PHENOMENOLOGY OF MAGNETIC BLACK HOLES

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MAGNETIC BLACK HOLES

Any charged black hole is described by the Reissner-Nordstrom metric:

$$ds^2 = f(r)\, dt^2 - \frac{dr^2}{f(r)} - r^2\, d\theta^2 - r^2\, \sin^2\theta\, d\phi^2$$

$$f(r) = 1 - 2MG/r + \pi Q^2 G/(e^2 r^2)$$

For reasons that will later become clear, we will take the BHs to be (near-)**extremal**

$$f(r) = \left(1 - \frac{R_{\rm eBH}^{\rm RN}}{r}\right)^2, \qquad M_{\rm eBH}^{\rm RN} = \frac{\sqrt{\pi}\,|Q|}{e}\, M_{\rm pl}\,, \qquad R_{\rm eBH}^{\rm RN} = \frac{\sqrt{\pi}\,|Q|}{e}\,\frac{1}{M_{\rm pl}}$$

Magnetic field:

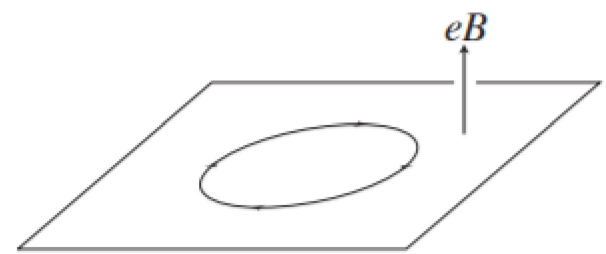
$$B(R_{\rm eBH}) = \frac{Q}{2\, e\, R_{\rm eBH}^2} \sim \frac{e\, M_{\rm pl}^2}{2\pi\, Q}$$

AMBJØRN-OLESEN CONDENSATION

Lowest Landau levels:

$$E^2 - P_3^2 = m^2 + |F|(1-2s) = \begin{cases} m^2 + |F| \, , & \text{for} \quad s = 0 \\ m^2 + 0 \, , & \text{for} \quad s = \frac{1}{2} \\ m^2 - |F| \, , & \text{for} \quad s = 1 \end{cases}$$

$$|F| = e|B|$$

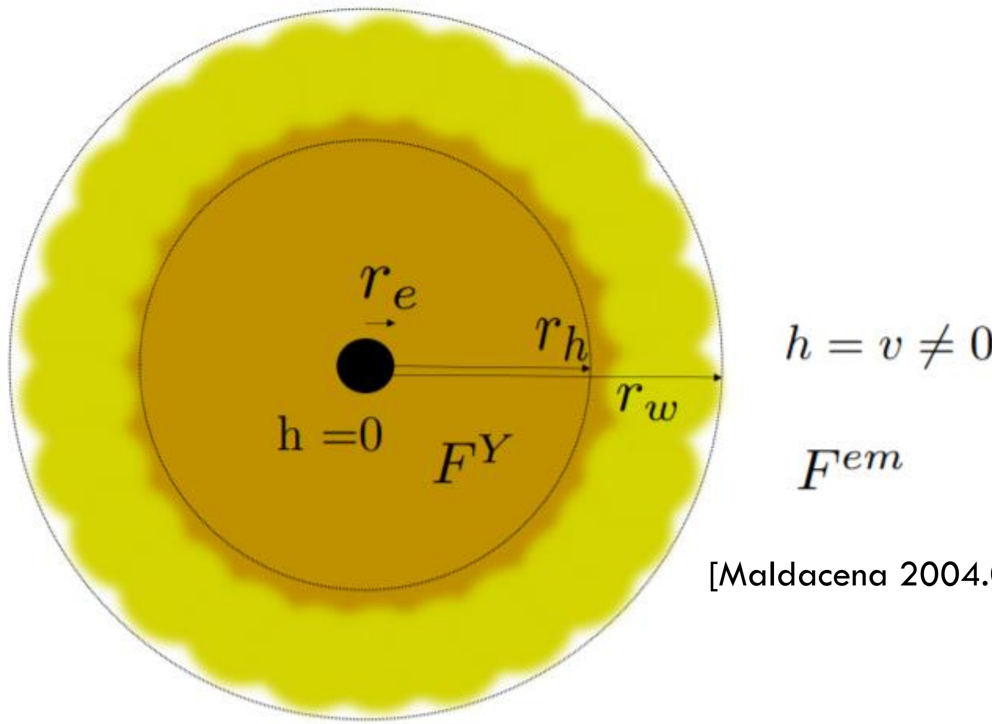


EW symmetry is restored when $eB \gtrsim m_h^2$ or $B_{\rm EW} \approx m_h^2/e \approx 3 \times 10^{24}$ gauss

For the (near-)extremal black hole to be EW-symmetric:

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

EW-SYMMETRIC CORONA



[Maldacena 2004.06084]

$$M_{\star}(Q) = c_W\, M_{\rm eBH}^{\rm RN}$$

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

See also earlier work [Lee, Weinberg hep-th/9406021]

FERMION MODES INSIDE THE CORONA

$$E^2 - P_3^2 = m^2 + |F|(1-2s) = \begin{cases} m^2 + |F| \ , & \text{for} \quad s = 0 \\ m^2 + 0 \ , & \text{for} \quad s = \frac{1}{2} \\ m^2 - |F| \ , & \text{for} \quad s = 1 \end{cases}$$

SM fermions are massless inside the EWS region.

There are $q_Y Q$ degenerate modes in the lowest energy Landau level (all other levels suppressed because of large magnetic field).

These are $2d$ modes:
They move along field lines in the radial direction.

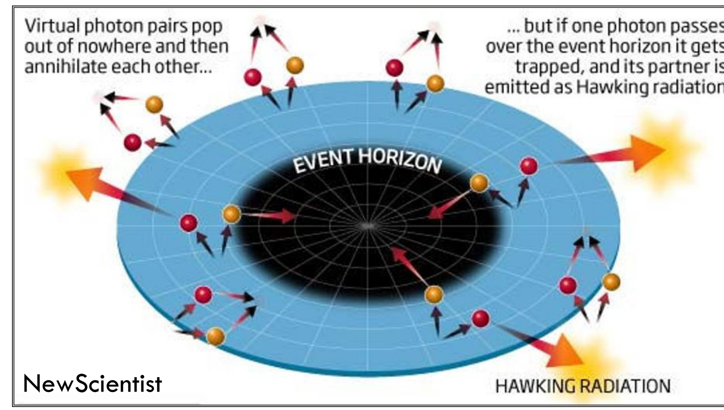
BH EVAPORATION

For non-extremal EWS BHs, Hawking radiation is into $2d$ modes.
This enhances the evaporation rate by Q compared to ordinary BHs:

$$T \approx \frac{M_{pl}^2}{M} \approx r_s^{-1}$$

$$P_2 \approx Q\, T^2$$

$$P_4 \approx r_s^2\, T^4 \approx T^2$$



Ex)

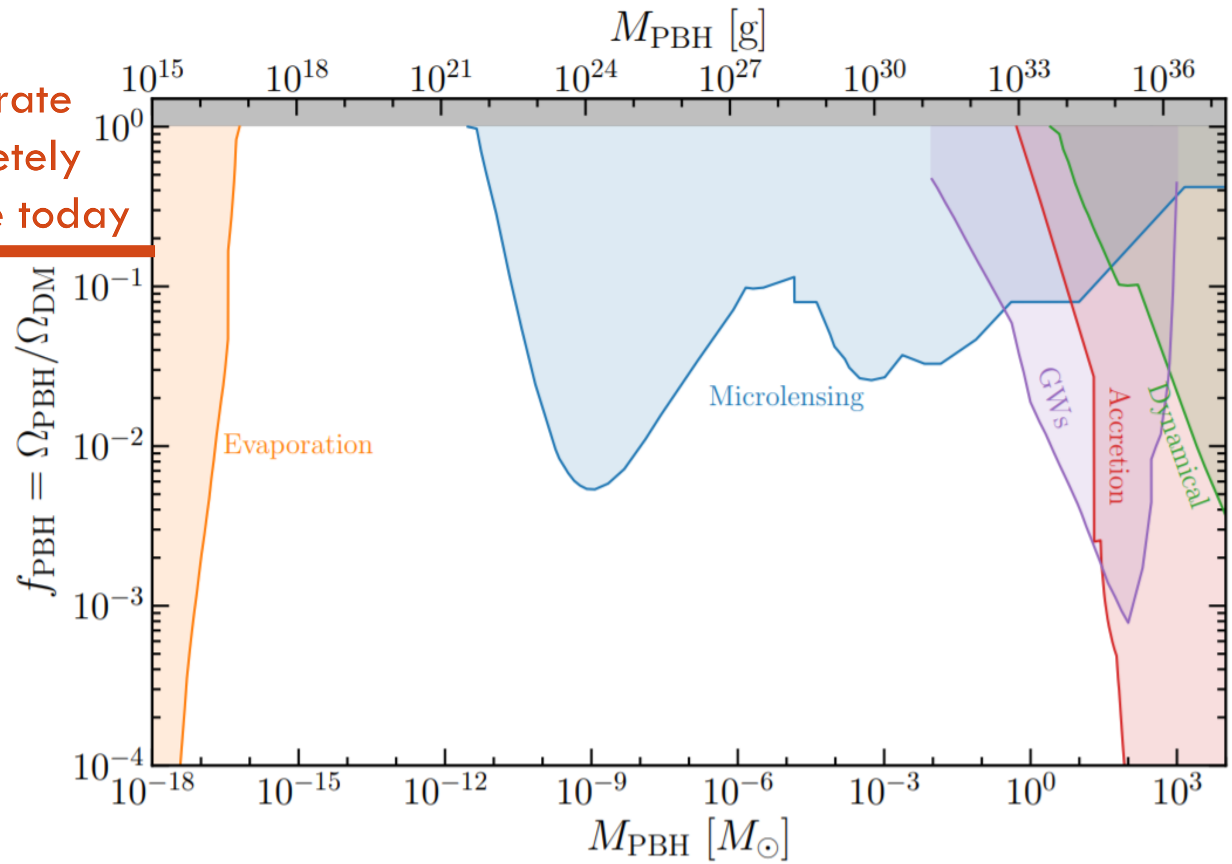
- 10^{15} g uncharged BH has a lifetime ≈ age of universe.
- EWS corona BH of the same mass has a lifetime ≈ milliseconds to decay to near-extremality (order 1 deviation)

