



Evolution of Starless Cores in Massive Clumps Seen by the ALMA ASHES and QUARKS Surveys

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Abstract

We present a systematic comparative analysis of 324 starless cores in early-phase infrared-dark clouds (IRDCs; ASHES survey) and evolved-phase infrared-bright clouds (IRBCs; QUARKS survey) using 1.3 mm continuum and line data by the Atacama Large Millimeter/submillimeter Array. Despite having comparable sizes (~ 2500 au), starless cores in IRBCs exhibit systematically higher median mass ($1.5 M_{\odot}$ versus $0.6 M_{\odot}$), number density, and surface density—enhancements of approximately a factor of 2 relative to starless cores in IRDCs. Starless cores in IRBCs also display relatively stronger nonthermal motions ($\sigma \sim 0.5 \text{ km s}^{-1}$ versus 0.3 km s^{-1}), higher total virial parameters (median $\alpha_{\text{vir,tot}} \sim 2.3$ versus 1.0), and steeper density profiles, indicating more centrally concentrated structures in feedback-driven, turbulence-enhanced environments. These findings support a dual evolutionary origin: (i) new core formation in evolved IRBCs under altered initial conditions and (ii) subsequent dynamical mass growth via accretion from extended reservoirs. The prevalence of low-mass starless cores—even in late-stage IRBC environments—challenges models requiring massive prestellar cores and instead favors competitive-like dynamical mass accretion scenarios for high-mass star formation.

Unified Astronomy Thesaurus concepts: [Interstellar medium \(847\)](#); [Dust continuum emission \(412\)](#); [Submillimeter astronomy \(1647\)](#); [Molecular clouds \(1072\)](#); [Star forming regions \(1565\)](#); [Massive stars \(732\)](#)

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1. Introduction

The formation mechanism of high-mass stars ($M_{*} \gtrsim 8 M_{\odot}$) remains one of the most challenging problems in modern astrophysics, despite decades of intensive research. Their formation in distant clustered environments, rapid evolution, and intense feedback processes (e.g., radiation pressure, outflows, H II regions) severely complicate observational



investigations (C. J. Lada & E. A. Lada 2003; H. Zinnecker & H. W. Yorke 2007; Q. Zhang et al. 2009; F. Motte et al. 2018; H. Beuther et al. 2025). It is widely accepted that high-mass stars originate within dense ($n \sim 10^6 \text{ cm}^{-3}$), compact ($\lesssim 0.1 \text{ pc}$) structures known as dense cores, which themselves reside within larger ($\sim 0.5\text{--}1 \text{ pc}$) molecular clumps (E. A. Bergin & M. Tafalla 2007; Q. Zhang et al. 2015; F. Motte et al. 2018). Among these, starless cores—dense cores lacking internal protostars—represent the earliest observable stage of star formation. A subset of these, if gravitationally bound, are termed prestellar cores (D. Ward-Thompson et al. 1994, 2007; P. André et al. 2014) and are direct progenitors of future stars.

Two mainstream theoretical frameworks attempt to explain high-mass star formation: the turbulent core accretion model (C. F. McKee & J. C. Tan 2003) and the competitive accretion model (I. A. Bonnell et al. 2001). The former requires the prior existence of massive prestellar cores (above a few $10 \times M_\odot$) that collapse monolithically to form a single high-mass star. In contrast, the latter posits that clumps first fragment into numerous low-mass, thermal-Jeans-scale cores, which then grow competitively by accreting gas from a common reservoir, likely via filamentary networks (R. J. Smith et al. 2009; E. Vázquez-Semadeni et al. 2019; P. Padoan et al. 2020). Critically, distinguishing between these scenarios hinges on the observational identification of genuine high-mass prestellar cores (Q. Zhang et al. 2009; J. C. Tan et al. 2013; F. Motte et al. 2018).

However, despite extensive searches over the past two decades, confirmed high-mass prestellar cores remain exceedingly rare (K. Wang et al. 2014; T. Liu et al. 2017; A. T. Barnes et al. 2023; X. Mai et al. 2024; M. Vaille-Manet et al. 2025; D. Yang et al. 2025b). The vast majority of observed starless cores—even in high-mass star-forming regions—are low-mass ($M \lesssim 10 M_\odot$). This observational reality necessitates a paradigm shift: rather than focusing solely on elusive massive cores, we must systematically study the properties of low-mass starless cores within high-mass star-forming regions to understand how high-mass stars assemble their mass over time. While such cores have been extensively characterized in low-mass star-forming regions (M. L. Enoch et al. 2008), their counterparts in high-mass regions lack a comprehensive statistical analysis, particularly across evolutionary stages, hindering our understanding of high-mass star formation.

Here, we leveraged high-resolution 1.3 mm continuum and spectral line data from two complementary surveys of the Atacama Large Millimeter/submillimeter Array (ALMA) to conduct the first systematic comparison of starless cores across the evolutionary sequence of high-mass star formation. The two surveys include the ALMA Survey of 70 μm dark High-mass clumps in Early Stages (ASHES; targeting quiescent infrared-dark cloud, IRDC, environments; P. Sanhueza et al. 2019; S. Li et al. 2022, 2023) and the Querying Underlying mechanisms of massive star formation with ALMA-Resolved gas Kinematics and Structures (QUARKS) survey (targeting evolved infrared-bright cloud, IRBC, environments; X. Liu et al. 2024; F. Xu et al. 2024a; D. Yang et al. 2025a). Here, IRDCs and IRBCs represent approximately early and late stages of the evolutionary sequence for star formation, respectively. IRDCs exhibit little to no ongoing activity, which preserves their dark appearance at infrared wavelengths (e.g., 8, 24, and 70 μm ; J. M. Rathborne et al. 2006;

P. Sanhueza et al. 2017, 2019). In contrast, IRBCs tend to be associated with active high-mass star formation, hosting strong feedback signatures such as molecular outflows and H II regions that produce prominent infrared features (e.g., extended green objects, EGOs; C. J. Cyganowski et al. 2008 and photodissociation regions, PDRs; J. M. Jackson et al. 2013; A. E. Guzmán et al. 2015; J. M. Rathborne et al. 2016).

This paper aims to explore core formation mechanisms, evaluate the influence of environmental evolution, and ultimately shed light on the physical pathways governing stellar mass growth in high-mass star-forming regions. To do so, we analyze the masses, densities, kinematics, and dynamical states of starless cores in both IRDC and IRBC environments. The paper is organized as follows. Section 2 describes the ALMA data from both surveys and the sample of candidate starless cores. Section 3 presents the results and analysis. Section 4 discusses the formation and evolution of starless cores. Section 5 summarizes the major results.

2. ALMA Data and Sample of Candidate Starless Cores

2.1. ALMA Data

This study utilizes high-resolution ALMA 1.3 mm observations from two complementary surveys, including the ASHES pilot survey focusing on IRDC environments and the QUARKS survey targeting IRBC environments. The combination of these datasets enables a comparative analysis of starless cores across distinct star-forming environments, facilitated by their well-matched observational configurations (see below).

The ASHES pilot survey (PI: Sanhueza; P. Sanhueza et al. 2019) observed 12 massive 70 μm dark clumps in IRDCs with typical sizes of $\sim 1 \text{ pc}$, masses of $\sim 10^2\text{--}10^3 M_\odot$, bolometric luminosities of $\sim 10\text{--}10^3 L_\odot$, luminosity-to-mass ratios (L_{bol}/M) of $\sim 0.05\text{--}1.7 L_\odot/M_\odot$, and distances of 2.9–5.4 kpc (P. Sanhueza et al. 2019; S. Li et al. 2022, 2023). Mosaic observations at 1.3 mm combined the 12 m array, Atacama Compact Array (ACA) 7 m array, and total power (TP). The combined 12 m and ACA 7 m continuum data have a maximum recoverable scale (MRS) of $\sim 29''$, a mosaic field of view (FoV) of $\sim 1'$ (1.5 times larger than that in QUARKS), a synthesized beam of $\sim 1.2''$, and a continuum sensitivity of $\sim 0.1 \text{ mJy beam}^{-1}$. General information about the survey is summarized in Table 1. Line data from the 12 m and ACA arrays were combined with TP, covering at least 10 transitions including $\text{N}_2\text{D}^+ J = 3\text{--}2$, $\text{DCN } J = 3\text{--}2$, and $\text{CO } J = 2\text{--}1$, with rms values of 9.5 and $3.5 \text{ mJy beam}^{-1}$ at velocity resolutions of 0.17 and 1.3 km s^{-1} , respectively. Detailed information on the spectral windows of the survey is listed in Table 2.

