Local scientific investigators on distributed compute islands

A GW190521 proof of concept and a framework for adaptive physics experiments

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Codex (AI)

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Abstract

Large scientific parameter spaces require more than efficient evaluation of a fixed model. A stalled search can indicate a poor coordinate system, insufficient numerical accuracy, missing physics, or a software defect. These possibilities require different experiments. We propose an architecture in which a small resident language model directs fast local investigations within a leased compute island, while a stronger coordinator occasionally reviews evidence, changes scientific assignments, and reallocates resources. Numerical refinement and inference remain the responsibility of explicit algorithms. The investigator chooses what those algorithms should investigate and when their assumptions need revision. As an executed proof of concept, a Gemma 4 E2B model on an Open Science Grid GPU confronted a capped black-hole birth-mass model with released GW190521 samples. It made 3 model calls and selected 5 experiments beyond a supplied baseline. The local loop completed in 16.39 seconds within a 300-second successful allocation. Enlarged mass envelopes accommodate much more of the event posterior, but an exact equivalence test rejects the agent's claim to identify a formation channel. This failure makes scientific adjudication part of the architecture. We specify topology-aware allocation, experiment contracts, evidence exchange, and a staged evaluation program, then develop a hydrodynamic transition-mapping example and a longer discussion of scale, model revision, and computational discovery. The demonstrated result is a remote evidence-to-experiment loop; multi-island coordination, hydro investigations, and an efficiency advantage remain to be tested.

1. Scientific motivation and scope

Adaptive computation usually begins with a well-defined model, an objective, and a parameterization. Within this setting, refinement can place evaluations where likelihood structure or numerical error requires them. RIFT provides an important example in compact-binary inference: its separation of likelihood evaluation and interpolation supports iterative exploration of intrinsic parameters [1]. Such machinery should remain available inside a scientific agent's toolkit. A language model should not replace an integrator merely because the integrator is embedded in an agent workflow.

The harder problem arises when the current task description is inadequate. Increasing resolution cannot create support outside a model's physical domain. An optimizer can converge while missing the mechanism that matters for the observation. A hydrodynamic result can change because a cooling layer is unresolved, because a boundary truncates the flow, or because the assumed physics omits an

important process. A useful investigator must choose experiments that distinguish these explanations. Its responsibility extends beyond ranking an immutable list of parameter points.

Our central proposal is to place that responsibility near the experiments. A local investigator receives a scientific question, an explicit resource budget, and access to a bounded set of scientific tools. It maintains state across evaluations, reads quantitative diagnostics, proposes discriminating tests, and changes its search strategy. A stronger coordinating investigator acts at a slower cadence. It reviews conflicts, reallocates effort between scientific subproblems, and evaluates proposed changes in model meaning. Local progress should usually continue without waiting for a wide-area model call.

This paper makes a narrow empirical contribution and a broader design contribution. The empirical contribution is an executed local LLM investigation of a real event on an opportunistic remote GPU, with preserved actions, outputs, failures, and a subsequent claim correction. The design contribution is a framework for extending this pattern to large spaces and simulation campaigns. The hydro example is a proposed experiment design, not a reported simulation result. A companion reduced binary-population study remains a separate numerical study; its distributed inference calculations do not supply evidence that a language model improves experimental design.

There are several meanings of agency. Here the minimum operational criterion is that an actual LLM receives results from completed experiments, selects new executable experiments, receives their results, and decides how to proceed. The present pilot meets this criterion within a supplied grammar. It does not invent an unprovided physical mechanism or implement a new solver. The stronger goal is scientifically useful agency: selecting better tests, diagnosing invalid assumptions, and producing better supported conclusions at comparable total cost. That goal requires the evaluation program described below.

2. A hierarchy of scientific responsibility

2.1 The local investigation loop

A local investigator owns a question rather than a stream of isolated prompts. Its durable state contains the current hypotheses, the experiments that could separate them, the available model families and coordinate maps, diagnostic thresholds, a resource ledger, and references to immutable results. Each iteration has four conceptual stages: inspect the current evidence; propose a bounded action with a predicted discriminating outcome; run the action through a validated executor; and update the scientific record. The local model can finish with an unresolved question. A requirement to always name a winner would encourage false conclusions.

The executor returns structured measurements, uncertainty and quality flags, and selected field summaries or plots. A failed job returns a typed failure rather than a fabricated low likelihood. Resource exhaustion is distinct from evidence against a hypothesis. Model output is a proposal, not an authoritative measurement. The proposal parser checks action type, parameter domain, resource cost, and artifact dependencies before execution. The numerical engine and the event log determine what actually happened.

Routine refinement can proceed for many evaluations without another language-model call. For example, an investigator may choose a coordinate system and ask a deterministic refinement engine to resolve a transition within a bounded region and tolerance. The next LLM interaction happens when

that batch produces a useful scientific distinction, a diagnostic failure, or a plateau. This places language-model reasoning around numerical work at a meaningful granularity.

2.2 Infrequent stronger coordination

The coordinator assigns complementary questions and periodically reviews compact evidence packets. It may ask one island to map a boundary, another to reproduce a surprising result independently, and another to test a competing physical explanation. Its decisions change objectives, admissible model branches, validation priorities, or resource leases. It need not approve each point in a grid.