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

STABILITY

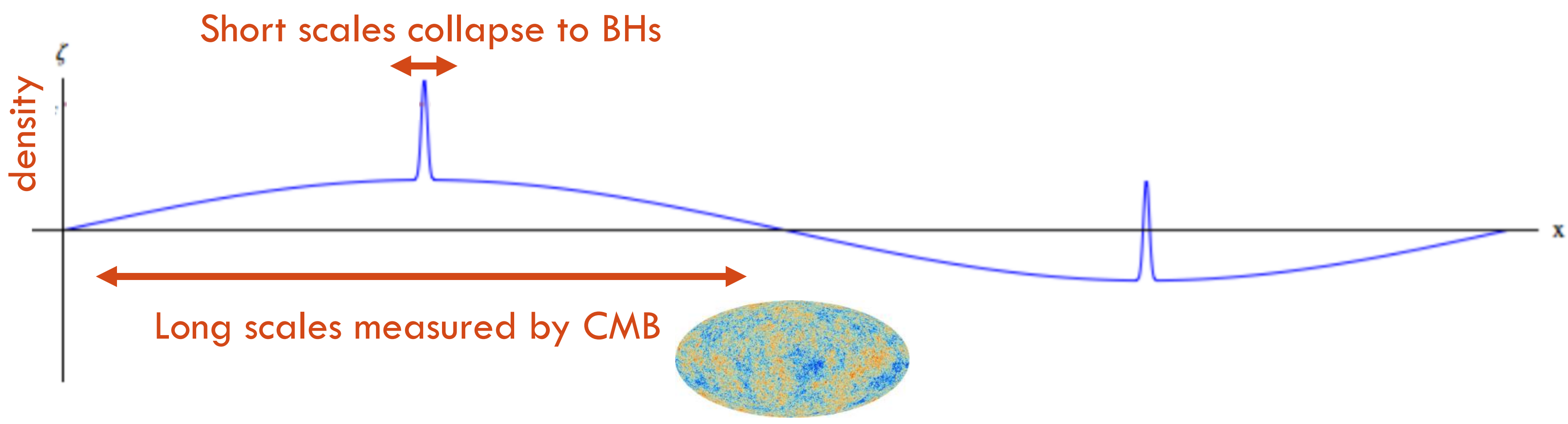
Unlike ordinary BHs, extremal black holes are stable (at least compared to the age of the universe); could be DM [Bai, **NO** 1906.04858]

Evaporate completely before today



Green Kavanaugh 2007.10722

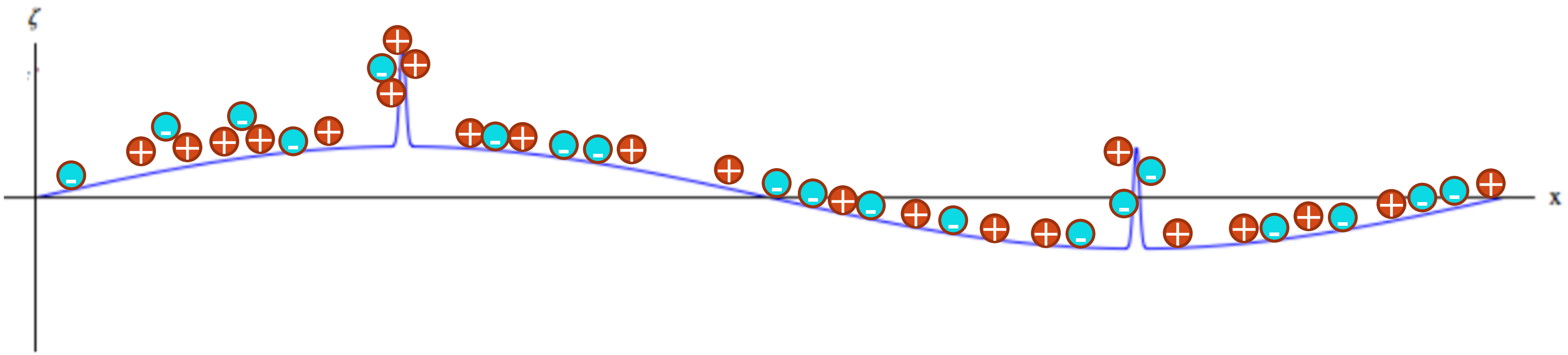
FORMATION



Short scales collapse to BHs
ζ
density
x
Long scales measured by CMB

FORMATION

BH in a bath of charges, absorbs some, so its net charge is a 1D random walk.



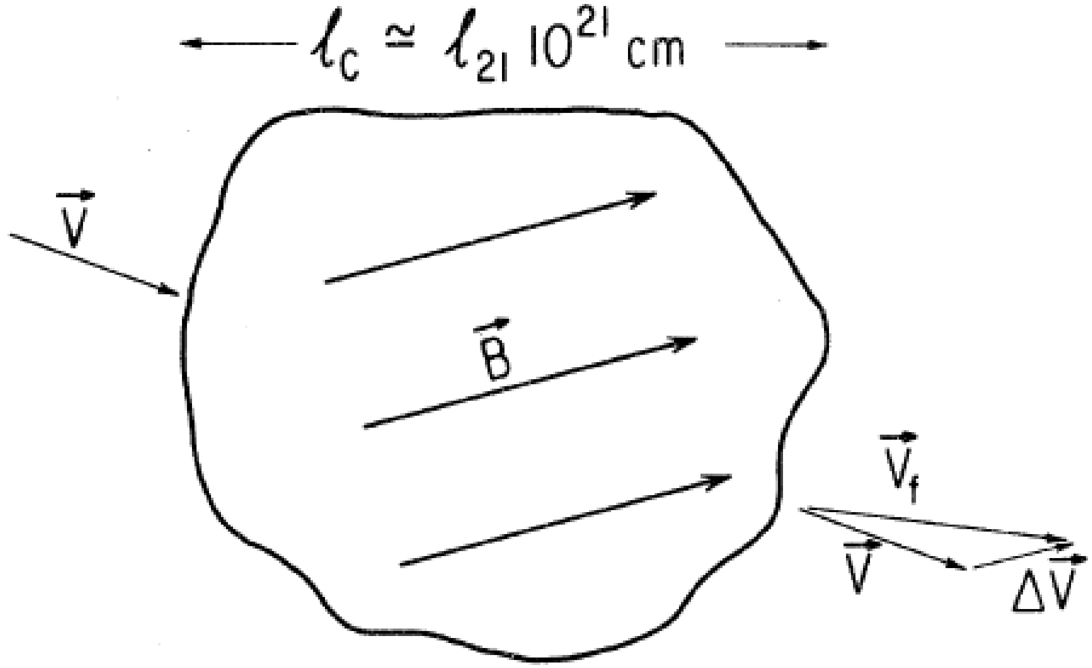
If BH absorbs N charges, get a typical charge $\sim\sqrt{N}$.

[Bai, **NO** 1906.04858; Stojkovic, Freese hep-ph/0403248]

PARKER BOUND

Monopoles are accelerated by magnetic fields and deplete their energy.

