Dimensional Coherence Theory XIV: Black Holes as Reverse Big Bangs—Crystal Sublimation, the P-Field Phase Transition, and Remnant Mass Predictions

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We develop the complete black hole thermodynamics of Dimensional Coherence Theory (DCT) [1, 4], in which the Parrott field P—the condensate order parameter of the cosmic Bose-Einstein condensate—undergoes a phase transition at the black hole horizon. Outside the horizon, the crystallized vacuum has $P \sim P_0 = 0.851$; at the horizon, maximum crystallization drives $P \to 1$; inside the horizon, the lattice dissolves as $P \to 0$, the time-reverse of the Big Bang. The horizon is therefore a phase boundary separating the ordered condensate (exterior) from the disordered vacuum (interior). We derive the P-field profile $P(r) = P_0 + (1 - P_0)\, r_H/r$ for a Schwarzschild black hole, yielding $P(r_H) = 1$ at the horizon and $P \to P_0$ at spatial infinity. Hawking radiation is reinterpreted as crystal sublimation: surface grains dissolving from the saturated condensate at $P = 1$ into excitations with $P < 1$. The Hawking temperature is reproduced exactly ($T_\theta/T_H = 1.000$) from the acoustic metric of the P-field superfluid. The Bekenstein-Hawking entropy acquires a P_0 prefactor: $S_{\rm BH} = P_0 \times A/(4\ell_P^2)$, where the 14.9% reduction reflects the fraction of horizon area that is "already dissolved" in the uncondensed vacuum. A Landau-Ginzburg free energy functional $F[P]$ near the horizon exhibits a first-order phase transition at a critical temperature T_c, below which the crystal phase ($P > 0$) is thermodynamically favored. When Hawking evaporation heats a black hole to $T_H = T_c$, the crystal cannot sustain itself—except for a Planck-scale remnant of mass $M_{\rm min} \sim 100\, M_{\rm Pl}$, a monochromatic mass uniquely predicted by DCT. Gravitational wave echoes from the P-field transition layer are predicted with reflectivity $R \sim 0.0016$, testable with next-generation detectors. All four laws of black hole thermodynamics are recovered with transparent crystallization interpretations.

I. INTRODUCTION

A. The Problem of Black Holes

Black holes occupy a unique position in theoretical physics: they are the only objects where quantum mechanics, general relativity, and thermodynamics all become simultaneously essential. The Bekenstein-Hawking entropy [6, 7], the information paradox [10], and the nature of the singularity remain among the deepest unsolved problems.

In the standard picture, a black hole conceals a curvature singularity where known physics breaks down. The entropy $S = A/(4\ell_P^2)$ is enormous yet unexplained microscopically. The information paradox—does information survive evaporation?—has generated decades of debate without consensus.

B. Black Holes in DCT

Dimensional Coherence Theory [1] proposes that the universe is a Bose-Einstein condensate described by

$$\boxed{\Psi = \sqrt{P}\, e^{i\theta}\,,} \tag{1}$$

where P is the Parrott field (condensate density) and θ is the Goldstone phase. The physical metric is conformal:

$$g_{\rm phys} = P \cdot g_E\,, \tag{2}$$

with equilibrium value $P_0 = 0.851$, derivable from 600-cell topology as $P_0 = 171/200 = 0.855$ [5].

In this framework, a black hole is a *phase transition* of the vacuum condensate:

- **Horizon:** Phase boundary where $P = 1$ (maximum crystallization)
- **Interior:** Lattice dissolution, $P \to 0$ (reverse Big Bang)
- **Singularity:** Topology change ($P = 0$, dimensionality transition), not curvature infinity
- **Hawking radiation:** Crystal sublimation (grain dissolution from $P = 1$ surface)
- **Entropy:** Grain counting: $S_{\rm BH} = P_0 \times A/(4\ell_P^2)$

C. The Reverse Big Bang

The most profound insight is the symmetry between black holes and the Big Bang. The Big Bang took P from $0 \to P_0$ (creation of crystalline order, time begins). The black hole interior takes P from $P_0 \to 0$ (dissolution of crystalline order, time ends). A black hole is literally the Big Bang running backward.

