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Metastable Star Clusters as Resonant Entropy Nodes: A Realistic Alternative to White Holes

Abstract

Compact star clusters are proposed as metastable, resonant structures capable of redistributing mass and energy asynchronously across cosmic time and space. This paradigm treats clusters as “phase-critical” nodes under the Universal Threshold Adaptive Criticality (UTAC) framework and the Frame Principle, enabling entropy-stabilizing energy return flows without violating thermodynamics or causality. We model star clusters as logistic critical systems residing in metastable zones characterized by an optimal entropy offset (σ_Φ ≈ 0.0625) [1]. In contrast to classical white holes – hypothetical objects that eject matter/energy spontaneously [2] – clusters achieve similar outcomes via well-understood physical processes (stellar winds, supernovae, tidal ejections) that obey conservation laws. We integrate entropy flux considerations, including a characteristic integration velocity *v*_{RIG} from UTAC [3] and cross-domain β-clustering of critical transitions [4], to describe how clusters buffer and release energy. The model is compared to white hole scenarios in terms of plausibility and observational signatures. We outline falsifiable predictions: for example, distinguishing tidal stripping from intrinsic entropy-return flows in star clusters using Gaia-resolved tidal tails versus isotropic outflows, and identifying high-energy emissions associated with cluster-driven cosmic ray acceleration [5]. Observations from Gaia and JWST are discussed as tests of the model. We also draw analogies to neural systems (astrocytic buffering of signals) to illustrate how star clusters might serve as galactic “buffer” cells regulating mass-energy flow. The results suggest that compact star clusters could function as distributed, realistic analogues to white holes, temporarily storing and later releasing energy in a manner that stabilizes entropy over long timescales.

Introduction

In classical general relativity, a **white hole** is the time-reverse of a black hole: an object that can only emit matter and energy, never absorbing it [2]. While mathematically valid, white holes have never been observed, and their spontaneous ejection of low-entropy matter would challenge thermodynamics and causality. **Astrophysical systems, however, do exhibit “energy return” processes** that redistribute mass-energy in ways that might mimic some white hole effects without violating physical laws. Notably, compact star clusters concentrate large amounts of mass in a small volume and eventually disperse much of that mass and energy back into their surroundings through stellar evolution and dynamical processes. This raises the hypothesis that **star clusters act as metastable entropy-redistribution nodes**, smoothing out and delaying the return of energy to the environment rather than instantaneously ejecting matter ex nihilo.

To rigorously explore this idea, we employ the framework of **Universal Threshold Adaptive Criticality (UTAC)** [6], which models emergent transitions with logistic responses, and the **Frame Principle**, which ensures that physical processes are consistently described across reference frames and scales. In UTAC terms, a star cluster can be viewed as a system near a critical threshold: small perturbations can trigger large responses due to critical steepness (characterized by a steepness parameter β). We posit that clusters operate near a phase transition between bound and unbound states, akin to **phase-critical nodes**. The **metastable zone** of operation is quantified by an entropy signature σ_Φ ≈

0.0625, meaning the cluster maintains an “optimal entropy offset” – a delicate balance between order and disorder [1]. This value stems from a proposed universal signature (1/16) for living or resilient systems, with σ_Φ staying within a narrow tolerance (≈0.0525–0.0725) to sustain stability [7]. In essence, a long-lived star cluster might self-regulate to remain in this quasi-stable entropy range, much as biological or neural systems maintain homeostasis.

The **Frame Principle** is applied to reconcile how a cluster’s internal energy dynamics can be viewed in different “frames” – for example, the cluster’s self-gravitating frame versus the host galaxy’s frame – without paradox. Any energy released by the cluster (e.g. kinetic energy of ejected stars or gas) appears as an entropy increase in the galaxy’s frame, offsetting the local entropy reduction when the cluster formed. By tracking energy and entropy in the appropriate frame, we ensure no violation of thermodynamic accounting: the cluster is not creating energy from nothing (as a white hole effectively would), but rather **storing and releasing energy** in a time-distributed manner.

We also integrate **entropy flux considerations** from open systems theory. Star clusters receive inflows of low-entropy material (cold molecular gas forming stars, or accreted stars via mergers) and later output higher-entropy material (heated gas, cosmic rays, dispersed stars). The UTAC framework provides tools to model these flows via logistic equations and coupling terms. A specific parameter we use is *v*_{RIG} (“resonant integration velocity”), defined in our model as *v*_{RIG} ≈ 1.352 km/s [3], which links 2D surface processes to 3D volumetric responses. In physical terms, this could represent a characteristic speed of entropy propagation in the cluster’s core (on the order of a sound speed or orbital speed for dense systems). *v*_{RIG} is small compared to relativistic speeds, underscoring that any information/energy flow remains causal and sub-relativistic, consistent with cluster processes like sound waves or Alfvén waves distributing energy internally.

Another aspect from UTAC is **β-clustering** – the observation that critical transition steepness values tend to fall into certain bands for different domains [4]. For instance, many complex systems have logistic $\beta \approx 3.6$–4.8 [8], whereas gravitational systems on galactic scales might exhibit higher β (the UTAC constants table lists β ≈ 11 for cosmological structures like black holes) [9]. We will examine whether star clusters have a domain-specific β. A plausible expectation is that clusters, bridging stellar and galactic scales, might show intermediate β (perhaps analogous to biological scaling laws β ~7.4 [10] or something between stellar and galactic). Identifying a consistent β for cluster-critical phenomena (e.g. the threshold between a stable cluster and one that rapidly disperses) would support the idea of universal criticality at work. It would also make **falsifiable predictions**: if clusters truly operate at a critical point, we might observe bimodal behaviors (either relatively intact or rapidly dissolving) rather than a smooth continuum.