The QUARKS survey (PIs: Lei Zhu, Guido Garay, Tie Liu; Project ID: 2021.1.00095.S; X. Liu et al. 2024; F. Xu et al. 2024a; D. Yang et al. 2025a) is a follow-up program to the ATOMS survey (T. Liu et al. 2020; H.-L. Liu et al. 2021) that provides higher angular resolution ($\sim 0.3''$ versus $2''$) at 1.3 mm in ALMA Band 6. The survey targeted 139 massive proto-cluster clumps in IRBCs, with sizes of $\sim 1.5 \text{ pc}$, masses of $\sim 10^2\text{--}10^5 M_\odot$, luminosities of $\sim 10^3\text{--}10^7 L_\odot$, L_{bol}/M of $\sim 4\text{--}400 L_\odot/M_\odot$, and distances of 1–12 kpc. To map extended filamentary structures, 17 clumps were observed with two pointings, resulting in 156 fields. Observations employed three configurations: the ACA 7 m array ($\sim 5''$ resolution), the 12 m compact array C-2/C-3 (TM2; $\sim 1''$), and the extended C-5/C-

Table 1
Parameters of Targeted Clumps and Observing Setups in the QUARKS and ASHES Surveys

Survey	N_{Clumps}	Distances (kpc)	Masses ($M_{\odot}$)	Luminosities ($L_{\odot}$)	FoV (arcsec)	MRS (arcsec)	Ang. Res. ^b (arcsec)	Mass Sen. ^c ($M_{\odot}$)	N_{starless}
QUARKS ^a	139	1.2–11.6	10^2 – 10^5	10^3 – 10^7	~ 40	~ 29	~ 1.2	~ 0.14	127
ASHES Pilot	12	2.9–5.4	10^2 – 10^3	10 – 10^3	~ 60	~ 29	~ 1.2	~ 0.10	197

Notes.

^a QUARKS ACA 7 m + TM2 12 m combined data.

^b Angular resolution.

^c Mass sensitivity.

6 (TM1; $\sim 0.3''$) (see X. Liu et al. 2024, Table 1). The spectral setup covered an 8 GHz frequency bandwidth at a velocity resolution of $\sim 1.3 \text{ km s}^{-1}$, including cold gas tracers (e.g., N_2D^+ 3–2), outflow tracers (e.g., CO 2–1, SiO 5–4), hot molecular core tracers (CH_3CN 12–11), and the H30 α ionized gas tracer. In this study, we mainly used the combined TM2 and ACA 7 m data (D. Yang et al. 2025a), which achieved MRSs of $20''$ – $29''$, an FoV of $\sim 40''$, a synthesized beam of $\sim 1.2''$, and a continuum sensitivity of $\sim 0.6 \text{ mJy beam}^{-1}$. The line data have an average rms of $\sim 10 \text{ mJy beam}^{-1} \text{ channel}^{-1}$ at a synthesized beam of $\sim 1.2''$ (see Table 2).

The ASHES and QUARKS datasets are well suited for comparative analysis due to their closely matched observational parameters, which are summarized in Table 1. Both surveys achieved similar MRSs ($\sim 29''$) and synthesized beams ($\sim 1.2''$), ensuring consistent spatial filtering and resolution. Their continuum sensitivities (QUARKS: $\sim 0.4 \text{ mJy beam}^{-1}$; ASHES: $\sim 0.1 \text{ mJy beam}^{-1}$) translate to comparable mass sensitivities of $\sim 0.1 M_{\odot}$ at typical distances of 4 kpc, accounting for environmental temperature differences (see Section 2.2). Note that the QUARKS continuum sensitivity of $\sim 0.4 \text{ mJy beam}^{-1}$ is adopted here, as it applies specifically to the fields containing candidate starless cores (see below). This consistency in sensitivity, resolution, and spatial scale recovery significantly enhances the reliability of comparing starless core properties across the two surveys. In addition, the differing L_{bol}/M ratios between ASHES and QUARKS clumps that host dense cores, as characterized by median values of 0.3 and $40 L_{\odot}/M_{\odot}$, respectively, indicate that the starless cores in the two samples reside in star-forming environments at distinct evolutionary stages. This contrast enables a robust comparative analysis across the evolutionary sequence of high-mass star formation.

2.2. Sample of Starless Cores

Our sample of starless cores was drawn from the ASHES and QUARKS surveys, selected based on the absence of star formation signatures in molecular line emission.

The ASHES survey identified 294 dense cores, with 197 classified as starless candidates based on the absence of warm gas or outflow signatures (P. Sanhueza et al. 2019; S. Li et al. 2023). Given the cold IRDC environment, these cores are assumed to have typical temperatures of $\sim 10 \text{ K}$ (P. Sanhueza et al. 2013; A. T. Barnes et al. 2023; X. Mai et al. 2024). The continuum sensitivity of $\sim 0.1 \text{ mJy beam}^{-1}$ yields a mass sensitivity of $\sim 0.1 M_{\odot}$ at an average distance of 4 kpc, comparable to the QUARKS sample. It is worth noting that although the ASHES complete survey observed an additional 27 massive IRDC clumps and yielded 297 more candidate starless cores within (K. Morii et al. 2023, 2024, 2026), the lack of kinematic analysis (e.g., virial parameters and gas

velocity dispersion) of them in the literature limits the present study to the subset (i.e., 197 candidate starless cores) well characterized by P. Sanhueza et al. (2019) and S. Li et al. (2022, 2023).

From the QUARKS TM2 and ACA 7 m combined data, D. Yang et al. (2025a) identified 1562 dense cores, classifying 127 as starless core candidates based on the lack of outflow, hot core, or ionized gas tracers. These cores reside in 60 of the 139 targeted IRBC clumps. The continuum sensitivity for this subset of targeted clumps is improved to be $\sim 0.4 \text{ mJy beam}^{-1}$, corresponding to a mass sensitivity of $\sim 0.14 M_{\odot}$ at an average distance of 4 kpc and a typical starless core temperature of 20 K within IRBC environments (e.g., T. Nony et al. 2018; M. Valeille-Manet et al. 2025; D. Yang et al. 2025a). This enhanced sensitivity enables robust detection of low-mass starless cores in IRBCs from the QUARKS survey, comparable to the ASHES survey (see above).

We stress that the criteria used to identify starless cores were consistent between the ASHES and QUARKS surveys due to their highly similar observing setups. Specifically, any source exhibiting signatures of outflows (as traced by broad CO and SiO emission), warm/hot molecular gas (e.g., CH_3OH (4–3), H_2CO ($3_{2,2}-2_{2,1}/3_{2,1}-2_{2,0}$), CH_3CN), or ionized gas (e.g., H30 α) was classified as protostellar or evolved and excluded from the starless core sample (P. Sanhueza et al. 2019; D. Yang et al. 2025a). We finally only retained as candidate starless cores those detected in molecular lines with upper energy levels $E_u < 22 \text{ K}$ (e.g., N_2D^+ (3–2), DCN (3–2), CO/ $^{13}\text{CO}/\text{C}^{18}\text{O}$ (2–1), and H_2CO ($3_{0,3}-2_{0,2}$)).

The combined sample of 324 candidate starless cores (197 from ASHES, 127 from QUARKS) provides an opportunity to study core properties across IRDC and IRBC environments, with consistent mass sensitivities ($\sim 0.1 M_{\odot}$) minimizing bias in comparative analysis. It is worth noting that the candidate starless cores (for simplicity, hereafter called starless cores) from the two surveys were identified using different source extraction algorithms. The potential influence of these methodological differences on comparative analyses will be discussed elsewhere as needed.

3. Results

3.1. Physical Parameters of Starless Cores

We retrieved the fundamental parameters of starless cores—including radius, mass, mass surface density, and number density—from the ASHES (P. Sanhueza et al. 2019; S. Li et al. 2023) and QUARKS (D. Yang et al. 2025a) catalogs. For the QUARKS sample, we primarily used the full catalog of 127 candidate starless cores in our analysis and subsequent discussion. However, we note that this catalog may contain a small fraction of protostellar contaminants; the potential

Table 2
Spectral Windows of the Two Surveys

Survey	Center Frequency (GHz)	Bandwidth (GHz)	Vel. Res. ^a (km s ⁻¹)	Ang. Res. ^b (arcsec)	Line Sens. ^c (mJy beam ⁻¹)	Note ^d
QUARKS	~[217.918, 220.319, 231.370, 233.520]	1.875	~1.3	~1.2	~10	CO (2 – 1), SiO (5 – 4), H ₂ CO(3 _{0,3} – 2 _{0,2}), H ₂ CO(3 _{2,2} – 2 _{2,1}), H ₂ CO(3 _{2,1} – 2 _{2,0}), CH ₃ OH (4 – 3), CH ₃ CN (12 – 11), H30 α
ASHES	~[216.087, 216.348, 217.079, 217.213]	0.06	~0.07	~1.2	~9.5	SiO (5–4)
	~[218.825, 230.831]	1.875	~1.3	~1.2	~3.5	H ₂ CO(3 _{0,3} – 2 _{0,2}), H ₂ CO(3 _{2,2} – 2 _{2,1}), H ₂ CO(3 _{2,1} – 2 _{2,0}), CH ₃ OH (4 – 3)
	~[231.193, 231.295]	0.06	~0.17	~1.2	~9.5	CO (2–1)

Notes.

^a Velocity resolution.

^b Angular resolution.

^c Line sensitivity.

^d The primary molecules used to trace protostars in the two surveys, which are described in Section 2.2 (see also P. Sanhueza et al. 2019 and D. Yang et al. 2025a for the ASHES and QUARKS survey, respectively). Among them, CO and SiO are employed to trace molecular outflows.

impact of such sources on our results is assessed in detail in Section 4.3. In the following, we examine several key uncertainties that may affect the parameter estimates in both surveys.

