Shrouded black holes in Einstein-Gauss-Bonnet gravity

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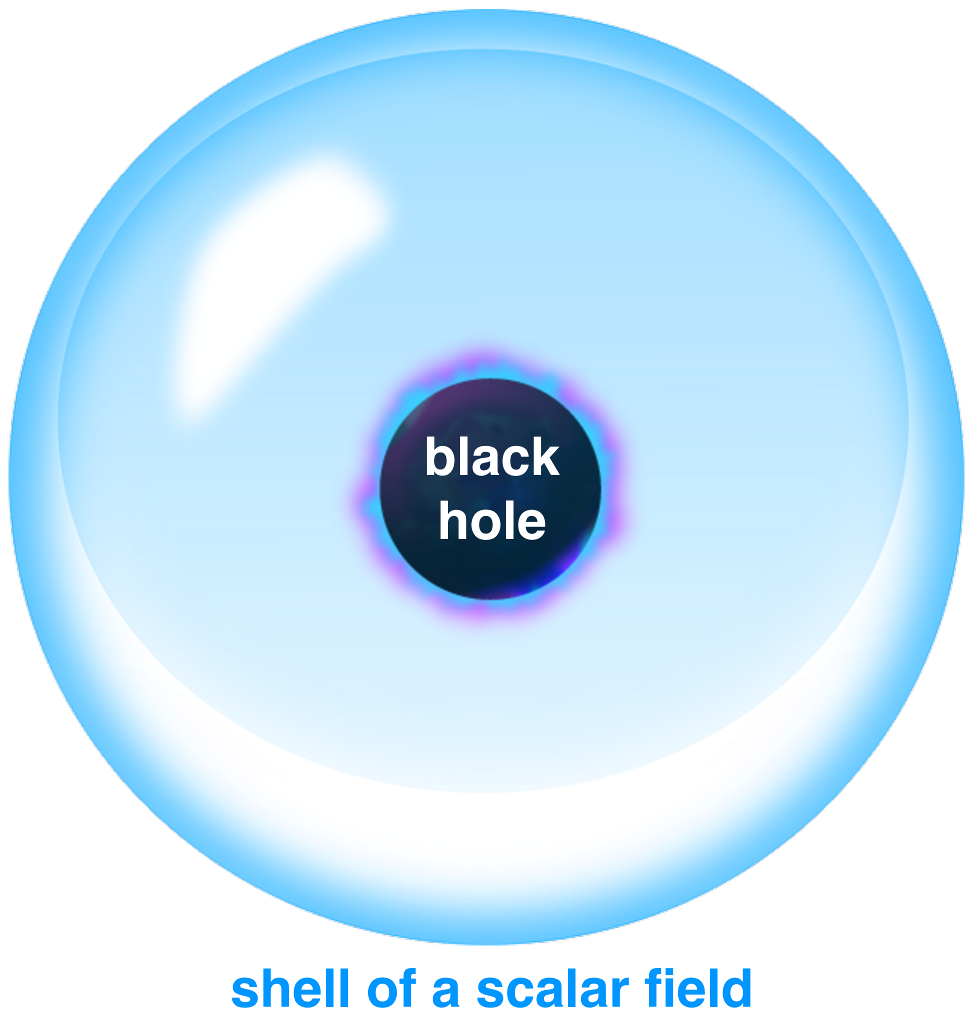
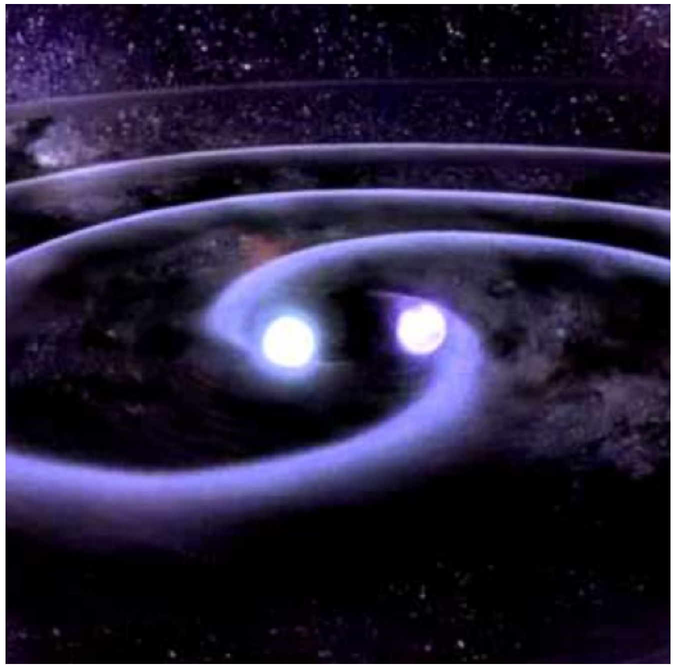
Translation from google

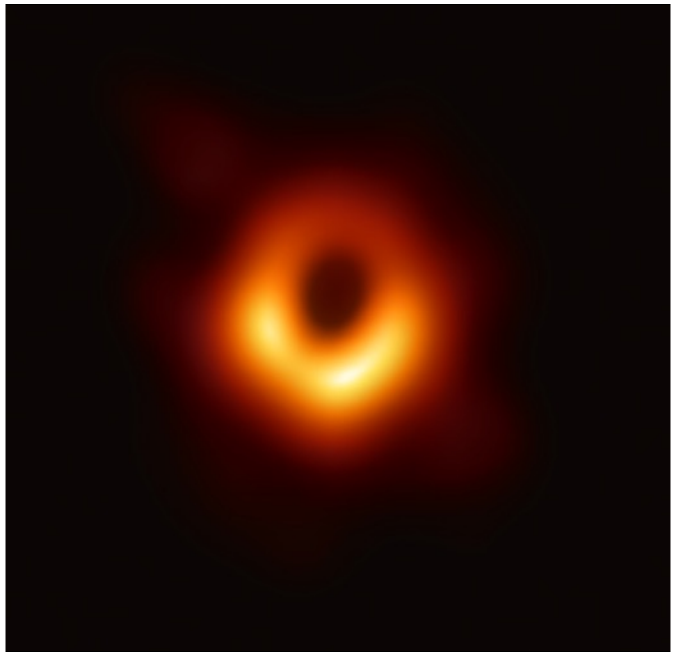
"Shrouded" means covered or enveloped, so as to conceal from view

