A black hole as big as a universe?

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Outline

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Solitons

localized, finite energy, stable, regular (particle-like) solutions in flat and curved space-time

Topological solitons

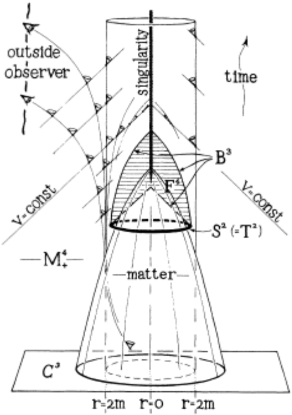
- carry topological charge (non-trivial vacuum manifold)
- In theories with spontaneous symmetry breaking
- Examples: (Cosmic) Strings, Monopoles, Domain walls ...

Non-topological solitons

- carry globally conserved Noether charge
- In theories with continuous symmetry
- Examples: Q-balls, boson stars ...

Black holes

- form whenever mass M collapses to within its **Schwarzschild radius** $r_s = 2m$, $m = MG/c^2$
- **physical singularity** hidden behind event horizon
- **event horizon** $r = r_s$: infinite redshift of photons
- come in different masses
  - supermassive ($10^6 - 10^9 M_{\rm sun}$)
  - stellar mass (a few $M_{\rm sun}$)
  - primordial (atomic)



Taken from:
R. Penrose, *Gravitational collapse and space-time singularities*, PRL 14 (1965) 57.

Black holes (BHs)

- Exact solutions of the full, i.e. non-linear Einstein equation
- Simplest case: vacuum [1]

$$ds^2 = -\left(1 - \frac{2m}{r}\right) dt^2 + \left(1 - \frac{2m}{r}\right)^{-1} dr^2 + r^2 \left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

with $m = MG/c^2$

- $r = 0$ is a **physical singularity**

[1] Schwarzschild, 1916

Some analytically given BH solutions

Vacuum (uncharged) or + electromagnetic field (charged)

	Non-rotating (static) J=0	**Rotating (stationary) $J \neq 0$**
Uncharged $Q = 0$	Schwarzschild (1916)	Kerr (1963)
Charged $Q \neq 0$	Reissner-Nordström (1916)	Kerr-Newman (1965)

Simplicity of BHs : Theory

- ISRAEL'S THEOREM [2] : The only **static vacuum** (charged) space-time being *non-singular* (on and outside the horizon) is the **spherically symmetric Schwarzschild** (Reissner-Nordström) space-time.
- STRONG RIGIDITY THEOREM [3] : **Stationary rotating** black holes are either **axisymmetric** or have a non-rotating horizon.
- NO-HAIR THEOREM [4] : A **stationary rotating** black hole solution to the vacuum (Maxwell-) Einstein system is uniquely determined by its **mass**, **angular momentum** (and charge) and described by the corresponding **Kerr**(-Newman) solution.

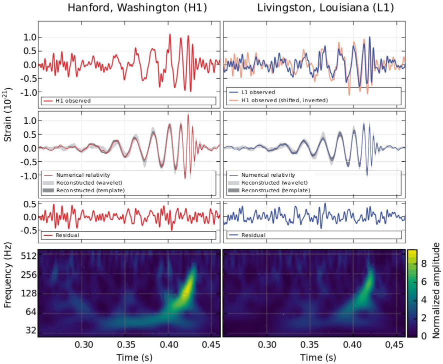
[2] Birkhoff, 1923; Israel, 1967/1968

[3] Hawking, 1973

[4] Wheeler, 1971; Carter, 1972; Robinson, Mazur, 1982; Chrusciel, 1996; and many more

Simplicity of BHs : Observations

Gravitational waves @ LIGO/VIRGO[5]

