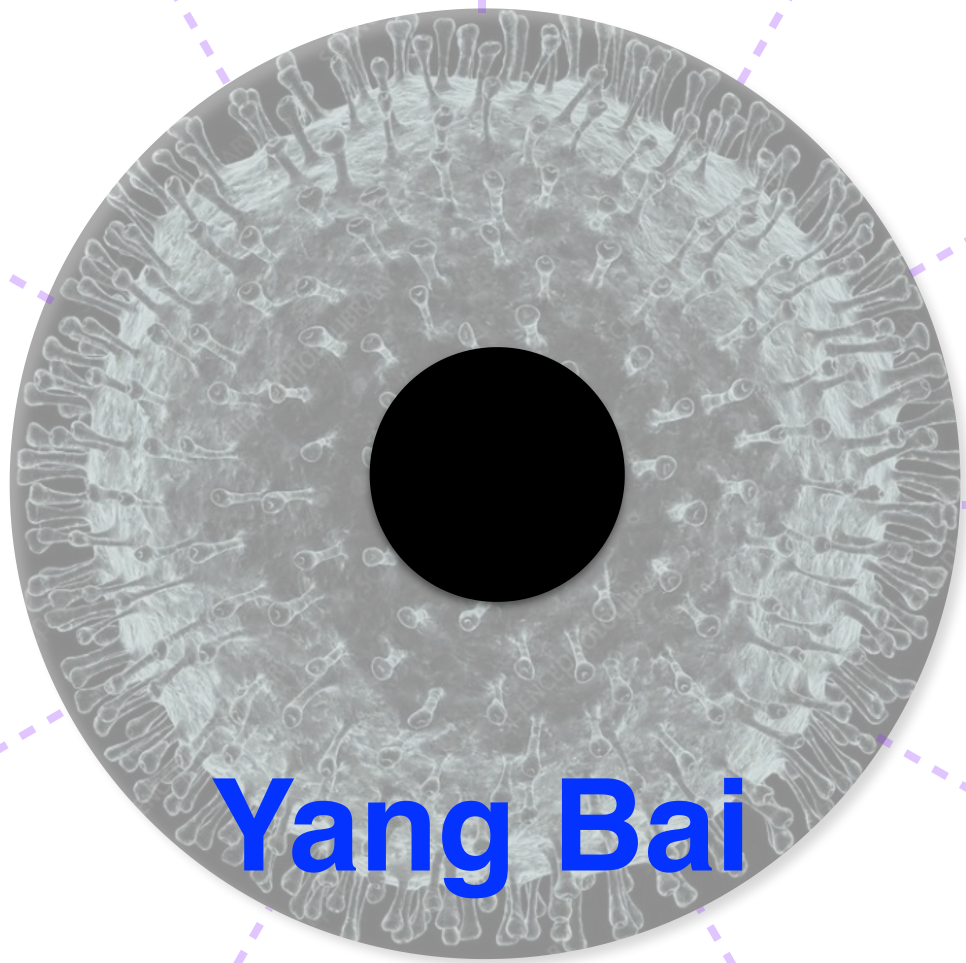
Magnetic Black Holes with Electroweak-Symmetric Coronas



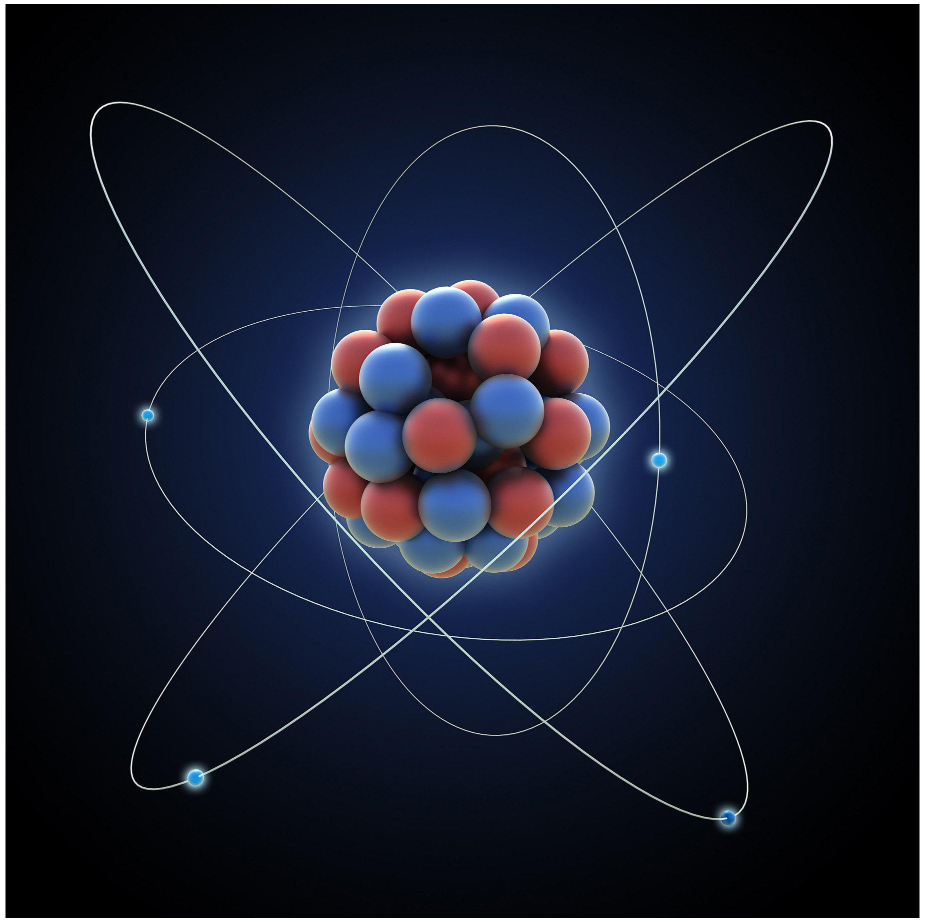
Yang Bai

University of Wisconsin-Madison

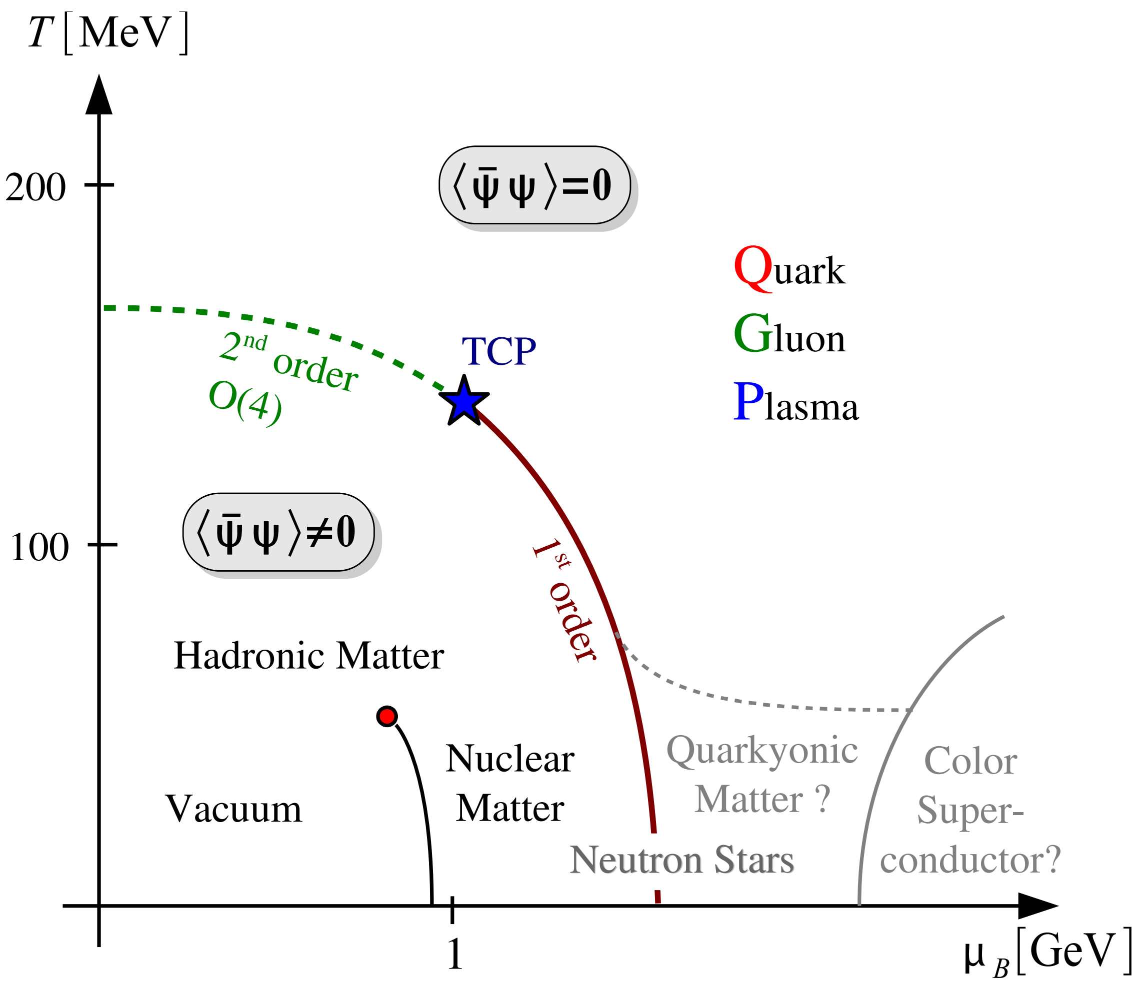
Virtual THEP Seminar, Univ. of Toronto, Oct. 20, 2020

