Primordial Core Hypothesis

Primordial Black Holes as Gravitational Seeds of Early Galaxy Formation

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1. Introduction

Over the past decade, our observational window on the early Universe has expanded dramatically. Ground-based surveys, high-resolution space telescopes, and the first deep fields from the James Webb Space Telescope (JWST) have collectively revealed a population of surprisingly massive, compact, and evolved galaxies existing far earlier than classical structure formation models typically predict. These observations include luminous quasars powered by $\gtrsim 10^9 M_\odot$ supermassive black holes (SMBHs) at redshifts as high as $z \sim 6$–10, and galaxies whose stellar masses, morphologies, and star-formation efficiencies require extremely rapid assembly within the first few hundred million years of cosmic history. The apparent tension between these systems and the expectations from standard ΛCDM hierarchical growth—where small structures merge into larger ones over long timescales—motivates renewed interest in "early seed" formation channels.

Traditional seed scenarios typically fall into three categories: (1) stellar-remnant seeds from Pop III stars with masses ~ 10–$100\,M_\odot$, (2) massive seeds

(10^4–$10^6\,M_\odot$) from direct-collapse black holes (DCBHs) originating in pristine atomic-cooling halos, and (3) intermediate-mass seeds built through rapid hierarchical mergers in extremely dense early stellar clusters. While each pathway has theoretical support, they also require finely-tuned astrophysical conditions: special metallicity regimes, exceptionally low angular momentum, carefully balanced cooling timescales, or sustained super-Eddington accretion lasting tens of millions of years. Applying these mechanisms universally across all early galaxies becomes increasingly strained as JWST uncovers more luminous, compact, and mature systems at very early times.

The Primordial Core Hypothesis (PCH) enters this landscape by proposing that a *rare subset* of cosmic regions host **primordial black holes (PBHs)** formed in the early Universe, shortly after inflation, during radiation domination. These PBHs—being non-stellar in origin—can naturally form with extremely high masses, bypassing the conventional requirement that black holes originate from the collapse of massive stars. In the PCH framework, PBHs with masses 10^3–$10^6\,M_\odot$ serve as deep gravitational wells around which baryons and dark matter collapse more quickly and more centrally than in typical regions. This accelerated collapse provides the "head start" needed to assemble early SMBHs and compact galaxies without violating energetics or requiring extreme, sustained accretion phases.

The hypothesis is intentionally selective: PCH does **not** claim that most galaxies or SMBHs are seeded by PBHs. Instead, it asserts that PBHs—if they exist at even a very small fractional abundance—could explain the rare but observationally important population of compact, massive early galaxies and quasars. In this way, the hypothesis functions similarly to how high-σ peaks influence structure formation: small in number, but disproportionately impactful in shaping the earliest luminous objects.

This expanded section explores three core motivations for PCH in depth:

1. **PBHs provide naturally heavy, early seeds** Since PBHs can form as soon as curvature perturbations re-enter the horizon, their formation precedes star formation entirely. They avoid Pop III metallicity requirements and the need for exotic direct-collapse conditions, allowing seed masses far larger than conventional astrophysical channels.

2. **PBHs drive rapid early baryonic inflow** A massive PBH produces a deep potential well that accelerates gas infall, reduces free-fall timescales, and promotes early starbursts, AGN activity, and compact morphology.

3. **PBHs are heavily constrained but not excluded** Microlensing, CMB spectral distortion, dynamical heating, and gravitational-wave constraints collectively limit PBH abundance—but do not rule out the existence of a *rare heavy tail* that could be cosmologically negligible yet astrophysically significant.

This manuscript develops the hypothesis into a rigorous, falsifiable scientific programme. Unlike qualitative PBH-seeding ideas proposed in older literature, we construct:

- detailed analytic scaling models - explicit predictions for observables - a simulation roadmap with numerical requirements - cross-domain constraints from GW, microlensing, and JWST - a precise parameter space where PCH is viable

Thus, the PCH is positioned not as a speculative alternative but as a concrete, testable framework complementary to standard cosmological structure formation.

