Magnetic Black Holes with Electroweak-Symmetric Coronas

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Bai, JB, Korwar, Orlofsky arXiv:2007.03703

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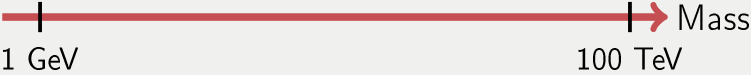
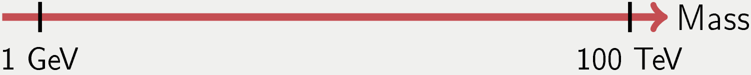
A narrow thermal paradigm



✓ Predictive! Signals of

- Soft nuclear recoil (direct detection)
- Astrophysical annihilations (indirect detection)
- Production at TeV-scale colliders

A narrow thermal paradigm

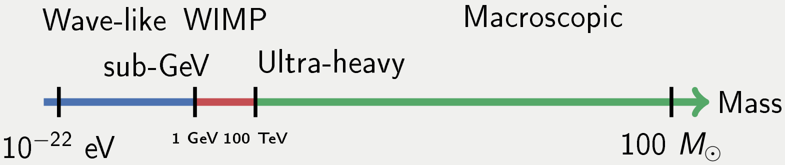


✓ Predictive! Signals of

- Soft nuclear recoil (direct detection)
- Astrophysical annihilations (indirect detection)
- Production at TeV-scale colliders

✗ Predictive. . . Easy to think it's all covered

A broad range of possibilities



Wave-like WIMP Macroscopic

sub-GeV Ultra-heavy

Mass

10^{-22} eV

1 GeV 100 TeV

100 $M_\odot$

Many more interesting, testable possibilities!

- Wave-like: Axions & ALPs
- sub-GeV: Boosted DM
- Ultra-heavy: Multi-scattering
- Macroscopic: Primordial black holes

Why (magnetic) black holes?

- Because all the ingredients are already in the SM

  No need for low E BSM: naturally consistent with exp.

- Because it's now testable

  Microlensing, gravitational waves, etc.

- Because it's cool?

  Exotic objects, interesting physical situations

The big picture: EWS PMBHs

- SM+gravity admits magnetically charged BH solutions
- Primordial MBH could be a component of DM
- At large Q, the EW vacuum is destabilized and a region of EW restoration forms around the MBH

  Maldacena: arXiv:2004.06084
- Any such MBH that forms quickly radiates down to an extremal state, which can be very stable
- Constraints on PMBHs in galaxies, stars, planets restrict their abundance (10^{-7} to 10^{-3} of DM abundance)

Outline

- Magnetic black hole properties
- Parker limits from galactic magnetic fields
- Limits from solar neutrino production
- Limits from emissions in the Earth
- Limits from heating neutron stars
- Summary and outlook

Magnetic black hole properties

Reissner-Nordström picture

- (Magnetically) charged BH described by the metric

$$ds^2 = f(r)\,dt^2 - \frac{dr^2}{f(r)} - r^2\,d\Omega^2, \quad f(r) = 1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2}$$

- $r_s = 2\,G\,M$: Schwarzschild radius
- $r_Q = \pi\,Q^2\,G/e^2$ for magnetically charged black

- Two horizons in general: $r_\pm = (r_s \pm \sqrt{r_s^2 - 4\,r_Q^2})/2$
- When the two coincide ($4\,r_Q = r_s$): Extremal black hole

Properties of extremal magnetic BH

- Mass and radius:

$$M_{\mathrm{eBH}} = \frac{\sqrt{\pi}\,|Q|}{e}\,M_{\mathrm{pl}}, \quad R_{\mathrm{eBH}} = \frac{\sqrt{\pi}\,|Q|}{e}\,\frac{1}{M_{\mathrm{pl}}}$$

- Magnetic field:

$$B = \frac{Q}{2\,e\,r^2} \to \frac{Q}{2\,e\,R_{\mathrm{eBH}}^2} = \frac{e\,M_{\mathrm{pl}}^2}{2\,\pi\,Q}$$

- In an extremal state, no Hawking radiation

$$T = \frac{M_{\mathrm{pl}}^2}{2\,\pi}\,\frac{\sqrt{M^2 - M_{\mathrm{eBH}}^2}}{M + \sqrt{M^2 - M_{\mathrm{eBH}}^2}}$$

Vacuum at high B

- Shown that at high B, $m_W \to 0$ at

$$B_w \sim \frac{m_W^2}{e}, \quad r_w \sim \sqrt{\frac{Q}{2}}\frac{1}{m_W}$$

- Subsequently, EW symmetry is restored at

$$B_h \sim \frac{m_h^2}{e}, \quad R_{\mathrm{EW}} = r_h \sim \sqrt{\frac{Q}{2}}\frac{1}{m_h}$$

