3ªEscola do Programa de Pós-Graduação em Física da UERJ

Massive scalar wave packet emission by a charged Black Hole and Cosmic Censorship Conjecture Violation

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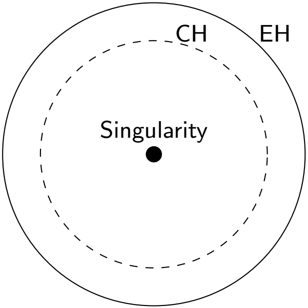
Introduction



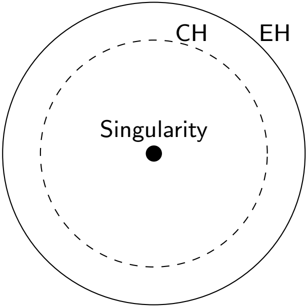
Black Hole: M, Q, J

$$M^2 \geqslant Q^2 + (J/M)^2$$

$$r_{CH} = M - \sqrt{M^2 - Q^2 - (J/M)^2}$$

$$r_{EH} = M + \sqrt{M^2 - Q^2 - (J/M)^2}$$

The CCC



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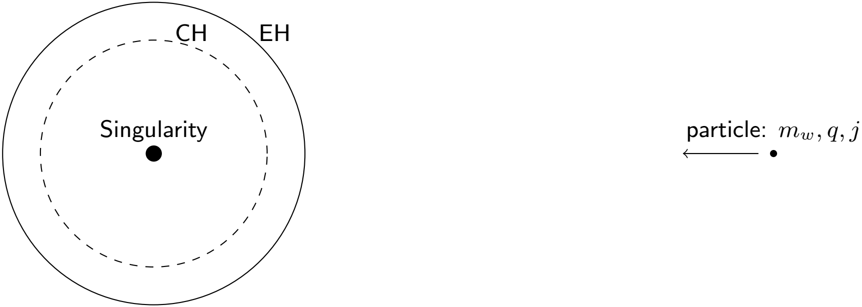
Particle absorption



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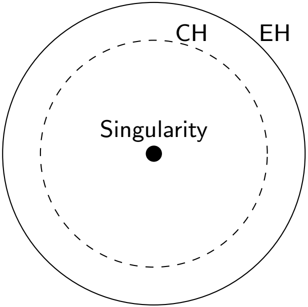
After absorption



$$M' = M + m_w,\ Q' = Q + q,\ J' = J + j$$

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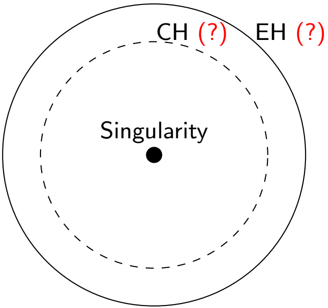

$$M' = M + m_w,\ Q' = Q + q,\ J' = J + j$$

Does $M'^2 \geqslant Q'^2 + (J'/M')^2$ upholds?

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Singularity

Does $M'^2 \geqslant Q'^2 + (J'/M')^2$ uphold?

If not, then r_{CH} and r_{EH} becomes imaginary, exposing the singularity!

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Massive scalar field scattering

Static, charged black hole:

$$ds^2 = -\left(1 - \frac{r_s}{r} + \frac{r_q^2}{r^2}\right) dt^2 + \left(1 - \frac{r_s}{r} + \frac{r_q^2}{r^2}\right)^{-1} dr^2 + r^2\, d\theta^2 + r^2 \operatorname{sen}^2\theta\, d\varphi^2 \tag{1}$$

Klein-Gordon equation:

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}\, g^{\mu\nu}\partial_\nu \Phi(t, \mathbf{r})\right) - \mu^2\Phi(t,(r)) = 0 \tag{2}$$

$R(r)$ and $\Theta(\theta)$:

$$r^2\left(1 - \frac{r_s}{r} - \frac{r_q^2}{r^2}\right)\frac{d^2R}{dr^2} + r\left(2 - \frac{r_s}{r}\right)\frac{dR}{dr} + \left(\frac{\omega^2 r^2 + [(r_s - r)r + r_q^2]\mu^2}{1 - \frac{r_s}{r} - \frac{r_q^2}{r^2}} - \mathcal{A}\right)R = 0, \tag{3}$$

