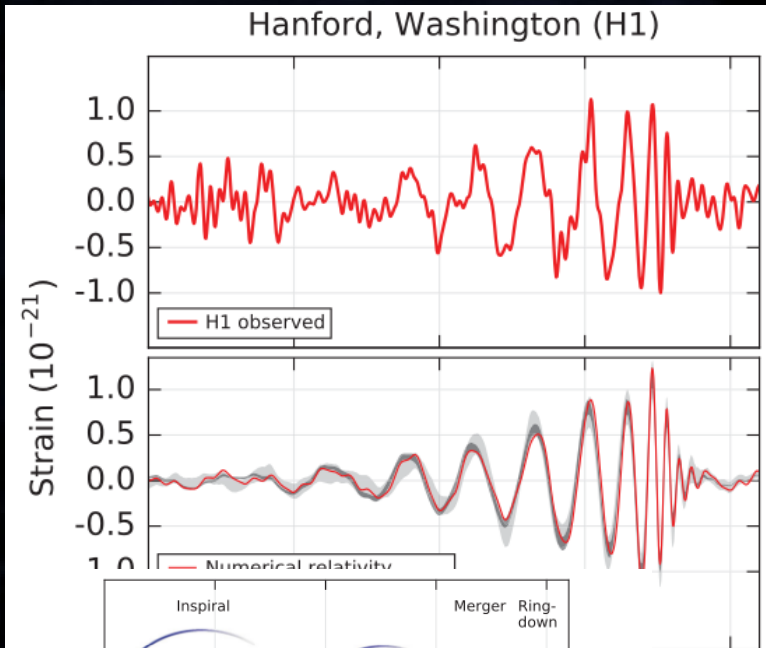
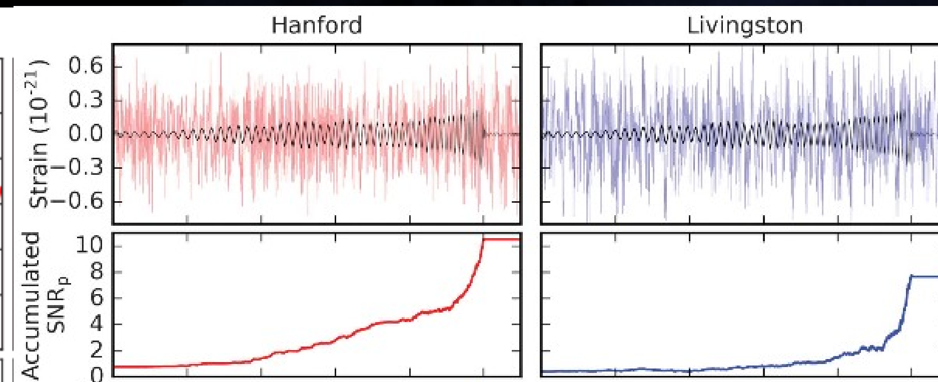
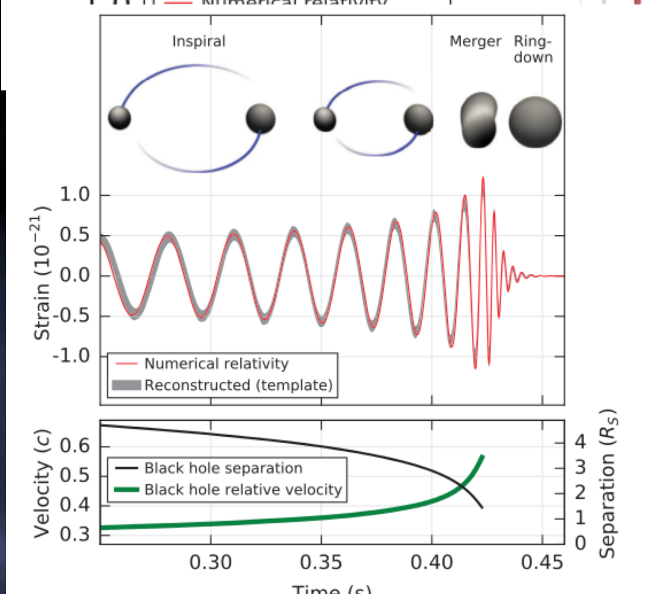
First direct GW detections in 2015







GW150914 & GW151226

Consistent with the merger of two BHs

$M = 65\ M_\odot$ ($M_1 = 36\ M_\odot$, $M_2 = 29\ M_\odot$)

$M = 22\ M_\odot$ ($M_1 = 14.2\ M_\odot$, $M_2 = 7.5\ M_\odot$)

What can we learn from these GWs?

- If you (only) believe gravity is described by GR → Astrophysics
  - populations, formation channels,...
  - existence of Exotic Compact Objects (ECOs)

COMPACT BOSE-EINSTEIN CONDENSATE

NEUTRON STAR WITH DARK MATTER

- If you (only) believe it was a binary BH merger → Gravity
  the dynamical strong-field regime might put constraints
  on alternative theories of gravity [Yunes++2016,Abbot++2016]

BINARY BLACK HOLES IN EINSTEIN-MAXWELL-DILATON

Compact Bose-Einstein condensate
(or compact boson stars)

BHs vs Exotic Compact Objects (ECOs)

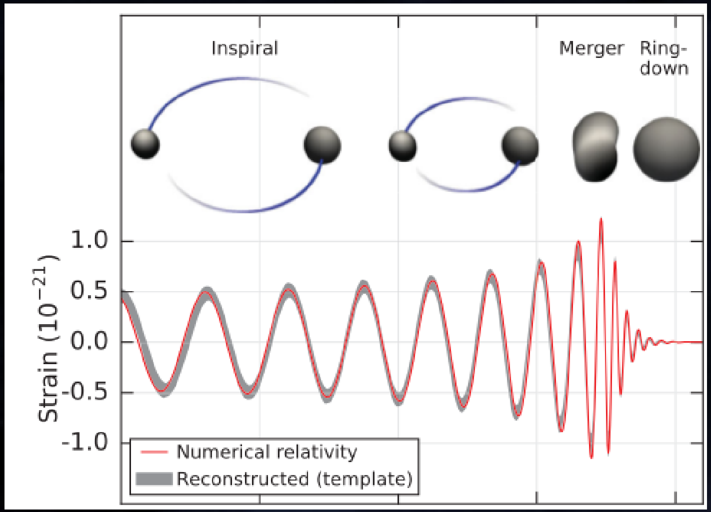
- GW150914 is consistent with the merger of a binary black hole system… but is this the only possibility?

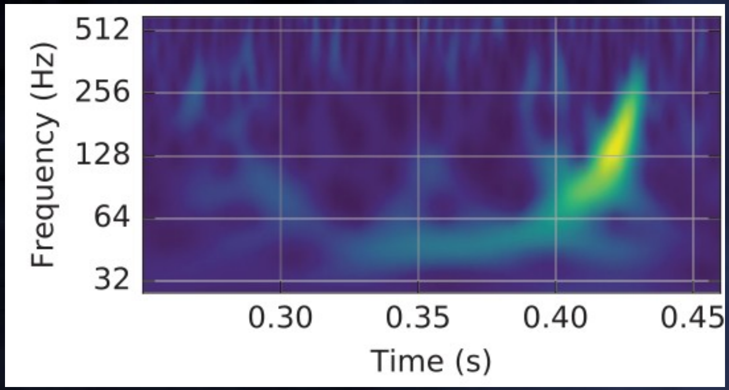
- Merger of Exotic Compact Objects?
  ECOs can be characterized by their interaction forces, the presence of a well defined surface and their compactness C=M/R

ECOS	Only gravity forces	Matter interaction
“Hard” surface	Dark stars (fermion, boson, N-body)	Solitonic BS C<0.3 Gravastars C<0.5
“Soft” surface	BHs C=0.5	Boson Stars C<0.1

Why ECOS? GW150914

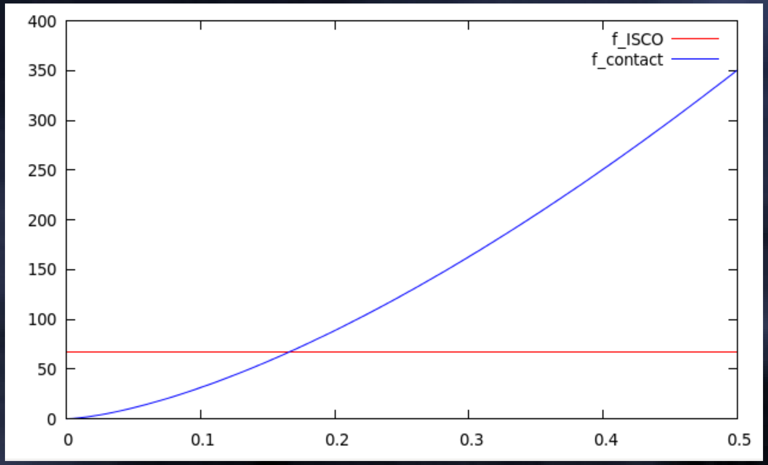
- Explain the frequency increase at f ≈ 64 Hz (plunge)





- Innermost Stable Circular Orbit (ISCO) of BH

$$f_{ISCO} = 1/(6^{3/2}\,\pi M) \sim 67 \text{ Hz}$$



- Contact frequency of stars (i.e, a=2R)