The rate of depletion must be slower than the rate of regeneration:



[Turner, Parker, Bogdan 1982]

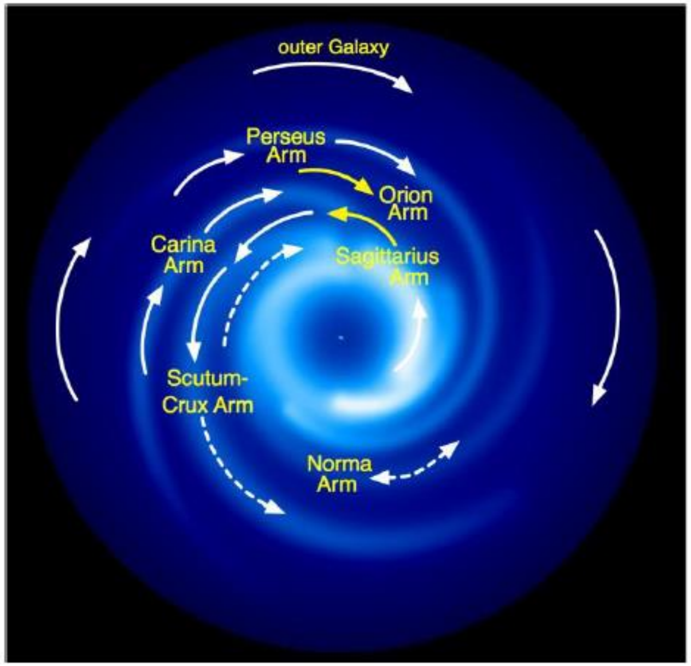
PARKER BOUND

Bound on DM fraction is independent of mass (since charge and mass are proportional) or magnitude of B-field:

$$f_{\star} \lesssim 50 \times \frac{v_{-3}}{\rho_{0.4}\,\ell_{21}\,t_{15}}$$

Independent of $M \propto Q$, B

These are quantities relevant to Milky Way:



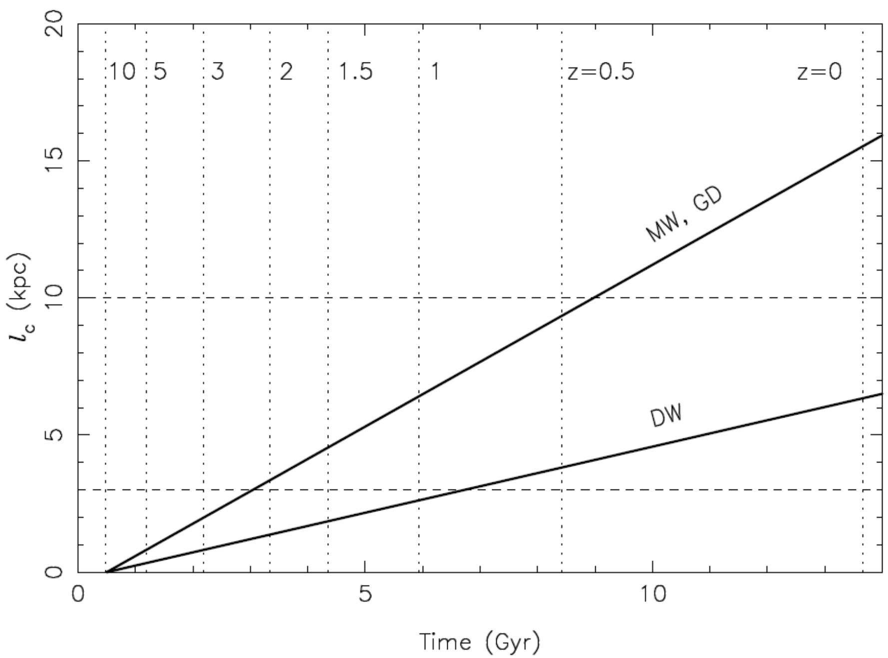
[Jo-Anne Brown; see also Beck, Wielebinski 2013]

PARKER BOUND

Bound on DM fraction is independent of mass (since charge and mass are proportional) or magnitude of B-field:

$$f_{\star} \lesssim 50 \times \frac{v_{-3}}{\rho_{0.4}\,\ell_{21}\,t_{15}}$$

Coherence length and regeneration time are correlated:



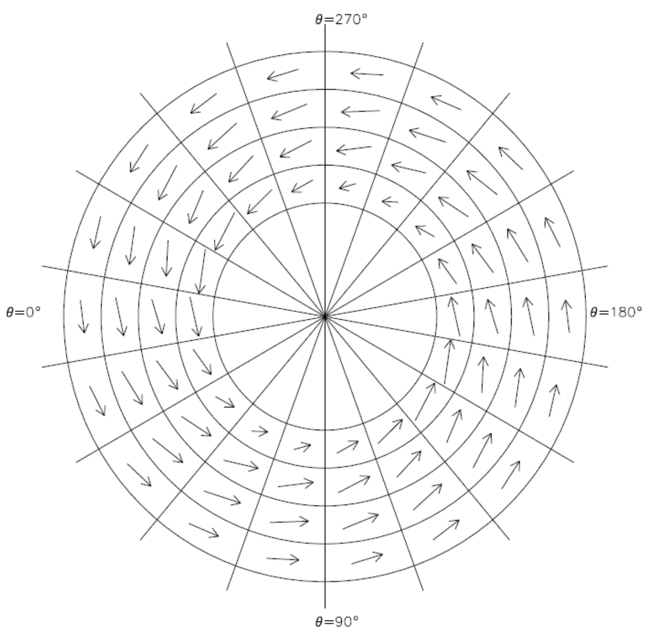
[Arshakian, Beck, Krause, Sokoloff 0810.3114]

PARKER BOUND

Bound on DM fraction is independent of mass (since charge and mass are proportional) or magnitude of B-field:

$$f_{\star} \lesssim 50 \times \frac{v_{-3}}{\rho_{0.4}\, \ell_{21}\, t_{15}}$$

M31 has much more ordered fields (that take much longer to produce):



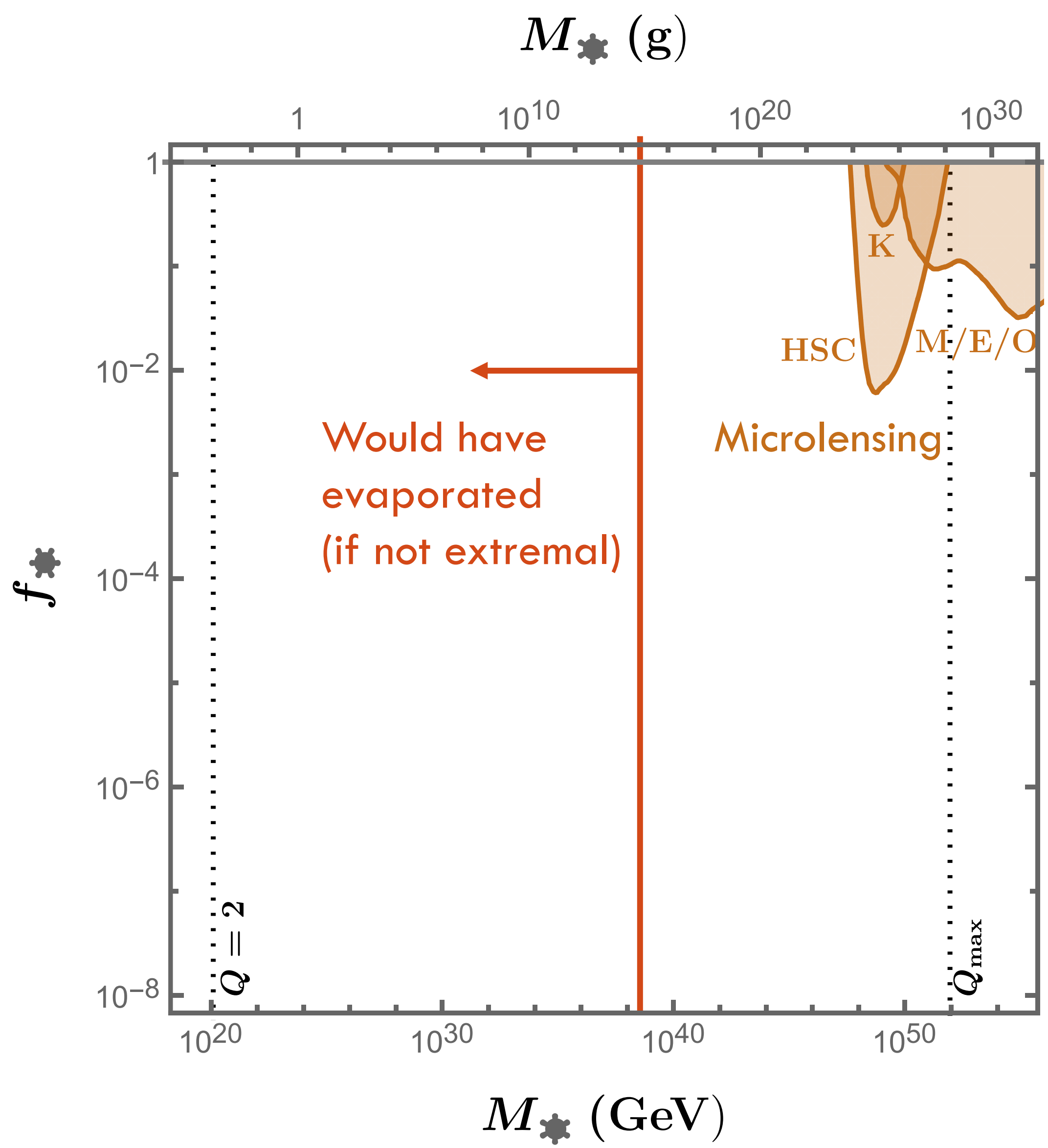
$$\ell_c \sim 10 \text{ kpc} \Rightarrow \ell_{21} \sim 30$$
$$t_{\text{reg}} \sim 10 \text{ Gyr} \Rightarrow t_{15} \sim 300$$

$$\boxed{f_{\star} \lesssim 6 \times 10^{-3}}$$

(Can also be applied to ordinary monopoles to get a better constraint)

