

Born in the Dark: The Catastrophic Collapse of Fuzzy Dark Matter Solitons as the Origin of Little Red Dots

TAK-PONG WOO^{1,2}

¹*Institute of Astrophysics, National Taiwan University, Taipei 10617, Taiwan*

²*Department of Physics, National Taiwan University, Taipei 10617, Taiwan*

ABSTRACT

JWST surveys have uncovered a population of compact, red sources (“Little Red Dots,” LRDs) at $z \gtrsim 5$ that exhibit broad Balmer emission yet remain X-ray faint, implying heavy obscuration with $N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2}$. We propose that LRDs may trace a short-lived, obscured phase associated with rapid baryonic inflow inside the deep solitonic cores of fuzzy dark matter (FDM) halos. Combining the soliton size scaling with (i) the observed compact radii ($r_e \sim 30\text{--}100 \text{ pc}$) and (ii) the requirement that Compton-thick columns be achievable within a region of order the core radius, we find that particle masses $m \sim \text{few} \times 10^{-22} \text{ eV}$ are plausible for soliton masses $M_s \sim 10^8\text{--}10^9 M_{\odot}$; we adopt $m_{22} = 2$ as a fiducial choice. A conservative mass-budget estimate for the obscuring column, together with isothermal hydrostatic stratification, indicates that configurations reaching $N_{\text{H}} \gtrsim 10^{24}\text{--}10^{25} \text{ cm}^{-2}$ require densities for which radiative losses (cooling and/or diffusion) occur faster than the dynamical time, suggesting that a long-lived static hot atmosphere is unlikely (an “Opacity Crisis”) and that rapid inflow or radiation-pressure-driven evolution is favored. Using 512^3 pseudo-spectral Schrödinger–Poisson simulations of idealized soliton mergers, we illustrate that compact, high-density soliton cores can form via violent relaxation under representative scalings. We discuss observational implications and tests, and outline the need for future radiation-hydrodynamic modeling to predict demographics and detailed spectra.

Keywords: dark matter (353); early universe (432); quasars (1319); high-redshift galaxies (734); star formation (1569)

1. INTRODUCTION

The origin of supermassive black holes (SMBHs) residing in the centers of galaxies remains one of the most puzzling questions in modern astrophysics. The detection of quasars at redshift $z > 7$ with black hole masses exceeding $10^9 M_{\odot}$ (Mortlock et al. 2011; Bandoos et al. 2018) places stringent timing constraints on their growth. Standard scenarios, such as light seeds from Pop III stars or heavy seeds from Direct Collapse Black Holes (DCBH), face significant challenges regarding accretion rates and rare environmental requirements (Bromm 2013).

The advent of the James Webb Space Telescope (JWST) has added a new layer of complexity. JWST

surveys have revealed a ubiquitous population of “Little Red Dots” (LRDs) at $z \sim 5\text{--}10$ (Labbé et al. 2023; Greene et al. 2024). These objects are characterized by their compact morphology ($r_e \lesssim 50\text{--}100 \text{ pc}$), extremely red spectral energy distributions (SEDs), and broad H α lines indicating SMBH masses of $10^7\text{--}10^9 M_{\odot}$. Crucially, despite their apparent black hole activity, many LRDs are surprisingly X-ray faint (Maiolino et al. 2024), implying Compton-thick obscuration with column densities $N_{\text{H}} > 10^{24} \text{ cm}^{-2}$.

Fuzzy Dark Matter (FDM) provides a novel framework for addressing these issues. FDM halos host a stable, dense ground-state solution known as a *soliton* (Schive et al. 2014a). In this paper, we propose that LRDs are the direct observational signatures of the **catastrophic breakdown of the hydrostatic atmosphere** triggered by FDM soliton thermodynamics. We identify a regime of “Opacity Crisis” where the static atmosphere becomes unphysical. We present analytic

Corresponding author: Tak-Pong Woo
 bonwood@phys.ntu.edu.tw

derivations and 3D numerical simulations to show that: (1) deep solitonic potential wells form robustly, and (2) gas within these wells must undergo rapid cooling and inflow.