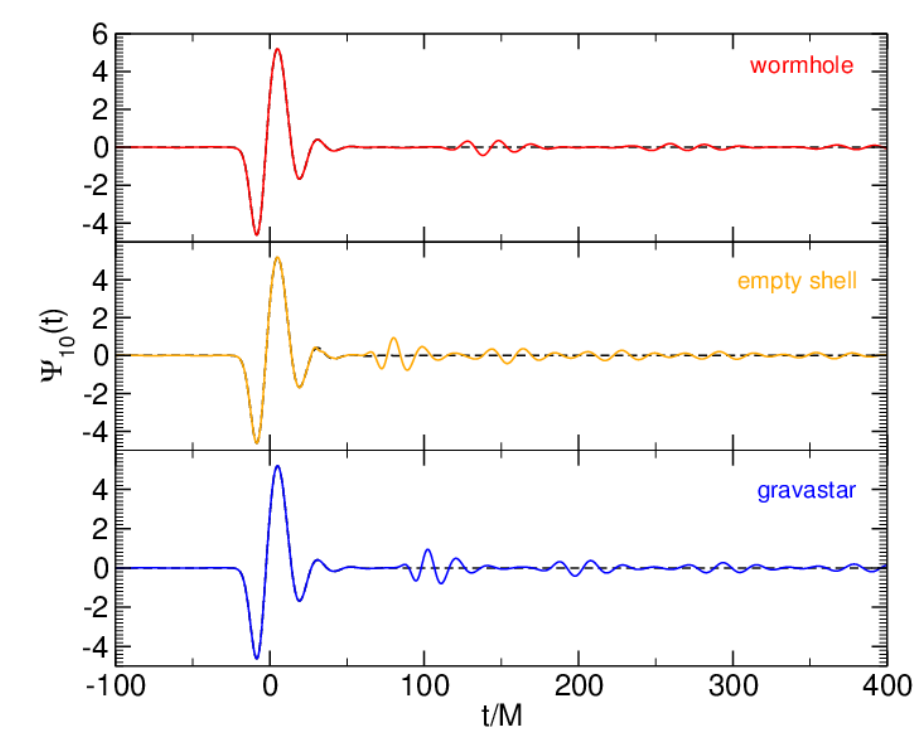
$$f_c \approx C^{3/2}/(\pi M)$$

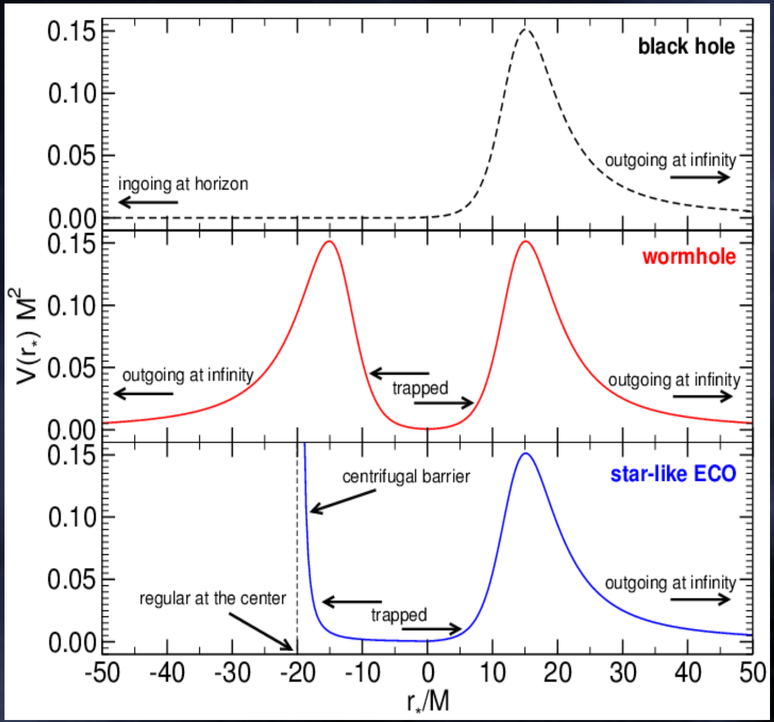
C=M/R

Echos of ECOS

•Explain the ring-down : the behavior of scattered wave packets is similar in BHs and very compact objects without an horizon [Cardoso,Pani++ 2015]

$$\left[-\frac{\partial^2}{\partial t^2}+\frac{\partial^2}{\partial r_*^2}-V_l(r)\right]\Psi_{lm}(t,r)=0$$





Boson Stars as ECOs

• Boson stars (BS) are compact solutions made of a complex scalar field Φ, modeled by the Einstein-Klein-Gordon equations

$$R_{ab} = 8\pi\,(T_{ab} - T\,g_{ab}/2)$$

$$T_{ab} = \nabla_a\Phi^*\nabla_b\Phi + \nabla_a\Phi\nabla_b\Phi^* - g_{ab}\,[\nabla_c\Phi^*\nabla^c\Phi + V(\Phi^2)]$$

$$g^{ab}\nabla_a\nabla_b\Phi = (dV/d\Phi^2)\;\Phi$$

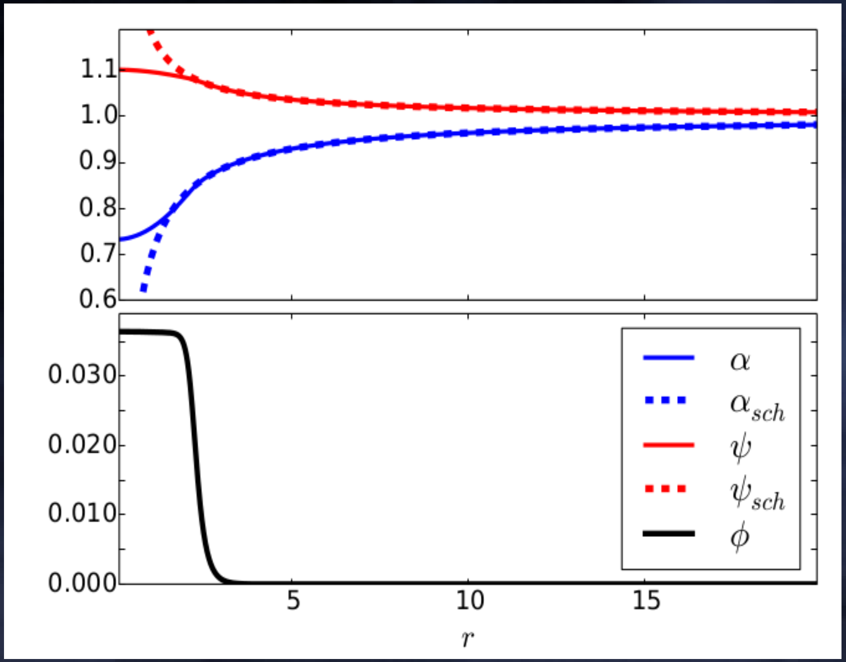
- Harmonic ansatz $\{\Phi_0(r), \omega\}$

$$\Phi = \Phi_0(r)\exp(i\,\omega\,t)$$

•

- Self-interacting potential

$$V(\varphi^2) = \mu^2\Phi^2(1 - 2\Phi^2/\sigma^2)^2$$



Solitonic non-topological BS

(C_{max}=M/R ~ 1/3)

Binary solitonic BS

• ECOS (BSs) can be BH mimickers in the linear regime, but what happens in the non-linear regime? perform simulations of binary solitonic BSs to study their general dynamics, the remnant after the merger and the GW emission → implication for LIGO

• Previous works considered less compact massive BSs → longer dynamical timescales, difficult to analyze [CP,Lehner++2005,2006]

• What is the final fate of binary BS merger?

BH - BS - dispersion

- $C \geq 1/2\, C_{max}$ the remnant collapses to a BH [Cardoso,Pani,CP+2016]
- $C \leq 1/3\, C_{max}$ the remnant losses angular momentum and decays to a non-rotating BS [Bezares, CP++ 2017]

Binary solitonic BS

- Consider three scenarios

1- head-on collisions of low compactness non-identical BSs
→ large variety of different behaviors

2- orbital binaries of low compactness identical BSs varying J_z
→ final fate of boson stars with angular momentum

3- orbital binaries at fixed J_z (QCO) varying compactness C
→ GWs as a function of compactness

Head-on collisions of compact BS

- Consider two non-identical boson stars, taking advantage that the solutions are invariant to a phase shift θ and sign of ω

$$\phi_0(r) = \phi_0^{(1)}(r_1) e^{-i\omega t} + \phi_0^{(2)}(r_2) e^{-i(\epsilon\omega t + \theta)}$$

$$\alpha(r) = \alpha^{(1)}(r_1) + \alpha^{(2)}(r_2) - 1$$

$$\psi(r) = \psi^{(1)}(r_1) + \psi^{(2)}(r_2) - 1$$

- 4 boson-boson cases with θ = {0, π/2, π, 3π/2}

- 2 boson-antiboson cases (ε=-1) with θ = {0, π}

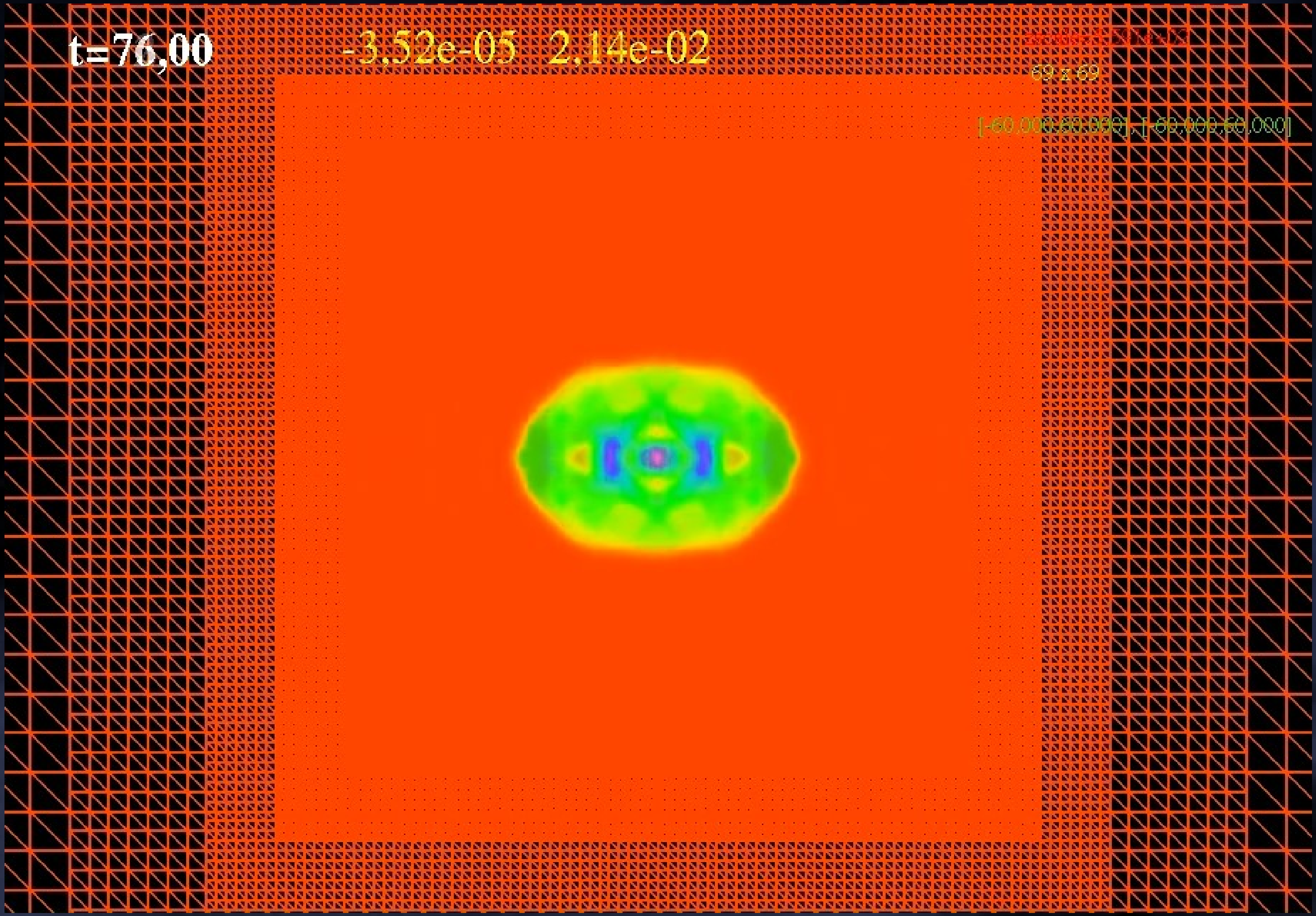
Noether charge (boson number)