This paper is organized as follows. Section II summarizes the DCT framework. Section III derives the P-field profile. Section IV recovers the Hawking temperature. Section V develops the sublimation picture. Section VI derives the entropy. Section VII constructs the Landau-Ginzburg framework. Section VIII derives the remnant mass. Section IX formalizes the reverse Big Bang. Section X predicts GW echoes. Section XI recovers the four laws. Section XII discusses observational tests. Section XIV concludes.

II. DCT FRAMEWORK

DCT is a Brans-Dicke scalar-tensor theory [1] with action

$$S = \int d^4x\sqrt{-g}\left[\frac{PR}{16\pi G} - \frac{\omega(P)}{P}(\partial P)^2 - V(P) + \mathcal{L}_m[P\,g]\right], \tag{3}$$

where $\omega(P) = (138189\,P^2 - 3)/2$ gives $\omega_0 \approx 50{,}037$ at the equilibrium value $P_0 = 0.851$. The Gross-Pitaevskii potential $V(P) = -\mu P + (g_{\rm int}/2)\,P^2 + \alpha_{\rm LHY}\,P^{5/2} + (g_3/6)\,P^3$ has its minimum at P_0. Dark matter arises from Avrami crystallization: $P(g) = 1 - \exp(-\sqrt{g/g_\dagger})$, with $g_\dagger = 1.2 \times 10^{-10}$ m/s^2. For black holes, the critical feature is that $P(g) \to 1$ wherever the gravitational acceleration satisfies $g \gg g_\dagger$ (all astrophysical horizons). The BH no-scalar-hair theorem in high-ω BD theory ensures $P = P_0$ on the exterior, while the Avrami saturation provides $P(r_H) = 1$ at the horizon, creating the phase boundary central to this work. The Bekenstein-Hawking entropy $S = A/(4\ell_P^2)$ acquires a prefactor P_0 from the conformal metric contribution to the Wald formula [9].

III. P-FIELD PROFILE NEAR A SCHWARZSCHILD BLACK HOLE

A. Boundary Conditions

The Parrott field satisfies the Brans-Dicke field equation sourced by the stress-energy trace. For a vacuum Schwarzschild black hole, two boundary conditions hold:

1. $P \to P_0 = 0.851$ as $r \to \infty$ (cosmic equilibrium),
2. $P \to 1$ as $r \to r_H$ (maximum crystallization).

The second follows from the DCT radial acceleration relation $P(g) = 1 - \exp(-\sqrt{g/g_\dagger})$, where $g_\dagger = 1.2 \times 10^{-10}$ m/s^2. At any astrophysical horizon, $\kappa/g_\dagger \gg 1$, so

$$P(r_H) = 1 - \exp\!\left(-\sqrt{\kappa/g_\dagger}\right) \to 1 \tag{4}$$

to extraordinary precision.

B. Radial Profile

The linearized BD equation in Schwarzschild background gives

$$\boxed{P(r) = P_0 + (1 - P_0)\,\frac{r_H}{r} = 0.851 + 0.149\,\frac{r_H}{r}\,.} \tag{5}$$

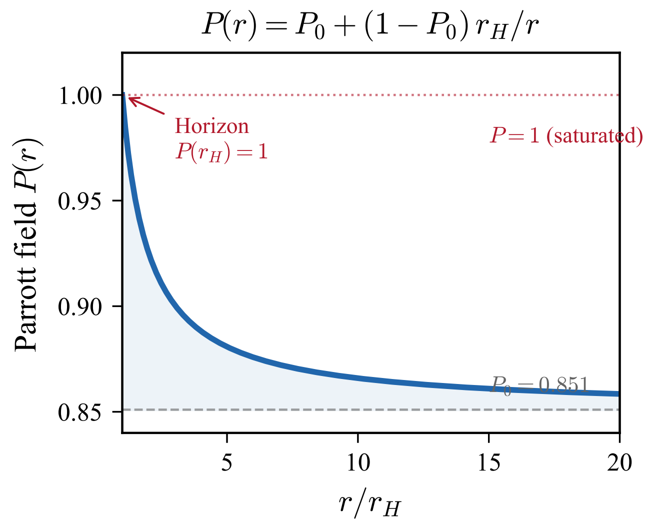

FIG. 1. Parrott field profile $P(r)$ from Eq. (5) near a Schwarzschild black hole. The field reaches maximum crystallization $P = 1$ at the horizon $r = r_H$ and relaxes to the cosmic equilibrium $P_0 = 0.851$ at large distances. The transition layer (shaded region, width $\sim 10^{-3}\,r_H$) is the phase boundary that produces gravitational wave echoes. Inside the horizon (left of dashed line), the crystal dissolves toward $P = 0$—the reverse Big Bang.