Ambjorn, Olesen: hep-ph/9304220

- Hypothesized that non-standard QCD phase at

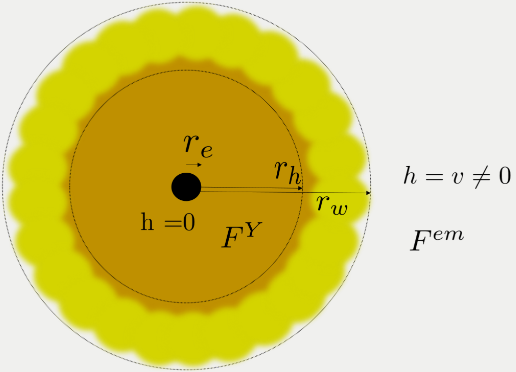
$$B_{\mathrm{QCD}} \sim \frac{\Lambda_{\mathrm{QCD}}^2}{e}, \quad R_{\mathrm{QCD}} \sim \sqrt{\frac{Q}{2}}\frac{1}{\Lambda_{\mathrm{QCD}}}$$

Kharzeev, Landsteiner, Schmitt, Yee: 1211.6245

Structure of EW corona BH

Higgs configuration acquires non-spherical at $B \sim m_W^2$

Region between r_h & r_w dubbed "EW corona" (✹)

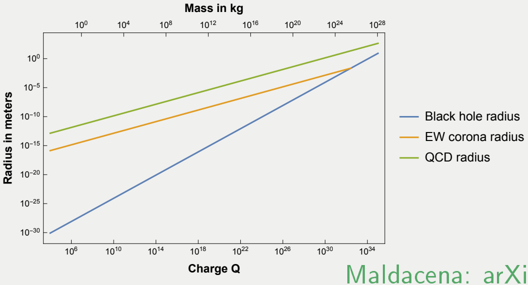


Maldacena: arXiv:2004.06084

Properties of EW corona BH

- Upper Q: existence of EWS corona
- Lower Q: Schwinger discharge by GUT monopoles

$$Q_{\text{max}} \approx \frac{e^2\, M_{\text{pl}}^2}{2\,\pi\, m_h^2} = 1.4 \times 10^{32}, \qquad Q_{\text{min}} \approx \frac{M_{\text{pl}}}{\pi\, M_{\circ M}^{\text{GUT}}} \sim 5 \times 10^3$$



Maldacena: arXiv:2004.06084

Non-extremal BH radiation

- Extremal BH are very stable, but any additional mass beyond extremality is unstable
- For $r < r_h$: Dominant modes are $2d$ massless fermions
  Fermions travel along "wires" of magnetic field lines
  Only EM charged fermions w/ $m \lesssim T$ escape corona
- Charged massless bosons get mass squared $\sim B$
- The power radiated is given by

$$P_2 = \frac{g_* \pi}{24} T^2 \gg \frac{g_* \pi^2}{120} (4 \pi r_+^2) T^4$$

Non-extremal BH radiation, part II

- If $T \lesssim m_e$, $2d$ modes can't escape
  EWS region should thermalize and radiate
  $$P_4 = \frac{g_* \pi^2}{120} (4\pi R_{\rm EW}^2)\, T^4$$

- After merger of two MBH, $2d$ radiation quickly makes resulting BH nearly extremal
  $$\tau_{\rm BH} \approx \frac{3000\, \pi^{3/2}\, c_W}{e} \frac{M_\odot^2}{M_{\rm pl}^3} = (1.8 \times 10^{-25}\ {\rm s})\, M_{26}^2$$

Baryon number violation

- GUT monopoles violate baryon number

  Callan: PRD**26** (1982), 2058, Rubakov: Nucl.Phys.B 203 (1982) 311

- EWS MBH have 2 possible mechanisms for BNV
  1. Absorption of baryon number into the event horizon

     Maldacena: 2004.06084
  2. Sphaleron processes in EWS region

- From the first: for $M_{\ast} \lesssim 10^{27}$ GeV, absorbed baryon energy efficiently re-emitted until near-extremality

- Take R_{EW} as radius at which BNV is efficient

Summary of properties

- Phenomenologically, magnetic extremal BH are large mass monopoles with small $Q/M_{✹} \sim 1/M_{\mathrm{pl}} < 1/M_{\mathrm{GUT}}$
- Take BNV radius (somewhat conservatively) as R_{EW}
- Benchmark point:

$$M_{✹} = 10^{26}\ \mathrm{GeV} \approx 0.2\ \mathrm{kg}, \quad Q \approx 1.6 \times 10^{6}, \quad R_{\mathrm{EW}} \approx 1.4\ \mathrm{fm}$$

