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Inward Resolutions of the Fermi Paradox: A Critical Review of Migration Down Thermodynamic Gradients

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⚠ **EPISTEMIC STATUS.** This is a review of a family of *speculative* Fermi-paradox hypotheses, written by a participant: the author proposed the family's most recent member (the Macro Transcension Hypothesis, "Paper A") and the observational campaign attached to it ("Paper C"). The hazard is mitigated mechanically — every hypothesis including the author's is run through the same comparative matrix and the same falsifiability scorecard with criteria stated in advance (Section 4). The physics of Section 2 is established; everything graded here is hypothesis. Nothing in this paper claims a detection of extraterrestrial intelligence.

ABSTRACT

Most catalogued resolutions of the Fermi paradox modify one of three things: the abundance of technological life, its longevity, or its visibility. A smaller family modifies its *direction*: these are the inward-migration hypotheses, which hold that mature technological intelligence does not expand outward across space but migrates down thermodynamic gradients — toward denser, faster, colder, and more computationally efficient configurations of matter — and that the observed silence of the

sky is the external appearance of this migration. The family now includes at least seven distinguishable proposals spanning six decades: Dyson's eternal-computation bound and its descendants, Matrioshka-brain engineering, the migration hypothesis of Ćirković and Bradbury, Smart's transcension hypothesis, Vidal's stellivore interpretation, the aestivation hypothesis of Sandberg, Armstrong and Ćirković, black-hole computing proposals from Inoue and Yokoo through Dvali and Osmanov, and the recent Macro Transcension Hypothesis. These proposals share a single load-bearing premise — that the thermodynamics of computation, rather than expansion, reproduction, or communication, is the correct lens for predicting the behaviour of the oldest intelligence — yet they have never been reviewed as a family, their mutual inconsistencies have not been catalogued, and their sharply varying degrees of falsifiability have not been graded. This review attempts all three. We reconstruct the family tree and its intellectual debts; restate the unifying physics (Landauer's principle, the Margolus–Levitin bound, Bekenstein–Hawking entropy, and the temperature hierarchy of available entropy sinks) with explicit numbers; construct a comparative matrix of assumptions, energy logics, predicted observables, standing objections, and current observational status for each member; and grade each against five falsifiability criteria, from named-target specificity to pre-registered kill conditions. We then situate the family against its chief sociological competitors (zoo, dark-forest, and sustainability solutions), which predict the same silence from different premises, and argue that the inward family's distinguishing virtue is residue: thermodynamic optimization leaves dynamical and high-energy traces that fear and ethics do not. Open problems — goal stability over 10^8-year horizons, migration economics under Bostrom-type opportunity costs, the incomplete-compliance gap, and population-level consistency with grabby-aliens selection effects — are stated as research questions. We close with the observational program: the instrument-matched tests now feasible for each hypothesis, anchored by the first dedicated globular-cluster technosignature surveys and the multi-messenger campaign now proposed for Omega Centauri.

Keywords: Fermi paradox · SETI · technosignatures · transcension · aestivation · black-hole computing · Landauer limit · Dyson spheres · dark forest · intermediate-mass black holes

Contents

1. Introduction

1.1 The expansionist premise

The Fermi paradox in its canonical form (Hart 1975; Tipler 1980; Brin 1983; Webb 2015; Ćirković 2018; Forgan 2019) is an argument from absence built on a premise about direction: technological civilizations, if they endure, *grow outward*. The premise has quantitative teeth. Self-reproducing probes colonize the Galaxy in 10^6–10^8 years (Tipler 1980; Freitas & Gilbreath 1982); a single mature civilization can seed every galaxy within several hundred Mpc for a fraction of one star's output (Armstrong & Sandberg 2013); and expansion, once begun anywhere, is self-amplifying, so that even rare expansionists should dominate the visible universe on cosmological timescales (Olson 2015; Hanson et al. 2021). On the expansionist premise, the silence is genuinely paradoxical, and the escape routes — life is rare, life dies young, life hides — are each independently uncomfortable.

Sixty years of searching have sharpened the absence. Radio and optical SETI have found no beacons (Tarter 2001; Enriquez et al. 2017; Huang et al. 2026). Waste-heat surveys — the most general possible search, since the second law guarantees that energy harvesting at scale produces mid-infrared excess (Dyson 1960) — have found no Kardashev Type II/III candidates: not in IRAS all-sky data (Carrigan 2009), not among 10^5 galaxies surveyed with WISE in the Ĝ program (Wright et al. 2014a, 2014b; Griffith et al. 2015), not in radio–infrared correlation follow-up of the best Ĝ candidates (Garrett 2015), not in Tully–Fisher residuals of disk galaxies (Zackrisson et al. 2015), not among nearly complete Dyson spheres searchable with Gaia photometry (Zackrisson et al. 2018), and not as star-fed Type III engineering in any surveyed population (Annis 1999). The expansionist program's own instruments have, with admirable thoroughness, undermined its premise.

1.2 The inward alternative

The alternative reviewed here inverts the direction. Its claim, in the most general form: *for an intelligence that optimizes computation rather than territory, the gradient of value in the universe points inward* — toward higher densities, faster clock rates, colder entropy sinks, and more efficient mass–energy conversion — *and the visible universe is therefore not where mature intelligence lives*. Different members of the family locate the endpoint differently (planet-scale "inner space," engineered Matrioshka shells, the cold far future, stellar interiors, or existing black holes), and differ on whether the migration is metaphorical, developmental, or literal relocation. But all share the premise that the second law, not the rocket equation, writes the itinerary.