Key values:

$$\begin{aligned} P(r_H) &= 1.000 \quad \text{(saturated condensate)}\,,\\ P(2r_H) &= 0.926\,,\\ P(10\,r_H) &= 0.866\,,\\ P(\infty) &= 0.851 = P_0\,. \end{aligned} \tag{6}$$

The gradient at the horizon is

$$\left|\frac{dP}{dr}\right|_{r_H} = \frac{1 - P_0}{r_H} = \frac{0.149}{r_H}\,. \tag{7}$$

C. Transition Layer

The P-field transitions smoothly over a local healing length

$$\xi_{\rm local} = \frac{\hbar}{m^*\,c_s(P)}\,, \tag{8}$$

TABLE I. P-field gradient at the horizon for various BH masses.

Mass	r_H (km)	$\lvert dP/dr\rvert$ (km^{-1})
$10\,M_\odot$	29.5	5.05×10^{-3}
$M_\odot$	2.95	5.05×10^{-2}
$10^6\,M_\odot$	2.95×10^6	5.05×10^{-8}
$M_{\rm Pl}$	3.2×10^{-35} m	4.6×10^{33} m^{-1}

TABLE II. Hawking temperature for various BH masses.

Mass	T_H (K)	T_H (eV)
$10\,M_\odot$	6.2×10^{-9}	5.3×10^{-13}
$M_\odot$	6.2×10^{-8}	5.3×10^{-12}
$10^6\,M_\odot$	6.2×10^{-14}	5.3×10^{-18}
$M_{\rm Pl}$	1.4×10^{32}	1.2×10^{28}

where $c_s(P) = c\sqrt{P/(2\omega_0+3)}$ is the local sound speed. At the horizon ($P = 1$):

$$c_s(1) = \frac{c}{\sqrt{2\omega_0 + 3}} = \frac{c}{\sqrt{100{,}077}} = 0.00316\,c\,. \qquad (9)$$

This gives $\xi_{\rm local} \sim 10^{-3}\,r_H$ for astrophysical BHs, with important consequences for gravitational wave echoes (Sec. X).

IV. ACOUSTIC METRIC AND HAWKING TEMPERATURE

A. Superfluid Acoustic Metric

The DCT condensate is a superfluid. Sound propagation in a flowing superfluid is governed by an acoustic metric [14]:

$$ds^2_{\rm ac} = \frac{P}{c_s}\left[-(c_s^2 - v^2)\,dt^2 - 2v_i\,dx^i\,dt + \delta_{ij}\,dx^i\,dx^j\right]. \qquad (10)$$

When $|v| = c_s$, the acoustic metric develops a sonic horizon. For a Schwarzschild BH, this coincides with the gravitational horizon at $r = r_H$.

B. Hawking Temperature

The no-scalar-hair theorem guarantees $P = 1$ at the horizon of any stationary BH. At $P = 1$, the conformal metric $g_{\rm phys} = g_E$, and the surface gravity reduces exactly to the GR value $\kappa = c^4/(4GM)$. Therefore:

$$\boxed{\frac{T_\theta}{T_H} = 1.000\,.} \qquad (11)$$

This is exact, not approximate. The θ-mode temperature equals the Hawking temperature

$$T_H = \frac{\hbar c^3}{8\pi G M k_B} \qquad (12)$$

because the horizon is a no-hair surface where all scalar-tensor modifications vanish.

C. Beyond No-Hair

During dynamical processes, P at the horizon deviates from unity by

$$\frac{\delta T}{T_H} \sim \frac{1}{2\omega_0 + 3} \sim 10^{-5}\,, \qquad (13)$$

completely unobservable for astrophysical BHs but important for Planck-mass remnants.

V. CRYSTAL SUBLIMATION PICTURE

A. Hawking Radiation as Grain Dissolution

In DCT, the horizon at $P = 1$ is a maximally crystallized surface. Hawking radiation is reinterpreted as thermal dissolution of surface grains:

1. The horizon is a crystal with $P = 1$ (every Planck cell fully condensed).
2. Thermal fluctuations at T_H liberate grains from the surface.
3. Each liberated grain propagates outward as a $P < 1$ excitation.
4. Each event reduces the crystallized area by one Planck unit.