with Berger, Korwar, Orlofsky, arXiv: 2007.03703

Motivation



ANDRZEJ WOJCICKI/Getty Images

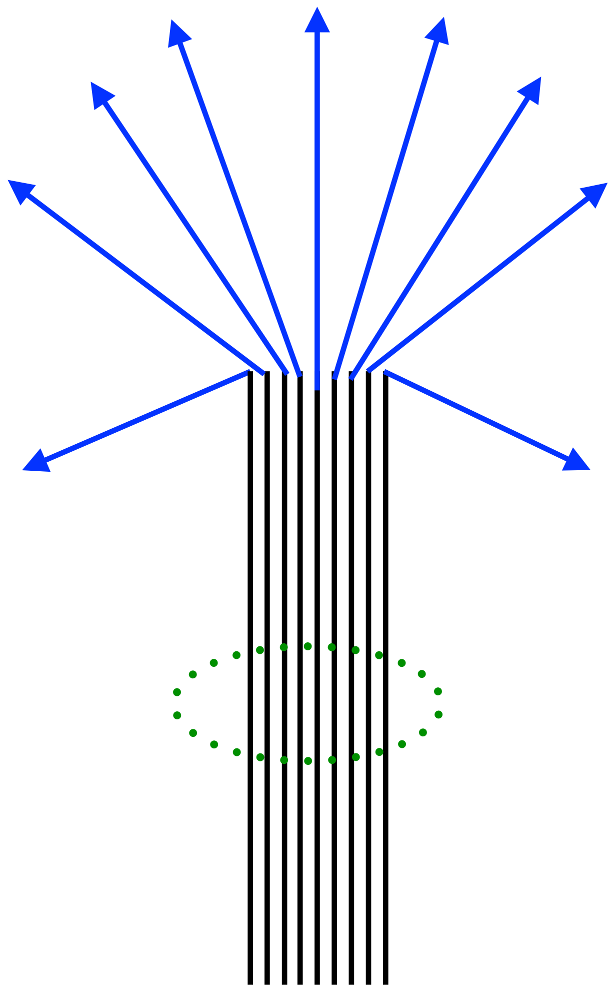


Forcrand, et. al., arXiv:1503.08140

- **Any interesting states in the electroweak sector?**

Dirac Monopole

- In E&M, we have learned that there is no monopole
- Dirac in 1931 proposed the possible existence of monopole



$$\mathbf{B} = Q\,\frac{h\,\hat{\mathbf{r}}}{4\pi r^2}$$

$$Q = 1$$

$$h = \frac{2\pi}{e} \approx 68.5\,e$$

t 'Hooft-Polyakov Monopole

- **Based on spontaneously broken gauge theory: SU(2)/U(1)**

$$\mathscr{L} = \frac{1}{2}(D_\mu \Phi)^2 - \frac{1}{4}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) - \frac{\lambda}{4}\left(|\Phi|^2 - f^2\right)^2$$

$$D_\mu \Phi^a = \partial_\mu \Phi^a + g\,\epsilon^{abc} A_\mu^b \Phi^c \qquad F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g\,\epsilon^{abc} A_\mu^b A_\nu^c$$

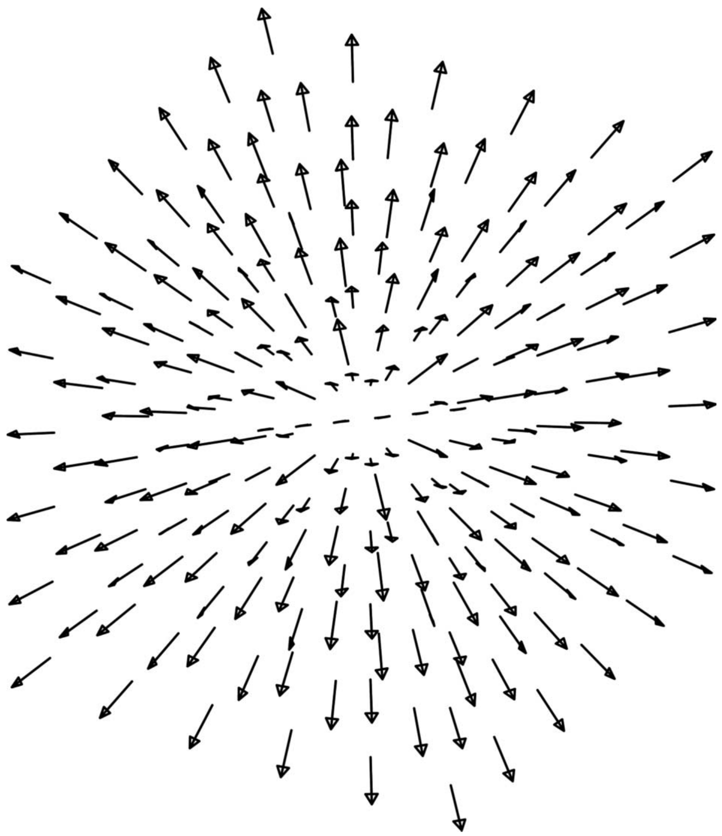
triplet

- **In the "hedgehog gauge" with $A_0^a = 0$ (spherically symmetric)**

$$\Phi^a = \hat{r}^a f \phi(r)$$

$$A_i^a = \frac{1}{g}\epsilon^{aij}\,\hat{r}^j \left(\frac{1 - u(r)}{r}\right)$$

$Q = 2$



t 'Hooft-Polyakov Monopole

- **Classical equations of motion ($\bar{r} \equiv g\,f\,r = m_W\,r$)**

$$\frac{d^2\phi}{d\bar{r}^2} + \frac{2}{\bar{r}}\frac{d\phi}{d\bar{r}} = \frac{2\,u^2\,\phi}{\bar{r}^2} + \frac{\lambda}{g^2}\phi\,(\phi^2 - 1)$$

$$\frac{d^2u}{d\bar{r}^2} = \frac{u\,(u^2-1)}{\bar{r}^2} + u\,\phi^2$$

- **Boundary conditions**

$$\phi(0) = 0\,, \quad \phi(\infty) = 1\,, \quad u(0) = 1\,, \quad u(\infty) = 0$$

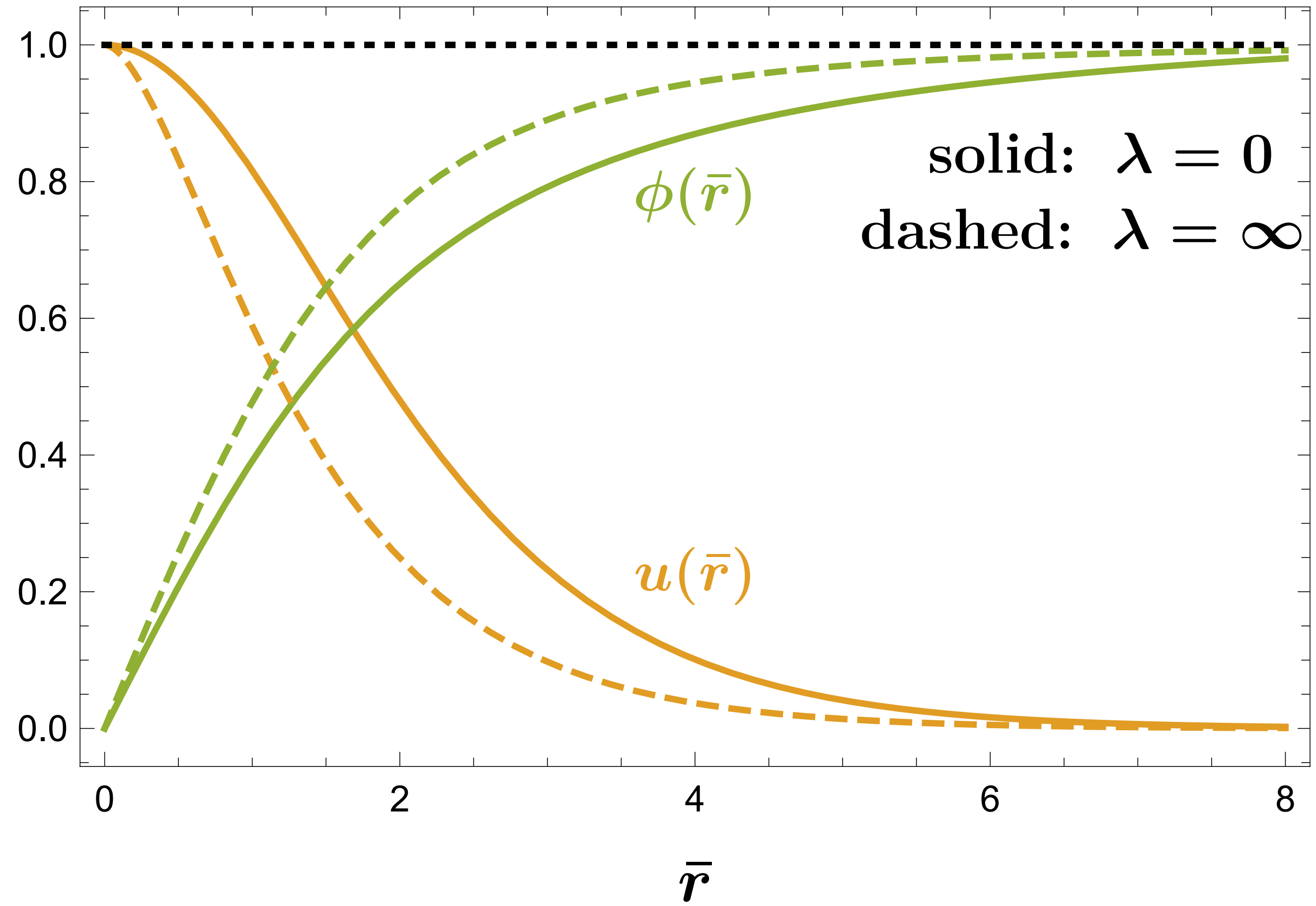
- **Total energy or mass (finite)**

$$M_{\mathscr{M}} = \int 4\,\pi\,r^2 \left(\frac{1}{2} B_i^a B_i^a + \frac{1}{2}(D_i\Phi^a)(D_i\Phi^a) + V(\Phi) \right)$$

$$= \frac{4\pi f}{g} \int d\bar{r}\bar{r}^2 \left(\frac{\bar{r}^2\,\phi'^2 + 2\,u^2\phi^2}{2\,\bar{r}^2} + \frac{(1-u^2)^2 + 2\,\bar{r}^2\,u'^2}{2\,\bar{r}^4} + \frac{\lambda}{4g^2}(\phi^2-1)^2 \right)$$

t 'Hooft-Polyakov Monopole

$$M_{\mathscr{M}} \equiv \frac{4\pi f}{g} Y(\lambda/g^2) \qquad Y(0) = 1 \qquad Y(\infty) \approx 1.787$$



- **Topological reason:** $\pi_2[G/U(1)] = \pi_1[U(1)] = \mathbb{Z}$
- **GUT monopole:** $SU(5) \to SU(3) \times SU(2) \times U(1)$

$$M_{\mathscr{M}}^{\text{GUT}} \sim 10^{17}\,\text{GeV}$$

Monopole in the Standard Model

- **In the SM:** $SU(2)_W \times U(1)_Y \to U(1)_{\rm EM}$ **with a Higgs doublet**

- **Topological reason:** $\pi_2[SU(2)_W \times U(1)_Y / U(1)_{\rm EW}] = 0$ **, no finite-energy EW monopole**