In the following, we develop a theoretical model of star clusters as metastable resonant systems (using UTAC and the Frame Principle), present observational evidence that motivates this model, construct a simulation framework to quantify entropy flows, and finally propose concrete predictions to test the hypothesis. Throughout, we draw interdisciplinary parallels – for example, comparing cluster-regulated energy flows to astrocytic buffering in neural networks – to illustrate the potential universality of these principles.

Theory: UTAC Model of Metastable Clusters

UTAC Framework and Logistic Criticality: In UTAC, systems near a critical threshold are described by a logistic activation function [6]:

$$\sigma(\beta(R-\Theta)) = \frac{1}{1+\exp[-\beta(R-\Theta)]},$$

where R is a control parameter (e.g. pressure, density or “resource” level), Θ is the threshold, and β is the steepness. A star cluster can be mapped onto this formalism by identifying a relevant control parameter and threshold. For example, R could represent the cluster’s **binding energy per unit mass** or central gravitational potential, and Θ a critical value where the cluster transitions from bound (ordered) to unbound (disordered). When $R < \Theta$, the cluster is strongly bound (activation ~ 0, indicating little mass loss); when $R > \Theta$, the cluster “tips over” into dispersal (activation ~ 1, indicating complete dissolution). The steepness β determines how sharp this transition is. We expect β to be high if the transition is abrupt – perhaps due to a runaway process like core collapse or rapid mass loss once a tipping point is reached. **Empirical UTAC studies find β typically of order 4–5 for many systems** [8], but gravitational systems can exhibit higher non-linearities. In our model, we will treat β as a parameter to tune and will later discuss how it might be constrained by data (see §Observational Evidence and §Modeling).

Phase-Critical Nodes and σ_Φ Metastability: The notion of star clusters as **phase-critical nodes** means that they operate at the edge of stability. In statistical physics terms, a globular cluster, for instance, might sit in a long-lived but metastable state, slowly evolving via two-body relaxation until a core collapse instability occurs. We associate this poised state with a specific **entropy fraction**. Following the UTAC “living crystal” hypothesis, we assume the **optimal entropy offset** σ_Φ ~ 0.0625 (i.e., 1/16) for a resilient metastable system [1]. Here σ_Φ can be defined as a normalized entropy: σ_Φ = *H*/*H*_{max}, where *H* is the system’s current entropy and *H*_{max} the maximum possible entropy (for a given number of components or “state space” size) [11] [12]. Intuitively, σ_Φ ~ 0.0625 indicates the system retains a high degree of order (only ~6.25% of the maximum entropy), yet it is not perfectly ordered (which would be 0%). This slight entropy allows flexibility and adaptation. For a star cluster, *H* could represent the phase-space entropy of its stars (taking into account positions and velocities). A very low entropy cluster would be a rigid crystal-like object (e.g., all stars on nearly identical orbits – highly ordered), whereas a very high entropy cluster would be a diffuse, unbound swarm (chaotic and thermalized). The metastable cluster lies in between – mostly ordered but with enough internal “noise” to adapt to perturbations. This resonates with the concept of **criticality** in complex systems, where systems poised near critical points can respond to inputs in a maximally flexible way. By maintaining σ_Φ in the narrow band ~0.0625 ± 0.01, a cluster avoids both “crystal death” (too ordered to evolve) and “thermal chaos” (too disordered to stay bound) [13].

Mathematically, if we model the cluster’s entropy over time, σ_Φ should remain roughly constant in a metastable epoch. Only when external perturbations or internal evolution push the cluster out of this range (e.g., increasing entropy beyond ~0.07) does the cluster likely undergo a phase transition (disintegration). **The Frame Principle** ensures we evaluate this criterion in the correct context: the entropy here is the cluster’s *self-entropy*, not including the entropy of radiation or matter it ejects into the galaxy. In the galaxy’s frame, the cluster’s formation initially *decreased* local entropy (gas to stars), but later the cluster’s dissolution returns entropy to the environment, balancing the cosmic ledger. Our approach keeps track of entropy in each frame separately to ensure the Second Law holds globally.

Resonant Structure and Energy Redistribution: We describe star clusters as **resonant systems** in two senses. First, internally, clusters can support resonant modes (e.g., oscillations in the core-halo structure). For instance, gravothermal oscillations observed in some core-collapsed clusters indicate repeated cycles of contraction and re-expansion of the core – a resonance between heating (from binary stars or dark remnants transferring energy outward) and cooling (core collapse increasing binding, then binaries heat it again). These oscillations could enable clusters to intermittently release energy rather than all at once. Second, a cluster orbiting in a galaxy can resonate with tidal fields. If the cluster's orbital period or internal dynamical timescale is commensurate with external perturbations, it might preferentially lose stars at specific orbital phases (similar to resonant stripping). **UTAC's coupling term** $\mathcal{M}[\psi, \phi]$ in the logistic equation [14] can represent this interaction between the cluster's internal field (ψ) and external tidal field (φ). In our logistic model equation (a simplified form of UTAC's membrane equation [15]), we might add a term $+\mathcal{M}[\text{cluster}, \text{galactic tide}]$ that spikes when the cluster is at pericenter of its galactic orbit, for example, to simulate stronger mass loss at that point.

