Astrophysical Signatures of Scalar Fields (arXiv:1710.00830; arXiv:1806.07331)

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Motivation

We have **strong evidence** in favor of the **existence** of a scalar field (Higgs boson);

Scalar fields appear as **fundamental elements** of a number of theories, from **extensions of well known setups**, as the Standard Models of Particles and Cosmology, or as part of **String Theory**; [Hu+,2000] [Peccei&Quinn,1977] [Svrcek&Witten,2006]

Some of these scalar fields are predicted to be **ultra light** - $[10^{-33}, 10^{-10}]$ eV - and because of that they interact very weakly; [Arvanitaki+,2010] [Hui+,2017]

What about scalar fields? $c = G = \hbar = 1$

$$S = \int d^4x\sqrt{-g}\left(\boxed{\frac{R}{16\pi}} - \frac{1}{2}\boxed{g^{\mu\nu}}\Phi^*_{,\mu}\Phi_{,\nu} - \frac{\mu^2\Phi\Phi^*}{2}\right), \quad \mu = m_S$$

$g_{\mu\nu}$ is the Kerr metric

$$\Phi \sim \exp(-\mathrm{i}\omega t)\varphi(r)Y_{\ell m}(\theta,\phi);$$

If $\mathrm{Re}(\omega) < m\Omega_H$ then $\mathrm{Im}(\omega) > 0$;

Some modes of the field grow and develop non-trivial profiles.

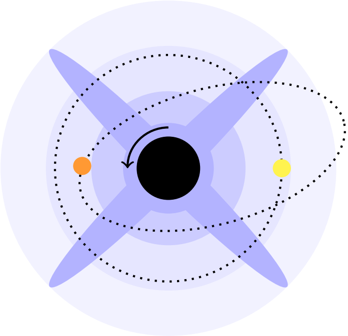
$g_{\mu\nu}$ is a spherically symmetric metric

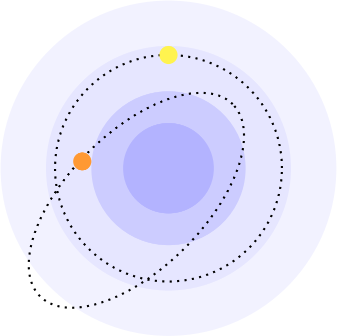
$$\Phi \sim \exp(-\mathrm{i}\omega t)\varphi(r)$$

$$\Phi \sim \cos(\omega t)\varphi(r)$$

Self-gravitating structures whose **characteristics depend on the mass of the scalar field**.