- **In more detail and again making a spherical configuration**

$$H = \frac{v}{\sqrt{2}}\,\phi(r)\,\xi\,, \qquad \xi = i\begin{pmatrix} \sin(\frac{\theta}{2})\,e^{-i\phi} \\ -\cos(\frac{\theta}{2}) \end{pmatrix} \qquad H^\dagger\,\vec{\sigma}\,H = -\frac{v^2}{2}\,\phi(r)^2\,\hat{r}$$

↑ **as the triplet case**

$$A_i^a = \frac{1}{g}\,\epsilon^{aij}\,\hat{r}^j\left(\frac{1-u(r)}{r}\right) \longleftarrow SU(2)_W$$

$$B_i = -\frac{1}{g_Y}(1-\cos\theta)\,\partial_i\phi \longleftarrow U(1)_Y$$

Nambu, NPB130 (1977) 505

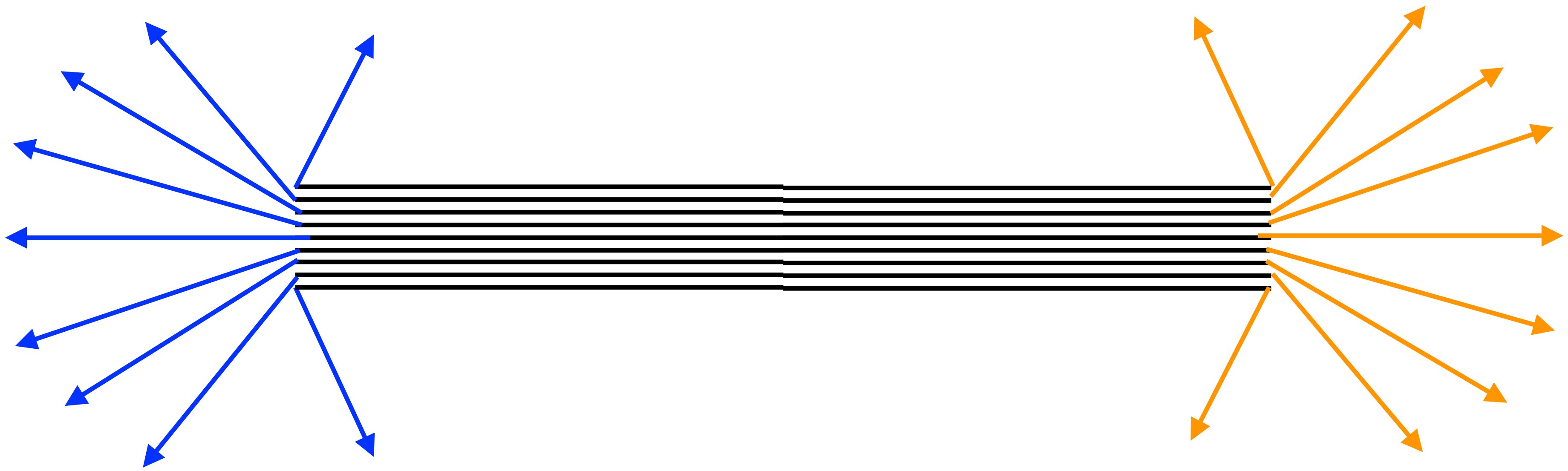
Cho, Maison, hep-th/9601028

Monopole in the Standard Model

$$S = -4\pi \int dt\, dr\, r^2\, (K + U)$$

$$K = \frac{(u')^2}{g^2 r^2} + \frac{1}{2} v^2 (\phi')^2 \qquad U = \frac{(u^2-1)^2}{2\, g^2 r^4} + \frac{v^2 u^2 \phi^2}{4\, r^2} + \frac{\lambda_h v^4}{8} \left(\phi^2 - 1\right)^2 + \frac{1}{2\, g_Y^2\, r^4}$$

- **The spherical EW monopole has an infinite mass**
- **Nambu's monopole-anti-monopole dumbbell configuration**



- **Unstable! May be produced at a future collider**

- **Introduce BSM physics to have a finite-energy monopole**

  for instance, $U(1)_Y \subset SU(2)_R$

- **Or hide the divergence part behind the event horizon of a black hole**

- **For the second avenue, no new BSM physics is needed. We just need to study the possible states based on**

Standard Model + General Relativity

Black Hole

https://www.nobelprize.org/prizes/physics/2020/press-release/

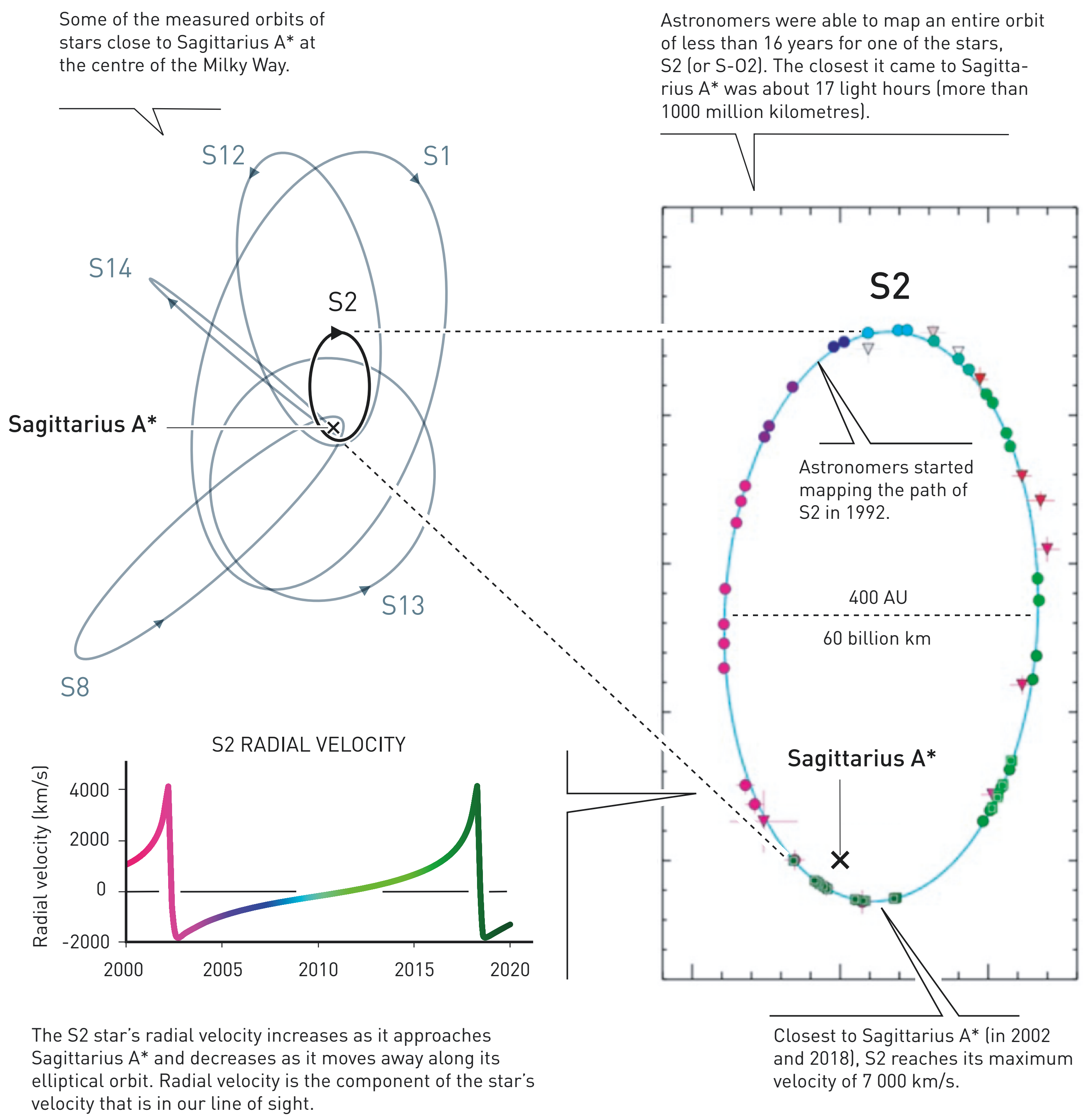


Figure 4. The stars' orbits revealed that something invisible and heavy governed their paths at the heart of the Milky Way.

Black Holes

- **Schwarzschild black hole**

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

($2GM$ in the second term circled and labelled R_e)

- **Charged or Reissner-Nordstrom black hole**

$$ds^2 = -B_{RN}(r)dt^2 + B_{RN}(r)^{-1}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$B_{RN}(r) = 1 - \frac{2GM}{r} + \frac{G\sqrt{Q_E^2 e^2 + Q_M^2 h^2}}{4\pi r^2}$$

- **The outer horizon radius is**

$$r_+ = \frac{\left(M_{eBH} + \sqrt{M_{eBH}^2 - (Q_E^2 e^2 + Q_M^2 h^2)M_{pl}^2/4\pi}\right)}{M_{pl}^2}$$

$$M_{eBH} = \frac{\sqrt{Q_E^2 e^2 + Q_M^2 h^2}}{\sqrt{4\pi}} M_{pl}$$

Hawking Radiation and PBH Lifetime

- **According to the first law of the black hole thermal dynamics, the thermal radiation temperature has (for non-extremal BH)**

$$T = \frac{M_{\rm pl}^2}{8\pi M_{\rm BH}}$$

- **Using the black body radiation formula, $P \propto R^2 T^4$, the lifetime of a Schwarzschild black hole is**

$$\tau \approx \frac{5120\pi}{g_*} \frac{M_{\rm BH}^3}{M_{\rm pl}^4}$$

- **Requiring it to be longer than the age of our universe, one has a lower bound on PBH mass**