The two surveys employed distinct source extraction algorithms in identifying dense cores: *astrodendro* for ASHES and *getsf* for QUARKS. Previous studies indicate that *getsf* tends to favor spherical structures but could miss irregular ones (Y. Cheng et al. 2024; F. Xu et al. 2024b). This leads to a direct consequence of the detection number of density structures. For instance, when *getsf* was applied to the ASHES data, it identified only 66 cores compared to 297 with *astrodendro* (F. Xu et al. 2024b). However, the influence of this methodological difference on the systematic analysis of starless core properties investigated here could be ignored (see below and Appendix A).

Temperature assumptions also differed: ASHES starless core temperatures were measured via NH₃ (1,1)/(2,2) line ratios, yielding $T_{\text{NH}_3} \sim 7\text{--}22.8$ K (median ~ 14 K; S. Li et al. 2023), consistent with the cold IRDC environment. QUARKS adopted a fixed $T_{\text{dust}} = 20$ K, typical for starless cores in clustered IRBC regions (Á. Sánchez-Monge et al. 2013). This temperature difference could introduce systematic biases in mass estimates and thus in the following systematic analysis, as $M \propto 1/T_{\text{dust}}$ under optically thin assumptions, which will be discussed below.

Despite these methodological differences, the starless cores exhibit similar radius distributions (Figure 1(a)). The ASHES starless cores span 1200–7000 au (median 2500 au), while QUARKS ones span 500–10,000 au (median 2800 au). A two-sided Kolmogorov–Smirnov (K-S) test²⁸ yields $p \sim 0.11$, indicating that the radii are statistically consistent with being

drawn from the same parent distribution. This suggests that we are detecting density structures on comparable physical scales, and that methodological differences in source extraction do not systematically bias radius measurements.

Figures 1(b)–(d) compare the mass, mass surface density, and number density distributions between the two samples. Starless cores within IRBCs (QUARKS sample) exhibit a median mass of $1.51 M_{\odot}$, approximately 2.4 times greater than those in IRDCs (ASHES sample; $0.63 M_{\odot}$). This result aligns with F. Xu et al. (2024b). A two-sided K-S test yields $p \ll 0.05$, indicating that the mass distributions are drawn from statistically distinct parent populations, and a one-sided test confirms that QUARKS cores are systematically more massive ($p \ll 0.05$). Similarly, QUARKS cores show significantly greater mass surface density and number density than ASHES cores (Figures 1(c) and (d); both K-S tests yield $p \ll 0.05$).

Furthermore, we evaluated the robustness of these differences against three potential biases (see Appendices B and C for details). First, limiting both samples to a common distance range (2.9–5.4 kpc) did not alter the mass difference. Second, comparing 127 randomly selected QUARKS starless cores with 127 certain ASHES starless cores preserved the mass difference. Third, Monte Carlo (MC) simulations with randomized T_{dust} (7–22.8 K for ASHES; 10–30 K for QUARKS) confirmed that temperature uncertainties cannot account for the observed mass difference. These evaluations collectively demonstrate that the observed differences in core properties are robust against methodological and observational biases. The systematic enhancement in mass, number density, and surface density of QUARKS starless cores relative to ASHES cores could reflect actual environmental differences between IRBCs and IRDCs, rather than analysis artifacts.

3.2. Analysis of Molecular Line Data

To analyze the kinetic properties (e.g., virial analysis) of starless cores, it is necessary to characterize their associated

²⁸ The K-S test assesses whether two samples originate from the same distribution by calculating a p -value; a value below 0.05 typically rejects this null hypothesis. A two-sided test detects any significant difference between distributions, while a one-sided test evaluates a specific directional difference (e.g., whether one sample is stochastically larger than the other).

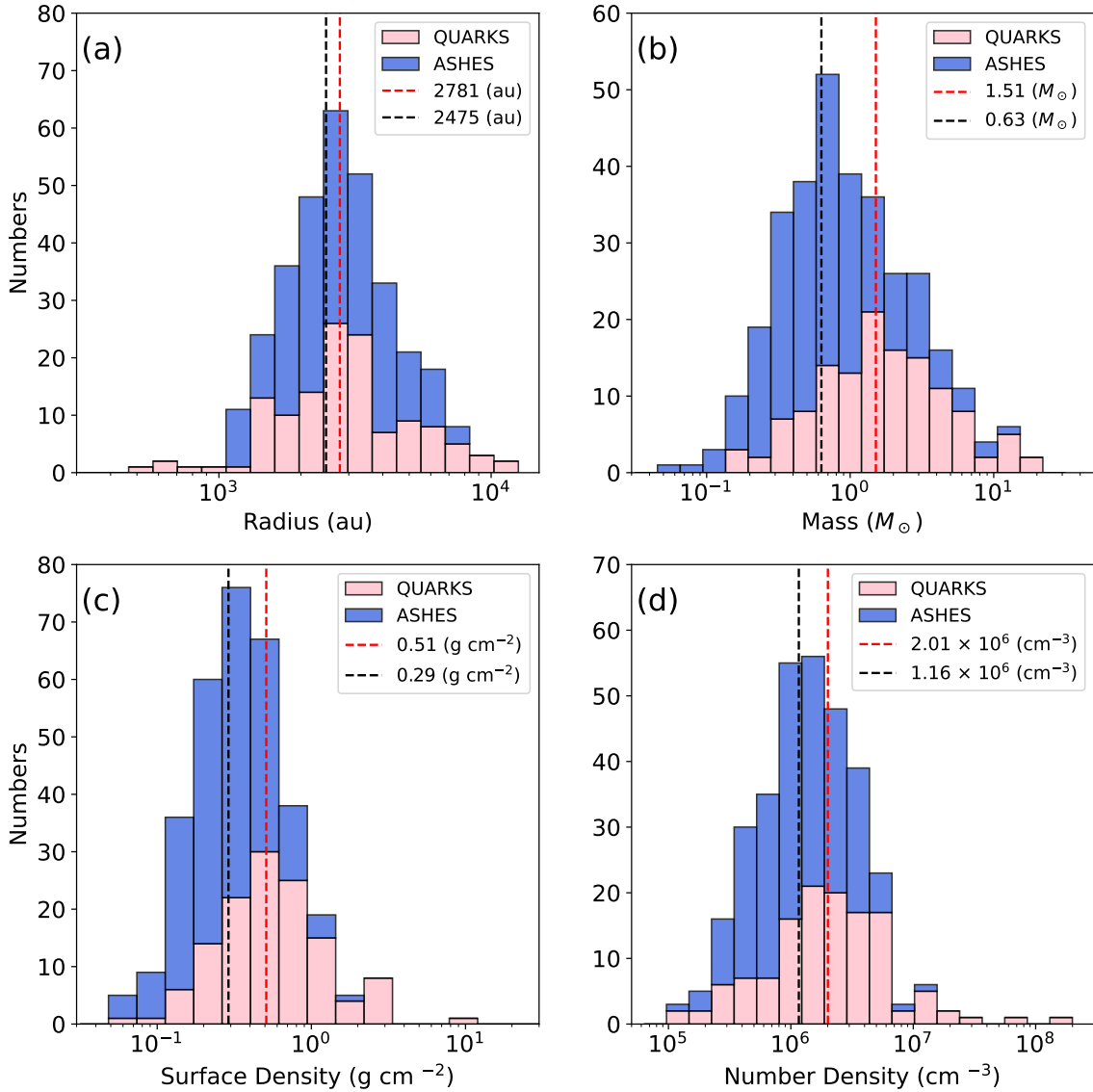


Figure 1. Distribution of the physical parameters of starless cores from the ASHES and QUARKS surveys, including the radius (panel (a)), mass (panel (b)), surface density (panel (c)), and number density (panel (d)). The black and red dashed lines in each panel represent the median values for the ASHES and QUARKS samples, respectively.

gas velocity dispersion. For ASHES starless cores, S. Li et al. (2023) measured the velocity dispersion of the observed DCO^+ (3–2) and N_2D^+ (3–2) lines. For QUARKS starless cores, we do the same measurement but using several molecular line emissions, including the H^{13}CO^+ (1–0) line from the ATOMS survey (T. Liu et al. 2020; H.-L. Liu et al. 2021) and H_2CO ($3_{0,3}-2_{0,2}$), DCN (3–2), and N_2D^+ (3–2) line data from the QUARKS survey.

From the core-averaged spectra extracted for the 127 QUARKS starless cores, we find that H^{13}CO^+ has the highest detection rate of $\sim 74.8\%$ (95/127), followed by H_2CO at $\sim 61.4\%$ (78/127), N_2D^+ at $\sim 28.3\%$ (36/127), and DCN at $\sim 20.5\%$ (26/127). Both N_2D^+ and DCN emission were detected toward eight QUARKS starless cores (6%). In total, 54 cores (42.5%) were detected in either N_2D^+ , DCN , or both. As examples, Figure 2 presents the spectral lines of these molecules for three selected QUARKS starless cores. Among the 127 cores, 23 ($\sim 18.1\%$) show no detection in any of the four lines investigated here, while 104 ($\sim 81.9\%$) cores have at least one molecular line detection.