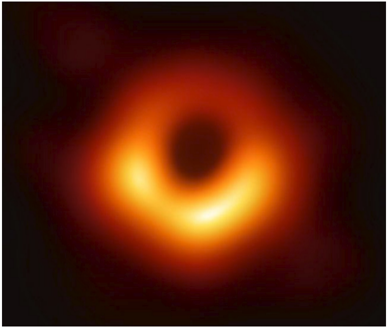


- merger of **two black holes**
- O(10) solar masses, i.e. astrophysical
- Final black hole *very well* described by **Kerr black hole**
- **only gravitational waves** (and no other radiation) emitted

[5] LIGO/VIRGO collaboration, since 2015

Simplicity of BHs : Observations

Shadow of black hole @ Event Horizon Telescope (EHT) [6]



- supermassive black hole (6.5 billion solar masses)
- at center of galaxy M87
- event horizon radius approx. 120 x Earth-Sun distance
- emission from plasma close to horizon observed in radiowaves (1.3 mm)
- “picture” compatible with that of **Kerr black hole**

[6] EHT Collaboration, since 2019

Outline

Why scalar fields?

- Scalar fields
  - appear in (nearly) all extensions of SM + GR, e.g. Kaluza-Klein theory, String Theory, Supergravity, ...
  - are important in **early universe cosmology**, e.g. scalar field ("inflaton") driving exponential expansion of early universe (inflation) [7]
  - are often used to describe collective phenomena, e.g. superconductivity [8]
- **No scalar hair theorem**: [9]

A **static, asymptotically flat, bare** black hole can be endowed with **no** exterior classical massive or massless, charged or uncharged, real or complex valued **scalar fields**.

[7] Starobinsky, 1980; Guth, 1981; Linde, 1982

[8] Ginzburg, Landau, 1950

[9] Chase, 1970; Bekenstein, 1972 & 1995; Heusler 1992; Sudarsky, 1995

Uncharged Q-balls & Boson stars

Complex scalar field with potential $V(|\Phi|)$ coupled to GR [10] [11]

$$S = \int d^4x \sqrt{-g}\left(\frac{R}{16\pi G} - \partial_\mu \Phi^* \partial^\mu \Phi - V(|\Phi|)\right)$$

with scalar field potential

$$V(|\Phi|) = m_\Phi^2 |\Phi|^2 + V_{\rm int}(|\Phi|)$$

m_Φ^2: scalar boson mass $\qquad$ $V_{\rm int} \sim \mathcal{O}(|\Phi|^4)$ self-interaction

- invariant under global U(1) symmetry $\Phi \rightarrow \exp(i\alpha)\Phi$, $\alpha \in \mathbb{R}$

$\Rightarrow$ **globally conserved Noether charge** Q_N

[10] Kaup, 1968; Ruffini & Bonazzola, 1969; Jetzer, 1992; Mielke & Schunck, 2003

[11] $c = \hbar \equiv 1$ here and in the following

Uncharged Q-balls and boson stars

- spherically symmetric solutions

$$\Phi = \exp(i\omega t)\phi(r)$$

  with ω constant, real $\rightarrow$ harmonic time-dependence

- **flat space-time limit: Q-ball** [12]
  needs (at least) $V_{\rm int} \sim |\Phi|^6/m_\Phi^2 - |\Phi|^4$
- boson star with $V_{\rm int} = 0$: mass $M/M_{\rm sun} \sim 10^{-10}$ eV$/m_\Phi$
- boson star with $V_{\rm int} \sim |\Phi|^6/m_\Phi^2 - |\Phi|^4$: mass $M/M_{\rm sun} \sim (10^{15}$ eV$/m_\Phi)^3$
- viable **alternative to supermassive BHs**, but **without**
  - event horizon
  - physical singularity

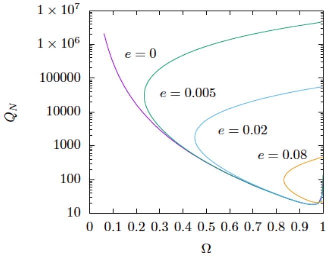
[12] Coleman, 1986

Charged Q-balls & boson stars

- global U(1) symmetry can be gauged $\rightarrow$ charged generalization:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ieA_\mu \quad , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