2. ANALYTIC FRAMEWORK

2.1. Soliton Scaling and Parameter Constraints

The FDM soliton radius r_c scales inversely with the boson mass m and soliton mass M_s (Schive et al. 2014a):

$$r_c \approx 160 \text{ pc} m_{22}^{-2} \left(\frac{M_s}{10^9 M_\odot} \right)^{-1}, \quad (1)$$

where $m_{22} = m/10^{-22}$ eV. We constrain m_{22} by requiring consistency with LRD observables: compact sizes ($r_e \sim 30\text{--}100$ pc) and Compton-thick obscuration ($N_H > 10^{24} \text{ cm}^{-2}$). For a typical LRD host halo, the core-halo relation implies $M_s \sim 10^9 M_\odot$.

As shown in Figure 1, we identify the parameter space where FDM is consistent with observations. To ensure robustness, we also perform a sensitivity analysis regarding the baryon loading parameters. We note that the derived constraints depend on the assumption that the observed effective radius r_e traces the soliton core scale r_c (i.e., $\eta_r \equiv r_e/r_c \sim \mathcal{O}(1)$). If r_e corresponds to a larger scattering photosphere, the constraints would shift; however, for our fiducial assumptions, a window around $m_{22} \approx 2$ emerges.

2.2. Derivation of the Opacity Crisis

We ask whether a quasi-static baryonic atmosphere inside a soliton can simultaneously (i) produce Compton-thick obscuration and (ii) remain pressure-supported on a dynamical time. Rather than assuming a unique static solution, we explicitly parameterize the baryon loading and show that the regime required for obscuration generically implies rapid radiative losses, invalidating the long-lived hydrostatic picture.

A conservative column estimate from the baryon mass budget.—Let a gas mass $M_g = f_g f_b M_s$ be loaded into an obscuring region of radius $r_{\text{out}} = \xi r_c$, where $f_g \leq 1$ is the loaded fraction of the cosmic baryon budget, $f_b \simeq 0.16$, and $\xi \sim 1\text{--few}$. A geometry-limited characteristic column is

$$N_H \simeq \frac{M_g}{\pi r_{\text{out}}^2 \mu_H m_p} = \frac{f_g f_b M_s}{\pi (\xi r_c)^2 \mu_H m_p}, \quad (2)$$

with $\mu_H \simeq 1.4$ accounting for He. Using the soliton scaling (Eq. 1), this implies that for fixed (f_g, ξ) the achievable column increases rapidly with deeper, more compact cores. In Fig. 1 we define the “Too Transparent” region by $N_{H,\text{max}}(f_g = 1, \xi = 1) < 10^{24} \text{ cm}^{-2}$. As

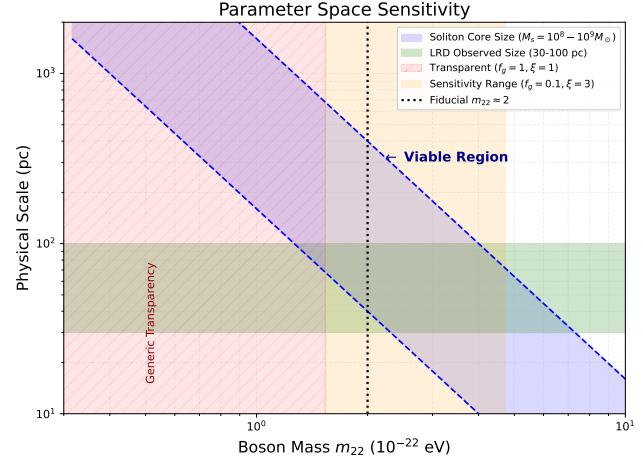


Figure 1. Constraints on boson mass (m_{22}). The viable region is defined by the intersection of the observed LRD size range (green band, $r_e \sim 30\text{--}100$ pc) and the requirement that Compton-thick columns be achievable within a compact core. The red hatched region marks parameters for which even a maximally loaded core ($f_g = 1, \xi = 1$) fails to reach $N_H = 10^{24} \text{ cm}^{-2}$. The opacity constraint curves assume a soliton mass scale of $M_s \sim 10^9 M_\odot$ (typical of LRD hosts). We treat the observed r_e as a proxy for the soliton core radius r_c ; if r_e traces a larger photosphere, the constraints would shift. To address uncertainties in baryon physics, the orange shaded area shows the sensitivity range: under conservative assumptions ($f_g = 0.1, \xi = 3$), the exclusion region expands. Under these working assumptions, a parameter window around $m_{22} \sim \text{few}$ is favored.

shown by the orange band in Fig. 1, adopting conservative values ($f_g = 0.1, \xi = 3$) shifts this threshold, but $m_{22} \approx 2$ remains a plausible solution for $M_s \sim 10^9 M_\odot$. We note that Eq. (2) is a conservative geometric estimate; gas clumping would increase the effective line-of-sight column, while feedback might reduce f_g .