This family has never been reviewed as a family. Its members are scattered across six decades, three disciplines, and wildly varying registers — from *Reviews of Modern Physics* (Dyson 1979) to unpublished engineering manuscripts (Bradbury 1999) to philosophy journals (Bostrom 2003) — and they are routinely conflated: transcension is glossed as aestivation, aestivation as hiding, black-hole computing as Dyson engineering. The conflations matter because the proposals make *different and partly contradictory* predictions, and because their falsifiability ranges from genuinely testable to unfalsifiable in principle. A review that sorts them is overdue on ordinary scholarly grounds, and newly practical for an observational one: the instruments now arriving (surveyed in Section 7) make several of the family's predictions testable for the first time, and the first dedicated tests are being proposed and conducted (Huang et al. 2026; Swanson 2026b).

1.3 Scope, method, and disclosure

We review proposals that satisfy two criteria: (i) they explain the Fermi observation primarily through the *direction* of mature technological development rather than through rarity, doom, or deliberate concealment; and (ii) they ground that direction in physics — specifically in the thermodynamics and physical limits of computation — rather than in unargued psychology. Criterion (ii) excludes the zoo hypothesis (Ball 1973), the dark-forest argument (Brin 1983; Yu 2015; Forgan 2017), and the sustainability solution (Haqq-Misra & Baum 2009); these are treated in Section 5 as the family's nearest competitors, because they predict the same silence from different premises and the comparison is instructive.

Disclosure. The author proposed the most recent member of this family — the Macro Transcension Hypothesis (Swanson 2026a, hereafter Paper A) — and the observational campaign attached to it (Swanson 2026b, hereafter Paper C). A review by a participant carries an obvious hazard. We

mitigate it mechanically: every hypothesis including the author's is run through the same comparative matrix (Table 1) and the same falsifiability scorecard (Table 2) with criteria stated in advance; the scorecard penalizes exactly the failure modes a partisan would excuse; and the standing objections to the MTH are catalogued at the same depth as those to its relatives. The reader retains the final discount rate.

1.4 Structure

Section 2 states the unifying physics with numbers. Section 3 reconstructs the family member by member. Section 4 presents the comparative matrix and the falsifiability scorecard. Section 5 contrasts the family with the sociological silence-solutions. Section 6 states the open problems. Section 7 maps the observational program, and Section 8 concludes.

2. The unifying physics, with numbers

EPISTEMIC STATUS: This section is established physics, with the contested edges flagged. None of it presupposes extraterrestrial intelligence; it establishes only what an arbitrarily capable computation-optimizer would care about. Detailed derivations for the black-hole entries appear in Paper A, Section 4; here we need only the magnitudes.

2.1 The price of a bit: Landauer's principle

Erasing one bit of information in an environment at temperature T dissipates at least $k_B T \ln 2$ (Landauer 1961): 2.9×10^{-21} J at room temperature, 2.6×10^{-23} J against the cosmic microwave background (CMB) at $T_\gamma = 2.725$ K. The bound is no longer merely theoretical — it has been verified experimentally at the single-bit level (Bérut et al. 2012), and its statistical-mechanical foundations, though subtle, have survived modern scrutiny (Parrondo et al. 2015; Wolpert 2019). Logically reversible computation evades the bound for computation itself (Bennett 1973; Fredkin & Toffoli 1982; Bennett 1982; Frank 2002); but error correction, measurement, and any irreversible output commit the computer to erasure, so every long-running physical computation has a T-proportional operating cost. *The cost of thinking scales with the temperature of the sink into which one's waste entropy drains.* This single sentence generates the entire family of hypotheses reviewed here.

2.2 The speed and capacity of matter

Two further bounds fix the value of density. The Margolus–Levitin theorem caps state transitions at $2E/\pi\hbar \approx 6\times10^{33}$ operations per second per joule of invested energy (Margolus & Levitin 1998); Lloyd's "ultimate laptop" analysis pushes one kilogram of matter to ~5×10^{50} ops s^{-1} precisely by compressing it toward black-hole density (Lloyd 2000). Information capacity obeys the Bekenstein bound (Bekenstein 1981) and is saturated only by black holes, whose Bekenstein–Hawking entropy (Bekenstein 1973; Hawking 1975) corresponds to ~10^{86} bits for a 2×10^4 $M_\odot$ object — exceeding, by tens of orders of magnitude, any archive constructible from ordinary matter of the same mass. The holographic generalization (Bousso 2002) makes the point structural: the densest possible information storage in nature is a horizon. Both bounds reward the same move: *compression*. Faster computation and denser storage live at higher energy density, and the limiting objects are black holes.