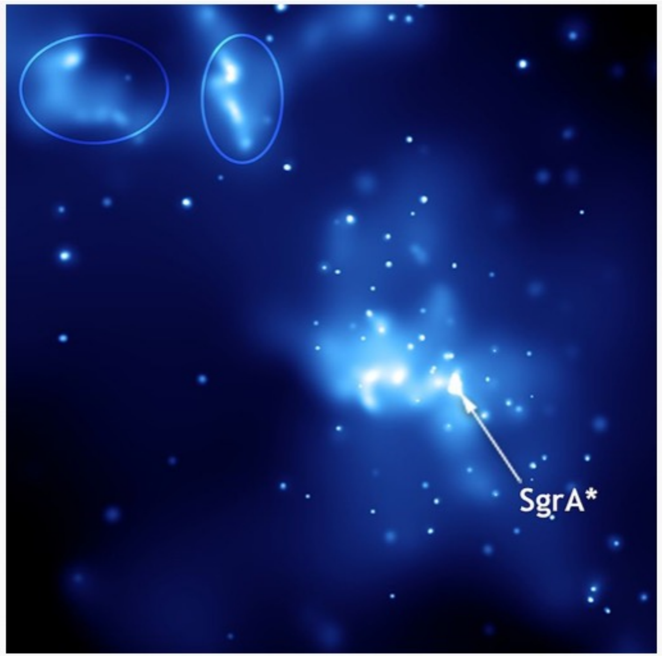


Motivation

Observation of black holes and neutron stars: a breakthrough







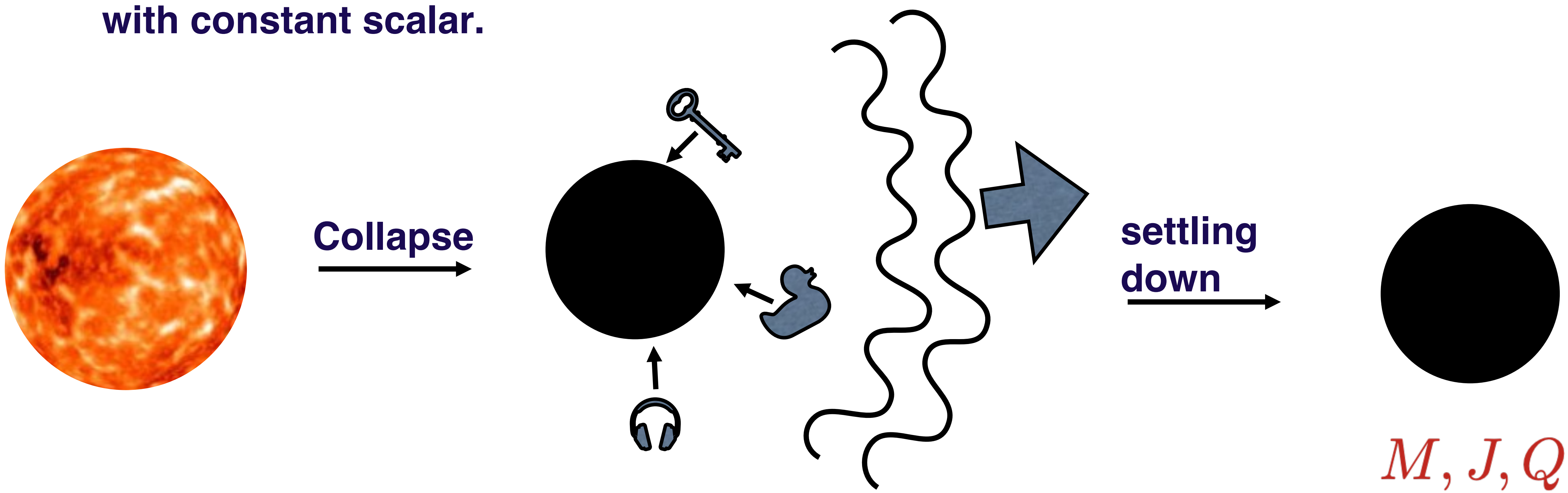
GW signals from binaries at their ringdown phase (LIGO/Virgo)	Image of M87 black hole with its light ring (from array of radio telescopes, EHT)	Observation of star trajectories orbiting SgrA central black hole (GRAVITY)

- Alternatives to GR black holes and stars as precise rulers of departure from GR?

Black holes are bald in GR

- Gravitational collapse...
- Black holes eat or expel surrounding matter
- Their stationary phase is characterised by a limited number of charges
- No details about collapse
- Black holes are bald

- **No hair theorems/arguments dictate that adding degrees of freedom lead to trivial (General Relativity) or singular solutions.**
- **E.g. in the standard scalar-tensor theories BH solutions are GR black holes with constant scalar.**

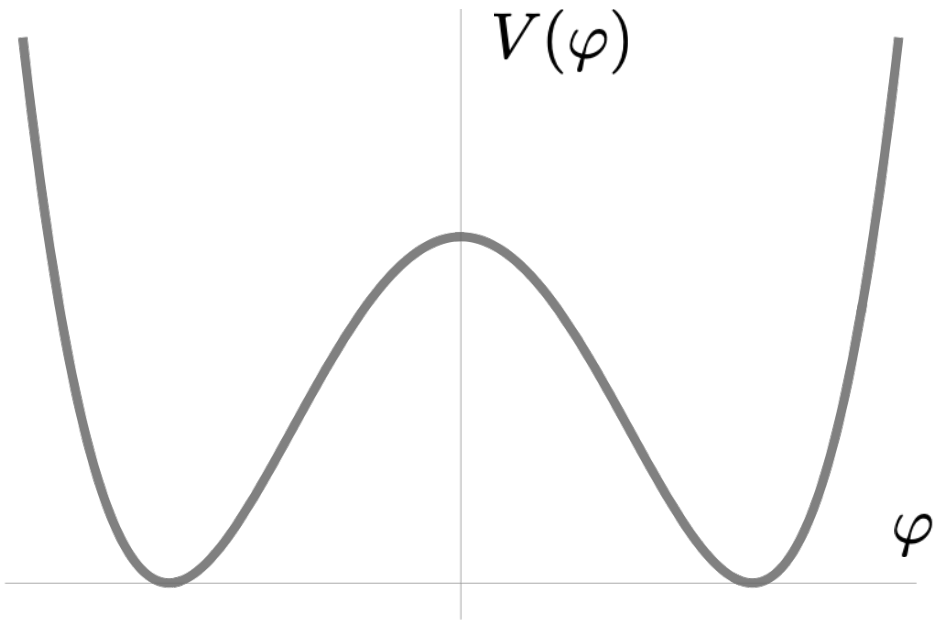


"Standard" domain walls

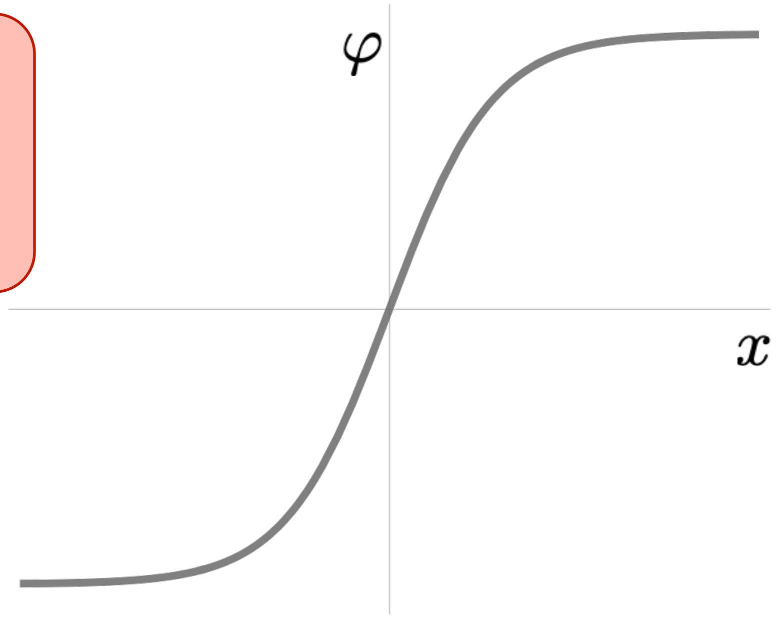
$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi)$$