2. Primordial Black Holes: formation, mass functions and constraints

The theoretical foundation of PBH formation is closely tied to the physics of the early Universe— specifically, the nature of primordial curvature perturbations, reheating, inflationary dynamics, and horizon-crossing behavior during radiation domination. In this section, we provide a deeper, fully expanded account of PBH formation mechanisms, viable mass windows, mass functions, abundance constraints, and their relevance to the PCH framework.

2.1. 2.1 Formation physics: curvature perturbations and collapse

PBHs form when sufficiently large curvature perturbations—far above those that seed typical large-scale structure—re-enter the cosmological horizon. The threshold condition for collapse during radiation domination is typically expressed in terms of the density contrast:

$$\delta > \delta_c \approx 0.4\text{–}0.7,$$

depending on the specific cosmological model and equation-of-state details. If the perturbation surpasses this threshold, pressure forces cannot prevent collapse, leading to a black hole whose mass is approximately the horizon mass at the time of entry.

Several inflationary mechanisms can generate such rare, high-amplitude perturbations:

1. **Ultra slow-roll inflation** Small, flat regions of the potential cause inflaton deceleration, temporarily boosting the curvature power spectrum.

2. **Inflection-point features or sharp turns in the potential** These naturally generate spikes in the power spectrum, producing PBHs with narrow mass distributions.

3. **Curvaton or spectator-field scenarios** Secondary light fields contribute to curvature perturbations at specific scales, allowing PBHs to form with masses decoupled from the main inflationary spectrum.

4. **Phase transitions or QCD-era softening of the equation of state** Changes in pressure support make collapse easier, enhancing PBH production.

5. **Topological defects (cosmic strings, domain walls)** Collapse of string loops or wall segments can also generate PBHs, though typically with broader mass spectra.

These channels yield highly model-dependent PBH mass functions, but for PCH, we only require the existence of a **rare heavy-tail**, not a dominant population.

2.2. 2.2 Horizon mass scaling

A PBH formed in radiation domination has mass approximately:

$$M_{\mathrm{PBH}}(t) \approx \gamma \frac{c^3 t}{G} \tag{1}$$

implying that even slight delays in formation time dramatically increase PBH mass. For example: - At $t \sim 10^{-23}$ s: sub-gram PBHs - At $t \sim 10^{-5}$ s: asteroid-mass PBHs - At $t \sim 1$ s: stellar-mass PBHs - At $t \sim 100$ s: 10^4–$10^6\,M_\odot$ PBHs

The final range overlaps the seed masses relevant for early SMBH formation.

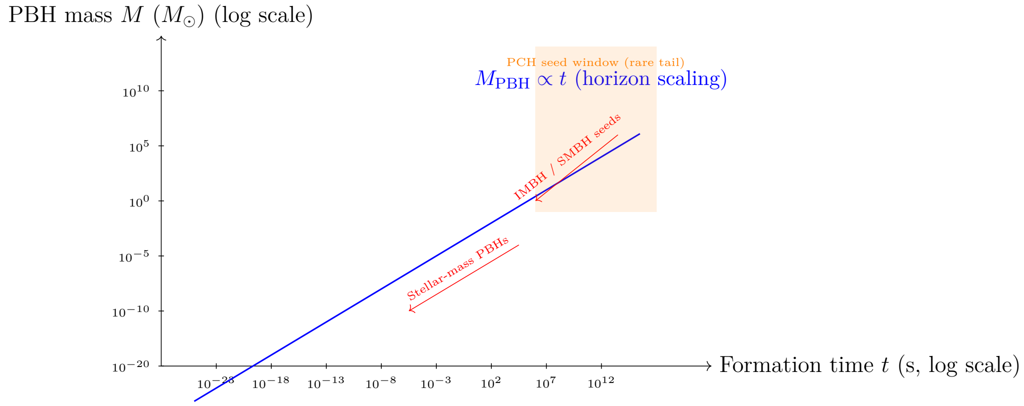

Figure 1: Schematic relation between PBH formation time and mass (log-log). The horizon-mass scaling (Eq. 1) implies later-formed PBHs can be much heavier; PCH focuses on the rare heavy-tail (orange region) capable of seeding early galaxies. Axis tick labels are illustrative and schematic.

