Phenomenology of Magnetic Black Holes with Electroweak-Symmetric Coronas

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1) 2007.03703 (*JHEP* 10 (2020) 210) with Yang Bai, Joshua Berger, and Nicholas Orlofsky
2) 2012.15430 (*JHEP* 04 (2021) 119) with Yang Bai

Introduction

- Open Problems in Fundamental Physics:

    1) Nature of Dark Matter and Dark Energy

    2) Baryogenesis

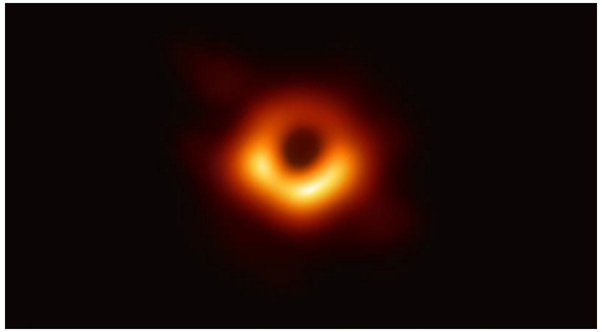
    3) Naturalness/Hierarchy Problem

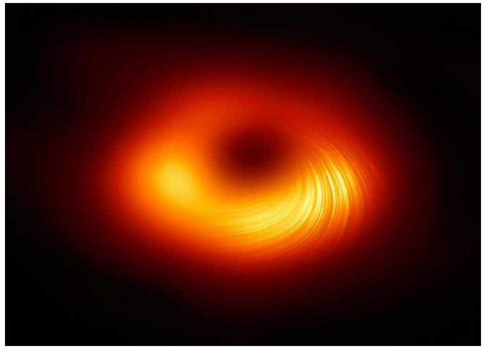
    .....

    n) Exotic Objects or states in the SM or BSM

Magnetic BH with Electroweak-Symmetric Hair

- Observational probes for BHs:





(LIGO collaboration, EHT Collaboration)

Hairy Black Holes

- Types of BHs:

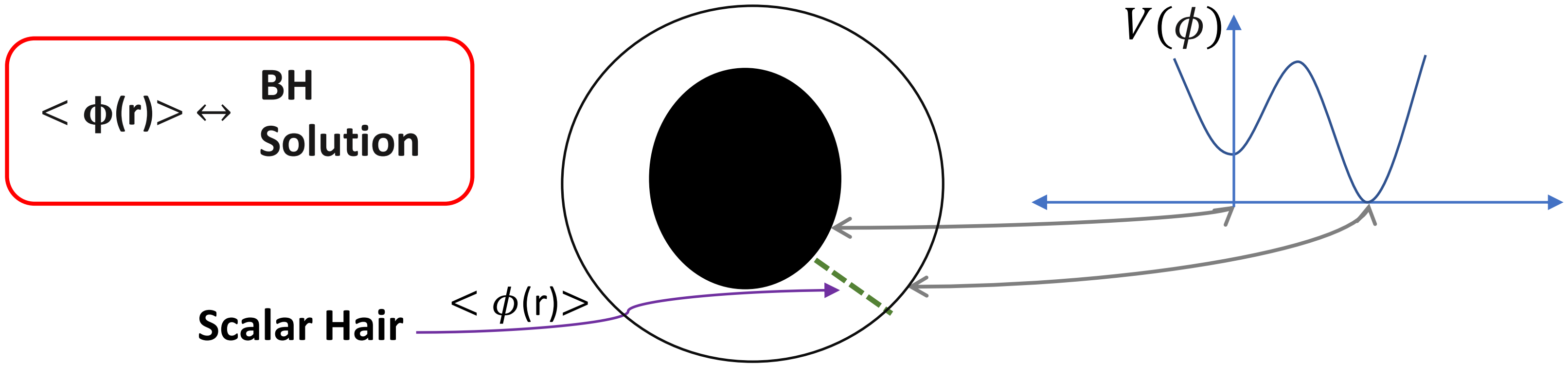
  1) Schwarzschild BH 2) Reissner–Nordström BH 3) Kerr BH 4) Kerr-Newman BH

- No-Hair Theorem: All BH solutions are described completely by observable quantities M, Q, a. Other information about matter that formed BH is inaccessible.