To characterize the line profiles, we fitted each line spectrum to Gaussian functions with the best-fit parameters—brightness temperature (T_b), central velocity (V_{LSR}), and observed velocity dispersion (σ_{obs})—provided in Table D1 for each starless core and molecular line. It is noteworthy that while a multi-Gaussian fitting was applied to spectra with multiple velocity components, Table D1 only reports the parameters of the major component with the higher T_b . Subsequently, the intrinsic observed velocity dispersion follows $\sigma_{\text{obs,int}} = \sqrt{\sigma_{\text{obs}}^2 - \text{FWHM}^2/8\ln 2}$, where σ_{obs} is the observed velocity dispersion as shown in Table D1 and FWHM is the velocity resolution ($\sim 0.4 \text{ km s}^{-1}$ for H^{13}CO^+ and $\sim 1.3 \text{ km s}^{-1}$ for other molecules).

As shown in Figure 3, the H_2CO and H^{13}CO^+ lines show slightly greater $\sigma_{\text{obs,int}}$ (median $\sim 0.6 \text{ km s}^{-1}$) than the N_2D^+ and DCN lines (median $\sim 0.5 \text{ km s}^{-1}$). This implies that the former pair of molecular lines primarily may probe the slightly outer envelope gas of the cores, whereas the latter pair traces relatively denser, inner regions. In comparison, the $\sigma_{\text{obs,int}}$ of

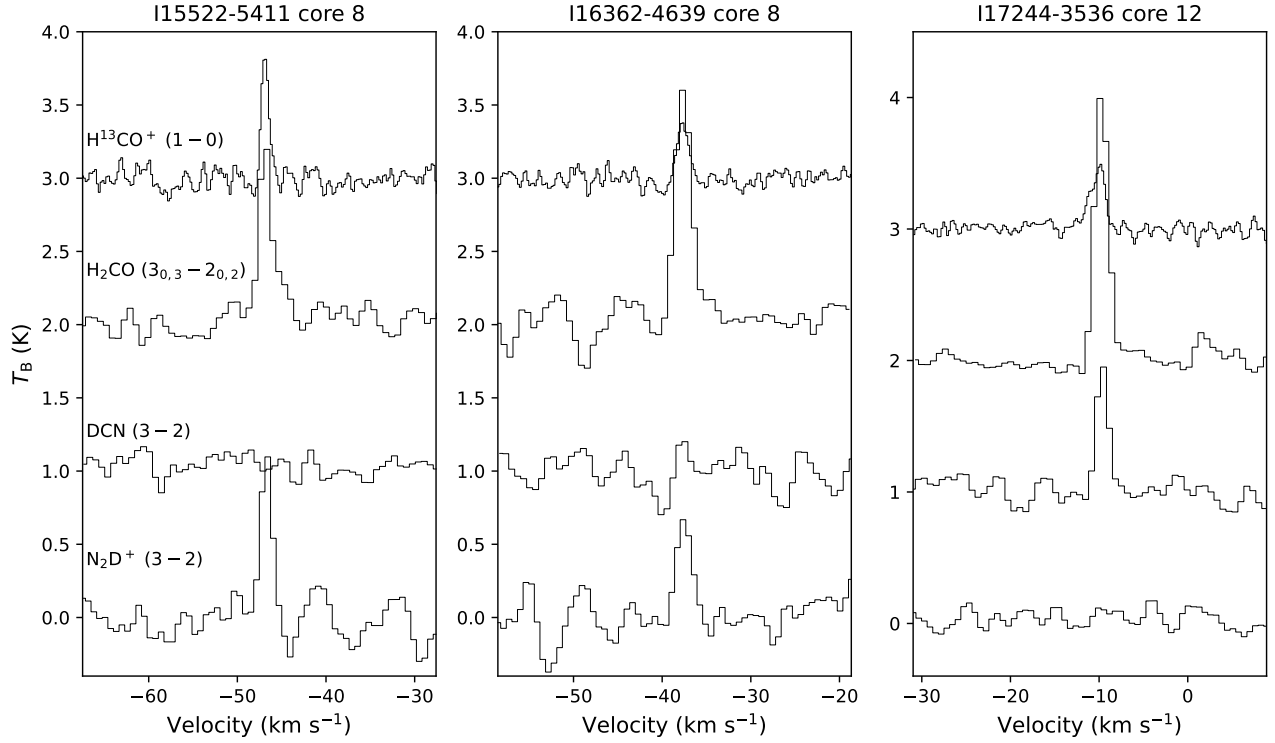


Figure 2. Example of core-averaged spectra of molecular lines from the QUARKS sample. The transitions of H^{13}CO^+ , H_2CO , DCN , and N_2D^+ are indicated in the first panel.

the QUARKS starless cores are overall 1.6–2.0 times higher than those measured in the ASHES starless cores (median value $\sim 0.3 \text{ km s}^{-1}$; S. Li et al. 2023). However, we note that the ASHES measurements were based on $\text{DCO}^+(3-2)$ and $\text{N}_2\text{D}^+(3-2)$ emission. To ensure a robust comparison, we consider the common tracer only, N_2D^+ , between both surveys. A direct comparison of $\sigma_{\text{obs}, \text{N}_2\text{D}^+, \text{int}}$ for 17 ASHES and 36 QUARKS starless cores confirms the significant difference, with median value 0.51 km s^{-1} versus 0.22 km s^{-1} , respectively (Figure 3(b)). The increase in $\sigma_{\text{obs}, \text{int}}$ could stem from the higher turbulence expected in IRBC environments due to strong stellar feedback (e.g., outflows, H II regions; M. R. Krumholz et al. 2014; J. C. Tan et al. 2014) than in IRDC environments due to quiet star formation.

3.3. Stability of the Dense Cores

The virial parameter (α_{vir}), which is commonly used to assess the gravitational stability of a dense core, is defined as follows (F. Bertoldi & C. F. McKee 1992; S. Dib et al. 2007):

$$\alpha_{\text{vir}} = \frac{5 \sigma_{\text{eff}}^2 R}{a \beta G M_c}, \quad (1)$$

where $a = (1 - b/3)/(1 - 2b/5)$ is the correction factor for a power-law density profile ($\rho \propto R^{-b}$) and β is the geometry factor. Following D. Li et al. (2013) and S. Li et al. (2023), we adopted $\beta = 1.2$ and a typical density profile index of $b = 1.6$ (e.g., H. Beuther et al. 2002; M. J. Butler & J. C. Tan 2012; A. Palau et al. 2014; F. Louvet et al. 2019). σ_{eff} is the effective velocity dispersion, R is the radius of the core, G is the gravitational constant, and M_c is the mass of the core. Dense cores with $\alpha_{\text{vir}} \leq 2$ are considered to be in a gravitationally bound state (J. Kauffmann et al. 2013; H.-L. Liu et al. 2022).

3.3.1. Thermal Support

If only thermal motions are considered, the term σ_{eff} in Equation (1) can be replaced by the sound speed of the gas, $c_s = \sqrt{k_B T / \mu_p m_H}$, where $\mu_p = 2.33$ is the mean molecular weight per free particle and m_H is the mass of the hydrogen atom (J. Kauffmann et al. 2008). Under the assumption of a dust temperature of 20 K, our analysis of the QUARKS 127 starless cores shows that the thermal virial parameter ($\alpha_{\text{vir}, \text{th}}$) ranges from ~ 0.1 to 4, with a mean value of ~ 0.5 —most (98%; 124/127) of which are below 2. Similarly, 94% (186/197) of the ASHES starless cores have an $\alpha_{\text{vir}, \text{th}}$ below 2 with a median value of ~ 0.7 . Taken together, we suggest that, when only the contribution of thermal motions is considered, most of both the ASHES and QUARKS starless cores can be in a gravitationally bound state.

Figure 4 presents the correlation between the thermal virial parameter ($\alpha_{\text{vir}, \text{th}}$) and core mass for starless cores in both the ASHES and QUARKS surveys. A gradual decrease in $\alpha_{\text{vir}, \text{th}}$ with increasing mass is observed, characterized by a linear regression slope of $\sim 0.62 \pm 0.02$ and a strong negative Spearman correlation coefficient ($r_s \sim 0.88$). This trend is consistent with the mathematical formulation in Equation (1), where α_{vir} is inversely proportional to core mass. A similar trend was previously reported by S. Li et al. (2023) for the full ASHES sample (containing both starless and prestellar cores), suggesting that more massive cores tend to be more gravitationally unstable.

Furthermore, we find from Figure 4 that QUARKS starless cores in IRBC environments exhibit systematically lower virial parameters (median $\alpha_{\text{vir}, \text{th}} = 0.53$) compared to ASHES cores in IRDC environments (median $\alpha_{\text{vir}, \text{th}} = 0.74$). A one-sided K-S test confirms that this difference is statistically significant ($p \ll 0.05$). This result implies enhanced gravitational

instability in the QUARKS starless cores, rendering them more susceptible to collapse than their ASHES counterparts. The difference in gravitational stability between the two samples could arise from their distinct density profiles, as discussed in Section 4.1.2.

3.3.2. Turbulent Support

We incorporated both thermal and turbulent motions by substituting the effective velocity dispersion in Equation (1) with the total velocity dispersion, defined as $\sigma_{\text{tot}}^2 = \sigma_{\text{nt}}^2 + c_s^2$. The nonthermal velocity dispersion was calculated as $\sigma_{\text{nt}} = (\sigma_{\text{obs,int}}^2 - k_B T / m_{\text{obs}})^{1/2}$, where m_{obs} is the molecular mass of the tracer species ($m_{\text{obs}} = 30m_{\text{H}}$ for H_2CO , N_2D^+ , and H^{13}CO^+ ; $m_{\text{obs}} = 28m_{\text{H}}$ for DCN).