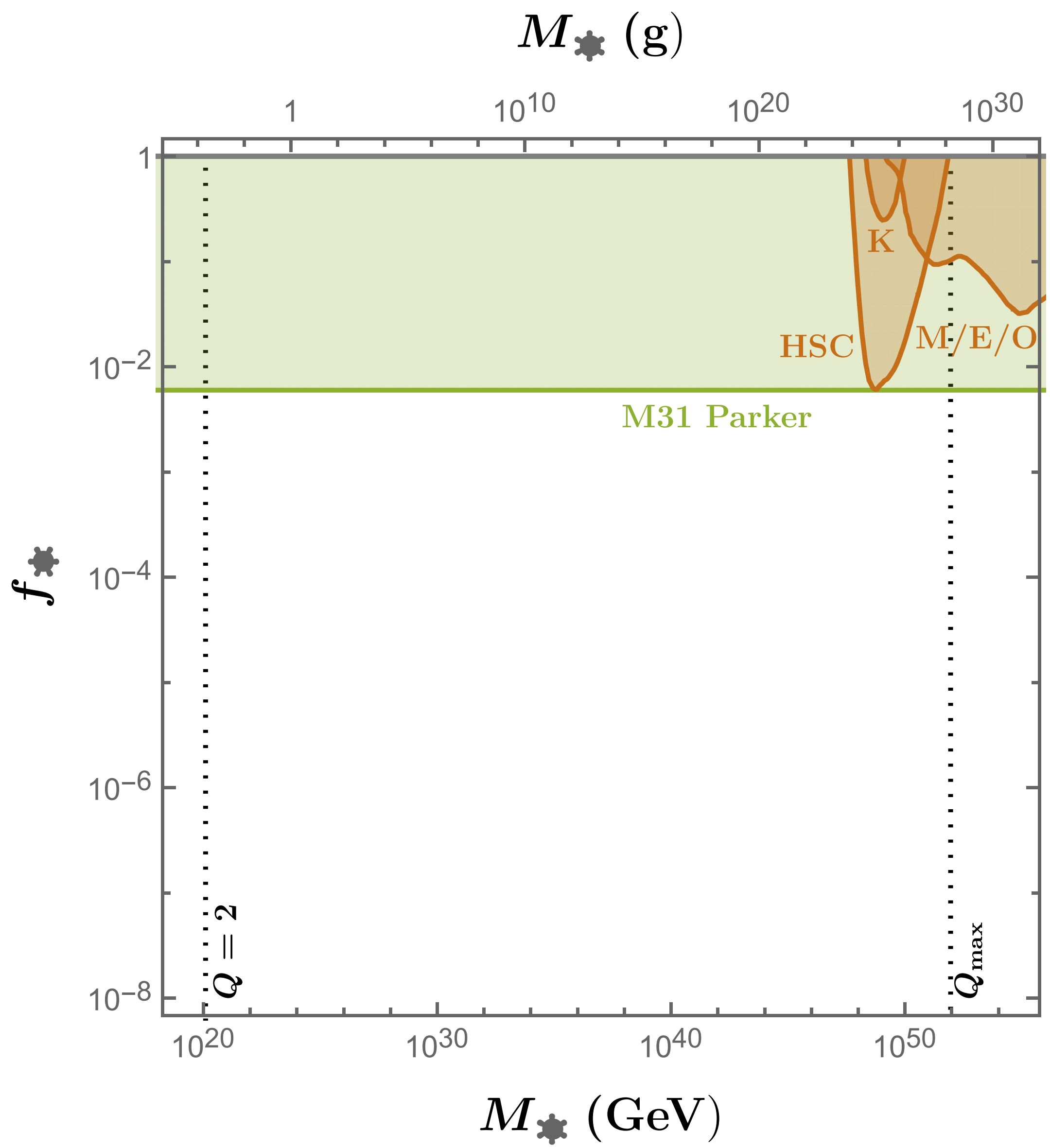
[Fletcher, Berkhuijsen, Beck, Shukurov astro-ph/0310258]

BOUNDS



M_{*} (g)
1
10^{10}
10^{20}
10^{30}
f_{*}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{20}
10^{30}
10^{40}
10^{50}
M_{*} (GeV)
K
HSC
M/E/O
Would have evaporated (if not extremal)
Microlensing
$Q = 2$
$Q_{\max}$

BOUNDS



M_{*} (g)
1
10^{10}
10^{20}
10^{30}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
f_{*}
K
HSC
M/E/O
M31 Parker
$Q = 2$
$Q_{\max}$
10^{20}
10^{30}
10^{40}
10^{50}
M_{*} (GeV)

BH MERGERS ("ANNIHILATIONS")

When they merge, oppositely-charged BHs become non-extremal.

Unless their charges are extremely close, the merged BH will also have an EWS corona.

For charges Q_1 and $-Q_2$ satisfying $Q_1 \geq Q_2 > 0$, in the limit $Q_1 - Q_2 \ll Q_1 + Q_2 \equiv 2Q$, the merged BH has

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

$$\tau_{\rm BH} \approx \frac{3000\,\pi^{3/2}\,c_W}{e}\,\frac{M_{\star}^2}{M_{\rm pl}^3} \approx (1.8 \times 10^{-25}\,{\rm s})\,M_{26}^2$$

$$\left\{ M_{26} = M_{\star}/10^{26}\ {\rm GeV} \right\} \quad \approx 200\ {\rm g}$$

CAPTURE OF MAGNETIC BH

Parametrically, the stopping power in materials is

$$\frac{dW}{dx} \sim \frac{n_e\, e^2\, h_Q^2\, V}{v_F\, m_e} \qquad h_Q \equiv Q\, h \text{ with } h = 2\pi/e$$

(For plasmas, replace the Fermi velocity v_F with the thermal velocity)

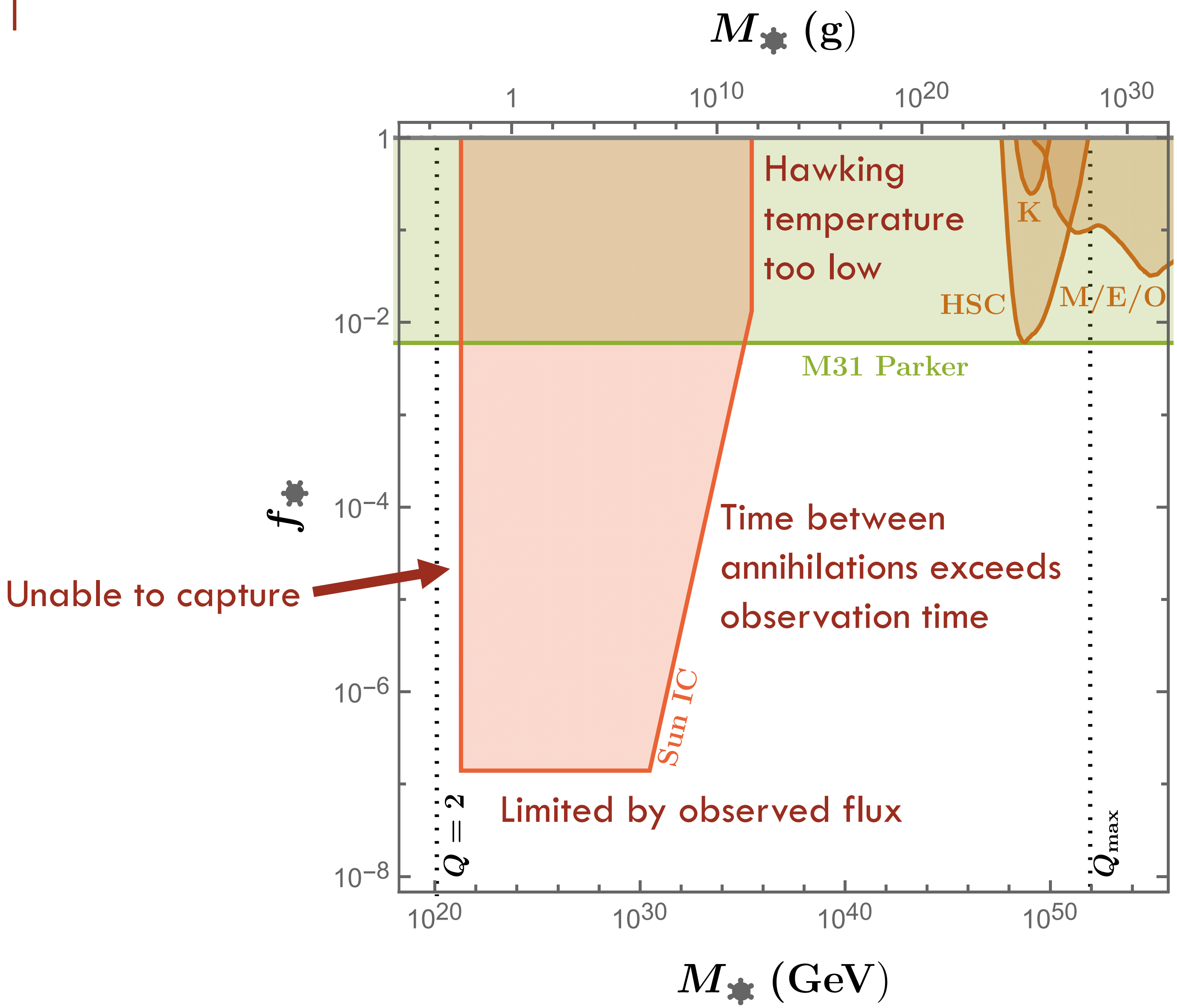
The stopping length decreases as Q increases:

$$L_S \sim \tfrac{1}{2} M_{\ast} V^2 (dW/dx)^{-1} \propto Q V^2 (dW/dx)^{-1} \qquad \propto Q^{-1}$$

