AB INITIO COSMOLOGICAL SIMULATIONS OF CR7 AS AN ACTIVE BLACK HOLE

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ABSTRACT

We present the first ab initio cosmological simulations of a CR7-like object that approximately reproduce the observed line widths and strengths. In our model, CR7 is powered by a massive ($3.25 \times 10^7 M_\odot$) black hole (BH), the accretion rate of which varies between $\sim 0.25$ and $\sim 0.9$ times the Eddington rate on timescales as short as $10^3$ years. Our model takes into account multi-dimensional effects, X-ray feedback, secondary ionizations, and primordial chemistry. We estimate Ly$\alpha$ line widths by post-processing simulation output with Monte Carlo radiative transfer and calculate emissivity contributions from radiative recombination and collisional excitation. We find the luminosities in the Ly$\alpha$ and He$\,\Pi\,$1640 Å lines to be $5.0 \times 10^{44}$ and $2.4 \times 10^{43}$ erg s$^{-1}$, respectively, in agreement with the observed values of $>8.3 \times 10^{43}$ and $2.0 \times 10^{43}$ erg s$^{-1}$. We also find that the BH heats the halo and renders it unable to produce stars as required to keep the halo metal free. These results demonstrate the viability of the BH hypothesis for CR7 in a cosmological context. Assuming the BH mass and accretion rate that we find, we estimate the synchrotron luminosity of CR7 to be $P \approx 10^{40} - 10^{41}$ erg s$^{-1}$, which is sufficiently luminous to be observed in $\mu$Jy observations and would discriminate this scenario from one where the luminosity is driven by Population III stars.

Key words: galaxies: active – hydrodynamics – quasars: general – radiation: dynamics – X-rays: galaxies

1. INTRODUCTION

One of the most intriguing observations of the high-redshift universe is the detection of the extraordinarily bright Ly$\alpha$ emitting object in CR7, which exhibits some of the principal characteristics predicted for a galaxy composed solely of pristine primordial gas (Sobral et al. 2015). Among these characteristics are bright He$\,\Pi\,$1640 Å emission, indicative of a hot nebula powered by radiation with a particularly hard spectrum (e.g., Bromm et al. 2001; Oh et al. 2001; Tumlinson et al. 2001; Schaerer 2002); the absence of emission features from elements heavier than the helium produced during Big Bang nucleosynthesis; and a nearby ($\geq 5$ kpc) metal-enriched galaxy, ultraviolet (UV) radiation from which could have suppressed star formation, and the resultant metal enrichment from supernovae, in its progenitor dark matter (DM) halos.

These characteristics are consistent with two possibilities for the sources of the radiation powering CR7: a massive ($\geq 10^7 M_\odot$) cluster of Population III stars formed from the rapid collapse of primordial gas photo-heated by the neighboring galaxy (Johnson 2010; Visbal et al. 2016), and an accreting black hole (BH) with a mass $\geq 10^6 M_\odot$ (Pallottini et al. 2015) that may drive a strong outflow that imprints features in the Ly$\alpha$ line profile (Dijkstra et al. 2016; Smith et al. 2016). Concerning the latter possibility, it appears likely that the neighboring galaxy may have produced sufficient UV radiation for the BH to have been born with a mass $\sim 10^5 M_\odot$ via direct collapse (Agarwal et al. 2016; Hartwig et al. 2016); if so, this would confirm the validity of this mode of BH seeding that has been previously invoked to explain the most massive BHs at $z \geq 6$ (for reviews see Volonteri 2012; Haiman 2013; Johnson & Haardt 2016; Latif & Ferrara 2016).

In this Letter, we present the first cosmological hydrodynamic simulations aimed directly at modeling the Ly$\alpha$ emitting object in CR7, under the assumption that it is indeed powered by accretion of primordial gas onto a BH that is seeded at higher redshift ($z \sim 15$).3 In the next section, we describe our Enzo radiation hydrodynamic simulations of the growth and radiative feedback from the BH. In Section 3, we present our modeling of the nebular emission powered by the accretion process at the observed redshift $z \sim 6.6$ of CR7. Finally, we conclude with a brief discussion of our results in Section 4.