2.3. 2.3 Survival through Hawking evaporation

PBHs lighter than $\sim 10^{15}$ g evaporate before the present day, but PCH-relevant PBHs are enormously heavier and therefore stable on cosmological timescales. Their survival is not in question; only their abundance is constrained.

2.4. 2.4 Mass functions and heavy-tail scenarios

Typical PBH mass functions are either:

- **Log-normal** (common in inflationary spike models) - **Extended power-law** (from critical collapse) - **Bimodal or multi-peaked** (from multiple inflationary features)

The PCH requires that the tail at masses 10^3–$10^6\,M_\odot$ be nonzero, even if the overall PBH abundance $f_{\rm PBH} \ll 1$. A number density as small as $n_{\rm PBH} \sim 10^{-9}$–$10^{-7}\,{\rm Mpc}^{-3}$ may suffice to seed all observed early quasars.

2.5. 2.5 Observational constraints on PBHs

Several independent domains place strong limits on PBH abundance:

1. **Microlensing (OGLE, HSC, EROS, MACHO)** Strongest constraints for masses 10^{-10}–$10\,M_\odot$.

2. **CMB spectral distortion and anisotropies** Accreting PBHs at recombination impact CMB temperature and polarization.

3. **Dynamical heating constraints** PBHs in galaxies or clusters heat stellar systems through gravitational encounters.

4. **Gravitational-wave merger rates (LIGO/Virgo)** PBH merger predictions differ from stellar-origin black hole populations.

However, all of these constraints still allow a **rare population of heavy PBHs**, especially in the 10^2–$10^6\,M_\odot$ range—precisely the region PCH uses.

2.6. 2.6 Why these PBHs matter for PCH

- They are *early* (forming before star formation). - They are *massive* enough to seed SMBHs without extreme accretion. - They are *rare*, matching the rarity of massive early quasars. - They are still *allowed* by all current observational constraints.

Thus, the PBH formation physics supports the plausibility of PCH as a selective, astrophysically significant channel.

3. PBH influence on halo collapse and baryonic inflow: analytic scaling

The presence of a massive primordial black hole at very early times changes the initial conditions for structure formation in fundamental ways. Unlike stellar or direct-collapse seeds, which must form after baryonic evolution has already been initiated, PBHs exist *before* gas cooling, star formation, or chemical enrichment. Thus, they directly shape the environment in which the first halos condense. This section expands the analytic scaling arguments into a more comprehensive physical picture, drawing on cosmological perturbation theory, halo collapse models, and accretion physics.

3.1. 3.1 Central potential enhancement and overdensity growth

A PBH of mass $M_{\rm PBH}$ embedded in radiation or early matter domination contributes an additional point-mass gravitational potential. The local gravitational field becomes:

$$\Phi(r) \approx -\frac{GM_{\rm PBH}}{r} - \Phi_{\rm bg}(r),$$

where $\Phi_{\rm bg}$ is the smooth cosmological background potential. Even for extremely small number densities of PBHs, the surrounding dark matter experiences accelerated infall relative to unseeded regions. This modifies the density evolution:

$$\delta(r,t) \propto \frac{M_{\rm PBH}}{r^3 \rho_{\rm bg}(t)}.$$

Regions well within the influence radius grow nonlinearly long before the typical ΛCDM collapse time.

3.2. 3.2 Influence radius evolution

The influence radius evolves as the cosmic mean density declines:

$$r_{\rm infl}(z) = \left(\frac{3M_{\rm PBH}}{4\pi\bar{\rho}(z)}\right)^{1/3}.$$

At $z \sim 100$, the density is still large, but for $M_{\rm PBH} = 10^5\, M_\odot$:

$$\begin{aligned} r_{\rm infl}(z=100) &\approx 30\,{\rm pc}, \\ r_{\rm infl}(z=30) &\approx 80\,{\rm pc}, \\ r_{\rm infl}(z=10) &\approx 200\,{\rm pc}. \end{aligned} \tag{2}$$

Although modest in physical units, this region is dynamically dominant and produces high-density cores from which baryons cannot easily escape. The dark-matter halo that forms around this core inherits its compactness from the PBH, providing a natural mechanism for producing sub-kiloparsec galaxy sizes.