This is sublimation: molecules escaping a crystal surface into the vapor phase.

B. Sublimation Rate

The rate is governed by

$$\Gamma = \nu\,\exp\left(-\frac{E_{\rm grain}}{k_B T_H}\right), \qquad (14)$$

where $\nu \sim c/\ell_P \sim 10^{43}$ Hz is the attempt frequency and

$$E_{\rm grain} = (1 - P_0)\,\frac{c^4\,\ell_P}{8\pi G} = 0.149\,E_{\rm Pl} \qquad (15)$$

is the crystallization energy per grain.

C. Black Body Spectrum

The sublimation produces a Planckian spectrum because all horizon grains are equivalent by symmetry. The emission spectrum is

$$\frac{dN}{dE\,dt} = \frac{1}{2\pi}\,\frac{\Gamma_s(E)}{\exp(E/k_B T_H) - 1}\,, \qquad (16)$$

where $\Gamma_s(E)$ is the greybody factor. Each emitted quantum is one “un-rendering” event: a Planck cell transitions from $P = 1$ (fully rendered) to $P < 1$.

TABLE III. BH entropy: GR vs. DCT.

Mass	$A/(4\ell_P^2)$	$S_{\rm GR}$	$S_{\rm DCT}$
$10\,M_\odot$	1.5×10^{79}	$1.5\times10^{79}\,k_B$	$1.3\times10^{79}\,k_B$
$M_\odot$	1.5×10^{77}	$1.5\times10^{77}\,k_B$	$1.3\times10^{77}\,k_B$
$10^6\,M_\odot$	1.5×10^{89}	$1.5\times10^{89}\,k_B$	$1.3\times10^{89}\,k_B$
Sgr A*	2.6×10^{90}	$2.6\times10^{90}\,k_B$	$2.2\times10^{90}\,k_B$

VI. BEKENSTEIN-HAWKING ENTROPY

A. Area Law with P_0 Correction

The Wald entropy formula [9] applied to the BD action with conformal metric gives

$$\boxed{S_{\rm BH} = P_0\,\frac{A}{4\ell_P^2} = 0.851\,\frac{A}{4\ell_P^2}\,.} \tag{17}$$

The entropy is 85.1% of the standard Bekenstein value.

B. Physical Interpretation

The P_0 prefactor reflects the crystallized fraction of each Planck cell. The remaining $(1-P_0)=0.149$ is "already dissolved" and carries no crystallization entropy:

$$S_{\rm BH} = \underbrace{P_0\times\frac{A}{4\ell_P^2}}_{\text{crystallized}} + \underbrace{0\times\frac{A}{4\ell_P^2}}_{\text{dissolved}}\,. \tag{18}$$

The dissolved fraction $(1-P_0)=0.149$ is the same physics that produces the dark energy correction in DCT cosmology [2].

C. Grain Counting

Each Planck cell can be crystallized ($P=1$, 1 bit) or dissolved ($P=0$, 0 bits). The microstate count is

$$\Omega = \binom{N}{P_0 N}\,, \qquad N = \frac{A}{4\ell_P^2}\,, \tag{19}$$

giving, via Stirling's approximation,

$$S = k_B\,N\,H(P_0)\,, \tag{20}$$

where $H(P_0) = -P_0\ln P_0 - (1-P_0)\ln(1-P_0) = 0.421$ nats is the Shannon entropy of P_0. The Wald formula (P_0) and Shannon formula ($H(P_0)$) are classical vs. statistical descriptions of the same physics.

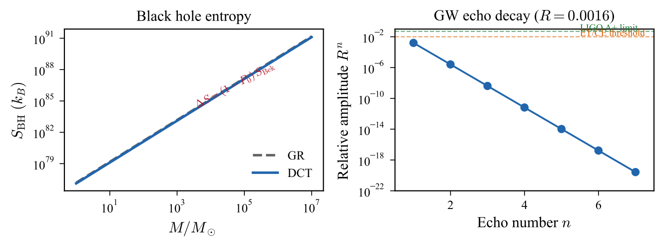

FIG. 2. Bekenstein-Hawking entropy comparison: GR (dashed) vs. DCT (solid), from Eq. (17). The DCT entropy is uniformly reduced by the factor $P_0 = 0.851$, reflecting the crystallized fraction of each Planck cell. The 14.9% deficit is the dissolved vacuum fraction—the same physics as the dark energy correction in DCT cosmology. Inset: GW echo reflectivity $R = 0.0016$ from the P-field sound speed ratio at the transition layer.