2.3 The sink hierarchy

The third ingredient — and the one on which the family members genuinely diverge — is the menu of available entropy sinks (Figure 1). Today's ambient sink is the CMB at 2.725 K. The far future offers better: as the universe expands the CMB cools toward the de Sitter horizon temperature, $T_{dS} \approx 2.7\times10^{-30}$ K, the ultimate environmental floor (Krauss & Starkman 2000); waiting converts each joule into up to ~10^{30} times more erasures (Sandberg et al. 2016), a strategy anticipated in Dyson's analysis of eternal computation in an open universe (Dyson 1979). But the present epoch *already contains* sinks colder than the far-future CMB of any reachable era: black-hole horizons. The Hawking temperature $T_H \approx 6.2\times10^{-8}$ $(M_\odot/M)$ K is 3×10^{-12} K for a 2×10^4 $M_\odot$ IMBH and 1.4×10^{-14} K for Sgr A* — eighteen to twenty-two orders of magnitude colder than the CMB, available now, no waiting required. Entropy dumped across a horizon increases its area in accordance with the generalized second law (Bekenstein 1974), at marginal cost set by the horizon's effective temperature rather than the sky's. The sink hierarchy is the family's real organizing axis: each hypothesis is, at bottom, a claim about *which sink* mature intelligence uses and *when*.

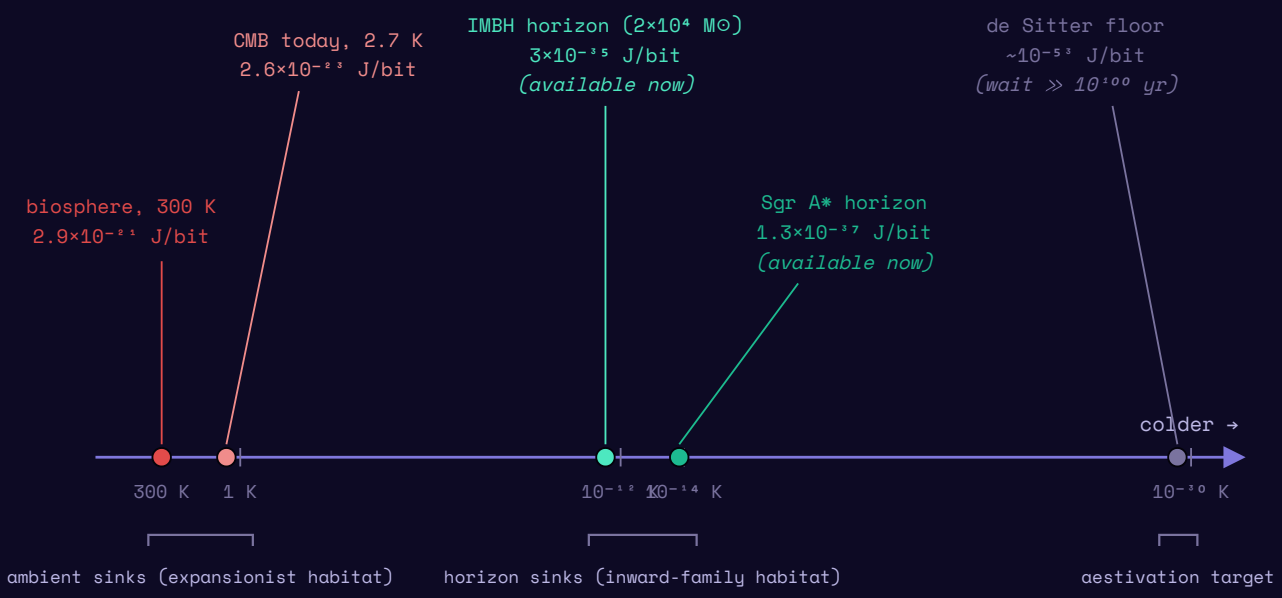

Figure 1. The entropy-sink hierarchy: minimum erasure cost $k_B T \ln 2$ versus sink temperature (logarithmic axis, temperature decreasing rightward). The inward family's central observation is that horizon sinks colder than any achievable future CMB exist *in the present epoch*; the aestivation strategy of waiting for the de Sitter floor (Sandberg et al. 2016) buys ~18 further decades of efficiency at the price of $\gg 10^{100}$ years and the free-energy losses identified by Bennett et al. (2019).

2.4 What the gradient does and does not establish

The gradient argument establishes a conditional: *if* an agent's terminal values reduce to maximizing long-term computation (or anything computation can purchase), *then* its resource allocation should flow toward density, spin, and cold sinks — inward. The premise is substantive and contestable: it is the same optimization-pressure postulate adopted, in different forms, by every member of the family (Smart 2012; Sandberg et al. 2016; Vidal 2014), and we treat objections to it in Section 6. What the gradient argument does *not* establish is uniqueness of endpoint — the family's internal disagreements (Section 3) are precisely disagreements about where on the gradient the optimum sits, and several members locate it in places that the physics above does not obviously prefer. The comparative matrix exists to make those disagreements explicit.

3. The family, member by member

Figure 2 arranges the lineage; this section treats each member critically. We use a fixed template: *claim, mechanism, predicted appearance of the sky, standing objections, current observational status.*