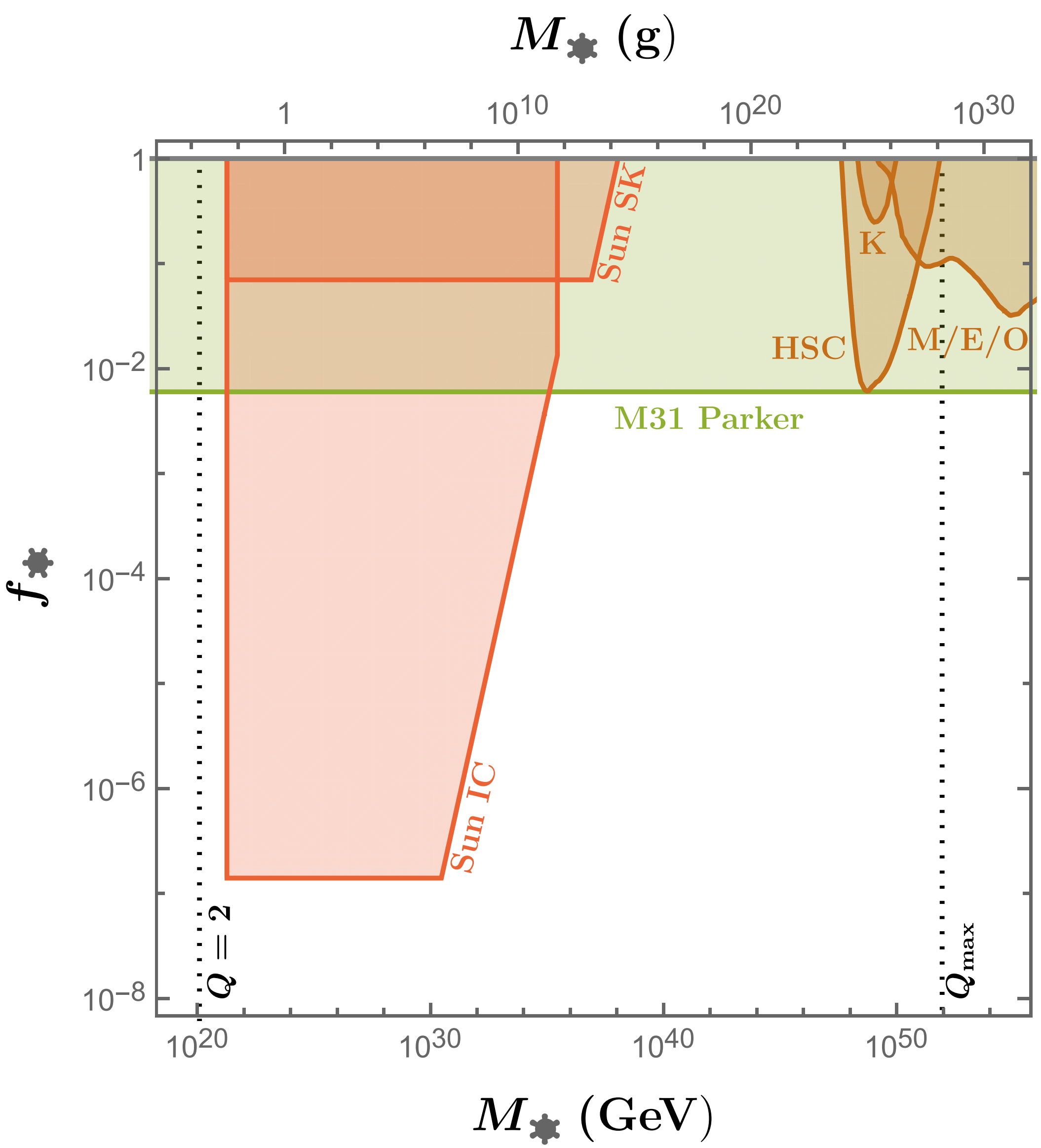
When does object radius exceed stopping length?
For the Sun, $Q_{min} \approx 30$
For Earth, $Q_{min} \approx 2000$
For neutron stars, $Q_{min} \approx 1$

[Kazama, Yang, Goldhaber '77; Ahlen, Kinoshita '82; Hamilton, Sarazin '83; Drell, Kroll, Mueller, Ruderman '83; Meyer-Vernet '85; Ahlen, Mitri, Hong '96]

BOUNDS

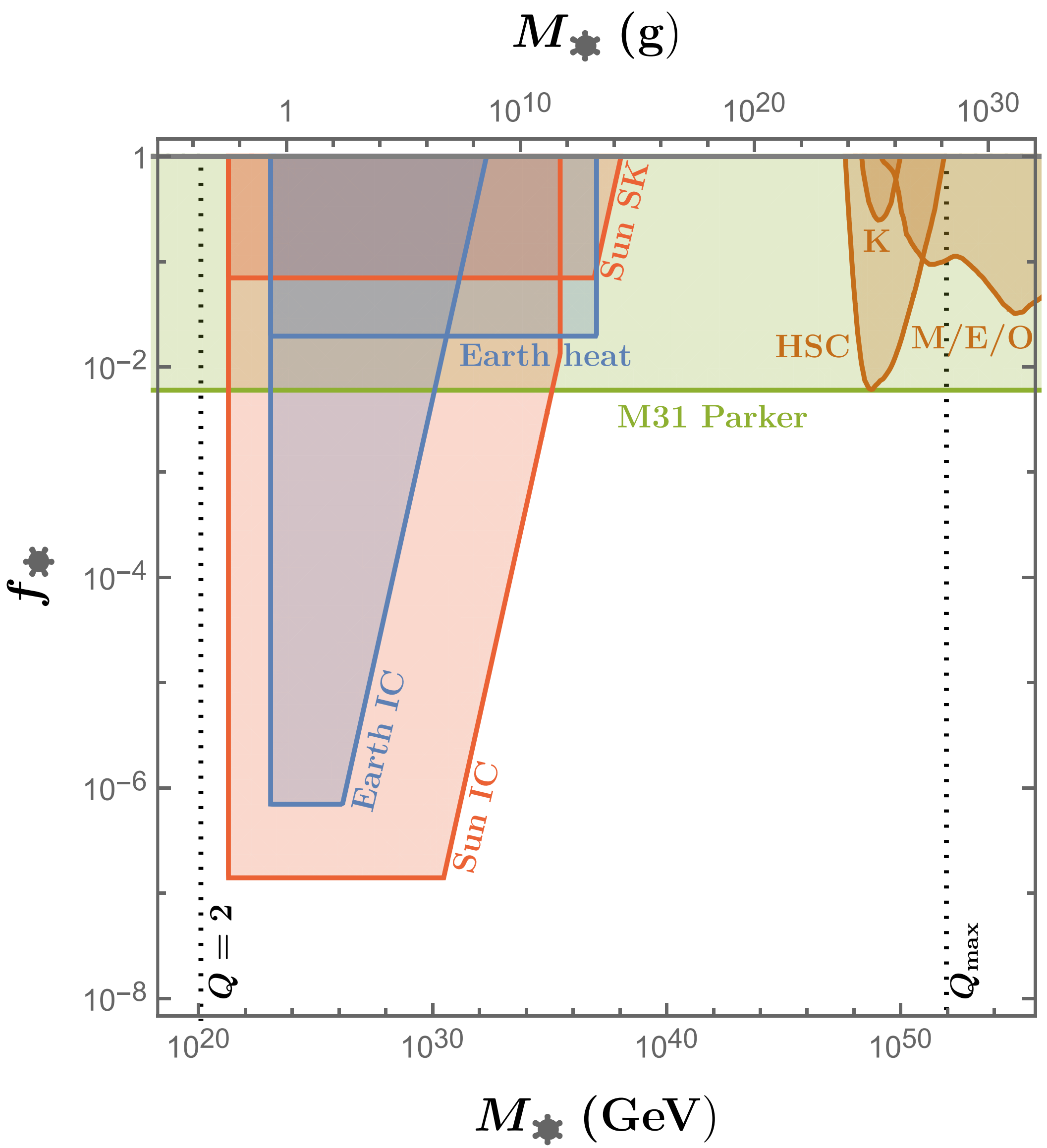

$M_{✹}$ (g)
1
10^{10}
10^{20}
10^{30}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$f_{✹}$
Hawking temperature too low
K
HSC
M/E/O
M31 Parker
Time between annihilations exceeds observation time
Sun IC
Limited by observed flux
$Q = 2$
$Q_{\max}$
10^{20}
10^{30}
10^{40}
10^{50}
$M_{✹}$ (GeV)
Unable to capture

