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Screened Scalars and Black Holes

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1402.4737 & coming soon..

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Image Credit: photojournal.jpl.nasa

Outline

- Black holes and no hair
- Screened scalars
- Chameleon hair
- Observational prospects

Black Hole Theorems

Black holes in 4D obey a set of theorems: We know they are spherical, that they obey laws of thermodynamics, and that they are characterized by relatively few “numbers” – or “Black Holes Have No Hair”.

i.e. electrovac solutions are uniquely specified by 3 parameters: M, Q, and J

No Scalar Hair

The essence of “no hair” is that the scalar field must have finite energy, and fall off at infinity. Integrating the equation of motion gives a simple relation, only satisfied for $\varphi = \varphi' \equiv 0$

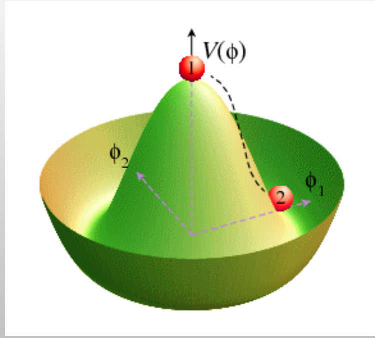
$$\int_{2GM}^{\infty} \left\{ r^2 V_{,\phi}^2 + r(r-2GM)\phi' \frac{d}{dr}\left(V_{,\phi}\right) \right\} = \left[V_{,\phi} r(r-2GM)\phi'\right]_{2GM}^{\infty} = 0.$$

Sotiriou, Faraoni, 1109

No-No Hair!

But this is highly idealised:

- Static
- Vacuum
- Potential must be convex



And no hair has come to mean the much stronger "no field profiles".

Screened Scalars

The screening arises because the scalar couples to matter via a metric term – typically due to a conformal rescaling.

$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m\left[\Psi_i, A^2(\phi)g_{\mu\nu}\right].$$

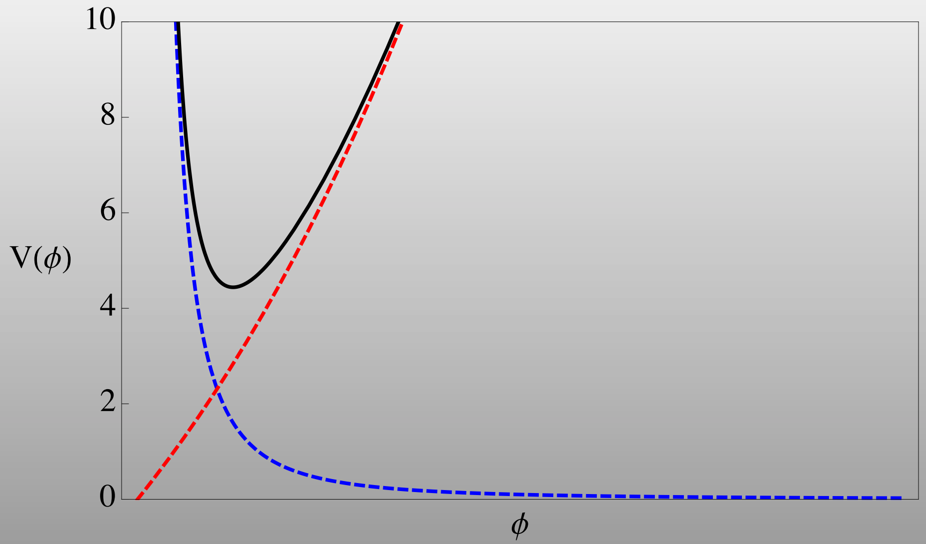
$$\Box\phi = \frac{\partial}{\partial\phi}\left[V(\phi) + (A(\phi) - 1)\rho\right] \equiv \frac{\partial V_{\text{eff}}(\phi,\rho)}{\partial\phi}.$$