Escalation is event-driven. Examples include an inability to meet numerical tolerances, contradictory results across islands, exhausted improvement within the current model, a proposed new physical degree of freedom, or a claim whose interpretation affects other investigations. A configurable maximum interval also provides a liveness check. The interval and escalation thresholds are protocol parameters to measure, not universal constants. Local loops continue within their current authority during an ordinary coordination delay; a dependent model change waits for its decision.

A stronger model is not a substitute for scientific validation. The coordinator must identify the evidence underlying each inference, seek counterexamples, and distinguish model-fit changes from physical identification. Independent numerical checks and human scientific judgment remain necessary for consequential conclusions. In the executed pilot, a post-run Codex review served this critical function. An automatic online hierarchy of local and coordinating agents was not deployed.

2.3 Two different hierarchies

The scientific hierarchy decomposes questions and hypotheses. The resource hierarchy partitions allocations, devices, memory, and storage. These hierarchies need not coincide. A single scientific question can require independent replicas at several sites; a single site allocation can host several questions sharing an expensive dataset. Giving each MPI rank a language model would confuse simulation decomposition with scientific responsibility.

We therefore introduce a compute island: a leased resource domain with an explicit execution and data-access contract. An island may be a substantial multicore node, a GPU node, or a site-allocated group of nodes with a suitable interconnect. One investigator can direct many deterministic workers inside that domain. The investigator’s identity and question survive replacement of a failed allocation; the allocation identifier does not define the scientific identity.

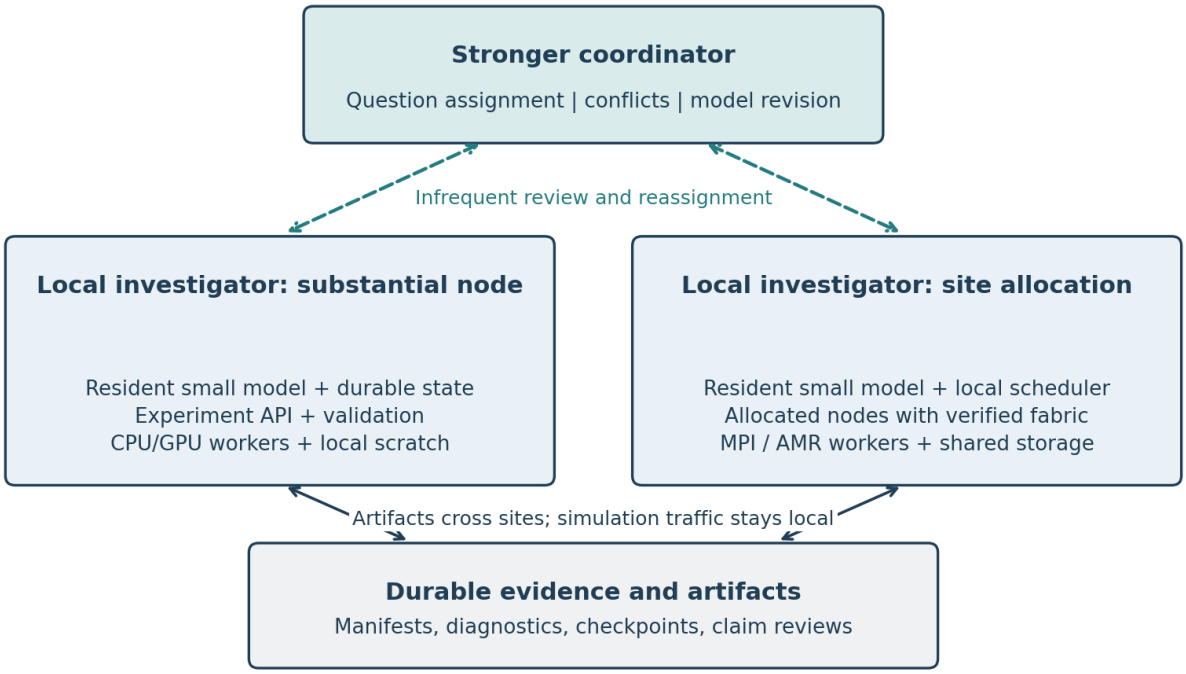

Figure 1. Proposed architecture. Fast feedback stays within each compute island. Cross-site exchange carries evidence and artifact references; stronger coordination is intermittent. The completed pilot exercised one local island and post-run review.

3. Framework and topology-aware assignment

3.1 Capability discovery and leases

An island advertises scheduler-authorized resources and measured capabilities: CPU and accelerator types, usable memory, remaining walltime, local scratch quota, supported runtimes, checkpoint support, storage namespaces, and permitted network paths. For multi-node work, the advertisement also describes the allocated fabric and measured latency and bandwidth relevant to the application. Filesystem visibility, consistency semantics, and concurrent I/O limits are separate attributes. A common subnet or site label is not evidence of a fast interconnect or shared filesystem.

A lease records ownership, expiration, renewal rules, resource ceilings, and permitted subprocesses. It is granted by the actual scheduler or site allocation mechanism. Discovery does not confer authority to occupy nearby nodes. The investigator works within the lease, and the executor reserves enough time and storage for checkpointing before accepting a new experiment. An expired lease cannot produce a second authoritative completion after the question has been reassigned; results may be retained as late evidence under their original attempt identifier.