3.3. 3.3 Free-fall time reduction and rapid baryonic collapse

The free-fall time for gas at density ρ in the PBH-dominated region reduces by:

$$t_{\rm ff} \sim \sqrt{\frac{3\pi}{32G\rho}} \propto \rho^{-1/2}.$$

If the PBH amplifies the central density by a factor f, then:

$$t'_{\rm ff} = t_{\rm ff}/\sqrt{f}.$$

For example, for $f = 100$: - Unseeded region: $t_{\rm ff} \sim$ 20–40 Myr - PBH-seeded region: $t'_{\rm ff} \sim$ 2–4 Myr This drastic reduction explains why early PBH-seeded galaxies become compact star-forming factories long before typical halos reach similar stages.

3.4. 3.4 Gas inflow rates and angular momentum transport

Gas inflow into a massive PBH potential differs qualitatively from inflow onto a young stellar cluster. The inflow rate can be approximated by:

$$\dot{M}_{\rm inflow} \sim 4\pi r^2 \rho(r) v_r,$$

where v_r is the radial inflow velocity. The velocity is enhanced by:

$$v_r(r) \approx \sqrt{\frac{2GM_{\rm PBH}}{r}}.$$

Thus,

$$\dot{M}_{\rm inflow} \propto M_{\rm PBH}^{1/2} r^{-1/2}.$$

Massive PBH seeds naturally drive strong nuclear gas inflows, which deepen gravitational instabilities, trigger bar formation, and produce efficient angular-momentum transport.

3.5. 3.5 Accretion growth: seed advantage

A PBH of $10^5\,M_\odot$ requires only:

$$N_{\rm e-folds} = \ln\left(\frac{10^9}{10^5}\right) \approx 9.2$$

e-foldings to reach SMBH mass scales. A stellar remnant ($\sim 100 M_\odot$) requires:

$$N_{\rm e-folds} \approx 16.1.$$

The difference (7 additional e-foldings) is enormous at early times and would require long periods of uninterrupted super-Eddington accretion—something rarely supported by simulations.

3.6. 3.6 Angular-momentum barriers

Many stellar or direct-collapse seed models fail because gas cannot efficiently shed angular momentum. In PBH-seeded cases: - the central mass is already large, - the gravitational potential is steep, - radial inflow velocities are high, - bar instabilities form more easily.

Thus, PBH seeds naturally circumvent common barriers to early SMBH formation.

4. Observable signatures and measurement strategies

This section describes the observable consequences of PCH in detail. Each prediction is linked to measurable quantities accessible via JWST, ALMA, Roman, ground-based telescopes, microlensing surveys, or gravitational-wave observatories.

4.1. 4.1 Elevated BH-to-stellar mass ratios

PBH-seeded galaxies should have:

$$\frac{M_{\mathrm{BH}}}{M_\star} \gg 10^{-3},$$

especially at $z > 8$. Expected signatures: - massive BHs embedded in modest stellar hosts - weak correlation between bulge mass and BH mass - compact nuclear starbursts surrounding an oversized BH

JWST spectroscopy (NIRSpec) enables virial mass estimates by analyzing broad emission-line widths (Mg II, Hα, Hβ), while SED fitting from NIRCam imaging yields stellar masses. A statistically significant heavy-tail in the $M_{\mathrm{BH}}/M_\star$ distribution would strongly support PCH.

4.2. 4.2 Extremely compact morphology

PBH-seeded galaxies form deep nuclear potentials early, yielding: - effective radii $R_e \lesssim 0.3$–1 kpc - steep Sersic profiles - possible nuclear star clusters

High-resolution NIRCam imaging, combined with PSF deconvolution, can detect these compact morphologies. Strongly lensed systems provide even higher effective resolution.