$$V(\chi) = \frac{\lambda}{4}\left(\varphi^2 - \eta^2\right)^2$$

(-+++) signature



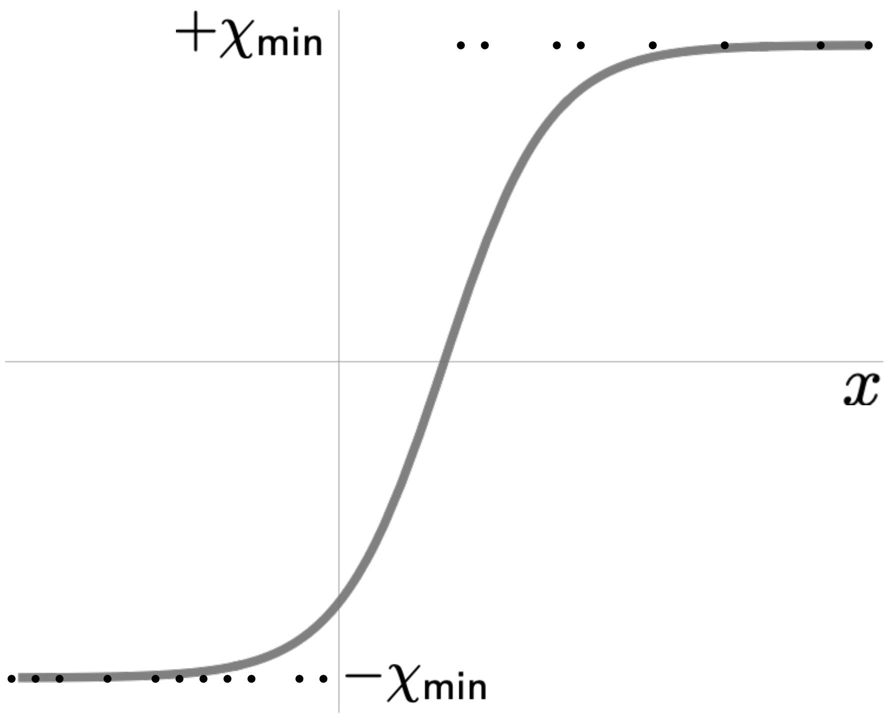
Kink solution $\varphi(x) = \eta \tanh\left(\sqrt{\frac{\lambda}{2}}\eta x\right)$

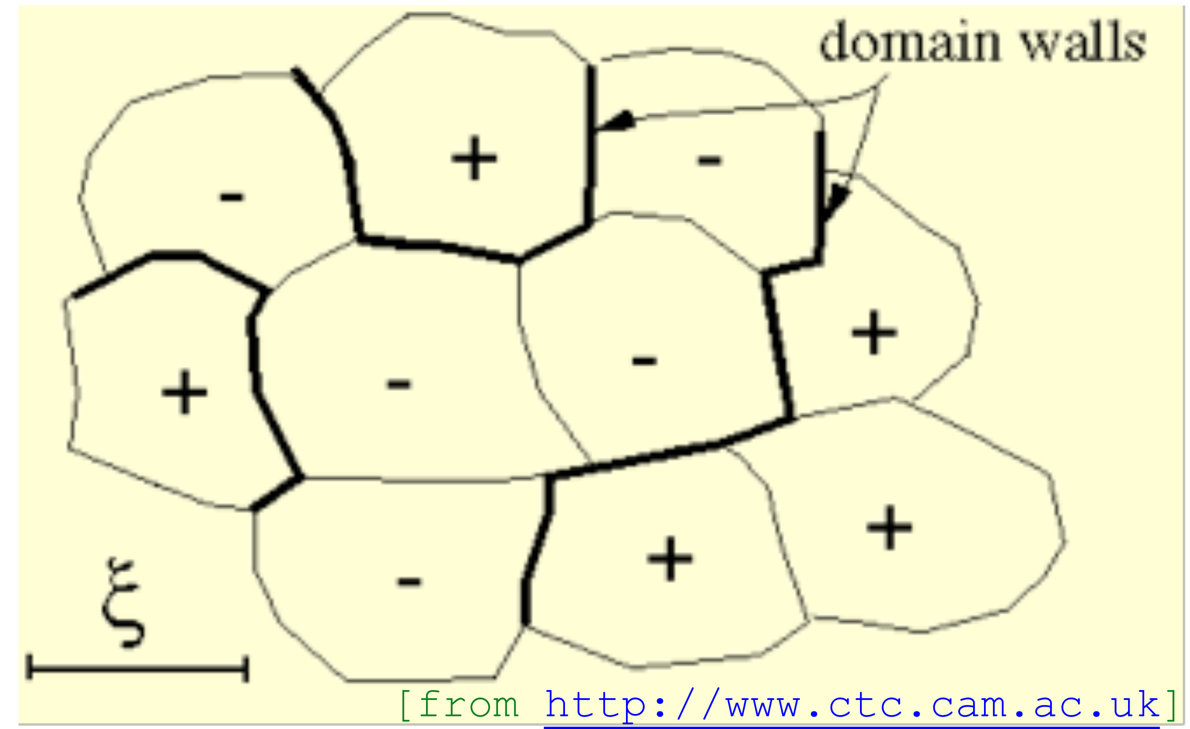


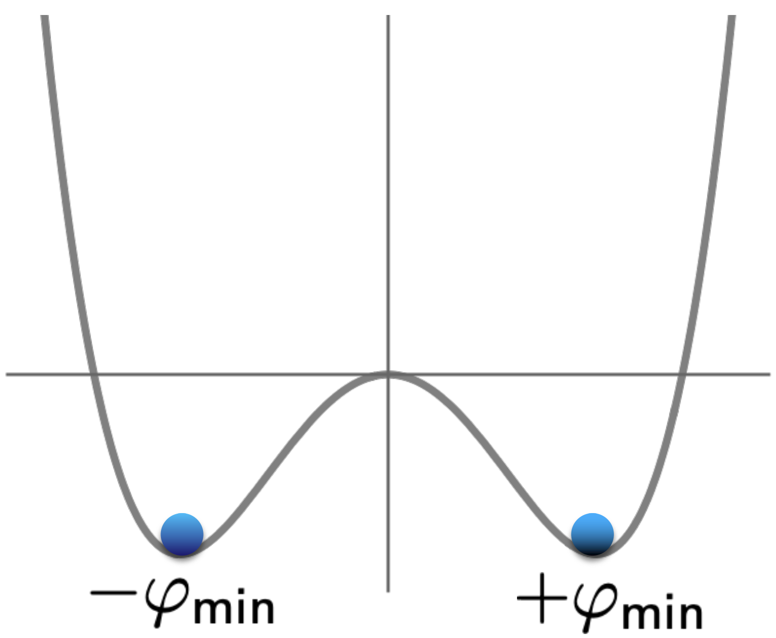
Width $\delta \sim \left(\sqrt{\lambda}\eta\right)^{-1}$

Surface density $\sigma \sim \sqrt{\lambda}\eta^3$

Black hole + domain wall ?