BOUNDS



$M_\star$ (g)
1
10^{10}
10^{20}
10^{30}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$f_\star$
Sun SK
Sun IC
K
HSC
M/E/O
M31 Parker
$Q = 2$
$Q_{\rm max}$
10^{20}
10^{30}
10^{40}
10^{50}
$M_\star$ (GeV)

BOUNDS



$M_{\circledast}$ (g)
1
10^{10}
10^{20}
10^{30}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$f_{\circledast}$
Sun SK
K
HSC
M/E/O
Earth heat
M31 Parker
Earth IC
Sun IC
$Q = 2$
$Q_{\max}$
10^{20}
10^{30}
10^{40}
10^{50}
$M_{\circledast}$ (GeV)

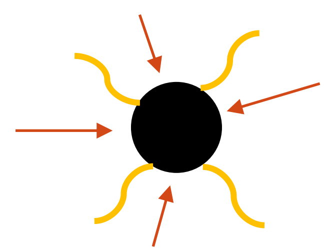
BARYON NUMBER VIOLATIONS

Particles entering the corona can become bound and/or directed radially (as a $2d$ mode) towards the event horizon.

Black holes eating particles and reemitting energy as Hawking radiation violates baryon number.

Even a single proton can trigger a prompt ($2d$ mode) evaporation to an electron for $M_{*} \lesssim 10^{27}\ \mathrm{GeV}$ $\approx 2\ \mathrm{kg}$

If a magnetic black hole is in a dense medium, this could produce a steady flux of high energy particles.

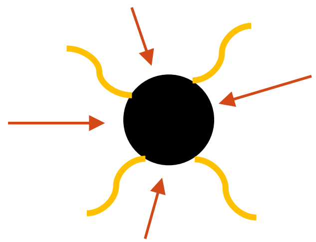


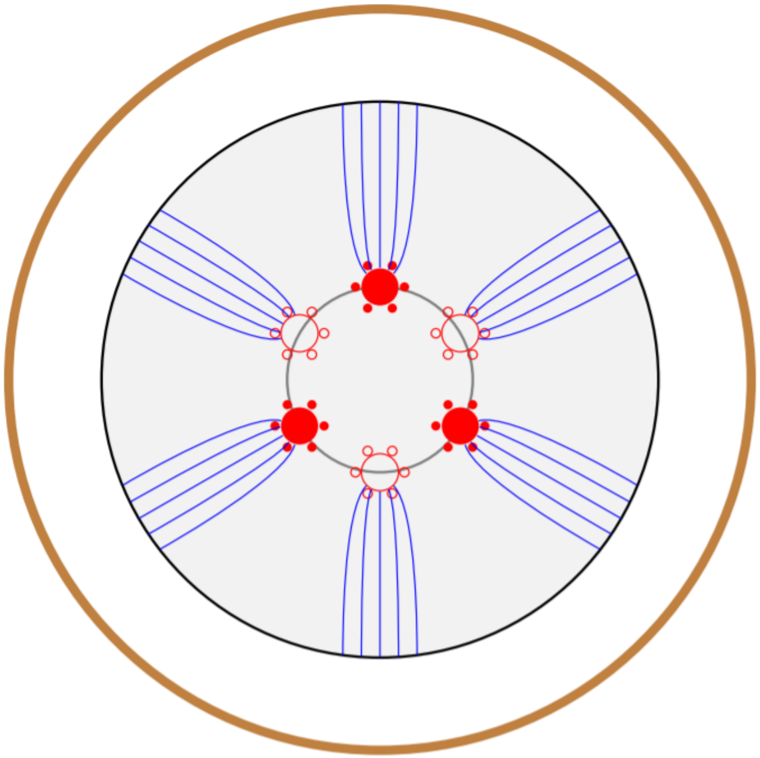
(Also, sphalerons could be active [Ho, Rajantie 2005.03125])

CAPTURE IN NEUTRON STARS

Some neutron star phases (like proton or pion superconductors) confine magnetic fields into flux tubes.

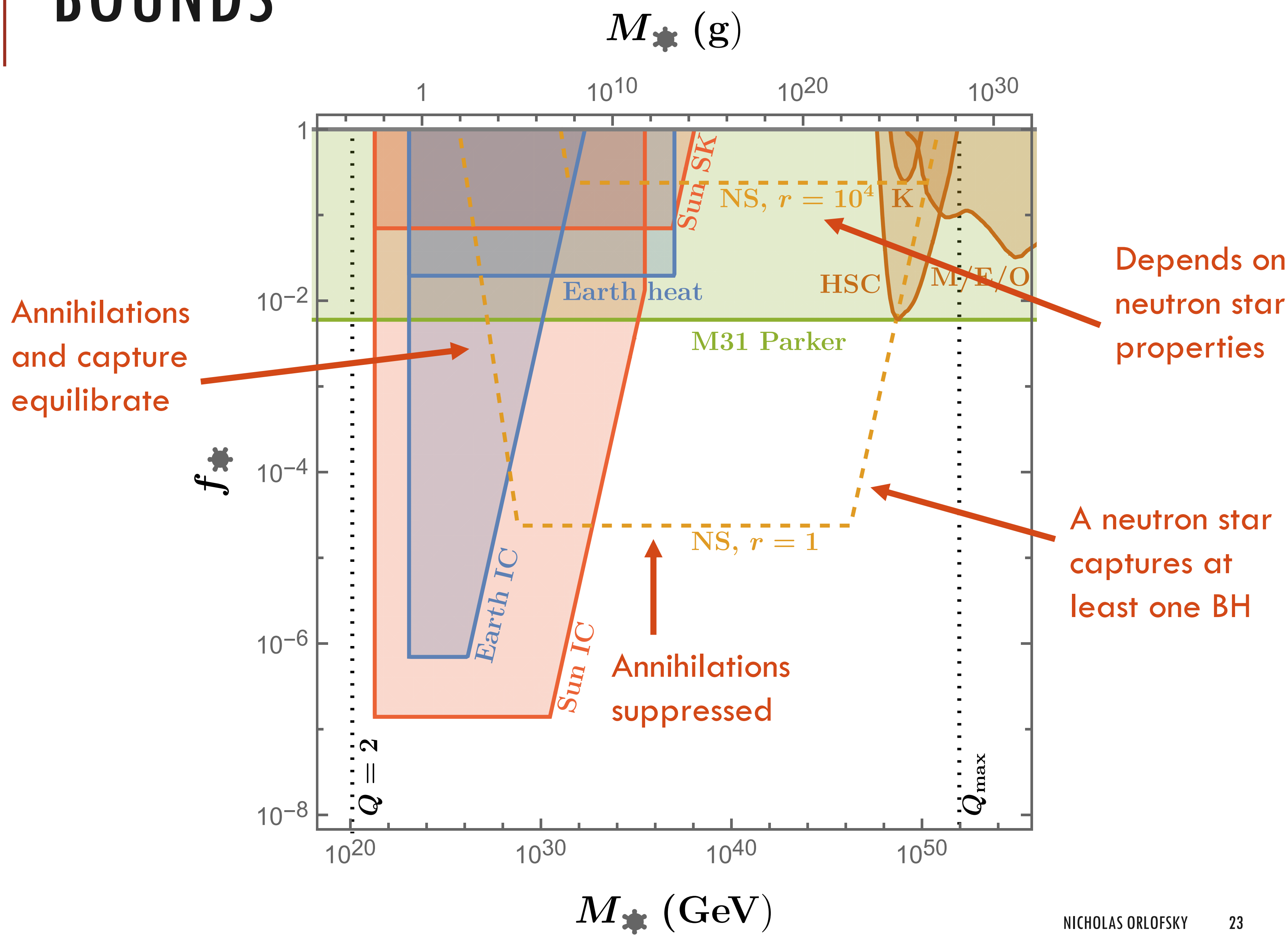
BHs "hang around" with little annihilation.