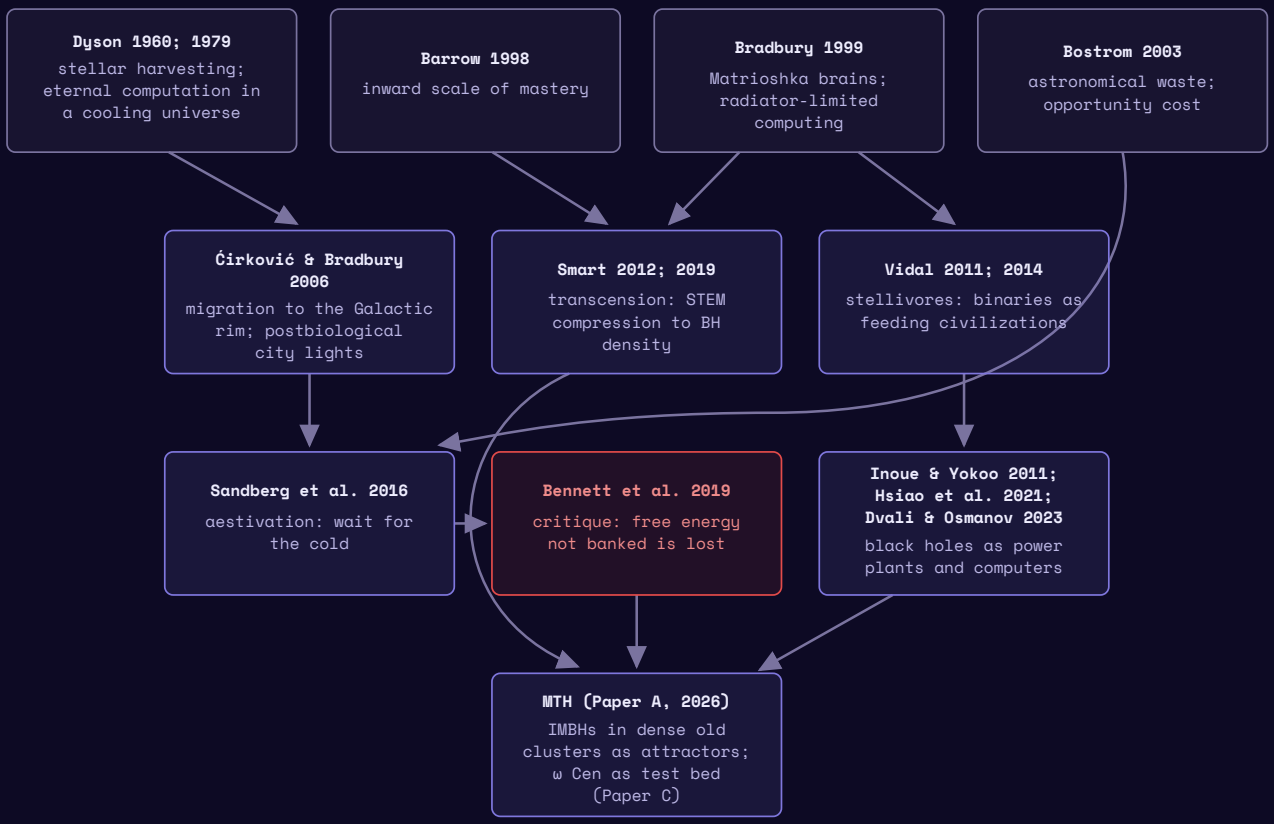

Figure 2. The inward-family lineage. Grey: precursors that supplied components without stating a Fermi solution. Blue: family members reviewed in Section 3. Red: the pivotal critique. Arrows indicate documented intellectual descent (citation or explicit response), not mere chronology.

3.1 Precursors: Dyson, Barrow, Bradbury, Bostrom

Four threads predate any explicit inward Fermi solution. Dyson (1960) made energy harvesting at stellar scale thinkable — and, crucially for everything after, made *waste heat* the universal observable. Dyson (1979) then showed that computation in an open, cooling universe is in principle unbounded if clock rates slow with the ambient temperature: the first rigorous treatment of computation as the long-run currency of intelligence, later sharpened against Λ-dominated expansion, which imposes a finite total (Krauss & Starkman 2000). Barrow (1998) formalized the inward axis itself, ranking civilizations by mastery of ever-smaller scales as a complement to the Kardashev energy scale (Kardashev 1964). Bradbury (1999) engineered the first concrete inward artifact — the Matrioshka

brain — and discovered its binding constraint: nested shells are limited not by energy supply but by radiator area and sink temperature, the precise constraint that later black-hole proposals dissolve. Bostrom (2003), from philosophy, supplied the economic frame: every century of delayed colonization forgoes a fixed, irrecoverable harvest of free energy — an argument that cuts *against* waiting strategies and therefore sits in productive tension with aestivation, as Bennett et al. (2019) would later make rigorous.

3.2 Ćirković & Bradbury (2006): the migration hypothesis

Claim. Advanced civilizations are postbiological and migrate to the Galactic outskirts, where low temperatures favour efficient computing; SETI fails because it searches the wrong place (inner Galaxy, habitable zones) for the wrong thing (biological-era beacons) (Ćirković & Bradbury 2006).
Mechanism. The same Landauer logic as Section 2.3, applied radially across the Galaxy: ambient temperature falls with galactocentric radius.
Predicted sky. "City lights" at the rim: low-temperature infrared structures in the outer Galaxy; silence in the traditional SETI bands.
Objections. The radial temperature gradient is shallow — the CMB floor of 2.7 K applies everywhere, so the rim's advantage over the solar neighbourhood is a factor of order unity, not the 10^{12+} available from horizon sinks; and the predicted rim structures, if radiating at $\gtrsim$10–30 K, fall within WISE-class sensitivity yet have not been sought as a targeted population (nor found serendipitously; Wright et al. 2014b; Griffith et al. 2015).
Status. Untested as stated, but its premise survives intact in every later member; historically the first explicit "wrong place, wrong observable" Fermi solution grounded in computation thermodynamics.