$$N \equiv \int_{\Sigma_t} (-n_a J^a) \sqrt{\gamma}\, d^3x,$$

$$J^a = i g^{ab} (\phi^* \nabla_b \phi - \phi \nabla_b \phi^*)$$

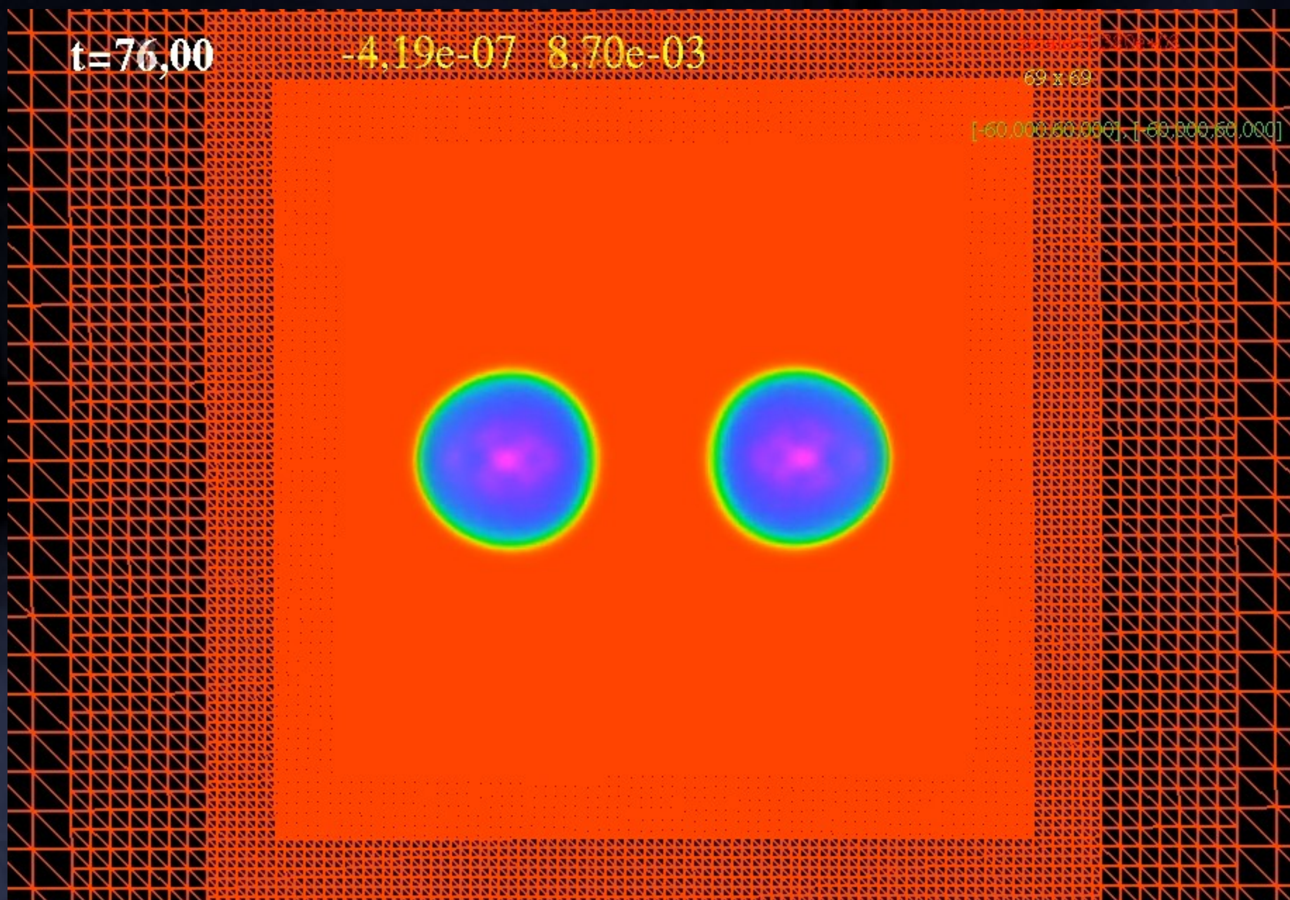
Head-on collisions of compact BS

- Boson-Boson pair with $\theta = 0$



Head-on collisions of compact BS

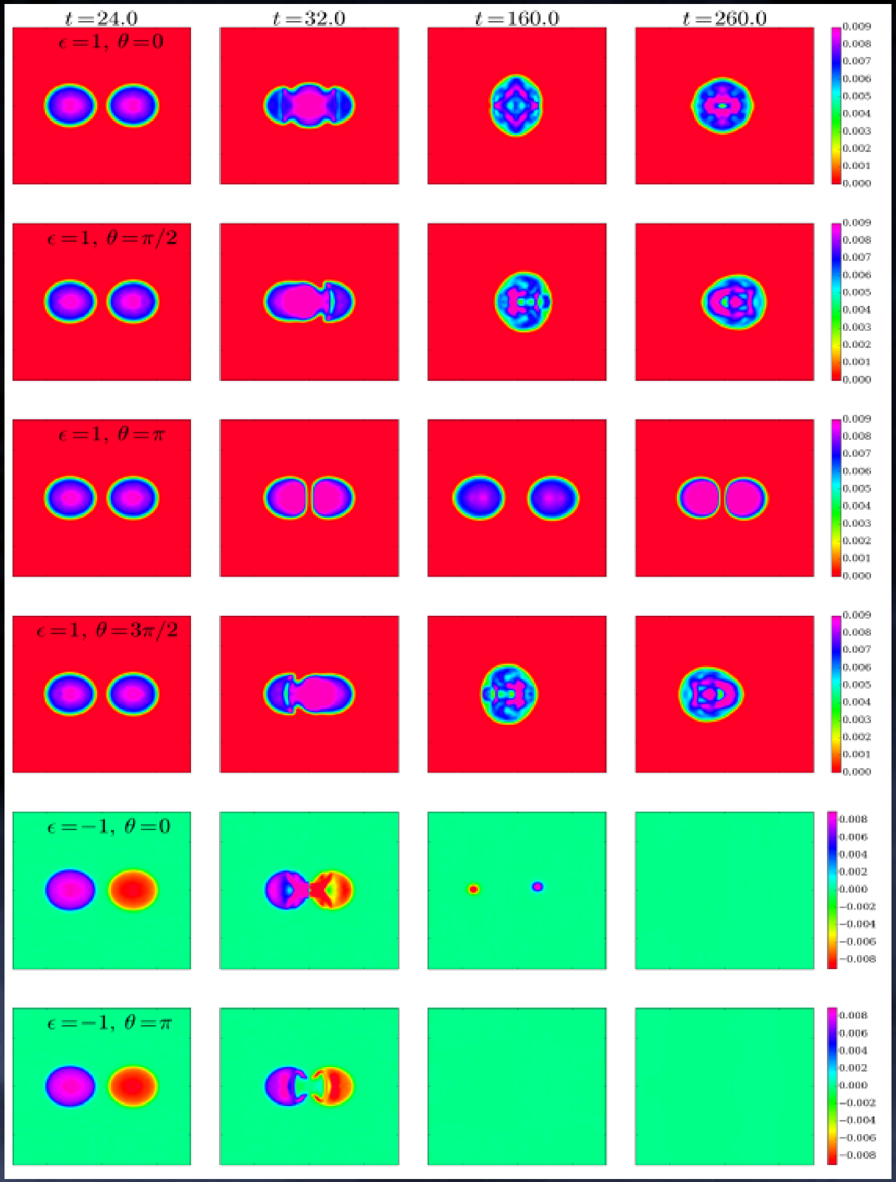
- Boson-Boson pair with $\theta = \pi$



Head-on collisions of compact BS

- Boson-AntiBoson pair with θ = 0

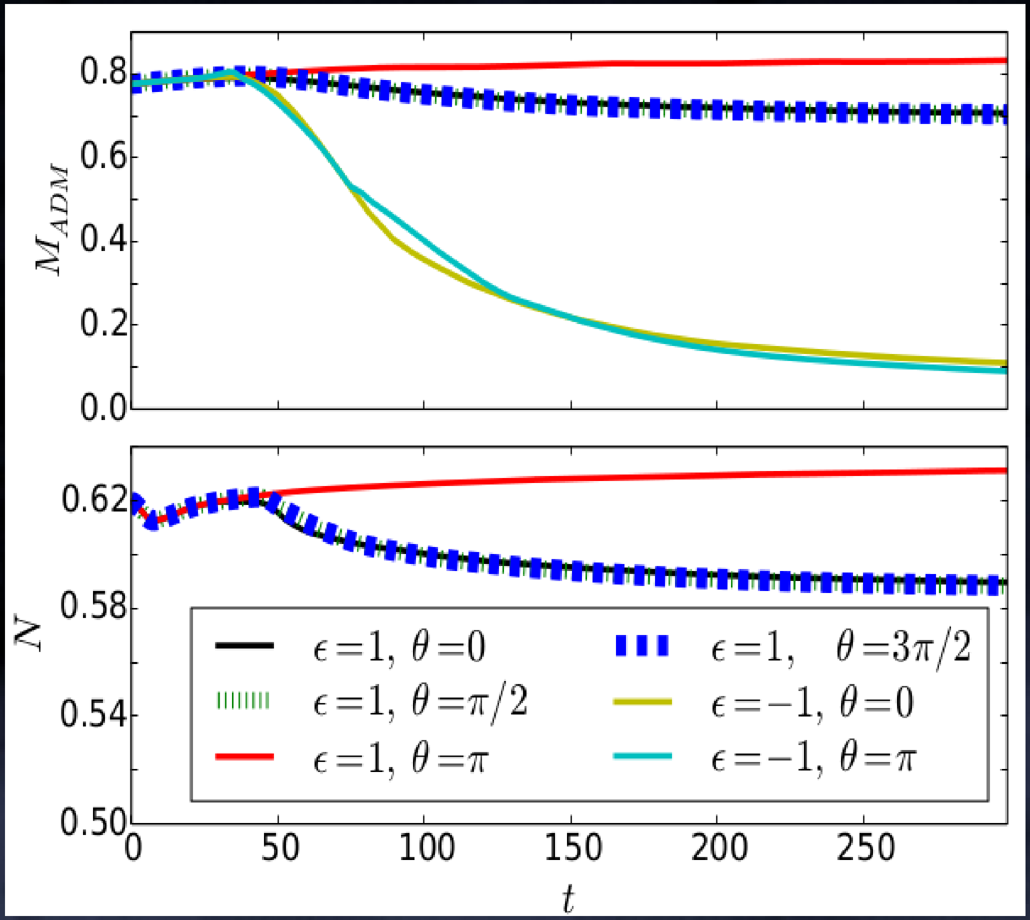
Head-on collisions of compact BS



- Boson-Boson pair mergers into a single boson star for all the phase shifts except $\theta = \pi$, where the two stars suffer inelastic collisions