$$M_{\rm PBH} \gtrsim 10^{15}\,\mathrm{g}$$

Extremal Black Hole

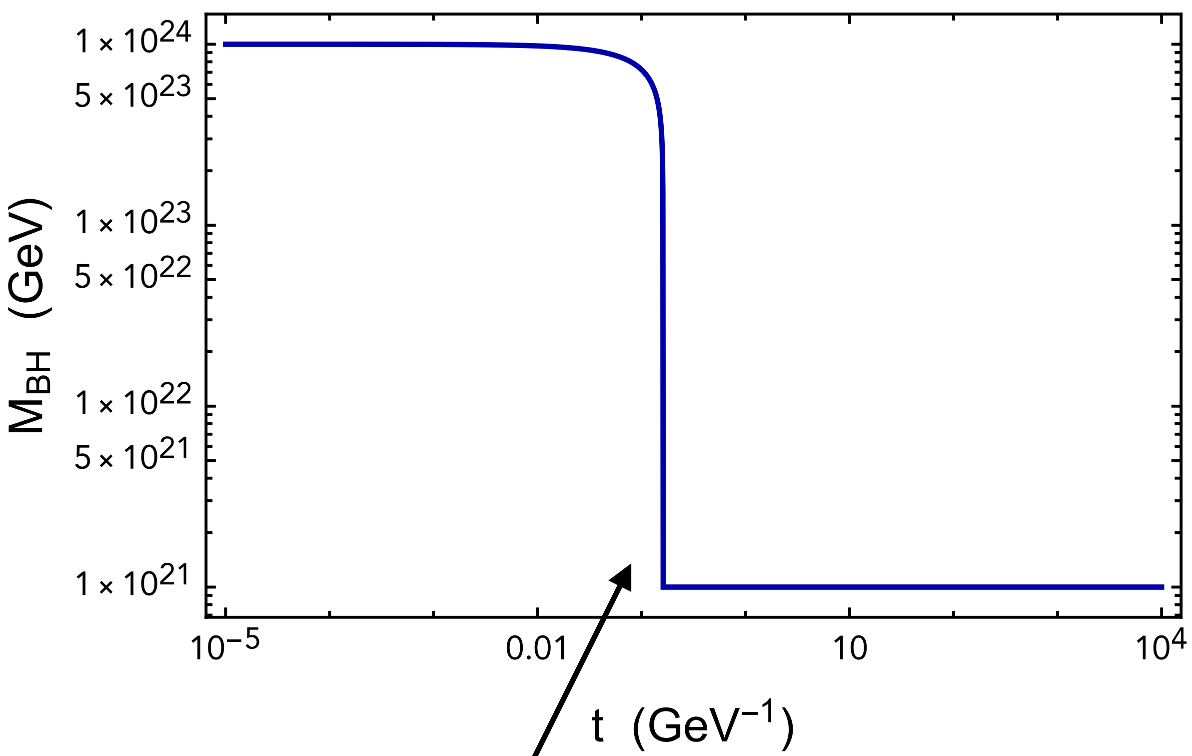
- **The Hawking radiation is fourth power of T . One way to suppress T is to make it extremal**

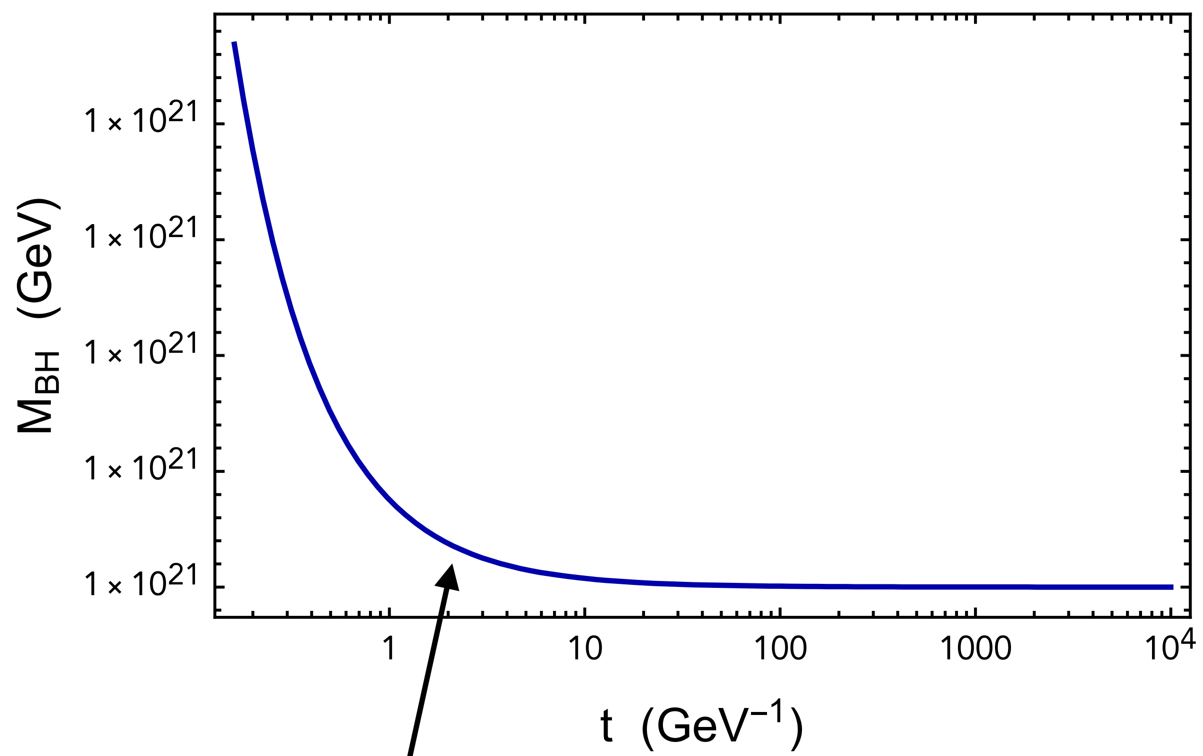
$$T(M_{\rm BH}, M_{\rm eBH}) = \frac{M_{\rm pl}^2}{2\pi} \frac{\sqrt{M_{\rm BH}^2 - M_{\rm eBH}^2}}{\left(M_{\rm BH} + \sqrt{M_{\rm BH}^2 - M_{\rm eBH}^2}\right)^2}$$

- **A PBH with a charge Q will evolve towards a near extremal one, which has suppressed T**

$$\frac{dM_{\rm BH}}{dt} \approx -\frac{\pi^2}{120} g_* \, 4\pi r_+^2 \, \left[T(M_{\rm BH}, M_{\rm eBH})\right]^4$$

Evolution of the Black Hole Mass





$$\tau \approx \frac{5120\pi}{g_*} \frac{M_{\rm BH}^3}{M_{\rm pl}^4}$$

$$M_{\rm BH}(t) = M_{\rm eBH} + \frac{120\pi\, M_{\rm eBH}^4}{g_*\, M_{\rm pl}^4\, t}$$

$$T_{\rm eBH} = \sqrt{\frac{60\, M_{\rm eBH}}{\pi\, g_*\, t}}$$

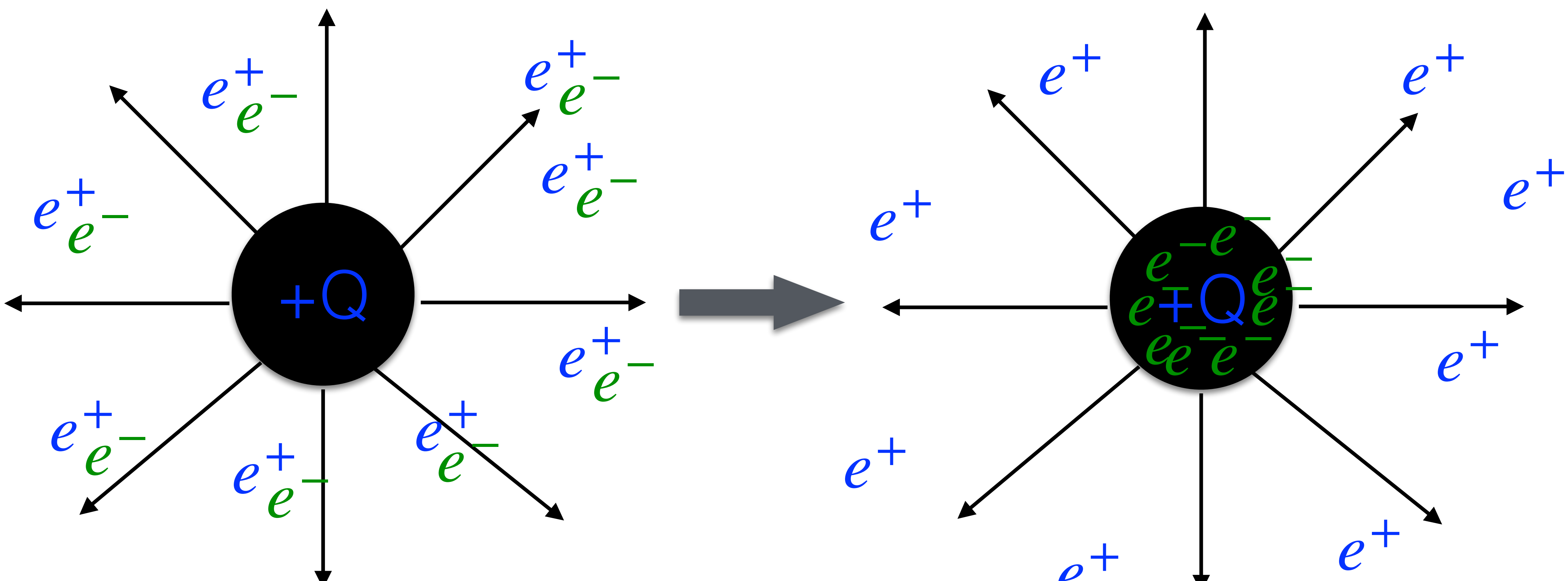
- **The initial BH evaporation still generates lot of Hawking radiations**

Electrically-Charged BH in SM

- **The charged BH has a large electric field close to the event horizon**

$$E = \frac{M_{\rm pl}^3}{\sqrt{4\pi}\, M_{\rm eBH}}$$

- **The Schwinger effects can generate electrons and positrons from vacuum and discharge the eBH**



Electrically-Charged BH in SM

- **The Schwinger discharge rate**

$$\frac{d\Gamma_{\text{Schwinger}}}{dV} = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{\pi\, n\, m_e^2}{e\, E} \right)$$

- **This sets a lower bound on the eBH mass**

$$M_{\text{eBH}} > M_{\text{eBH}}^{\text{min}} \approx \frac{e M_{\text{pl}}^3}{2\pi^{3/2}\, m_e^2} \ln\left(\frac{e^3\, M_{\text{pl}}\, t_{\text{univ}}}{16\, \pi^{7/2}} \right)$$