  Exceptions :- Einstein-Yang-Mills-Higgs(EYMH), …

- Hairy BHs: Consider scalar field $\phi(x)$ which has a potential with two minimas.

(Lee, Nair, E. Weinberg' 91 (hep-th:9112008))



Electroweak Monopoles?

- Lagrangian:

$$\mathcal{L}_{\text{EW}} = -\frac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + |D_\mu H|^2 - V(H) \qquad V(H) = \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2$$

- Ansatz: Spherically symmetric ansatz in hedgehog gauge (Cho & maison'96 (hep-ph:9601028))

$$H = \frac{v}{\sqrt{2}} \rho(r) \begin{pmatrix} \sin\left(\frac{\theta}{2}\right) e^{-i\phi} \\ -\cos\left(\frac{\theta}{2}\right) \end{pmatrix} \qquad W^a_i = \epsilon^{aij} \frac{r^j}{r^2} \left(\frac{1 - f(r)}{g}\right) \qquad Y_i = -\frac{1}{g_Y}(1 - \cos\theta)\partial_i \phi$$

$SU(2)_L \times U(1)_Y \to U(1)_{EM}$

$$A_i = -\frac{1}{e}(1 - \cos(\theta))\partial_i \phi \quad \rightarrow \quad B_i = \frac{2 e_M}{4\pi r^2} \hat{r}^i$$

- Mass: (Lee & E. Weinberg'94 (hep-th:9406021))

$$M = \int_0^\infty dr\, 4\pi r^2 \left(\frac{\rho'^2 v^2}{2} + \frac{f'^2}{g^2 r^2} + \frac{v^2 f^2 \rho^2}{4 r^2} + \frac{(1 - f^2)^2}{2 g^2 r^4} + \frac{\lambda}{8} v^4 (\rho^2 - 1)^2 + \frac{1}{2 g_Y^2 r^4} \right)$$