- Boson-antiBoson pair merges and annihilates, radiating away all the scalar field

Head-on collisions of compact BS



- Boson-Boson pair total mass and Noether charge barely changes during the merger
- Boson-AntiBoson pair total mass decreases as the scalar field is radiated away from the domain

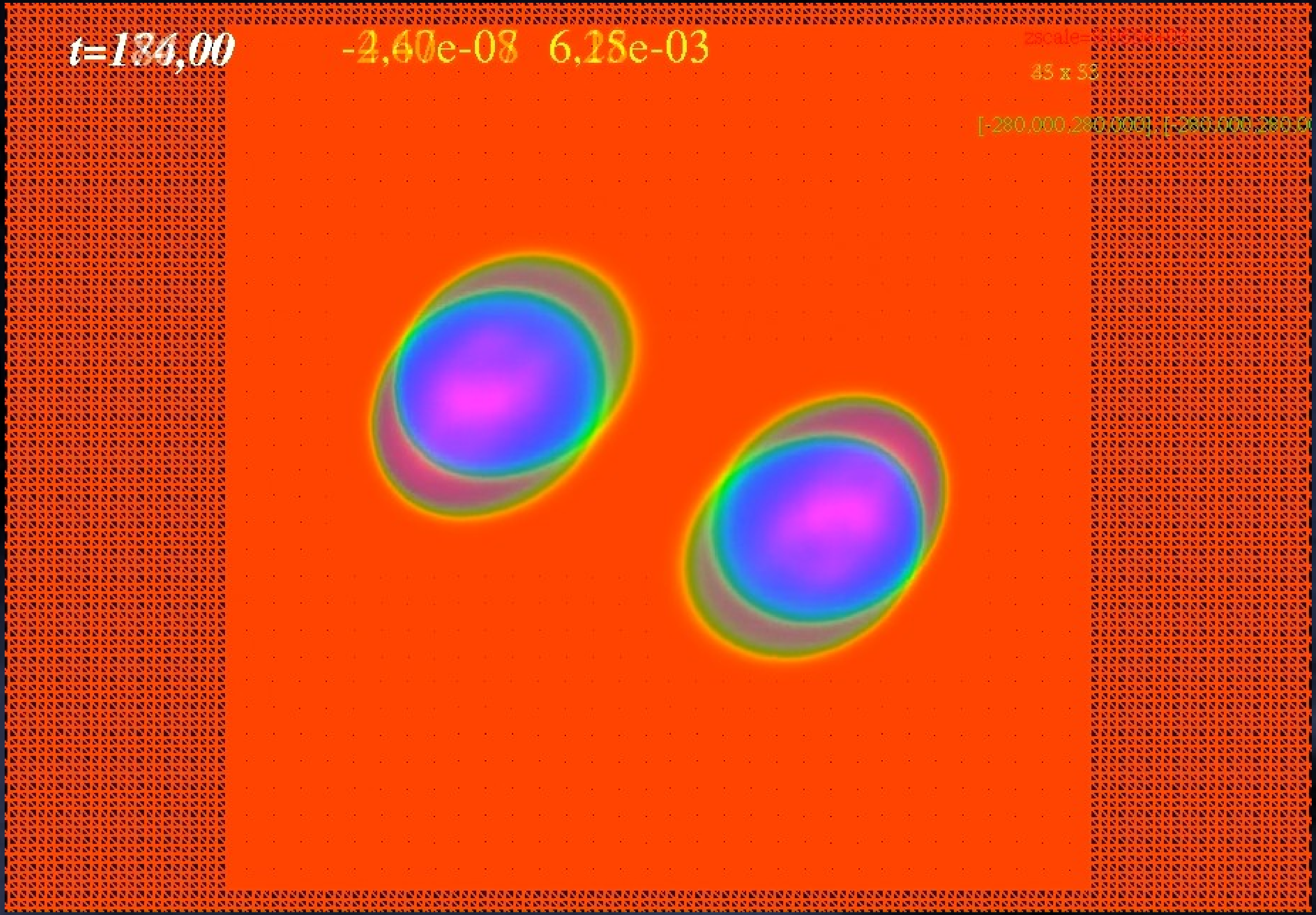
Orbital collisions of compact BS varying Jz

- Consider identical boson stars with an initial boost velocity v_x in the axial direction

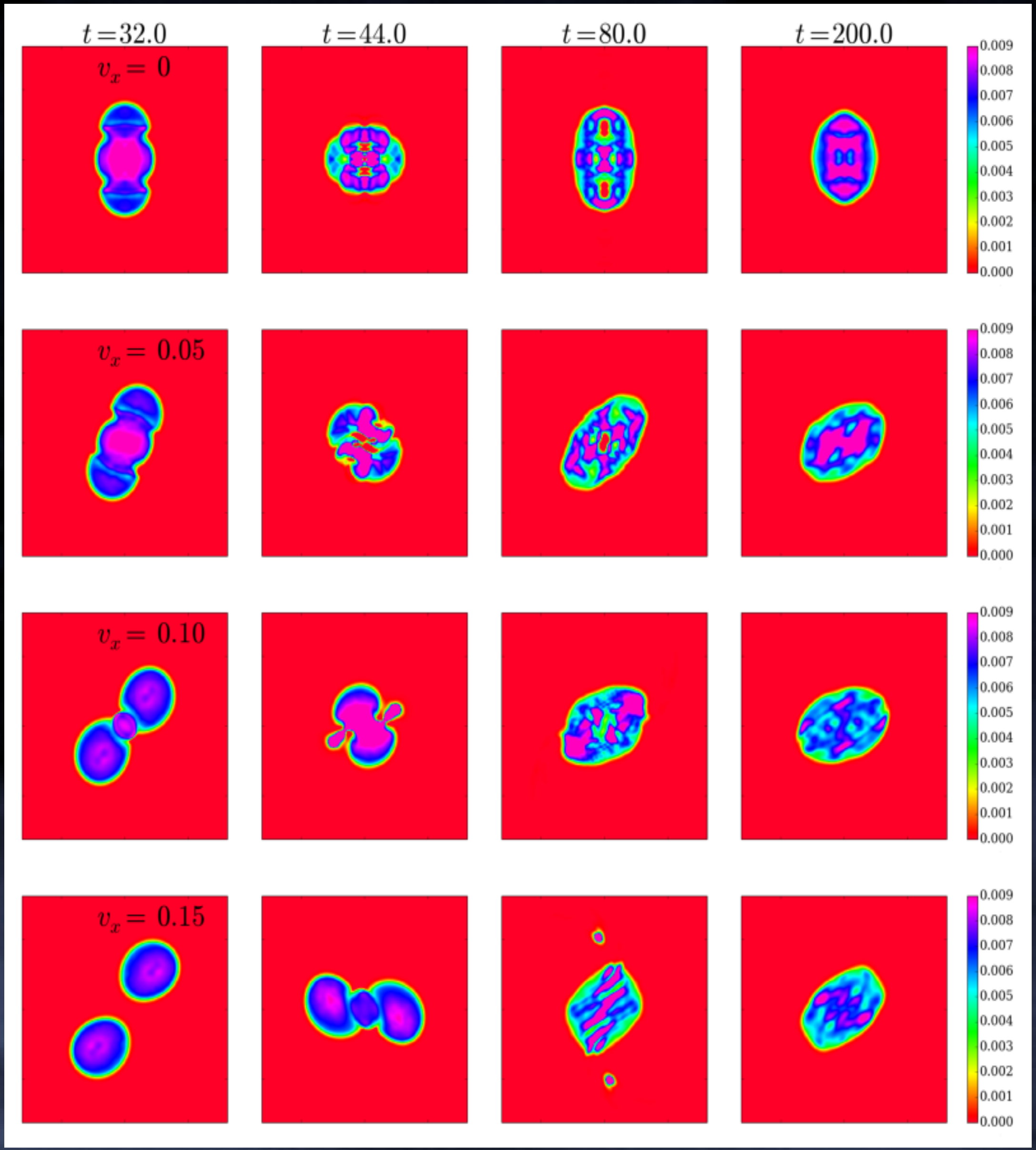
- 4 boson-boson cases with $v_x = \{0, 0.05, 0.1, 0.15\}$

Orbital collisions of compact B-B pairs

- Boson-Boson pair with $v_x = 0.15$ (QCO)



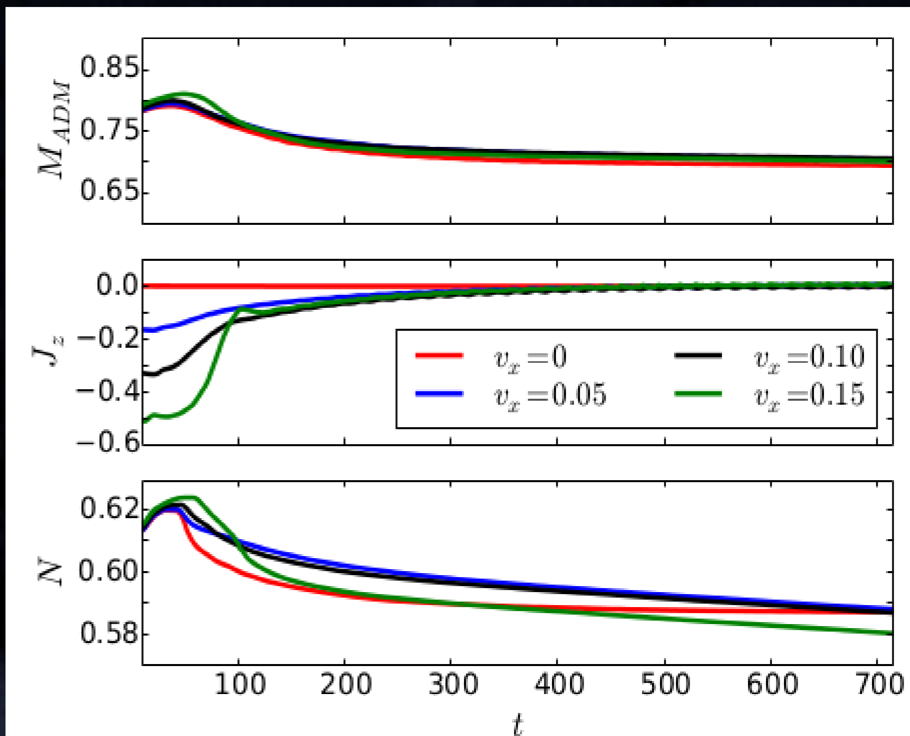
Orbital collisions of compact BS



- Binary BS merges into a rotating bar that relaxes to a BS

  - two blobs of scalar field are ejected at light speed for the case with highest angular momentum