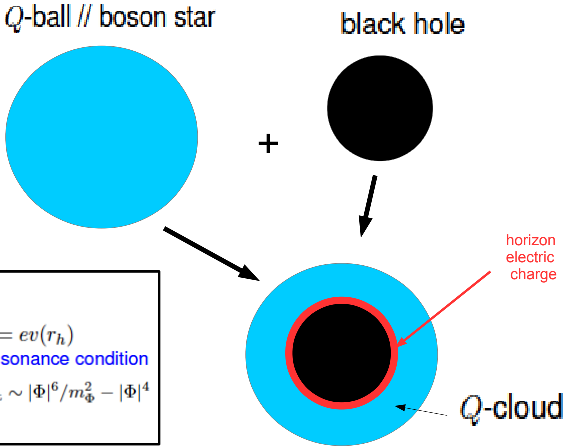
- spherically symmetric case
  - electric field $\vec{E} = -\partial_r v(r)\vec{e}_r$, $A_t(r) = v(r)$ electric potential
  - $\omega \rightarrow \Omega := \omega - ev_\infty$, $v_\infty = v(\infty)$
  - electric charge $Q = eQ_N$, Q_N Noether charge



Taken from: Y. Brihaye, F. Cônsole, B.H. gr-qc 2010.15625

Q-clouds on Schwarzschild black holes

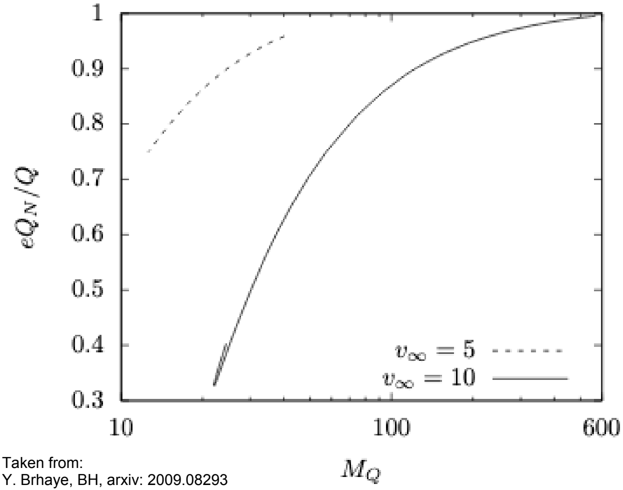
Hod, 2012; Hong, Suzuki, Yamada, 2019; Herdeiro & Radu, 2020



works if

- $\omega = e v(r_h)$
  resonance condition
- $V_{\rm int} \sim |\Phi|^6/m_\Phi^2 - |\Phi|^4$

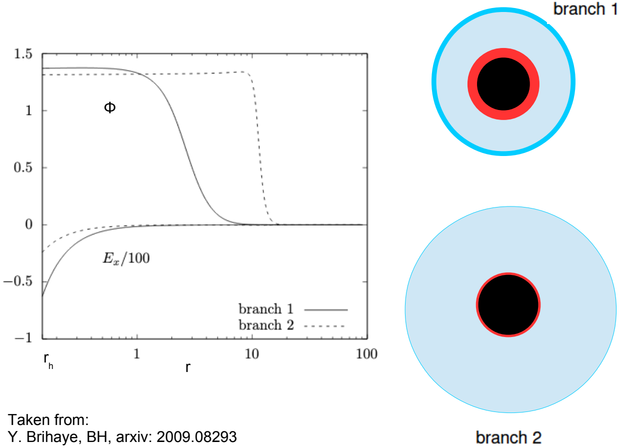
Q-clouds: electric charge of the cloud



Taken from:
Y. Brhaye, BH, arxiv: 2009.08293

Two different Q-cloud solutions

For the exact same values of the couplings: two distinct solutions



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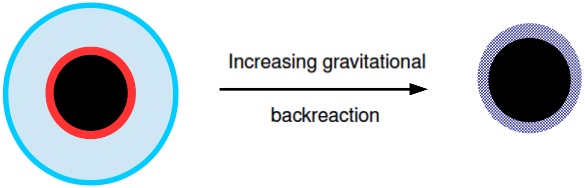
Backreaction of Q-cloud on black hole