Incorporating v_{RIG} and β-Regimes: The parameter *v*_{RIG} introduced earlier is conceptually the speed at which information (or a perturbation) integrates from a 2D surface to a 3D volume [3]. If we imagine a cluster undergoing an influx or outflux of energy, *v*_{RIG} could correspond to how fast the cluster's core responds to changes in its halo or environment. Interestingly, the numerical value *v*_{RIG} ≈ 1.35 km/s is on the order of the internal velocity dispersion of a loose open cluster or the sound speed in a cool molecular cloud. This suggests it might be a natural feedback speed – perhaps related to the **Group velocity of pressure waves** or the drift speed of stars slowly evaporating from the cluster. In our model, we ensure that any presumed "return flow" of energy from cluster to environment does not exceed *v*_{RIG} in terms of propagation, aligning with causality (no instantaneous large-scale coordination – changes diffuse out at ~km/s speeds or less).

As for **β-regimes**, UTAC posits that different scales cluster around characteristic β values [4]. We hypothesize that **star clusters fall into a specific β regime** that can be tested. If, say, multiple clusters show a common critical exponent in their mass-loss behavior, that would hint at an underlying universality. For example, there may be a critical cluster mass or density beyond which the cluster's mass loss rate accelerates dramatically (a threshold effect). If the steepness of that acceleration is similar across clusters of various sizes, it implies a universal β. UTAC constants list a few intriguing β: ~4.5 for information systems, ~7.4 for biological (perhaps related to 3/4 power laws), and ~11 for cosmological (holographic scaling for black holes) [16] [9]. Star clusters might bridge the gap: they are astrophysical but not as extreme as black holes. It wouldn't be surprising if **β ~ 7–8** emerges for critical cluster phenomena, aligning with the idea that clusters could adhere to volumetric scaling laws like stars (which often follow 3/4 power laws in metabolic scaling contexts, analogous to cluster luminosity or feedback scaling with mass). In absence of direct evidence for a specific value yet, we treat β as a free parameter but constrain it in simulations to see how cluster behavior changes (discussed in §Modeling).

Analogy to Neural Systems: As an interdisciplinary aside, we draw an analogy between star clusters in galaxies and **astrocytes in neural networks**. Astrocytes are glial cells that do not carry electrical impulses like neurons but modulate and buffer the neurotransmitters and ions in the synaptic environment. They soak up excess neurotransmitters and release them slowly, preventing either a complete quench or runaway excitation in neural circuits. Similarly, a **star cluster might buffer "astrophysical signals" (mass-energy)**: when a burst of star formation occurs, a cluster forms (accumulating mass, reducing entropy locally), then over a long time it releases gas, dust, even high-energy particles. This prevents the galaxy from immediately heating all that gas (some is locked into stars for millions to billions of years), yet eventually the energy finds its way out as starlight, supernovae, and expelled material. The cluster thus acts like a galactic capacitor or buffer, analogous to astrocytic regulation. This analogy, while not part of the formal model, is useful to conceptualize how such a system can stabilize the larger environment's entropy budget.

Summary of Theoretical Framework: We have constructed a picture where compact star clusters are modeled as critical, metastable systems under UTAC. They sit at a threshold (phase-critical point) with a characteristic entropy fraction σ_Φ ~ 0.0625, can respond resonantly to internal/external stimuli, and redistribute energy on delayed timescales. The Frame Principle ensures consistency in energy accounting between the cluster and its environment, so no physical laws are broken even as the cluster mimics a “white hole” by eventually ejecting what it earlier absorbed. Next, we turn to observational evidence that supports or inspires these concepts, before developing a quantitative model and code.

Observational Evidence

Stellar Feedback and Energy Outflows from Clusters: Young massive star clusters are known to be sources of intense feedback – stellar winds, radiation, and supernovae emanating from a compact region. Recent studies have quantified how significant this energy input is. For instance, *Celli et al. (2024)* analyzed hundreds of Galactic open clusters (age < 30 Myr) using Gaia data and found that **cluster winds can carry enormous power**, with wind luminosities up to ~3×10^38 erg/s [5]. This rivals the kinetic power of a supernova explosion occurring every few 10^5 years. Crucially, the study notes that such **cluster wind energy could efficiently accelerate cosmic rays** [17] [5]. In other words, clusters might act as “cosmic engines” pumping high-energy particles into the galaxy. This is a concrete example of an entropy-redistribution flow: the cluster converts the gravitational potential energy (low entropy, ordered in star formation) into kinetic energy and cosmic rays (high entropy, dispersed). The fact that many clusters contribute to this and that the distribution of wind power extends to very high values [5] suggests clusters collectively have a galaxy-wide impact. Instead of a single white hole pouring out matter, we have many clusters injecting energy in a distributed way. Importantly, none of this violates physics – massive stars blow winds because of radiation pressure and line-driving, all well within known processes. Yet the **cumulative effect** is a net return of energy (and mass in the form of wind ejecta) from the cluster back to the interstellar medium (ISM). This supports our view of clusters as **entropy stabilizers**: they temporarily lock matter into stars (reducing entropy as the gas cools and condenses), then over the cluster’s lifetime return that matter in a heated, diffuse form (increasing entropy in the ISM). Observationally, this is seen in **X-ray emitting gas bubbles** around young clusters and increasing metallicity of surrounding gas due to supernova yields – evidence that clusters disperse their material and energy.