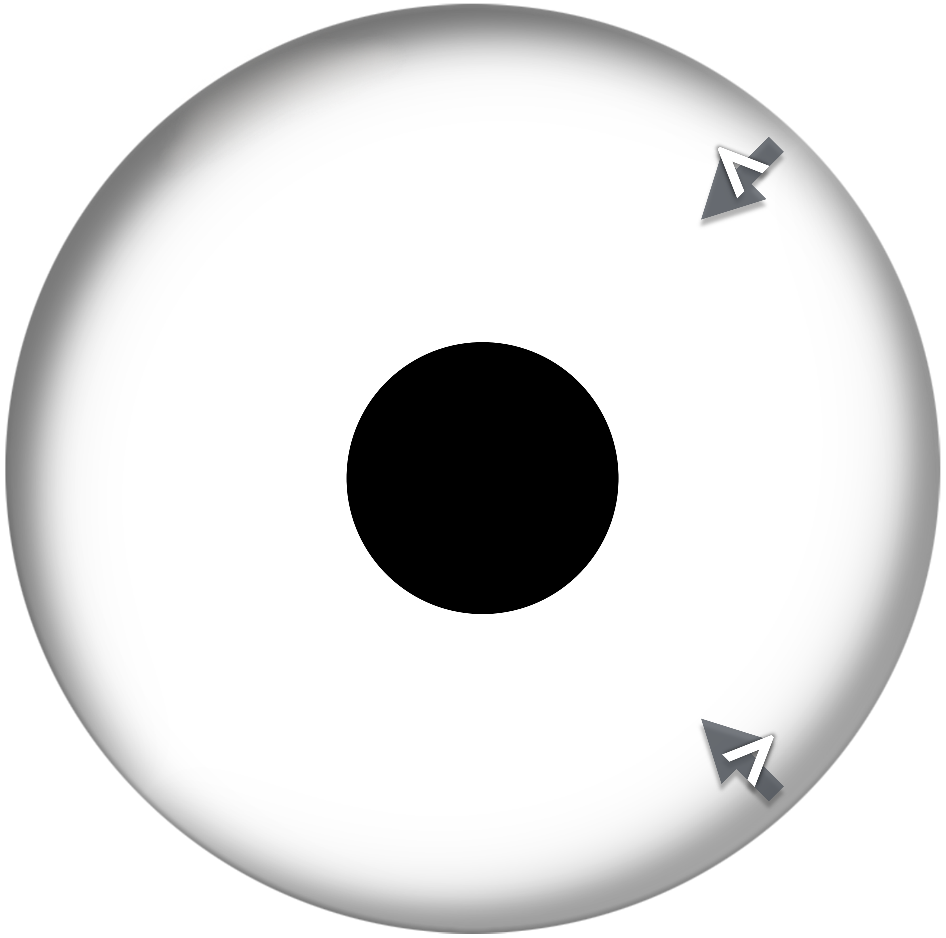






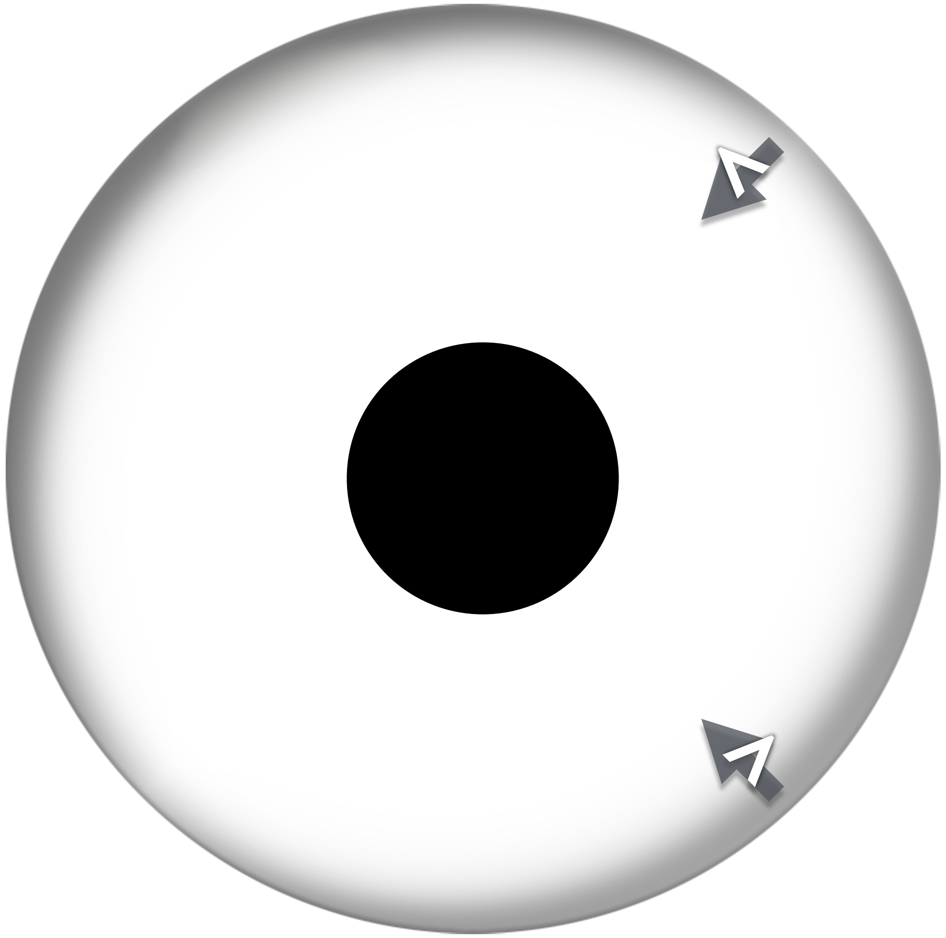
$$S = \int d^4x \left[-\frac{1}{2} \nabla_\mu \varphi \nabla^\mu \varphi - \frac{h^2}{4} \left(\varphi^2 - v^2 \right)^2 \right]$$

Black hole + domain wall ?



Domain wall will collapse because of tension

Black hole + domain wall ?

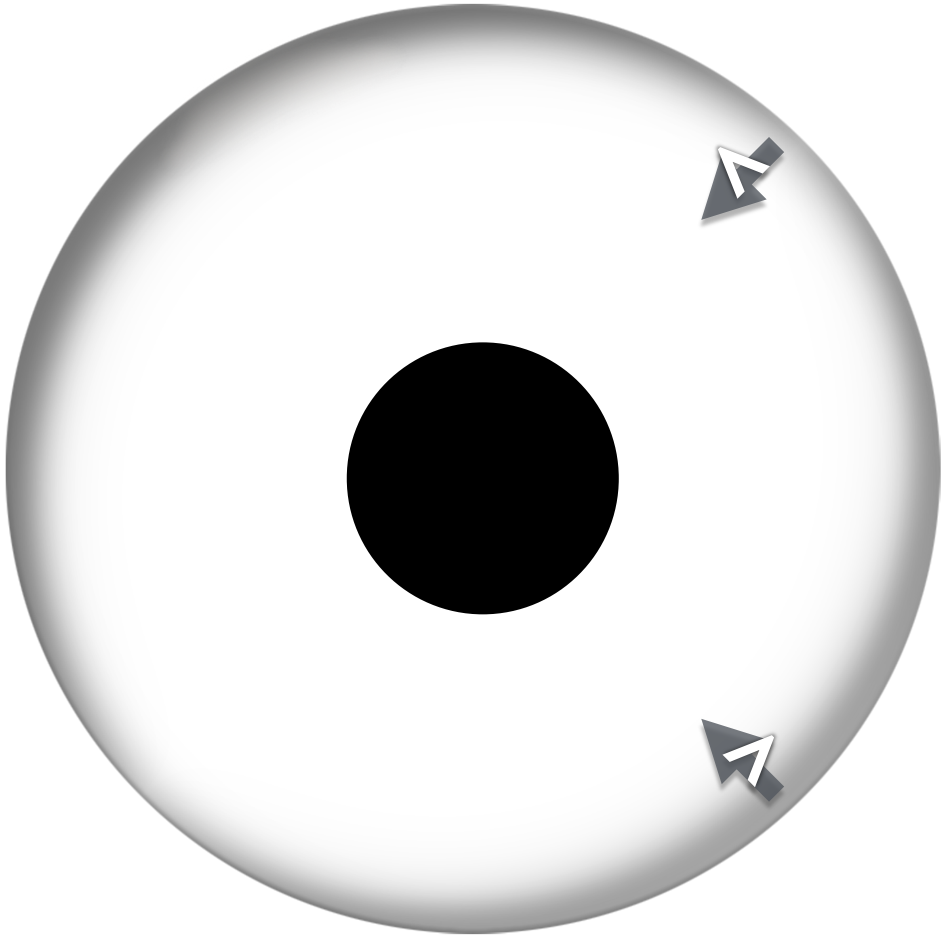


Domain wall will collapse because of tension

Change vacuum near black hole?