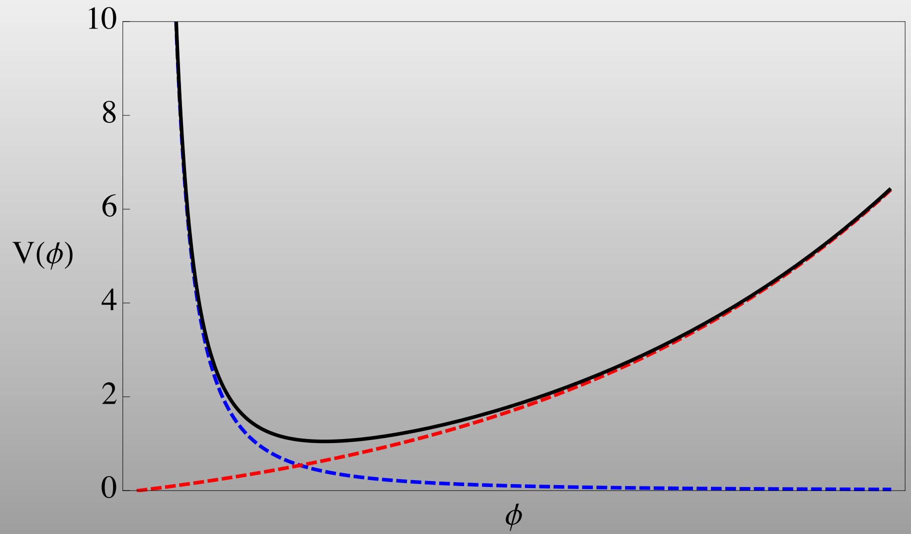
When calculating the e.o.m. a ρ dependent term appears.

Chameleon

The effective potential for the chameleon is a sum of two terms and looks different at different densities

$$V(\phi) = M^{4+n}\phi^{-n} = V_0\phi^{-n} \qquad A(\phi) = e^{\beta\phi/M_p}$$





Khoury, Weltman 0309

Chameleon

Useful to sum up bounds in terms of Compton wavelengths:

Environment	Density	Compton wavelength upper bound	
		$n = 1$	n large
Earth	$\rho_\oplus \sim 10^{29}\rho_{\rm cosm}$	10^{-5} m	10^{-5} m
Accretion disc	$10^{-8}\rho_\oplus$	10 m	0.1 m
Galaxy	$10^{6}\rho_{\rm cosm}$	10^{12} m	10^{7} m

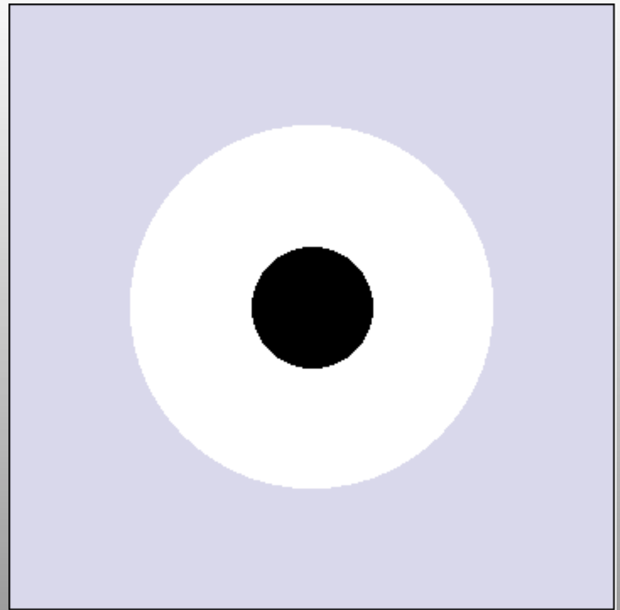
So for a stellar size black hole with an accretion disc, λ_c small, but for a SMBH in ambient galactic density λ_c more comparable.

Chameleon Hair

The “no-hair” theorem does not apply because dV/dr is not monotonic – the density profile may jump.

Demonstrate explicitly within the rules of the no-hair game: static, spherically symmetric black hole, but with density profile

$$\rho(r) \equiv \begin{cases} 0 & R_s < r < R_0 \text{ (Region I)} \\ \rho_\star & r > R_0 \text{ (Region II)} \end{cases}$$



Analytic Approximations

Always important to develop analytic understanding where possible. Analyse in regions I, II with small and large Compton wavelength in probe limit.