2. PROBLEM SETUP

The simulations were preformed using Enzo (Bryan et al. 2013), which contains the necessary modules for hydrodynamics, radiation, primordial chemistry, and BH physics required in this calculation. The initial conditions were generated by MUSIC (Hahn & Abel 2011) using the Planck 2015 TT, TE, EE+lowP+lensing+ext best-fit parameters (Ade et al. 2015). MUSIC was run using the Eisenstein & Hu transfer function with second-order perturbation theory enabled and an initial redshift of $z = 200$.

To find the optimal halo, several 4 Mpc/$h$ boxes with 256$^3$ resolution were generated with MUSIC. These boxes were then run in Enzo with both baryons and DM down to $z = 6.6$ with one level of AMR refinement everywhere in the box. YT’s (Turk 2011) HOP halo finder was used on several redshift snapshots for each box to find a halo with the right final mass and stability properties: since a nested-refinement simulation was to be run, it is important that the halo remain stationary on the grid down to the final redshift with no large mergers from other halos that formed off the nested grid. One box containing a $3 \times 10^9 M_\odot$ halo, roughly consistent with estimates from the literature (Agarwal et al. 2016; Hartwig et al. 2016), was chosen to be the simulation described in the rest of this Letter.

3 While our simulations do not capture every process contributing to the formation of a CR7-like object, starting from the Big Bang, they are ab initio in the sense that they track the key processes impacting the formation of such an object starting from realistic cosmological initial conditions.
MUSIC was then rerun with nested grids to create a central fine-grid region, extending 25% across the box centered on the known halo, with an effective resolution of 1024 and the same random seeds as before. This central fine-grid region contains $9.11 \times 10^{10} h^{-1} M_{\odot}$ of matter with a DM particle mass resolution of 4305.74 $h^{-1} M_{\odot}$, and a baryon mass resolution of 803.9 $h^{-1} M_{\odot}$. These initial conditions became the basis for our production run.

These initial conditions were evolved in Enzo with nine-species primordial chemistry and cooling (H, H+, He, He+, He++, e-, H2, H2+, and H-) allowing up to nine levels of AMR refinement in the fine-grid region triggered by overdensities in DM or baryons and the additional criteria of 32 cells across a Jean’s length. Nine levels of refinement represents a spatial resolution of $\sim 30 \text{ pc}/h$. The simulation was run until our candidate halo reached $10^8 M_{\odot}$ around $z \sim 15$. At this point a massive BH seed was inserted in the center of the halo, and radiation feedback using an X-ray spectrum taken from Johnson et al. (2011; see also, e.g., Kuhlen & Madau 2005) was emitted from the seed as feedback. This spectrum was binned into four equal bins representing the first through fourth 25% bins of energy of that spectrum (with bin centers at 227, 388, 566, and 838 eV). The accretion onto the BH was regulated by the subgrid alpha disk formalism of DeBuhr et al. (2010) and a Lyman-Werner background of $J_{21} = 10^4$ (in units of $10^{-21}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$) was turned on, in order to mimic the radiative feedback from the galaxies nearby CR7 (e.g., Agarwal et al. 2016).

A few initial BH seeds were attempted. The reason being that large BH seeds, the $10^{-5} M_{\odot}$ suggested in the direct collapse model, reach $10^7 M_{\odot}$ rather quickly and then loiter in that region with significantly sub-Eddington accretion. In contrast, $10^3$ BH seeds take longer to grow to $10^7 M_{\odot}$ and thus are closer to the near-Eddington accretion proposed in the literature. We find that candidates that are still within a factor of a few from Eddington at $z = 6.6$ have line ratios that match the observations best with our best seed presented in this Letter being 3160 $M_{\odot}$. It must be stressed, however, that this seed is dependent on the dynamics of the halo chosen. For example, had we simulated a halo that arrived at $10^9 M_{\odot}$ later on through mergers, a larger BH seed more like $10^4 M_{\odot}$ may have been needed. Given our simplified approach to modeling the Lyman Werner radiation field, which in the CR7 system is likely dominated by nearby star-forming galaxies, our simulations do not capture details of the initial collapse of the primordial gas in the formation of the BH seed that relate to the anisotropic radiation field produced by nearby sources (e.g., Dijkstra et al. 2008; Ahn et al. 2009; Agarwal et al. 2014, Regan et al. 2014; Visbal et al. 2014; Chon et al. 2016; Habouzit et al. 2016; Valiante et al. 2016) or to the impact of higher-energy radiation, which can alter the chemistry of the primordial gas (e.g., Inayoshi & Omukai 2011; Regan et al. 2016a, 2016b). That said, given that a BH does in fact form, our simulations track the impact of the radiation produced in the accretion process, which we expect to play a dominant role in determining the chemical and dynamical state of the gas in the host halo.