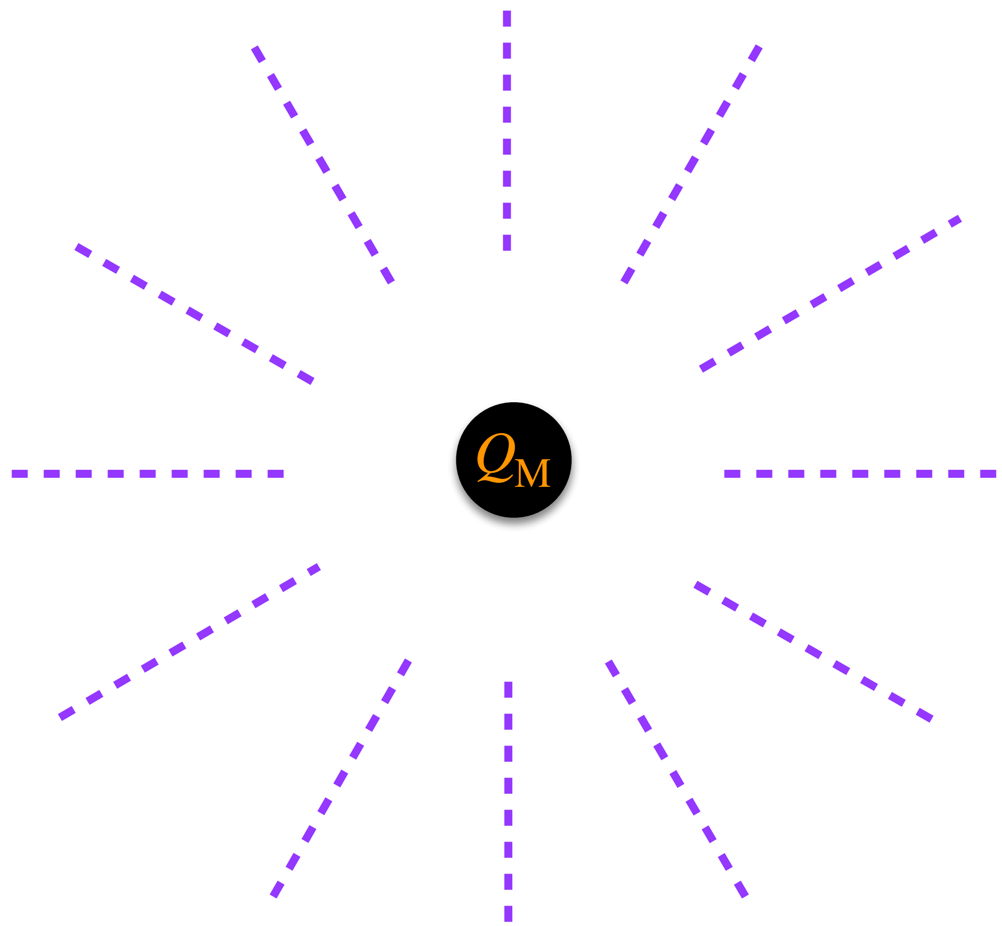
- **Because the electron mass is small in SM, the minimum eBH mass is very large**

$$M_{\text{eBH}}^{\text{min}} \approx 10^8\, M_{\odot} \qquad \text{for} \quad m_e = 0.511\, \text{MeV}$$

for dark electrically-charged BH, see YB, Orlofsky, arXiv: 1906.04858

Magnetically-Charged BH in SM

- Since there is no finite-energy magnetic monopole in the SM, no worry about Schwinger discharge
- If the GUT exists, it may worry its emission of GUT monopole



$$B(R_{\rm eBH}) = \frac{Q}{2\,e\,R_{\rm eBH}^2} \approx \frac{e\,M_{\rm pl}^2}{2\,\pi\,Q}$$

Electroweak Symmetry Restoration

- **In a large B field background, the electroweak symmetry is restored**

Salam and Strathdee, NPB90 (1975) 203

Ambjorn and Olesen, NPB330 (1990) 193

$$\mathscr{E} = \tfrac{1}{2}|D_iW_j - D_jW_i|^2 + \tfrac{1}{4}f_{ij}^2 + \tfrac{1}{4}Z_{ij}^2 + \tfrac{1}{2}g^2\varphi^2 W_i W_i^\dagger + (g^2\varphi^2/4\cos^2\theta)Z_i^2$$
$$+ ig(f_{ij}\sin\theta + Z_{ij}\cos\theta)W_i^\dagger W_j + \tfrac{1}{2}g^2\left[(W_iW_i^\dagger)^2 - (W_i^\dagger)^2(W_j)^2\right]^2$$
$$+ (\partial_i\varphi)^2 + \lambda(\varphi^2 - \varphi_0^2)^2,$$

$$(W_1^\dagger, W_2^\dagger)\begin{pmatrix} \tfrac{1}{2}g^2\varphi_0^2 & ief_{12} \\ -ief_{12} & \tfrac{1}{2}g^2\varphi_0^2 \end{pmatrix}\begin{pmatrix} W_1 \\ W_2 \end{pmatrix}$$

- **For a large $|f_{12}|$, a negative determinant leads to W-condensation and electroweak restoration. This happens when**

$$eB \gtrsim m_h^2$$

Electroweak Symmetry Restoration

$$B(R_{\rm eBH}) = \frac{Q}{2\,e\,R_{\rm eBH}^2} \approx \frac{e\,M_{\rm pl}^2}{2\,\pi\,Q} \qquad e\,B(R_{\rm eBH}) \gtrsim m_h^2$$

- **Electroweak symmetry restoration happens for**

$$Q \lesssim Q_{\rm max} \equiv \frac{e^2\,M_{\rm pl}^2}{2\pi\,m_h^2} \approx 1.4 \times 10^{32}$$

Lee, Nair, Weinberg, PRD45(1992) 2751

Maldacena, arXiv:2004.06084

- **For Q=2, one can obtain the spherically symmetric configuration**

- **For Q > 2, a non-spherically symmetric configuration is anticipated, and requires complicated numerical calculations**

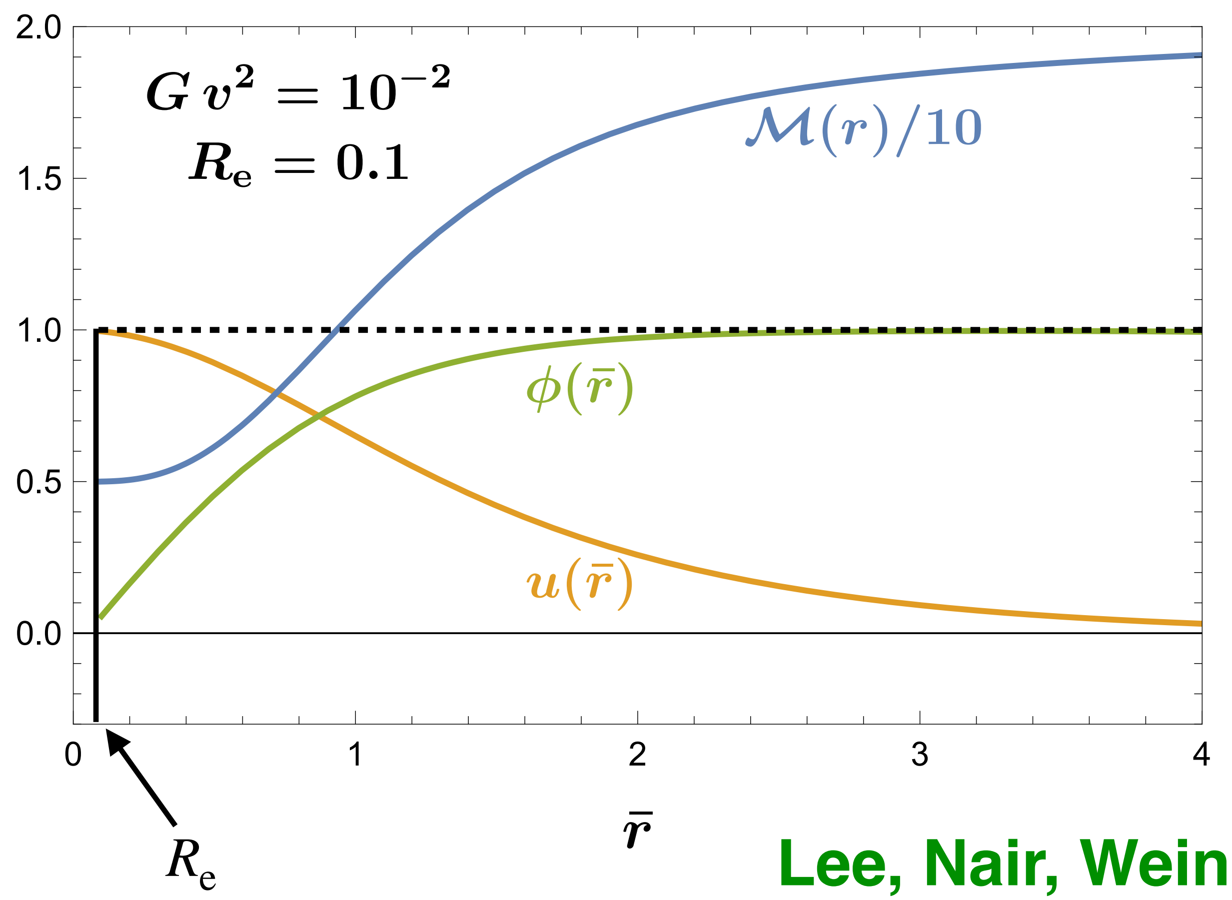
Guth, Weinberg, PRD14(1976) 1660

Q=2: spherical solution

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

$$S_{\rm matter} = -4\pi \int dt\, dr\, r^2 \sqrt{A\, B} \left(\frac{K}{A} + U\right)$$

