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The Physics of Planck-scale Relics

Stefano Profumo

IPMU, December 2, 2025

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PLANCK-TON

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Planck-Scale Relics: Existence, Abundance, and Detection

If **Hawking evaporation** ever occurs*,

and if **primordial BH** were ever produced**,

the Universe may be full of **Planck-mass leftovers** —

these **Plancktons** can be the **Dark Matter**,

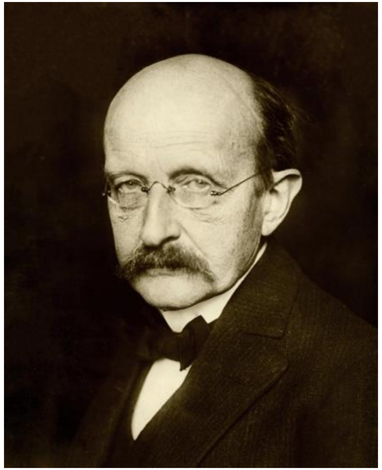
and we might be able to **detect them**

* it does

** they were

What is the Planck scale?

$$G = \frac{hc}{2\pi M_{\text{Pl}}^2}$$



$$R_s = \frac{2Gm}{c^2}$$

Schwarzschild radius

$$\lambda = \frac{h}{mc}$$

Compton wavelength

$$R_s(M_{\text{Pl}}) = \frac{2hcM_{\text{Pl}}}{2\pi c^2 M_{\text{Pl}}^2} = \frac{h}{\pi M_{\text{Pl}} c} \sim \lambda(M_{\text{Pl}})$$

Standard Hawking Evaporation (Semi-Classical)

A field theory defined on a black-hole background is in a **thermal** state whose temperature at infinity is $T = M_P^2 / M_{BH}$

Black holes radiate (~)like any **black body**, and, as such, shed their mass at a rate

$$\frac{dM}{dt} \propto A(T)T^4 \propto \frac{M^2}{M^4} \propto M^{-2}$$

[Stefan-Boltzmann]

The resulting runaway evaporation process gives a lifetime "**Black Hole Explosion**"*

$$\tau \approx 407 \left(\frac{f(M)}{15.35} \right)^{-1} M_{10}^3 \text{ s.}$$

Black holes formed in the early universe, with a mass ***below M_U ~ 5x10^{14} grams***, **T~100 MeV** have exploded by **today**
WHAT DID THEY **LEAVE BEHIND**? **Nothing** or **Relics**?

Why Question Runaway Hawking Evaporation to $M \to 0$?

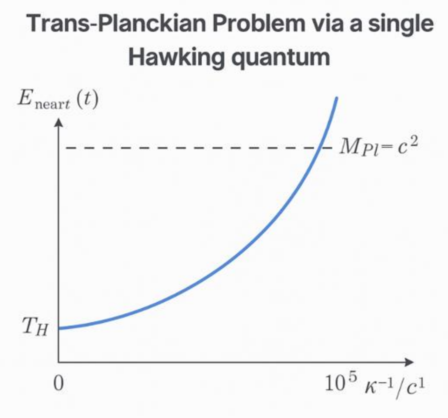
(1) **Curvature becomes Planckian** → Hawking quanta originate from modes blue-shifted by arbitrary, trans-Planckian factors

(2) **Quantum backreaction** becomes uncontrolled

(3) **String theory effects**: higher-curvature terms lead to a turnover in $T(M)$

(4) **Information-theory** considerations: Planck-scale relics & information paradox

(1) The Trans-Planckian Problem in Hawking Radiation



Given Hawking **temperature** $T_H = \frac{\hbar\kappa}{2\pi k_B}$ and **curvature** $\kappa = \frac{c^3}{4GM}$

…a quantum detected by an **asymptotic observer** with energy $E_\infty \sim T_H$.

…corresponds to a **blue-shifted mode** emitted near horizon, an (as. observer's) time t before of frequency

$$\omega_{\rm near}(t) \simeq \omega_\infty e^{\kappa t} \sim \frac{T_H}{\hbar} e^{\kappa t}$$

the blue-shifted energy E_{near} is **Trans-Planckian** for at distances/times larger than $ln(M_{Pl}/T_H)/\kappa$

$$E_{\rm near}(t) \sim E_\infty e^{\kappa t} \gg M_{\rm Pl} c^2$$

…for instance, for a **stellar mass** black hole, $\kappa \approx 5 \times 10^4\ {\rm s}^{-1}$ and a mode with $E=T_H$ is trans-Planckian a backward time of only ~**10^{-2} sec** !!

(2) The Quantum Backreaction Problem

Semiclassical **Einstein** equation: $G_{\mu\nu} = 8\pi G \langle T_{\mu\nu} \rangle_{\text{QFT}} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R,$

…**valid** if the quantum stress-energy is **small** compared to the **geometric source** term

$$\langle T_{\mu\nu} \rangle \ll \frac{1}{GL^2},$$

…where L is the **local curvature** length scale ($L \sim r_s$)

Near the **Planck** scale, $\langle T_{\mu\nu} \rangle_{\text{Hawking}} \sim \frac{1}{GL^2}.$

…hence quantum stress-energy becomes comparable to spacetime curvature and **backreaction cannot be treated perturbatively**

Roadmap for the Talk

- **Existence**:
  What does quantum gravity say about the *endpoint* of Hawking evaporation?

- **Abundance & cosmology**:
  If small PBHs formed, what relic abundance do we get today? Do relics behave as cold dark matter?

- **Detection**:
  Charges, discharge physics, recombination, high-frequency GWs, binary mergers, accelerator-array concepts (Windchime), etc.

Quantum Gravity Arguments for Remnants

In **quantum gravity** (string theory, LQG, etc.), high momentum means concentrating enough **energy** to **significantly curved spacetime** — eventually forming a *micro black hole*.

→ Below a certain scale (≈ Planck length), probing **smaller** distances leads to **horizon formation**.

This leads to a **minimal measurable length**.

A widely used phenomenological **Generalized Uncertainty Principle**

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}\left[1 + \frac{2\alpha' \ell_{\mathrm{Pl}}^2}{\hbar^2}(\Delta p)^2\right]$$

- $\ell_{\mathrm{Pl}} = \sqrt{\hbar G / c^3}$ is the Planck length,
- α' is a dimensionless parameter (~ 1) encoding the strength of quantum-gravity corrections.

The second term grows with momentum — preventing Δx from ever reaching zero.

Quantum Gravity Arguments for Remnants

$$\Delta x \geq \frac{\hbar}{2\Delta p} + \alpha' \, \ell_{\rm Pl}^2 \frac{\Delta p}{\hbar}$$ yields several **consequences**:

(i) minimum physical/measurable length $(\Delta x)_{\rm min} = \ell_{\rm Pl}\sqrt{2\alpha'}.$