Probing astrophysical scalar field structures





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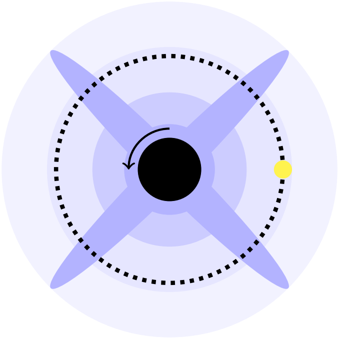
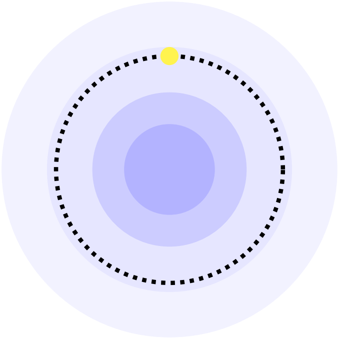
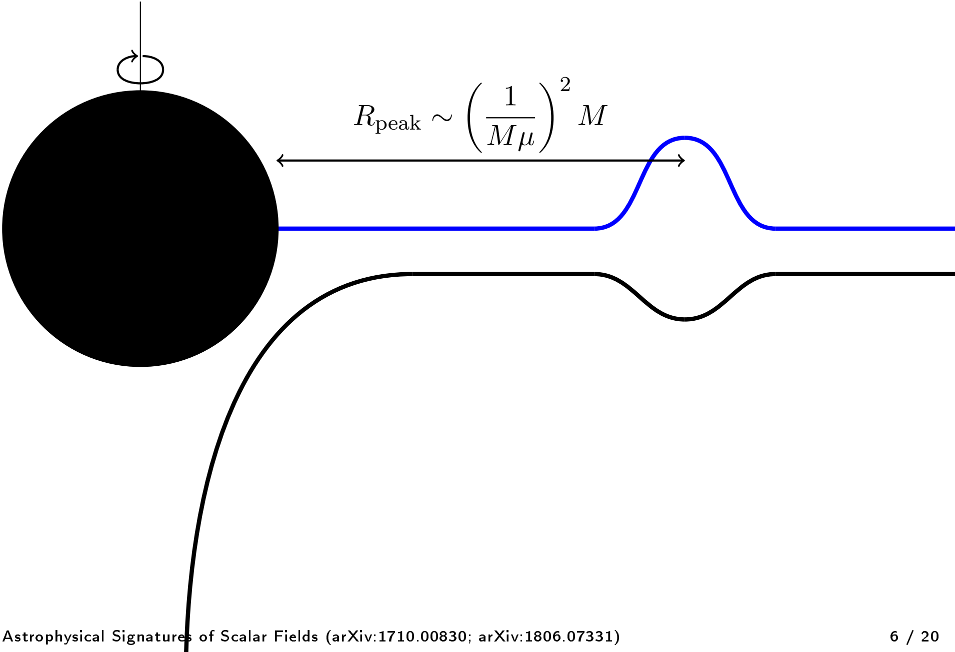





$R_{\text{peak}} \sim \left(\frac{1}{M\mu}\right)^2 M$

Scalar fields around a Kerr BH

We focus on the real part of the most unstable mode [Brito+,2015(b)] :

$$\Phi = A_0 \tilde{r} e^{-\tilde{r}/2} \cos(\phi - \omega_R t) \sin(\theta)$$

and since we're considering an ultra-light scalar field - $M\mu \ll 1$ - it is valid to use

$$\omega_R = \mu.$$

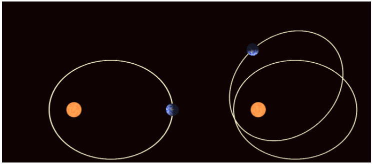
The maximum value of the profile of the scalar field goes like $\sim (M\mu)^{-2}$, i.e., sufficiently far from the BH such that *Newtonian approximation* is allowed.

[Yoshino&Kodama,2013]

The effective gravitational potential far from the BH is given by (for a planar orbit)

$$\Psi(r,\phi) = \Psi_r(r) + \delta\Psi(r,\phi) = \left[-\frac{M}{r} + P_1(r)\right] + P_3(r)\cos(2(\phi - \omega_R t))$$

Precession

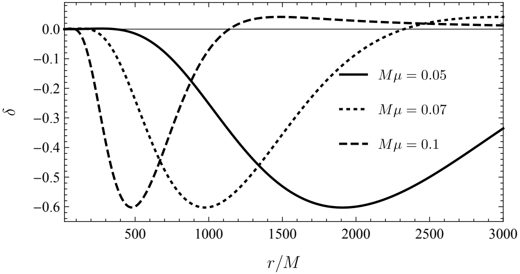


Apsidal angle: number of radians it takes to go from the furthest distance to the shortest distance

$$\psi = \pi \left[3 + r \frac{\Psi_r''(r)}{\Psi_r'(r)} \right]^{-1/2}$$

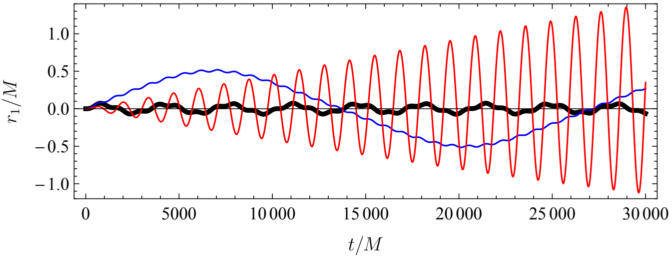
Number of radians an orbit precesses in each period:

