Piercing of a boson star by a black hole

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Motivation

- Evidence for existence of matter of unknown nature and properties which interacts gravitationally
- We can expect "dark stars", making up a significant fraction of astrophysical environments
- We will assume the existence of new fundamental, scalar degrees of freedom minimally coupled to gravity
- For complex scalar fields, boson stars (BSs) form rather generically as a consequence of gravitational collapse
- There are indications that such solutions describe well dark matter cores in haloes.
  - These models are often referred to as fuzzy dark matter models

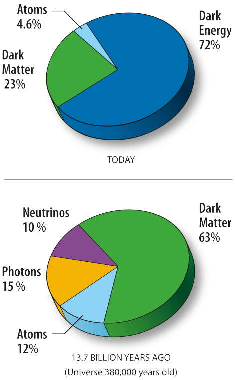

Figure: WMAP (2008)

Motivation

- Dark stars have so far gone undetected, Understanding the behavior of dark matter when moving perturbers drift by may be crucial for detections
- **Here we consider the motion of a small black hole as it pierces a large boson star structure**

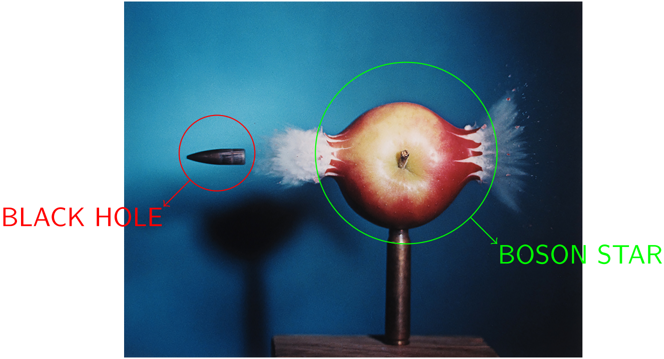

Figure: Harold Edgerton, Bullet Through Apple (1964)

Motivation

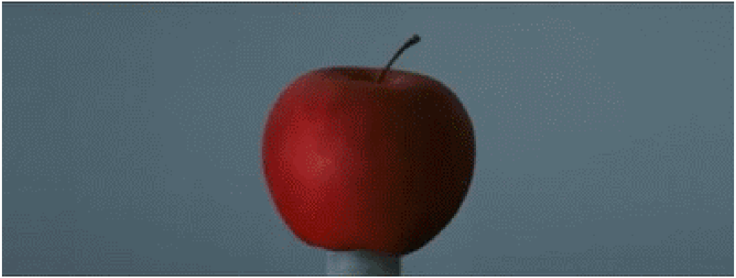

Figure: **The motion of a small black hole as it pierces a large boson star structure**

Model

A **minimally coupled**, massive scalar field Φ described by the Einstein-Klein-Gordon action

$$S = \int d^4x\sqrt{-g}\left[\frac{\mathcal{R}}{16\pi} - \left(g^{ab}\nabla_a\Phi\nabla_b\Phi^* + \mu^2\Phi\Phi^*\right)\right]$$

- BSSN
- Einstein Toolkit
  - Canuda

Figure: Einstein Toolkit

Initial Data

- Spherically-symmetric mini-boson star

$$\Phi(t,R) = \phi(R)e^{i\omega t}$$
$$dl^2 = \psi_{\rm BS}(R)^4\left(dx^2+dy^2+dz^2\right)$$

- Boosted Schwarzschild black hole

$$dl^2 = \left(1+\frac{M}{2R}\right)^4\left(dx^2+dy^2+B_0(x,y,z)dz^2\right)$$

- Superposition of the conformal factors

$$dl^2 = \psi^4\left(dx^2+dy^2+B(x,y,z)dz^2\right)$$
$$\psi = 1+\frac{M_{\rm BH}}{2R}+\psi_{\rm BS}$$

Initial Data: Boosted Black Hole + Boson Star

Run	M_{BH}	$R_{98}/(2M_{\text{BH}})$	v_0	M_{tot}
IB	1	6	0.5	1.68
IVB	0.1	62	0.5	0.65

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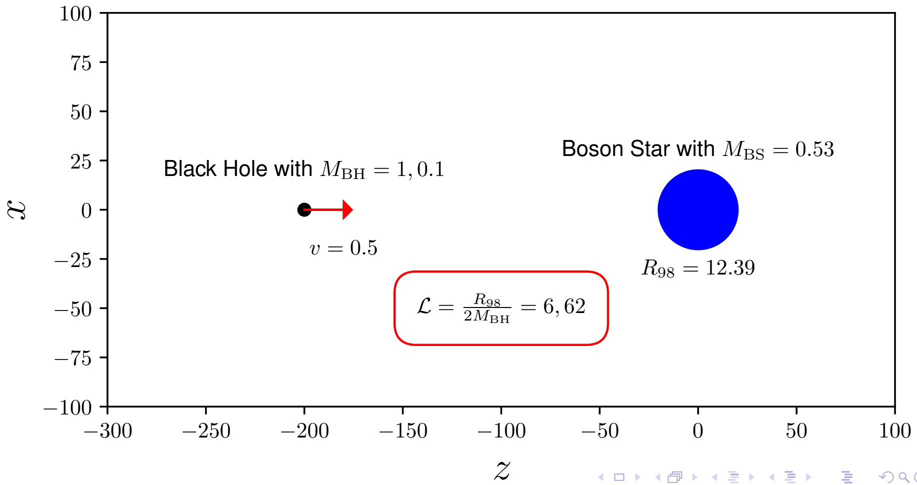
$$\psi = 1 + \frac{M_{\text{BH}}}{2R} + \psi_{\text{BS}}$$