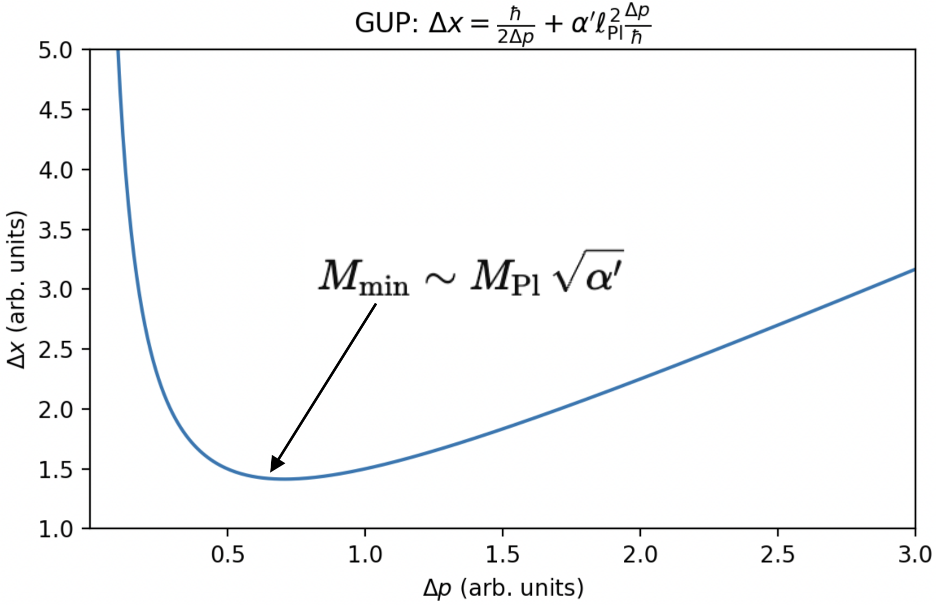
(ii) modified **Hawking temperature-mass** relation:

$$T_{\rm GUP}^{\rm (cool)}(M) = T_H(M)\sqrt{1 - \frac{\alpha' M_{\rm Pl}^2}{2M^2}}, \qquad T_H(M) = \frac{\hbar c^3}{8\pi G M k_B}$$

(iii) because T_H stops rising, **evaporation** effectively **halts** at $M_{\rm min} \sim M_{\rm Pl}\sqrt{\alpha'}$

…yielding a **stable** or very long-lived **relic**

Quantum Gravity Arguments for Remnants



$$\Delta x \geq \frac{\hbar}{2\Delta p} + \alpha' \, \ell_{\rm Pl}^2 \frac{\Delta p}{\hbar},$$

Quantum Gravity Arguments for Remnants

Loop quantum gravity treats **geometry** of spacetime as a **quantum system**

simplified (1D) version of LQG, replace momentum by a periodic "**polymerized**" function

$$p \to \frac{\sin(\mu p)}{\mu}$$

where μ is the polymer scale, of order inverse Planck-length

The corresponding modified **kinetic energy saturates** at high momentum (thus no infinite bluesh

$$E(p) = \frac{\hbar^2}{2m\mu^2}\sin^2(\mu p)$$

The BH temperature reaches a finite maximum as $M \rightarrow M_{Pl}$

$$T_H^{(\text{poly})} = \frac{\hbar c^3}{8\pi G M k_B}\left(1 - \frac{\mu^2 M_{\text{Pl}}^2}{2M^2} + \cdots\right).$$

…again, a **stable relic** arises

String Theory Higher-Curvature Corrections

In **string theory**, the Einstein–Hilbert action is just the *low-energy limit* of a richer effective action.

It gets corrections in powers of the **string length** $\ell_s^2 = \alpha'$:

$$S = \int d^4x\sqrt{-g}\,\left(R + \alpha' R^2 + \alpha'^2 R^3 + \cdots\right).$$

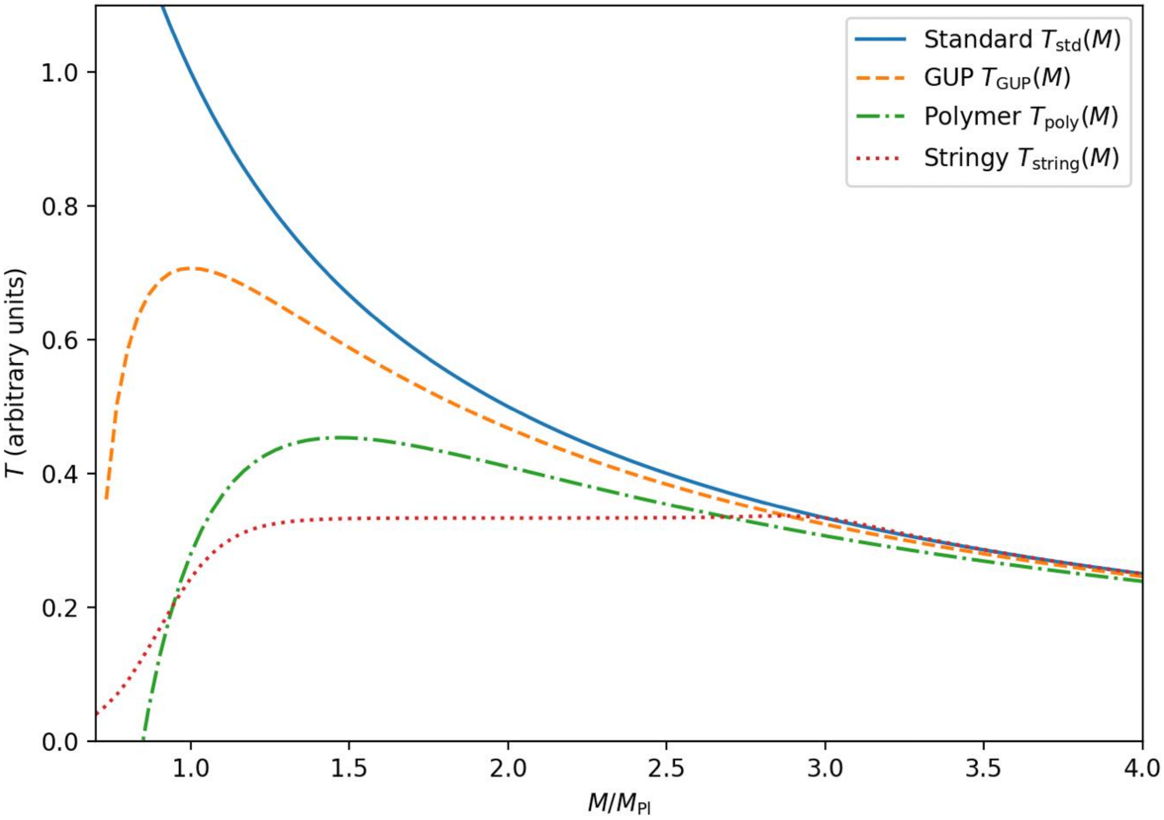
These higher-curvature terms encode effects of stringy excitations and quantum gravity at energies $E \sim 1/\ell_s$.

Temperature saturates around the string mass-scale M_s

$$T(M) \approx \begin{cases} \frac{1}{M} & (M \gg M_s) \\ T_{\max} \text{ or constant} & (M \sim M_s) \\ 0 \text{ or small} & (M < M_s) \end{cases}$$

Depending on specific compactification/moduli content,
long-lived or quasi stable objects arise as **string microstates**

Quantum Gravity Arguments for Remnants



Charged, Topological, and Quantum Hair-Stabilized Remnants

Even if neutral black holes fully evaporate, **charged BHs** do not

- If a BH carries gauge charge Q, extremality bound:

$$M^2 \geq Q^2 \quad \text{(in Planck units)}$$

→ **electrically/magnetically charged remnants** with $M = |Q|$ are stable.

- **Magnetic monopole / dyonic charges:** relics protected by Dirac quantization.
- **Dark-sector gauge charges:** if charged under hidden U(1) with heavy charge carriers, discharge is suppressed → stable charged relic.
- **Non-Abelian remnants** possible if evaporation cannot radiate certain topological charges.

Why Planck Relics Are Plausible - Summary

1. Semi-classical **Hawking evaporation cannot be extrapolated** to the Planck regime
2. Multiple **quantum-gravity** frameworks (GUP, LQG, String theory) **allow/predict stabilized relics**
3. Gauge, topological, and dark **charges** can force long-lived or stable remnants (barring discharge…)

If relics can exist, **how many** would we expect, and how to they behave **cosmologically**?