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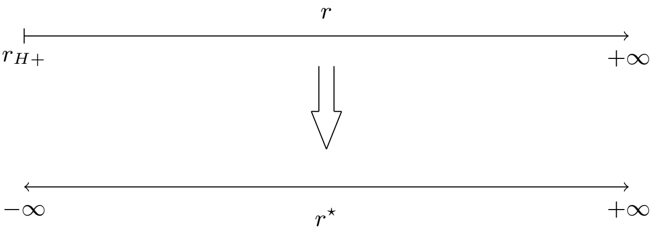
"Detour"

Tortoise coordinate:

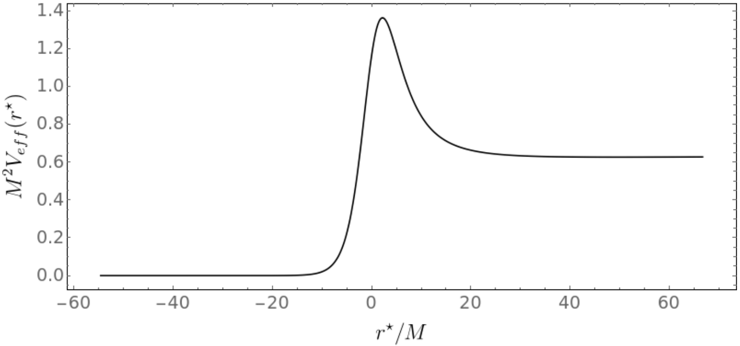
$$\frac{\mathrm{d}r}{\mathrm{d}r^{\star}} := 1 - \frac{r_s}{r} + \frac{r_q^2}{r^2} \tag{5}$$



Schrödinger? Just like it.

$$\left[\frac{\mathrm{d}^2}{\mathrm{d}r^{\star 2}} + \omega^2 - V_{eff}(r)\right] u_{\omega\ell m}(r) = 0,$$

$$V_{eff}(r) := \left(1 - \frac{r_s}{r} + \frac{r_q^2}{r^2}\right)\left(\frac{\ell(\ell+1)}{r^2} + \frac{r_s}{r^3} - \frac{2r_q^2}{r^4} + \mu^2\right) \quad (6)$$



Issues

- The effective potential in equation (6) is not analytically integrable to find $u_{\omega\ell m}(r)$.
- Most common approaches: Low (or high) frequency regimes; numerical analysis.
- Our approach: Toy model

$$V_{toy}(r^\star) = \begin{cases} V_1(r^\star) := b_1 \operatorname{sech}^2[a_1(r^\star - c_1)], & r^\star < r_0^\star \\ V_2(r^\star) := (b_2 - \mu^2)\left\{\left[1 - e^{-a_2(r^\star - c_2)}\right]^2 - 1\right\}, & r^\star \geqslant r_0^\star \end{cases} \tag{7}$$

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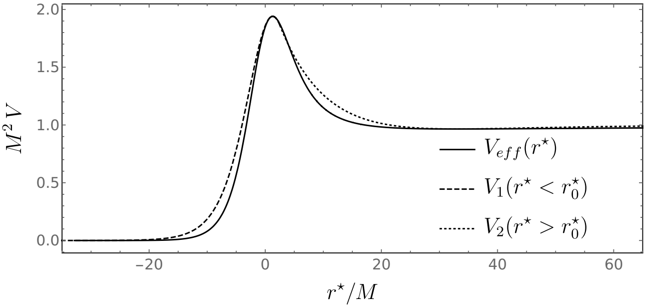

Asymptotic limit and plane waves

In the asymptotic limit $r^\star \pm \to \infty$, we recover plane waves.

$$u_{\ell m}(r^\star) \approx \begin{cases} t_{\omega \ell m} e^{-i\omega r^\star}, & r^\star \to -\infty \\ k_{\omega \ell m} e^{-\varpi r^\star} + r_{\omega \ell m} e^{+\varpi r^\star}, & r^\star \to +\infty \end{cases} \tag{8}$$

with $\varpi := \sqrt{\mu^2 - \omega^2}$.