There are three useful deployment modes. Independent opportunistic jobs support local single-node loops and exchange durable artifacts asynchronously. A substantial node supports shared-memory ensembles or a solver that fits on its CPU/GPU resources. A site allocation supports tightly coupled jobs across a connected block, with a local scheduler subdividing the block. OSPool documents GPU, multicore, and OpenMPI jobs [7-9]; its documented MPI example requests cores in one job rather than a multi-node allocation. The design must not assume arbitrary pool jobs form a multi-node MPI allocation. Flux offers nested resource-management instances and a graph-based resource model as

candidate building blocks for site allocations [5,6]. We have not integrated or benchmarked Flux in this pilot.

3.2 Matching questions to resources

Assignment begins with feasibility: solver compatibility, memory, fabric, storage, and sufficient remaining lease time. Among feasible islands, the scheduler weighs expected scientific information against total cost, queue delay, and data movement. A useful proposed objective is information gained per unit of resource cost, with explicit penalties for transfer volume and restart risk. Expected information is uncertain; it should be estimated from measured campaign history and compared with simpler scheduling policies.

Within an island, a deterministic scheduler chooses batch sizes and placement. Tightly coupled hydro runs require gang allocation of their ranks and devices. Independent initial conditions can occupy separate workers. A resident model can share a node with science workers only if memory and compute interference are budgeted. Options include a dedicated modest accelerator, CPU inference between simulation batches, or explicit time multiplexing. Reserving a large GPU indefinitely for a lightly used small model could erase the hoped-for advantage.

The allocation unit should change with the scientific stage. Broad surveys favor many independent small experiments. A narrow transition with expensive convergence requirements may warrant concentrating resources into fewer larger runs. Replication needs diversity of numerical realization and sometimes site or implementation, not merely more workers replaying one setup. The coordinator changes these allocations after reviewing progress; the local investigator controls execution within the assigned envelope.

3.3 Data and message contracts

An assignment contains a question identifier, model version, scientific domain, allowed actions, stopping rules, validation obligations, and a resource lease. An experiment proposal adds the exact configuration, seed or realization identifier, anticipated discriminator, expected cost, and input artifact hashes. A result contains measured observables, numerical diagnostics, exit status, code and container identity, data identity, and output artifact references. An evidence packet reports which hypotheses were tested, which remain indistinguishable, and which claims are supported at what scope.

The artifact store is separate from the conversation. Large simulation fields stay near the computation until an explicit analysis or replication requires transfer. Compact diagnostics move first, accompanied by references to the full fields and a retention policy. Checkpoints are not scientific evidence by themselves; they make an experiment recoverable. Content hashes identify files, while manifests describe their meaning, units, transformations, and parent experiments.

A robust executor supports at-least-once delivery without double counting. Experiment identifiers describe scientific intent; attempt identifiers distinguish retries. Only a validated completion is admitted to the analysis ledger, and independent replicas are marked as such. Restarting a stochastic simulation with the same seed is not an independent realization. A model-family fork produces a new model identifier even if it reuses most of the code and data.

3.4 A minimal implementation boundary

The next framework increment should provide a durable local controller, a scheduler adapter, an artifact interface, a typed experiment API, a validation service, and an evidence exchange endpoint. The controller should be restartable without asking a model to reconstruct state from prose. Scheduler adapters can implement single-node HTCondor pilots and site allocation backends without changing scientific experiment schemas. The stronger coordinator consumes the same evidence objects that a human reviewer can inspect.

The pilot implements a subset: structured bounded decisions, a real local model transport, sequential experiment execution, result feedback, immutable output directories, and hashed provenance. It does not implement distributed leasing, artifact federation, gang scheduling, or automatic model-branch approval. Those are explicit interfaces to build, rather than capabilities inferred from the existence of a remote job.

4. Executed proof of concept: a black-hole mass ceiling

4.1 Question, observations, and model scope

The scientific question is deliberately concrete: can a model in which directly born black holes have a fixed upper mass accommodate GW190521? The published discovery and astrophysical interpretation already motivate this question [2,3]. This is a test of the investigation protocol using a known challenging observation, not a new discovery about the event.

We use the released joint source-frame component-mass samples in LIGO-P2000158-v4 [4], retaining the association between the two masses. The NRSur7dq4 dataset contains 65723 posterior samples and 6001 prior samples. The other released waveform datasets provide posterior support checks in our extraction but no matching nonempty prior sample set for this calculation. Their support fractions are therefore not converted into evidence ratios. The original release checksum and the compact extract hash are preserved.

Let the ordered source masses be m1 >= m2 and let c be a stipulated stellar birth ceiling. The direct envelope requires both component masses to be at most c. A one-remnant envelope permits the heavier component to reach 2(1-epsilon)c while the lighter remains below c. A two-remnant envelope permits both components to reach 2(1-epsilon)c. These upper limits represent mass reachability if capped parents can merge and lose a fraction epsilon of their combined mass. They are necessary support bounds, not normalized astrophysical formation distributions.