Figure 1 shows profiles of the halo at $z = 6.6$.

3. POST-PROCESS

In primordial galaxies, Ly$\alpha$ primarily originates from a sequence of de-excitations in atomic hydrogen following recombination. If the ionizing spectrum is harder than that produced by massive Pop III stars, soft X-rays ($\sim$1 keV) can escape largely ionized regions and be absorbed in the neutral IGM. Ionizations by high-energy photons result in correspondingly energetic free electrons that can serve to also ionize and excite additional neutral hydrogen. Up to 30% of an electron’s energy in such scenarios can result in Ly$\alpha$ luminosity (Valdes & Ferrara 2008; Baek & Ferrara 2013). We note that this scenario will not take place with a softer ionizing spectrum as ionizing photons are liable to be absorbed in a larger H II region and electron energies only contribute to heat the gas through electron–electron scatterings.

ENZO+MORAY treats secondary ionizations (Wise & Abel 2011). The Ly$\alpha$ emissivity in the frame of the fluid $\epsilon(\nu)$ of a parcel of gas of volume $V$ with electron and proton number densities $n_e$ and $n_p$ from radiative recombinations is just

$$\epsilon(\nu) = C n_e n_p \alpha_B E_{Ly\alpha} \phi(\nu) V,$$

where $C$ is the fraction of recombinations resulting in the Ly$\alpha$ transition, $\alpha_B$ is the case-B recombination coefficient, $E_{Ly\alpha}$ is the energy of the $2 \rightarrow 1$ transition, and $\phi(\nu)$ is the Voigt line profile that takes into account the effects of thermal Doppler broadening and is normalized to 1. The escape fraction $f_{esc}$ of Ly$\alpha$ photons for a BH scenario is $\sim$0.5 and $\sim$0.1 for primordial stellar populations, respectively (see Hartwig et al. 2016). Our process also takes into account contributions from collisional excitation and the effects of collisional de-excitation.

Ly$\alpha$ is a resonant line, so line strengths and widths must be calculated with a method that takes into account scattering. Our Monte Carlo (MC) Ly$\alpha$ transfer calculation, facilitated by the HOT framework (Warren & Salmon 1995) is identical to that found in Dijkstra (2014), but we do not take into account energy losses from recoil (e.g., Barnes et al. 2014) or relativistic effects that are negligible at these energies. Our MC process further takes into account destruction of Ly$\alpha$ via collisional de-excitations and photoionization of excited hydrogen that can be effective in metal-free environments (Dijkstra et al. 2016). We calculate Ly$\alpha$ spectra via a peel-off method (e.g., Zheng & Miralda-Escudé 2002) and accelerate the scheme with the prescription in Barnes (2009). We verified our code against the static slab and expanding sphere test cases. We
further assume steady-state transfer, i.e., we post-process only a single data dump at $z = 6.6$.

He II 1640 Å emission may also be recombinatory, but at temperatures $10^5$–$10^6$ K, emission from collisional excitations dominate. To derive He II 1640 Å emission, we use the method in Yang et al. (2006). Such emission is not resonant, so will only be thermally and kinematically broadened by bulk-fluid motions.

4. DISCUSSION AND CONCLUSIONS

CR7 is the brightest Ly$\alpha$ emitter known at $z > 6$. At a redshift of $z = 6.6$, it is estimated to have a Ly$\alpha$ luminosity $L_{\text{Ly}\alpha} \gtrsim 8.0 \times 10^{43} \text{ erg s}^{-1}$ with a narrow line width of $\sim 266 \pm 15 \text{ km s}^{-1}$. The He II 1640 Å line is luminous $L_{\text{He II}} \approx 2.0 \times 10^{43} \text{ erg s}^{-1}$ with a width of $130 \pm 30 \text{ km s}^{-1}$. This implies a large $L_{\text{He II}}/L_{\text{Ly}\alpha}$ ratio $\approx 0.22$ (Sobral et al. 2015), which is strongly suggestive of a hard ionizing spectrum (Pallottini et al. 2015).