Transmission and Reflection rates

$$T_w := \left| \frac{t}{k} \right|^2, \quad R_w := \left| \frac{r}{k} \right|^2 \tag{9}$$

Conservation of flux

$$R_w + \left| \frac{\omega}{\varpi} \right| T_w = 1 \tag{10}$$

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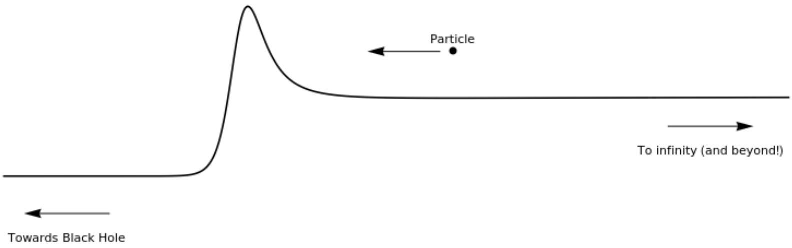
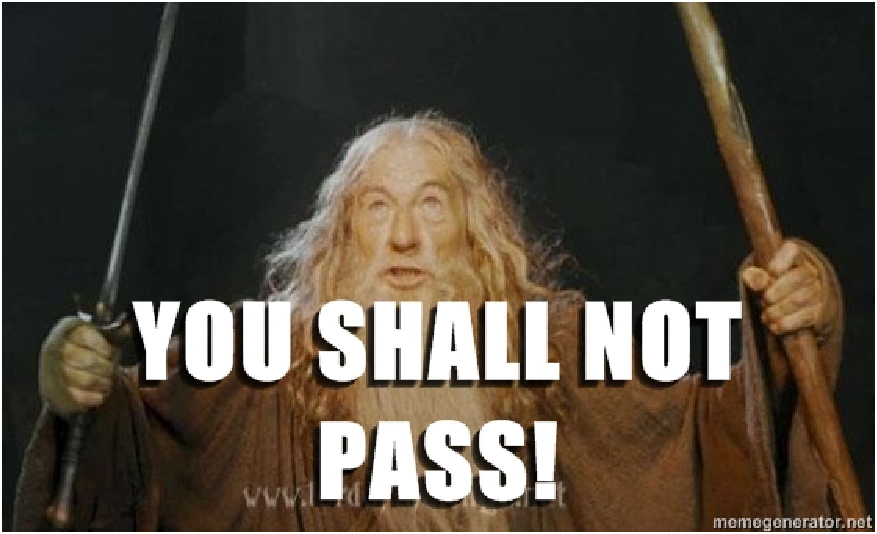
Low energy...

First case: Energy lower than the potential barrier.

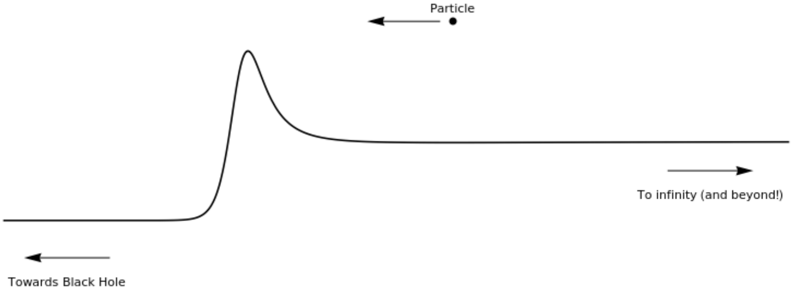


The “censor”



High as fly!

Second case: Energy greater than the potential barrier.