- Coupling to curvature $\sim R\varphi^2$? (*A priori* no, because for black holes in vacuum $R = 0$)

Black hole + domain wall ?



Domain wall will collapse because of tension

Change vacuum near black hole?

- Coupling to curvature $\sim R\varphi^2$? (*A priori* no, because for black holes in vacuum $R = 0$)
- Another curvature invariant is Gauss-Bonnet term:

  $\mathcal{R}^2_{\rm GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\lambda\rho}R^{\mu\nu\lambda\rho}$ (non-zero for the black hole background)

  $\mathcal{R}^2_{\rm GB} = \frac{12r_S^2}{r^6}$ for the Schwarzschild black hole

Higgs-like potential + nonminimal coupling to gravity

Action for scalar-tensor model:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}\nabla_\mu\varphi\nabla^\mu\varphi - V(\varphi) - \ell^2\varphi^2\mathcal{R}^2_{\rm GB}\right]$$

$$8\pi G_N = 1$$

where

$$V(\varphi) = \frac{h^2}{4}\cdot\left(\varphi^2 - v^2\right)^2,$$

$$V_{eff}(\varphi) = \frac{h^2}{4}\cdot\left(\varphi^2 - v^2\right)^2 + \ell^2\varphi^2\mathcal{R}^2_{\rm GB}$$

$$\mu = hv$$

Higgs-like potential + nonminimal coupling to gravity

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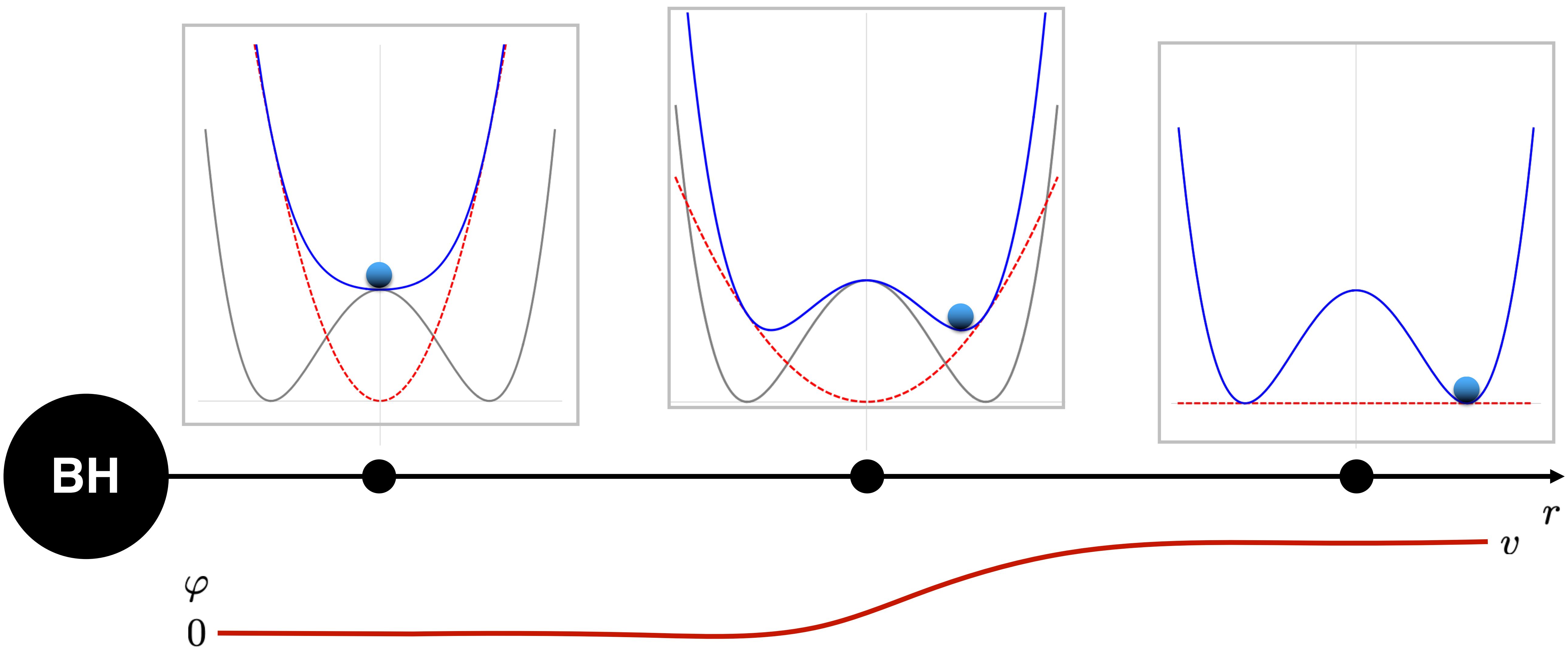


Test field approximation

Assume background geometry and solve equation for the scalar

$$ds^2 = -e^\nu dt^2 + e^\lambda dr^2 + r^2 d\Omega^2, \quad e^\nu = e^{-\lambda} = 1 - \frac{r_S}{r}$$

$$\varphi'' + \left(\nu' + \frac{2}{r}\right) \cdot \varphi' + \frac{8\ell^2\varphi}{r^2} \cdot \left[(1 - e^\nu) \cdot \left(\nu'' + \nu'^2\right) - e^\nu \cdot \nu'^2\right] - e^{-\nu} \cdot V_{,\varphi} = 0$$

Boundary conditions:

$\varphi(\infty) = v$ the scalar is in the vacuum at ∞

$\varphi'_S - \frac{24\ell^2}{r_S^3}\varphi_S - r_S V_{,\varphi}(\varphi_S) = 0$ regularity at the horizon

Test field approximation: cases

Scales in the problem μ, ℓ, r_S ($\mu = hv$).

And extra composite scales: $r_{\rm cross} = \left(\frac{\ell r_S}{\mu}\right)^{1/3}$ and $\frac{1}{\sqrt{\ell r_S}}$.

the crossover radius, where the scalar-Gauss-Bonnet coupling is of the order of the bare mass term $\sim \mu^2$:

$$\mu^2 \sim 2\ell^2 \mathcal{R}^2_{\rm GB}(r_{\rm cross})$$

Always assume $r_{\rm cross} \gtrsim r_S$.
Otherwise, the field φ remains in the spontaneously broken phase

$$\begin{cases} \ell \ll r_S & & \text{(Case I)} \\ \ell \gg r_S & \mu \ll \frac{1}{\sqrt{\ell r_S}} & \text{(Case II)} \\ \ell \gg r_S & \mu \gg \frac{1}{\sqrt{\ell r_S}} & \text{(Case III)} \end{cases}$$

Test field approximation: cases

Case I

$\ell \ll r_S$: Perturbative regime, expansion in terms of ℓ^2.

φ deviates by a small value (including at φ_S) from the expectation value at infinity v.

$$\frac{\delta\varphi}{v} \simeq -\frac{10\ell^2}{r_S r} e^{-\sqrt{2}\mu r}$$

Case II

$$\varphi = \begin{cases} \text{exponentially close to } 0 \text{ at small } r \\ \frac{v}{2} \cdot \left(\frac{\sqrt{6}\ell r_S}{r^2}\right)^{1/4} K_{1/4}\left(\frac{\sqrt{6}\ell r_S}{r^2}\right) & r_S \ll r \ll \mu^{-1} \\ \text{exponentially close to } v \text{ at large } r \end{cases}$$

Case III

Rather similar to the *Case II*, however can be made much steeper.