By $z = 6.6$, our halo has acquired $3 \times 10^{10} M_\odot$ and the 3162 $M_\odot$ initial seed has grown to $3.23 \times 10^7 M_\odot$. In our cosmological model, CR7 is situated on a major filament and is fed strongly aspherically (see Figure 2). Recombinatory Ly$\alpha$ emissivity originates from the inner $\sim 3 \text{kpc}$ while He II 1640 Å emission appears in the direct vicinity of the BH. In Figure 1, we plot azimuthally averaged number densities of primordial species as a function of radius and overlay gas temperature in blue. Throughout the halo, temperatures and gas pressures are prohibitive for star formation.4

We summarize our results in Table 1. At $z = 6.6$, the instantaneous Ly$\alpha$ emissivities in our model due to recombination and collisional excitation are $7.6 \times 10^{33}$ and $4.2 \times 10^{44} \text{ erg s}^{-1}$, respectively. This would imply a very large fraction ($\sim 60\%$) of the BH luminosity, $L_\odot = 7.87 \times 10^{44} \text{ erg s}^{-1}$, being converted into Ly$\alpha$. However, the accretion rate in the snapshot we chose to post-process is quite low compared to the near-Eddington accretion rates observed over $10^5$ year timescales (see Figure 4). The accretion rate varies from $0.9 \text{ to } 0.25 \text{ Eddington}$ on a timescale of $\approx 600$ years immediately before the post-processed snapshot, which is shorter than the cooling time (of the order of $10^4$ years) for metal-free gas at temperatures and densities of the most Ly$\alpha$-luminous zones in the domain. Because of this, the Ly$\alpha$ luminosity lags the luminosity of the BH in our calculation. The FWHM of the He II 1640 Å line is $210 \text{ km s}^{-1}$, which is broader than the observations ($130 \pm 30 \text{ km s}^{-1}$), while Ly$\alpha$ exhibits a width of $\sim 280 \text{ km s}^{-1}$ after MC post-process, which is in rough agreement with observed values of $\sim 266 \pm 15 \text{ km s}^{-1}$ (see Figure 3). This is achieved with $M_\bullet = 3.23 \times 10^7 M_\odot$, $M_\odot = 0.16 M_\odot \text{ yr}^{-1}$, and $L_\odot = 7.87 \times 10^{44} \text{ erg s}^{-1}$. We note that the instantaneously low accretion rate of the BH may be reflected in a lower luminosity in continuum photons originating from the disk, which could contribute to raising the observed equivalent width of the He II 1640 Å line.

The He II 1640 Å and Ly$\alpha$ lines in CR7 are offset in velocity space by $\Delta v = +160 \text{ km s}^{-1}$ (Sobral et al. 2015). 1D calculations by Smith et al. (2016) are able to reproduce this offset by demonstrating that a luminous central source with a hard spectrum drives an outflow that would separate He II and Ly$\alpha$ emission in velocity space. Our model does not incorporate feedback from Ly$\alpha$, but we are able to reproduce an offset by selecting a fortuitous viewing angle of our 3D model, which has a complex bulk-fluid velocity and density field. The relative size of the two Ly$\alpha$ peaks varies depending on the orientation of observations. A single Ly$\alpha$ feature is observed in CR7, but we do not take into account extinction of the Ly$\alpha$ profile through the IGM, which could further diminish the blue peak giving the appearance of a single peak displaced redward of the He II 1640 Å emission (Dijkstra et al. 2016). The major feature in the spectrum that agrees best with the observed spectrum of CR7 (solid line) is asymmetric and offset with respect to the He II 1640 Å emission as is observed (Sobral et al. 2015), though our offset ($+220 \text{ km s}^{-1}$) is larger than CR7’s ($+160 \text{ km s}^{-1}$). An expanding shell of material is not evident in our model. There are several possible explanations for this. Our CR7 model is largely ellipsoidal, not spherical, being compressed along the direction of the angular momentum vector. This strong flattening of the system allows for radiation to escape CR7 through higher angles of latitude.