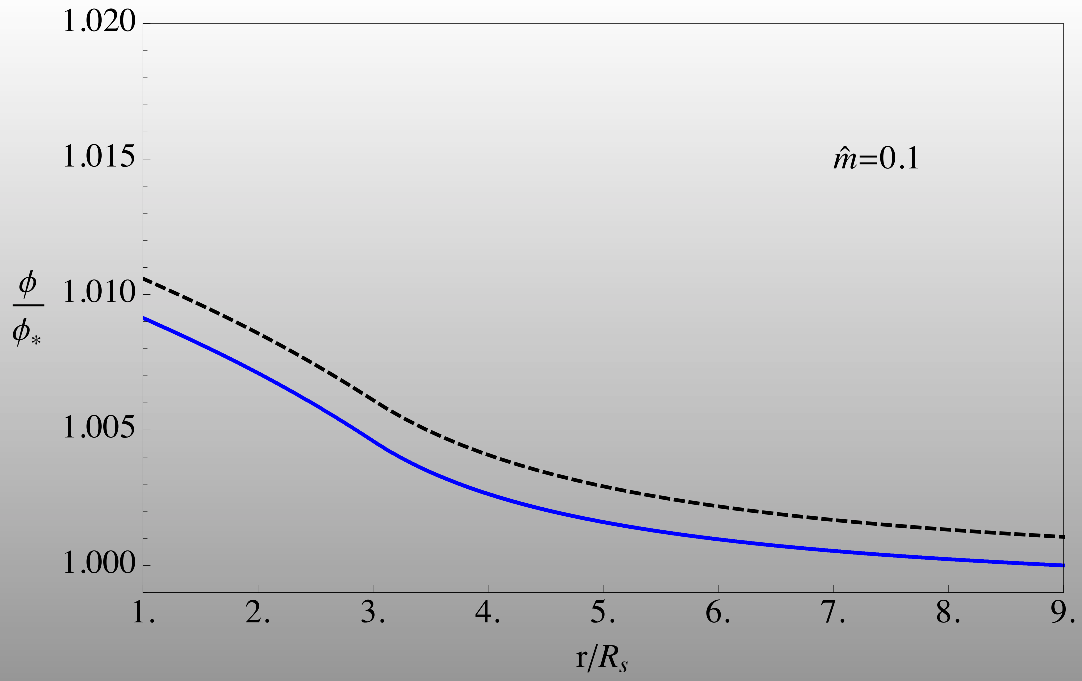
$$\hat{\phi} = \frac{\phi}{\phi_\star}\ , \quad x = \frac{r}{R_s}\ , \quad \hat{m}^2 = m_*^2 R_s^2 = (n+1)\frac{\rho_* \beta R_s^2}{M_p \phi_*}$$

$$\hat{\phi}'' + \frac{2x-1}{x(x-1)}\hat{\phi}' = \frac{x}{(x-1)}\frac{\hat{m}^2}{(n+1)}\left[\Theta[x-x_0] - \frac{1}{\hat{\phi}^{n+1}}\right]$$

Large Compton

For long Compton wavelength expect a small perturbation to the scalar, so model perturbatively.

$$\hat{\phi} \simeq 1 + \begin{cases} \frac{\hat{m}^2}{6(n+1)} \left[3x_0^2 - x^2 + 4x_0 - 2x + 2 + 2\ln\frac{x_0}{x}\right] & x < x_0 \\ \frac{\hat{m}^2}{3(n+1)} \left(x_0^2 + x_0 + 1\right) \frac{x_0}{x} e^{-\hat{m}(x-x_0)} & x > x_0 \end{cases}$$