As noted in Section 3.2, 104 of the 127 QUARKS starless cores have detections of at least one of the aforementioned molecular lines, and thus only these cores are considered in the following analysis. For the QUARKS sample, we prioritized using N_2D^+ and DCN emission to derive σ_{nt} , as these molecules preferentially trace the inner dense gas of cold cores. For cores lacking N_2D^+ or DCN detections, we use H^{13}CO^+ and H_2CO , which may trace relatively outer envelope gas. Note that the difference in probing depth between these tracers may not be significant in the present study (Section 3.2). For the ASHES sample, S. Li et al. (2023) used DCO^+ (3–2) and N_2D^+ (3–2) lines to obtain σ_{nt} for 73 starless cores with line detection above 3σ .

After accounting for both thermal and turbulent support, we find that 44 (42.3%) of the 104 QUARKS starless cores have total virial parameters ($\alpha_{\text{vir,tot}} < 2$) and are thus potentially gravitationally bound, compared to 55 (75.3%) of the 73 ASHES starless cores. Because different molecular tracers can probe distinct density regimes within prestellar cores (T. Gerner et al. 2015; D. Sahu et al. 2021, 2023), we report here for readers as a reference the distribution of tracers used in estimating $\alpha_{\text{vir,tot}}$, particularly for the QUARKS sample: 36 cores ($\sim 34.6\%$) are traced by N_2D^+ , 18 ($\sim 17.3\%$) by DCN, 43 ($\sim 41.3\%$) by H^{13}CO^+ , and 7 ($\sim 6.7\%$) by H_2CO . Despite this tracer diversity, the QUARKS cores overall exhibit significantly higher median $\alpha_{\text{vir,tot}}$ values (~ 2.3) than the ASHES cores (~ 1.0), with a one-sided K-S test confirming that this difference is statistically significant ($p \ll 0.05$). Even when restricting the comparison to cores detected in the same tracer—specifically, N_2D^+ (36 in QUARKS and 17 in ASHES; see Figure 3(b))—the median $\alpha_{\text{vir,tot}}$ remains much higher in QUARKS (~ 1.7) than in ASHES (~ 0.8). This can be attributed primarily to enhanced turbulence in IRBC environments, which increases the derived $\alpha_{\text{vir,tot}}$ for starless cores therein.

We also examined in Figure 5 the relationship between $\alpha_{\text{vir,tot}}$ and core mass (M_{core}) for both samples. A tentative anticorrelation is observed, with more massive cores tending to have lower $\alpha_{\text{vir,tot}}$ values, consistent with the trend found when considering thermal support alone (see Figure 4). This trend is quantified by power-law fits: $\alpha_{\text{vir,tot}} \propto M_{\text{core}}^{-0.54 \pm 0.07}$ for the QUARKS sample (red dashed line) and $\alpha_{\text{vir,tot}} \propto M_{\text{core}}^{-0.46 \pm 0.07}$ for the ASHES sample (blue dashed line). Spearman rank correlation coefficients ($r_s \sim -0.57$ for QUARKS, $r_s \sim -0.58$ for ASHES) indicate a moderate-strength inverse relationship. However, this global trend exhibits substantial intrinsic scatter where, at any given mass, $\alpha_{\text{vir,tot}}$ spans nearly an order of magnitude (e.g., from ~ 0.3 to $\gtrsim 10$ for the QUARKS starless

cores). This large dispersion suggests that mass alone is insufficient to determine a core’s dynamical state, and that other factors—such as the local environment, turbulence, and/or magnetic fields—could play roles in governing virial equilibrium. Apparently, the slope of the virial parameter–mass relation observed here could be in agreement with that found in numerical simulation results for turbulent and magnetized clouds (e.g., S. Dib et al. 2007). Nevertheless, the observational study of magnetic fields in early-stage cores remains challenging (e.g., P. Sanhueza et al. 2025), and given the lack of observational constraints, we refrain from speculating in this direction.

It is worth noting that in our QUARKS sample, some very low-luminosity protostellar cores below the observing detection of the QUARKS survey may have been misclassified as starless sources (see below). Consequently, this misclassification could be artificially inflating the measured nonthermal velocity dispersions (σ_{nt}) in the QUARKS sample, thereby skewing the virial analysis. Indeed, when scrutinizing the QUARKS sample using higher-resolution and sensitivity ALMA data, we find that about 21.3% of the current QUARKS starless cores could be protostellar and thus misclassified (see more in Section 4.3). The observed velocity dispersion of these misclassified starless cores is slightly higher than that of the remaining candidate starless cores in the QUARKS sample ($\sim 0.72 \text{ km s}^{-1}$ versus $\sim 0.61 \text{ km s}^{-1}$; tracer: H^{13}CO^+). Accordingly, this suggests that some misclassifications present in our QUARKS starless sample could slightly bias our virial parameter analysis, which should be cautioned.

3.4. Core Mass Function

We investigated the core mass function (CMF) to quantify differences in starless core masses between IRDC and IRBC environments. To mitigate biases inherent in differential CMF analysis—such as sensitivity to binning parameters and non-Gaussian noise in log-log space (A. Clauzet et al. 2009; F. Louvet et al. 2024)—we adopted the inverse cumulative number density, $P(M_{\text{core}} \geq M)$, following A. Coletta et al. (2025). This cumulative representation is immune to binning choices and better preserves the high-mass tail (L. Olmi et al. 2013; M. Fernández-López et al. 2021; S. Pezzuto et al. 2023). Prior to constructing the cumulative distributions, we assessed the impact of dust temperature uncertainties on mass estimates through 1000 MC simulations, assigning random temperatures within the observed ranges: 7.0–22.8 K for ASHES (based on NH_3 measurements, T_{NH_3} ; S. Li et al. 2023) and 10–30 K for QUARKS (accounting for warmer IRBC environments).

Figure 6 presents the inverse cumulative distribution for starless cores with $M_{\text{core}} > 1 M_{\odot}$, a threshold corresponding to the peak of the mass distribution for all starless cores from both surveys (Figure 1(b)). The ASHES and QUARKS mass distributions from the 1000 temperature simulations are represented by green and blue bands, respectively. The black line shows ASHES core masses estimated from T_{NH_3} , while the red line represents QUARKS core masses assuming $T = 20 \text{ K}$. The cumulative distribution reveals a systematic shift: the QUARKS population consistently lies above the ASHES population, indicating a higher fraction of massive cores at any given mass threshold. For instance, at $M = 2 M_{\odot}$, $P \sim 0.59$ for QUARKS versus ~ 0.41 for ASHES; at $M = 5 M_{\odot}$, the probabilities drop to ~ 0.21 and ~ 0.09 , respectively—demonstrating a clear enrichment of massive cores ($\gtrsim 2 M_{\odot}$) in

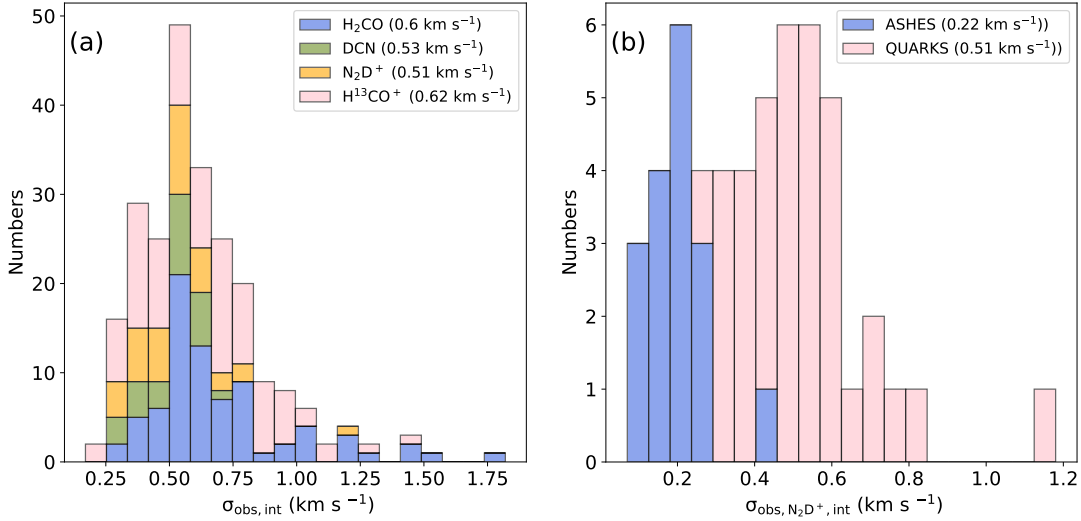


Figure 3. Panel (a): distribution of the intrinsic observed velocity dispersions (corrected by the velocity resolution; see Section 3.2) in the QUARKS starless cores. The color-coding corresponds to different molecular tracers. Panel (b): distribution of the intrinsic observed velocity dispersion from the N_2D^+ molecule between the ASHES (17) and QUARKS (36) starless core samples. The median value with the standard deviation for each group is provided in parentheses.