Relation to hydrostatic stratification.—For reference, an isothermal atmosphere in hydrostatic equilibrium satisfies $\nabla P = -\rho_g \nabla \Phi_s$, with

$$\rho_g(r) = \rho_{g,0} \exp \left[-\frac{\Phi_s(r) - \Phi_s(0)}{c_s^2} \right], \quad c_s^2 = \frac{k_B T}{\mu m_p}. \quad (3)$$

This becomes a closed problem only after specifying a normalization. Hydrostatic stratification can increase the central line-of-sight column relative to Eq. (2); we therefore treat Eq. (2) as a conservative baseline.

Cooling versus dynamical support.—The mean density corresponding to a loaded core is $\bar{n} \simeq \bar{\rho}/\mu m_p$. For the dense cores relevant here ($\bar{n} \gtrsim 10^4\text{--}10^5 \text{ cm}^{-3}$), optically thin metal-line cooling at $T \sim 10^6$ K implies a short

cooling time,

$$t_{\text{cool}} \sim \frac{3k_B T}{2\bar{n} \Lambda(T, Z)}, \quad (4)$$

which can be much shorter than the dynamical (free-fall) time $t_{\text{ff}} \sim (G\bar{\rho})^{-1/2}$.

Radiative trapping: electron scattering vs. IR dust opacity.—In an optically thick core, radiative losses may be limited by diffusion rather than by optically thin cooling. A conservative lower bound is the diffusion time due to electron scattering,

$$\begin{aligned} t_{\text{diff,es}} &\sim \frac{\tau_T r_{\text{out}}}{c} = \frac{\sigma_T N_H r_{\text{out}}}{c} \\ &\simeq 1.6 \times 10^3 \text{ yr} \left(\frac{\tau_T}{10} \right) \left(\frac{r_{\text{out}}}{50 \text{ pc}} \right), \end{aligned} \quad (5)$$

which is typically shorter than t_{ff} in the parameter range where Compton-thick columns are attainable.

If the gas cools and becomes dusty, UV/optical photons can be efficiently reprocessed into the IR, and the relevant mass opacity can be much larger than the electron-scattering opacity $\kappa_{\text{es}} \simeq 0.34 \text{ cm}^2 \text{ g}^{-1}$. In that regime, an upper-range diffusion estimate is

$$t_{\text{diff,IR}} \sim \frac{\tau_{\text{IR}} r_{\text{out}}}{c}, \quad \tau_{\text{IR}} = \kappa_{\text{IR}} \Sigma, \quad \Sigma = \mu_H m_p N_H, \quad (6)$$

so that

$$\begin{aligned} t_{\text{diff,IR}} &\simeq 3.8 \times 10^4 \text{ yr} \left(\frac{\kappa_{\text{IR}}}{10 \text{ cm}^2 \text{ g}^{-1}} \right) \\ &\quad \times \left(\frac{N_H}{10^{25} \text{ cm}^{-2}} \right) \left(\frac{r_{\text{out}}}{50 \text{ pc}} \right). \end{aligned} \quad (7)$$

We stress that dust opacity is only relevant once the gas has cooled to temperatures where dust can survive; in an initially hot ($T \sim T_{\text{vir}}$) phase, electron scattering provides the appropriate minimal trapping floor.

Working definition of the “Opacity Crisis.”—We use “Opacity Crisis” to denote the breakdown of a long-lived, hot hydrostatic atmosphere inside the soliton: in the same parameter space where $N_H \gtrsim 10^{24} \text{ cm}^{-2}$ is achievable within $r_{\text{out}} \sim O(r_c)$, the effective radiative-loss or energy-redistribution time $t_{\text{rad}} \equiv \max(t_{\text{cool}}, t_{\text{diff,es}})$ is not $\gg t_{\text{ff}}$. The system therefore cannot remain as a quasi-static hot atmosphere; it must evolve dynamically, either via rapid cooling-driven collapse ($t_{\text{cool}} \ll t_{\text{ff}}$) or into a radiation-pressure-supported optically thick inflow/envelope if IR trapping becomes important ($t_{\text{diff,IR}} \gtrsim t_{\text{ff}}$). In either case, the initial static HSE picture is invalid in the regime relevant for LRD-like obscuration.