Cosmological Planck Relics

- Early-Universe PBH population characterized by formation mass M_{PBH} and fraction $\beta(M)$.
- Each evaporating PBH leaves a relic mass $M_{\mathrm{rel}} \sim \alpha M_{\mathrm{Pl}}$.
- Total relic abundance today set by integrated mass converted into relics.

$$\Omega_{\mathrm{rel}} h^2 \simeq \int dM \, \beta(M) \, \frac{M_{\mathrm{rel}}}{M} \left(\frac{a_{\mathrm{evap}}}{a_0} \right)^3 .$$

abundance at a given mass

one relic per BH

redshift dilution

Toy Calculation of Relic Abundance

$\beta(M)$ = fraction of the Universe's mass in PBHs of mass M **at formation**:

$$\beta(M) \equiv \frac{\rho_{\rm PBH}(t_{\rm form})}{\rho_{\rm tot}(t_{\rm form})}.$$

During radiation domination, the PBHs behave as matter, so their relative density increases $\propto a(t)$. By the time they evaporate, the PBH energy fraction has grown by roughly $(a_{\rm evap}/a_{\rm form}) \propto (t_{\rm evap}/t_{\rm form})^{1/2} \propto M^{1/2}$ $M^{1/2}$.

Hence, the relic density fraction today scales as:

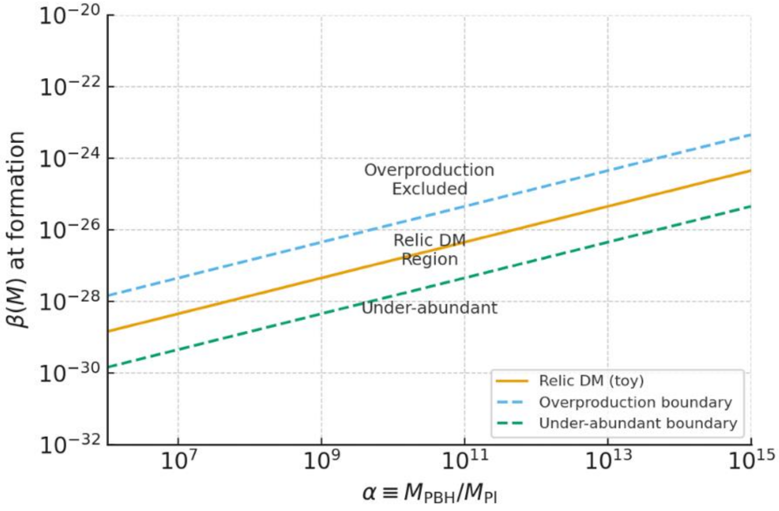
$$\frac{\Omega_{\rm rel}}{\Omega_{\rm DM}} \propto \beta(M) \left(\frac{M_{\rm rel}}{M}\right) \left(\frac{t_{\rm evap}}{t_{\rm form}}\right)^{1/2}.$$

Both related to the initial mass!

Toy Calculation of Relic Abundance

1. PBH with mass M forms at $t_{\rm form}$.
2. Evaporates at $t_{\rm evap} \sim M^3$.
3. Leaves one relic of mass $M_{\rm rel}$.

$$\frac{\Omega_{\rm rel}}{\Omega_{\rm DM}} \approx 0.3 \left(\frac{\beta(M)}{10^{-27}}\right)\left(\frac{M_{\rm rel}}{M_{\rm Pl}}\right)\left(\frac{10^5\ {\rm g}}{M}\right)^{1/2}$$



initial PBH mass
[10^{-2} g, 10^{13} g]

Even tiny $\beta \sim 10^{-27}$ can saturate DM if $M \lesssim 10^5$ g.

Relics provide a unique “fossil record” of very early PBH production.

Planck Relic Kinematics: Ultra-Cold Despite Endpoint Recoil

- **Endpoint recoil:**

Last Hawking quantum has $E \sim M_{\rm Pl}$.

→ If $M_{\rm rel} \sim \alpha M_{\rm Pl}$, then $v_i \sim 1/\alpha$.

Even for $v_i \sim c$, early evaporation ensures extreme redshift.

Note: $z_{BBN} \sim 10^{10}$, $z_{RH} <\sim 10^{25}$

- **Cosmological redshifting:**

$$v_0 = \frac{v_i}{1 + z_{\rm evap}}.$$

PBHs evaporating before BBN ($z_{\rm evap} \gtrsim 10^{10-25}$) yield

$$v_0/c \lesssim 10^{-10\text{–}25}.$$

➔ even with Planck-scale recoils (and neglecting random directions), and with late-time evaporation, **relics today are ultra-cold, collisionless** dark matter

Unlike for more massive PBH dark matter candidates, **no effects on structure formation** (e.g. Poisson, or small-scale enhancement from clustering)

Lehmann-Profumo, 2105.01627 (PDU)

How Could We Detect Planckton?

If Plancktons exist and form DM, what observable signatures could **reveal** them?

Detection avenues:

1. **Gravitational**: stochastic GW background from evaporation (and possibly mergers)
2. **Electromagnetic**: charged relics are detectable; but can a Planckton be charged?
3. **Direct mechanical probes**: precision accelerometers (Windchime)

Gravitational Waves from Evaporation

…**redshifting** is non-trivial, as PBH may come to **dominate** the universe's energy density…

$$t_{\rm eq} \simeq \left(\frac{1-\Omega_{{\rm BH},i}}{\Omega_{{\rm BH},i}}\right)^2 \frac{M}{M_{\rm Pl}^2}$$

the resulting **redshifting** then is

$$a(t) = \begin{cases} a_i \left(\frac{t}{t_i}\right)^{1/2} & t \lesssim t_{\rm eq} \\ a_i \left(\frac{t_{\rm eq}}{t_i}\right)^{1/2} \left(\frac{t}{t_{\rm eq}}\right)^{2/3} & t_{\rm eq} \lesssim t \lesssim t_* \end{cases}$$

(time of evaporation)

We found simple expressions for the **peak frequency**

$$f_{\rm peak} \simeq (1.8 \times 10^{16}\,{\rm Hz}) \left(\frac{M}{10^5\,{\rm g}}\right)^{1/2}$$

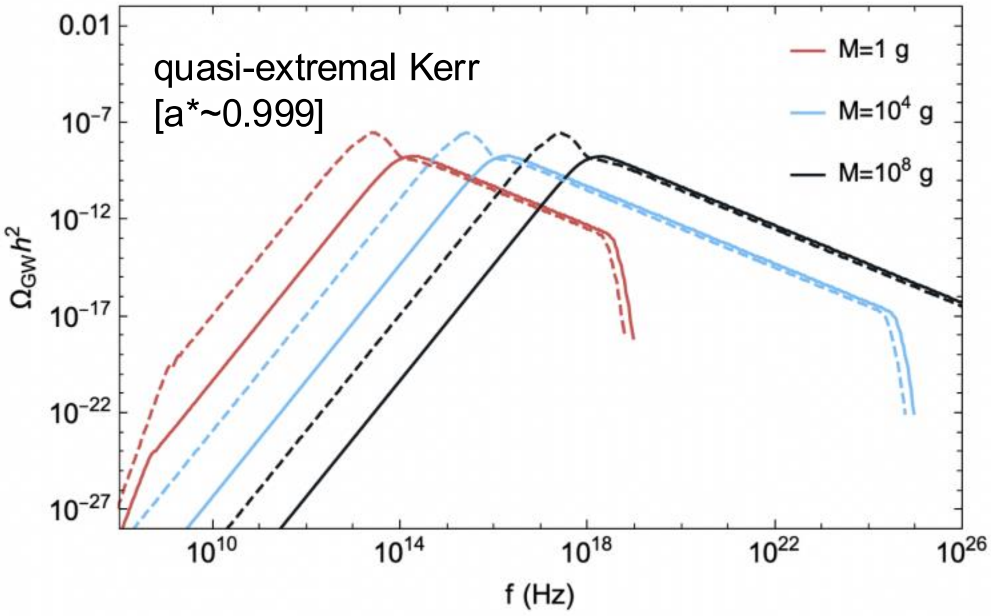
and the **corresponding SED**

$$\Omega_{\rm GW} h^2\big|_{\rm peak} \simeq 4.2 \times 10^{-7}$$

Note: **independent of initial conditions**, as long as PBH dominate universe's energy density; also independent of **initial PBH mass**!