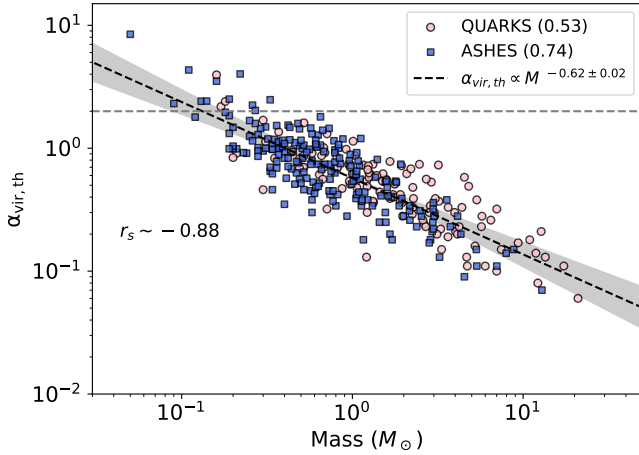


Figure 4. Relation of $\alpha_{\text{vir,th}}$ with mass for starless cores from the ASHES (filled squares) and QUARKS (filled circles) surveys. The values in parentheses in the legend at top right correspond to the median values of $\alpha_{\text{vir,th}}$. A linear regression fit to all sample points (black dashed line) yields a slope of -0.62 ± 0.02 . The Spearman's rank test returns a coefficient of $r_s = -0.88$. The horizontal dashed line marks the critical value of the virial parameter, which equals 2.

QUARKS. This systematic shift is robust against observational uncertainties, as the uncertainty bands remain separated even at their extremes, confirming that the mass offset is not an artifact of temperature assumptions. In addition, an alternative artifact from the methodological difference on extraction of cores between the *astrodendro* algorithm for the ASHES survey and the *getsf* algorithm for the QUARKS survey can get ruled out, since correcting for the influence of the core extraction algorithm will widen the mass shift between the ASHES and QUARKS samples (see Section 4.3 and Appendix A).

4. Discussion

4.1. Formation and Evolution of Starless Cores

The comparative analysis reveals a systematic enhancement in the mass, number density, and surface density of starless cores in the QUARKS survey relative to the ASHES survey,

with QUARKS cores exhibiting values approximately twice as high across all three parameters (see Figures 1(b)–(d)). This trend is corroborated by the cumulative core mass distribution, which shows the QUARKS population consistently above the ASHES population (see Figure 6), indicating a higher prevalence of relatively massive cores. We interpret this systematic shift as a signature of evolutionary progression given that ASHES targets cold, quiescent IRDC clumps while QUARKS samples warmer, actively star-forming IRBC environments (extending to the ultracompact H II region phase). More evolved clumps from QUARKS host more massive starless cores (see also Section 3.1), consistent with recent findings from the ALMAGAL survey (A. Coletta et al. 2025). This raises a key question: through what physical mechanisms do starless cores acquire mass and density within natal clumps at different evolutionary stages? Two plausible scenarios are considered: (1) core growth over time via dynamical mass accretion and (2) core formation under distinct initial conditions, where low-mass cores originate in cold, turbulence-quiescent IRDCs, while higher-mass cores form in warm, turbulence-active IRBCs.

4.1.1. Scenario of Core Growth over Time

The first scenario aligns with the dynamical mass accretion paradigm, which posits that young stellar objects grow primarily through prolonged dynamical mass accretion from their natal collapsing clump-scale reservoirs, rather than via isolated monolithic core collapse. A central prediction of this framework is that more evolved protostellar systems are systematically more massive, having benefited from longer accretion histories. This idea is foundational to the competitive accretion model (I. A. Bonnell et al. 2001, 2003), wherein protostars embedded in a common, turbulent, gravitationally collapsing gas reservoir accrete at rates proportional to their instantaneous mass, leading to accelerated growth for centrally located objects. Our results—showing enhanced mass and density of starless cores in IRBCs (late stage) relative to IRDCs (early stage)—are consistent with this picture. Additional observational support comes from studies of dense cores in IRDCs versus IRBCs with hub–filament structures, which

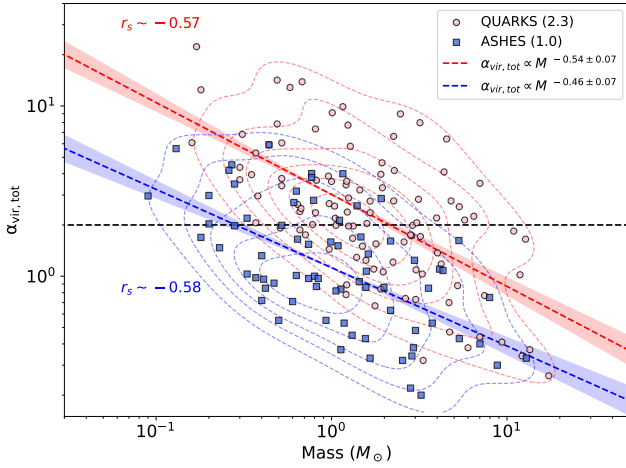


Figure 5. Relation of $\alpha_{\text{vir,tot}}$ with mass for starless cores from the ASHES (filled squares) and QUARKS (filled circles) surveys. The blue and red contours represent the kernel density estimation distributions of the scatter points from the two survey samples, respectively. The red and blue dashed lines denote the linear regression fits to the two samples, yielding slopes of ~ -0.5 for both. The Spearman's rank test yielded correlation coefficients of $r_s = -0.57$ and $r_s = -0.58$, respectively. The horizontal dashed line corresponds to a critical value of $\alpha_{\text{vir,tot}} = 2$. The values in parentheses in the legend at top right correspond to the median $\alpha_{\text{vir,tot}}$ values.

report systematic increases in core mass and surface density interpreted as the result of hierarchical, multiscale gas inflow (R. Galván-Madrid et al. 2010; H.-L. Liu et al. 2022, 2023; R. Liu et al. 2022; F.-W. Xu et al. 2023; D. Yang et al. 2023). Furthermore, recent statistical analyses of dense cores in diverse regions—including the Dragon IRDC (S. Kong et al. 2021), the Orion Molecular Cloud (H. Takemura et al. 2023), the ASHES IRDC sample (S. Li et al. 2023), the ALMA-IMF survey (T. Nony et al. 2023; Y. Pouteau et al. 2023), the ASSEMBLE survey (F. Xu et al. 2024b), and the ALMAGAL survey (A. Coletta et al. 2025)—consistently find that protostellar cores are significantly more massive than starless cores, strongly suggesting mass growth over time.

Regarding timescales, M. L. Enoch et al. (2008) derived a mean lifetime of 0.5 ± 0.3 Myr for starless/prestellar cores ($0.2\text{--}10 M_\odot$) in low-mass star-forming regions, while a similar lifetime has been found for prestellar cores in high-mass regions like the ASHES sample (K. Morii et al. 2026). These lifetimes are several times the freefall time of dense cores. Following M. Vaille-Manet et al. (2025), the lifetime of QUARKS starless cores is estimated to be $\sim (1\text{--}8) \times 10^5$ yr. Moreover, H.-L. Liu et al. (2021) determined that at least 47% of the protocluster clumps targeted by QUARKS are already in the compact H II region phase, which has a characteristic lifetime of $\sim 10^5$ yr (D. O. S. Wood & E. Churchwell 1989; B. Davies et al. 2011). Taken together, these constraints suggest that the lifetimes of starless cores (primarily below $10 M_\odot$) in both IRDC and IRBC environments investigated here are comparable to or shorter than the evolutionary timescales of their natal clumps. We therefore suggest that starless cores in both ASHES and QUARKS samples have sufficient time to grow in mass and density through dynamical mass accretion as their host clumps evolve from the early IRDC to the late IRBC stage. For instance, at a gas infall rate of $\sim 10^{-4} M_\odot \text{ yr}^{-1}$, typical of high-mass star formation (e.g., J. Yuan et al. 2018; H.-L. Liu et al. 2022; H. Beuther et al. 2025; S. Gupta et al. 2026), a $1 M_\odot$ core would gain approximately $10 M_\odot$ over a timescale of $\sim 10^5$ yr.

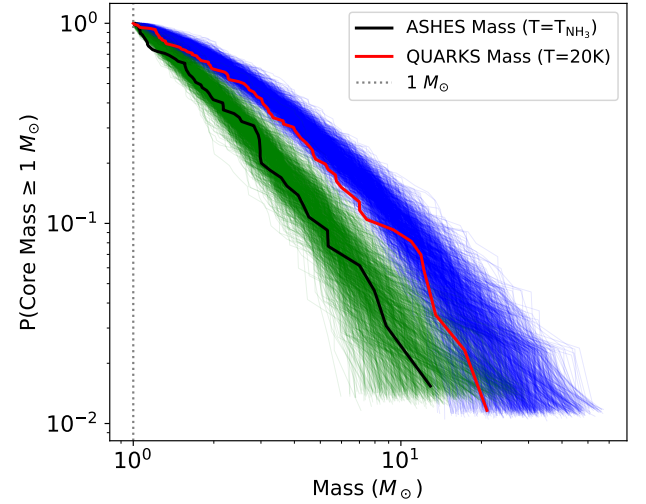


Figure 6. Inverse cumulative distribution of the starless core mass in the ASHES and QUARKS samples. The green and blue bands represent the masses from 1000 simulations with two specific temperature ranges for the ASHES and QUARKS sample (see text), respectively. The black and red lines present the mass distributions derived from the individual T_{NH_3} measurement for the ASHES sample (S. Li et al. 2023) and from an assumed dust temperature of 20 K for the QUARKS sample, respectively. The dashed line stands for a threshold of $M_{\text{core}} > 1 M_\odot$, corresponding to the peak of the mass distribution for all starless cores from both surveys (Figure 1(b)).