Y. Brihaye, BH, arxiv: 2009.08293

branch 1:

strong backreaction $\rightarrow$ extremally charged black hole + singular scalar field

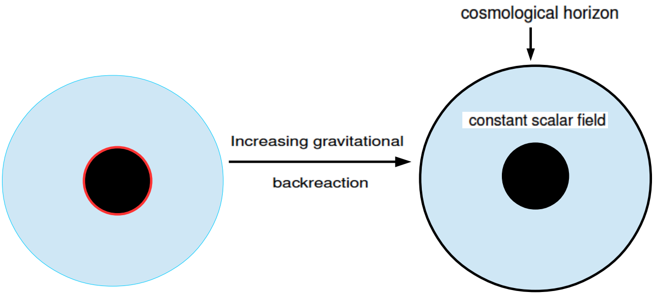


Backreaction of Q-cloud on black hole

Y. Brihaye, BH, arxiv: 2009.08293

branch 2:

strong backreaction $\rightarrow$ extremally charged black hole + constant scalar field

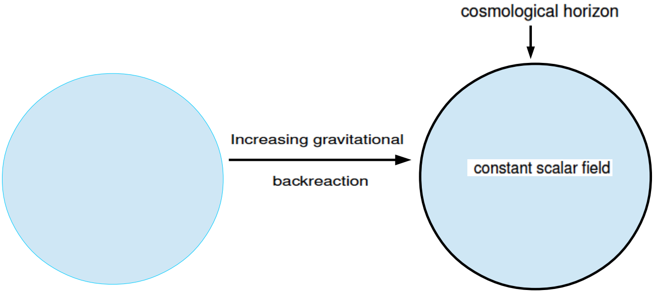


Charged Boson stars at strong backreaction

Y. Brihaye, F. Cônsole, BH, arxiv: 2010.15625

branch 2:

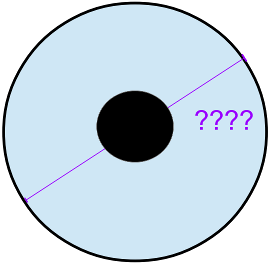
strong backreaction $\rightarrow$ extremally charged black hole with cosmological horizon + constant scalar field



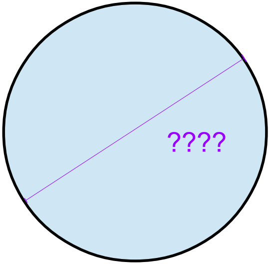
Outline

- Static, spherically symmetric black holes can carry scalar hair if
  - scalar field complex charged under U(1)
  - harmonic time dependence of scalar field $\sim \exp(i\omega t)$
  - (at least) 6th order self-interaction
  - resonance condition $\omega = ev(r_h)$ fulfilled
- Typically two different branches of solutions
  - branch 1: cloud localized on horizon; horizon and cloud carry electric charge
  - branch 2: cloud strongly extended; nearly all charge in the cloud
- Gravitational backreaction of Q-cloud
  - branch 1: scalar cloud disappears; formation of extremal black hole; diverging scalar field derivative on horizon
  - branch 2: scalar field constant inside cloud $\rightarrow$ potential scalar field energy $\rightarrow$ solution forms cosmological horizon that looks like extremal black hole from outside

A black hole as big as a universe?



A boson star as big as a universe?



Thank you for your attention