In particular, the envelopes omit how likely parent masses are, how binaries pair, whether remnants are retained, their spin distributions, their delay times, and detector selection. A bound on birth mass does not prohibit subsequent growth. The initial direct model additionally excludes such growth by restricting observed component masses. The starting ceiling of 65 solar masses is an experimental assumption; this paper does not establish a universal supernova cutoff.

4.2 A normalized single-event calculation

For each specification we define a nonnegative weight on the released parameter-estimation prior. It is the indicator of the allowed mass region multiplied by a primary-mass tilt, (m1 / m_ref)^(-alpha), where m_ref equals the baseline ceiling. The model prior is the released prior multiplied by this weight and renormalized. All unspecified parameter distributions and correlations are inherited from that prior.

$$\pi_H(\theta) = \frac{\pi_{\mathrm{PE}}(\theta) w_H(\theta)}{E_{\pi_{\mathrm{PE}}}[w_H]}, \qquad \frac{Z_H}{Z_{\mathrm{PE}}} = \frac{E_{p_{\mathrm{PE}}(\theta \mid d)}[w_H]}{E_{\pi_{\mathrm{PE}}}[w_H]}.$$

This identity follows by substituting the reweighted prior into the evidence integral. It requires the new prior to be absolutely continuous with respect to the released prior. The numerator and denominator are estimated with the posterior and prior draws respectively. For an untilted envelope the numerator is the posterior fraction inside the mass bounds, but that fraction alone is not an evidence ratio. The denominator accounts for how much prior volume the envelope retains.

The numerical gate requires both weight effective sample sizes to exceed or equal 100, together with split-half evidence estimates within a relative tolerance of 25 percent of the full estimate. Effective sample size here is the weight diagnostic (sum w)^2 / sum(w^2), not a proof of independent posterior draws. The split is a sensitivity check, not a convergence test from independent chains. A zero sampled numerator is recorded as unresolved evidence rather than an exact impossibility. Further sampling would be required for reliable extreme-tail comparisons.

All tabulated ratios are pointwise comparisons at the stated parameters. The investigator’s adaptive search does not integrate over a hyperparameter prior. Selecting the largest ratio after seeing the data does not produce a family Bayes factor. A population analysis would additionally require a physical population density and appropriate detection normalization; the single-event exercise does not supply either.

4.3 Local agent and execution protocol

The actual investigator was Gemma 4 E2B in Q4_0 form, served with a pinned llama.cpp runtime on an OSG GPU. The model endpoint was local to the execute host. The prompt supplied the scientific question, the baseline result, the permitted family and parameter grammar, and explicit cautions about evidence and formation-channel interpretation. Each accepted action included a hypothesis, an expected discriminator, and either new specifications or a finish decision. The executor rejected invalid fields, out-of-domain values, and duplicate specifications. There was no scripted numerical fallback reported as a model decision.

The action space was supplied in advance. Thus the model selected family changes and new parameter values, but did not independently invent hierarchical merging or a new dimension absent from its tools. This boundedness makes the executed claim auditable and identifies the next challenge: supporting justified extensions to a model registry without silently changing the inferential target.

The successful allocation used 2 requested CPU cores and 1 GPU, with 8 GiB requested host memory and 12 GiB requested scratch. The device was a GeForce GTX 1080 Ti. Runtime and model files were staged into execute-node scratch, and compact results returned to the access point. This matters operationally when access-point home quotas are small. The deployment container used OSDF-backed storage; model weights were not accumulated in the access-point home directory.

4.4 Actions and numerical results

The agent first tested a higher direct ceiling and both remnant envelopes at the baseline birth ceiling. After reading those outputs, it tested a much broader two-remnant envelope and changed the radiated-fraction parameter. It then finished. All selected tilts remained zero. Table 1 gives the full numerical sequence including the supplied baseline. Experiments within a round were chosen together, so their order should not be interpreted as intervening feedback.

Choice	Family	c	epsilon	Limits	S	R
Baseline	direct	65	0.05	65.0, 65.0	0.003241	0.038819
Round A	direct	70	0.05	70.0, 70.0	0.036228	0.270066
Round A	one remnant	65	0.05	123.5, 65.0	0.456872	0.639983
Round A	two remnants	65	0.05	123.5, 123.5	0.993990	1.224330
Round B	two remnants	100	0.05	190.0, 190.0	1.000000	1.004183
Round B	two remnants	65	0.15	110.5, 110.5	0.971684	1.421520

Table 1. Executed specifications and NRSur7dq4 results. Limits and birth ceilings are in solar masses. S is posterior mass support; R is a Monte Carlo point estimate of evidence relative to the released PE prior; uncertainty intervals are not supplied. The baseline was supplied; subsequent rows were selected by the local LLM.

The direct baseline admits only 0.324 percent of the NRSur posterior, with relative evidence 0.0388. The ordinary two-remnant envelope admits 99.40 percent, with relative evidence 1.2243. Their pointwise evidence ratio is 31.54. This is a comparison of explicitly normalized support models, not posterior odds for stellar-collapse and hierarchical-merger formation channels. The alternative waveform samples also place little support inside the baseline direct envelope, but their tail counts and lack of matching prior draws limit the comparisons that can be made.