Orbital collisions of compact B-B pairs



- Mass and Noether charge are roughly the initial ones, but all the angular momentum $J_z/M^2 = 0.78$ is radiated after the merger

  - the merger of two boson stars produce a non-rotating BS

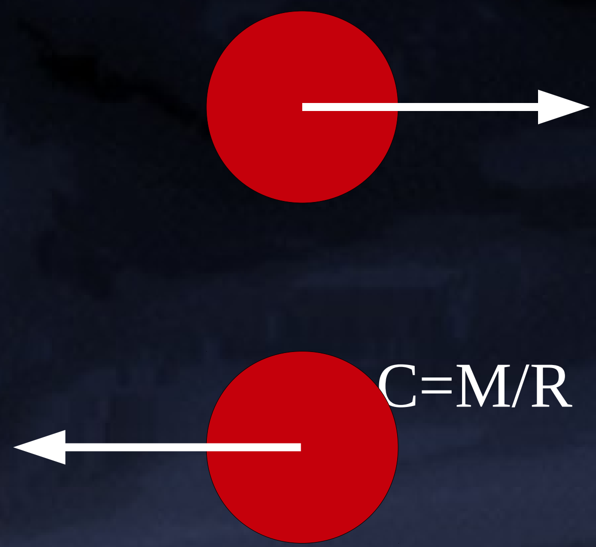
Rotating BS has a quantized angular momentum

$$\phi(\mathbf{r}, t) = \phi_0(r, \theta) e^{i(\omega t + k\varphi)}$$

J_z=k N={0, 0.62, 1.24, ... }

Orbital collisions of BS in QCO varying compactness

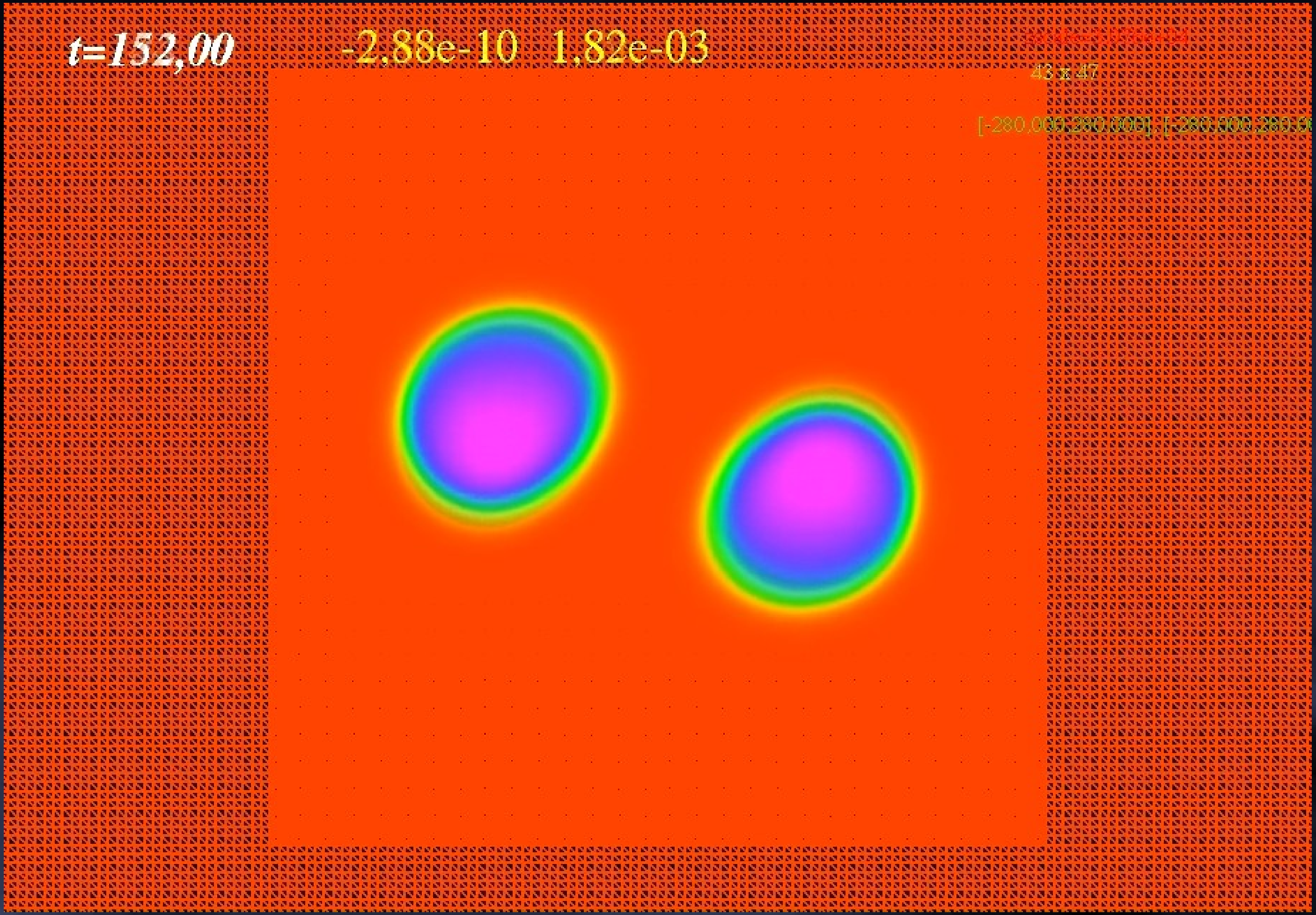
- Consider identical boson stars with an initial boost velocity v_x in the axial direction such that the orbits are quasi-circular