$$\delta = 2(\pi - \psi)$$



Quasi-circular approximation to circular orbits of the BH (R_0, Ω_0):

$$\begin{cases} r(t) & = R_0 + r_1(t) \\ \phi(t) & = \phi_0(t) + \phi_1(t) = (\Omega_0 - \omega_R)t + \phi_1(t) \end{cases}$$



Resonant radii depend on the mass coupling parameter as

$$\frac{R_{-,L}}{M} \approx \left(\frac{1}{4M^2\mu^2}\right)^{1/3}, \quad \frac{R_C}{M} \approx \left(\frac{1}{M^2\mu^2}\right)^{1/3}, \quad \frac{R_{+,L}}{M} \approx \left(\frac{9}{4M^2\mu^2}\right)^{1/3}$$

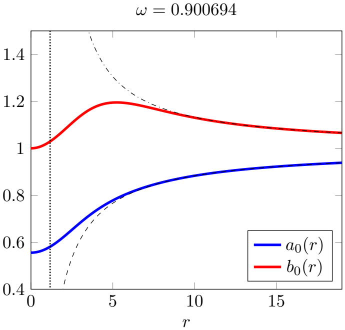
Oscillatons

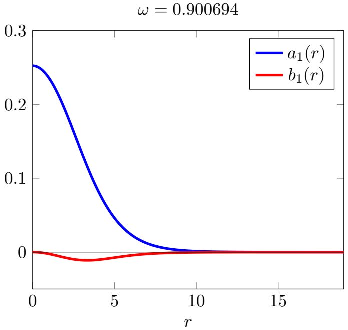
Self-gravitating structures of a time-periodic real scalar field

$$\Phi(t,r) = \phi_1(r)\cos(\omega t) + \phi_3(r)\cos(3\omega t)$$

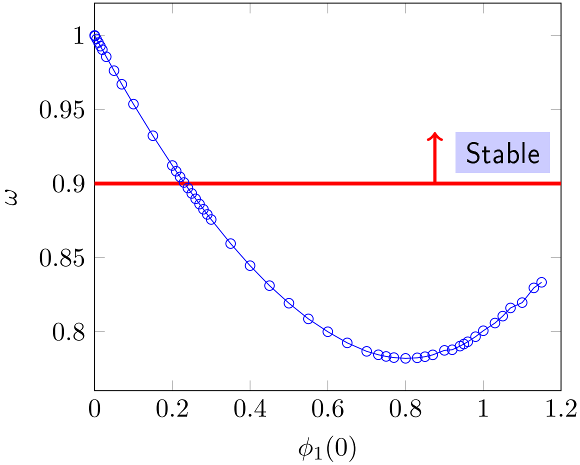
$$ds^2 = -A(t,r)dt^2 + B(t,r)dr^2 + r^2(d\theta^2 + \sin\theta d\phi^2)$$

$$A(t,r) = a_0(r) + a_1(r)\cos(2\omega t) \qquad B(t,r) = b_0(r) + b_1(r)\cos(2\omega t)$$



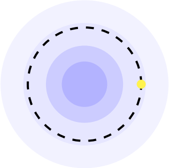


Not all oscillatons are stable [Guzman & Urena-Lopez, 2004]



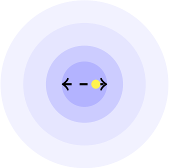
Oscillatons' orbits (planar)

$$\frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0$$



Quasi-circular orbits:

$$\begin{cases} r(\tau) = R_0 + r_1(\tau), \\ \phi(\tau) = \Omega_0\tau + \phi_1(\tau), \\ t(\tau) = \gamma_0\tau + t_1(\tau) \end{cases}$$