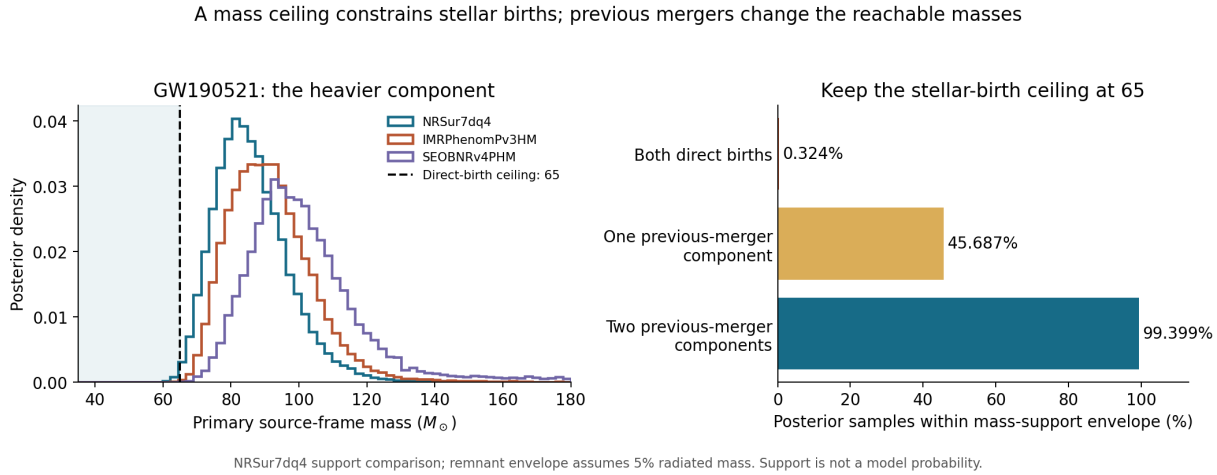

Figure 2. Released GW190521 mass samples and the tested envelopes. The curves and support fractions are computed from the compact joint sample extract. Envelopes show permitted mass support; they do not encode formation rates or channel probabilities.

The investigator completed 3 model calls, 5 selected experiments, and the supplied baseline in 16.39 seconds after the model service became available. The successful scheduler record reports 300 seconds of allocation walltime. These are different timing scopes. Queue delays, failed attempts, staging, startup, and model loading matter to campaign cost; the short loop is not an end-to-end speedup measurement. There is no equal-cost non-LLM comparison in this pilot.

4.5 A useful failure of interpretation

The local model concluded that the two-remnant family identified the physical explanation and overstated the strength of preference for the larger radiated fraction. A post-run review rejected these claims using an exact counterexample. At zero tilt, the two-remnant envelope with baseline birth ceiling and radiated fraction 0.05 is identical to a direct envelope with ceiling 123.5. Changing the radiated fraction to 0.15 gives a direct-equivalent ceiling 110.5. The support functions, normalizations, and event evidences are identical for each corresponding pair.

The ratio between the higher-loss and ordinary two-remnant specifications is only 1.16, before any hyperparameter integration. In this construction, changing the loss parameter simply changes a support boundary. The data cannot identify a merger history from that boundary alone. An enlarged direct ceiling supplies the same mass-only counterexample. The accepted conclusion is that the original narrow direct envelope poorly accommodates these released mass posteriors, and broader envelopes accommodate them better under the stated prior construction.

This correction is part of the result. The system successfully closed the experiment loop and still produced an unsupported scientific interpretation. Prompt cautions did not prevent the mistake. The stronger post-run review found it by executing equivalence checks, rather than by appealing to the reviewer’s confidence. An online coordinator could request precisely this kind of counterexample before allowing a claim to propagate, but that intervention remains a proposed extension.

4.6 Reliability and retained failures

The deployment history includes a GPU initialization failure before any model call and a packaging failure after the model loaded but before the investigator could import its dependencies. Other queued attempts were canceled during deployment revision. The final package was checked with an isolated import before submission. These engineering repairs were performed during development; the local agent did not autonomously diagnose or repair them.

The completed numerical records were replayed locally against the frozen data and source identities. Agreement supports record consistency across hosts, not independent validation of the physical model. The transcript preserves prompts, raw model responses, parsed actions, observations, and the final interpretation. The claim-review artifact preserves both rejected statements and their counterexamples. Reporting only the successful terminal job would conceal costs and failure modes relevant to the proposed architecture.

5. A proposed hydrodynamics investigation

5.1 Mapping a process instead of filling a grid

A suitable next demonstration is a radiatively cooling cloud in a hot flow. Published work motivates comparing the cooling time of mixed gas with the cloud-crushing time and emphasizes the role of the computational domain [10]. We would use that established problem to test whether local investigators choose informative simulation configurations, not claim rediscovery of its known qualitative behavior. AMReX provides adaptive mesh infrastructure [11], and Castro is one possible astrophysical solver framework [12]; no hydro backend has yet been attached to the present investigator.

The proposed experiment begins with a documented initial-boundary-value problem: pressure-balanced phases, a specified equation of state and cooling function, an imposed flow, defined perturbations, and a fixed measurement convention. Useful coordinates include Mach number, density contrast chi, and a cooling ratio tau. Define the nominal cloud-crushing time by t_cc = sqrt(chi) R_c / v_flow and let tau = t_cool,mix / t_cc. These coordinates compress meaningful timescale comparisons, but they need not collapse the entire physics. The definition of the mixed-gas cooling time must be recorded, including the thermodynamic state used to evaluate it.