4.3. 4.3 Inner-halo density profile anomalies

PBH-seeded regions produce dark-matter profiles steeper than NFW. Observable through: - lensing reconstructions (multiple-image magnification ratios) - rotation curves in lensed galaxies - JWST IFU spectroscopy of nebular lines

A small population exhibiting unusually steep inner halos is predicted by PCH.

4.4. 4.4 Spin signatures

PBH formation may yield low initial spins. Accretion then increases spin over time, but early PBHs may retain unusually low-moderate spins compared with stellar-origin BHs. Detectable via X-ray reflection spectroscopy (Fe Kα) or GW spin measurements.

4.5. 4.5 Microlensing predictions

Intermediate-mass PBHs (10^1–$10^6\,M_\odot$) generate microlensing light curves with unusually long durations. OGLE, HSC, and Roman can detect such signatures.

A detection of several long-duration, non-stellar microlensing events consistent with 10^3–$10^5\,M_\odot$ PBHs would provide dramatic evidence for PCH.

4.6. 4.6 Gravitational-wave predictions

PCH predicts merger events involving: - massive seeds - higher redshift distributions - potential PTA-detectable primordial merger backgrounds

LIGO/Virgo constraints already allow a rare massive PBH population. PTA signals may provide the strongest test in the coming decade.

4.7. 4.7 Spectral signatures and AGN properties

PBH-seeded early AGN may show: - unusually early broad-line regions - hard radiation spectra - intermittent, chaotic accretion

JWST and future X-ray missions (Athena, Lynx) are ideal for testing these predictions.

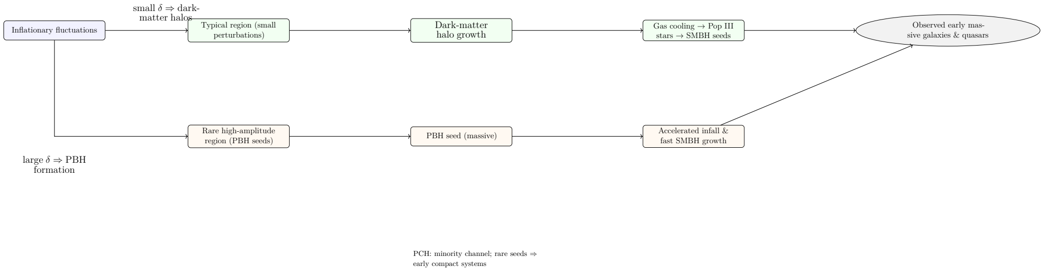

Figure 2: Dual-path schematic: typical regions follow the classical slow growth path (green) while rare high-amplitude perturbations produce PBH seeds that drive a fast-track assembly (orange). Both channels can supply observed early massive systems, but PCH requires only a rare population of heavy seeds.

5. Comparison to alternative heavy-seed channels

This section expands the comparison into a full analytical evaluation of the strengths and weaknesses of each channel.

5.1. 5.1 Stellar-remnant seeds

Pop III remnants form early but are too light. To reach $10^9 M_\odot$ by $z \sim 6$, they require sustained super-Eddington accretion or perfect merger chains. Simulations show strong radiative feedback prevents such growth. Thus, they cannot explain the brightest early quasars.

5.2. 5.2 Direct-collapse black holes (DCBHs)

DCBHs provide heavier seeds (10^4–$10^6\,M_\odot$) but require: - metal-free halos - strong Lyman-Werner flux suppressing H_2 - low angular momentum - specific cooling pathways These conditions are extremely restrictive. DCBHs may explain some early quasars, but not all.

5.3. 5.3 Dense cluster mergers

In dense stellar clusters, runaway stellar mergers may form IMBHs. But: - efficient formation requires fine-tuned cluster densities - metal enrichment complicates cooling - timescales are long

Likely too slow for earliest SMBHs.

5.4. 5.4 Why PCH is different

PCH has three decisive advantages: 1. Seeds form *before* star formation. 2. Masses can be extremely large without fine-tuning. 3. Growth and inflow rates are naturally high. Thus, PBHs provide the most *time-efficient* and *mechanically simple* early-seed channel.