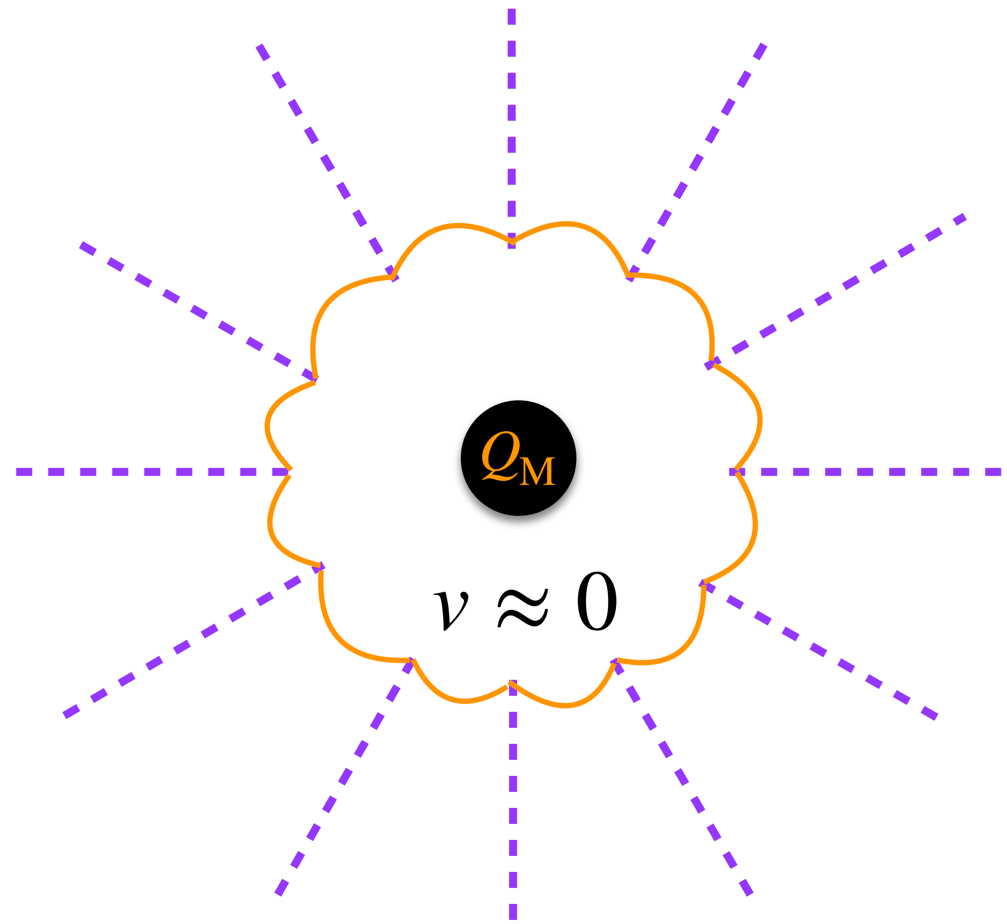
- **Defining** $A(r)^{-1} = \left(1 - \frac{2\,G\,\mathcal{M}(r)}{r}\right)$**, and solving the EOMs**



Lee, Nair, Weinberg, PRD45(1992) 2751

YB, Korwar, in progress

Q>2: non-spherical



$v = 246\,\text{GeV}$

$$R_{\rm EW} \simeq \sqrt{\frac{Q}{2}}\,\frac{1}{m_h}$$

$$\begin{aligned} M^{\rm tot}_{\rm MeBH}(Q) &\simeq c_W\,\frac{\sqrt{\pi}\,Q}{e}\,M_{\rm pl} + \frac{4\pi}{3}\,R^3_{\rm EW}\,\frac{m_h^2\,v^2}{8} = c_W\,\frac{\sqrt{\pi}\,Q}{e}\,M_{\rm pl} + \frac{\pi}{12\sqrt{2}}\,Q^{3/2}\,\frac{v^2}{m_h} \\ &\equiv M_{\star}(Q) + \frac{\pi}{12\sqrt{2}}\,Q^{3/2}\,\frac{v^2}{m_h}\,, \qquad M_{\star}(Q) = c_W\,M^{\rm RN}_{\rm eBH} \end{aligned}$$

- For $Q < Q_{\rm max} \simeq 10^{32}$, $M_{\star} \lesssim 9 \times 10^{51}\,\text{GeV}$ $M_{\oplus} = 6.0 \times 10^{27}\,\text{g} = 3.4 \times 10^{51}\,\text{GeV}$

2d Modes

- **For non-extremal BH, the Hawking temperature is**

$$T(M_{\rm BH}, M_{\star}) = \frac{M_{\rm pl}^2}{2\pi} \frac{\sqrt{M_{\rm BH}^2 - M_{\star}^2}}{\left(M_{\rm BH} + \sqrt{M_{\rm BH}^2 - M_{\star}^2}\right)^2}$$

- **In the existence of magnetic field, the massless 2d modes exist for a Dirac 4D massless fermion**

$$ds^2 = e^{2\sigma(t,x)} \left(-dt^2 + dx^2\right) + R^2(t,x) \left(d\theta^2 + \sin^2\theta \, d\phi^2\right) \qquad A_\phi = \frac{Q}{2} \cos\theta$$

$$dx = \frac{dr}{f(r)}, \qquad e^{2\sigma(t,x)} = f(r) \equiv (1 - R_{\rm e}/r)^2 , \qquad R(t,x) = r$$

$$\not{D}\widetilde{\chi} = m_\chi \widetilde{\chi} \qquad \widetilde{\chi}_{\alpha\beta} = \frac{e^{-\frac{1}{2}\sigma}}{R} \psi_\alpha(t,x) \, \eta_\beta(\theta,\phi)$$

$$\left[\sigma_y \frac{\partial_\phi - iA_\phi}{\sin\theta} + \sigma_x \left(\partial_\theta + \frac{\cot\theta}{2}\right)\right]\eta = 0 ,$$

$$(i\sigma_x\partial_t + \sigma_y\partial_x)\,\psi = m_\chi \, e^\sigma \psi \, .$$ ← **2d fermion**

2d Modes

- **Solutions for Q > 0,**

$$
\begin{aligned}
\eta_1 &= 0\,, \\
\eta_2 &= \left(\sin\frac{\theta}{2}\right)^{j-m}\left(\cos\frac{\theta}{2}\right)^{j+m} e^{im\phi} = \frac{(1-\cos\theta)^{\frac{q-m}{2}}(1+\cos\theta)^{\frac{q+m}{2}}}{2^{q-\frac{1}{2}}(\sin\theta)^{\frac{1}{2}}}\, e^{im\phi}
\end{aligned}
$$

$$j = (|Q|-1)/2 \equiv q - 1/2 \text{ and } -j \leq m \leq j$$

- **There are |Q| massless modes for** $m_\chi = 0$

Field	$SU(3)\times SU(2)\times U(1)$	Number of 2d modes (left - right)
q_L	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	Q
u_R	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	- 2 Q
d_R	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	Q
l_L	$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	- Q
e_R	$(\mathbf{1},\mathbf{1})_{-1}$	Q

Maldacena, arXiv:2004.06084

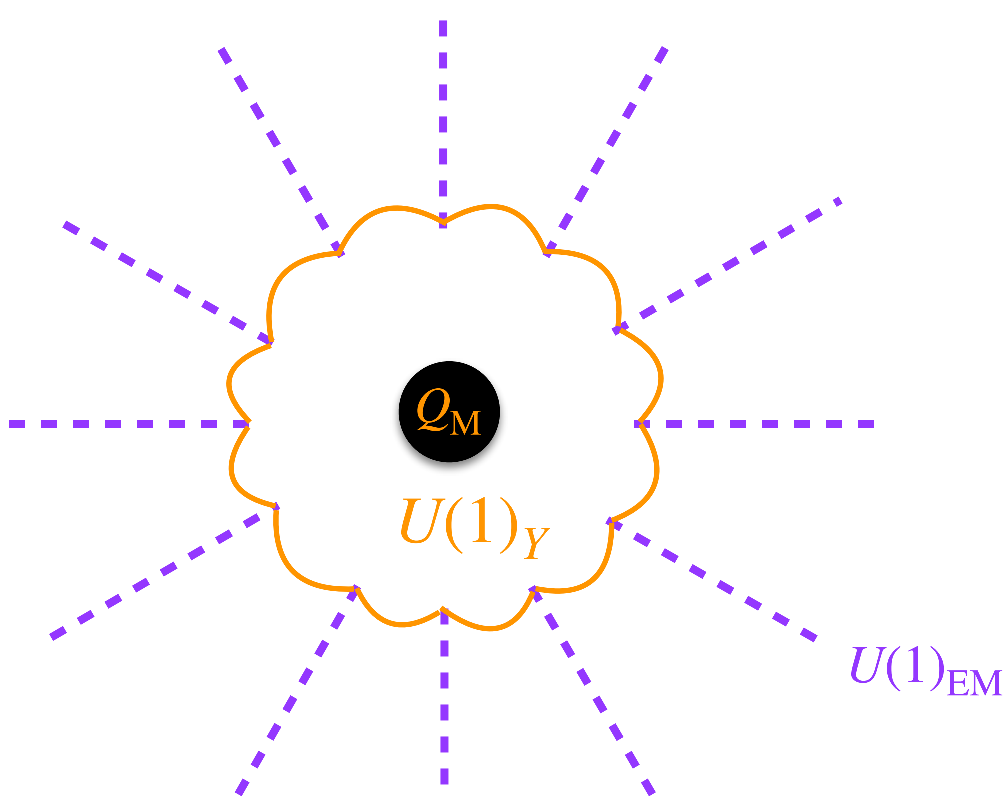
2d Hawking radiation

- **Fermions are massless (ignoring QCD vacuum) inside the EW-corona region**

$$P_2 = \frac{dE}{dt} = \frac{\pi\, g_*}{24} T^2(M_{\rm BH}, M_{\ast})$$

- **For high T, $g_* = 18\,|\,Q\,|$ for three-family fermions**

- **The 2d radiation is very fast; it reaches extremal very quickly**



- 2d neutrino modes can not escape
- EM charged states can travel outside of coronas

2d Hawking radiation

- **For $T < m_e$, the 2d radiation is suppressed. The 4D radiation dominants**

$$P_4 = \frac{dE}{dt} \approx \frac{\pi^2 g_*}{120} (4\pi R_{\rm EW}^2) T^4 (M_{\rm BH}, M_{\odot})$$

with $g_* = 2$ for photon and $g_* = 21/4$ for neutrinos

- **For $T > m_e$, the 2d radiation usually dominants over 4D**

Primordial MBHs ?