The target is a response map for cold-mass retention or growth, momentum transfer, and energy exchange over a declared time interval. A cold-gas threshold and treatment of gas crossing the domain boundary are part of the observable definition. Tracer-tagged initial cloud material must be distinguished from newly cooled ambient gas. Otherwise a measurement called cloud survival can quietly change its meaning when condensation becomes important.

5.2 Scientific decomposition and allocation

One investigator maps broad regimes using inexpensive configurations. Another focuses on a candidate transition and selects nearby counterexamples. A third owns resolution, domain-size, and boundary-condition checks. A separate replication assignment tests selected configurations with independent perturbations or, when practical, an alternative numerical method. These are distinct scientific questions with different resource requirements. The coordinator compares their evidence rather than averaging incompatible answers.

The broad survey can run many single-node jobs. A high-resolution calculation may require a site allocation with tightly coupled ranks. Large fields remain on the relevant island while diagnostic time series, conservation budgets, and selected slices are reduced locally. The mesh-refinement algorithm decides where spatial resolution is needed inside a simulation. The investigator decides which physical configuration, numerical sensitivity test, or diagnostic to run next. Parameter-space refinement and spatial AMR therefore remain separate layers.

An informative next action might double a domain length while preserving the local resolution, refine the cooling layer at fixed physical parameters, alter the observation time, or perturb the initial condition. Such tests discriminate a boundary artifact, a numerical-resolution effect, a transient, and an ensemble response. Refining every physical parameter simultaneously would obscure that discrimination and spend resources on a question the current result has not posed.

5.3 Opening new physics dimensions

Suppose the response map fails to organize under Mach number, density contrast, and cooling ratio even after numerical checks pass. The investigator should retain the mismatch and propose a reasoned extension: perhaps an omitted transport process, magnetic configuration, non-equilibrium cooling treatment, or a geometric property of the initial state. Each proposal must identify an observable that could distinguish it from numerical error and from the existing model. These examples are candidate branches, not assertions that any is required by a result we have computed.

A new branch includes its governing assumptions, parameter units and domains, a reduction to a known limit when possible, and validation experiments. The coordinator can allocate a limited branch budget while retaining the original model as a control. Discontinuous model changes should not be disguised as coordinate transformations. A transport coefficient added to the equations changes the physical model; a new coordinate for an existing coefficient changes the representation. The evidence ledger must preserve this distinction.

5.4 A measurable targeting task

For the first hydro benchmark, define success before launching the agents: recover a transition region and its uncertainty under a fixed experiment budget, while meeting declared numerical-error requirements. Reserve configurations that do not participate in adaptive targeting, and evaluate predictions there. Also reserve some uniform or space-filling exploration to detect missed regimes. Validation near a learned boundary alone could miss disconnected behavior elsewhere.

Compare the language-model investigator against the same refinement machinery with deterministic targeting and against a standard active-learning policy. Give all methods the same simulation catalog, permitted model changes, initial information, and total resource budget. Count failed runs, inference time, storage, and validation calculations. Assess not only prediction error but also diagnostic accuracy: did the method request the experiment that distinguished numerical failure from physical change? This is a proposed benchmark whose success would be more informative than an attractive narrative about selected simulations.

6. Evaluation and scaling plan

The immediate next stage is repeated execution of the existing event task with controlled variations in prompt, seed where supported, and model size. It should include withheld challenges where an expanded envelope is physically non-identifying and cases where a numerical gate fails. The benchmark must score incorrect claims and unnecessary experiments, not just whether the model reaches a large evidence value. The present event and its interpretation are already public and can be familiar to a model, so they do not establish discovery on an unseen scientific problem.

The next systems stage is concurrent local investigators with durable state and a coordinator invoked by recorded triggers. Ablations should compare independent local loops, always-central decisions, and intermittent stronger review. Coordinator calls, local inference cost, result latency, duplicate work, and recovery after interruption should all be measured. A successful hierarchy should preserve scientific quality while reducing centralized communication or improving useful throughput, rather than merely reducing the number of visible prompts.

A scaling model separates startup from repeated work. For a sequential local loop with K rounds, the elapsed time is approximately startup and staging plus the sum over rounds of local reasoning,

experiment-batch execution, validation, and checkpoint costs. In parallel execution the critical path and resource contention replace a simple sum. Amortizing startup over many useful rounds can help, but only if longer leases do not introduce excessive idle reservation or restart loss. The pilot's loop and allocation timings expose why both scopes must be reported.

If A investigators each emit an evidence packet of size B every interval Delta, their mean control-plane traffic is approximately A B / Delta. This is a design estimate, not a throughput result. Burst traffic, full-artifact requests, and coordinator reasoning load can dominate the mean. A hierarchical review scheme may aggregate site evidence, but aggregation must preserve contradictory outcomes and unresolved quality flags. Storage and I/O can become bottlenecks before language-model tokens do.

The staged path is therefore: reproducible single-island loops; multiple independent islands with durable evidence exchange; one site allocation with verified shared storage and tightly coupled experiments; then heterogeneous campaigns that mix all modes. Each stage has a failure-injection test and an equal-cost scientific comparison. Larger node counts alone are not evidence of better scientific exploration.