Ireland, Profumo, Scharnhost, *Phys.Rev.D* 107 (2023) 10, 104021, 2302.10188

Gravitational Waves from Evaporation



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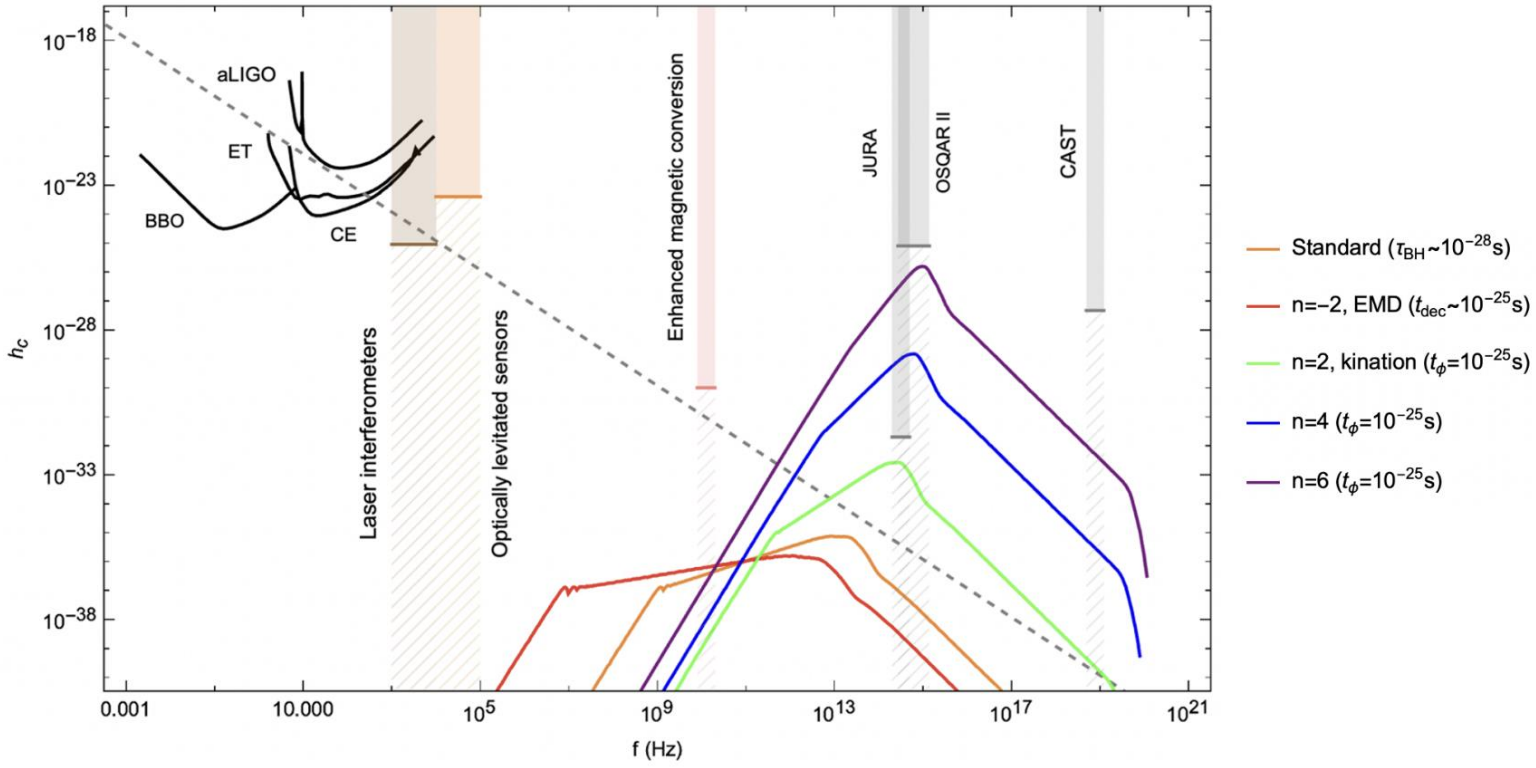
Ireland, Profumo, Scharnhost, *Phys.Rev.D* 107 (2023) 10, 104021, 2302.10188

Lowering the GW Frequency via Modified Cosmology



Ireland, Profumo, Scharnhost, *Phys.Rev.D* 107 (2023) 10, 104021, [2302.10188](2302.10188)

Lowering the GW Frequency via Extra Dimensions

Lowering the **fundamental scale of gravity** via large extra dimensions naturally moves GW frequencies into potentially measurable ranges

In models with Large Extra Dimensions (LED):

$$M_{\mathrm{Pl}}^2 = R^n M_*^{n+2}.$$

Lower fundamental scale M_* ⇒ cooler Hawking temperature:

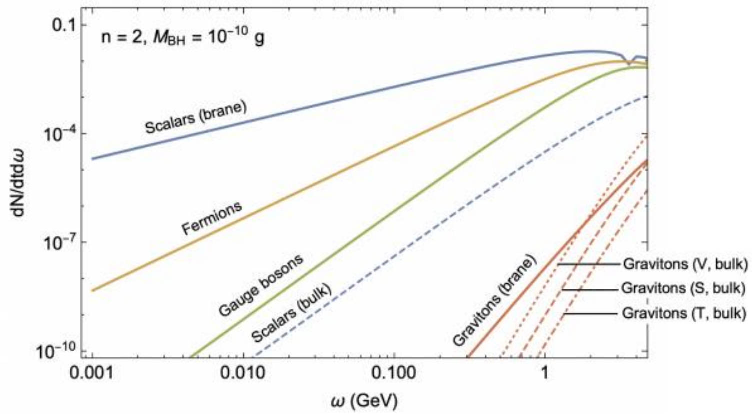
$$T_H \sim \frac{n+1}{4\pi r_h} \propto \left(\frac{M_*}{M}\right)^{1/(n+1)} M_*.$$

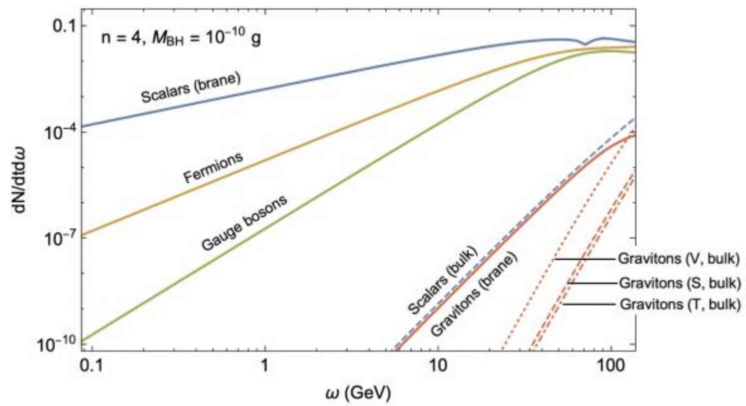
Hence the **emitted GW frequency** scales as

$$f_{\mathrm{em}} \propto M_* \left(\frac{M_*}{M}\right)^{1/(n+1)}.$$

Lowering the GW Frequency via Extra Dimensions

Technical challenge: **grey-body calculation**, with graviton emission from the bulk from scalar, vector, and tensor perturbations