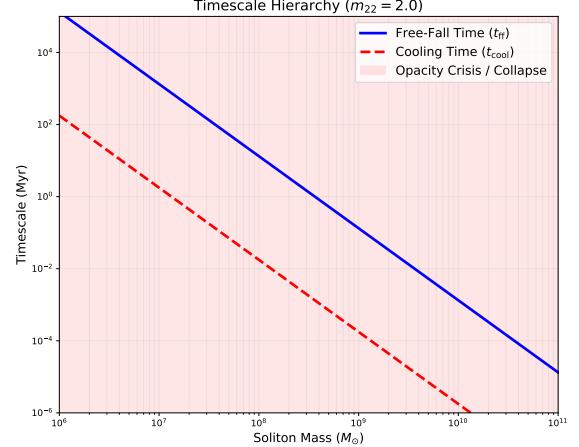


Figure 2. The instability region. Comparison of free-fall (t_{ff}) and cooling (t_{cool}) timescales versus soliton mass for $m_{22} = 2.0$. The shaded region indicates $t_{\text{cool}} < t_{\text{ff}}$, where a long-lived, optically-thin hot hydrostatic atmosphere cannot persist. The system is driven either toward rapid inflow/collapse (if radiative losses escape efficiently) or toward a radiation-pressure dominated, optically thick configuration (if radiation is trapped).

2.3. Timescale analysis and inflow rate

Figure 2 summarizes the timescale hierarchy for our fiducial choice $m_{22} = 2.0$. In the parameter space where Eq. (2) allows $N_H \gtrsim 10^{24} \text{ cm}^{-2}$, radiative losses are rapid compared to dynamical support.

A direct implication is that the effective sound speed can drop substantially during collapse, enhancing the capture rate. For a black hole of mass M_{BH} , the Bondi rate is

$$\dot{M}_{\text{B}} = 4\pi \lambda \frac{G^2 M_{\text{BH}}^2 \rho}{c_s^3}. \quad (8)$$

The ratio to the Eddington rate is

$$\begin{aligned} \frac{\dot{M}_{\text{B}}}{\dot{M}_{\text{Edd}}} &\approx 10^3 \left(\frac{\lambda}{1} \right) \left(\frac{\eta}{0.1} \right) \left(\frac{M_{\text{BH}}}{10^8 M_{\odot}} \right) \\ &\quad \times \left(\frac{n}{10^5 \text{ cm}^{-3}} \right) \left(\frac{T}{10^6 \text{ K}} \right)^{-3/2}, \end{aligned} \quad (9)$$

indicating that inflow at the capture scale can exceed \dot{M}_{Edd} in dense cores. Granule-driven fluctuations (Quantum Bondi Boost) may further modulate this (Chiu et al. 2025).

3. RADIATIVE IMPLICATIONS

3.1. X-ray obscuration

The primary observational puzzle of LRDs is their X-ray faintness. Using the conservative estimate in

Eq. (2), typical columns can reach $N_{\text{H}} \sim 10^{24} - 10^{25} \text{ cm}^{-2}$. The Thomson optical depth is $\tau_T = \sigma_T N_{\text{H}} \approx 0.67 (N_{\text{H}}/10^{24} \text{ cm}^{-2})$. For $\tau_T \gtrsim 1$, the direct soft X-ray continuum is strongly suppressed. We expect the observed X-ray signal to be dominated by a scattered fraction f_{scat} . For typical AGN geometries, $f_{\text{scat}} \sim 1 - 5\%$, implying a suppression of the apparent L_X by $\sim 1.5 - 2$ dex, consistent with Maiolino et al. (2024).

3.2. Dust Attenuation and Broad Line Visibility

While electron scattering suppresses X-rays, dust provides the dominant opacity for UV/optical photons. We treat A_V as an order-of-magnitude indicator of heavy reprocessing.

To explain the visibility of broad H α lines despite this obscuration, we propose a clumpy dust cocoon geometry. Assuming a bi-conical geometry with half-opening angle $\theta \sim 45^\circ$, the covering factor is $f_{\text{cov}} = \cos \theta \approx 0.7$. This allows a sufficient fraction of the broad-line region flux to escape or be scattered into the line of sight, matching the high detection rate of LRDs.