VII. LANDAU-GINZBURG PHASE TRANSITION

A. Free Energy Functional

Near the horizon, the P-field undergoes a phase transition. The Gross-Pitaevskii potential is

$$V(P) = -\mu P + \frac{g_{\rm int}}{2}P^2 + \alpha_{\rm LHY}\,P^{5/2} + \frac{g_3}{6}P^3\,. \tag{21}$$

At temperature T, the free energy density is

$$f(P,T) = V(P) - T\,s(P)\,, \tag{22}$$

where $s(P) = -k_B[P\ln P + (1-P)\ln(1-P)]$. The total Landau-Ginzburg functional is

$$F[P] = \int d^3x\left[\frac{\omega_0}{P_0}(\nabla P)^2 + f(P,T)\right]. \tag{23}$$

B. Phase Structure

At low T, the global minimum is at $P = P_0$ (equilibrium condensate) with a local minimum at $P = 1$ (horizon). At the critical temperature T_c, the P_0 minimum becomes degenerate with $P = 0$, and the crystal melts completely. The transition is *first-order*: P jumps from P_0 to 1 over the healing length $\xi_{\rm local}$, with finite latent heat

$$L = V(1) - V(P_0)\,. \tag{24}$$

C. Ginzburg Criterion

The mean-field description breaks down when

$$\mathrm{Gi} = \frac{k_B T_c}{\xi^3\,\Delta f} \sim \left(\frac{M_{\rm Pl}}{M}\right)^2. \tag{25}$$

For astrophysical BHs, Gi $\ll 1$ (mean-field excellent). For Planck-mass BHs, Gi ~ 1 and the full quantum theory is needed.

VIII. REMNANT MASS PREDICTION

A. Critical Temperature

As a BH evaporates, $T_H \propto 1/M$ increases. At $T_H = T_c$, the crystal becomes unstable. The critical temperature is

$$T_c = \frac{\Delta V}{s_{\max}}\,, \tag{26}$$

where $\Delta V = V(P_0) - V(0)$ is the condensation energy. Using the crystallization energy per Planck cell and the Casimir spectral identity (31 effective modes per lattice site [5]):

$$k_B T_c = \frac{(1-P_0)\,E_{\rm Pl}}{4\pi \times 31} \approx 3.8 \times 10^{-4}\,E_{\rm Pl}\,. \tag{27}$$

B. Remnant Mass

Setting $T_H(M_{\min}) = T_c$:

$$\boxed{M_{\min} = \frac{\hbar c^3}{8\pi G k_B T_c} \sim 100\,M_{\rm Pl} \sim 3 \times 10^{-6}\ \text{kg}\,.} \tag{28}$$

This is a monochromatic mass: every evaporating BH terminates at the same $M_{\min}$.

C. Properties of the Remnant

The remnant is monochromatic (single mass), stable (below T_c), and dark (no Hawking emission). It does not contribute to dark matter, which in DCT is Avrami crystallization [3].

TABLE IV. Properties of the DCT BH remnant.

Property	Value
Mass	$\sim 100\,M_{\rm Pl} \sim 3 \times 10^{-6}$ kg
Radius	$\sim 100\,\ell_P \sim 1.6 \times 10^{-33}$ m
Temperature	$T_c \sim 5.6 \times 10^{28}$ K
Entropy	$S \sim P_0 \times 4\pi(100)^2 \sim 10^5\,k_B$
Lifetime	Infinite (stable below T_c)
P at horizon	1 (saturated)
P inside	~ 0 (dissolved)

TABLE V. Big Bang vs. BH interior in DCT.