Furthermore, if clusters accelerate cosmic rays, there’s an implication for entropy flow on larger scales: cosmic rays propagate and can eventually escape the galaxy, carrying energy with them. A hypothetical white hole might dump energy into the universe arbitrarily; star clusters, by contrast, channel a portion of their energy into cosmic rays which could leave the galaxy, effectively distributing energy on intergalactic scales. This is speculative but not implausible – indeed **gamma-ray observations have hinted that star-forming clusters (like Westerlund 1 and 2, or 30 Doradus) are associated with TeV gamma-ray sources**, consistent with particle acceleration in cluster environments. Our model would predict such associations as a natural outcome (see §Predictions).

Tidal Tails and Mass Redistribution: As star clusters age, many do not remain bound forever. Both internal processes (two-body relaxation, mass loss from stellar evolution) and external tidal forces gradually unbind clusters. The debris of clusters – stars that have escaped – often forms **tidal tails** stretching out along the cluster’s orbit. Gaia has revolutionized our ability to detect these sparse tidal tails in the Milky Way. A recent survey of Gaia Early Data Release 3 by Tian et al. (2023) found **at least 72 open clusters with tidal tails** in the solar neighborhood [18]. These structures are direct evidence of clusters **redistributing their stars (mass) into the galactic field over time**. For example, the Hyades, the nearest open cluster, was shown to possess elongated tidal tails extending hundreds of parsecs [18], containing stars that used to be part of the cluster. The **degree of asymmetry** in leading vs. trailing tails can inform the mechanism of mass loss. Gaia data revealed that clusters like Hyades, Praesepe, Coma Berenices, etc., have asymmetric tails (one arm might be more populated than the other) [19]. This is interpreted as the result of **Galactic tidal forces and the cluster’s orbital motion** – a cluster loses stars more easily on the side facing Galactic rotation (trailing or leading depending on orbit) due to Coriolis and tidal effects.

From our model perspective, these observations highlight a key point: **external tidal stripping** is a significant channel of cluster mass redistribution (entropy increase in the galaxy). However, it's an asynchronous process – it happens gradually as the cluster orbits over hundreds of Myr. This asynchrony matches our hypothesis of clusters as delayed distributors. If clusters simply blew apart (like an instantaneous white hole explosion), we wouldn't see well-defined tidal streams; instead we'd see a more isotropic dispersion with no coherence. The presence of long tails aligned with past orbits shows the cluster's breakup is a slow, dynamical process shaped by gravity – consistent with metastability being lost gently rather than in a violent singular event.

Dynamical Ejections of Massive Remnants: A striking example of clusters returning mass to the galaxy involves heavy stellar remnants. The recent discovery of **Gaia BH3**, a 33 M⊙ black hole in a wide binary, provides insight [20] [21]. This black hole is the most massive stellar black hole found in the Milky Way and it appears to reside in a **stellar stream** (ED-2) that is likely the remains of a disrupted globular cluster [21]. The authors studying Gaia BH3 concluded that the black hole likely formed in a dense cluster environment and was **dynamically ejected or released when the cluster was torn apart** [22]. The fact that such a massive black hole "survived" and is now free-floating in the galactic halo is remarkable – it's a form of mass (and gravitational potential energy) that has been redistributed far from its origin. In a sense, the **cluster acted as an incubator for an object that is now contributing to the galaxy's mass budget elsewhere**. This is again a process that unfolds over billions of years (the progenitor cluster was ancient, >10 Gyr [23]). It's asynchronous and metastable: the cluster held onto its black holes for most of its life; only late in its life (or at its end) were these massive objects released. We can think of the cluster as a **container of low-entropy nuggets (black holes)** that eventually releases them into a higher-entropy configuration (widely dispersed in the galaxy). Gaia BH3's existence in a tidal stream confirms the connection between cluster disruption and field objects [21]. It also provides a falsifiable point: if our model is correct, we should expect more cases of massive remnants being liberated by cluster dissolution (Gaia DR4 and DR5 may find dozens of dormant black holes in streams [24]). If instead massive black holes are rarely found in tidal streams, that might mean clusters typically retain or remove them via mergers (contrary to a distributed return flow). Current evidence, however, is aligned with clusters contributing to the field population of exotic objects.

Multiple Populations and Internal Recycling: Globular clusters famously host **multiple stellar populations (1P, 2P, etc.)** with distinct chemical abundances. This implies some of the gas ejected by the first generation of stars was retained and used to form a second generation – an internal recycling of matter. Recent high-resolution simulations by Lahén et al. (2024) support this scenario: **massive clusters in a dwarf starburst trapped stellar wind material and formed new stars enriched in that material within a few Myr** [25] [26]. In their simulation, the fast winds of very massive stars ($\gtrsim$100 M⊙) did not escape the cluster's gravitational well; instead, the ejecta cooled and accreted onto the cluster, creating a more metal-rich second generation of stars. This process was efficient for winds, whereas supernova ejecta (which carry more energy) were mostly lost – "supernova-material is very inefficiently recycled" but "**stellar wind-material is trapped in massive clusters**" [27] [26]. This finding has two important implications: (1) Clusters can act as **entropy buffers even for their own feedback** – they temporarily hold onto the energetic wind gas, effectively delaying its release into the wider galaxy. Only later, perhaps when the cluster mass drops or winds abate, will that material escape. (2) The outcome of this internal recycling is the creation of new, enriched low-entropy structures (stars) from the high-entropy gas – a local entropy reduction – *followed by* eventual entropy increase when those stars later die or the gas leaks out. Observationally, the multiple populations in globular clusters (with enrichment in N, Na, Al etc.) [28] [29] are evidence that such a two-phase process happened in real clusters early on. The second-generation stars are centrally concentrated in simulations and scale with cluster mass (more massive clusters hold more wind ejecta) [26]. Eventually, to reconcile with today's observations, a fraction of stars (especially 1P) must have been lost from clusters over time [30] – again supporting extensive **mass loss over time**.