3.3. Thermodynamic Equilibrium

Assuming the obscured luminosity is re-radiated in the IR, a characteristic effective temperature follows from the Stefan–Boltzmann law. For $L_{\text{bol}} \sim 10^{46} \text{ erg s}^{-1}$ and a photospheric scale $R_{\text{ph}} \sim \mathcal{O}(r_c)$, we obtain $T_{\text{eff}} \approx 150 - 200 \text{ K}$, implying a rest-frame mid-IR bump (peak near $\sim 20 \mu\text{m}$). The very red JWST colors at shorter wavelengths likely require an additional hotter dust component (near the sublimation radius) and/or anisotropic leakage/scattering through a non-uniform cocoon; quantifying the detailed SED requires radiative-transfer/radiation-hydrodynamic modeling.

4. NUMERICAL METHODOLOGY

Our analytic picture requires that deep, compact solitonic potentials form robustly. We validate this using 3D simulations.

4.1. Setup and Initial Conditions

We solve the Schrödinger–Poisson system using a pseudo-spectral code on a $N = 512^3$ grid with periodic boundary conditions (see Schive et al. 2014a). Our aim is not to claim the discovery of soliton formation, but to demonstrate that compact cores with LRD-like scales form robustly in this setup. To model the formation of the potential well, we initialize the wavefunction with eight identical ground-state solitons with zero initial phases (free-fall merger). While we use zero phase for demonstration, previous studies have shown soliton formation is robust against random phase fluctuations

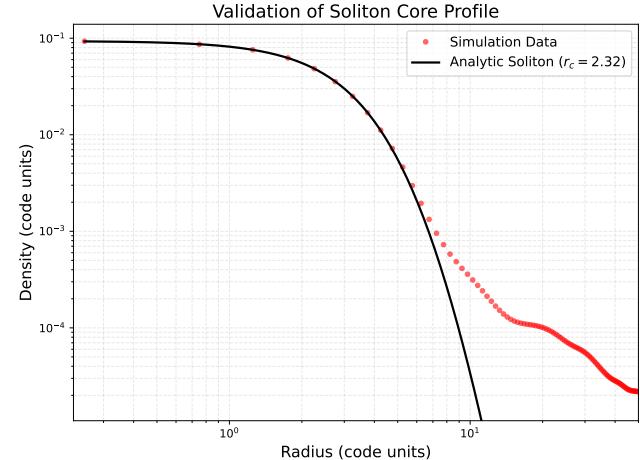


Figure 3. Validation of a compact soliton core in an idealized merger. Radial density profile of the simulated core (red points) plotted against the analytic soliton solution (black line). The inner region is well described by the soliton profile.

(Schive et al. 2014b). The code is GPU-accelerated (CUDA) and was executed on an NVIDIA RTX 3080, requiring approximately one day of runtime.

4.2. Physical Scaling

For $m_{22} = 2.0$, we scale our simulation box to $L_{\text{phys}} = 2.0 \text{ kpc}$. This maps our initial configuration to 8 solitons of mass $M_{\text{ini}} \approx 3.9 \times 10^8 M_{\odot}$ each. The final central soliton contains $M_c \approx 7.8 \times 10^8 M_{\odot}$ with a radius $r_c \approx 51 \text{ pc}$. This creates a representative scaling consistent with LRDs.

5. SIMULATION RESULTS

Figure 3 shows the density profile of the final core. The inner region is well described by the soliton profile, illustrating that violent relaxation in idealized mergers can form a compact solitonic potential well. Under our representative physical scaling, the core has $M_c \sim 8 \times 10^8 M_{\odot}$ and $r_c \sim 50 \text{ pc}$, placing it in the range considered in our analytic estimates.

6. DISCUSSION

6.1. The Tension with Lyman- α Forest

We acknowledge that $m_{22} \approx 2.0$ is in tension with some Lyman- α constraints ($m_{22} \gtrsim 20$). However, the LRD size-based argument is a direct constraint on the compact gravitational potential shape. Under the working assumptions adopted here ($M_s \sim 10^8 - 10^9 M_{\odot}$ and $r_e \sim \mathcal{O}(r_c)$), the observed compact sizes favor $m_{22} \sim \text{few}$. If Lyman- α forest analyses robustly require $m_{22} \gtrsim \mathcal{O}(10)$, possible resolutions include a sub-

dominant FDM fraction or revisions to IGM thermal history assumptions.