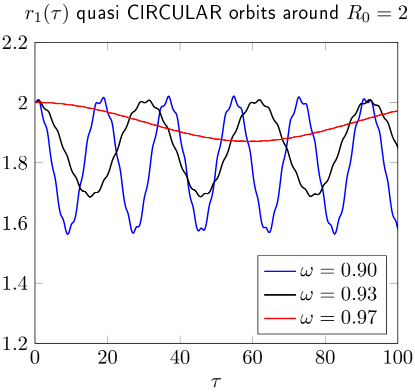


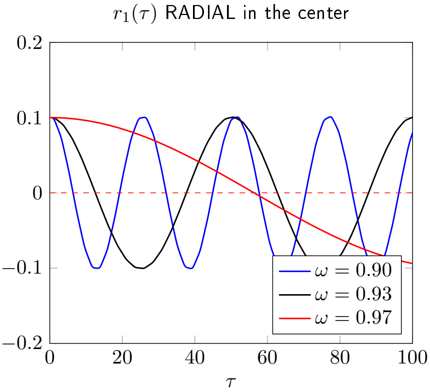
Centered radial orbits:

$$\begin{cases} r(\tau) = r_1(\tau), \\ t(\tau) = \gamma_0\tau + t_1(\tau) \end{cases}$$

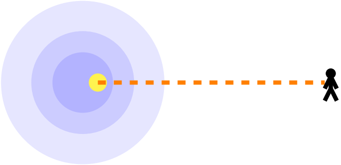
$$|r_1| \ll R_0, \quad |\dot{\phi}_1| \ll \Omega_0, \quad |\dot{t}_1| \ll \gamma_0$$

Quasi-circular and radial orbits





Gravitational redshift



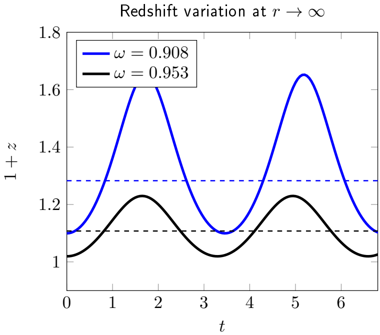
Gravitational redshift formula:

$$1 + z \equiv \frac{\omega_e}{\omega_r} = \sqrt{\frac{A(t_e, R_e)}{A(t_r, R_r)}} \frac{P^t(R_e)}{P^t(R_r)}$$

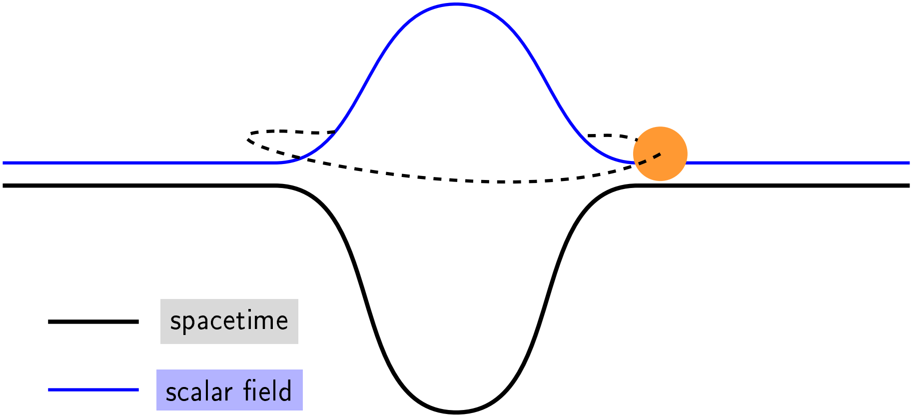
Radial trajectory of a photon:

$$\frac{dP^\mu}{d\lambda} + \Gamma^\mu_{\alpha\beta}(t) P^\alpha P^\beta = 0$$

We obtain that the gravitational **redshift varies with a frequency equal to the one of the corresponding oscillaton**.