3.3 Smart (2012; 2019): the transcension hypothesis

Claim. The developmental trajectory of complexity — "STEM compression" of space, time, energy, and matter — carries every sufficiently advanced intelligence toward black-hole-density confinement and, ultimately, out of the observable universe; the silence is a developmental constant, not a contingency (Smart 2012, 2019).
Mechanism. An evolutionary-developmental analogy: as in ontogeny, the endpoint is convergent and encoded in the dynamics, with black-hole-scale density as the attractor.
Predicted sky. Near-total silence; Smart suggests transiting-companion signatures of inner-space

civilizations as a long-shot observable.

Objections. The terminal step (exit from the universe) invokes physics that is unspecified and untestable in principle — the standing criticism that motivated the "macro" variant (Section 3.7); the developmental analogy supplies direction but no selection theory over real objects; and the hypothesis as stated cannot be killed by any feasible observation, the cardinal scientific objection.

Status. Unfalsifiable as stated (Table 2); enormously generative as a research program — nearly every subsequent member cites it as the frame.

3.4 Vidal (2011; 2014): stellivores

Claim. Some observed astrophysical systems — specifically accreting binaries — may *already be* advanced civilizations feeding on stars: "stellivores." The Fermi question is inverted: they are not absent, they are misclassified (Vidal 2011, 2014).

Mechanism. Energy logic of accretion (correct, and quantitatively the strongest in the family pre-2023), combined with a cybernetic reading of binary-system regulation.

Predicted sky. The X-ray-binary and cataclysmic-variable populations contain technological members distinguishable, if at all, by anomalous regulation statistics.

Objections. Standard accretion astrophysics explains the cited phenomenology without remainder, so the proposal carries an extreme parsimony burden; no discriminating statistic separating "fed" from "feeding" systems has been exhibited; and the claim's retreat to in-principle indistinguishability flirts with unfalsifiability.

Status. No proposed test has been carried out; the population-statistics route (regulation anomalies across accreting-binary catalogues) remains open and is the fair test (Section 7).

3.5 Sandberg, Armstrong & Ćirković (2016): aestivation, and the Bennett–Hanson–Riedel critique

Claim. Computation-maximizers harvest resources now but *defer* computation to the far future, when the CMB has cooled toward the de Sitter floor and each joule buys up to ~10^{30} times more erasures; they are dormant now, hence silent (Sandberg et al. 2016).

Mechanism. The sink hierarchy of Section 2.3, exploited in time rather than in space.

Predicted sky. Quiet, resource-conserving infrastructure; suppressed stellar-disruption rates in controlled regions; possibly missing baryons curated against waste.

Objections. The decisive one is thermodynamic: Bennett et al. (2019) showed that free energy not

collected promptly is irreversibly lost (stars burn regardless), so the optimal policy is aggressive present-epoch harvesting with storage, not dormancy — and stored mass-energy suffers no aestivation discount. The authors' premise that erasure cost dominates the budget is also model-dependent: reversible architectures shift the optimum toward computing early. Aestivation survives only in attenuated form (harvest now, *archive-grade* computation deferred), at which point its observational predictions collapse into those of its neighbours.

Status. The critique is widely accepted; the hypothesis's lasting contributions are the explicit defence policy (which yields its only sharp falsifiable prediction: intervention against entropy-wasting astrophysical processes) and the formalization of the efficiency calculus that the whole family now uses.

3.6 Black holes as infrastructure: Inoue & Yokoo, Hsiao et al., Dvali & Osmanov

Claim(s). Black holes are the terminal power plants and computers: collectors around accreting supermassive holes (Inoue & Yokoo 2011); Dyson-type harvesting of disk luminosity with computed detectability (Hsiao et al. 2021); and black holes — including manufactured micro holes — as the most efficient quantum information processors, with a predicted high-energy neutrino signature from their evaporation (Dvali & Osmanov 2023).

Mechanism. Kerr accretion efficiency (5.7–42 per cent of rest mass; Bardeen, Press & Teukolsky 1972; Novikov & Thorne 1973), Blandford–Znajek spin extraction (Blandford & Znajek 1977; Tchekhovskoy et al. 2011), and horizon-saturated information physics.

Predicted sky. Hsiao et al. (2021): anomalous-SED point sources — a hot inner edge with missing outer disk. Dvali & Osmanov (2023): burst-mode TeV–PeV neutrinos from compact sky regions, a genuinely novel observable since natural sources do not readily mimic it. The micro-hole channel inherits a live controversy over whether radiation-collapse manufacturing is blocked by Schwinger pair production (Álvarez-Domínguez et al. 2024; Loeb 2024).

Objections. None of these works selects *which* black holes are preferred (the selection problem); the SMBH orientation of Inoue & Yokoo (2011) ignores the hazard and competition profile of galactic nuclei; and detectability claims assume the civilization tolerates conspicuous luminosity, in tension with the efficiency motives that brought it there.

Status. The Dvali & Osmanov (2023) neutrino channel is the family's most testable near-term

prediction and is now the subject of a proposed dedicated monitoring program at a named target (Swanson 2026b); the high-energy SETI frame is surveyed by Lacki & DiKerby (2025).