Divergent.
No Finite Energy Electroweak Monopoles in SM

Magnetic BH with Electroweak Hair ← Hide Singularity behind event horizon of BH

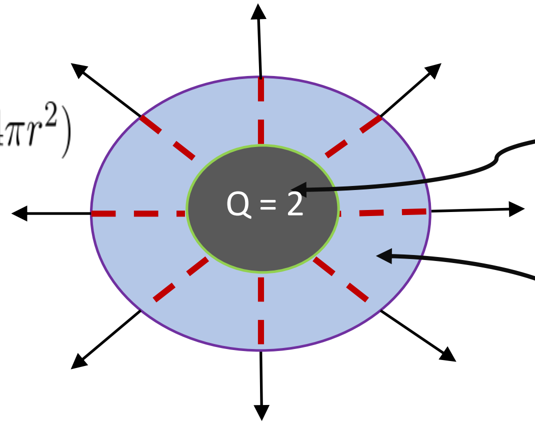
Hairy Magnetic Black Holes

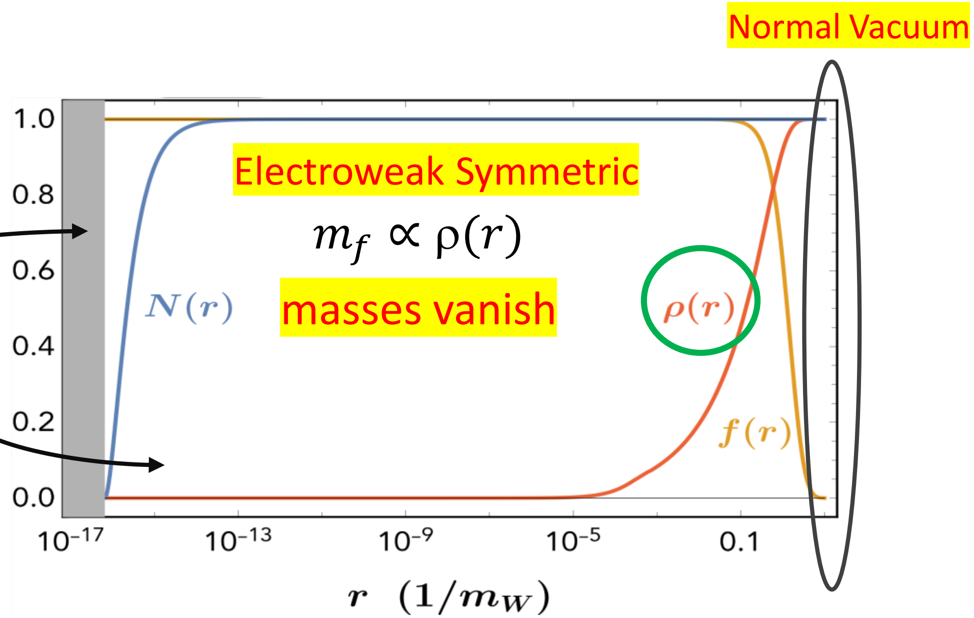
- Action:

$$S = \int d^4x\sqrt{-g}[-\frac{1}{16\pi G}R + \mathcal{L}_{\rm EW}] \qquad g_{\mu\nu} = {\rm diag}(P^2(r)N(r), N(r)^{-1}, r^2, r^2\sin^2(\theta))$$

- Profile of Electroweak hair:

$\mathbf{B}(\mathbf{r}) = Qe_{\rm M}\hat{\mathbf{r}}/(4\pi r^2)$





(Bai & **MK**, 2012.15430)

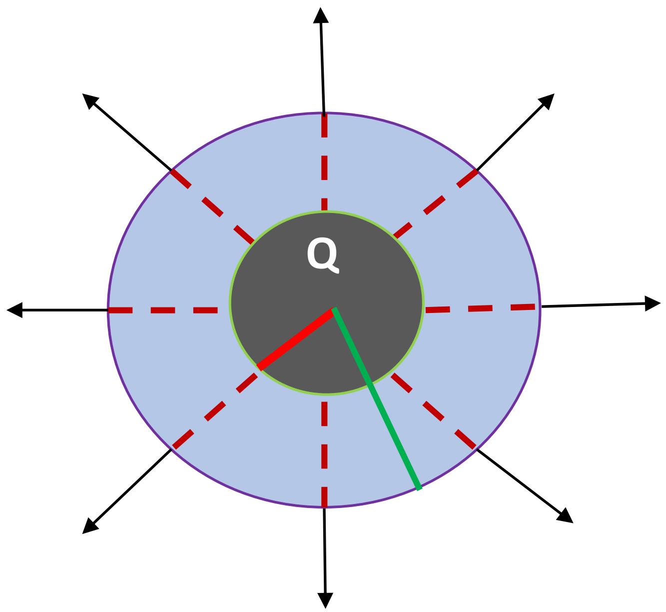
Extremal Hairy magnetic BH

$$r_H = r_H^{\rm min} = \frac{\sqrt{4\pi G}}{g_Y}$$

$$M \approx \cos(\theta_w)\frac{\sqrt{4\pi}M_{\rm pl}}{e} < M_{\rm eMBH}^{\rm RN}$$