Ireland, Profumo, Scharnhost, *JCAP* 08 (2024) 033, 2312.08508

Lowering the GW Frequency via Extra Dimensions

…still getting low frequency gravitational waves is generally not easy

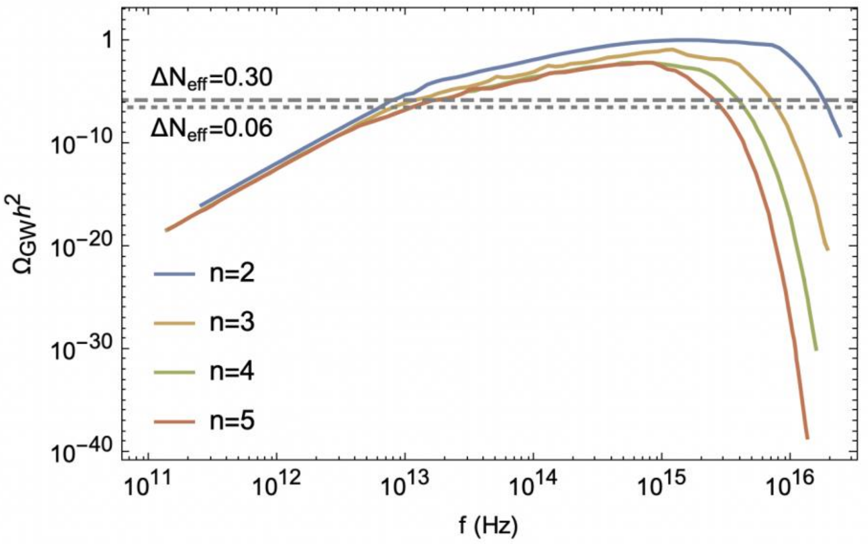


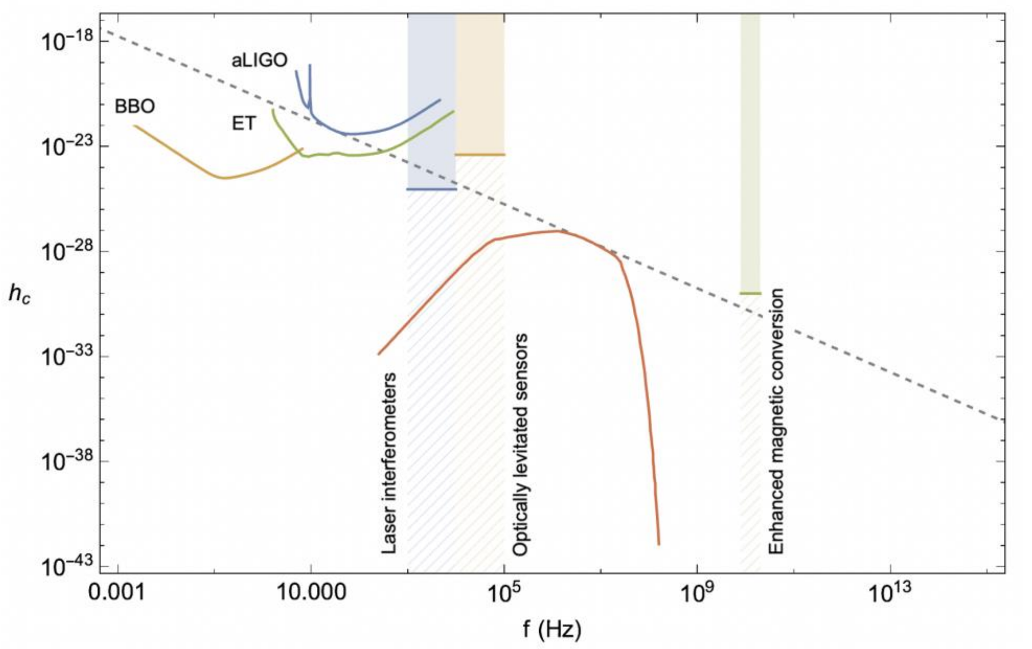
Figure 2. Gravitational wave spectra (in terms of the spectral density parameter $\Omega_{\rm GW}h^2$) for various numbers of extra dimensions $n = 2, 3, 4, 5$ and a benchmark set of parameters: $M_* = 10^3$ TeV, $t_i = 10^{-30}$ s, $M = 1$ g, $T_{\rm re} = 10^5$ GeV.

Ireland, Profumo, Scharnhost, *JCAP* 08 (2024) 033, 2312.08508

Lowering the GW Frequency via Extra Dimensions

…in the "best possible" scenario there may be a detectable signal

$$n = 2,\ \beta = 1,\ T_{\rm re} = 16.5\,{\rm GeV},\ t_i = 10^{-30}\,{\rm s},\ M_* = 10^3\,{\rm TeV},\ M = 10M_*$$



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Gravitational Wave Emission: Mergers

Can Plancktons form **gravitational** bound states?

If they are neutral, **no**: even if **formed** at T_{RH}, and even if they are 100% of the DM today

…and the ratio decreases with redshift as ~*1/a*…

$$\left.\frac{\Gamma_{\rm bs}}{H}\right|_{T_{\rm RH}} \sim 10^{-36}$$

However, **binaries may form***, e.g. with a **dark charge**, **no dark plasma**, and $\alpha_D > 10^{-8}$

$$\sigma_{\rm cap} \sim \pi \frac{\alpha_D^2}{M_{\rm Pl}^2 v_{\rm BBN}^4}\,. \qquad \Gamma_{\rm bs} \sim n_{\rm BBN}\,\sigma_{\rm cap}\,v_{\rm BBN} \sim 1\ {\rm s}^{-1}$$

* thanks to Philip Liu for pointing this out to me!

Gravitational Wave Emission: Mergers

…assuming binaries **form**, they **~immediately merge** via GW emission

$$t_{\rm GW} = \frac{5}{256}\frac{a^4}{G^3 M^3}.$$

for M=$M_{\rm Pl}$

$$t_{\rm GW} \simeq 10^{-42}{\rm s}\left(\frac{a}{10\,\ell_{\rm Pl}}\right)^4.$$

basically **instantaneous** for a dark coupling that leads to bound states, since the orbital separation

$$a_{0,D} \simeq \frac{2}{\alpha_D}\ell_{\rm Pl}$$

the resulting **GW frequency** is then

$$f_{\rm GW} \simeq 2 f_{\rm orb} = \frac{\Omega}{\pi} = \frac{\alpha_D^{3/2}}{2\pi} \quad \text{(in Planck frequency units).}$$

$$f_{\rm Pl} = \frac{1}{t_{\rm Pl}} \simeq 1.85\times 10^{43}\ {\rm Hz}.$$

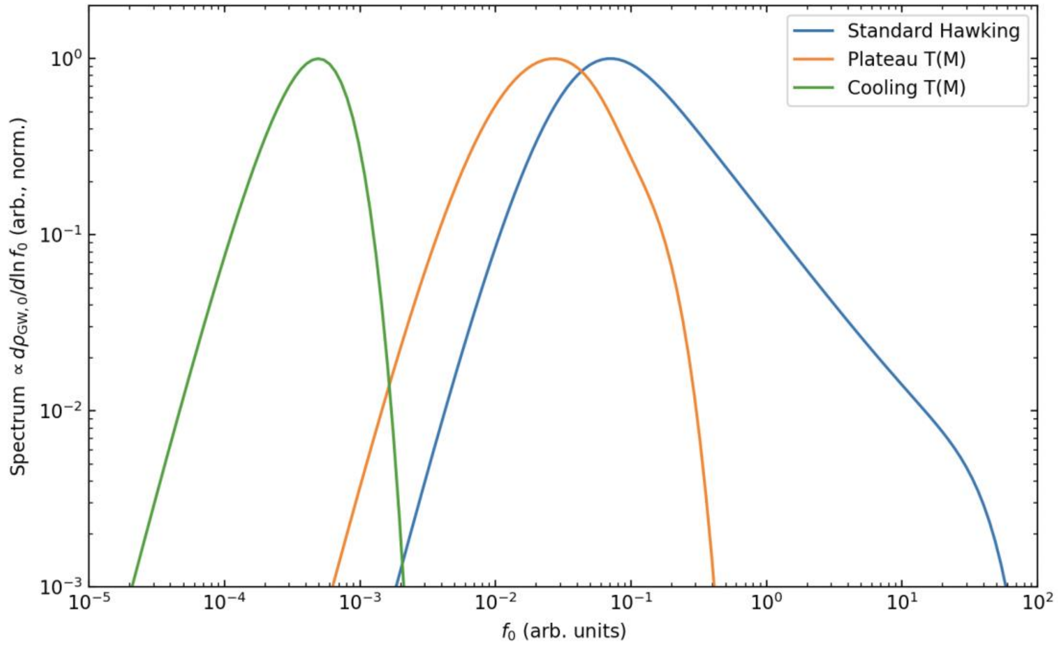
$$f_{\rm GW}(\alpha_D) \simeq \frac{\alpha_D^{3/2}}{2\pi} f_{\rm Pl} \approx 3\times 10^{42}\,\alpha_D^{3/2}\ {\rm Hz}.$$