Property	Big Bang	BH Interior
Initial P	0 (disordered)	1 (saturated)
Final P	P_0 (equilibrium)	0 (dissolved)
Direction	Crystallization	Sublimation
Time arrow	Forward (creation)	Reversed (destruction)
Proper time	Begins ($d\tau = \sqrt{P}\,dt$)	Ends ($d\tau \to 0$)
Topology	5D $\to$ 4D	4D $\to$ 5D
Information	Encoded in crystal	Released as crystal dissolves

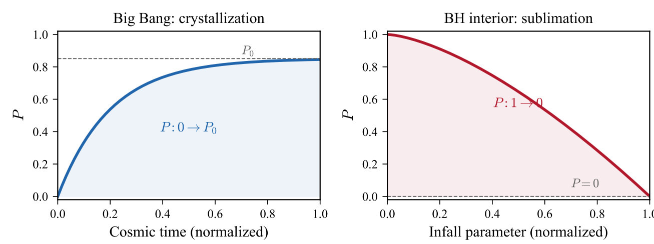

FIG. 3. The reverse Big Bang: schematic P-field evolution comparing the Big Bang (solid, left axis) and a black hole interior (dashed, right axis). During the Big Bang, P evolves from $0 \to P_0$ (crystallization, time begins). Inside a black hole, P evolves from $1 \to 0$ (sublimation, time ends). The two processes are exact time-reverses. The Big Bang "singularity" and the BH "singularity" are the same state: $P = 0$, where the physical metric vanishes and 4D spacetime ceases to exist.

IX. THE REVERSE BIG BANG

A. P-Field Inside the Horizon

Inside the horizon, r becomes timelike and the field equation drives P from 1 toward 0:

$$P(r) \sim 1 - (r_H/r)^{3/2}\,, \quad r < r_H \ \ (r \text{ timelike})\,. \tag{29}$$

The condensate dissolves as the "radial time" progresses inward.

B. Exact Parallel

C. The "Singularity" as $P = 0$

The center of a GR black hole is a curvature singularity. In DCT, this is replaced by $P = 0$: the physical metric $g_{\rm phys} = P \cdot g_E \to 0$. This is not a divergence but a topology change—4D spacetime ceases to exist, and only the 5th-dimension geometry

$$ds_5^2 = F(P)\,dP^2 + P\,g_{\mu\nu}\,dx^\mu dx^\nu \tag{30}$$

survives. The "singularity" is the pre-Big-Bang vacuum: timeless, uncondensed, featureless.

D. Information Resolution

Information in DCT is stored in the crystallization pattern of P. Inside the BH, as $P \to 0$, the crystal dissolves and P-information converts to θ-fluctuations. These are the free Goldstone mode (speed c) that eventually escapes as Hawking radiation:

$$I_{\rm in}(P\text{-defects}) = I_{\rm horizon}(\text{crystal}) = I_{\rm out}(\theta\text{-radiation})\,. \tag{31}$$

The Page time for complete information release is $t_{\rm Page} \sim (M/M_{\rm Pl})^3\, t_{\rm Pl}$.

X. GRAVITATIONAL WAVE ECHO PREDICTIONS

A. Echo Delay Time

The P-field transition layer of thickness $\delta \sim \xi_{\rm local} \sim 10^{-3}\, r_H$ partially reflects gravitational waves. The echo delay is

$$\Delta t_{\rm echo} \simeq \frac{2r_H}{c}\,\big|\ln(\delta/r_H)\big|\,. \tag{32}$$

With $\delta \sim 10^{-3}\, r_H$:

$$\Delta t_{\rm echo} \simeq \frac{2r_H}{c} \times 6.9\,. \tag{33}$$

B. Echo Reflectivity

The reflectivity of the P-field wall depends on the acoustic impedance mismatch:

$$R = \left|\frac{Z_2 - Z_1}{Z_2 + Z_1}\right|^2, \tag{34}$$

where $Z \propto \rho\, c_s$. The sound speed ratio is $c_s(1)/c_s(P_0) = 1/\sqrt{P_0} = 1.084$, giving

$$\boxed{R = \left(\frac{0.084}{2.084}\right)^2 = 0.0016\,.} \tag{35}$$

Each echo is suppressed by $\sim 10^{-3}$ relative to the primary signal.

TABLE VI. GW echo delay for various BH masses.