Higher charged Hairy Magnetic Black Holes

- Mass and Radius:



$$r_H = \frac{\sqrt{\pi}|Q|\,cos(\theta_W)}{e\,M_{\rm pl}}$$

$$R_{EW} = \frac{\sqrt{|Q|/2}}{m_h}$$

Determined by condition that $eB(R_{EW}) = m_h^2$

$$M_{ext} = \frac{\sqrt{\pi}|Q|M_{\rm pl}cos(\theta_W)}{e}$$

$$r_H(Q_{max}) = R_{EW}(Q_{max})$$

$$2 < Q < Q_{max} \cong 10^{32}$$

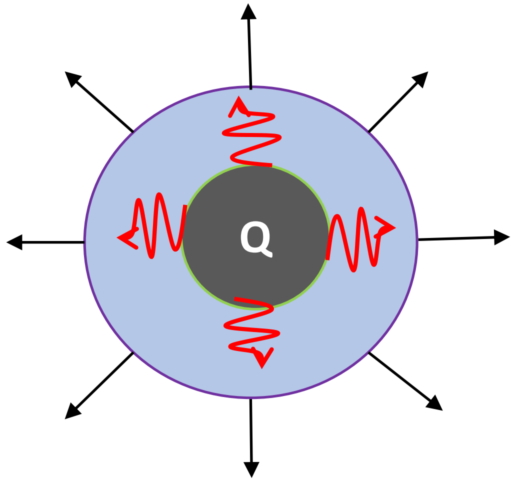
$$0.1\,mg < M < 10^{28}\mathrm{gm}$$

For $Q > Q_{max}$ electroweak symmetric region does not exist, so no hairy magnetic BHs

(Maldacena, 2004.06084)

2-D Hawking Radiation

- 2-D massless modes: Landau levels in presence of magnetic fields



$$E^2 - p_3^2 = m^2 + eB(1-2s) = m^2 = 0$$

for s=1/2 fermions   in EW symmetric region

Degeneracy of lowest landau level: $N = Qq_Y$
Two-dimensional(time + radial) massless modes

- Hawking Radiation: (Maldacena, 2004.06084)

$T > m_e$	$T < m_e$
$P_2 = \frac{\pi g_*}{24} T^2$ $\quad \tau_2 = 10^{-25} s \left(\frac{M}{100\, g}\right)^2$ g_*=2Q for electrons	$P_4 \approx \frac{\pi^2 g_*}{120} (4\pi R^2_{\rm EW}) T^4$ g_*=2 for photon and $\frac{21}{4}$ for neutrinos

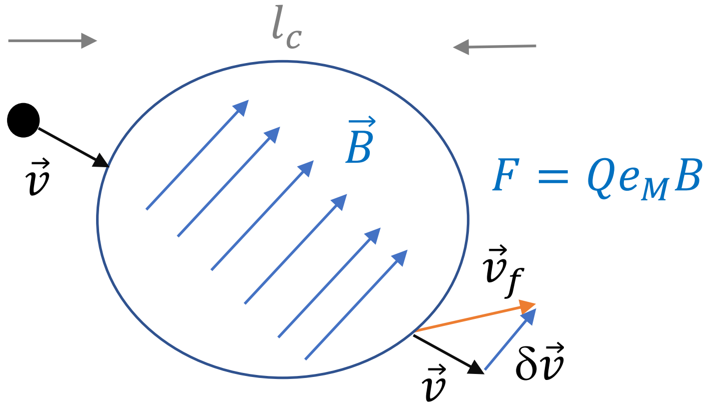
For phenomenological purpose BHs can be taken to be extremal.

Parker Limit

- Magnetic BHs get accelerated and extract energy from large coherent magnetic fields present in galaxies