7. Discussion: toward distributed experimental science

7.1 What local intelligence is for

The most promising role for a local agent is choosing among qualitatively different next actions. A refinement algorithm is effective when the relevant model and error criterion are already established. The investigator is useful when it must decide whether to refine, replicate, transform coordinates, inspect a diagnostic, or test another model. This is a higher-level experimental-design problem whose costs and rewards depend on scientific context.

Local execution gives the investigator repeated access to the details that are easy to lose in a central summary: evolving residuals, field morphology, solver warnings, and the history of failed configurations. That access can help formulate a precise follow-up experiment. It can also encourage overfitting to one region or one solver's behavior. The coordinator should request cross-region and cross-method checks when conclusions begin to generalize beyond the local evidence.

There is no requirement that every local decision use language. A well-tested numerical rule should handle ordinary interpolation, convergence checks, and cheap acquisition optimization. The small model is best used when a decision benefits from scientific context or a change in strategy. An implementation that makes a model call for every grid point would often increase latency without adding scientific value.

7.2 Coordinates, support, and changing the question

Physics-based coordinates can make a large search tractable. Dimensionless ratios can align a transition that is curved in raw inputs; conserved quantities can reduce redundant dimensions; derived stellar structure variables can organize models more directly than initial labels. But a coordinate transformation must preserve the represented model and account for the measure when used in inference. The transformed search should retain a map back to physical inputs and explicitly identify singularities or excluded regions.

The mass-ceiling example gives a sharp boundary between representation and physics. No coordinate change can put probability outside an unchanged support restriction. Raising the ceiling or allowing

growth changes the model. Conversely, two physically suggestive labels can define exactly the same mathematical support model. A good investigator should check both directions: whether a proposed rescue actually changes support, and whether apparently different explanations remain observationally identical under the tools being used.

For high-dimensional models, this suggests an explicit model graph. Nodes represent versioned physical assumptions and parameter spaces; edges represent coordinate maps, added processes, restricted limits, or alternative numerical implementations. Only coordinate-equivalent edges permit direct transfer of some inference objects without further interpretation. A new physical branch requires its own validation and normalization. This structure would make an agent's change of mind inspectable.

7.3 From hydrodynamics to the black-hole population

A larger astrophysical program could connect stellar structure, explosion or envelope dynamics, remnant formation, binary evolution, and gravitational-wave observations. These components have very different costs and natural decompositions. Hydro islands could investigate how prescribed progenitor structures and energy-deposition histories affect ejection and fallback. Population islands could explore how uncertain remnant prescriptions propagate into a black-hole mass distribution. Inference islands could identify which regions of that uncertainty are relevant to observed events.

This would not amount to assigning a separate agent to each arbitrary Cartesian block. The assignments should follow physical interfaces. A hydro experiment returns a conditional response with units, assumptions, numerical errors, and an applicability domain. A population calculation consumes that response only within its validated domain and propagates its uncertainty. When observational inference demands extrapolation, it generates a targeted hydro request rather than silently extending a surrogate. A strong coordinator decides whether that request addresses the dominant uncertainty or merely an available calculation.

The feedback can be expressed as an experimental-design cycle. Observations identify a consequential uncertainty in a population prediction; the population model traces it to a remnant or interaction prescription; a local simulation investigator selects configurations that discriminate the relevant physical alternatives; updated response information returns to the population calculation. Several such cycles can proceed in parallel. The scientific challenge is preserving conditional dependencies, selection effects, and model discrepancy across the interfaces.

A credible black-hole mass study would need more than the present envelopes: distributions of progenitors and environments, calibrated remnant mappings, binary pairing and evolution, possible later growth, and an observation model. Multiple gravitational-wave events should constrain population-level quantities with selection accounted for. Hydro response maps would inform part of this hierarchy, not directly become an event likelihood. The existing reduced population study can develop the inference and validation backbone while the new agent framework develops experiment selection. Their conclusions should remain distinct until an explicitly validated bridge is implemented.

7.4 Debugging as an experiment

Unexpected physics and broken software can produce similar symptoms. A discontinuity might signal a physical threshold, an interpolation failure, a unit mismatch, or an invalid boundary condition. An investigator needs tools that narrow the alternatives: minimal reproductions, conservation diagnostics, analytic limits, symmetry tests, and independent implementations. A debugging action should state what failure mechanism it tests and which result would falsify that explanation.

The eventual framework can permit proposed code patches in an isolated branch. It should record the failing case first, run focused regression and scientific validation after the patch, and bind subsequent results to the new code identity. A patch that changes physics or numerics invalidates assumptions that earlier results can simply be pooled. Existing campaign outputs remain attached to their original versions. New code requires review appropriate to its scientific impact before it becomes an admitted experiment tool.

The current pilot did not exercise this capability. Its infrastructure faults were repaired by the development process, and the executor accepted only parameter data. Those failures nevertheless suggest realistic future evaluation cases: inaccessible accelerators, missing runtime components, exhausted scratch, and interrupted transfers. A useful agent must know when it has an infrastructure failure, when it has a numerical failure, and when it has a scientific result. Automatic resubmission alone does not resolve that distinction.