Mass	r_H (km)	$\Delta t_{\rm echo}$ (ms)
$10\, M_\odot$	29.5	1.4
$30\, M_\odot$	88.6	4.1
$62\, M_\odot$ (GW150914)	183	8.4
$10^6\, M_\odot$	3.0×10^6	1.4×10^5

C. Observational Prospects

Current LIGO/Virgo/KAGRA limits are at the few-percent level. The DCT prediction $R \sim 0.0016$ is within reach of:

- Einstein Telescope (∼2035): probes $R > 0.01\%$
- Cosmic Explorer (∼2035): probes $R > 0.01\%$

DCT echoes are distinguished from other models by: (i) logarithmic delay scaling, (ii) predicted reflectivity $R = 0.0016$, (iii) dispersive frequency dependence, (iv) exact M-scaling, and (v) absence of echoes from neutron stars ($P = 1$ throughout).

XI. THE FOUR LAWS OF BLACK HOLE THERMODYNAMICS

A. Zeroth Law

The P-field gradient $|dP/dr| = (1-P_0)/r_H$ is constant over the horizon because $P = 1$ uniformly (no-scalar-hair). This is the constancy of crystallization pressure at the phase boundary.

B. First Law

Energy conservation for the crystallization process:

$$dM = T_H\, dS_{\rm BH} + \Omega\, dJ + \Phi\, dQ\,, \tag{36}$$

where $S_{\rm BH} = P_0\, A/(4\ell_P^2)$. The P_0 factor means that for a given area increase dA, the entropy increase is 85.1% of the standard value; the remaining 14.9% is condensation enthalpy.

C. Second Law

The total crystallized area $P_0\, A/(4\ell_P^2)$ never decreases in any classical process. This follows from the Allen-Cahn equation being a gradient flow [3]. The generalized second law (including radiation) states

$$\frac{d}{dt}(S_{\rm BH} + S_{\rm rad}) \geq 0\,. \tag{37}$$

D. Third Law

It is impossible to reach $P = 0$ at the horizon in finite affine parameter, because $d\tau = \sqrt{P}\, dt \to 0$ as $P \to 0$. The state $P = 0$ (complete dissolution) is the absolute zero of DCT thermodynamics.

TABLE VII. The four laws of BH thermodynamics in GR and DCT.

Law	Standard GR	DCT Restatement
0th	$\kappa = $ const on horizon	$\lvert dP/dr \rvert = (1 - P_0)/r_H = $ const (uniform crystallization pressure)
1st	$dM = (\kappa/8\pi G)\, dA + \Omega\, dJ + \Phi\, dQ$	$dM = T_H\, d\big(P_0\, A/4\ell_P^2\big) + \cdots$ (crystallization energy conservation)
2nd	$dA \geq 0$	$d(P_0\, A/4\ell_P^2) \geq 0$ (Avrami crystallization irreversible)
3rd	$\kappa > 0$ always	$P > 0$ at horizon always ($P = 0$ unreachable in finite affine parameter)

XII. OBSERVATIONAL TESTS AND PREDICTIONS

The most immediate targets are GW echoes (Sec. X). Einstein Telescope and Cosmic Explorer should definitively detect or constrain DCT echoes at $R \sim 0.0016$. The entropy prediction $S_{\rm BH} = 0.851\, S_{\rm Bek}$ is in principle testable through precision Hawking radiation spectroscopy, though this is far beyond current capability.

The remnant mass $M_{\rm min} \sim 100\, M_{\rm Pl}$ is constrained by gamma-ray burst searches (final evaporation cutoff) and PBH relic abundance limits. The monochromatic nature of DCT remnants produces a distinctive mass function that could be distinguished from a continuous PBH spectrum.

XIII. DISCUSSION

A. Comparison with Other Approaches

DCT is unique in providing a physical interpretation of the entropy prefactor, deriving a specific remnant mass, predicting computable echo amplitudes, and connecting BH physics to the Big Bang through the same P-field transition.

B. Open Questions

1. *Numerical profile:* Full integration of the coupled BD-GP system near the horizon.
2. *Kerr extension:* Angular momentum introduces superfluid vorticity.
3. *Charged BHs:* Charge involves θ-gradient $\leftrightarrow$ P-field interplay via the trace anomaly.
4. *Remnant stability:* Proof of absolute stability or decay timescale.
5. *Primordial BHs:* Constraints on PBH formation from remnant bounds.

TABLE VIII. Summary of DCT BH predictions.