- 4 boson-boson compactness C= {0.06, 0.12, 0.18, 0.22}

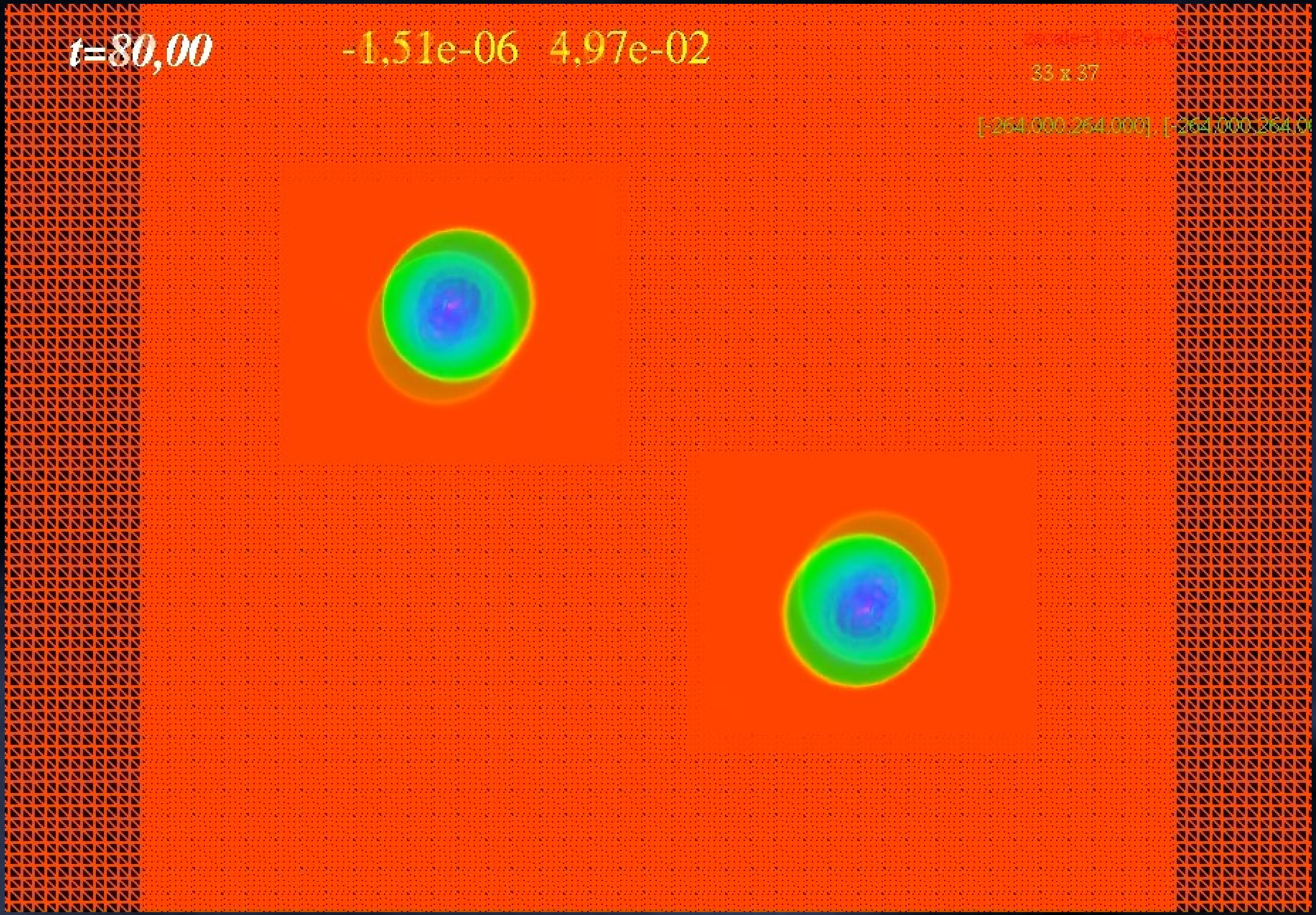
Orbital collisions of Bss in QCO

- Boson-Boson pair with C = 0.06

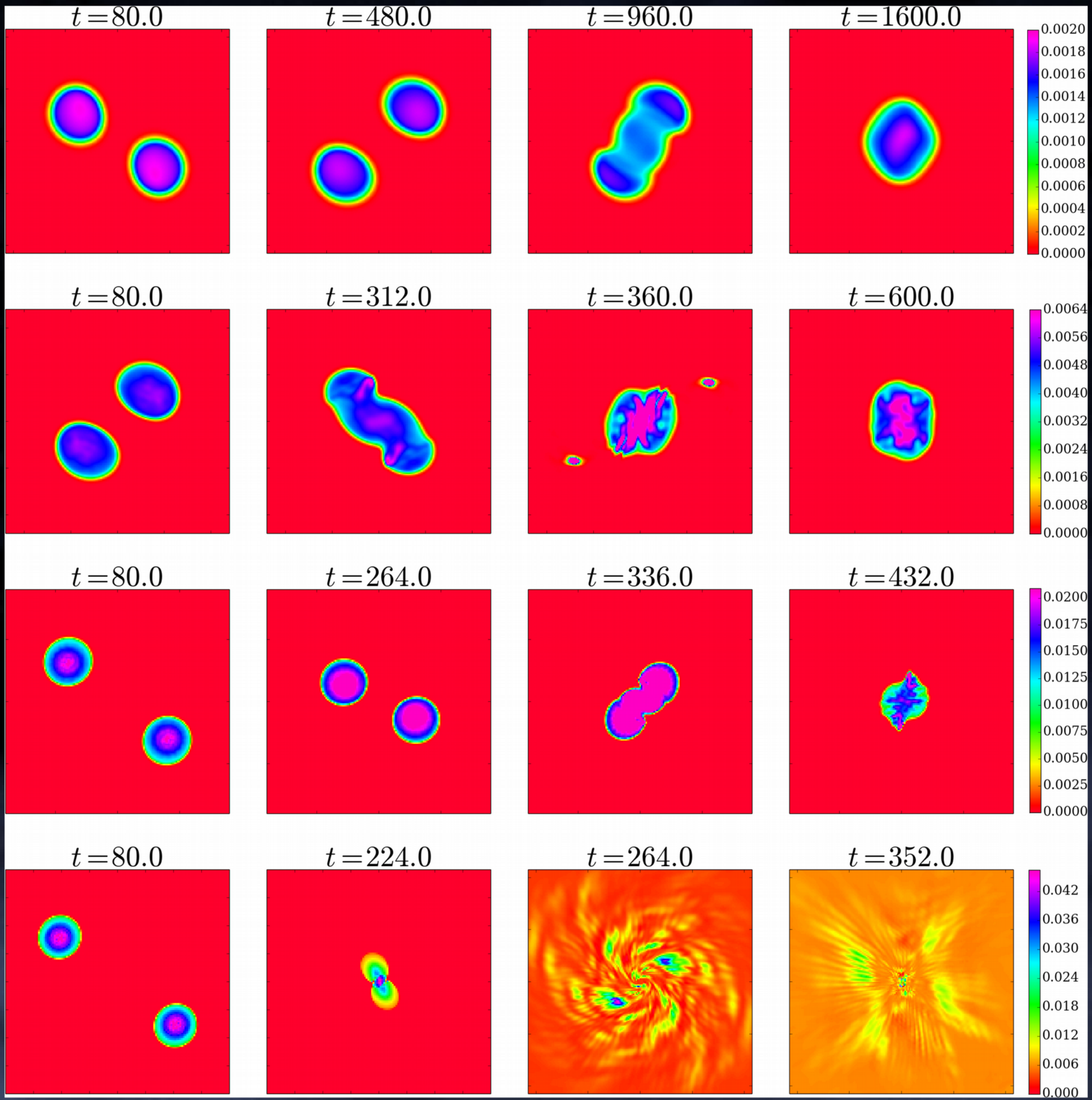


Orbital collisions of Bss in QCO

- Boson-Boson pair with C = 0.22

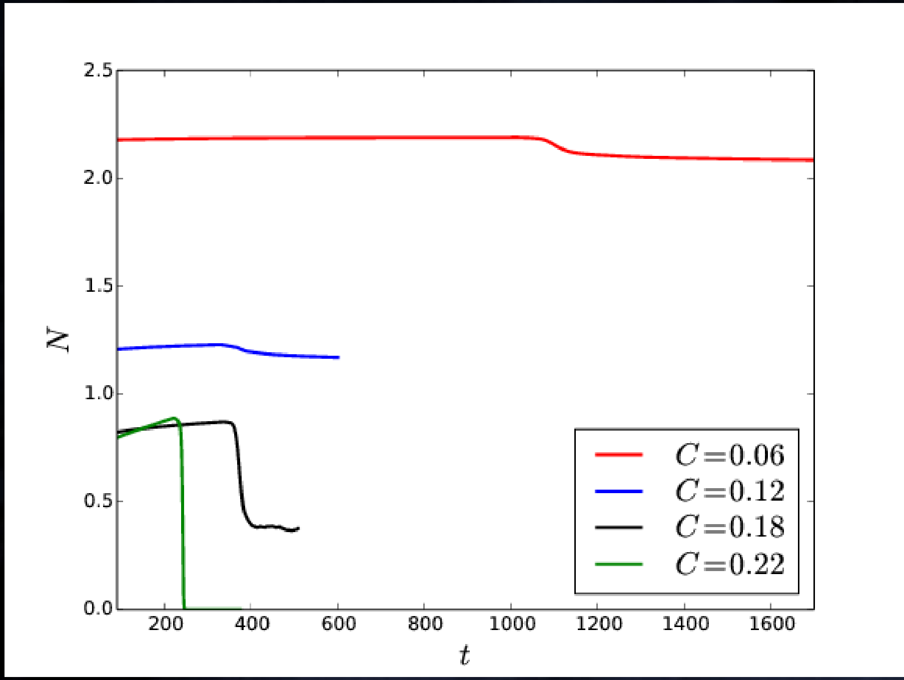


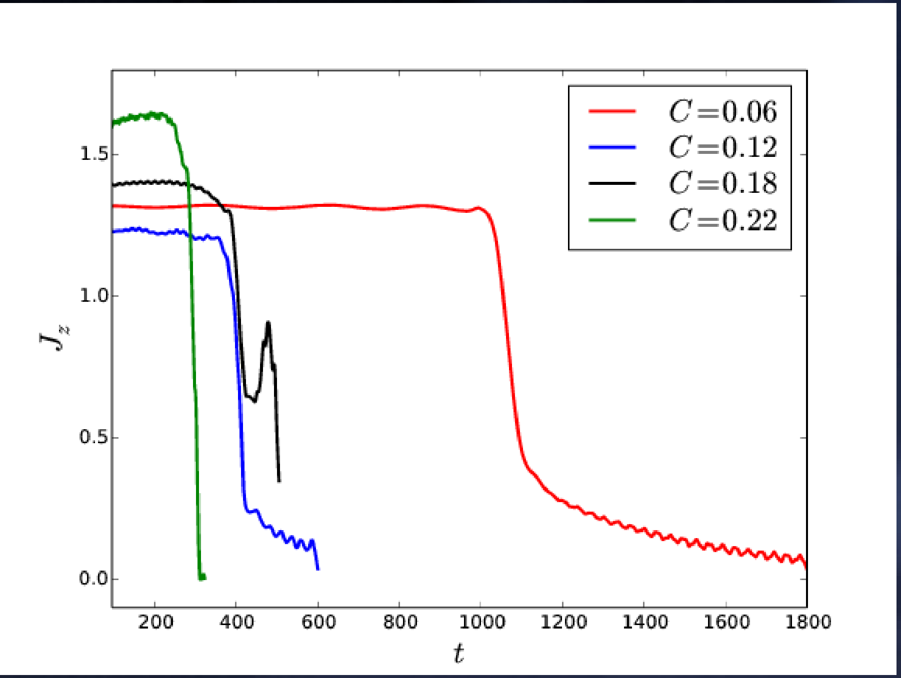
Orbital collisions of BS in QCO



- Binary BS merges into a rotating bar that relaxes to a BS for low-medium compactness (C≤0.18) but collapses to black hole for high compactness (C≥0.22)