7.5 Exploration, confirmation, and evidence accounting

Adaptive investigations can preferentially pursue striking outcomes. This is valuable for finding phenomena but hazardous for evaluating claims using the same data and stopping rule. The protocol should distinguish exploratory experiments from confirmatory ones, preserve the acquisition history, and reserve independent realizations or observations for validation. There is no universal correction for every adaptive workflow; the statistical target must be specified for each campaign.

An importance-sampling calculation has different requirements from a phase-map emulator or a rare-event search. A likelihood result requires correct normalization and error control. A classifier needs calibrated predictive uncertainty on relevant held-out configurations. A claimed new mechanism needs discriminating observations and competing explanations. The evidence packet should declare its target and diagnostics rather than reduce all results to a scalar called confidence.

Local agreement is especially weak when investigators share the same prompt, model weights, solver, and input library. Their answers may share both statistical dependence and conceptual blind spots. Diversity can be introduced through independent realizations, alternate numerical methods, different observables, or explicitly adversarial counterexample assignments. A coordinator should prefer such tests to a vote among similar agents. The exact-envelope counterexample in the pilot illustrates the value of checking identifiability before debating which narrative sounds more plausible.

7.6 Keeping rare coordination effective

Infrequent supervision is viable only if escalation is reliable and the scientific contracts are clear. A local investigator should be able to identify a plateau or an unresolved contradiction without concluding that a new theory is required. Conversely, a coordinator should not insist on more refinement after the local record shows that support or model structure is the obstacle. Evidence packets need enough detail to make that distinction without retransmitting every simulation field.

We propose a compact review packet containing the question, current competing hypotheses, most informative experiments, failed diagnostics, a counterexample search, resource consumption, and the requested decision. Selected plots or field slices may be necessary when morphology matters, with links to recover the full data. The packet should include what the local investigator did not test. This makes limited review time useful and reduces the temptation to mistake a polished summary for exhaustive investigation.

Coordinator workload can still grow too quickly. Intermediate domain coordinators may summarize several related islands, while top-level coordination handles changes that affect the global scientific objective. Such delegation adds another potential information bottleneck. Its value should be measured through missed conflicts, decision delay, and loss of scientific detail, not only message compression. A rare coordinator that systematically misses decisive caveats is cheaper but scientifically ineffective.

7.7 Storage, locality, and interrupted work

Small access-point quotas make storage architecture a scientific operational concern. Model weights, container layers, checkpoints, field outputs, and analysis caches should have distinct placement and retention policies. Home directories should hold small manifests and control files, not repeated runtime downloads. Execute scratch can host transient work; durable storage retains validated checkpoints and irreplaceable evidence. A storage budget must cover temporary expansion and cleanup, not just final output size.

Sharing storage within an island can amortize expensive data and model staging. It can also create contention or correlated failure. The framework should distinguish a shared namespace from a storage service that can sustain the expected access pattern. Immutable artifact references help cross-site exchange without assuming a globally mounted disk. When bandwidth is scarce, an investigator can request a derived diagnostic first and fetch a field only when that diagnostic warrants it.

Interruption should lose as little scientific state as practical. A restartable investigator saves its accepted actions, completed results, pending experiment identifiers, and remaining budget. Resuming the model conversation should be an implementation detail; the evidence ledger is canonical. Checkpoint frequency trades write cost against expected lost work and should reflect measured eviction and failure behavior. We have not measured this tradeoff in the short pilot.

7.8 A falsifiable research program

The proposal would be weakened if careful deterministic targeting achieves the same scientific outcomes with lower total cost, or if occasional coordination fails to correct local interpretation errors reliably. It would also be weakened if resident inference consumes resources that are more valuable for additional simulations. These are plausible outcomes and should be reported rather than hidden by selecting favorable demonstrations.

A successful program would show that local investigators find useful changes in representation or experimental strategy, diagnose failures accurately, and request model extensions whose value survives independent validation. It would quantify when stronger review is necessary and when numerical routines suffice. It would expose the full cost of deployment and recovery, not only the fast inner loop. The contribution is then a practical method for directing scientific computation under changing assumptions, with clear conditions under which the method helps.

The present proof of concept establishes the first operational link: a small model can run beside a remote experiment engine, use actual observations, and choose follow-up experiments. Its mistaken interpretation establishes an equally important limit. Scaling this pattern should preserve fast local work while strengthening the evidence required for global scientific claims.

Data, code, and draft status

The original observational data are public [4]. The implementation, compact derived samples, deployment archives, transcripts, and claim review are preserved in the private rift-agent-paper repository. The frozen pilot revision is recorded in the companion provenance files. Manuscript numbers and tables are generated from those records through the repository's logged-results utility. No new numerical campaign was run for this draft. This aiXiv edition is released at the direction of Richard O'Shaughnessy. Codex drafted the manuscript, developed and operated the computational workflow, and performed the post-run claim review; the local Gemma model selected the recorded experiments. Richard O'Shaughnessy supplied the scientific direction, resource access, and publication instruction and serves as corresponding human. AI authorship and computational assistance do not establish independent scientific acceptance. This is a methods and architecture proposal with a bounded operational demonstration, not a claim of new astrophysical discovery. The private repository has not been made public by this submission; public independent replay is therefore not yet provided.

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