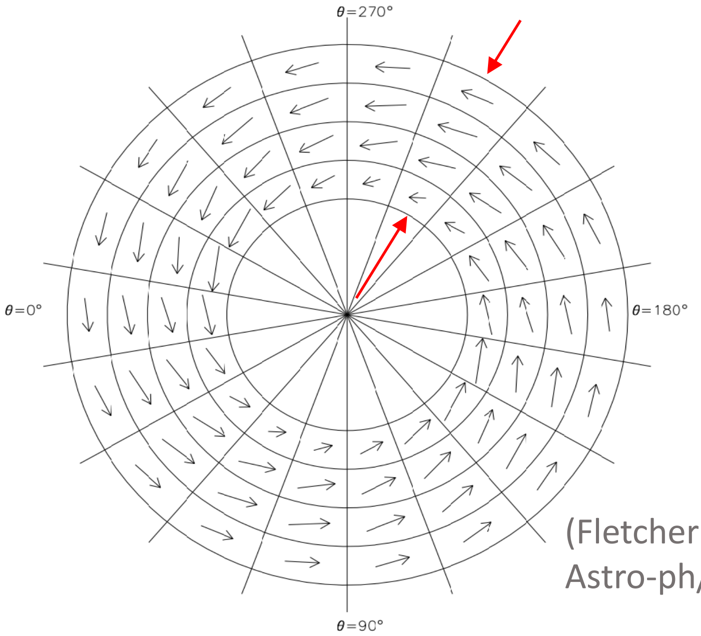
$$\Delta E \times F_* \times (\pi \ell_c^2) \times (4\pi\ \mathrm{sr}) \times t_{\mathrm{reg}} \lesssim \frac{B^2}{2}\frac{4\pi\ \ell_c^3}{3}$$

$$\Delta E \simeq \frac{B^2 h_Q^2 \ell_c^2}{2Mv^2}$$



For M31(Andromeda) galaxy: $l_c = 10\ kpc, t_{reg} = 10\ Gyr$

$f_* < 6 \times 10^{-3}$



(Fletcher et al. Astro-ph/0310258)

(Bai, Berger, **MK**, Orlofsky; 2007.03703)

(Turner, Parker, Bogdan’1982)

Limits from Sun and Earth

1. MBHs with Q>30 (sun) and 1900(earth) can be stopped.

2. For $N > N_*^{crit}$ the Coulomb attractive force dominates the repulsive force

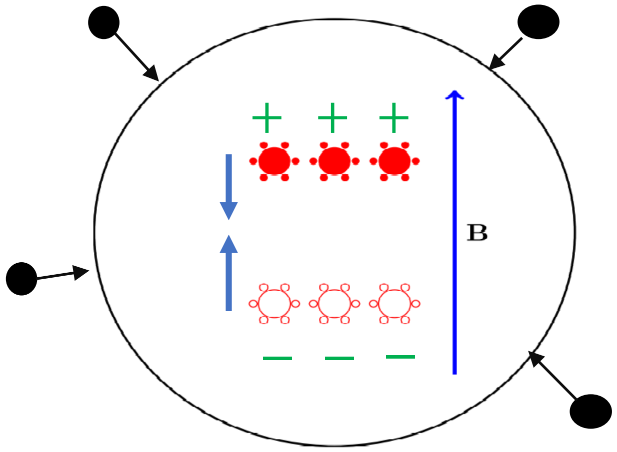
3. Annihilation produce neutrino flux

$$I_\nu = \frac{N_\nu \, \Gamma_A}{4\pi \, d^2}$$

$$N_\nu = \eta_\nu \frac{M_{BH}}{T_{BH}}$$

4. Earth Heat

$$P_A \simeq (2.4 \times 10^{15}\ \mathrm{W})\, f_* < 4.7 \times 10^{13}\ \mathrm{W}$$



(Bai, Berger, **MK**, Orlofsky; 2007.03703)