- There are various ways to form primordial black holes
  - Large primordial fluctuations
  - Phase transitions, boson stars, ……
- Produce large number of monopoles and anti-monopoles (maybe Nambu's dumbbell configurations)
- The formation of black holes eat totally N objects
- Anticipate the net BH magnetic charge: $\sim \sqrt{N}$

YB, Orlofsky, arXiv: 1906.04858

- To be studied more. Let's discuss how to search for them

Parker Limits

- **Requiring the domains of coherent magnetic field are not drained by magnetic monopoles**

$$M_{\ast}/Q = c_W\sqrt{\pi}M_{\rm pl}/e \approx 5.1\,M_{\rm pl}$$

- **The mass per charge is much larger than GUT monopoles**
- **PMBH flux:** $F_{\ast} \approx (9.5\times 10^{-21}\,{\rm cm}^{-2}{\rm sr}^{-1}{\rm s}^{-1})\, f_{\ast}\left(\frac{10^{26}\,{\rm GeV}}{M_{\ast}}\right)\left(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV\,cm}^{-3}}\right)\left(\frac{v}{10^{-3}}\right)$

- **Mean energy gained by PMBHs for the regeneration time is smaller than the energy stored in B**

Turner, Parker, Bogdan, PRD26(1982) 1296

$$\Delta E \times F_{\ast} \times (4\pi\ell_c^2) \times (\pi\ {\rm sr}) \times t_{\rm reg} \lesssim \frac{B^2}{8\pi}\,\frac{4\pi\,\ell_c^3}{3}$$

$$\Delta E \simeq M_{\ast}\Delta v^2/2 \qquad \Delta v \simeq B\,h_Q\,\ell_c/(M_{\ast}v)$$

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

$\rho_{0.4} = \rho_{\rm DM}/(0.4\,{\rm GeV\,cm}^{-3})$

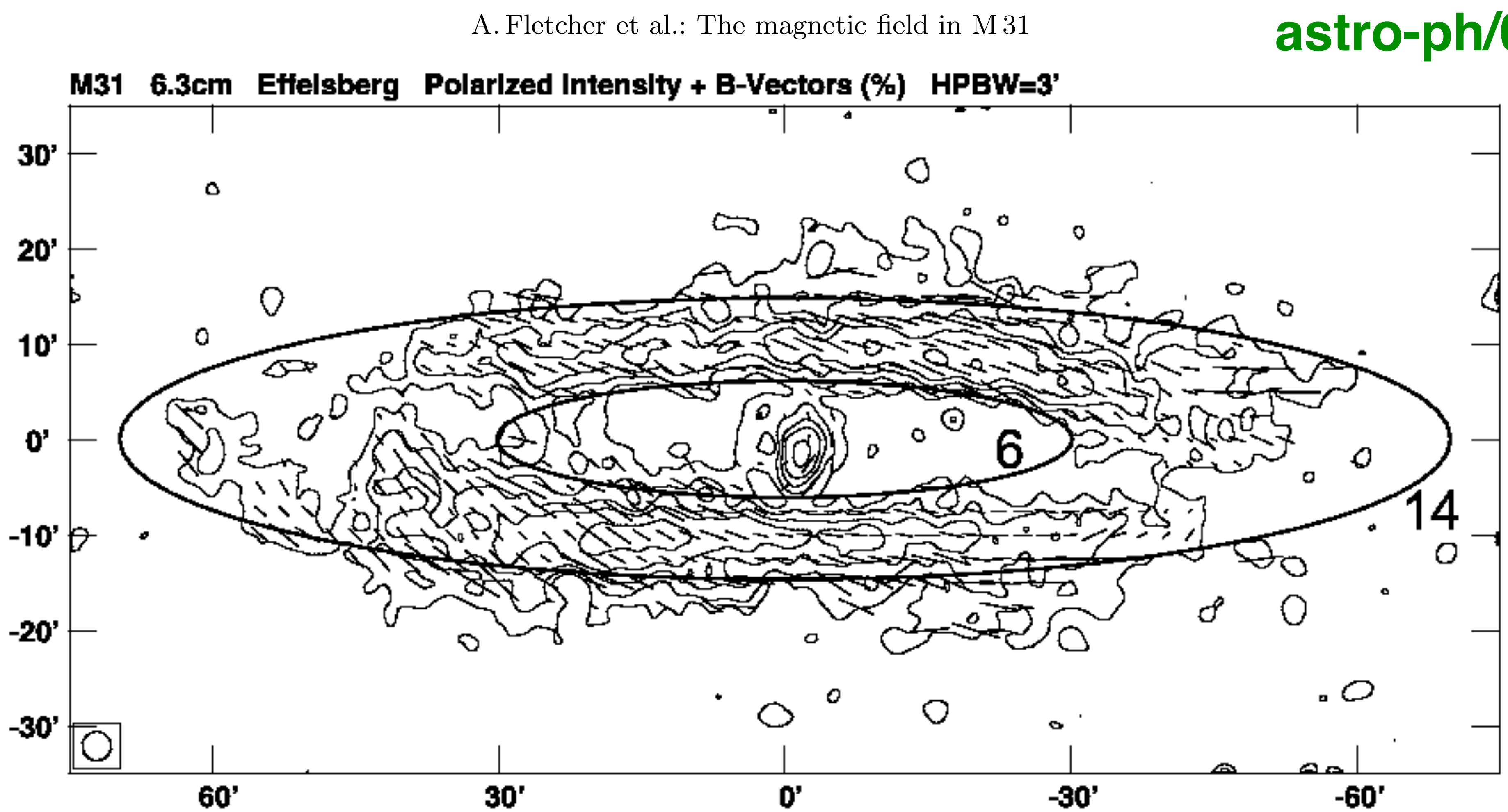
$v_{-3} = v/(10^{-3})$

$t_{15} = t_{\rm reg}/(10^{15}\,{\rm s})$

$\ell_{21} = \ell_c/(10^{21}\ {\rm cm})$

Parker Limit from M31

astro-ph/0310258



$$\ell_c \sim 10 \text{ kpc} \Rightarrow \ell_{21} \sim 30 \text{ and } t_{\rm reg} \sim 10 \text{ Gyr} \Rightarrow t_{15} \sim 300$$

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

which is independent of PMBH mass

PMBHs Captured by Astrophysical Objects

- **Taking the finite size into account, the PMBH power loss rate is**

$$\frac{dW}{dt} = -\frac{\mu_0 V h_Q^2}{4\pi R^2}\left[\log\left(\frac{R}{l}\right) + \frac{1}{4}\right]$$

$V = 10^{-3}$ $\quad$ $l = \pi^{-1/4}(v_{\rm th}/V)^{1/2}\omega_p^{-1} \approx 3\times 10^{-6}$ cm $\quad$ $R_{\rm EW} = \sqrt{\frac{Q}{2}}\frac{1}{m_h} \approx (10^{-8}\ {\rm cm})\sqrt{\frac{Q}{10^{16}}}$

attenuation length

	n_e	electron $v_{\rm th}$ or $v_{\rm F}$	$Q_{\rm stop,min}$
Sun	10^{24} cm^{-3}	$v_{\rm th} = 0.058$ (from $T = 10^7$ K)	30 [53, 55]
Earth	$(5.5\ {\rm cm}^{-3})\,\frac{Z}{A}\,N_A \sim 1.7\times 10^{24}\ {\rm cm}^{-3}$	$v_{\rm F} \sim \sqrt{\frac{2(1\ {\rm eV})}{(0.511\ {\rm MeV})}} \sim 2\times 10^{-3}$	1900
Neutron star	6×10^{37} cm^{-3}	$v_{\rm F} \sim 1$	1
White dwarf	6×10^{29} cm^{-3}	$v_{\rm F} \sim 0.7$	1

Table 1: Physical quantities relevant for stopping.

[53] J. A. Frieman, K. Freese, and M. S. Turner, *Superheavy Magnetic Monopoles and Main Sequence Stars*, *Astrophys. J.* **335** (1988) 844–861.

[55] S. Ahlen, I. De Mitri, J. Hong, and G. Tarle, *Energy loss of supermassive magnetic monopoles and dyons in main sequence stars*, *Phys. Rev. D* **55** (1997) 6584–6590.

PMBHs inside the Sun

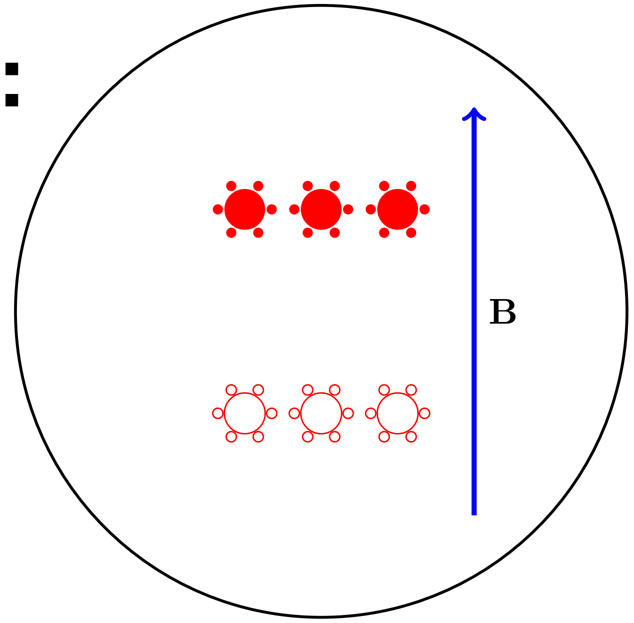
- **The capture rate is**

$$C_{\rm cap} \approx \epsilon\, \pi\, R_\odot^2 \left[1 + (v_{\rm esc}/v)^2\right]\, 4\,\pi F_{*} \approx \left(9.2 \times 10^3\,{\rm s}^{-1}\right)\, \epsilon\, f_{*}\, M_{26}^{-1}$$

- **Then, it drifts to the center region with a time scale**

$$t_{\rm drift} \sim \frac{R_\odot}{v_{\rm drift}} \sim \frac{R_\odot^3}{M_\odot} \frac{n_e\, e^2}{c_W^2\, m_e\, v_{\rm th}} M_{*} \sim (8 \times 10^4\,{\rm s})\, M_{26}$$

- **Force-balance equation:**



$$0 = F = B\,\frac{2\pi Q}{e} - \frac{4\pi}{3}\, G\, \rho_c\, M_{*}\, z - \frac{G\, N_{*}\, M_{*}^2}{(2\,z)^2}$$

PMBHs inside the Sun

$$0 = F = B\,\frac{2\pi Q}{e} - \frac{4\pi}{3}\,G\,\rho_c\,M_\odot\,z - \frac{G\,N_\odot\,M_\odot^2}{(2\,z)^2}$$

- **For** $N < N_\odot^{\rm crit} \simeq \dfrac{18\,M_{\rm pl}^3\,B^3}{\sqrt{\pi}\,c_W^3\,M_\odot\,\rho_c^2} = (3.8\times 10^{10})\,B_{100}^3\,M_{26}^{-1}$ **the first two terms are important**

$$z_B \simeq \frac{3\,B\,M_{\rm pl}}{2\sqrt{\pi}\,c_W\,\rho_c} = (2.0\times 10^3\,{\rm cm})\,B_{100}$$

- **For** $N > N^{\rm crit}$, **an equilibrium is quickly reached between capture and annihilation rates with**

$$\Gamma_A = \frac{1}{2}\,C_A\,N_\odot^2 \approx \frac{1}{2}\,C_{\rm cap} = \left(4.6\times 10^3\,{\rm s}^{-1}\right)\,f_\odot\,M_{26}^{-1}$$