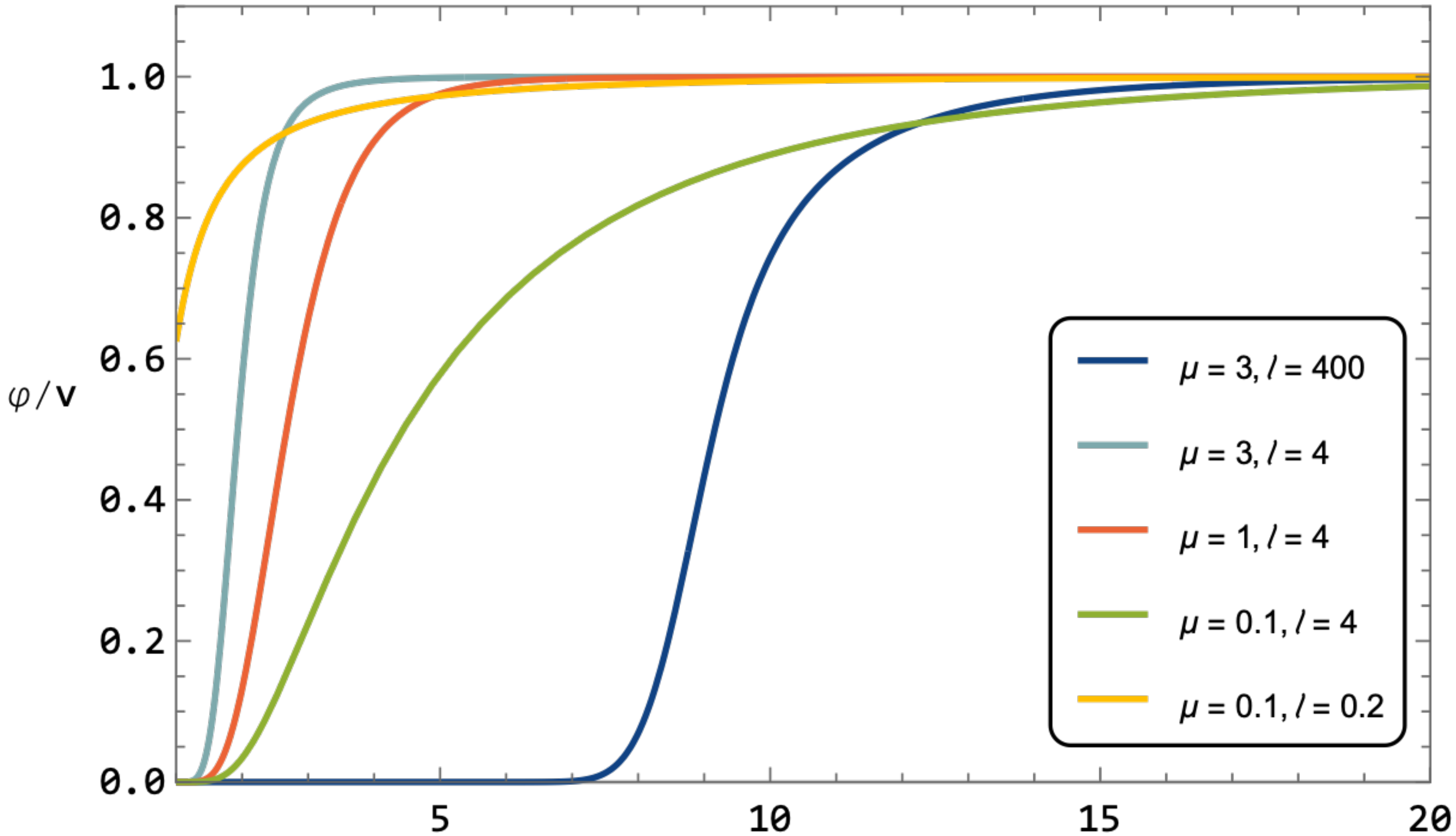
$$r_{\text{wall}} \sim r_{\text{cross}} \sim 1.7 \cdot \left(\frac{\ell r_S}{\mu}\right)^{1/3}$$