This internal cluster phenomenon ties into our model by showing **resonant or repeated cycles of entropy flow**: first generation injects energy (winds), cluster core absorbs it and produces second generation, later supernovae or mass loss will expel the combined material. It's as if the cluster had a built-in feedback loop that moderated how quickly the energy was released – much like an astrocyte cell buffering a surge of neurotransmitter, the cluster buffered the wind ejecta surge.

Early-Universe Clusters Shaping Galaxies: JWST has provided glimpses of galaxies in the early universe (within a few hundred Myr after the Big Bang) and found them teeming with star clusters. Mowla et al. (2024) report a galaxy at $z \approx 8.3$ (just 600 million years old) whose stellar mass is dominated by **10 compact star clusters accounting for ~50% of the galaxy's mass** [31]. Each cluster is ~10^5–10^6 $M_\odot$ and extremely dense (>10^3 $M_\odot$/pc^2), exceeding the density of any globular clusters today [32]. This observation – nicknamed the "Firefly Sparkle" galaxy – demonstrates that **star clusters were fundamental building blocks of galaxies** [33]. The clusters in that high-redshift galaxy presumably will merge and/or disperse to form the bulk of the galaxy over time. This is an ideal example of asynchronous mass distribution: the galaxy didn't form smoothly; it formed in clumpy bursts (clusters) which then **redistribute their mass** into a more diffuse galaxy structure over cosmic time. The fact that half the galaxy's mass is in clusters means those clusters will likely merge or evaporate, injecting their stars into the galaxy's field later. It also underscores the **resonant nature**: these clusters might merge with each other (a resonance between nodes) or interact via their combined potential. The **Frame Principle** perspective here is that what we call a "galaxy" at early times is essentially a frame holding multiple cluster substructures – one could almost treat each cluster as a "white hole candidate" spitting out stars later, except they're physically just normal clusters obeying gravity. JWST's spectroscopic data even hints at a top-heavy IMF in the central cluster [34], which would lead to more massive stars and hence stronger feedback. This could accelerate the clusters' ability to disperse their gas (perhaps these early clusters had short lifetimes as bound entities due to intense feedback). The *Firefly* galaxy and similar findings [35] [36] serve as **empirical support for our model on a cosmological scale**: galaxy evolution can be viewed as the formation and metastable existence of star cluster "nodes" followed by their dissolution or coalescence, thereby distributing matter and energy.

In summary, observations across scales – from local clusters losing stars and gas, to clusters birthing cosmic rays, to ancient clusters seeding the halo with black holes, to protogalaxies composed of super clusters – all reinforce the concept that star clusters are **transient repositories of low entropy that later release their contents**. No exotic physics is needed to explain these; we see the processes directly or via their remnants. This bodes well for the idea that star clusters could indeed act as "distributed white holes" in effect. Next, we proceed to model these ideas with a computational approach, making the concepts quantitative.

Modeling and Simulation

To formalize the above ideas, we construct a simple model using the Feldtheorie/NeuroProfile architecture (an open-source framework for UTAC-based analysis). Our goals are to **simulate entropy flow metrics** in a cluster and to **analyze observational-like inputs** such as time series of cluster mass or energy output. The model will illustrate how a cluster might maintain metastability (σ_Φ ~ 0.0625) and when it transitions to dispersal, as well as how one could extract the β parameter from data.

Model Setup

We represent a **cluster's state** by a small set of variables: e.g. total bound mass *M(t)*, core radius *r_c(t)*, and perhaps a measure of energy output *E_{out}(t)* (from winds/supernovae). The cluster is considered metastable as long as *M* stays above a critical fraction of the initial mass and *r_c* does not run away to large values. We include a **logistic trigger** for mass loss: when some stress exceeds a threshold, the mass loss rate increases sharply (simulating a critical event like core collapse or tidal shock).

We also implement the **σ_Φ metric**: given the distribution of stars or energies, we compute σ_Φ = H/H_max. For simplicity, one can treat H as the information entropy of the stellar velocity distribution or spatial distribution. In code, we may use the spectral entropy of a time series as a proxy (as done in NeuroProfile).

Finally, we allow an external tidal field to influence the cluster periodically (mimicking an orbit). The tidal field adds to the control parameter R in the logistic model at each pericenter.

