# (New) entropic (and) classicality condition(s) for brane-world black holes

(Light or not light black holes?)

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# Summary

- Compton classicality condition
- Entropic classicality condition
- ADD black holes
- Tidal brane-world black holes
- Two (three...) scenarios

# Compton classicality condition

Black hole = classical space-time

$\downarrow$

Black hole production by particle collisions = quantum to classical transition

$\downarrow$

Black hole existence = negligible quantum fluctuations

$\downarrow$

Compton condition: $R_{\mathrm{H}} \gg \lambda_{\mathrm{C}}$ $\rightarrow$ $M \gg M_{\mathrm{C}}$

(BH = one particle)

4D Schwarzschild metric:

$$R_{\mathrm{H}} = 2\,\ell_{\mathrm{P}}\,\frac{M}{M_{\mathrm{P}}} \gg \ell_{\mathrm{P}}\,\frac{M_{\mathrm{P}}}{M} = \lambda_{\mathrm{C}} \qquad \Rightarrow \qquad \boxed{M \gg M_{\mathrm{P}}}$$

$$k_{\mathrm{B}} = c = 1\ , \qquad G_{\mathrm{N}} = \frac{\ell_{\mathrm{P}}}{M_{\mathrm{P}}}\ , \qquad \hbar = \ell_{\mathrm{P}}\,M_{\mathrm{P}} = \ell_{\mathrm{G}}\,M_{\mathrm{G}}$$

# Entropic classicality condition

Black hole "area law": horizon area = thermodynamical entropy

$$S_{\mathrm{BH}} = \frac{M_{\mathrm{P}}\, A}{16\,\pi\,\ell_{\mathrm{P}}}$$

Entropic classicality condition:
(BH = composed object)

$$\tilde{S}^{\mathrm{E}}_{(4)} \equiv \frac{S_{\mathrm{BH}}}{\ell_{\mathrm{P}}\, M_{\mathrm{P}}} = \frac{4\,\pi\,R_{\mathrm{H}}^2}{16\,\pi\,\ell_{\mathrm{P}}^2} \gg 1$$

$$M \gg M_{\mathrm{deg}}$$

4D Schwarzschild metric:

$$\tilde{S}^{\mathrm{E}}_{(4)} \simeq \left(\frac{R_{\mathrm{H}}}{\ell_{\mathrm{P}}}\right)^2 \simeq \left(\frac{M}{M_{\mathrm{P}}}\right)^2 \gg 1$$

$$\boxed{M \gg M_{\mathrm{P}}}$$

# ADD black holes

No exact metric

Use 4+d-dimensional Schwarzschild:

$$ds^2 = -A\,dt^2 + A^{-1}\,dr^2 + r^2\left(d\theta^2 + \sin^2\theta\,d\phi^2\right)$$

$$A = 1 - \frac{c_d\,\ell_{\rm G}^{1+d}\,M}{M_{\rm G}\,r^{1+d}}$$

$$\downarrow$$

$$R_{\rm H} = \frac{\ell_{\rm G}}{\sqrt{\pi}}\left(\frac{M}{M_{\rm G}}\right)^{\frac{1}{1+d}}\left(\frac{8\,\Gamma\left(\frac{d+3}{2}\right)}{2+d}\right)^{\frac{1}{1+d}}$$

# ADD black holes

Compton condition:

$$R_{\mathrm{H}} \simeq \ell_{\mathrm{G}} \left(\frac{M}{M_{\mathrm{G}}}\right)^{\frac{1}{1+d}} \gg \ell_{\mathrm{G}} \frac{M_{\mathrm{G}}}{M} = \lambda_{\mathrm{C}} \qquad \Rightarrow \qquad M \gg M_{\mathrm{G}}$$