- Upper limit point:

$$M_{✹} \approx 3 \times 10^{52}\ \mathrm{GeV} \approx 8\, M_{\oplus}, \quad Q \approx 4 \times 10^{32}, \quad R_{\mathrm{EW}} \approx 4\ \mathrm{cm}$$

Primordial MBHs

- Consider a primordially formed population
- Can be a component of dark matter based on "microscopic" properties
- Don't worry about primordial production in this talk
- Parameterize the galactic flux as

$$F_{\ast} = \frac{1}{4\,\pi}\, f_{\ast}\, \frac{\rho_{\mathrm{DM}}}{M_{\ast}}\, v$$

$$\approx \left(9.5 \times 10^{-21}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\right) f_{\ast}\, M_{26}^{-1}\, \frac{\rho_{\mathrm{DM}}}{0.4\ \mathrm{GeV\,cm}^{-3}}\, \frac{v}{10^{-3}}$$

Parker limits from galactic magnetic fields

Monopoles dissipate magnetic fields

- Magnetic fields do work on monopoles and lose energy:

$$dE = h_Q\, B\, dx, \quad h_Q = 2\,\pi\, Q/e$$

- No significant change to monopole v compared to virial
- Galactic domains of coherent B on scale ℓ_c
- Regenerate on a time scale t_{reg}
- Need total energy loss in t_{reg} < total energy stored

$$\Delta E\, F_{\ast}\, (4\,\pi \ell_c^2)\, \pi\, t_{\mathrm{reg}} < \frac{B^2}{8\,\pi}\, \frac{4\,\pi\, \ell_c^3}{3}$$

Dissipation in MW and Andromeda

- For Milky Way:

$$\ell_c \sim 10^{21}\ \text{cm}, \quad B \sim 3 \times 10^{-6}\ \text{gauss}, \quad t_{\text{reg}} \sim 10^{15}\ \text{s}$$

- No bound for baseline parameterization

$$f_{\circledast} \lesssim 3.8 \times \frac{v_{-3}}{\rho_{0.4}\,\ell_{21}\,t_{15}}$$

Turner, Parker, Bogdan: PRD**26** (1982) 1296

- For Andromeda:

$$\ell_c \sim 30 \times 10^{21}\ \text{cm}, \quad t_{\text{reg}} \sim 300 \times 10^{15}\ \text{s}$$

$$f_{\circledast} \lesssim 4 \times 10^{-4}$$

Fletcher, Berkhuijsen, Beck, Shukurov: AA 414 (2004) 53
Arshakian, Beck, Krause, Sokoloff: AA 494 (2009) 21

Limits from solar neutrino production

Overview

- MBH that hit the Sun are captured
- Monopole and anti-monopole BH thermalize and build up in the core
- Merger of opposite charge BH yields non-extremal BH
- Hawking radiation of ν of this non-extremal BH can be detected by neutrino detectors

MBH Capture

- PMBH captured by a body of radius R:

$$C_{\rm cap} \;\approx\; \epsilon\,\pi\,R^2\,\frac{1+\left(v_{\rm esc}^2/v^2\right)}{1-v_{\rm esc}^2}\,4\,\pi\,F_{\odot}$$

- For the Sun, we find

$$C_{\rm cap} \;\approx\; \left(9.2\times10^3\ {\rm s}^{-1}\right)\,f_{\odot}\,M_{26}^{-1}$$

- Scattering off of plasma electrons stops MBH for $Q > 30$: we take the capture efficiency $\epsilon \approx 1$

Ahlen, De Mitri, Hong, Tarle: PRD**55** (1997) 6584

MBH Annihilation

- PMBH build up in the core within a thermal radius

$$R_{\mathrm{th}} \approx 0.13\, R_{\odot} \sqrt{\frac{m_p}{M_{\text{☀}}}} = (8.8 \times 10^{-4}\ \mathrm{cm})\, M_{26}^{-1/2}$$

- Opposite charged PMBH merge when within roughly R_{eBH} of each other, equilibrates within age of Sun

$$\Gamma_A = \frac{1}{2}\, C_{\mathrm{cap}}$$

- Solar magnetic field not strong enough to affect dynamics for parameters of interest