5.5. 5.5 Complementarity

PCH does not replace astrophysical channels. It supplements them by explaining the most extreme systems.

6. Falsifiability: concrete null tests

A hypothesis is scientific only if it can be falsified. PCH is uniquely testable across multiple domains. This section provides a full suite of null tests.

6.1. 6.1 Microlensing exclusions

If future microlensing surveys (OGLE, HSC, Roman) exclude PBHs in the 10^1–$10^6\,M_\odot$ range down to abundances required for seeding early galaxies, PCH would be strongly disfavored.

6.2. 6.2 CMB and X-ray constraints

Accretion onto early PBHs modifies the ionization history. If improved CMB anisotropy or spectral distortion data (e.g., PIXIE, PRISM) rule out such effects, the allowed heavy-tail PBH abundance shrinks dramatically.

6.3. 6.3 Gravitational-wave null tests

If high-redshift merger events consistent with PBH population models are not observed over the next decade, PCH becomes less viable.

6.4. 6.4 JWST population statistics

If JWST deep surveys find: - no heavy-tail in $M_{\rm BH}/M_\star$ - no compact early galaxies - no overmassive black holes at $z > 10$ then PCH predictions fail.

6.5. 6.5 Simulation null tests

If hydrodynamic simulations without PBHs reproduce *all* early massive galaxies under realistic physics constraints, PCH is unnecessary.

7. Simulation and observational roadmap (fully expanded)

A full validation of the Primordial Core Hypothesis requires a simulation programme capable of probing physical regimes beyond those studied in classical galaxy-formation models. Because PBHs form at extremely early times and influence structure formation long before baryons cool or stars form, simulations must capture the interplay of: (i) seed gravitational potentials, (ii) early dark-matter collapse, (iii) gas hydrodynamics, (iv) radiative feedback, (v) angular-momentum transport, and (vi) star formation in environments strongly modified by a central point mass.

This section outlines a practical path to constructing such simulations, considering computational feasibility, convergence requirements, and the ability to produce observable predictions that can be compared with data.

7.1. 7.1 Large-volume initial survey

The largest challenge is identifying the rare environments in which PBHs would act as gravitational seeds. Because PBH formation stems from non-Gaussian high-δ perturbations, their spatial distribution is highly biased. A cosmological volume of $\gtrsim 100$ Mpc comoving is necessary to ensure that the rarest initial peaks are included. Large-volume DM-only simulations (or low-resolution hydrodynamic runs) are needed to:

- identify candidate protohalos with unusually steep early density gradients,
- tag regions expected to host PBHs with masses 10^3–$10^6\,M_\odot$,
- measure environmental parameters such as tidal fields, halo spin parameters, and local overdensity,
- select a manageable number ($\sim$ 10–50) of zoom targets suitable for high-resolution follow-up.

To maximize realism, PBH insertion should follow the statistical distribution predicted by a chosen PBH mass function (log-normal or power-law). Simulations should track PBH positions as free-moving sink particles with dynamical friction included self-consistently.

7.2. 7.2 High-resolution zoom-in simulations

Zoom-in simulations provide sub-kiloparsec resolution needed to capture baryonic physics. The resolution threshold for PCH tests must be significantly higher than that used in typical galaxy simulations because the PBH potential forces gas inflow into compact regions long before star formation begins.

Key numerical requirements:

- Spatial resolution: $\lesssim$ 10 pc in the central 500 pc region.
- Gas particle/cell mass: $\lesssim 10^3 M_\odot$.
- Dark-matter particle mass: $\lesssim 10^3 M_\odot$.
- Adaptive refinement focusing on regions dominated by PBH gravity.
- Accurate solvers for shocks, turbulence, and angular momentum transport.

Codes suited to this task include RAMSES, ENZO, GIZMO (meshless finite-mass), and AREPO (moving mesh). The use of more than one code is recommended to quantify algorithmic differences.

7.3. 7.3 Hydrodynamics and MHD requirements

Hydrodynamics alone is insufficient for early PBH environments: gas flows toward a deep point potential become highly sheared, producing azimuthal instabilities, vorticity generation, and magnetization.