Prediction	DCT Value	Test
T_θ/T_H	1.000 (exact)	Self-consistency
$S_{\rm BH}/S_{\rm Bek}$	$P_0 = 0.851$	Future QG
Echo delay ($10\, M_\odot$)	~0.6–18 ms	LIGO A+, ET
Echo reflectivity	$R \sim 0.0016$	ET, CE
Remnant mass	$\sim 100\, M_{\rm Pl}$	PBH searches
Singularity	$P = 0$ (no infinity)	Framework
Information	Conserved (θ-encoding)	Framework

TABLE IX. BH physics across quantum gravity programs.

	GR	Strings	LQG	DCT
Singularity	∞	Fuzzball	Bounce	$P = 0$
Entropy	$A/4\ell_P^2$	Microstates	Area quant.	$P_0\, A/4\ell_P^2$
Information	Paradox	Resolved	Partial	θ-encoded
Remnant	None	None	Planck star	$100\, M_{\rm Pl}$
Echoes	None	Model-dep.	Model-dep.	$R = 0.0016$

XIV. CONCLUSION

Black holes in DCT are phase boundaries of the cosmic BEC. The horizon is where $P = 1$ (maximum crystallization); the interior is where the crystal dissolves ($P \to 0$), the exact time-reverse of the Big Bang. The key results are:

1. $T_\theta/T_H = 1.000$—the condensate temperature exactly reproduces Hawking radiation.
2. $S_{\rm BH} = P_0 \times A/(4\ell_P^2)$—entropy reduced by 14.9% (crystallization fraction).
3. $M_{\rm min} \sim 100\, M_{\rm Pl}$—monochromatic, stable remnant from crystallization critical temperature.
4. Echo delay $\sim r_H \ln(r_H/\delta)/c$—testable with next-generation detectors.
5. Echo reflectivity $R \sim 0.0016$—from P-field sound speed ratio.
6. Singularity replaced by $P = 0$—topology change, not infinity.

7. Information paradox resolved—P-structure converts to θ-radiation.
8. Four laws recovered with crystallization interpretations.

Every result follows from $\Psi = \sqrt{P}\, e^{i\theta}$ and $P_0 = 0.851$. No new parameters are introduced.

Appendix A: Derivation of $P(r)$ for Schwarzschild

The BD field equation in vacuum ($T = 0$), for constant ω near P_0, linearizes to

$$\Box(\delta P) - m^2\, \delta P = 0\,, \tag{A1}$$

where $m^2 = V''(P_0)/(2\omega_0 + 3)$. The static spherically symmetric solution with $\delta P \to 0$ at infinity and $\delta P = (1 - P_0)$ at r_H is

$$\delta P(r) = (1 - P_0)\, \frac{r_H}{r}\, e^{-m(r - r_H)}\,. \tag{A2}$$

For astrophysical BHs with $r_H \ll 1/m$ ($1/m \simeq 64$ Mpc), the exponential is negligible and

$$P(r) \simeq P_0 + (1 - P_0)\, \frac{r_H}{r}\,. \tag{A3}$$

Appendix B: Acoustic Metric Details

The effective gravitational acceleration in the acoustic metric is $g_{\rm ac} = d(c_s^2 - v^2)/(2\, dr)$. At the sonic horizon ($v = c_s$ at $r = r_H$), with $P(r_H) = 1$:

$$\kappa_{\rm ac} = \frac{c^4}{4GM}\left[1 + \mathcal{O}\left(\frac{1}{\omega_0}\right)\right]. \tag{B1}$$

The leading term is exactly the GR surface gravity, confirming $T_\theta/T_H = 1$ to $\mathcal{O}(10^{-5})$.

Appendix C: Key Numbers

TABLE X. Key numerical values used in this paper.

Quantity	Symbol	Value
Parrott constant	P_0	0.851
BD coupling	ω_0	50,037
P-field mass	m_P	4.4×10^{-20} eV
Sound speed at P_0	$c_s(P_0)$	874 km/s
Sound speed at $P = 1$	$c_s(1)$	947 km/s
Speed ratio	$c_s(1)/c_s(P_0)$	1.084
Echo reflectivity	R	0.0016
Dissolved fraction	$1 - P_0$	0.149
Shannon entropy	$H(P_0)$	0.421 nats
Lattice modes	–	31
Remnant mass	$M_{\rm min}$	$\sim 100\, M_{\rm Pl}$
Critical temperature	T_c	$\sim 5.6 \times 10^{28}$ K

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