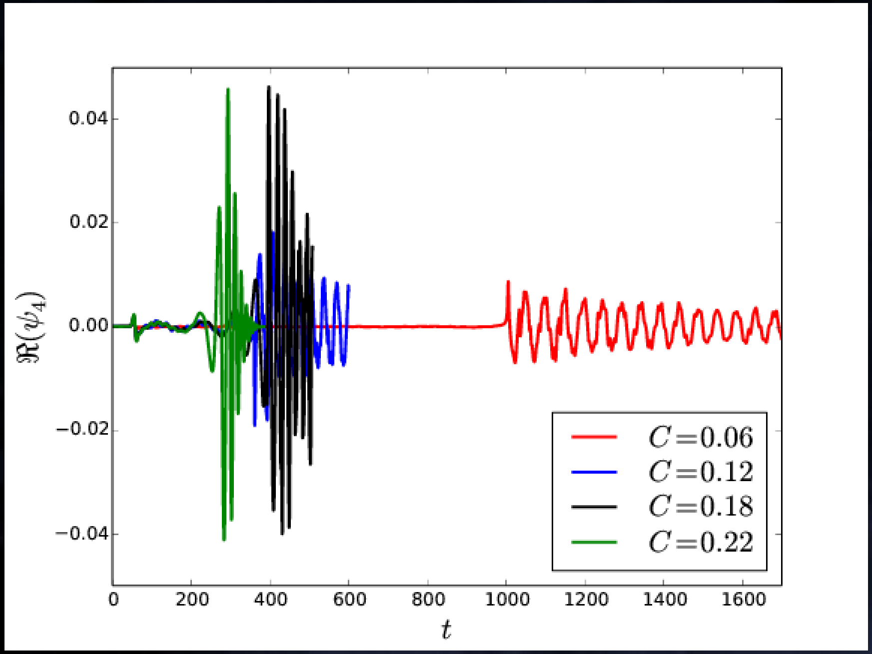
Orbital collisions of Bss in QCO

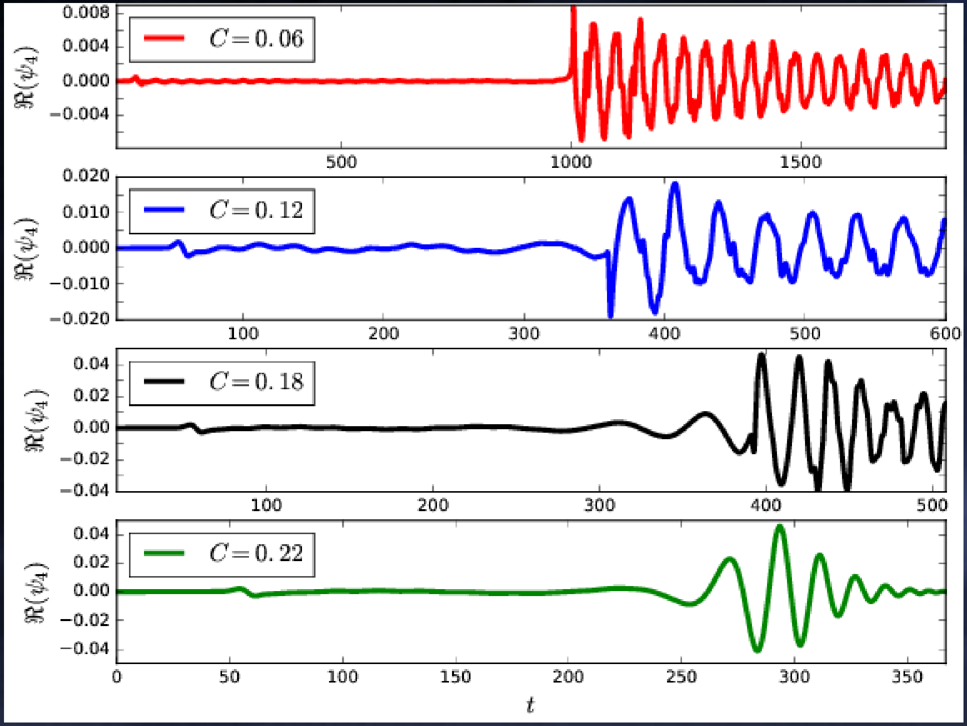




- For low compactness the Noether charge remains almost constant, but it is largely radiated for C≥0.18
- Most of the angular momentum is radiated soon after the merger in all the cases

Orbital collisions of BSs





- For low compactness the signal is really small before the merger
- For high compactness the final object quickly collapse to a black hole → features similar to BH merger
- There is a characteristic GW signal after the merger

Fermion-boson star binaries

Dark matter accretion onto neutron stars

- Planck measurements of CMB indicates that the total energy of the Universe contains 5% baryons + 27% dark matter + 68% dark energy

- Dark matter interaction with matter is proportional to density → stronger in neutron stars near the galaxy center's.

- DM accretion rate of a typical neutron star ($M=1.4\ M_{\Theta}$,$R=10$km) [Kouvaris 2008]

$$[\ 3 \times 10^{25} / m_{\chi}\,(\mathrm{GeV})\ ]\ \ [\ \rho_{DM}/(0.3\ \mathrm{GeV/cm^3})\ ]\qquad [\text{particles/s}]$$

- Oldest neutron stars ~ 10 billion years

Dark matter accretion onto neutron stars

• Dark matter particles will lose energy and settle at the center of the star, leading to two different scenarios:

- symmetric DM : the dark matter particles annihilate as they settle down in the center, releasing energy and heating the star

the star will be hotter (and look younger)

- asymmetric DM : they accumulate inside the star and form a Bose-Einstein condensate after reaching a critical density

fermion star with a boson component

• Can the presence of DM in the NS interior lead to a GW signature detectable by LIGO?

Fermion-Boson Stars

- Fermion-Boson stars (FBS) are compact solutions made by combining a perfect fluid with a complex scalar field Φ

$$T_{ab} = T_{ab}^{SF} + T_{ab}^{PF}$$

$$T_{ab}^{SF} = \nabla_a \Phi^* \nabla_b \Phi + \nabla_a \Phi \nabla_b \Phi^* - g_{ab} [\nabla_c \Phi^* \nabla^c \Phi + V(\Phi^2)]$$

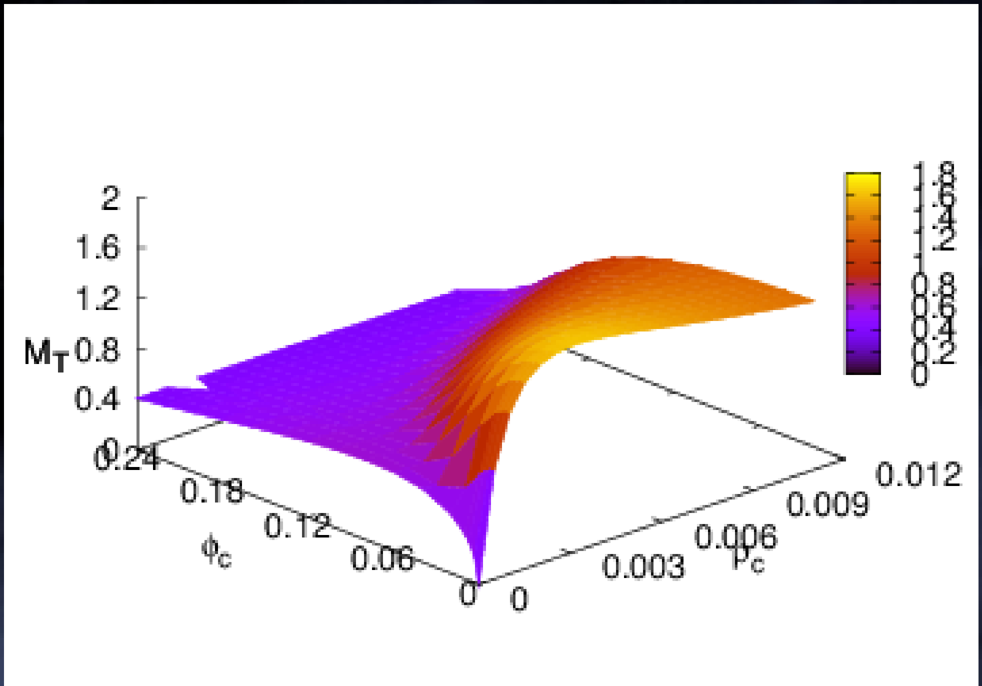
$$T_{ab}^{PF} = [\rho(1 + \varepsilon) + p] u_a u_b + p\, g_{ab}$$

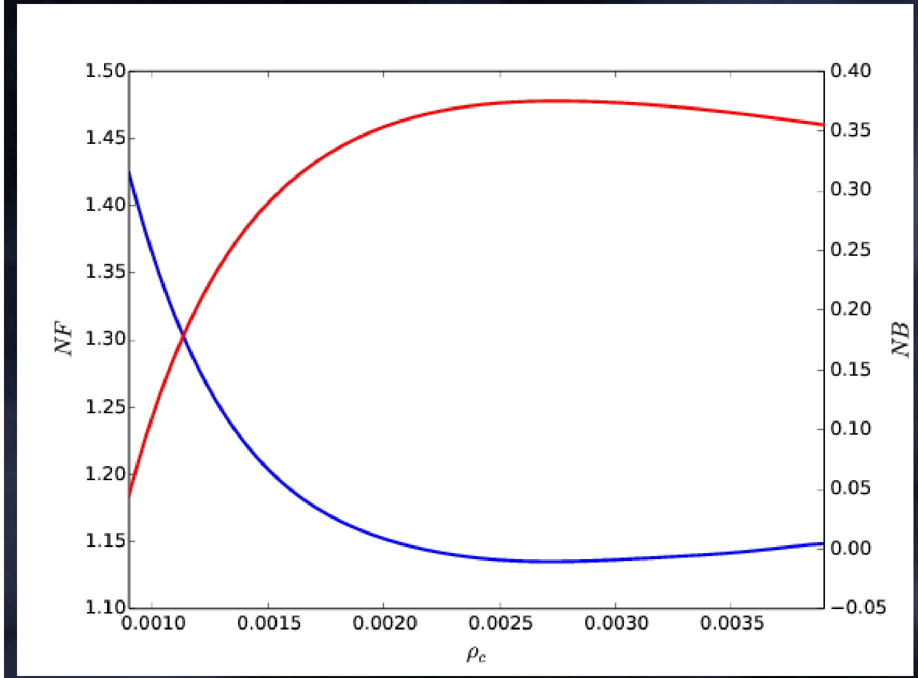
- Harmonic ansatz $\{\Phi_0(r), \omega\}$ $\quad \Phi = \Phi_0(r) \exp(i\, \omega\, t)$

- Massive potential $V(\varphi^2) = \mu^2 \Phi^2$

FB stars: equilibrium configurations

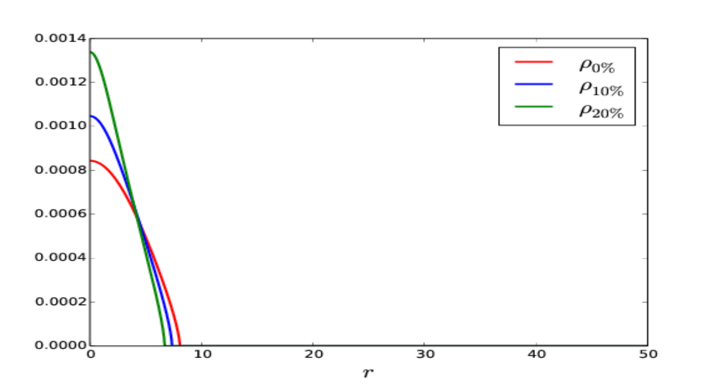
- Critical solutions separating stable from unstable equilibrium configurations can be found setting M=constant and looking for extremas $\partial N_F/\partial\rho_c = \partial N_B/\partial\rho_c = 0$ [Valdez,Ureña,CP++2013]