6.2. Observational Signatures

We provide specific observational predictions:

- **Inverse Size–Mass Relation:** For soliton cores at fixed m_{22} , the soliton scaling implies $r_c \propto M_c^{-1}$. Figure 4 serves as an illustrative mapping assuming M_{BH} tracks M_c . Establishing this as a discriminator will require joint constraints on host masses.
- **Polarization:** Our clumpy dust cocoon model inevitably imprints a polarization signal on the broad emission lines (e.g., Greene et al. 2024).
- **Compact Hot Dust vs. ALMA Non-detections:** Recent ALMA observations constrain the cold dust mass ($M_{\text{dust}} \lesssim 10^6 M_\odot$; Casey et al. 2025). The “Opacity Crisis” creates extreme gas column densities within a tiny volume, consistent with low total dust mass despite high optical depth.

6.3. Demographics and Duty Cycle

A key question is whether the transient obscured phase implied by the “Opacity Crisis” can match the observed abundance of LRDs, $n_{\text{LRD}} \sim 10^{-5} \text{ comoving Mpc}^{-3}$ (here cMpc denotes comoving Mpc). For massive halos at $z \sim 5\text{--}7$, a representative number density is $n_{\text{halo}} \sim 10^{-4} \text{ cMpc}^{-3}$ (e.g., Kokorev et al. 2024), suggesting an instantaneous occupancy fraction of order $f_{\text{occ}} \equiv n_{\text{LRD}}/n_{\text{halo}} \sim 0.1$.

More generally, the occupancy can be written as a time-averaged duty cycle,

$$n_{\text{LRD}} \simeq n_{\text{halo}} P_{\text{trig}} N_{\text{evt}} \left(\frac{t_{\text{evt}}}{t_H} \right), \quad (10)$$

where P_{trig} is the probability that a given halo experiences an LRD-triggering event within the relevant redshift window, N_{evt} is the number of such episodes per

halo, t_{evt} is the observable duration of each episode, and t_H is the Hubble time at that epoch. While the free-fall time of the dense core can be short ($t_{\text{ff}} \sim 10^5 \text{ yr}$), feedback, clumpy obscuration, and/or repeated episodes can extend the effective observable duration to $t_{\text{evt}} \sim 10^6\text{--}10^7 \text{ yr}$. Matching $f_{\text{occ}} \sim 0.1$ then requires $P_{\text{trig}} N_{\text{evt}}$ to be of order unity to several, motivating multiple merger-driven or inflow-driven obscured episodes during early assembly.

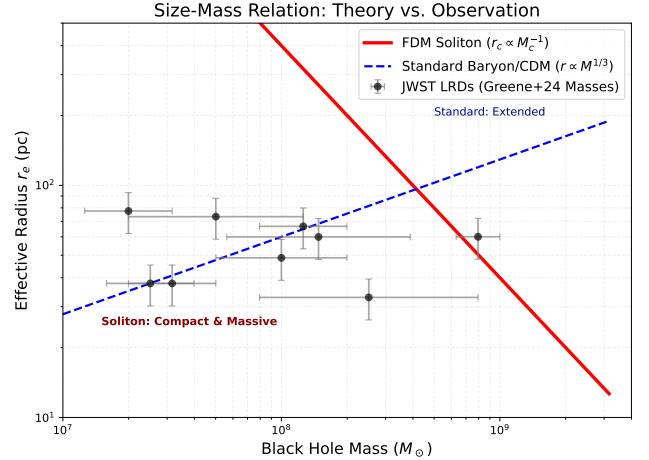


Figure 4. Size–mass illustration. Black points show SMBH masses from broad H α in spectroscopically confirmed LRDs (Greene et al. 2024), plotted against characteristic effective radii ($r_e \sim 30\text{--}100 \text{ pc}$; Kokorev et al. 2024). The red line indicates the soliton-inspired inverse scaling, shown here only as an illustrative mapping under the assumption that M_{BH} roughly traces the soliton core mass with large scatter.

7. CONCLUSION

We have presented a compact model in which LRD-like systems arise during a transient, heavily obscured phase inside FDM soliton cores. Combining size scaling with opacity constraints suggests $m_{22} \sim \text{few}$. A conservative column estimate, including sensitivity analysis for baryon loading, indicates that reaching $N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2}$ typically implies radiative losses faster than dynamical support (or radiation-pressure dominance), disfavoring a long-lived static hot atmosphere and motivating rapid inflow or radiation-pressure-driven evolution.

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