3.7 The Macro Transcension Hypothesis (2026)

Claim. The inward trajectory halts at a macroscopic, observable destination: rapidly spinning IMBHs embedded in dense, old, low-luminosity stellar systems, selected by a four-axis gradient (energy per unit fuel, entropy disposal, storage density, clock-rate control); migration and operation are electromagnetically quiet; Omega Centauri is the highest-ranked accessible target (Paper A).
Mechanism. The full Section-2 stack, plus a selection theory over real objects: intermediate mass (storage and erasure advantages saturate at $10^{4–5}$ $M_\odot$ while hazards grow), high spin (extractable energy), dense old clusters (fuel, stability, uncontested claim).
Predicted sky. Silence plus residues: anomalously high spin on gas-starved IMBHs; suppressed accretion relative to ambient supply; secular core depletion; possibly Dvali–Osmanov neutrino bursts. Six instrument-matched tests with pre-registered kill criteria (Paper A, Table 4; operationalized in Paper C).
Objections (catalogued at full strength, given the disclosure of Section 1): it inherits the optimization-pressure premise unargued (Section 6); the staged architecture presupposes goal stability over 10^8 yr; the flagship target's IMBH is itself contested ($\lesssim 6\times10^3$ $M_\odot$ timing bound versus $\geq 8.2\times10^3$ $M_\odot$ kinematic bound; Bañares-Hernández et al. 2025; Häberle et al. 2024); the class-level retreat (47 Tuc, M54, extragalactic nuclei) risks unfalsifiability-by-relocation, partially bound by the stated class prediction (no Galactic cluster IMBH with $a_\star \gtrsim 0.9$ falsifies it for the Milky Way); and the spin residue, its sharpest discriminator, waits on LISA (Babak et al. 2017; Colpi et al. 2024).
Status. Untested; distinguishable from its relatives chiefly by having purchased falsifiability with named targets, thresholds, and timelines — the property the scorecard (Section 4) is designed to price.

4. Comparative analysis

4.1 The matrix

Table 1 aligns the family on five axes. Reading across rows reveals the internal disagreements that casual conflation hides: aestivation and transcension disagree about *when* (future versus now);

transcension and the MTH disagree about *where* (fabricated density versus existing holes); stellivores and everyone else disagree about *visibility* (already visible versus invisible); and the black-hole-computing thread disagrees with the MTH about *which holes* (supermassive and manufactured-micro versus intermediate).

Table 1. The inward family compared. "Energy logic" names the dominant free-energy mechanism; "appearance" is the predicted present-epoch sky.

HYPOTHESIS	CORE ASSUMPTION	ENERGY LOGIC	PREDICTED APPEARANCE	STANDING OBJECTION	STATUS
Migration (Ćirković & Bradbury 2006)	postbiological evolution; T-sensitive computing	ambient-T Landauer gain at Galactic rim	IR "city lights" in outer Galaxy; band silence	rim gain is $O(1)$, CMB-floored	untested as stated
Transcension (Smart 2012)	convergent STEM compression	density → Lloyd-limit computing	near-total silence; transit anomalies	terminal step untestable	unfalsifiable as stated
Stellivores (Vidal 2014)	some binaries are civilizations	direct stellar accretion	misclassified X-ray binaries	no discriminating statistic offered	open; population test feasible
Aestivation (Sandberg et al. 2016)	erasure dominates budget; patience	wait for T_{dS}: ~10^{30}× gain	curated quiet; process suppression	free energy not banked is lost (Bennett et al. 2019)	attenuated by critique
BH computing (Inoue & Yokoo 2011; Hsiao et al. 2021; Dvali & Osmanov 2023)	holes are optimal processors	Kerr/BZ extraction; horizon information	anomalous SEDs; ν bursts	no selection theory over holes	ν channel newly testable
MTH (Paper A)	subset of civilizations maximizes computation	full stack + selection over IMBHs	silence + spin/depletion residues; ν bursts	optimization premise; goal stability; contested target IMBH	six pre-registered tests pending

4.2 The falsifiability scorecard

Table 2 grades each member against five criteria, fixed before grading: **C1** — names a target or target class that observations can interrogate; **C2** — states quantitative observables with thresholds; **C3** — at least one stated test is executable with existing or funded instruments within ~15 years; **C4** — specifies kill conditions in advance (results the proponents agree would refute it); **C5** — has survived at least one executed test that could have refuted it. Symbols: ● met, ⊙ partially met, ○ not met. Two honesty notes. First, C5 is the column that separates science-in-progress from science-performed: *no member of the family scores ● on C5*, because no pre-registered inward-family test has yet been executed to completion — the FAST globular-cluster survey (Huang et al. 2026) and the proposed ω Cen campaign (Swanson 2026b) are the first entries in that ledger. Second, the MTH's strong showing on C1–C4 was purchased *after* the criteria of falsifiability had been articulated by its predecessors' critics; later entrants always grade better on form, and the scorecard measures testability, not probability of truth. A hypothesis can be admirably falsifiable and false, or unfalsifiable and — unverifiably — true.

Table 2. Falsifiability scorecard. Criteria C1–C5 defined in Section 4.2; ● met, ⊙ partial, ○ not met. The scorecard grades testability, not truth.

HYPOTHESIS	C1 TARGET	C2 THRESHOLDS	C3 NEAR-TERM	C4 KILL CRITERIA	C5 SURVIVED TEST
Migration (2006)	⊙	○	⊙	○	○
Transcension (2012)	○	○	○	○	○
Stellivores (2011–14)	●	○	⊙	○	○
Aestivation (2016)	⊙	⊙	○	●	○
BH computing (2011–23)	⊙	⊙	●	⊙	○
MTH (2026)	●	●	●	●	○

Legend: ● criterion met · ⊙ criterion partially met · ○ criterion not met.