Annihilation Products

- **For two eBHs with Q_1 and $-Q_2$ charges, the merge product has**

$$Q = Q_1 - Q_2$$

$$M_{\rm BH} \approx c_W \sqrt{\pi} (Q_1 + Q_2) M_{\rm pl}/e$$

- **It is a non-extremal MBH with**

$$T_{\rm BH} \simeq \frac{M_{\rm pl}^2}{2\pi} \frac{1}{8\, M_{\star}(Q_1)} = (2.8 \times 10^{10}\,{\rm GeV})\, M_{26}^{-1}$$

- **For $T_{\rm BH} > m_e$, it has quick 2d Hawking radiation to reach the extremal state**

- **The radiated charged particles can decay into photons, neutrinos and protons; only (not too high-energy) neutrinos can easily propagate out of the Sun**

Solar ν from PMBH Annihilation

- **To satisfy the neutrino energy cut,**

$$M_{\circledast} \lesssim M_{\max,E} = (2.8 \times 10^{35}\ \mathrm{GeV}) \left(\frac{10\,\mathrm{GeV}}{E_\nu^{\mathrm{cut}}}\right)$$

- **To have the time interval of two events shorter than the experimental operation time**

$$M_{\circledast} \lesssim M_{\max,t} = (2.1 \times 10^{37}\ \mathrm{GeV})\, f_{\circledast} \left(\frac{t_{\mathrm{exp}}}{532\,\mathrm{day}}\right)$$

- **The generated neutrino flux is** $E_\nu \simeq \langle E_f \rangle / \eta_\nu \approx (1.19/\eta_\nu)\, T_{\mathrm{BH}}$

$$I_\nu \approx \frac{N_\nu\, \Gamma_A}{4\pi\, d_\oplus^2} \approx (5.5 \times 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})\, M_{26}\, \eta_\nu\, f_{\circledast}$$

$$f_{\circledast} \lesssim \begin{cases} 1.4 \times 10^{-7}\,, & 2 \times 10^{21}\ \mathrm{GeV} \lesssim M_{\circledast} \lesssim 2.9 \times 10^{30}\ \mathrm{GeV}\,, \\ M_{\circledast}/(2.1 \times 10^{37}\ \mathrm{GeV})\,, & 2.9 \times 10^{30}\ \mathrm{GeV} \lesssim M_{\circledast} \lesssim 2.8 \times 10^{35}\ \mathrm{GeV}\,, \end{cases} \qquad \text{(IceCube)}$$

- **Super-K probes even heavier masses because a smaller energy cut**

PMBH inside Earth

- **Similar story as the Sun, the capture rate is**

$$C_{\rm cap} \approx \epsilon\, \pi\, R_\oplus^2\, 4\,\pi F_{\bullet} \approx \left(0.15\,{\rm s}^{-1}\right)\, \epsilon\, f_{\bullet}\, M_{26}^{-1}$$

- **Other than the neutrino signals, the total power generated from BH annihilation is**

$$P_A \simeq (2.4 \times 10^{15}\,{\rm W})\, f_{\bullet}$$

- **The internal heat of the Earth is $P_\oplus \approx 4.7 \times 10^{13}$ W, so**

$$f_{\bullet} \lesssim 0.02 \qquad\qquad (\text{Earth heat})$$

for $1.2 \times 10^{23}\ \text{GeV} \lesssim M_{\bullet} \lesssim 1 \times 10^{37}\ \text{GeV}$

Stop PMBH

$t_{\rm drift} < t_\oplus$

PMBH inside Neutron Stars

- **The capture rate is**

$$C_{\rm cap} \approx \epsilon\,\pi\,R^2 \left[\frac{1+(v_{\rm esc}/v)^2}{1-v_{\rm esc}^2}\right] 4\,\pi F_{\star} \approx (0.11\,{\rm s}^{-1})\, f_{\star}\, R_{10}^2\, M_{26}^{-1}$$

$$N_{\star}^{\rm NS} = C_{\rm cap}\,\tau_{\rm NS} \sim \left(3.3\times10^{16}\right)\; f_{\star}\, R_{10}^2\, M_{26}^{-1}\,\tau_{10} \qquad \tau_{\rm NS} = \tau_{10}\times 10^{10}\ {\rm yr}$$

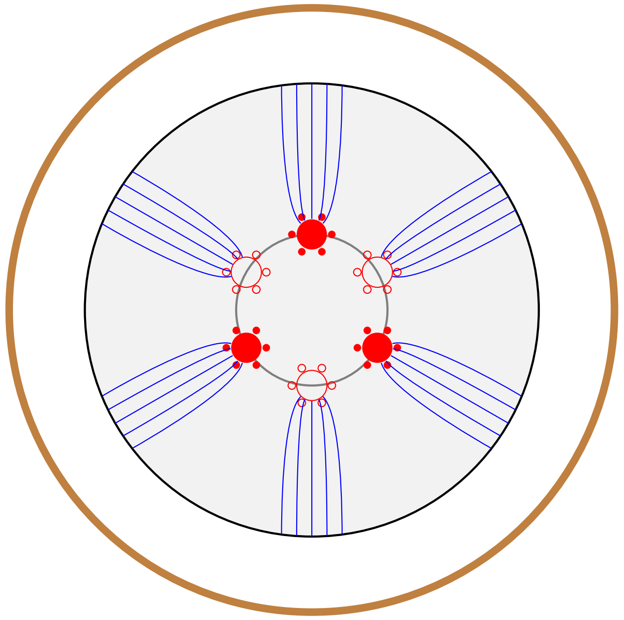
- **The inner core of a neutron star is anticipated to be a proton superconductor** Gezerlis, et. al, arXiv:1406.6109

- **The magnetic field of PMBH is confined to flux tubes with**

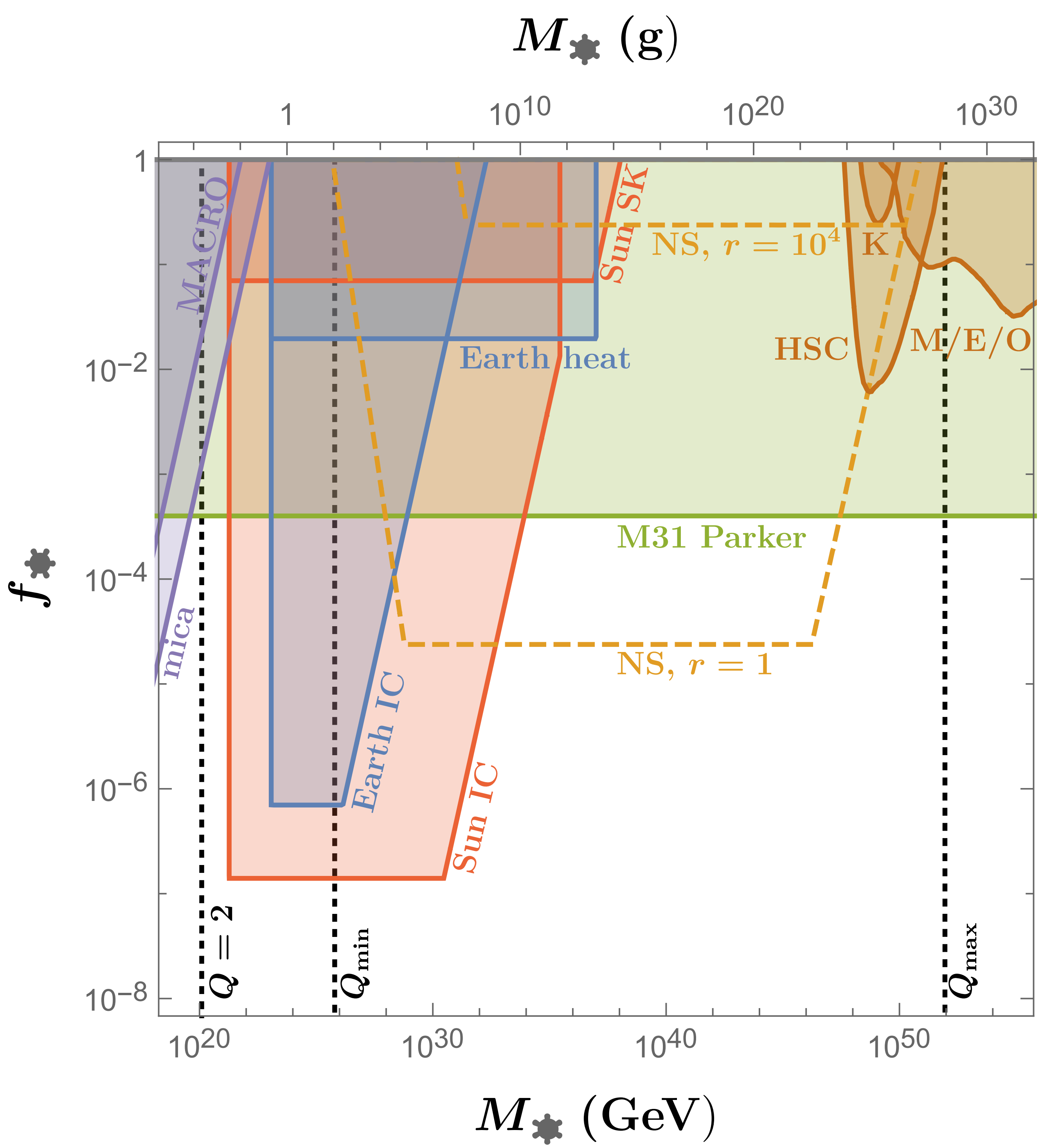
$$\lambda = \left(\frac{m_p}{e^2\,n_p}\right)^{1/2} \sim 10^{-12}\ {\rm cm}$$

$$B_\Phi \sim \frac{\Phi}{\pi\,\lambda^2} \sim 10^{16}\ {\rm gauss}$$

$$F_{\rm T} \sim B_\Phi^2\,\pi\,\lambda^2\,\ln\left(\lambda/\xi\right) \sim 10^4\ {\rm N}$$



Fraction of PMBH over dark matter



Conclusions

- Magnetic black holes have electroweak-symmetric coronas
- It has a fast 2d Hawking radiation rate and can reach the extremal state quickly
- Because of their heavy masses, they require astrophysical objects to infer their existence
- It is unlikely to account 100% of dark matter abundance, because of the Parker limit and neutrino and photon signals from the Sun, Earth and NS captures
- It does not require unknown new physics. More studies are deserved to search for them

Thanks!