Simulation Example

Below is a pseudocode snippet that demonstrates core pieces of this simulation using the **Feldtheorie/NeuroProfile** tools. It sets up a logistic response for cluster mass, checks the σ_Φ value, and estimates the β steepness from synthetic data. Comments in the code explain each step:

```
# Pseudocode for cluster entropy-flow simulation
from feldtheorie.utac import utac_activation, calculate_sigma_phi, is_alive
from feldtheorie.neuroprofile import NeuroProfileModel,
estimate_beta_from_series

# Define cluster parameters for simulation
Theta = 0.5   # threshold (e.g., critical mass fraction at which cluster
disrupts)
beta_true = 5.0   # steepness for logistic mass loss transition (unknown a
priori)
M0 = 1.0     # initial normalized cluster mass (1.0 = 100%)
t_max = 100  # simulate 100 time units (e.g., Myr)
dt = 1.0

# External tidal forcing (e.g., simple periodic shock)
orbital_period = 20
tidal_strength = 0.2  # how much the tidal field pushes R over threshold at
pericenter

# Arrays to store simulation outputs
M = M0
mass_history = []
sigma_phi_history = []

for t in range(int(t_max/dt)):
    # Compute control parameter R (e.g., remaining mass fraction)
    R = M / M0  # fraction of initial mass still bound
```

```
    # Include periodic tidal effect (spikes R when t is multiple of period)
    tidal_factor = tidal_strength if (t % orbital_period == 0 and t > 0) else 0.0
    R_effective = R + tidal_factor

    # Logistic activation: fraction of cluster mass lost this step
    loss_fraction = utac_activation(R_effective, Theta, beta_true)
    dM = - loss_fraction * M  # mass lost in this timestep
    M += dM
    M = max(M, 0.0)  # mass can't go below 0

    # Calculate sigma_phi (entropy fraction) proxy from mass distribution
# Here we use a simple proxy: if cluster still has >Threshold mass, treat it as ordered (low entropy)
    entropy = 0.0 if M/M0 > Theta else 1.0  # simplistic entropy: low until disruption
    sigma_phi_val = calculate_sigma_phi(entropy, max_entropy=1.0)  # normalize (max_entropy=1.0 for this proxy)

    # Store history
    mass_history.append(M)
    sigma_phi_history.append(sigma_phi_val)

    # Check if cluster is in "living" metastable zone
    if is_alive(sigma_phi_val):
        status = "metastable"
    else:
        status = "dispersing"
    # (In a real simulation, we could implement different dynamics once dispersing)

# After simulation, analyze results
model = NeuroProfileModel()
# Preprocess mass history to remove trend and estimate spectral entropy as sigma_phi proxy
normalized_series = model.preprocess(mass_history)
sigma_phi_est = model.estimate_sigma_phi_proxy(normalized_series)
beta_est = estimate_beta_from_series(normalized_series)

print(f"Final bound mass fraction: {M:.2f}")
print(f"Estimated sigma_phi from simulation: {sigma_phi_est:.3f}")
print(f"Estimated beta from simulation: {beta_est.value:.2f}")
```

In this pseudocode, we simulate a cluster starting with full mass *M0*. The `utac_activation` (logistic function) decides the mass loss rate at each step. We included a **tidal shock every 20 time units** that effectively raises R (stress) and triggers extra mass loss. We also compute a very naive entropy proxy (in reality we'd derive entropy from velocity-space or similar, but here just as a placeholder). The `is_alive` check uses the Feldtheorie criterion for σ_Φ being in [0.0525, 0.0725] to decide if the cluster is still in the "living" zone [13] [37].

After the loop, we use NeuroProfile's analysis to get a more data-driven estimate of σ_Φ (via spectral entropy of the mass time series) and an estimated β from the series (perhaps by fitting a logistic curve or other models). This kind of analysis mimics how we would treat **observational data** – for example, if we have a time series of cluster mass (or some proxy, like number of stars bound) from an N-body simulation or a sequence of snapshots, we could try to extract whether a logistic transition occurred and what β was.

Results of Simulation (Hypothetical)

If we run a simulation like this (with, say, β_true = 5, Θ = 0.5), we expect the cluster to lose mass slowly at first (as long as R_effective < Θ, utac_activation is small). Once the cluster mass drops below ~50% (especially if aided by a tidal shock pushing R_effective over Θ), the mass loss accelerates dramatically – the logistic curve turns on – and the cluster quickly disperses. The σ_Φ value would start near 0 (very ordered) and remain low while the cluster is mostly intact. As the cluster approaches the critical point, σ_Φ would rise, and once dispersal begins, σ_Φ would shoot up (indicating disorder). The model's `is_alive` flag would flip from true to false around that point.

This behavior encapsulates **metastability followed by a critical transition**. The timing of the transition might depend on the stochastic tidal hits in our simple model. In a more sophisticated model, it could depend on internal relaxation times (we could include a slow secular mass loss even without tides, representing evaporation).

By analyzing the output, we could obtain a **fitted β** (say the code's `estimate_beta_from_series` finds β ~ 4–6 with some confidence interval, matching the true value) and a σ_Φ proxy ~ maybe 0.06 during the stable phase. We would also compare alternative models to ensure this logistic-critical model is justified – e.g., check that a simple linear or power-law mass loss model fits much worse (NeuroProfile's `null_model` AIC comparisons do that implicitly).

The above pseudocode and its explanation would be part of our open-science approach: we can publish this model and code so others can reproduce and test various scenarios (e.g., change β, include multiple threshold stages for multiple populations, etc.). The flexibility of the UTAC approach means one can, for example, add an **adaptive threshold** Θ(t) if the cluster has self-regulation (UTAC suggests thresholds can shift with context [38]). A cluster could raise its own threshold if, say, contraction increases binding energy (making it harder to disrupt) until a point when fuel is exhausted. We did not implement that here, but the framework allows it.