Entropic condition:

$$\tilde{S}^{\mathrm{E}}_{(4+d)} \equiv \frac{S_{\mathrm{BH}}}{\ell_{\mathrm{G}}\, M_{\mathrm{G}}} \simeq \left(\frac{R_{\mathrm{H}}}{\ell_{\mathrm{G}}}\right)^{2+d} \simeq \left(\frac{M}{M_{\mathrm{G}}}\right)^{\frac{2+d}{1+d}} \gg 1 \quad \rightarrow \quad M \gg M_{\mathrm{G}}$$

$$\downarrow$$

$$\boxed{M_{\mathrm{C}} \simeq M_{\mathrm{deg}} \simeq M_{\mathrm{G}}}$$

# Tidal brane-world black holes

N. Dadhich et al, PLB 487 (2000) 1

No exact bulk metric

5D Einstein equations → project on brane → Effective 4D Einstein equations

## Tidal-charged black holes

$$ds^2 = -A\,dt^2 + A^{-1}\,dr^2 + r^2\left(d\theta^2 + \sin^2\theta\,d\phi^2\right)$$

$$A = 1 - \frac{2\,\ell_{\rm P}\,M}{M_{\rm P}\,r} - q\,\frac{\ell_{\rm G}^2}{r^2}$$

More solutions...

$$\begin{cases} M = M(M_0) \\ q = q(M_0) \end{cases}$$

# Tidal brane-world black holes

Horizon radius: $$R_{\mathrm{H}} = \ell_{\mathrm{P}} \left( \frac{M}{M_{\mathrm{P}}} + \sqrt{\frac{M^2}{M_{\mathrm{P}}^2} + q\,\frac{M_{\mathrm{P}}^2}{M_{\mathrm{G}}^2}} \right)$$

Tidal charge: $$q \geq 0$$

$$q(M=0) = 0$$

$$\downarrow$$

Approximations: $$q \simeq q(M_{\mathrm{C}}) \qquad M \sim M_{\mathrm{G}} \ll M_{\mathrm{P}}$$

Compton condition: $$R_{\mathrm{H}} \gg \lambda_{\mathrm{C}} \quad \rightarrow \quad \boxed{M \gtrsim M_{\mathrm{C}} \simeq \frac{M_{\mathrm{G}}}{\sqrt{q}}}$$

# Tidal brane-world black holes

Entropy: $$\tilde{S}^{\mathrm{E}}_{\mathrm{eff}} \simeq \frac{4\,\pi\,R_{\mathrm{H}}^2}{16\,\pi\,\ell_{\mathrm{P}}^2}$$

$M = M_{\mathrm{C}}$ not a minimum

$$\downarrow$$

Subtracted entropy: $$\tilde{S}^{\mathrm{E}}_{\mathrm{sub}} \simeq \tilde{S}^{\mathrm{E}}_{\mathrm{eff}}(M) - \tilde{S}^{\mathrm{E}}_{\mathrm{eff}}(M_{\mathrm{C}})$$

Entropic condition: $$\tilde{S}^{\mathrm{E}}_{\mathrm{sub}} \gg 1$$

$$q \simeq q(M_{\mathrm{C}}) \qquad M \sim M_{\mathrm{G}} \ll M_{\mathrm{P}}$$

$$\downarrow$$

$$\boxed{M \gtrsim M_{\mathrm{deg}} \simeq \frac{M_{\mathrm{G}}}{\sqrt{q}}}$$

## Two (three...) scenarios

$$M_{\rm deg} \simeq M_{\rm C} \simeq \frac{M_{\rm G}}{\sqrt{q}}$$

$\downarrow$

$q \simeq 1$ $\rightarrow$ Brane-world microscopic black holes similar to 5D ADD

$q \gg 1$ $\rightarrow$ Brane-world black holes at LHC even if $M_{\rm G} \gtrsim 10$ TeV and bulk graviton exchanges suppressed

$q \ll 1$ $\rightarrow$ No black holes at LHC even if $M_{\rm G} \simeq 1$TeV and bulk gravitons detectable

$\downarrow$

I) Black holes found at LHC $\longrightarrow$ Extra dimensions!

II) Black holes not found at LHC $\longrightarrow$ Not clear...

# Tidal charge from...

Independent estimates:

1) absence of spurious singularities in the bulk (requires solving 5D equations)

R.C. and O. Micu, PRD 81 (2010) 104024

$$q \gtrsim \frac{M}{M_{\mathrm{P}}} \left( \frac{M_{\mathrm{G}}}{M_{\mathrm{P}}} \right)^2$$

2) stellar models (matching conditions at star surface + "black hole" limit)

R.C. and J. Ovalle, in progress

3) ... suggestions?