4.1.2. Scenario of Core Formation under Distinct Initial Conditions

From the ALMAGAL survey's comprehensive analysis of fragmentation properties across 1013 high-mass star-forming clumps, A. Coletta et al. (2025) found not only that core mass increases with evolutionary stage but also that a population of lower-mass cores persists at all stages. This implies that dense cores can form continuously throughout a clump's evolution—not solely during its earliest phases. Inspired by this, we propose that some QUARKS starless cores may have formed recently within the more evolved, turbulence-enhanced IRBC environments, rather than being direct descendants of earlier-stage IRDC cores. This proposal is supported by two complementary lines of evidence.

First, the dynamical state of QUARKS starless cores reflects their birth environment. As shown in Figure 5, QUARKS cores exhibit a significantly higher median total virial parameter ($\alpha_{\text{vir,tot}} \sim 2.3$) compared to ASHES cores (~ 1.0). This suggests that QUARKS starless cores are born under conditions of elevated turbulence, rather than inheriting a quiescent state from earlier epochs. In addition, the higher Jeans mass in IRBC environments—due to elevated temperatures and turbulence—naturally favors the formation of more massive cores. Thus, the observed masses of QUARKS starless cores could not arise solely from prolonged accretion; they could also reflect a shift in the initial fragmentation scale driven by the evolving physical conditions of the natal clump.

Second, the structural properties of these cores differ systematically. Figure 7 shows the mass (M)–radius (R) relation for both samples. A linear fit yields $M \propto R^{1.83 \pm 0.09}$ for ASHES cores (correlation coefficient $r \sim 0.76$), corresponding to an average density profile of $\rho \propto R^{-1.2}$ (assuming spherical symmetry and uniform density). In contrast, QUARKS cores follow $M \propto R^{1.35 \pm 0.11}$ ($r \sim 0.74$), implying a steeper density profile of $\rho \propto R^{-1.7}$. Although the absolute slope values are sensitive to measurement uncertainties, the difference between the two slopes is statistically significant

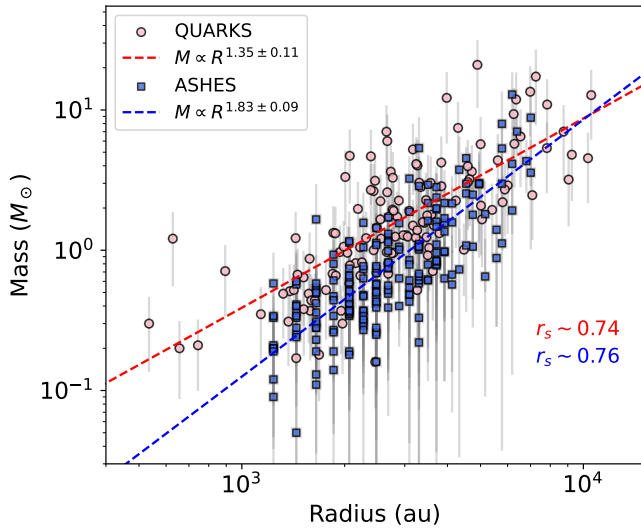


Figure 7. Mass versus radius (M – R) diagram. The core masses for the ASHES survey (filled squares) were derived from T_{NH_3} , and those for the QUARKS survey (filled circles) were estimated from a fixed 20 K dust temperature assumption. The error bars indicate the standard deviation from 1000 MC simulations of each core (see Appendix C).

($>3\sigma$, $\sigma \sim 0.1$), supporting a transition toward steeper density gradients of starless cores in evolved IRBC clumps. Similarly, such results can also be found in H.-L. Liu et al. (2023), where comparative studies of hub–filament systems further show that IRBC hubs exhibit more compact, spherical dust emission than their IRDC counterparts (see Figures 1 and A1 of H.-L. Liu et al. 2023). Together, these observations suggest that the initial conditions for core formation differ between IRDCs and IRBCs: in cold, low-turbulence IRDCs (ASHES), cores form with lower initial masses, lower central densities, and shallower density profiles, whereas in warm, turbulence-enhanced IRBCs (QUARKS), cores form with higher initial masses, higher central densities, and steeper radial profiles.

4.2. Implications for a Dynamical Mass Accretion Scenario of High-mass Star Formation

The observed mass distribution of starless cores in both early- and late-stage high-mass star-forming regions provides a crucial empirical test for competing theoretical models. Currently, the turbulent core accretion (C. F. McKee & J. C. Tan 2003) and competitive accretion (I. A. Bonnell et al. 2001) scenarios represent the two leading paradigms. The former posits that high-mass stars form via monolithic collapse of massive prestellar (i.e., gravitationally bound starless) cores with initial masses above a few $10 \times M_\odot$ (J. C. Tan et al. 2013, 2014), whereas the latter proposes that clumps first fragment into numerous low-mass, thermal-Jeans-scale cores ($\sim 1 M_\odot$), which subsequently grow to high masses through prolonged competitive accretion from their extended natal reservoirs—probably mediated by filamentary networks (E. Vázquez-Semadeni et al. 2019; P. Padoan et al. 2020).

Over the past decade, several candidate high-mass prestellar cores (typically $M \gtrsim 16 M_\odot$) have been reported (K. Wang et al. 2014; A. T. Barnes et al. 2023; X. Mai et al. 2024; M. Valeille-Manet et al. 2025; D. Yang et al. 2025b, 2025a). However, none have been unambiguously confirmed as truly prestellar and massive at birth. Critically, most candidates reside in evolved clumps, making it impossible to distinguish

whether they initially formed massive or grew significantly via accretion, which is a key degeneracy highlighted in Section 4.1.1. Combining both ATOMS 3 mm and QUARKS 1.3 mm dust continuum data (D. Yang et al. 2025b), we have tentatively identified a candidate high-mass prestellar core of $27 M_\odot$ within a radius of 2800 au, which is found as an early-phase object due to its location within an IR-dark lane within the IRAS 18290–0924 clump. This core remains a rare potential candidate supporting the turbulent core model.

Strikingly, the vast majority of starless cores are low-mass, regardless of the evolutionary stage of their host clumps. Specifically, QUARKS starless cores span 0.2 – $21 M_\odot$ with a median of $1.5 M_\odot$, while ASHES cores range from ~ 0.1 to $12 M_\odot$ with a median of $0.6 M_\odot$. Crucially, almost none (see below for the exception in the QUARKS sample) of these cores from both samples possess sufficient mass ($\gtrsim 16 M_\odot$) to form a high-mass star via monolithic collapse, even when accounting for core-to-star efficiencies of $\sim 30\%$ – 50% . Particularly, we identify from the QUARKS sample two high-mass starless cores with masses of 17.3 and $21 M_\odot$, which are above the $16 M_\odot$ threshold for high-mass star formation. Although both cores are not among the 27 potentially misclassified protostellar candidates (see Section 4.3), they lie within the ultra-compact HII clumps; thus, their high-mass origins require further confirmation to distinguish between the core growing over time (see Section 4.1.1) and new formation in evolved natal clumps (see Section 4.1.2).

The systematic lack of massive starless cores in our sample suggests that such cores are initially rare in clustered environments, and thus pure “turbulent core accretion” could not be the dominant pathway for high-mass star formation therein. Instead, it favors models in which high-mass stars assemble their mass dynamically over time. Indeed, abundant evidence shows that gas flows along filaments and streamers can efficiently feed central cores (A. Saha et al. 2022; J.-W. Zhou et al. 2022; H.-L. Liu et al. 2023; F.-W. Xu et al. 2023; D. Yang et al. 2023; S. Pan et al. 2024; Y. Q. Guo et al. 2025; X. Mai et al. 2025; L. M. Zhen et al. 2025), enabling sustained accretion rates compatible with competitive-like, dynamical mass accretion scenarios (F. Motte et al. 2018). Our findings thus support a picture wherein high-mass star-forming clumps first fragment into predominantly low-mass cores, and high-mass stars emerge primarily through dynamical mass accretion from beyond their initial core boundaries—with monolithic collapse from a massive prestellar core being, at best, a rare alternative.

4.3. Limitations

From a systematic comparative analysis for starless cores using the ASHES and QUARKS surveys, we have concluded that starless cores are on average more massive (by a factor of 2.4) and denser (by a factor of 1.7) in IRBC environments than in IRDC environments. However, several limitations should be noted.

First, different core extraction methods (*astrodendro* for ASHES versus *getsf* for QUARKS) may introduce systematic biases to our comparative analysis. We therefore investigate in Appendix A the potential impact of different algorithms on related analysis. As a result, we found that the significant differences in mass and density distributions between the starless cores from the ASHES and QUARKS

surveys are not an artificial result from different core identification methods.