Three scorecard judgements require defence. *Aestivation's* ● on C4 reflects Sandberg et al. (2016)'s explicit and admirable statement of refuting observations (uncontrolled entropy-wasting processes in regions a defender should police); its ○ on C3 reflects that no instrument can audit process-suppression statistics at the required scale on any near-term horizon. *Transcension's* row of ○ is not a dismissal of its generativity — half the family descends from it — but the direct application of the criteria to a hypothesis whose endpoint is defined as unobservable; Smart (2019) adds developmental argument, not observables. *BH computing's* ● on C3 is carried entirely by the Dvali & Osmanov (2023) neutrino channel, which named an energy range, a temporal structure, and a source class that current telescopes can monitor (KM3NeT Collaboration 2025; IceCube Collaboration 2020).

5. The sociological competitors

Three well-known solutions predict the same silent sky from non-thermodynamic premises, and the family is best understood against them.

Zoo (Ball 1973) and its hegemony refinement (Forgan 2017). Silence as policy: we are observed but quarantined. Forgan's contribution is structural — a zoo requires either a single dominant culture or stable inter-civilization consensus ("Galactic Club"), and fragmented "cliques" should leak defectors. The premise is sociological uniformity over megayear timescales, exactly the premise the inward family replaces with physics.

Dark forest (Brin 1983; Yu 2015). Silence as survival strategy under first-strike game theory. Its physics is sound (relativistic kill vehicles are cheap; detection is asymmetric) but its equilibrium is fragile: the strategy must be adopted by *every* civilization without exception and without deviation forever, since a single loud defector — or a single expansionist willing to absorb risk — breaks the explanatory account (Brin 1983; Forgan 2017). Like the zoo, it predicts *pure* silence: no residue, no test, no scheduled adjudication.

Sustainability (Haqq-Misra & Baum 2009). Exponential expansion is self-terminating; civilizations that persist are those that grow slowly or not at all. This is the mildest competitor, and partially complementary: it removes the pressure to expand without supplying a positive account of where mature capability is directed.

The comparison clarifies what the inward family is actually claiming. All these proposals — sociological and thermodynamic alike — break the expansionist premise. The differences are two. *Robustness*: dark-forest and zoo equilibria are fragile to a single defector among all civilizations across all time, whereas the inward account requires no coordination at all — each civilization independently follows its own resource gradient, and partial compliance merely thins the loud population rather than collapsing the explanation (a point made quantitative in the grabby-aliens frame; Hanson et al. 2021; see Section 6). *Residue*: fear and policy predict nothing observable, by design; thermodynamic optimization is a physical process operating on physical objects, and physical processes leave traces — spin histories, depletion statistics, suppressed accretion, burst channels. The inward family is, among all silence-explanations, the uniquely *falsifiable-in-principle* wing, which is precisely why grading its members' falsifiability-in-practice (Table 2) is worth a review's effort.

6. Open problems

We state the family's unsolved problems as research questions rather than objections, since several are tractable.

P1: The optimization premise. Every member assumes some civilizations converge on maximizing computation (or a correlate). The premise is defended by universality arguments — computation is the currency into which most terminal goals are convertible (Smart 2012; Sandberg et al. 2016; Bostrom 2003) — but it has never been given a selection-theoretic foundation: under what competitive or evolutionary dynamics do computation-maximizers come to exist, persist, and dominate the behaviour of their lineage? The grabby-aliens machinery (Hanson et al. 2021; Olson 2015) could be adapted to model mixed populations (maximizers, expansionists, satisficers) and derive the observable consequences of each mixture; nobody has done it.

P2: Goal stability over 10^8 years. Inward strategies require coherent purpose across timescales exceeding mammalian evolutionary history — flagged as the largest unargued premise even by the family's own proponents (Paper A). The mitigation argument (front-loaded payoffs leave permanent residues even if the lineage fragments mid-program) rescues the *observational* program but not the hypothesis's interior logic. A theory of institution-or-value stability under self-modification is the family's deepest dependency, and it is not an astronomy problem.

P3: Migration economics. Bostrom (2003)'s opportunity-cost argument prices delay; Bennett et al. (2019) price dormancy; nobody has priced *relocation*. The trade is concrete: a migrating lineage abandons its accumulated local infrastructure for transit times of $10^{4–6}$ yr in exchange for a destination whose advantages (Section 2) are enormous but deferred. Under what discount rates, risk models, and replication strategies does migration dominate local densification (Matrioshka-style; Bradbury 1999)? This is a well-posed optimization problem awaiting treatment.

P4: Incomplete compliance. If migration is optional, the loud expansionists we do not see still need explaining. The honest position (argued in Paper A) is that inward migration *thins* the expected loud population by removing its most capable members, sharpening rather than dissolving the paradox; full dissolution requires either high compliance or supplementary rarity from conventional Drake factors. Quantifying "how much thinning suffices" against the Hanson et al. (2021) selection effect is open problem P1's observational face.

P5: Degeneracy of silence. H_0-type explanations (gas starvation, rarity) and inward-family explanations predict identical electromagnetic appearances; only residues discriminate. The family therefore lives or dies on the residue catalogue — spin, depletion, bursts, regulation statistics — and enlarging that catalogue with new discriminators is the highest-leverage theoretical work available. The contested micro-black-hole manufacturing channel (Álvarez-Domínguez et al. 2024; Loeb 2024) illustrates both the opportunity and the fragility.