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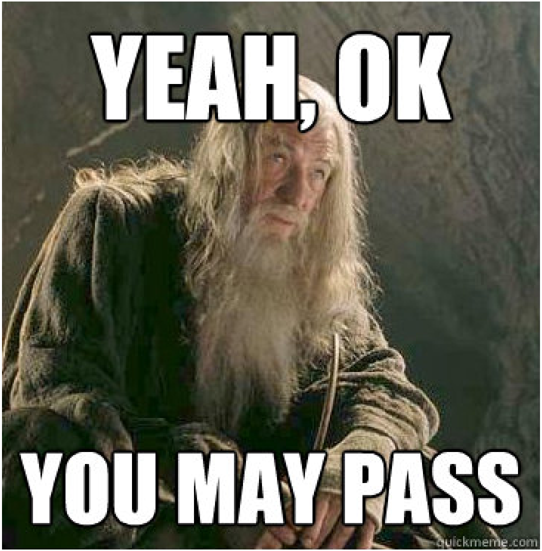
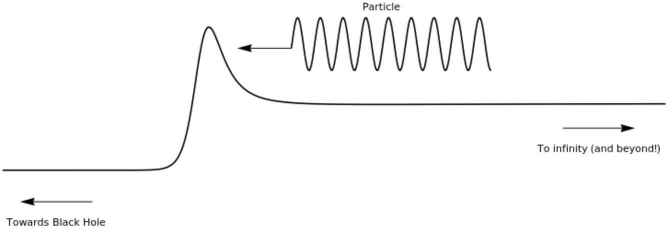


And what if...?

Third case: propagating wave



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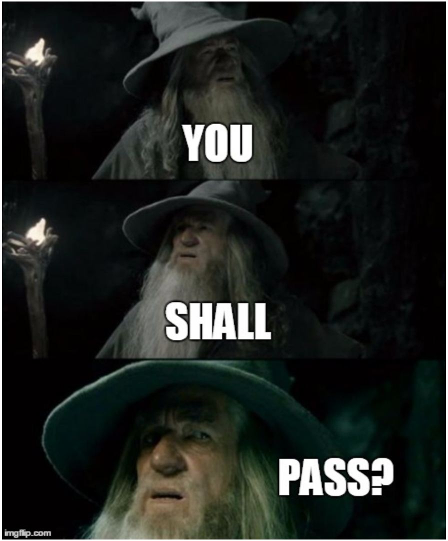
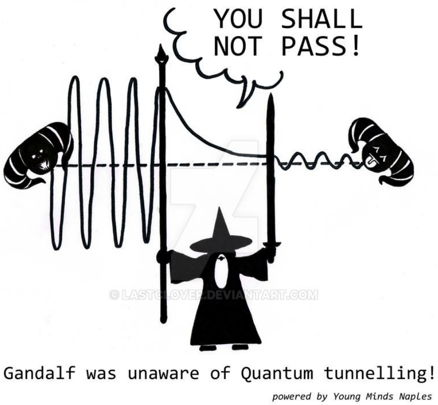


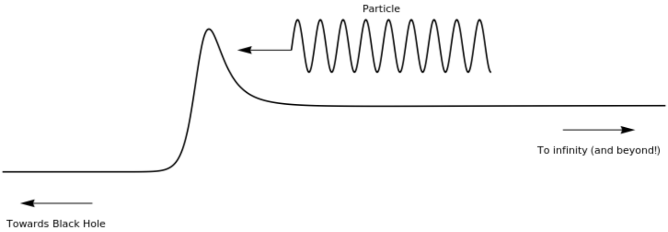
Quantum Tunneling



"...the 'cosmic censor' may be oblivious to process involving quantum effects"

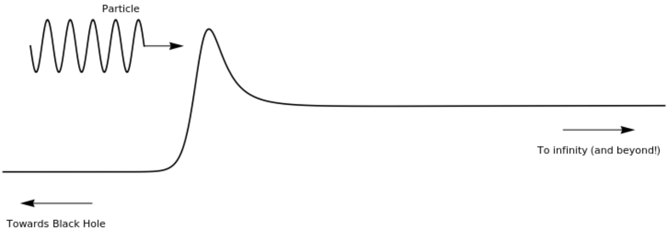
MATSAS, 2009 @ PRD79

If absorption...



Particle absorbed $\implies$ new black hole with mass $M' = M + m_w$

If emission...



Particle emitted $\implies$ new black hole with mass $M' = M - m_w$

Problem?