Any gravitationally bound pair of relics dies via rapid, **high-frequency GW emission**

Can high-freq. gravitational waves test Planck-scale physics?

Two sources: **evaporation** products + classical **inspiral** emission

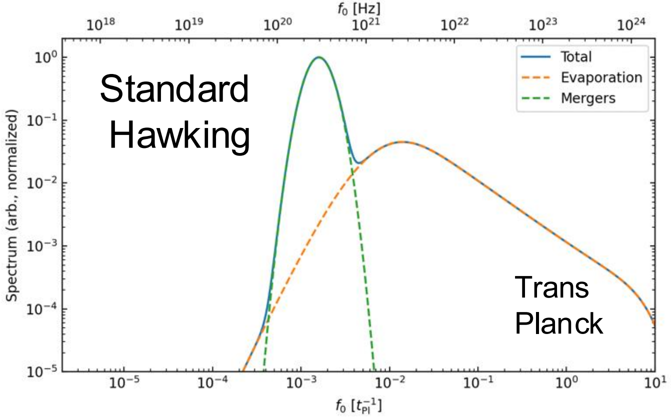
Assume modifications to **T(M)**: plateau (string theory), cooling via turnover (GUP)

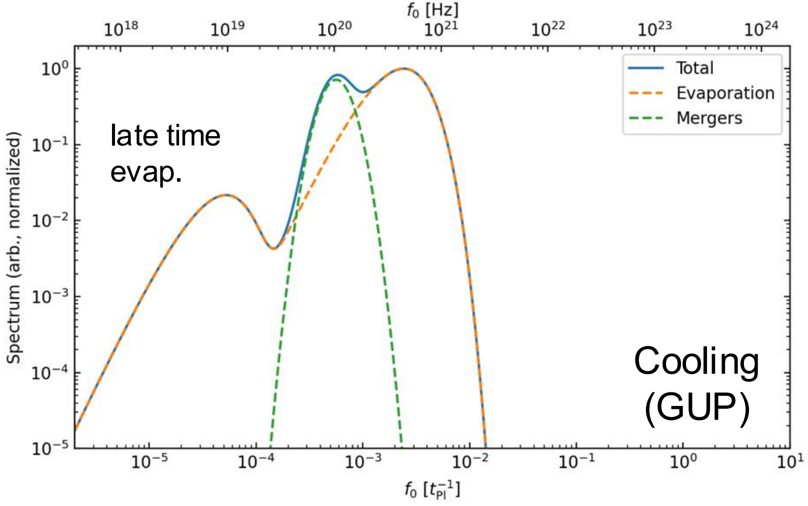


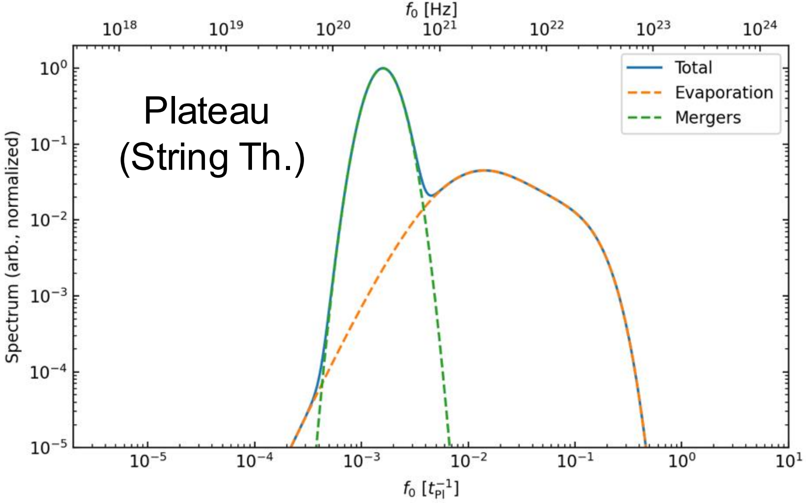
Can high-freq. gravitational waves test Planck-scale physics?

Now include **mergers**…

…this is what the standard semi-classical Hawking evaporation looks like (for $M_i = 100\, M_{\rm Pl}$)







Charged Planckton?

If **evaporation stops** around the Planck scale, the relic PBHs can acquire a significant stochastic **relic** electric **charge**

(under simple **assumptions**) the relic charge is approximately **Gaussian***

$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

$$(8\pi\alpha)^{-1/2} \approx 2.34$$

* Page, 1977

** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348 (JCAP10(2019)046)

Neutralization by Coulomb + gravitational focusing

$$V(r) = -\frac{GMm_c}{r} - \frac{|qQ|}{4\pi\epsilon_0 r}$$

c: electrons, protons

$$\dot{N}(Z) = n_{\rm ch}\, v\, \sigma(Z) = \frac{4\pi\, n_{\rm ch}}{v^3}\Big(GM + \kappa\,|Z|\Big)^2, \qquad \kappa \equiv \frac{e^2}{4\pi\epsilon_0\, m_c}$$

$$t_{\rm neut}(Z; M, n_{\rm ch}, v, m_c) \equiv \sum_{k=1}^{|Z|} \frac{1}{\dot{N}(k)} = \frac{v^3}{4\pi n_{\rm ch}} \sum_{k=1}^{|Z|} \frac{1}{(GM+\kappa k)^2}.$$

$$t_{\rm neut}(Z) = \frac{v^3}{4\pi n_{\rm ch}\,\kappa^2}\left[\psi_1\!\left(1+\frac{GM}{\kappa}\right) - \psi_1\!\left(1+\frac{GM}{\kappa}+|Z|\right)\right] \qquad \psi_1(x) \equiv \frac{d^2}{dx^2}\ln\Gamma(x)$$

Euler's trigamma function

Profumo, JCAP11(2025)023

Neutralization by Coulomb + gravitational focusing

Coulomb-dominated $GM \ll \kappa$

$$t_{\rm neut} \simeq \frac{\pi^2}{6}\,\frac{v^3}{4\pi n_{\rm ch}}\left(\frac{4\pi\epsilon_0\, m_c}{e^2}\right)^2$$

Gravity-dominated $GM \gg \kappa|Z|$

$$t_{\rm neut} \simeq \frac{v^3}{4\pi n_{\rm ch}}\,\frac{|Z|}{G^2 M^2}$$

Cross-over mass

$$M_\star(m_c) \equiv \frac{\kappa}{G} = \frac{e^2}{4\pi\epsilon_0\, G\, m_c} = \frac{\alpha\,\hbar c}{G\, m_c} \simeq \begin{cases} 3.8\times 10^{12}\,\mathrm{kg}, & m_c = m_e,\\ 2.1\times 10^{9}\,\mathrm{kg}, & m_c = m_p,\end{cases}$$