Monopoles: [Harvey, Ruderman, Shaham '86]

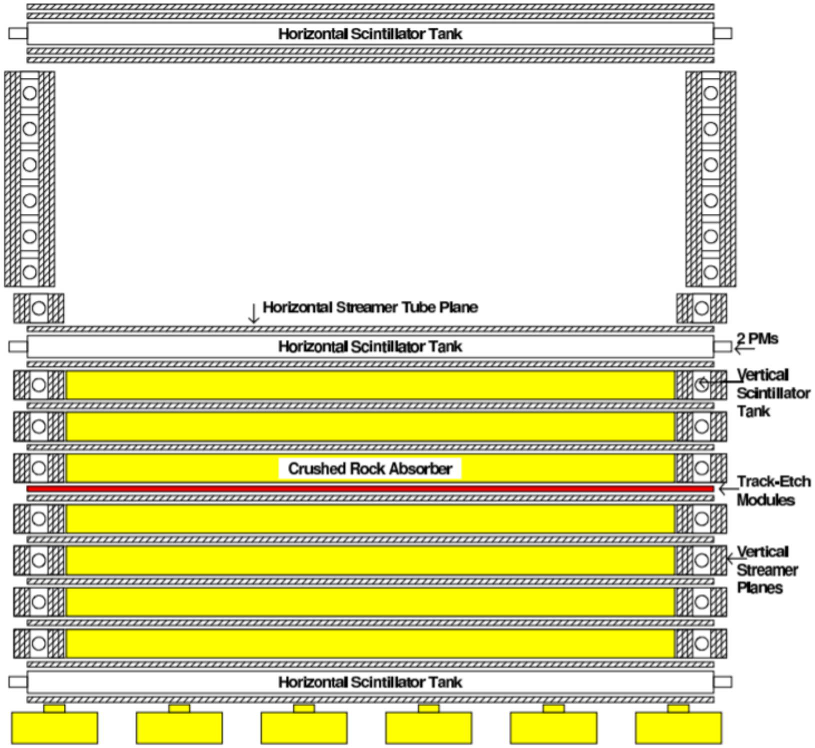
BOUNDS



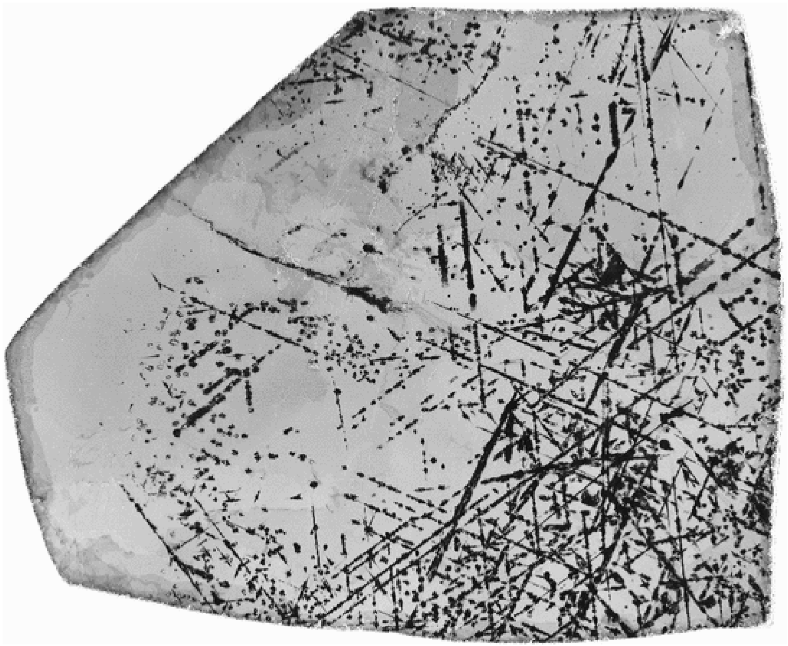
$M_{\star}$ (g)
1
10^{10}
10^{20}
10^{30}
$f_{\star}$
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{20}
10^{30}
10^{40}
10^{50}
$M_{\star}$ (GeV)
Sun SK
NS, $r = 10^4$ K
Earth heat
HSC
M/E/O
M31 Parker
NS, $r = 1$
Earth IC
Sun IC
$Q = 2$
$Q_{\max}$
Annihilations and capture equilibrate
Depends on neutron star properties
A neutron star captures at least one BH
Annihilations suppressed

DIRECT DETECTION

Magnetically-charged objects leave tracks in ancient mica or could be detected by dedicated monopole experiments like MACRO



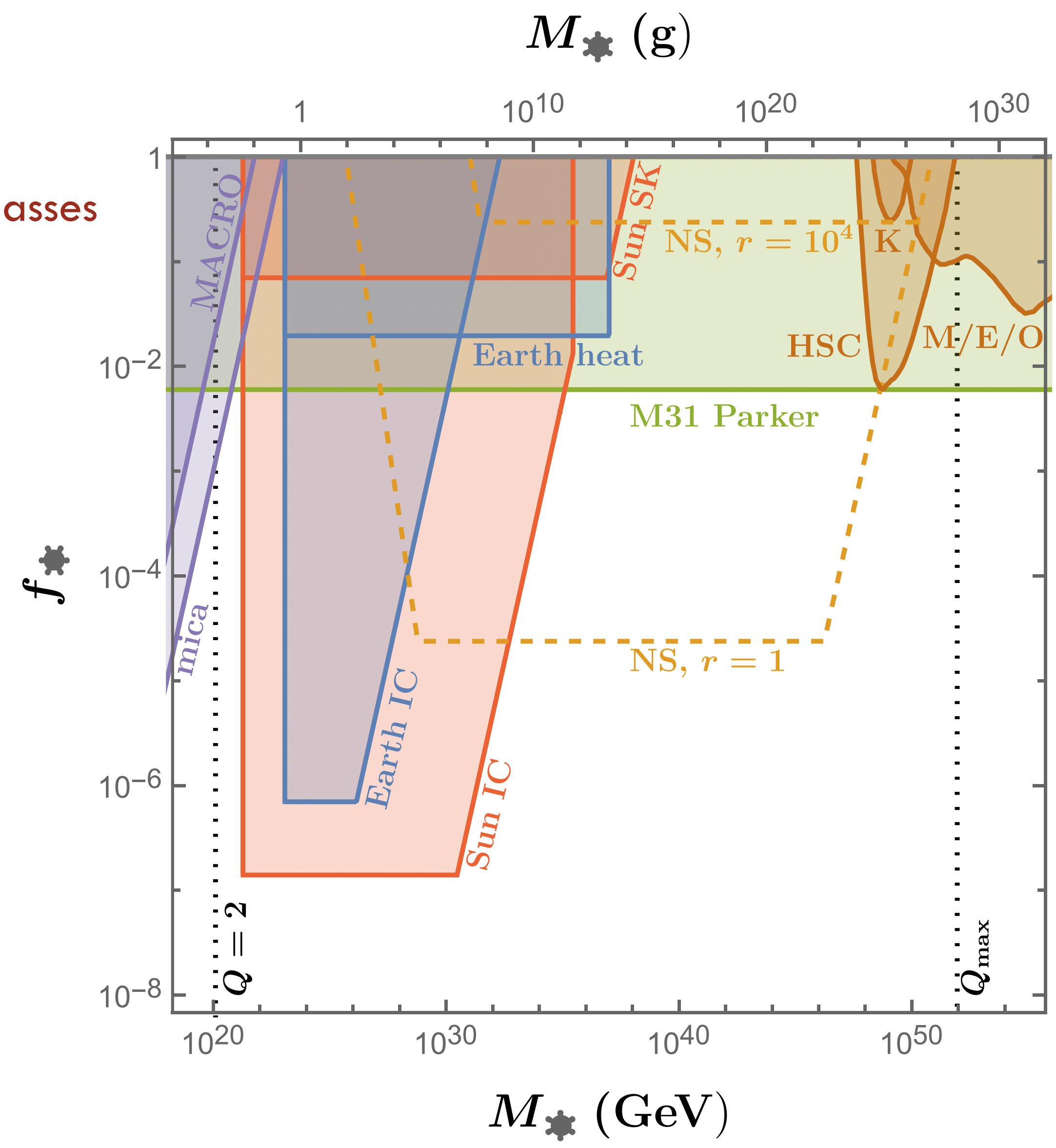
MACRO collab. hep-ex/0207020



Russell '15

BOUNDS

Bounds smallest masses —limited by flux



EARTH'S MAGNETIC FIELD

Magnetic black holes captured by Earth can induce a magnetic monopole moment in Earth's magnetic field

Number captured:

$$N = C_{\rm cap}\,\tau_{\oplus} \approx 3.4 \times (10^{22}/Q)\,(\rho/0.4\,{\rm GeV\,cm^{-3}})$$