Predictions and Tests

A compelling scientific hypothesis must yield falsifiable predictions. Here we outline several predictions that arise from treating star clusters as metastable resonant entropy-redistribution structures, and how observations could confirm or refute them:

- **Tidal Tail Morphologies – Stripping vs. Isotropic Outflows:** If external tidal stripping is the dominant mechanism (the "classical" view), then we expect **tidal tails aligned with orbital paths**, often with asymmetries (e.g., one tail longer due to Galactic rotation) [18]. If, however, clusters can also eject stars through internal processes (e.g., a rapid gas blowout or resonant mass shedding not strictly tied to orbit), we might observe more **isotropic or randomly oriented distributions of former members** around some clusters. *Prediction:* Identify clusters (perhaps in low tidal-field environments like galaxy halos or dwarf galaxies) and check if their lost members form coherent tails or more spherical halos. A cluster acting like a mini white-hole analog might show a **spherical "evaporative halo" of stars** instead of narrow tails. Gaia's upcoming data releases and all-sky cluster catalogs [39] can be used to systematically search for such patterns. If none are found – i.e., if every cluster with lost members shows tidal tails consistent with external stripping – that would indicate external processes dominate and there's little intrinsic "entropy release" in an isotropic sense. If some clusters do show isotropic evaporation (perhaps in environments where external tides are negligible), that would support our model's idea of internal asynchronous mass shedding.

- **Temporal Delay between Star Formation and Energy Return:** In our scenario, star clusters **delay energy return** (e.g., keeping supernova ejecta confined for a while, or not releasing all their stars at once). A prediction here is that **young starburst regions should show less immediate heating of the ISM than naive models predict**, because a lot of energy is temporarily locked in clusters. This could be tested by looking at, say, a starburst galaxy and comparing the kinetic energy in expanding shells to the expected supernova energy output – if clusters retain some energy, the observed kinetic energy might be lower, with the remainder coming out later (perhaps as cosmic rays or delayed wind after cluster dispersal). Another test: look at the multi-phase ISM around young clusters with JWST and ALMA. If clusters trap wind material as in Lahén et al. 2024, we might see **cold pockets of enriched gas in cluster cores** that only later leak out. JWST's mid-IR spectra or ALMA mapping of molecules could catch this. *Falsifiable outcome:* find evidence of enriched material still in clusters (support) or find that all enriched ejecta are already mixed in the ISM even around the youngest clusters (challenge to the model).

- **High-Energy Emissions from Clusters:** If clusters are acting as distributed energy sources, a clear prediction is **gamma-ray and neutrino emissions** from cluster regions, due to cosmic ray acceleration in cluster winds and supernovae [40] [5]. This is partially already supported (the starburst cluster Westerlund 1 is associated with a TeV source). We predict that *for the most massive young clusters*, their wind luminosities (10^38 erg/s range) [41] produce detectable gamma rays (in the GeV–TeV range) via hadronic interactions in the wind or inverse Compton scattering of the intense radiation fields. The upcoming Cherenkov Telescope Array (CTA) and advanced neutrino telescopes (IceCube-Gen2) could test this by surveying known massive clusters. If our model is right, clusters are like "slow white holes" emitting energy – not only in kinetic form but also as cosmic rays – so they should shine in high-energy skies. *Verification:* detection of significant gamma-ray flux from several massive clusters (with spectra consistent with cosmic-ray interactions). *Refutation:* if such clusters consistently lack high-energy emissions, then perhaps cluster winds are not as effective in accelerating particles as thought, weakening one aspect of the analogy.

- **Correlation of β with Cluster Properties:** Our hypothesis suggests a certain *β* (logistic steepness) governs cluster disruption. We predict that if one were to measure how fast different clusters go from bound to unbound (for example, in simulations or by comparing clusters of different ages in a statistical sense), the "criticality steepness" might cluster around a universal value. *Test:* Perform N-body simulations of star clusters with varying conditions (mass, concentration, tidal field) and fit a logistic curve to their mass-loss vs. time. If UTAC universality holds, these fits might reveal a common β (within error). Observationally, one might approximate this by looking at the fraction of mass retained vs. age for many clusters and seeing if there's a sharp drop at a certain age fraction. If cluster dissolution were a critical phenomenon, the distribution of cluster lifetimes could show a peak or feature reflecting that threshold. If instead lifetimes vary gradually with environment and initial conditions (no universality), then the concept of a single β-regime for clusters might be wrong. This is a subtle prediction requiring large data, but Gaia and future LSST data will provide statistics on cluster survival.

- **Astrocyte Analogy – Controlled Experiment:** While we cannot experiment on galaxies easily, the neural analogy suggests a thought experiment: if astrocytes are removed, neurons become erratic; by analogy, if **clusters did not exist**, would galaxies be drastically different in their star formation and feedback patterns? This is more of a theoretical experiment: simulations of galaxies where star formation is either clustered (in massive clusters) or smoothly distributed could be compared. If clustering leads to different global outcomes (e.g., a more regulated star formation history due to the "buffering" effect), that is evidence that the presence of clusters (vs. dispersed star formation) matters. Some cosmological simulations do indicate that clustered star formation results in burstier but slower overall feedback release, consistent with our ideas. Testing this in observations could involve galaxies of similar mass but different cluster formation efficiency (some galaxies form bound clusters more readily than others). Do those with more cluster-dominated star formation show different ISM properties or wind efficiencies? If yes, it supports the cluster buffering concept; if not, perhaps the ISM doesn't care how the stars are grouped.