Profumo, JCAP11(2025)023

Neutralization by Coulomb + gravitational focusing

Epoch	z	typical (n_e, T)	$t_{\rm neut}^{(+)}$ (electrons)	$t_{\rm neut}^{(-)}$ (protons)
MeV era	$\sim 10^{10}$	$n_e \sim 10^{28}\,{\rm m}^{-3}$, $T \sim$ MeV	$\sim 10^{-9}$ s	$\sim 10^{-7}$ s
Pre-recomb.	~ 2000	$n_e \sim 10^{9}\,{\rm m}^{-3}$, $T \sim 5 \times 10^{3}$ K	$\sim$ minute	$\sim$ 40 minutes
Recombination	~ 1100	$x_e \sim 2 \times 10^{-4}$, $n_e \sim 7 \times 10^{4}\,{\rm m}^{-3}$	$\sim$ 10–20 days	$\sim$ 1 yr
Dark ages	~ 100	$x_e \sim 2 \times 10^{-4}$, $n_e \sim 5 \times 10^{2}\,{\rm m}^{-3}$	$\sim$ 0.5 yr	$\sim$ 20 yr
Reionization	~ 7	$x_e \to 1$, $n_e \sim 10^{2}\,{\rm m}^{-3}$, $T \sim 10^{4}$ K	$\sim 10^{2}$ yr	$\sim 10^{3}$ yr
IGM today	0	$n_e \sim 0.25\,{\rm m}^{-3}$, $T \sim 10^{4}$ K	$\sim 4 \times 10^{4}$ yr	$\sim 1.6 \times 10^{6}$ yr
WIM (ISM)	0	$n_e \sim 0.03\,{\rm cm}^{-3}$	days	decades

*note that "atomic" states with bound electrons, protons **ionize** very quickly

$$\tau_{\rm ion} \sim 10^{-9}\,{\rm s} \ll H^{-1}(T) \quad \text{for all } T \gg 10\ {\rm eV}.$$

Profumo, JCAP11(2025)023

Neutralization by Schwinger discharge

Pair creation near the horizon generally expected to **kill residual charge**

- Local pair-production rate

$$w(E) \simeq \frac{(eE)^2}{4\pi^3} e^{-\pi m^2/(eE)}$$

- Integrated law ⇒ rapid charge loss until $E_h = E_{\rm crit}$.
- **Residual charge:**

$$Q^{(e)}_{\rm stop} = 4\pi \frac{m_e^2}{e} r_h^2 \Rightarrow Q^{(e)}_{\rm stop}/e \sim 10^{-43} \text{ for } r_h \sim \ell_{\rm Pl}$$

Discharge is suppressed, and charge persists, only for **very large masses**:

$$M^{(\rm ext)}_{\rm Sch} \simeq \frac{c^4}{(4\pi\epsilon_0)^{1/2}\, G^{3/2}\, E^{(e)}_{\rm crit}} \approx 1.1 \times 10^{36}\,\text{kg} \quad (\sim 5 \times 10^5\, M_\odot).$$

at those masses, of course, **gravitational discharge** is very efficient

Quantum gravity and Schwinger discharge

Generally, discharge occurs in the **exterior** of the compact object, where Maxwell theory on a **smooth background** is reliable.
If anything, **QG principles favor discharge**!

1. **Exterior fields are classical** and obey Gauss's law, independently of horizon microstructure
2. **Semiclassical QED** near the horizon is **trustworthy**
3. **Weak-gravity conjecture**: at some point there should exist a superextremal state with $q/m>1$ that opens discharge

Profumo, JCAP11(2025)023

Quantum gravity and Schwinger discharge

However, quantum gravity may well **shut off Schwinger** discharge!

1. Saturation / Cutoff of the Electric Field Near the Relic: Quantum-gravity effects could **smear out charge** over a minimal length ~ Planck scale, so that the field never exceeds some E_{max}
2. Schwinger formula assumes **local QFT on a smooth background,** Quantum gravity might render the vacuum response **non-local** on Planckian scales (e.g. fuzzball microstructure, wormhole "sponges"), so that a would-be strong local field cannot be treated as a constant background
3. Near Planckian curvature, the **effective charge** or **mass** of the electron could be **renormalized** by gravity in such a way that Ecrit becomes too large
4. Suppose $U(1)_{EM}$ is **emergent**, and Gauss's law or the field strength operator $F_{\mu\nu}$ ceases to be fundamental above some cutoff

…but what if **Schwinger discharge** is **shut off**?
What is the **maximal charge** that can survive?

Profumo, JCAP11(2025)023

Can Planck Relics Preserve their Charge (absent Schwinger)?

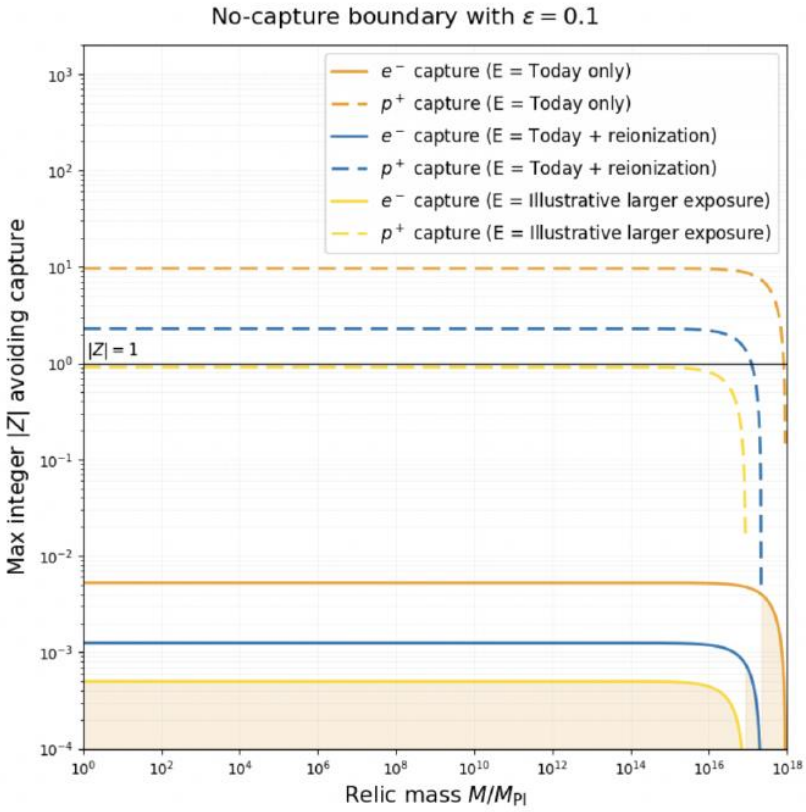
One possibility: relic is very **close to extremality**!
Define the parameter

$$\epsilon \equiv \frac{Mc^2 - |Q|\sqrt{G/(4\pi\epsilon_0)}}{Mc^2}$$

$$\epsilon = 1 - |Q|/M$$

e.g. with **extremality suppression** $\epsilon = 0.1$

negatively charged relics can have Z~1, but
positively charged relics are definitely neutralized!