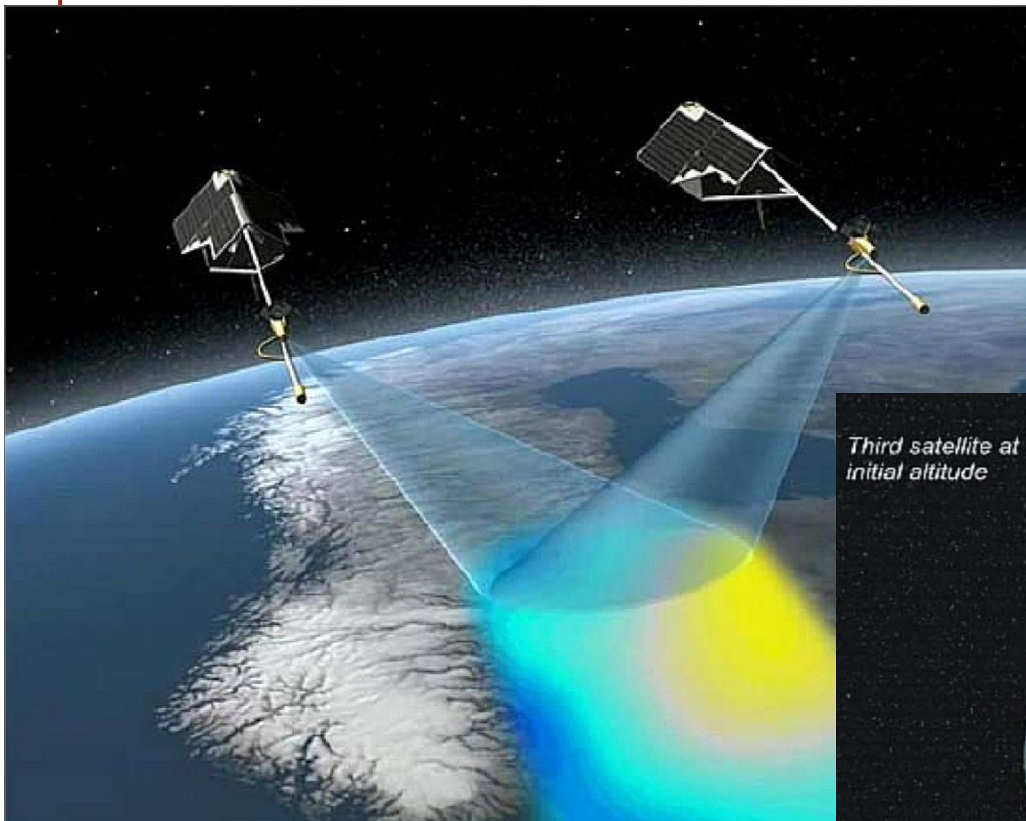
Net charge (random walk):

$$Q_{\rm net} \simeq \sqrt{N}\,Q$$

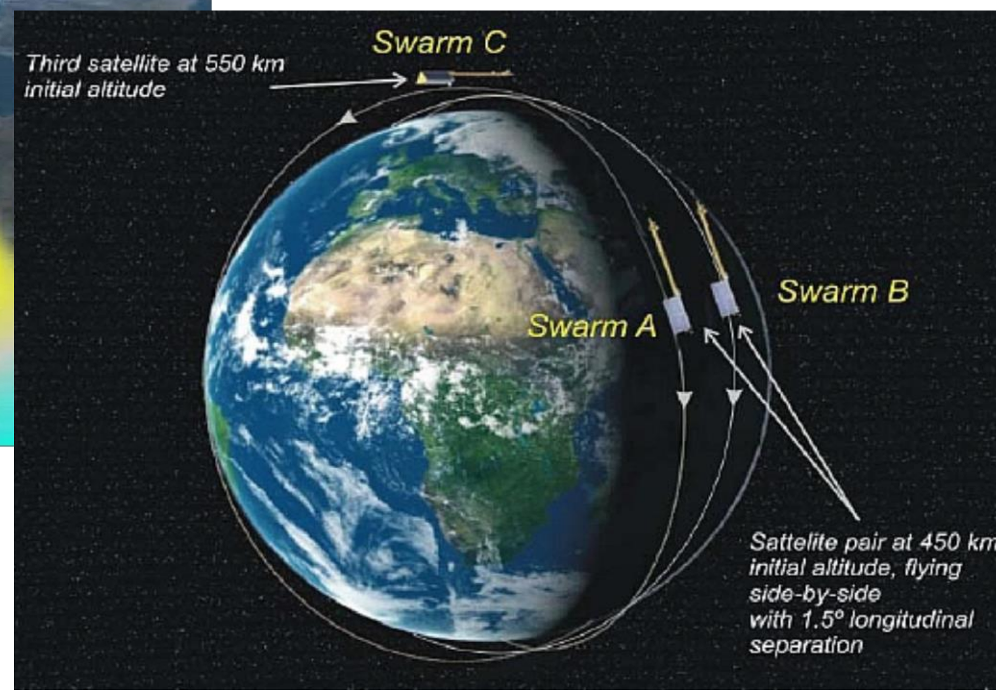
No one has searched Earth's monopole moment before.

(although it was suggested by Gauss in the 19th century, it was infeasible then)

SWARM SATELLITES



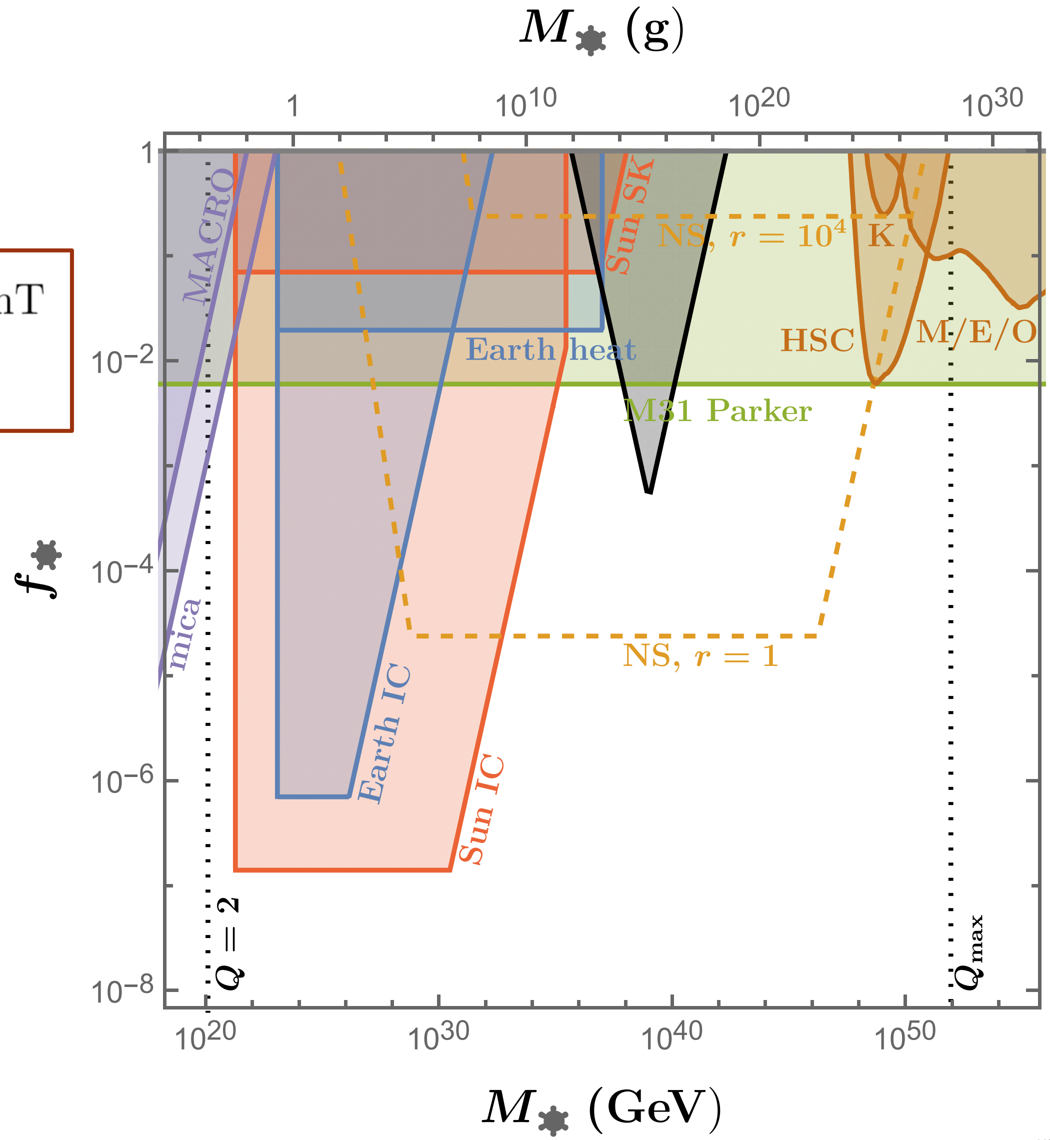
DTU Space



ESA

EARTH'S MAGNETIC FIELD BOUND

$$|B_{\rm m}(r = R_\oplus)| < 0.13\ {\rm nT}$$
$$|Q_{\rm net}| < 1.6 \times 10^{19}$$



SUMMARY

- Magnetic black holes are states requiring no new physics in principle (though their formation may require monopole particles?)
- Lots of ways to constrain/search for them:
  - Extension of Parker bound to M31
  - “Annihilations” inside the Sun, Earth
  - Baryon number violation inside of neutron stars
  - Direct searches
  - Precise magnetic field measurements
  - More ongoing work

  [Bai, **NO** 1906.04858; Ghosh, Thalapillil, Ullah 2009.03363; Diamond, Kaplan 2103.01850]
- “Annihilations” and baryon number violation would be the first detection of Hawking radiation