Backreaction of the field



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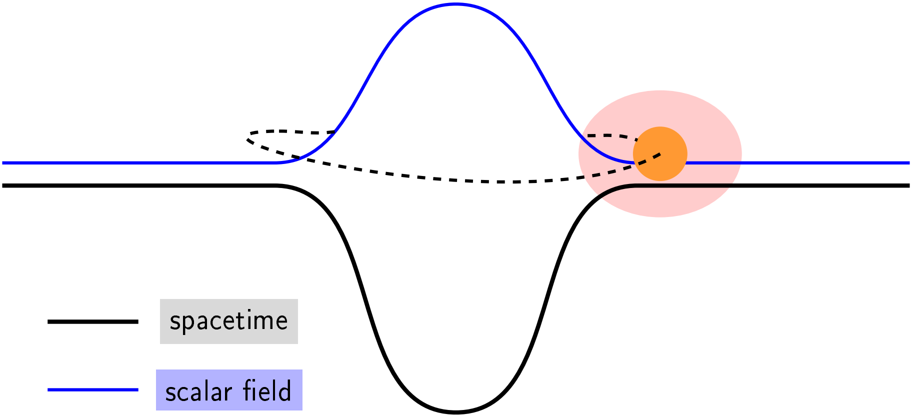

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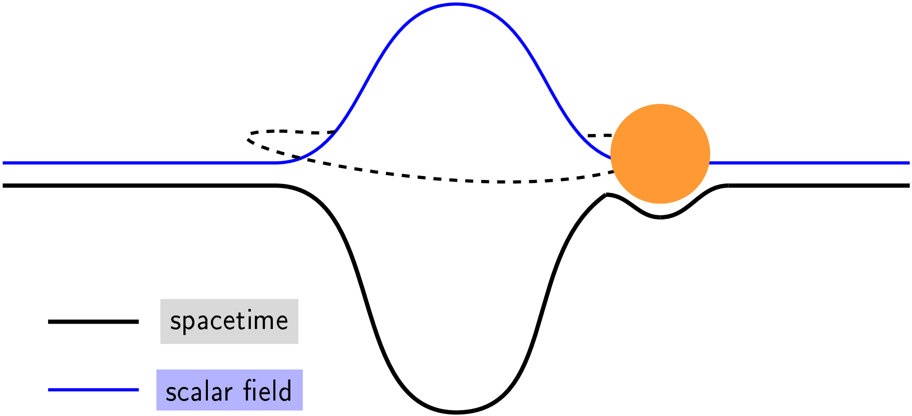

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G\left(T^S_{\mu\nu} + T^P_{\mu\nu}\right)$$

$$\frac{1}{\sqrt{-g}}\left(\sqrt{-g}g^{\mu\nu}\Phi_{,\mu}\right)_{,\nu} - m_S^2\Phi = 0$$

$$\Phi = \exp(-\mathrm{i}m_S t)\psi(t,\vec{x}), \quad \begin{cases} g_{00} \sim -1 + 2U \\ g_{0j} \sim 0 \\ g_{jk} \sim (1+2U)\delta_{jk} \end{cases}$$

$$\begin{cases} \mathrm{i}\partial_t\psi + \frac{1}{2m}\nabla^2\psi + \frac{m}{\hbar}U\psi = 0 \\ \nabla^2 U = -4\pi\left(m_P\delta^{(3)}(x - x_P) + m_S^2|\Phi|^2\right) \end{cases}$$

Final notes

1. Scalar field may be responsible for the development of structures of astrophysical relevance;
2. The behavior of stars in the vicinity of these structures depend on the characteristics of the scalar field;
3. Some of the aspects of this behavior can be related to the existence of **orbital resonances** or **gravitational redshift variation**;
4. The scalar field structures can react to the presence of the orbiting stars – studying this reaction will certainly uncover more phenomenology associated with this system.

Thanks for the attention!