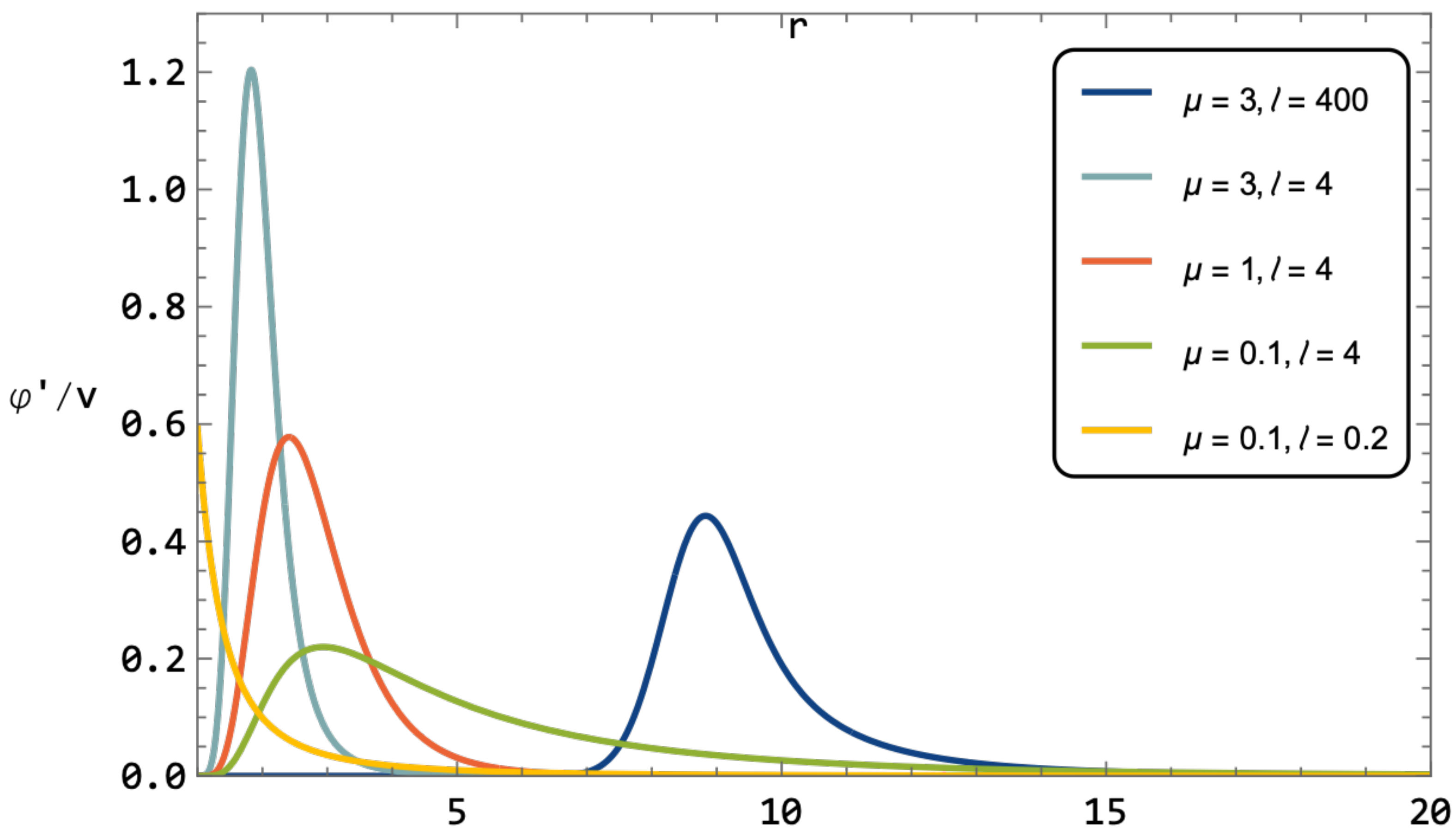
Position of wall

$$\delta_{\text{wall}} \sim \frac{(\ell r_S)^{1/9}}{\mu^{7/9}}$$

Width of wall

Test field approximation: plots





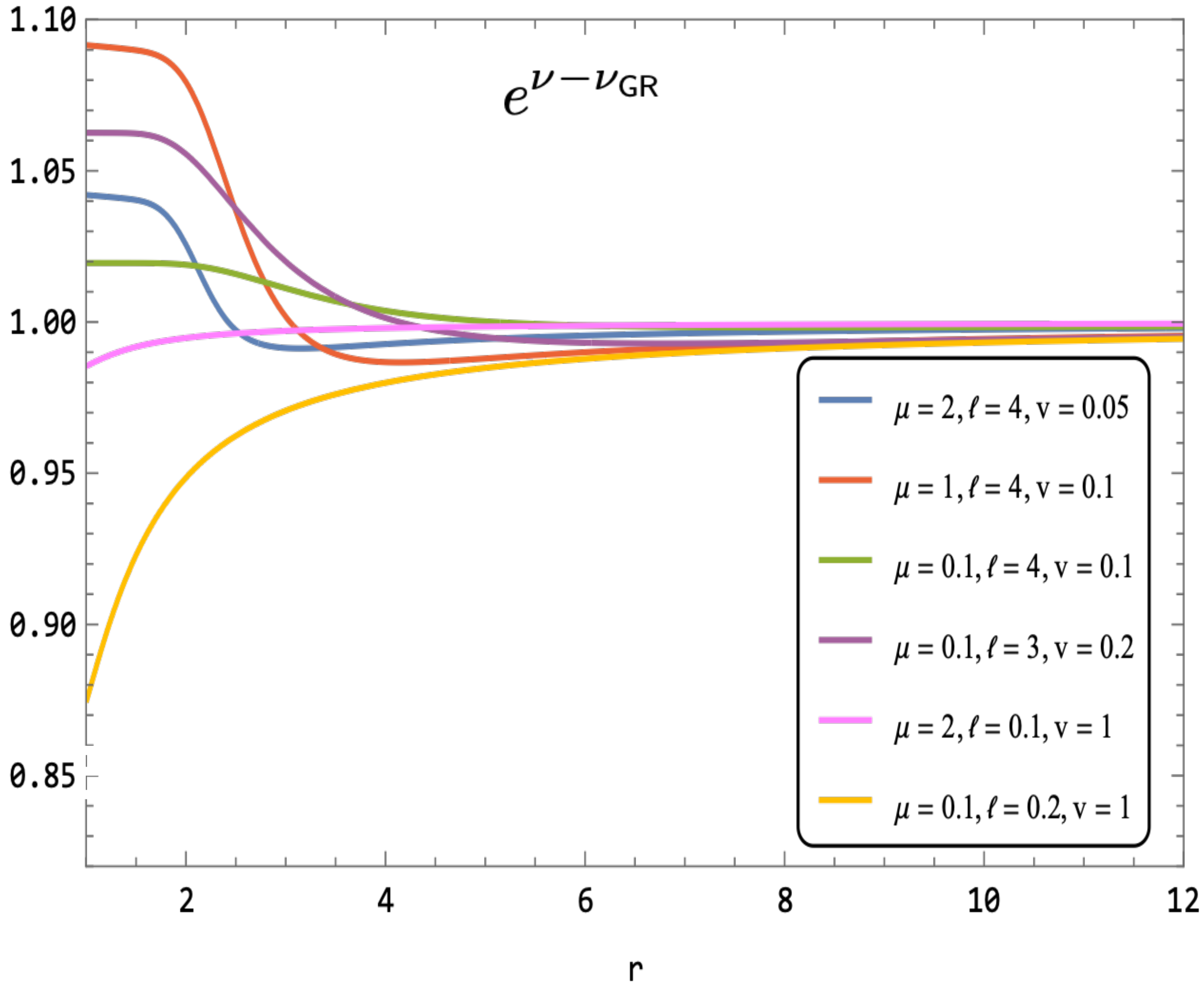
Full system including backreaction

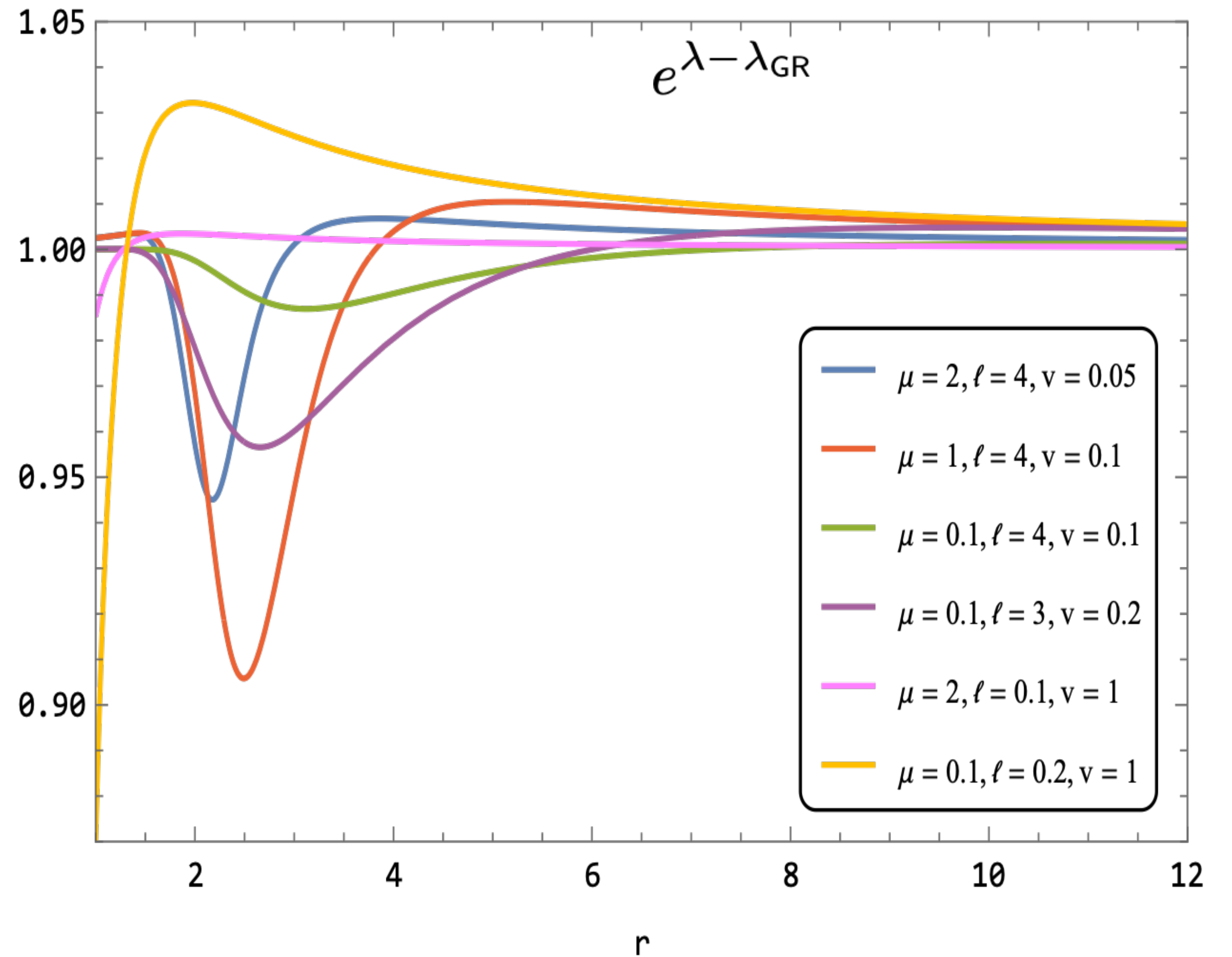
$$ds^2 = -e^\nu dt^2 + e^\lambda dr^2 + r^2 \cdot \left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

- Now solve for $\nu(r)$, $\lambda(r)$ and $\varphi(r)$.