- Waves are eternal

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  - Backreaction

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    - No geodesic motion; Superradiance

Semiclassical approach

Solutions:

- Build a (gaussian) wave packet from the incoming plane waves

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Solutions:

- Build a (gaussian) wave packet from the incoming plane waves
  - Packet is localized in the position space
- Still no charge $\implies$ no superradiance; geodesic motion

Wave packet

Gaussian wave packet from the incoming waves

$$\psi_i(t,r^\star) := \int_{\omega_0-2\tilde{\xi}}^{\omega_0+2\tilde{\xi}} k_{\omega\ell m}\tilde{\psi}(\omega)e^{-i\omega(t+r)}\,\mathrm{d}\omega, \quad \tilde{\psi}(\omega) := \frac{1}{(2\pi\tilde{\xi}^2)^{1/4}}e^{-\frac{(\omega-\omega_0)^2}{4\tilde{\xi}^2}} \tag{11}$$

Reflected and transmitted packets

$$\psi_r(t,r^\star) := \int_{\omega_0-2\tilde{\xi}}^{\omega_0+2\tilde{\xi}} r_{\omega\ell m}\tilde{\psi}(\omega)e^{i\omega(t-r)}\,\mathrm{d}\omega, \quad \psi_t(t,r^\star) := \int_{\omega_0-2\tilde{\xi}}^{\omega_0+2\tilde{\xi}} t_{\omega\ell m}\tilde{\psi}(\omega)e^{-i\omega(t+r)}\,\mathrm{d}\omega \tag{12}$$

Reflection and Transmission rates

$$R := \frac{\int_{r_p^\star-2\xi}^{r_p^\star+2\xi} |\psi_r|^2\,\mathrm{d}r^\star}{\int_{r_p^\star-2\xi}^{r_p^\star+2\xi} |\psi_i|^2\,\mathrm{d}r^\star}, \quad T := \frac{\int_{r_p^\star-2\xi}^{r_p^\star+2\xi} |\psi_t|^2\,\mathrm{d}r^\star}{\int_{r_p^\star-2\xi}^{r_p^\star+2\xi} |\psi_i|^2\,\mathrm{d}r^\star} \tag{13}$$

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The quantity f_ϵ

Ratio between the transmission rates for the packet for two configurations of the black hole

$$f_\epsilon := \log\left[\frac{T(\mathcal{M}_2)+\epsilon}{T(\mathcal{M}_1)+\epsilon}\right] \implies \begin{cases} f_\epsilon > 0 \implies \text{No CCC Violation} \\ f_\epsilon < 0 \implies \text{CCC Violation} \\ f_\epsilon = 0 \implies \text{Indiferent} \end{cases} \tag{15}$$

$$\left.\begin{array}{ll} \text{Config. 1: } \mathcal{M}_1 := M, & \mathcal{Q} := M - \delta Q \\ \text{Config. 2: } \mathcal{M}_2 := M + \delta M, & \mathcal{Q} := M - \delta Q \end{array}\right\} \text{Near-extremal BH: } \mathcal{Q} \lesssim \mathcal{M} \tag{16}$$

$$\text{CCC: } \mathcal{M} \geqslant \mathcal{Q} \implies M + \delta M - m_w \geqslant M - \delta Q \implies \delta M + \delta Q \geqslant m_w \tag{17}$$

Scale: $M\mu = 1$. For $M \approx 10 M_\odot \implies m_w \approx 10^{-11}\,\mathrm{eV}/c^2 \implies$ axion-like particle

- First set: $\delta Q = 10^{-15} M$
- Second set: $\delta Q = 10^{-70} M$

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- Second set: $\delta Q = 10^{-70} M$

The quantity f_ϵ

Ratio between the transmission rates for the packet for two configurations of the black hole