We note that Population III stars are expected to produce nebular Ly$\alpha$ emission principally from recombination, and not from collisional excitation as is the case for the harder X-ray spectrum emitted from an active BH. We estimate an upper limit for the Ly$\alpha$ luminosity of $1.14 \times 10^{44}$ that could be generated by recombination emission powered by Population III stars, by assuming that the gas within the halo is fully ionized.5 This is only luminous enough to explain the CR7 luminosity if the Ly$\alpha$ escape fraction is $f_{\text{esc}} \approx 0.8$, much higher than previously estimated (e.g., Hartwig et al. 2016). This, along with the extremely high star formation efficiency of $\geq 0.1$ that is required for Population III stars to explain the observed emission (Smith et al. 2016; Visbal et al. 2016), poses a strong challenge to this alternative model for CR7.

While Ly$\alpha$ is extended on the kiloparsec scale, much of the helium emission in our model originates from the vicinity of the BH. We find that to maintain line widths $\approx 100 \text{ km s}^{-1}$ in agreement with CR7 requires that the line be only broadened by virial velocities of bulk-fluid motion and thermal broadening. Our models with more massive BHs both diminish and broaden He II 1640 Å emission, in some cases giving rise to a double-peak profile that characterizes line observations of expanding shells of gas. The complex line profiles are not observed in CR7, which suggests an upper limit on BH luminosity in models of CR7 powered by an accreting BH.

Could CR7 be detected in the radio? Our estimate of the accretion rate suggests the BH is accreting within the “thin disk” regime or “quasar mode” (e.g., Dubois et al. 2011) where the prospects of launching a relativistic jet and powering radio lobes remains unclear. Yet, radio synchrotron emission could originate on scales of 100s of Schwarzschild radii from relativistic accretion shocks. For our values of $M_\bullet$ and $M_\odot$ in the analytic model by Ishibashi & Courvoisier (2011) and adopting the authors’ estimates for electron spectral index $p$ and ambient magnetic field $B$, we estimate a synchrotron luminosity of

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4 We note, however, that, using somewhat different prescriptions to model accretion and radiative feedback, Akutupol et al. (2014) find that star formation may occur in some cases.

5 For this estimate we have adopted the density field extracted from our simulation. If the gas is significantly more dense in the halo in the case of Population III star formation, then the luminosity in recombination lines could be higher due to the higher recombination rate. That said, the strong photoionization feedback from massive Population III stars would likely drive down the density of the gas very quickly after the formation of the stars (e.g., Whalen et al. 2004).
1.0 \times 10^{39} \text{erg s}^{-1} \text{ arising from subgrid scales. The total observed radio flux density } S_\nu \text{ of CR7 integrated over the source is}

\begin{equation}
S_\nu = \frac{P_{\nu_0}}{\nu_0 \cdot 4\pi D_L^2 (1 + z)^3} \text{ erg s}^{-1},
\end{equation}

where \( P_{\nu_0} \) is the power radiated at frequency \( \nu_0 \), \( D_L \) is the luminosity distance, and \( \nu \) is the frequency of observations related to the emitted frequency \( \nu_0 \) by the Doppler shift. We take \( \alpha \approx 1.5 \), accounting for the \( z \sim \alpha \) correlation for steepening radio spectral indices with increasing redshift (\( \alpha \approx 0.7 \) at \( z = 0 \); see Condon 1992; Cavagnolo et al. 2010) for emitted frequencies at 10.0 GHz. For sensitivities of a few \( \mu \)Jy per beam in the L-band (\( \nu \approx 1.3 \text{ GHz} \)), this imposes a detection limit of \( P_{\nu_0} \gtrsim 10^{41} \text{ erg s}^{-1} \). This quantity is mildly sensitive to the choice of \( \alpha \); for local-universe values, the detection limit becomes \( P_{\nu_0} \gtrsim 10^{40} \text{ erg s}^{-1} \).