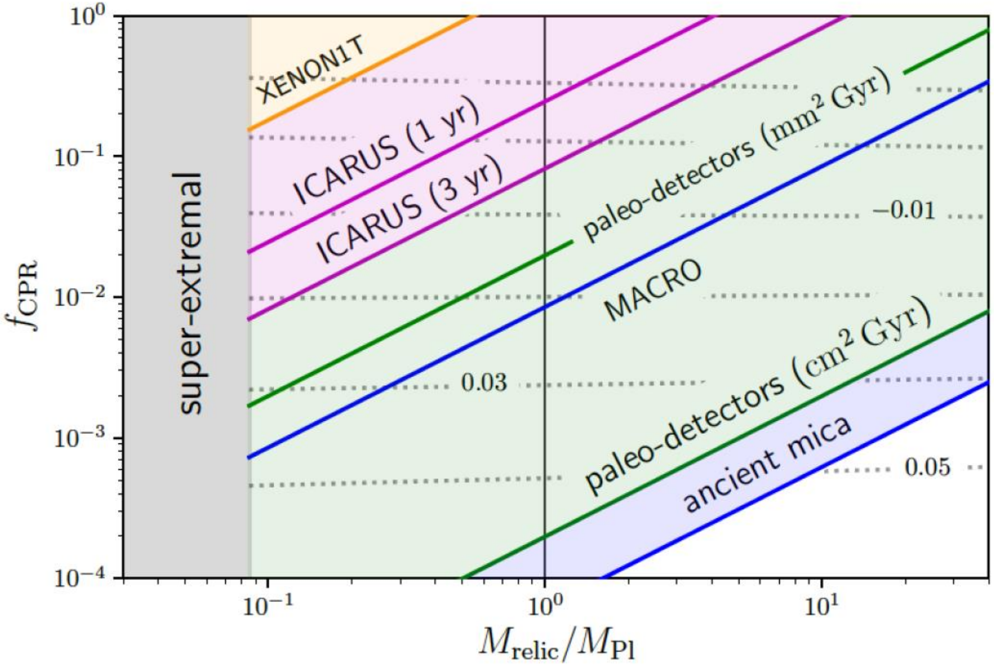


Only Viable Loopholes to have Charged Plancktons

Discharge is unavoidable except in **three scenarios**:

Mechanism	Requirement	Viability
(i) Near-extremal + no-Schwinger limit	$\epsilon \to 0$, pair creation turned off by quantum gravity	Highly fine-tuned

Charged Relic Detection: Electromagnetic Signatures



* Lehmann, Johnson, Profumo and Schwemberger, 1906.06348 (JCAP10(2019)046)

Mechanical Detection: Windchime Concept

Mechanical gravitational detectors like the proposed **Windchime** could probe Plancktons

Principle: detect **gravitational impulses** from passing relics using arrays of ultra-sensitive **test masses** in space

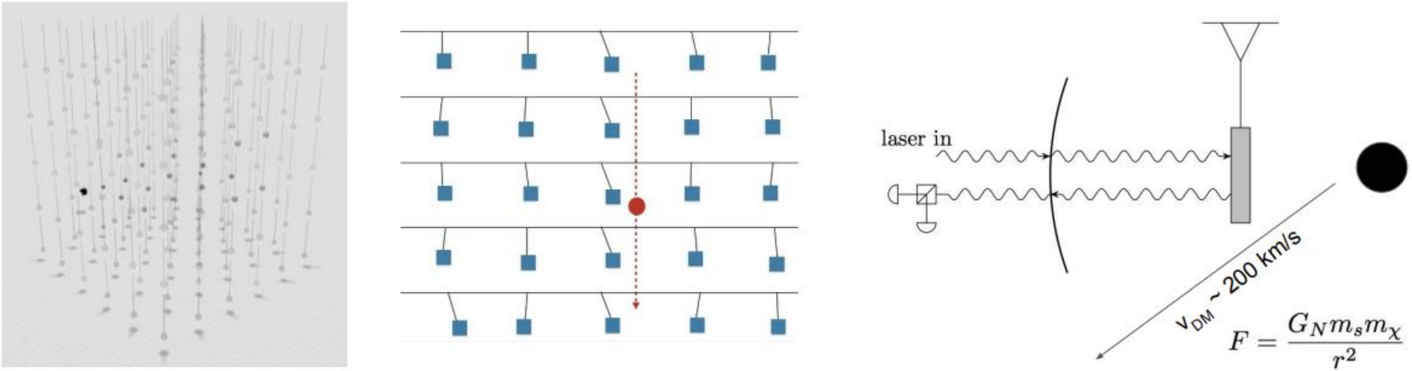
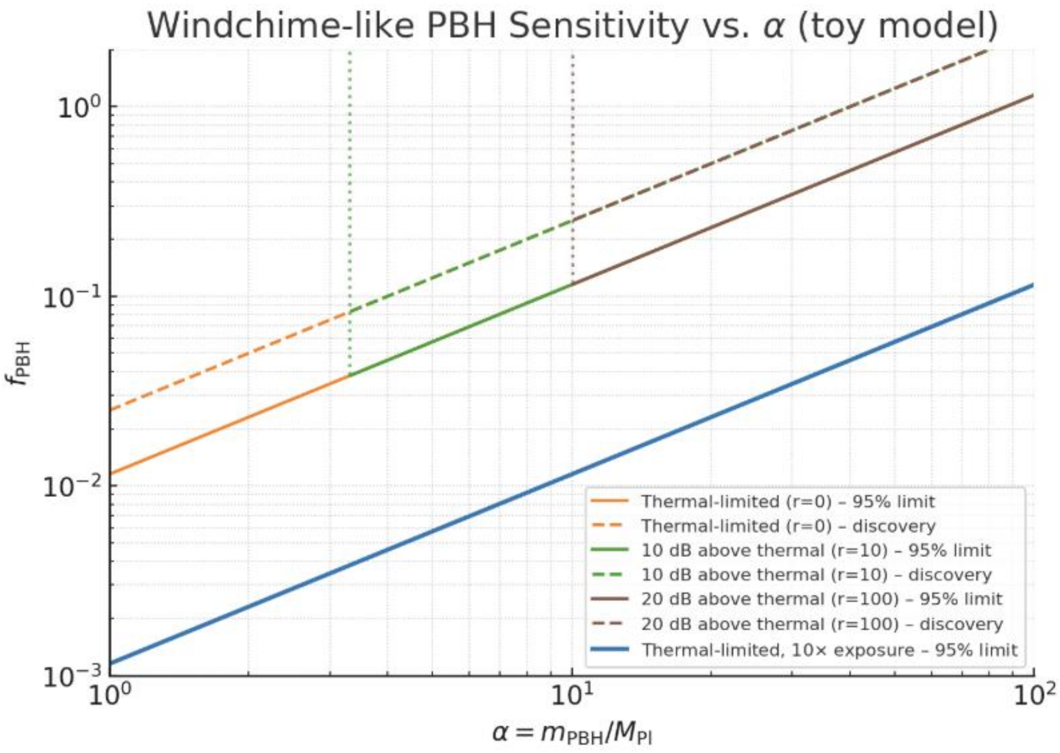


FIG. 1. Schematic illustration of the Windchime detector concept. Left: an array of mechanical sensors, here depicted as suspended pendula, with a potential DM track signal. Center: cross-section, emphasizing the "track" signal. Right: single-sensor depiction of a gravitational DM event. Here, for conceptual illustration, the sensor is depicted in a small optical cavity with laser readout. In practice, readout through either fibers or microwave transmission lines will be more convenient for a densely packed array.

Mechanical Detection: Windchime Concept



Best-case scenario:

- **f_{PBH}** down to ~10^{-3}
- **masses** up to ~ 10^3 M_{Pl}

Key Takeaways

(1) Existence:

- Quantum-gravity (GUP, LQG, string th.) → stable or long-lived Planck-mass endpoints.
- Charged and darkly charged remnants possible; semi-classical extrapolation fails near $M_{\rm Pl}$.

(2) Cosmology:

- PBH evaporation generically yields relics → natural CDM candidate.
- Tiny $\beta(M) \sim 10^{-27}$sufficient for $\Omega_{\rm DM}$.
- Relics are *ultra-cold* today regardless of initial recoil.

(3) Detection:

- Gravitational waves: very high frequency (evaporation/mergers); possible probe of QG?
- Charged Planckton: discharge very effective (three caveats); paleodetectors
- Mechanical detection: optimistically down to fPBH~10-3 and M~103MPl