- **No "Free Lunch" Energy:** Lastly, an overarching prediction: we expect **no observational evidence of energy appearing without antecedents** (which would be a white hole). In our model, any outflow of energy from a cluster can be traced back to prior stored energy (mass in stars, etc.). Practically, this means if one finds an outflow of gas or plasma in a galaxy, one should be able to find its source (a cluster or stars or black hole, etc.). If someday an outflow is found with absolutely no source (a true spontaneous emission), that would be beyond our model (and indeed revolutionary). So far, none such have been found – every superbubble has stars, every high-velocity cloud can be traced to some interaction, etc. This somewhat tautological prediction reinforces that our model adheres to conservation: clusters can only redistribute what they gathered earlier.

Each of these predictions can be refined into quantitative tests as data improve. The beauty of this framework is that it ties together phenomena on different scales (stars, clusters, galaxies) under a unifying principle of threshold dynamics and delayed feedback. It remains fully falsifiable: **if clusters are found to behave contrary to these expectations, the hypothesis would need revision or rejection**. For example, if star clusters were discovered that never disperse their material (contradicting entropy return) or if sudden, causally inexplicable mass ejections were observed (hinting at new physics), our current understanding would be inadequate.

Conclusions

We have explored the hypothesis that compact star clusters function as **metastable resonant structures** – nature's way of implementing energy-return "white holes" in a lawful manner. Using UTAC and the Frame Principle, we modeled clusters as critical systems that **absorb low-entropy mass and later release it as higher-entropy outputs** over extended periods. The key elements of our model include a logistic threshold for cluster stability, a characteristic entropy signature σ_Φ ~0.0625 marking metastability, and integration of cross-scale parameters like *v*_{RIG} and β-regimes that ensure consistency with known physical constants [3] [4]. We showed that the notion of clusters as "distributed white holes" is not merely fanciful: it is grounded in well-documented astrophysical processes – stellar winds, supernova feedback [40], tidal striping of stars [18], internal chemical enrichment cycles [25] [26], and the assembly of galaxies from star cluster units [31]. In all these processes, **entropy is conserved globally**: clusters only return what was initially available, just spread out in space and time.

We compared our model with classical white hole scenarios. White holes remain hypothetical partly because they seem to violate thermodynamics (emitting matter with no source). Our cluster model circumvents this by always having a source – the cluster's initial gas supply and gravitational binding energy. It also avoids causality issues: energy emerges from clusters through chain reactions of stellar evolution, entirely causal and local. In essence, **star clusters achieve what a white hole would, but through cumulative ordinary events**. If one were far enough away, one might see a galaxy and interpret a slow outflow of matter (from many clusters and supernovae) as a kind of continuous creation – but zoomed in, it's star clusters doing the work, not a new form of matter.

We included an analogy to astrocytes buffering neural activity, hinting that this principle of buffered feedback might be a common theme in complex systems across disciplines. Such interdisciplinary framing can inspire new ways to analyze data; for instance, applying network theory or information theory to star cluster distributions in a galaxy.

Crucially, we outlined several **falsifiable predictions**. These range from specific observable signatures (e.g., symmetric halos of ejected stars vs. tidal tails, gamma-ray emission from clusters, etc.) to statistical properties (e.g., a universal steepness for cluster dispersal, differences in galaxies with clustered star formation). Upcoming data from **Gaia DR4/DR5**, **JWST**, **the Vera Rubin Observatory (LSST)**, and high-energy observatories will provide opportunities to test these predictions. For example, Gaia DR4 will vastly improve detection of tidal streams and could reveal many more "orphan" black holes or neutron stars from clusters [24], directly testing how clusters distribute their remnants. JWST will continue to peer at high-z galaxies, potentially observing cluster formation and dissolution in real time (statistically speaking). If our model is accurate, these observations will increasingly show a universe where **energy flows are mediated by intermediate reservoirs (clusters)** rather than appearing abruptly.

From an open science perspective, we emphasize that our approach can be reproduced and built upon. We provided pseudocode illustrating how to simulate and measure the key quantities, leveraging the existing Feldtheorie/NeuroProfile framework. All the concepts like σ_Φ, logistic activation, etc., are implemented in open-source code [42] [37], enabling other researchers to tweak parameters and test alternative hypotheses (for instance, what if σ_Φ were different, or if multiple thresholds exist for multiple stellar populations). This transparency ensures that our claims can be scrutinized and the model refined.

In conclusion, **compact star clusters emerge as realistic agents of cosmic entropy redistribution**, bridging the gap between the highly-ordered state of star formation and the disordered state of dispersed matter. They do so in a manner consistent with known physics, yet their large-scale effect is to sustain the long-term evolution of galaxies in an orderly fashion – preventing too-rapid energy dumps that could destabilize galaxies, and instead enabling a gentler "return" of matter to the Universe. While the white hole will likely remain a theoretical curiosity, star clusters are out there in the millions, quietly performing this role. By studying them through the lens of criticality and adaptive thresholds, we gain not just astrophysical insights but also a deeper appreciation for how complex systems manage energy and entropy. Future observations and simulations will decide to what extent this picture holds true, but the framework laid out here provides a coherent, testable path forward in understanding the life cycle of cosmic structures.

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