-Metric equations tt, rr, $\theta\theta$ and the scalar equation. Only 3 equations are independent.

Scalar field profile similar to test field profile





Full system including backreaction

Condition

$$v \lesssim \frac{1}{\mu\ell}$$

Otherwise there is a singularity in EOMs.

Reason: when the system of equations is written in a canonical form, the coefficient(s) of higher-order derivative variables are equal to zero at some r.

$$\left(1 - \frac{128\ell^4\varphi^2\nu' e^{-\lambda}\cdot(1-e^{-\lambda})}{r^2\cdot[r+16\ell^2 e^{-\lambda}\varphi\varphi']}\right)\varphi'' + \ldots = 0$$

Can become zero for large $\mu v\ell$

On the speed of gravitational waves

$$|c_T - 1| \lesssim 10^{-15}$$

B. P. Abbott *et al.* [LIGO Scientific, Virgo, Fermi-GBM and INTEGRAL]

Almost all Horndeski (and beyond) are ruled out ?

$$c_T = 1 + 16\ell^2 \frac{H\dot{\varphi}\varphi - \ddot{\varphi}\varphi - \dot{\varphi}^2}{M_{\rm Pl}^2 - 16\ell^2 H\dot{\varphi}\varphi}$$

φ is in the minimum of spontaneously broken phase slowly drifting due to the Gauss-Bonnet coupling:

$$\varphi \approx v \cdot \left(1 + \frac{\ell^2}{\mu^2}\mathcal{R}_{\rm GB}^2\right)$$

For phenomenologically interesting parameters (e.g. $\ell \sim \mu^{-1} \sim r_S \sim 3$ km, $v \sim 0.1 M_{\rm Pl}$):

$$|c_T - 1| \sim 10^{-135}$$

Instability in early universe, Domain walls

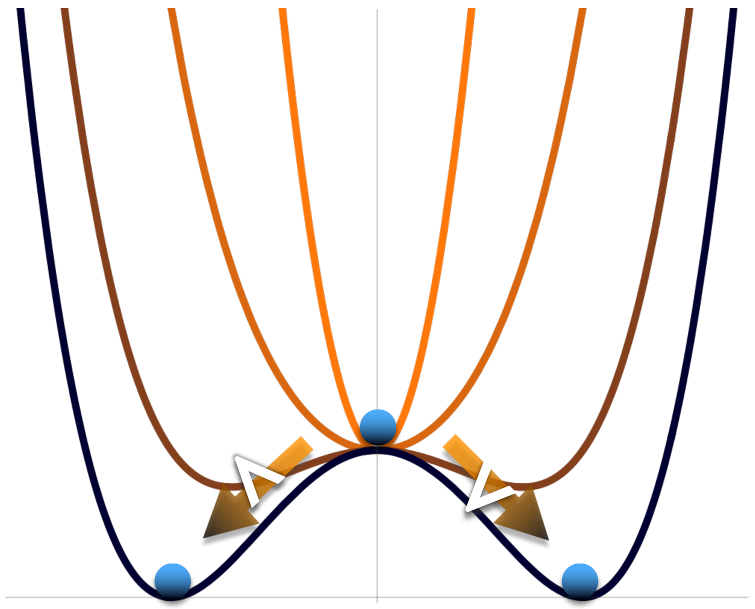
$$\mathcal{R}^2_{\rm GB} = 24H^2\frac{\ddot{a}}{a}$$

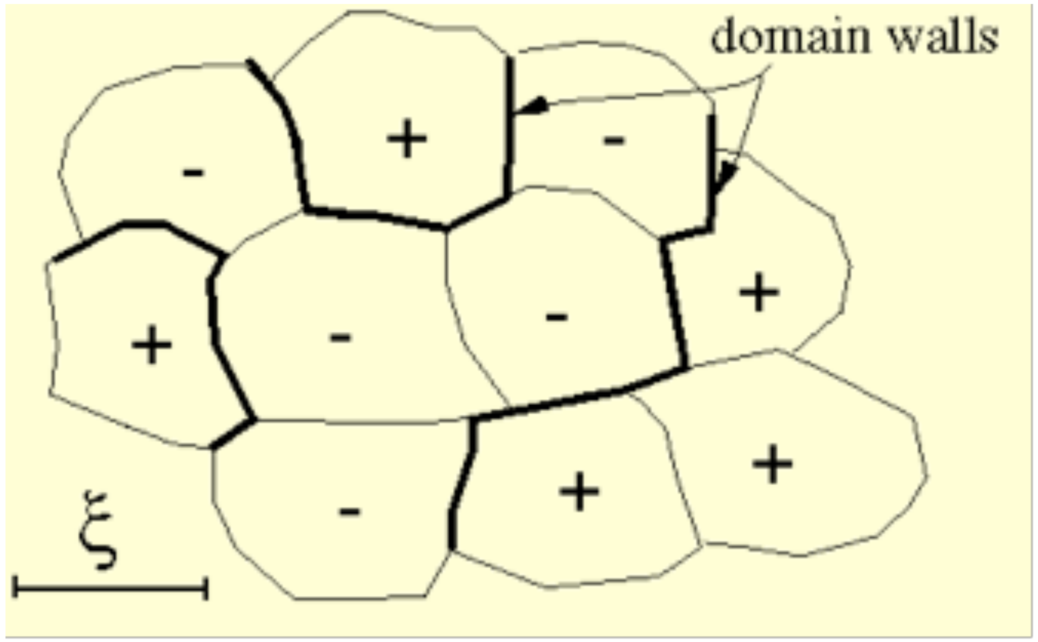
In our case $\ell^2 > 0$, the instability develops in the decelerating Universe.

Instability may still take place during the radiation-dominated stage and preheating. We require that φ, strongly decaying during inflation, does not experience a significant growth at preheating $\Rightarrow$

$$T_{\rm reh} \lesssim 3 \text{ GeV}$$

The symmetry breaks after inflation: domain walls?





a small explicit breaking of Z_2-symmetry $\Rightarrow$ domain walls desappear.

Solar system tests are OK

Conclusion and outlook

- Static black hole solutions in a model with Higgs-like potential and a non-minimal coupling to the Gauss-Bonnet invariant.
- Compared to the previous studies we have the spontaneous breaking of Z_2-symmetry: non-zero vacuum expectation value.
- For a range of parameters, Z_2-symmetry broken at infinity is restored near the BH, where the scalar is almost at zero. A black hole is surrounded by a scalar wall that separates two regions with broken and unbroken Z_2 symmetry.

- Stability of black hole solutions
- Neutron stars and rotating black holes in this model
- Quasinormal modes?
- Singularity in the equation? Look for other solutions?