Spin-induced scalarization and magnetic fields

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Motivation and context

Astrophysical magnetic fields

Magnetars' collapse remnant BHs? [Anderson+,1970]

BHs neutrally charged? [Gibbons,1975] - [Blandford+,1977]

Sources in radio-relics [Kempner+,2003] and around BHs, *e.g.* Sgr A* [Mori+,2013] and M87* [EHT,2021]

Accretion disks and magnetized plasma? [Lee+,2007]

Challenging the universality of the Kerr hypothesis

BHs from ~ 1 to 10^{10} $M_\odot$, and all spins really well described by the Kerr metric?

Kerr hypothesis violating models? New scales, hence mass/spin range of *non-Kerrness*

Example? Spontaneous scalarization [Damour+,1993]

In electrovacuum GR the Melvin Universe can scalarize [Brihaye+,2021]

Theory

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(\nabla\phi)^2 + \frac{\eta}{4}\mathfrak{f}(\phi)\mathcal{R}_{\rm GB}\right]$$

Nomenclature

GB$^+$ scalarization: the instability is promoted by regions wherein the GB is (sufficiently) *positive*.

- Schwarzschild BHs scalarize if $M/\sqrt{\eta}$ is small enough [Silva+,2017,Doneva+,2017,Antoniou+,2017]
- Adding spin quenches it [Cunha+,2019,Collodel+,2019]

GB$^-$ scalarization: when the GB is *negative*.

- For Kerr this occurs for dimensionless spin $j > 0.5$ (“spin-induced" [Dima+,2020])

A strong magnetic field in the vicinity of a spinning BH enhancing GB$^-$ for $j < 0.5$?

Melvin

$$ds^2 = \Lambda^2 \left(-dt^2 + d\rho^2 + dz^2\right) + \Lambda^{-2}\rho^2 d\varphi^2, \;\; \Lambda = 1 + (1/4)\, B^2\rho^2$$

Schwarzschild-Melvin

$$ds^2 = \Lambda^2(-f dt^2 + f^{-1}dr^2 + r^2 d\theta^2) + \Lambda^{-2} r^2 \sin^2\theta d\varphi^2, \;\; \Lambda = 1 + (1/4)\, B^2 r^2 \sin^2\theta$$

Kerr-Newman Melvin

$$ds^2 = H\left[-f dt^2 + R^2\left(\frac{dr^2}{\Delta} + d\theta^2\right)\right] + \frac{\Sigma\sin^2\theta}{HR^2}\left(d\varphi - \omega dt\right)^2$$

$$A_\mu = (\Phi_0 - \omega\Phi_3, 0, 0, \Phi_3)$$

[Wald,1974] - [Ernst,1976] - [Gibbons+,2013]

Spontaneous scalarization and necessary conditions

Any electrovacuum GR solution is a solution

$$\frac{\partial \mathfrak{f}}{\partial \phi}(\phi = 0) = 0$$

Tachyonic perturbations exist in regions where $\mathcal{R}_{\rm GB} < 0$ if

$$\eta < 0, \ \frac{\partial^2 \mathfrak{f}}{\partial \phi^2}(\phi = 0) > 0$$

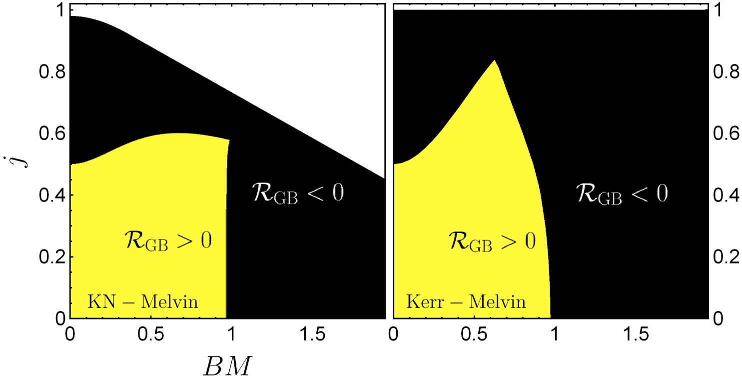
Simplest model

$$\mathfrak{f}(\phi) = \phi^2/2 \Longrightarrow \left(\Box - \mu_{\rm eff}^2\right)\phi = 0 \ \text{(linear perturbations)}$$

where

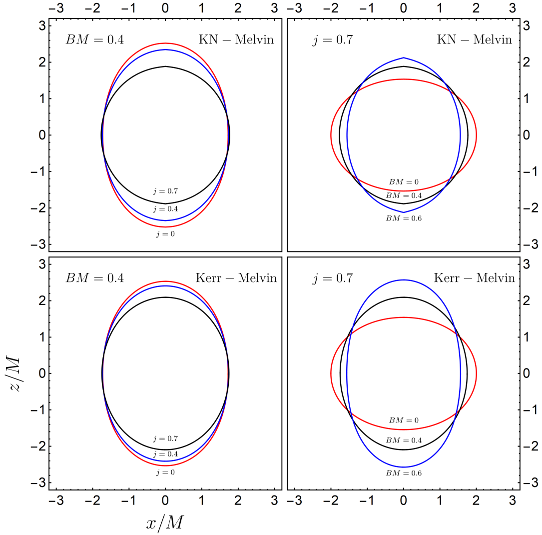
$$\mu_{\rm eff}^2 = -\frac{\eta}{4}\mathcal{R}_{\rm GB}$$

Necessary scalarization condition KN-Melvin



$$B \simeq 2 \times 10^{13}\,\mathrm{G} \left(\frac{4 \times 10^{6} M_{\odot}}{M} \right) ,$$

A geometrical interpretation



Final remarks

Spontaneous scalarization as a mechanism that leads to new field configurations

Objects solely formed by magnetic fields might undergo a *magnetic-induced* scalarization

In EMsGB BHs tend to be more stable once magnetic fields are included (at least poloidal ones)

A thorough analysis of scalar perturbations?