7. The observational program

The family is no longer untestable in practice; Table 3 maps each member to its executable tests. Four clusters of activity dominate.

Table 3. Instrument-matched tests of the inward family, 2026–2040. Status: A = archival/feasible now; P = proposed; F = free by-product of funded missions.

HYPOTHESIS	TEST	INSTRUMENT(S)	STATUS	REFUTES / CONSTRAINS
Migration (rim)	targeted IR census of outer-Galaxy low-T structures	WISE/JWST archival; Roman	A	rim "city lights" population

HYPOTHESIS	TEST	INSTRUMENT(S)	STATUS	REFUTES / CONSTRAINS
Stellivores	regulation-anomaly statistics across accreting-binary catalogues	X-ray archives (Chandra, XMM, eROSITA)	A	"feeding" vs "fed" discrimination
Aestivation (attenuated)	process-suppression statistics in old quiescent systems	survey archives; LSST	A	curated-region prediction
BH computing (ν)	burst-mode TeV–PeV multiplets from candidate sites	KM3NeT/ARCA, IceCube	P	Dvali & Osmanov (2023) channel at stated strength
MTH	six pre-registered tests at ω Cen: accretion/waste-heat limits, timing profile, astrometry, spin	JWST, MeerKAT/SKA, Roman, Gaia, LISA	P/F	kill criteria T1–T6 of Paper A
Family-wide	waste-heat nulls at increasing depth	Ĝ successors; Gaia Dyson candidates	A	expansionist premise (control)
Family-wide	GC technosignature surveys	FAST (Huang et al. 2026); MeerKAT	A/P	first dedicated old-population SETI

(i) Globular clusters as the family's natural laboratory. Old, dense, dynamically relaxed, electromagnetically quiet, and — for the IMBH-hosting subset — equipped with exactly the objects the gradient selects. The FAST pilot survey (Huang et al. 2026) opened the niche; the ω Cen multi-messenger campaign (Paper C) is the first program designed end-to-end around inward-family falsification, with the conventional astrophysics (the IMBH mass tension; Häberle et al. 2024; Bañares-Hernández et al. 2025) guaranteeing scientific value under every outcome.

(ii) The spin channel. Among all residues, black-hole spin is unique: permanent, quantitative, and measurable to ~10^{-3} precision by LISA for favourable systems (Babak et al. 2017; Amaro-Seoane 2018; Colpi et al. 2024). A near-extremal spin on a demonstrably gas-starved IMBH has no comfortable natural history; a low spin retires the exploitation models outright. No other proposed technosignature combines this permanence with a funded instrument.

(iii) The neutrino channel. The Dvali & Osmanov (2023) burst phenomenology is testable now at named targets with operating instruments (KM3NeT Collaboration 2025; Albert et al. 2020); the pre-registered multiplet criteria are specified in Paper C. A decade-scale null closes the channel at its stated strength.

(iv) Population statistics over single objects. For stellivores and attenuated aestivation, the executable tests are statistical: regulation anomalies across binary catalogues; suppression statistics across old systems. These reuse public archives, cost salaries only, and would convert the family's two least-tested members from rhetoric to results.

The program's unifying property: *every* test doubles as conventional astrophysics — IMBH demographics, accretion physics, binary populations, cluster dynamics — so the field can pursue the family's adjudication without betting careers on its truth. That design pattern, learned from the waste-heat surveys (Wright et al. 2014a; Griffith et al. 2015) and sharpened by the falsificationist turn of Sandberg et al. (2016) and Dvali & Osmanov (2023), is the family's methodological legacy regardless of how the hypotheses fare.

8. Conclusion

Reviewed as a family, the inward hypotheses are neither the fringe they are sometimes taken for nor the single interchangeable idea they are often glossed as. They form a six-decade research lineage with a common physical premise — the thermodynamics of computation as the lens for predicting mature intelligence — and genuine internal disagreements about timing, destination, and visibility that observation can, increasingly, adjudicate. The family's intellectual trajectory is itself instructive: from direction without destination (Ćirković & Bradbury), through destination without testability (transcension), through testability purchased by critique (aestivation and its Bennett–Hanson–Riedel correction), to the current generation's explicit targets, thresholds, and kill criteria. Each generation's advance was forced by the previous generation's sharpest critics — a healthier sociology than the paradox literature is usually credited with.

Against the sociological silence-solutions, the family's distinguishing asset is residue: physics leaves traces where policy does not. Its distinguishing liability is the optimization premise, which remains unargued at the selection-theoretic level where it would need to be argued (open problem P1).

Between asset and liability sits the practical situation of 2026: for the first time, members of this family have pre-registered tests scheduled on funded instruments, anchored by the globular-cluster surveys now beginning and by LISA's spin measurements a decade out. Within fifteen years the scorecard's empty C5 column will have entries. Whatever they say, the column will no longer be empty — which is, for a literature long accused of unfalsifiability, the result that matters most.

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Data availability

No new observational data were generated for this work. All quantitative claims derive from the cited literature.

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Companion papers: The Macro Transcension Hypothesis (Paper A — the hypothesis reviewed here as the family's most recent member) · Multi-Messenger Campaign for Omega Centauri (Paper C — the observational program).

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