Final Plot

1. MACRO: Magnetic monopole search

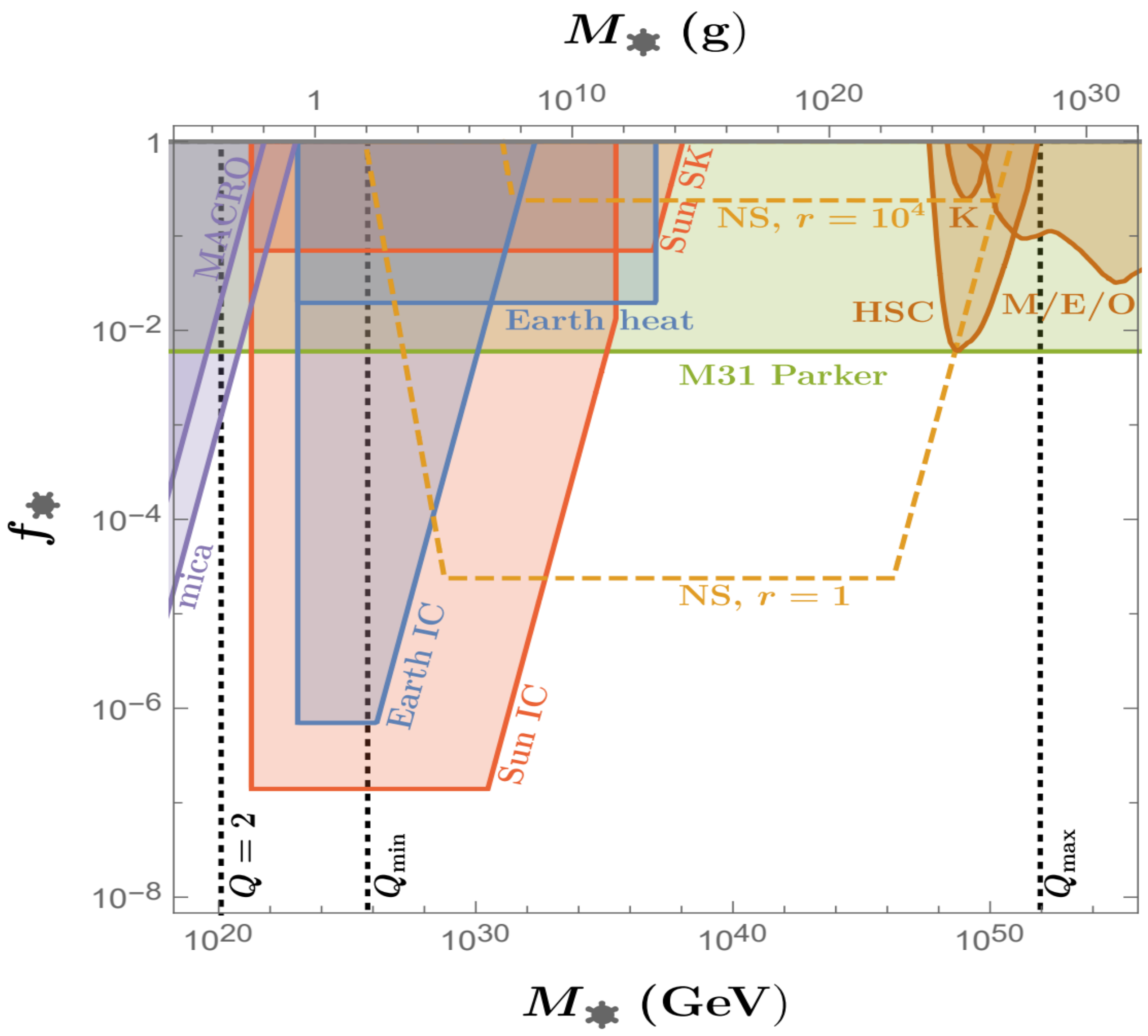
$$F_* < 1.6 \times 10^{-16}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

2. Mica: Track of monopoles in ancient mica

$$F_* < 10^{-17}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

3. HSC, MACHO/EROS/OGLE, Kepler(K)
4. Neutron Star:

   Here r is ration of total luminosity going to photon luminosity. With r=1 (proton superconductor) and r=10^4 (pion superconductor).



(Bai, Berger, **MK**, Orlofsky; 2007.03703)

Summary

1. New types of Black Holes (Hairy Magnetic BHs) exist in **SM + GR**, which have Electroweak Symmetric Vacuum around them where the elementary particles are massless.

2. This BHs hawking radiate efficiently via a new type of 2-D hawking radiation.

3. Annihilation of such BHs produce neutrinos and heat which can probed using current observations. Also see (Ghosh, Thalapillil, Ullah 2009.03363) and (Diamond, Kaplan 2103.01850) for other interesting constraints.