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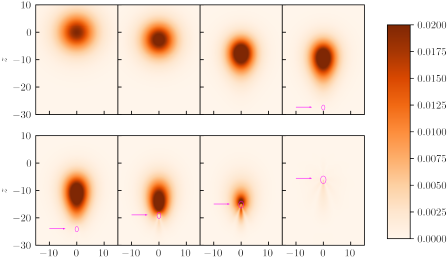

Figure: Run IB

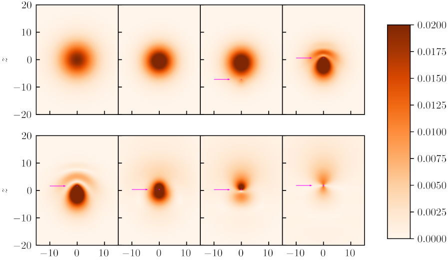

Figure: Run IVB

Accretion during collision

- even for case IVB: a BH which is 62 times smaller than the BS and moving at half the speed of light.
- after a relatively short timescale ~ 1000, and after the BH has had time to interact with the BS, the final BH mass is at least 95% of the total initial energy.

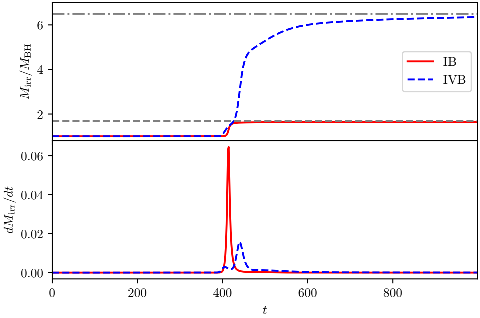

Figure: Accretion of scalar onto the BH, **BS is nearly totally accreted**

Black hole motion

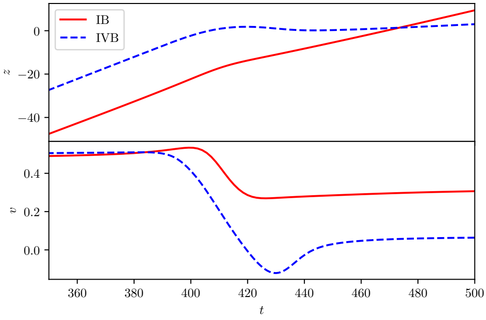

Figure: The location z and the speed v of the BH

- Interaction between BH and BS is clear, and translates into an deceleration starting at $t \sim 400$ lasting for time to cross bulk of BS
- Notice that the BH velocity is negative for a small amount of time, in simulation `IVB`: the BH is tidally captured by the boson star.

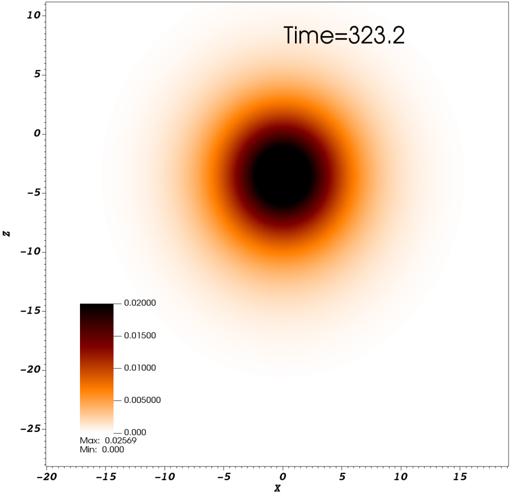

Figure: Movie for Run IB

- $M_{\text{BH}} = 1$
- $\mathcal{L} \sim 6$
- $v_0 = 0.5$
- $M_{\text{tot}} = 1.68$

Movie for Run IVB

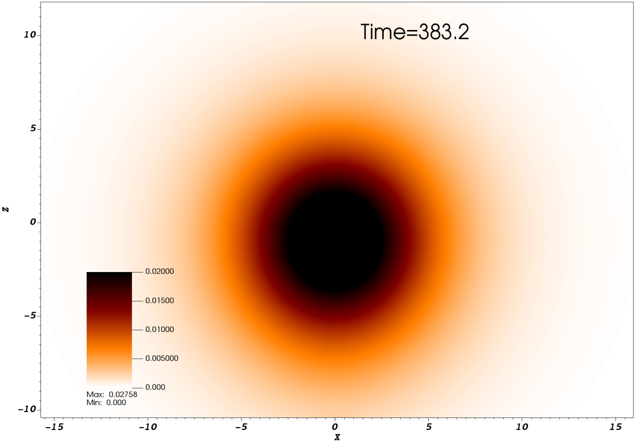

Figure: Movie for Run IVB

- $M_{\mathrm{BH}} = 0.1$
- $\mathcal{L} \sim 62$
- $v_0 = 0.5$
- $M_{\mathrm{tot}} = 0.65$

Final Remarks

- Challenging simulations of boosted BHs and BSs
- Even for length ratios ~ 62 the BS is entirely accreted by the BH
- At late times, a "gravitational atom" is formed: massive BH surrounded by a quasi-bound state of the scalar field (the BS remnant)
- One can expect that for even smaller BH masses the BH can pierce through without destroying the BS
  - In order to evolve such a small BH, one would need too large an amount of computational resources...
- Spinning and/or charged configurations may lead to new phenomena