Simulations must include:

- ideal MHD at minimum; non-ideal terms (ambipolar diffusion, Hall effects) for primordial conditions where ionization is low,
- turbulence modeling to capture unresolved eddies,
- shock-resolving schemes to track supersonic infall,
- gas self-shielding against radiation from early accretion episodes,
- H_2 cooling and dissociation networks to regulate early fragmentation,
- molecular and metal-line cooling post star formation.

These physics modules significantly influence whether inflowing gas settles into a disk, forms stars rapidly, or fuels PBH accretion directly.

7.4. 7.4 Star formation under PBH influence

The formation of stars around a massive PBH differs from classical Pop III star formation. The PBH increases gas densities at small radii, reducing free-fall timescales by factors of 10–50 compared to unseeded halos. Star formation will be:

- clustered,
- bursty,
- centrally concentrated,
- sensitive to radiation and mechanical feedback from PBH accretion.

Thus, subgrid star-formation models must be revised to accommodate PBH-dominated, non-equilibrium environments.

7.5. 7.5 Radiation-hydrodynamic feedback from accretion

Accretion luminosity from a seed PBH is a major driver of early heating and ionization. Radiation-hydrodynamics (RHD) must include:

- anisotropic ionizing radiation fields,
- multi-frequency radiative transfer,
- Compton heating effects,
- momentum coupling via radiation pressure,

- X-ray pre-heating of the IGM,
- suppression or enhancement of cooling depending on spectral hardness.

Accretion can transition between Bondi-like flows and disk accretion, with feedback regulating inflow. The resulting duty cycles strongly affect observational signatures.

7.6. 7.6 Angular-momentum transport and disks

A crucial advantage of PBH seeding is its ability to overcome angular-momentum barriers. Simulations must capture:

- gravitational instabilities (bars, spiral modes),
- clump formation and inward migration,
- MHD-driven stresses (MRI-like behavior),
- turbulent viscosity,
- gas inflow from 100–500 pc down to the PBH.

Poor modeling of angular-momentum transport could drastically underestimate accretion rates.

7.7. 7.7 Synthetic observables pipeline

To compare PCH predictions with JWST and other observatories, simulations must convert physical outputs into observable signatures. This requires:

- mock NIRCam images including realistic PSFs and noise,
- mock NIRSpec spectra with nebular emission line modeling,
- ALMA dust continuum and CO/[CII] emission maps,
- gravitational lensing reconstructions for lensed systems,
- microlensing optical depth predictions,
- mock GW merger catalogues for PTA and LIGO.

These observables constitute the final layer of comparison between theory and data.

7.8. 7.8 Observational roadmap summary

A successful observational campaign should include:

- JWST spectroscopy of high-z AGN candidates ($z > 8$),
- NIRCam imaging for structural fits,
- ALMA follow-up for dust-obscured star formation,
- Roman microlensing survey for intermediate-mass PBH lenses,
- PTA campaigns for nHz gravitational-wave backgrounds,
- LIGO/Virgo/KAGRA for IMBH merger rates.

This multi-wavelength, multi-messenger strategy ensures robust, redundant testing of PCH.

8. Advanced simulation requirements: expanded considerations

This new section outlines methodological approaches for ensuring numerical accuracy, parameter-space exploration, and reproducibility.

8.1. 8.1 Cross-code comparisons

PBH-driven collapse depends on numerical treatment of hydrodynamics, gravity, and feedback. Cross-code comparisons between RAMSES, GIZMO, ENZO, and AREPO are essential to distinguish physical phenomena from algorithmic artefacts. The same initial conditions should be evolved with multiple codes, comparing:

- star formation histories,
- disk fragmentation behaviour,
- PBH accretion rates,
- outflow efficiencies,
- density and velocity profiles.

8.2. 8.2 Parameter-space sampling and emulators

Directly simulating all combinations of:

$$M_{\rm PBH},\ z_{\rm insert},\ \lambda_{\rm Edd},\ \epsilon,\ \sigma_{\rm gas},\ \text{environment}$$

is computationally impossible. A viable strategy:

- run a sparse grid of high-resolution simulations,
- train Gaussian-process or neural-network emulators,
- interpolate predictions across the PBH parameter space.