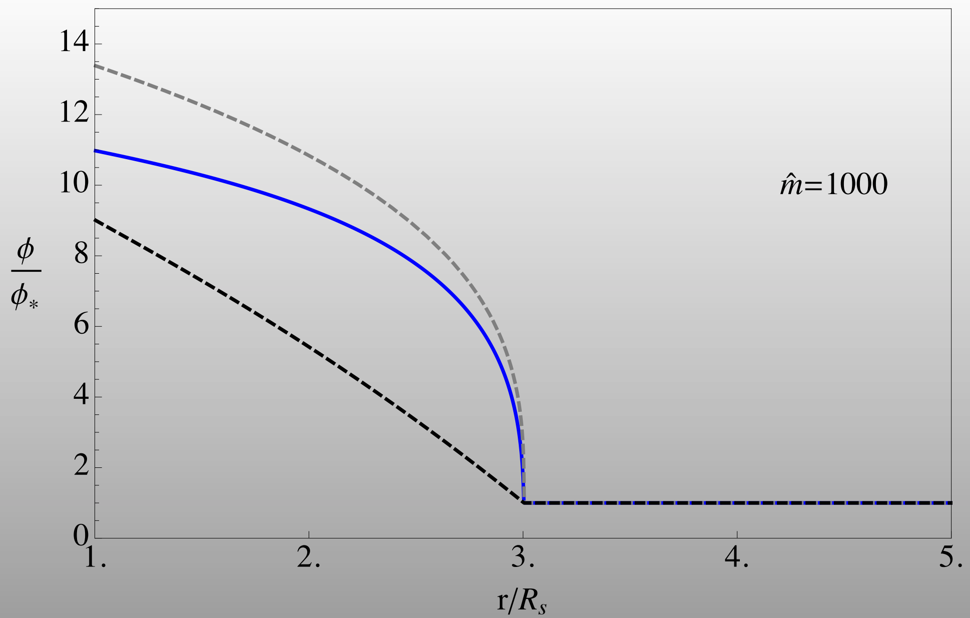


$$\delta\phi_h \approx \frac{\rho_\star \beta R_0^2}{2M_p}.$$

Small Compton

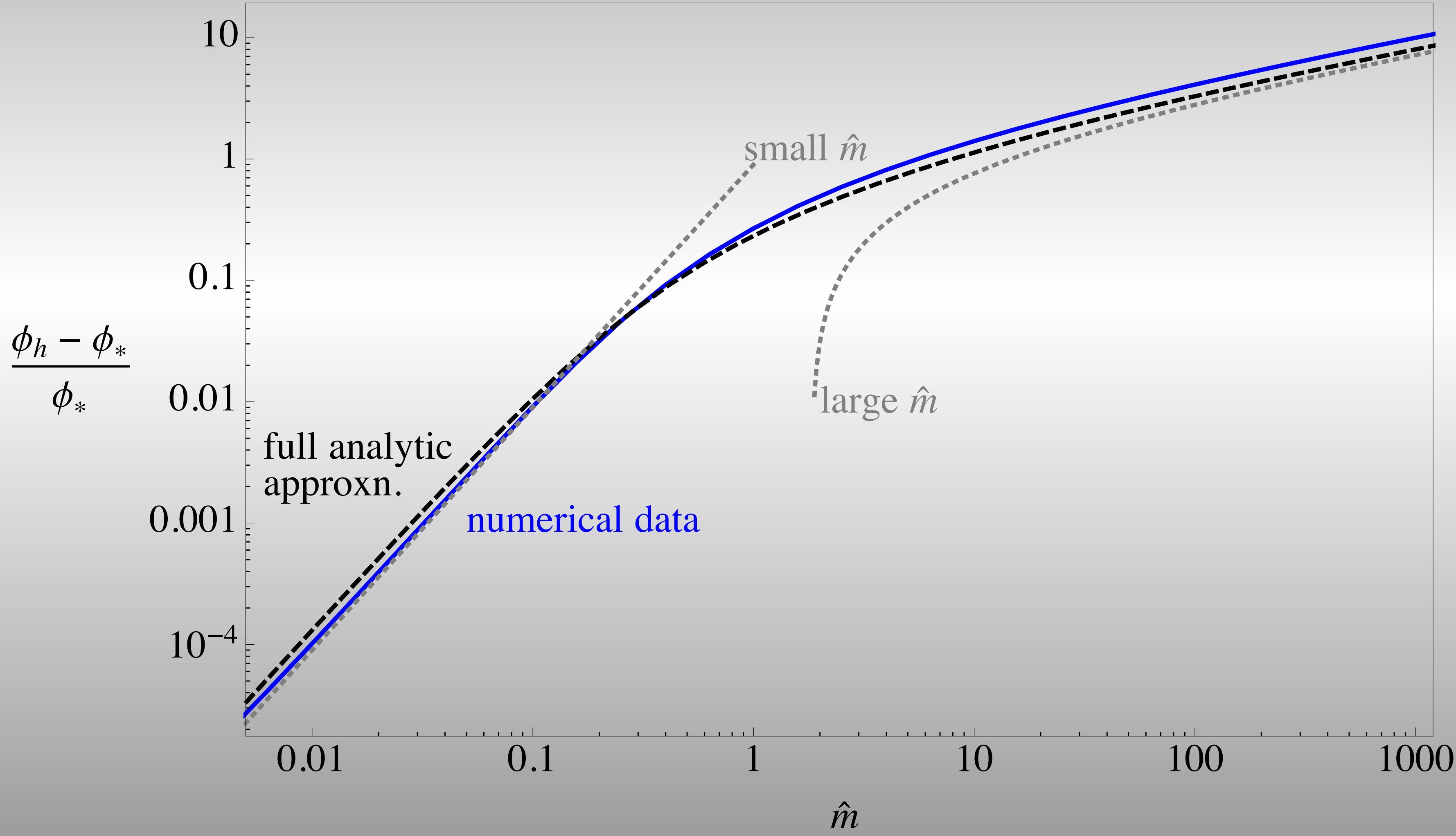
For low Compton wavelength expect the potential to be more important, but trickier to get analytic approximation more than indicative