Hawking radiation

- Most Hawking radiation trapped in Sun, but ν below 100 GeV can escape

$$N_\nu \approx \eta_\nu \frac{M_\odot}{T_{\mathrm{BH}}} = (3.4 \times 10^{15})\, \eta_\nu\, M_{26}^2$$

- Mass must be small enough that $\langle E_\nu \rangle \gtrsim E_\nu^{\mathrm{cut}}$ and at least one capture during experiment
- Mass must be large enough that PMBH stops in Sun

Constraints

- IceCube: Take $\eta_\nu = \max(1, T/100\ \mathrm{GeV})$

$$f_\ast \lesssim \begin{cases} 1.4 \times 10^{-7}\,, & 2 \times 10^{21} \lesssim M_\ast/\mathrm{GeV} \lesssim 2.9 \times 10^{30}\,, \\ \frac{M_\ast}{2.1\times 10^{37}\ \mathrm{GeV}}\,, & 2.9 \times 10^{30} \lesssim M_\ast/\mathrm{GeV} \lesssim 2.8 \times 10^{35} \end{cases}$$

IceCube: Eur. Phys. J. C (2017) 77: 146

- Super-K: Take $\eta_\nu = \max(1, T/55\ \mathrm{MeV})$

$$f_\ast \lesssim \begin{cases} 0.07\,, & 2 \times 10^{21} \lesssim M_\ast/\mathrm{GeV} \lesssim 5.1 \times 10^{37} \\ 0.03\, M_{38}^{-1}\,, & 5.1 \times 10^{37} \lesssim M_\ast/\mathrm{GeV} \lesssim 1.1 \times 10^{38} \end{cases}$$

Super-K: Astroparticle Physics 36 (2012) 131-136

Limits from emissions in the Earth

Overview

- Capture and annihilation work similarly to Sun
- Stopping scales similarly, but Earth is smaller: $Q \gtrsim 1900$
- Hawking radiation heats the Earth, leading to one bound from known Earth internal heat
- Stronger bound expected from ν at low mass

Constraints

- In capture-annihilation equilibrium:
  $P_A \approx (2.4 \times 10^{15}\ \mathrm{W})\, f_{\ast}$
- Compare to internal Earth heat 4.7×10^{13} W

$$f_{\ast} \lesssim 0.02$$

Davies, Davies: Solid Earth 1 (2010), no. 1 5âĂŞ24

- Use IceCube search for DM to ν annihilation in Earth:

$$f_{\ast} \lesssim \begin{cases} 7 \times 10^{-7}, & 1.2 \times 10^{23} \lesssim M_{\ast}/\mathrm{GeV} \lesssim 1.4 \times 10^{26} \\ \frac{M_{\ast}}{2\times 10^{32}\ \mathrm{GeV}}, & 1.4 \times 10^{26} \lesssim M_{\ast}/\mathrm{GeV} \lesssim 3 \times 10^{36} \end{cases}$$

IceCube: Eur. Phys. J. C 77 (2017), no. 2 82

Limits from heating neutron stars

Overview

- Capture works similarly (stopping very efficient)
- Core of neutron star expected to be superconducting
- Magnetic field of PMBH gets confined to flux tubes that stabilize well-separated PMBH population
- No bound expected from annihilation, but possible bound from PMBH-catalyzed baryon number violation

Neutron Star Structure

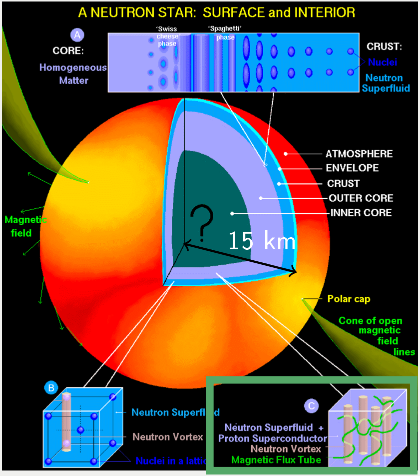
What is the inner core?

Pion superconductor?

Quark matter?

Color superconductor?

Strange meson condensate?