Scaling relationships for accretion, jet power, and radio luminosity exist in the literature. If we insert our active galactic nuclei (AGNs) luminosity in X-rays and \( M_\bullet \) into a model by Merloni et al. (2003), which is based on a theory of scale-invariant jets (Heinz & Sunyaev 2003), we obtain a log-mean

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**Figure 2.** Projection of logarithm of emissivity [erg s\(^{-1}\)] in Ly\(\alpha\) (left panels) and He \(\pi 1640\) Å (right panels). In the top panels, we plot emissivity due to radiative recombination. In the bottom panels, we plot emissivity due to collisional excitations. Note the difference in color scales.

**Table 1**

| Line          | Observations | Simulation |
|---------------|--------------|------------|
|               | Luminosity   | FWHM       | Luminosity | FWHM |
| Ly\(\alpha\)  | >8.3 \times 10^{43} | 266 ± 15  | 5.0 \times 10^{44} | 310 |
| He \(\pi 1640\) Å | 2.0 \times 10^{43} | 130 ± 30  | 2.4 \times 10^{43} | 210 |

**Note.** Line luminosities and length widths (FWHM) are given in erg s\(^{-1}\) and km s\(^{-1}\), respectively. Observed line widths and strengths are adopted from Sobral et al. (2015).
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The central, major peaks change size with viewing angle. The spectrum more closely resembling CR7 is emphasized with a solid line. We do not take into account processing through the IGM, which may further diminish the blue peak. The larger Lyα line pro

Figure 3. Lyα line profiles for two perpendicular viewing angles of the CR7 model after Monte Carlo radiative transfer post-processing through the simulation domain assuming steady-state emission (i.e., we only post-process a single data dump at z = 6.6), with a peel-off scheme (e.g., Zheng & Miralda-Escudé 2002). The two central, major peaks change size with viewing angle. The spectrum more closely resembling CR7 is emphasized with a solid line. We do not take into account processing through the IGM, which may further diminish the blue peak. The larger Lyα feature offset redward of the He II 1640 Å line has an FWHM of ~280 km s⁻¹ in approximate agreement with observations. Though our model predicts a velocity offset, we do not obtain the observed 160 km s⁻¹ offset for Lyα with respect to the He II 1640 Å line (see the text).

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Figure 4. Instantaneous accretion rate onto the black hole (blue line) over the 0.1 Myr of the simulation ending at the time of the snapshot we have post-processed at z = 6.6. In the last 600 years there has been a sharp drop in the accretion rate from roughly the Eddington luminosity down to roughly a fourth of this value. As the cooling timescale for the Lyα emitting gas is of the order of 10⁴ years, much of this nebular emission is powered by the accretion luminosity generated at earlier times and is not necessarily reflective of the instantaneous accretion rate.

radio luminosity of P ≈ 1.4 × 10⁴⁰ erg s⁻¹, though their model suffers from very large scatter, spanning a few orders of magnitude. If we apply our data to the models of Meier (2001), adopting the thin disk regime for the Schwarzschild case (his Equation (4)), we obtain a jet power of ~1.0 × 10⁴¹ erg s⁻¹. If we utilize the relation between jet power and radio output found in Cavagnolo et al. (2010), this corresponds to a radio luminosity of only 10³⁵ erg s⁻¹. Our BH is accreting at an appreciable fraction of Eddington, and such disks can be unstable and oscillate between a low, hard (LHS) state where radio brightness is expected to increase and a high, soft (HSS) state. At a reduced accretion rate of 0.1 Eddington, jet power for a rotating BH would be ≥10⁴⁴ erg s⁻¹ corresponding to a radio luminosity of P r ≈ 2.0 × 10⁴² erg s⁻¹, which would be detectable in µJy observations. Such jets may drive outflows and could be responsible for the 160 km s⁻¹ offset of the Lyα line from the systemic velocity. In our model, the BH accretes at a large fraction of Eddington for a large duration of the simulation, which may correspond to a thicker, radiation-dominated disk, greater probabilities of launching a jet, and hence larger radio luminosities. Any luminous radio emission from CR7 is likely to be evidence of AGN activity, as synchrotron emission in star formation regions primarily arises from supernova remnants that are thought to be absent in CR7 from the lack of observed metals.

Our work provides important additional support for the massive BH model of CR7 via detailed radiation hydrodynamic cosmological simulations.
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