$$\hat{\phi} \simeq 1 + \begin{cases} \left[\frac{\hat{m}^2(n+2)^2}{2n(n+1)}\right]^{\frac{1}{n+2}} \left(x_0 - x + \frac{2}{(n+2)\hat{m}}\right)^{\frac{2}{n+2}} & x < x_0 \\ \left[\frac{2}{n(n+1)}\right]^{\frac{1}{n+2}} \left(\frac{x_0}{x}\right)^{1+\hat{m}/2} e^{-\hat{m}(x-x_0)} & x > x_0 \end{cases}$$

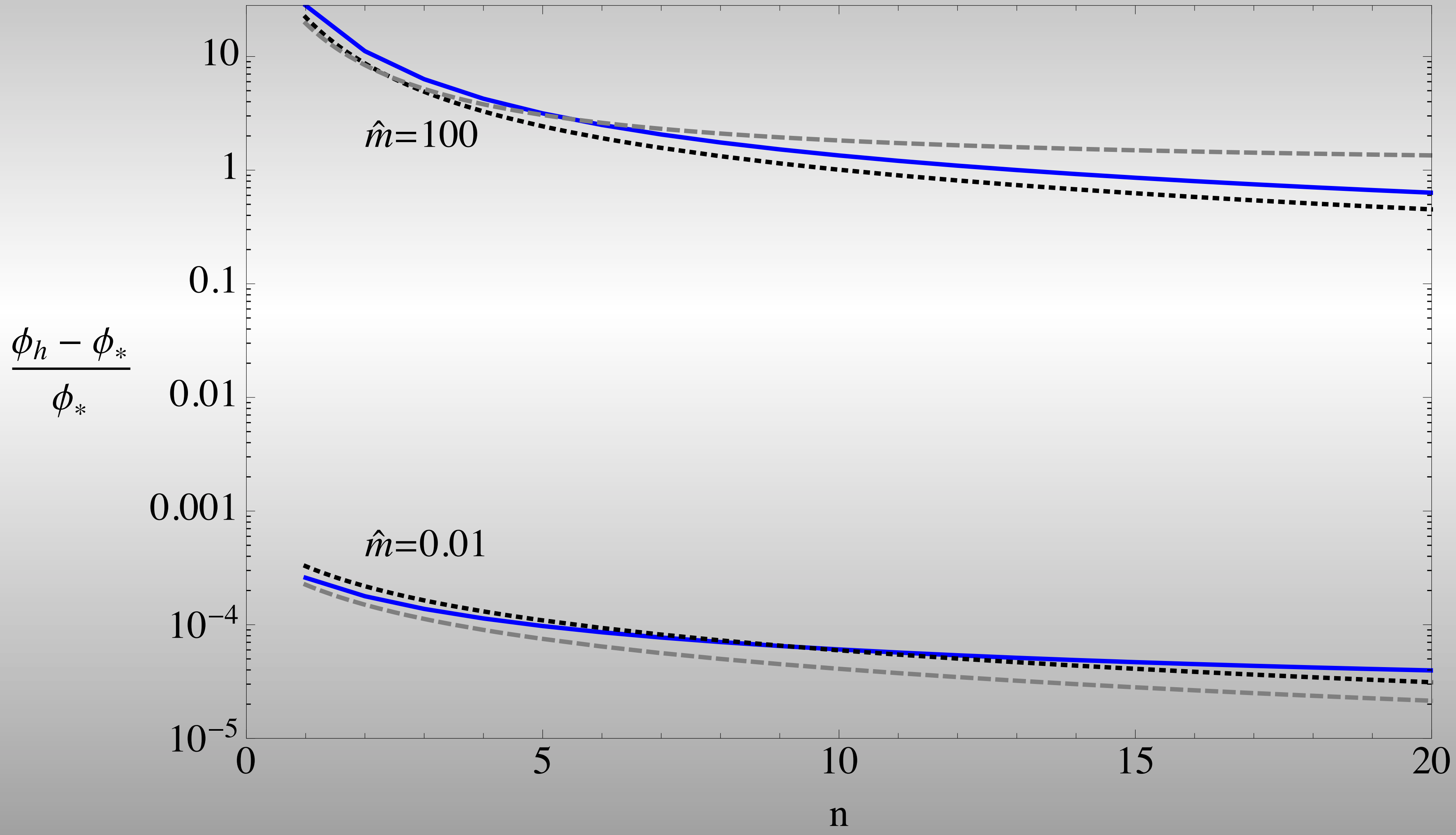


$$\phi_h \propto \left((n+2)^2 V_0 R_0^2\right)^{\frac{1}{n+2}}$$

Horizon Data : m



Horizon Data : n



Observation

Scalar forces are roughly of the form:

$$a_\phi \simeq -\frac{\beta\phi'}{M_p} \simeq \frac{\beta}{M_p}\left(\frac{\phi_h - \phi_*}{\Delta R}\right)$$

$$\Delta R \sim \mathrm{Min}\{R_0, R_0^{2/(n+2)} m_*^{-n/(n+2)}\}$$

Probe limit scalar does not back-react strongly on geometry – also means geometry dominates local motion. Instead compare energy loss from scalar to gravitational radiation.

$$\left|\frac{\dot{\mathcal{E}}_\phi}{\dot{\mathcal{E}}_{GR}}\right| \sim \beta(\phi_\star)\left(\frac{R_0}{R_s}\right)^{\frac{9}{2}}\left(\frac{\phi_h - \phi_\star}{\Delta R}\right)\frac{M_{BH}}{M_p^3}\left[\frac{M_{BH}}{m_t}\right].$$

Estimates

Best case scenario: infall of solar mass object to SMBH

Short range:

$$\left|\frac{\dot{\mathcal{E}}_\phi}{\dot{\mathcal{E}}_{GR}}\right| \sim 10^{-28-60/(n+2)}\,\beta_*\frac{M_{BH}^2}{M_p m_t}\left(\frac{m_*}{M_p}\right)^{\frac{n}{n+2}}$$

$$\sim 10^{-23+\frac{2(n+3)}{(n+1)(n+2)}}\left(\frac{M_{BH}}{M_\odot}\right)^2 \approx 10^{-11} - 10^{-5}$$