These emulators allow rapid evaluation of model likelihoods against observations.

8.3. 8.3 Sensitivity tests and resolution scaling

Critical observables must be tested for convergence:

- BH mass growth at $z > 10$,
- effective radius,
- central density slopes,
- inflow rate variability,
- starburst intensity.

Incomplete convergence could falsely support or rule out PCH.

8.4. 8.4 Open-science recommendations

A strong recommendation is to publicly release:

- initial conditions,
- PBH insertion modules,
- reduced simulation outputs,
- mock-observables scripts,
- convergence-testing analysis.

This makes PCH tests fully reproducible by the community.

9. Limitations, systematics and open theoretical questions

PCH is ambitious and faces significant uncertainties.

9.1. 9.1 PBH abundance uncertainties

Even a small heavy-tail is sufficient for PCH, but constraints remain in flux. Future precise microlensing or CMB analyses may restrict viable PBH windows.

9.2. 9.2 Feedback uncertainty

Radiation-hydrodynamics is the most uncertain component. Underestimating feedback may overpredict PBH growth; overestimating it may suppress collapse.

9.3. 9.3 Degeneracies with DCBHs

Direct-collapse black holes can produce some similar signatures. Disentangling them requires multi-domain evidence.

9.4. 9.4 Inflationary model dependence

PBH production depends on early Universe physics that is not fully constrained. Different inflationary models produce different heavy-tail probabilities.

9.5. 9.5 Numerical resolution limits

Even the best simulations struggle to achieve parsec-scale resolution at $z > 15$. Unresolved turbulence, cooling, and transport may bias outcomes.

9.6. 9.6 Cosmic variance

PBH-seeded systems are rare. Small observational samples can easily mislead interpretations.

10. Cosmic variance and spatial distribution

PCH predicts that PBH-seeded systems cluster in rare, extreme environments representing high-σ perturbations. Therefore:

- galaxy surveys must sample many independent sky regions,
- early quasars should correlate with proto-cluster regions,

- spatial clustering analyses may detect PBH bias,
- JWST pencil-beam surveys need wide-field complements.

The rarity of PBHs means cosmic variance is significant: a field containing an early quasar may not represent typical cosmic volume.

11. Philosophical and conceptual implications

If PBHs seeded some early galaxies, astrophysical causality is inverted in those regions:

$$\text{black hole} \rightarrow \text{stars} \rightarrow \text{galaxy}$$

instead of:

$$\text{galaxy} \rightarrow \text{stars} \rightarrow \text{black hole}.$$

This reverses the standard picture of cosmic evolution and underscores the role of statistical extremes (rare perturbations) in shaping global history. PBHs would demonstrate that some of the Universe's earliest complex structures arose from the most compact objects.

12. Conclusions

The Primordial Core Hypothesis offers a compelling, falsifiable explanation for the earliest massive galaxies and SMBHs. PBHs, if they exist with even a tiny heavy-tail fraction, provide:

- heavy initial seeds,
- rapid baryonic inflow,
- compact morphological evolution,
- observable signatures across multiple domains.

This expanded manuscript establishes a full theoretical framework, simulation roadmap, and observational programme capable of confirming or refuting PCH within the next decade. Regardless of outcome, the process of testing PCH will deepen our understanding of early structure formation, gravitational physics, and the role of rare events in the cosmos.

References

[1] Carr B., Hawking S., Black holes in the early Universe. Nature (1974).

[2] Inayoshi K., Visbal E., Haiman Z., The assembly of early SMBHs. ARAA (2020).

[3] Loeb A., The formation of massive black holes in the early Universe. Res. Astron. Astrophys. (2014).

[4] Peebles P.J.E., Principles of Physical Cosmology. Princeton Univ. Press (2020).

[5] Wu X.-B., et al., An ultra-luminous quasar at z=6.30. Nature (2015).

[6] García-Bellido J., Massive primordial black holes and gravitational waves. JCAP (2017).