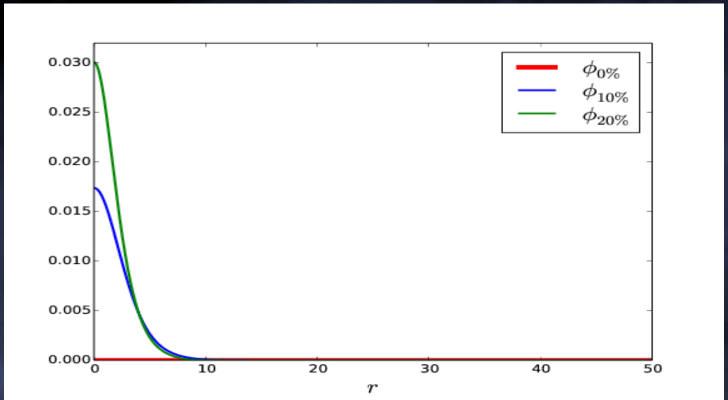


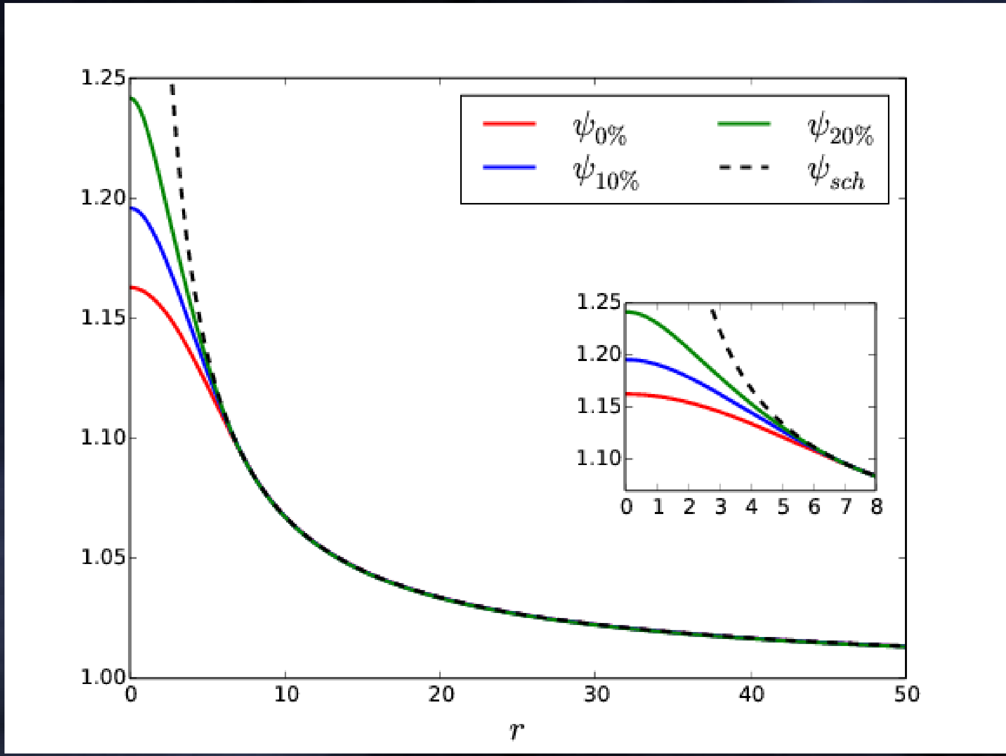


FB stars: equilibrium configurations

- Solutions with a larger boson fraction N_B/N_F lead to more compact objects with higher central densities







Binary FB stars

- ONGOING WORK! [CP,Bezares++late 2017]

- Our expectation:

Inspiral will be similar to neutron stars, but the remnant will have two sets of frequencies modes, one for the fermions (strongly coupled through HD equations) and another for the bosons (only coupled by gravity)

spectroscopy of GWs

Binary Black Holes
in
Einstein-Maxwell-Dilaton gravity

Alternative gravity theories

- Open questions: missing (dark) matter, expansion of the universe (dark energy),... → missing matter or modified theory of gravity?

-GR has passed stringent tests in the weak field regime

* Solar system (Cassini probe-time delay)
* Widely separated binary pulsars (GW in PN theory)

-But not so many in the strong field regime

* existence of black holes
* isolated NS
* GWs consistent with the merger of a binary BH

Study constraints alternative gravity theories based on the GWs produced during a binary BH coalescence

[Hirschmann,Lehner,Liebling,CP 2017]

Einstein-Maxwell-Dilaton gravity

-EMD is a well posed theory that appears as a low energy limit of string theory and includes a U(1) gauge field F_{ab} and a scalar field Φ

$$S=\int d^4x\sqrt{-\tilde{g}}\,e^{-2\phi}\left[R+\Lambda+4(\nabla\phi)^2-F^2-\frac{H^2}{12}\right]$$

JORDAN or PHYSICAL FRAME

-Rewrite the previous action as the standard GR + a minimally coupled scalar field and an EM field by performing a conformal transformation $g_{ab}=e^{-2\phi}\tilde{g}_{ab}$

$$S=\int d^4x\sqrt{-g}\left[R-2(\nabla\phi)^2-2V-e^{-2\alpha_0\phi}F^2\right]$$

EINSTEIN FRAME

α_0 parametrizes a family of theories ($\alpha_0=0$ Einstein-Maxwell, $\alpha_0=1$ EMD, $\alpha_0=\sqrt{3}$ Kaluza-Klein)

Evolution equations of EMD

-The evolution equations are the standard Einstein-Maxwell-Klein-Gordon equations with some additional source terms

$$
\begin{aligned}
R_{ab} &= 2\left(T_{ab} - \frac{1}{2} g_{ab} T\right) \\
\nabla^a \nabla_a \phi &= \frac{1}{2}\frac{\partial V}{\partial \phi} - \frac{\alpha_0}{2} e^{-2\alpha_0 \phi} F^2 \\
\nabla^a F_{ab} &= -I_b \quad .
\end{aligned}
$$

$$
\begin{aligned}
I_b &= -2\alpha_0 \nabla^a \phi F_{ab} \\
T_{ab} &= T^{\phi}_{ab} + e^{-2\alpha_0 \phi} T^{\mathrm{EM}}_{ab} \\
T^{\phi}_{ab} &= \nabla_a \phi \nabla_b \phi - \frac{1}{2} g_{ab} \left[\nabla_c \phi \nabla^c \phi + V(\phi)\right] \\
T^{\mathrm{EM}}_{ab} &= F_{ac} F_b{}^c - \frac{1}{4} g_{ab} F^2 .
\end{aligned}
$$

Single BH analytical solutions

- The gauge field F_{ab} might correspond either to:
  - gravity sector (i.e., like the scalar field): a priori there are no restrictions on its magnitude
  - EM sector: charge in BHs can not be large in general
    → but look for NS with strong B fields!!

- Analytical solutions for single charged BHs show that there is a scalar charge associated to the EM charge

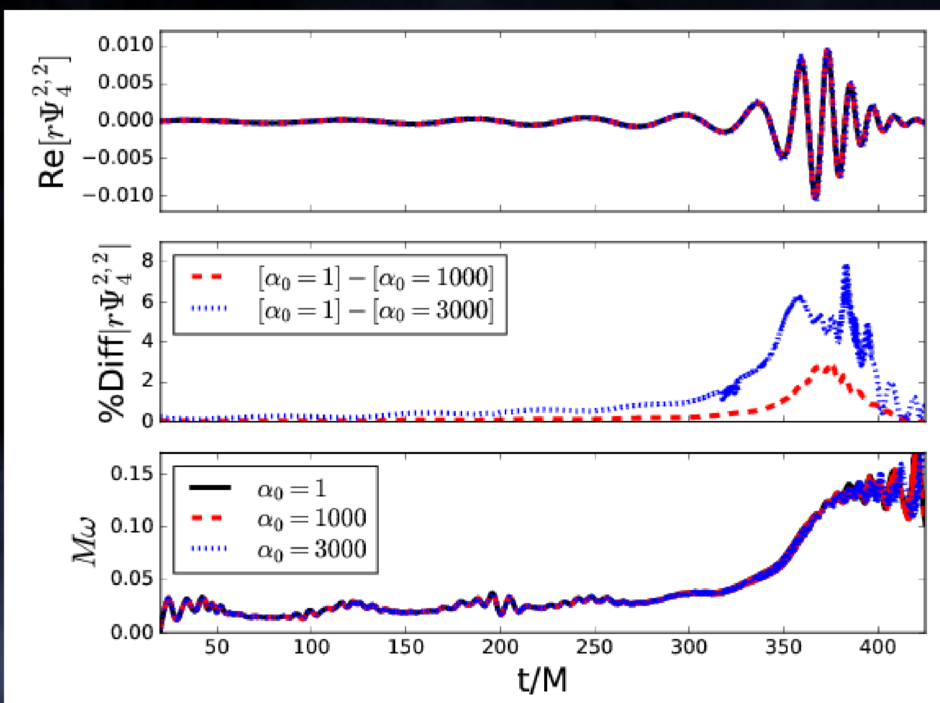
$$\Phi(r) \approx \Phi_0 + \Phi_1/r \qquad \Phi_1 \approx \alpha_0 Q^2/(2\,M)$$

Similar to Scalar-Tensor theories with matter!!

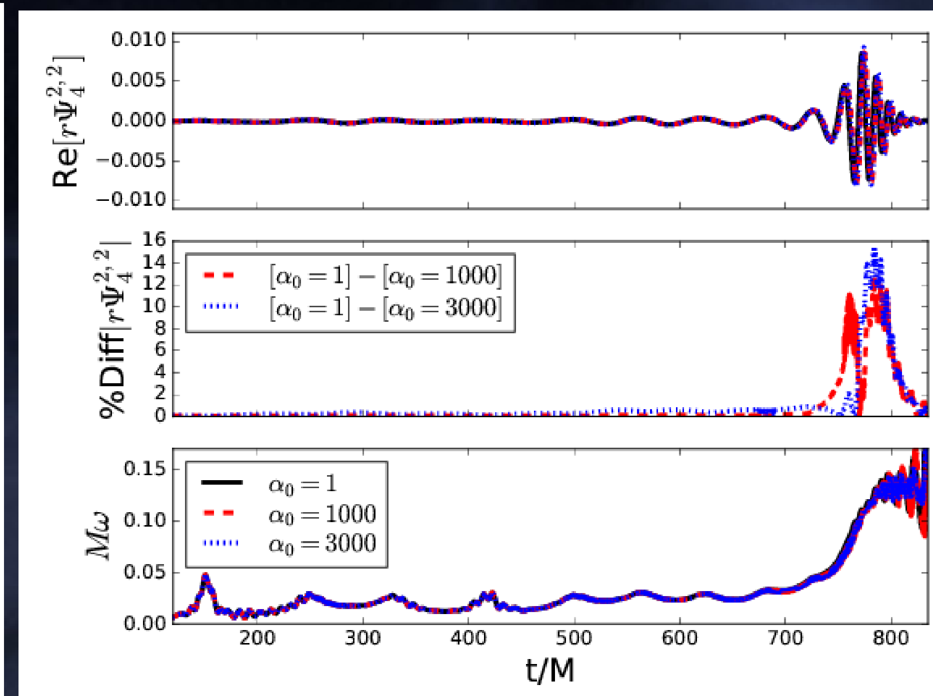
Enhancement of gravitational force & dipolar radiation

Binary BH numerical solutions

- Equal and unequal binary BHs with a small charge Q/M=0.001 and different values of α_0



equal mass



unequal mass

Summary

- Stability of black holes in EMD is similar than in GR
- The effects on the GWs produced during the merger of binary BHs are small for low values of the charge Q/M, even if α_0 >>1 (i.e., they scale as $\alpha_0(Q/M)^2$)

- Binary boson stars generically merge into either a black hole or a non-rotating boson stars, producing a variety of intense Gws in the post-merger stage

- Neutron stars with a bosonic component on its interior might produce a characteristic GW signature after the merger