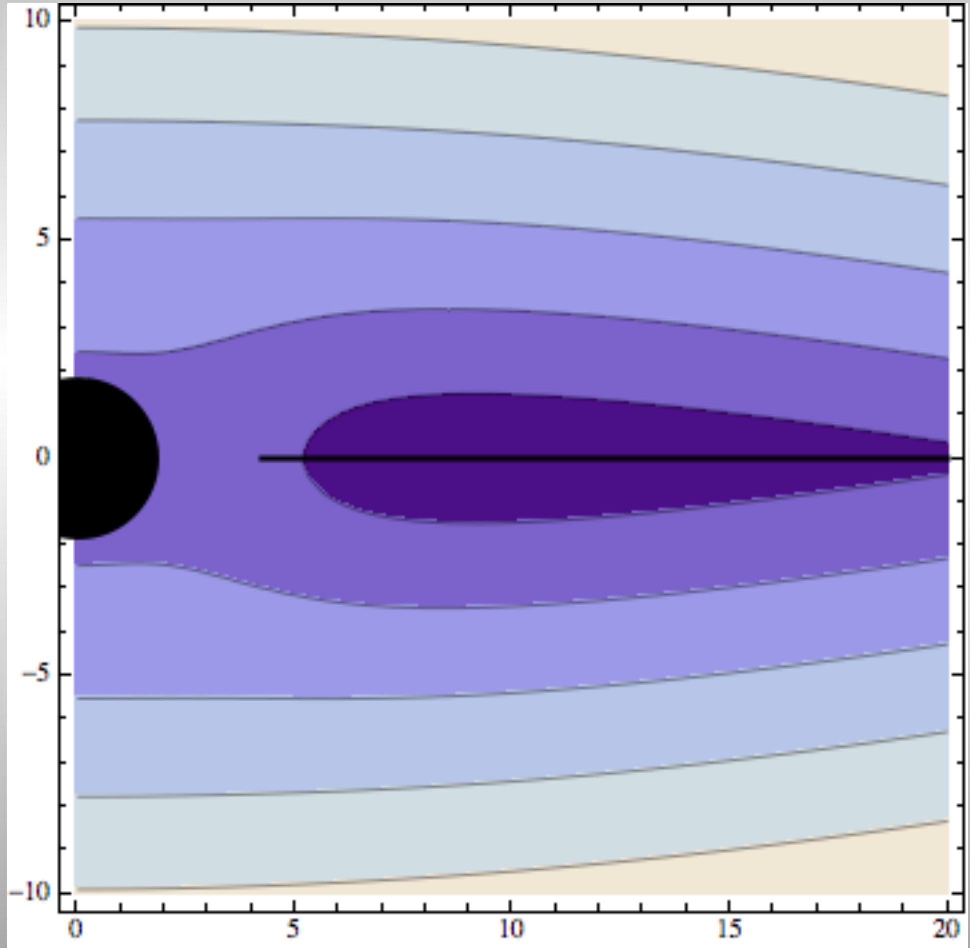
Long range:

$$\left|\frac{\dot{\mathcal{E}}_\phi}{\dot{\mathcal{E}}_{GR}}\right| \sim \beta\frac{(\phi_h - \phi_\star)}{M_p}\frac{M_{BH}}{m_t}$$

$$\sim 10^{-42}\beta^2\,\frac{\rho_\star}{\rho_{\cos}}\left(\frac{M_{BH}}{M_\odot}\right)^3 \sim 10^{-18} - 10^{-9}$$

In Progress: Kerr Accretion Disc

In reality black holes rotate, and the accretion disc is localized near the equatorial plane. Model this by a uniform matter shell extending from R_{ISCO} to ~100GM, and solve perturbatively for ϕ, roughly massless away from disc.



Summary

- No hair not applicable – screened scalars have nontrivial profiles even in static spherically symmetric black hole environments.
- Analytic tools are quite accurate predictors of actual profiles.
- General picture similar (nontrivial profiles sourced by varying density) with more realistic accretion disc model, though profile different.
- Unfortunately it seems these will not give observable effects.