Page: Ann. Rev. Nucl. Part. Sci. **56**, 327-374 (2006)

Properties of Superconductor

- Magnetic fields are confined to flux tubes

$$\Phi = \int d\mathbf{A} \cdot \mathbf{B} = \frac{\pi}{e}$$

- NS magnetic field expelled by the time NS is "old"

$$B_\Phi \sim \frac{\Phi}{\pi \lambda^2} \sim 10^{16} \text{ gauss}, \quad \lambda \sim 10^{-12} \text{ cm}$$

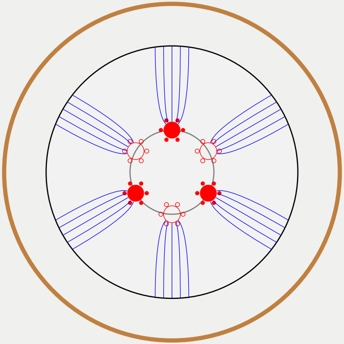
$$F_T = B_\Phi^2 \pi \lambda^2 \log(\lambda/\xi) \sim 10^4 \text{ N}, \quad \xi \sim \text{few} \times 10^{-13} \text{ cm}$$

Harvey, Ruderman, Shaham: PRD 33 (1986) 2084

Monopole in Superconductor

- PMBH that enter have B confined to $2\,Q$ flux tubes
- Tension wants to minimize curvature and length
- Gravity and tension balance (unlike GUT case)

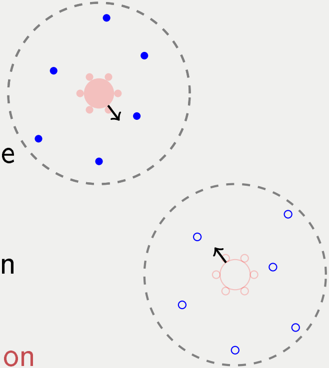
$$R_{\text{balance}} \approx \frac{6\,Q\,F_T}{4\,\pi\,G\,\rho_c\,M_{\odot}} \sim 1600 \text{ m}$$



Capture-Annihilation Balance

- Tubes drift in region where pressure larger than tension
- Entire bundle drifts along surface of SC region
- When tubes of opposite direction meet, they merge

  Enough merger causes annihilation



$$N_{\star}^{\mathrm{cap}} \sim \begin{cases} (1.2\times 10^{12})\, f_{\star}^{1/2}\, M_{26}^{-1/4}\, R_{c10}^{3/4}\, R_{10}\, \mathcal{P}, & \tau_{\mathrm{eq}} > \tau_{\mathrm{NS}} \\ (3.3\times 10^{16})\, f_{\star}\, R_{10}^{2}\, M_{26}^{-1}\, \tau_{10}, & \tau_{eq} < \tau_{\mathrm{NS}} \end{cases}$$

Constraints

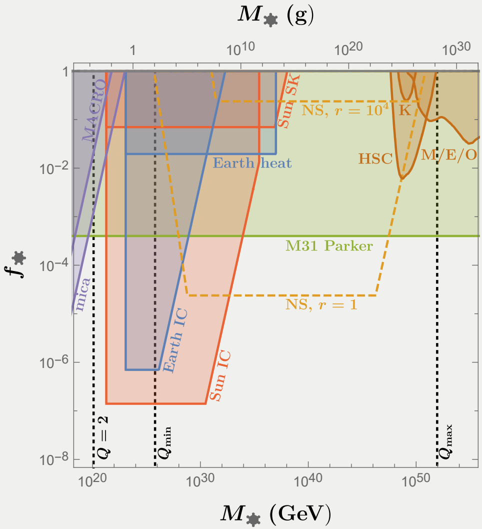
- Baryon number violation expected to dominate constraints (very dense nuclear medium!)
- Baryons that enter R_{EW} rapidly make it to event horizon (or possible $B + L$ non-perturbative processes)
- $r = L_{\mathrm{tot}}/L_{\gamma}$: Some phases have significant ν emissions

Kolb, Turner: ApJ 286 (1984) 702-710

$$f_{\bullet} \lesssim \begin{cases} 3.2 \times 10^{4}\, R_{c10}^{-5/2}\, R_{10}^{2}\, r^{2}, & C - A \text{ equilibrium, dense} \\ 0.69\, M_{26}^{-3/2}\, R_{c10}^{-3/2}\, R_{10}^{-2}\, r^{2}, & C - A \text{ equilibrium, diffuse} \\ (3 \times 10^{-5})\, R_{10}^{-2}\, \tau_{10}^{-1}\, r, & C - A \text{ equilibrium not reached} \\ \frac{M_{\bullet}}{(3.3 \times 10^{50}\ \mathrm{GeV})}\, R_{10}^{-2}\, \tau_{10}^{-1}, & \text{At least 1 MW capture} \end{cases}$$

Summary and outlook

Summary of Results



Outlook

- Magnetic black holes are intriguing solutions to the SM + gravity, with lots of cool properties and pheno
- How could they be produced in the early universe?
- Could they tie in to dark matter, baryogenesis, etc.?
- Can a firmer theoretical understanding of their structure and Hawking radiation be obtained?
- What happens at the QCD radius?
- How is baryon number violated in the EWS region?