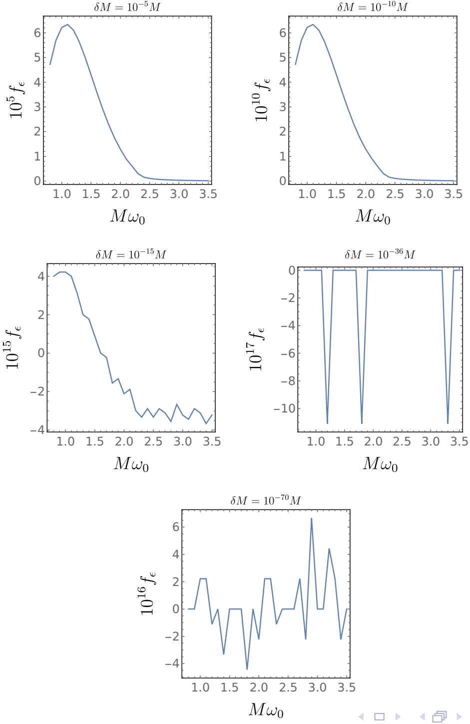
$$f_\epsilon := \log\left[\frac{T(\mathcal{M}_2)+\epsilon}{T(\mathcal{M}_1)+\epsilon}\right] \implies \begin{cases} f_\epsilon > 0 \implies \text{No CCC Violation} \\ f_\epsilon < 0 \implies \text{CCC Violation} \\ f_\epsilon = 0 \implies \text{Indiferent} \end{cases} \quad (15)$$

$$\left.\begin{array}{ll} \text{Config. 1: } \mathcal{M}_1 := M, & \mathcal{Q} := M - \delta Q \\ \text{Config. 2: } \mathcal{M}_2 := M + \delta M, & \mathcal{Q} := M - \delta Q \end{array}\right\} \text{Near-extremal BH: } \mathcal{Q} \lesssim \mathcal{M} \quad (16)$$

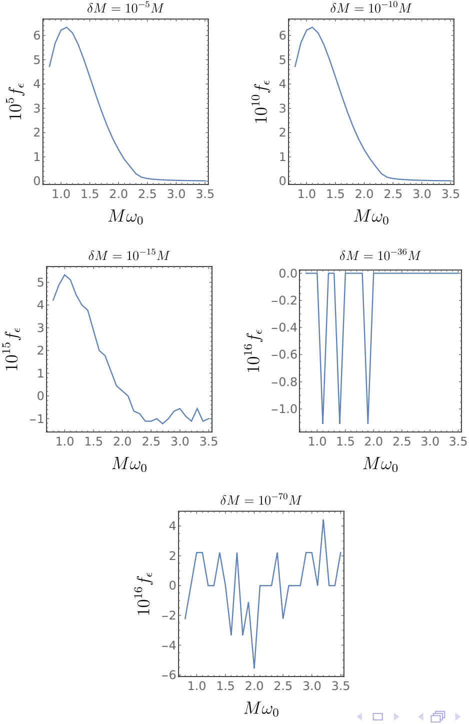
$$\text{CCC: } \mathcal{M} \geqslant \mathcal{Q} \implies M + \delta M - m_w \geqslant M - \delta Q \implies \delta M + \delta Q \geqslant m_w \quad (17)$$

Scale: $M\mu = 1$. For $M \approx 10 M_\odot \implies m_w \approx 10^{-11}$ eV/c^2 $\implies$ axion-like particle

- First set: $\delta Q = 10^{-15} M$
- Second set: $\delta Q = 10^{-70} M$



δM = 10^−5 M
10^5 f_ϵ
Mω_0
δM = 10^−10 M
10^10 f_ϵ
Mω_0
δM = 10^−15 M
10^15 f_ϵ
Mω_0
δM = 10^−36 M
10^17 f_ϵ
Mω_0
δM = 10^−70 M
10^16 f_ϵ
Mω_0



$\delta M = 10^{-5}M$
$10^5 f_\epsilon$
$M\omega_0$
$\delta M = 10^{-10}M$
$10^{10} f_\epsilon$
$M\omega_0$
$\delta M = 10^{-15}M$
$10^{15} f_\epsilon$
$M\omega_0$
$\delta M = 10^{-36}M$
$10^{16} f_\epsilon$
$M\omega_0$
$\delta M = 10^{-70}M$
$10^{16} f_\epsilon$
$M\omega_0$

Conclusion

The "censor" seems to know its limits once the CCC is close to be violated.

Fim!

Muito obrigado!

Grazie mille!