It is worth noting that in this work, we prefer to adopt the *astrodendro* cores (i.e., 197 sources) instead of the *getsf* ones (3.5 times less; see Appendix A) for the ASHES survey since the former population can provide a sufficient ASHES sample for systematic comparative analysis with the QUARKS sample. In addition, we opted to use the *getsf* cores for the QUARKS survey to maintain consistency with the core catalogs published and in preparation by the QUARKS survey team (D. Yang et al. 2025a; W. Y. Jiao et al. 2026, in preparation). This choice ensures alignment with ongoing survey-wide analyses, even at the cost of introducing a minor methodological heterogeneity in the cross-survey comparison. Although we have carefully addressed the potential biases introduced by the use of different core extraction methods, a fundamental methodological limitation remains. That is, conducting a direct, parameter-by-parameter comparison between cores identified with two distinct algorithms inherently compromises full consistency. A more robust approach for future studies would be to apply a single, uniform extraction tool—such as *astrodendro*, which was used for the ASHES data—to the QUARKS dataset as well, thereby enabling a truly standardized comparative analysis.

Second, the classification of starless cores may be influenced by differences in spectral line sensitivity between the ASHES and QUARKS surveys. While both surveys achieved comparable sensitivities (~ 10 mJy beam $^{-1}$; see Table 2) for the outflow tracers investigated here (i.e., CO and SiO), the ASHES data are approximately 3 times more sensitive than QUARKS for warm gas tracers (i.e., H₂CO and CH₃OH). Consequently, some very low-luminosity protostars—potentially driving only weak outflows or emitting faint warm molecular lines—may have been misclassified as starless cores in the QUARKS sample. Since protostellar cores are typically more massive than true starless cores, such contamination could systematically elevate the high-mass end of the QUARKS CMF. To assess this potential bias, we reexamined our QUARKS starless core sample using higher-resolution (~ 0.3) and more sensitive (~ 3 mJy beam $^{-1}$) ALMA TM1 continuum and line data from the same QUARKS survey (X. Liu et al. 2024; W. Y. Jiao et al. 2026, in preparation). This deeper inspection revealed that 27 out of 127 (21.3%) of the originally classified starless cores show signatures of either weak outflows or warm molecular gas emission, indicating that they are likely protostellar in nature. We therefore repeated our comparative analysis by examining mass and density distributions, the CMF and M – R relations using a refined QUARKS sample that excludes these 27 reclassified sources. The trends obtained with the full sample are retained in the refined sample. For instance, the refined QUARKS subsample shows that median masses and densities decreased slightly by $\sim 6\%$ and 15% , respectively, compared with those derived from the full sample. A one-sided K-S test confirms that the differences in both mass and density distributions remain highly significant ($p \ll 0.05$). Additionally, for the refined (“clean”) QUARKS cores, their M – R slope steepens from 1.35 ± 0.11 to 1.47 ± 0.13 , but its relation relative to that for the ASHES cores still holds (see Section 4.1.2).

Third, the impact of dust temperature assumptions on the derived mass distributions of the two starless core samples

may not be ignored in the analysis. Such an impact has been partially taken into account in Section 3.1. Note that for all QUARKS starless cores in IRBC clumps, we adopted therein a fixed $T_{\text{dust}} = 20$ K to compute temperature-dependent quantities such as mass and density. However, IRBCs often host luminous protostars and H II regions that would induce temperature gradients across the clump, raising concerns that a single temperature may introduce systematic uncertainties. To assess whether a realistic temperature gradient—approximately spanning 10–30 K across an IRBC clump—could substantially alter the derived trends in core properties, we performed MC simulations in which the dust temperature for each core was drawn uniformly from this range, rather than being fixed at 20 K with a narrow distribution around it. After such attempts, we find that the observed difference in core mass distributions between the two samples remains robust and not an artifact of dust temperature assumptions (see Appendix C for details).

In summary, even after accounting for potential protostellar contamination and potential biases from different core extraction methods and temperature assumptions, the systematic enhancement in core mass and density in IRBCs relative to IRDCs persists robustly, reinforcing our major conclusions. Forthcoming studies with both high-sensitivity and high-resolution observations are required to definitely characterize the physical properties of true starless cores in different environments for a better understanding of the physical origin of starless cores in two markedly distinct star-forming environments.

5. Summary and Conclusions

Using the ALMA data at 1.3 mm from both the ASHES and QUARKS surveys, we have conducted a systematic comparative analysis of the physical properties—including radius, mass, density, kinematics, and dynamical state—of 324 candidate starless cores identified in early-phase IRDCs (ASHES survey; P. Sanhueza et al. 2019; S. Li et al. 2023) and evolved-phase IRBCs (QUARKS survey; D. Yang et al. 2025a). Our major findings are summarized as follows.

(1) Despite having comparable sizes (~ 2500 au), starless cores in IRBCs exhibit systematically higher masses (median $1.5 M_{\odot}$ versus $0.6 M_{\odot}$), number densities (2.0×10^6 cm $^{-3}$ versus 1.2×10^6 cm $^{-3}$), and surface densities (0.5 g cm $^{-2}$ versus 0.3 g cm $^{-2}$) than those in IRDCs. These enhancements, approximately a factor of 2 across all three parameters, are robustly confirmed by the cumulative CMF, which shows the QUARKS population consistently above the ASHES population.

(2) Molecular line observations (H¹³CO⁺, N₂D⁺, DCN, H₂CO) reveal that starless cores in IRBCs possess significantly stronger turbulent motions ($\sigma_{\text{obs,int}} \sim 0.5$ km s $^{-1}$) compared to those cores in IRDCs (~ 0.3 km s $^{-1}$). Consequently, starless cores in IRBCs display a higher median total virial parameter ($\alpha_{\text{vir,tot}} \sim 2.3$) than those cores in IRDCs (~ 1.0), with only 42.3% of QUARKS cores satisfying $\alpha_{\text{vir,tot}} < 2$ (a common threshold for gravitational binding), compared to 75.3% in ASHES. The elevated $\alpha_{\text{vir,tot}}$ of starless cores in IRBCs is attributed to enhanced turbulence likely driven by feedback from ongoing star formation (e.g., outflows, H II regions), as further evidenced by the large intrinsic scatter in the $\alpha_{\text{vir,tot}}$ –mass relation.

(3) In the mass–radius (M – R) diagram, both samples follow power-law scaling relations, but the QUARKS cores exhibit a significantly flatter slope ($M \propto R^{1.35 \pm 0.11}$) than the ASHES cores ($M \propto R^{1.83 \pm 0.09}$), with the difference exceeding 3σ . This implies steeper average density profiles for starless cores in IRBCs ($\rho \propto R^{-1.7}$) compared to starless cores in IRDCs ($\rho \propto R^{-1.2}$), consistent with more centrally concentrated structures in evolved environments.

In conclusion, these results support a dual evolutionary picture: (i) dense cores can form anew in evolved, turbulent IRBC environments, not solely during the earliest IRDC phase, and (ii) the initial conditions in IRBCs—characterized by warmer temperatures, stronger turbulence, and steeper density gradients—shift the fragmentation scale toward higher masses and densities relative to IRDCs. Furthermore, the observed prevalence of low-mass starless cores within both early IRDC and late IRBC environments challenges the necessity of massive initial cores and instead underscores the importance of environment-mediated, time-dependent mass growth through dynamical mass accretion from extended reservoirs (e.g., filaments and clump-scale flows), with monolithic collapse from a massive core being at most a rare occurrence. Thus, both new formation under altered initial conditions and subsequent dynamical growth are essential to explain the observed properties of starless cores across the evolutionary sequence of high-mass star formation.

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Appendix A

Impact of Different Core Identification Methods

We evaluated the potential impact of different core identification algorithms (*astrodendro* and *getsf*) on related analysis of the ASHES and QUARKS samples. To this end, we primarily accessed the impact of different identification algorithms on the ASHES sample. We first cross-matched the 66 dust continuum cores previously identified by F. Xu et al. (2024b) using *getsf* from the ASHES pilot survey with the 294 cores identified by P. Sanhueza et al. (2019) using *astrodendro* from the same survey, resulting in 56 common sources. Subsequently, we computed following P. Sanhueza et al. (2019) the masses, radii, and number densities of these 56 cores. As shown in Figure 8, the masses and radii of *astrodendro* cores are overall significantly higher—by roughly a factor of 2—than those *getsf* counterparts. This difference is reinforced by the one-sided K-S tests with p -values of about 0.03 for the distributions of both parameters. Also, this finding is consistent with recent results from K. Morii et al. (2026). Moreover, the one-sided K-S test of the number density produced a p -value of ~ 0.12 , indicating no significant difference between the *astrodendro* and *getsf* cores.

Furthermore, we present in Figure 9 the M – R relations for the 56 common ASHES cores identified using the two different methods. Both *astrodendro* and *getsf* cores appear to follow similar M – R trends. However, the one-sided K-S test for the two populations of cores cannot quantitatively confirm their similarity in the M – R relations, which could be due to the limited dynamic range in mass for the *getsf* cores (i.e., no sample points for *getsf* sources in the upper right corner of the figure).

Taken together, we therefore suggest that the differences in mass and density distributions between the starless cores from the QUARKS and ASHES surveys are not attributable to the core identification methods. Particularly, correcting for the influence of the core extraction algorithm will widen the overall gap in mass distributions between the ASHES and QUARKS starless cores, thereby facilitating comparative analysis of the CMF between ASHES and QUARKS samples (see Section 3.4). While we cannot entirely rule out a subtle influence of methodological differences on the derived mass–radius (M – R) relations, the seemingly similar M – R trends seen in the two core populations (see Figure 9)—despite being identified with different algorithms—are consistent with their nearly identical density distributions as mentioned earlier. This further supports the robustness of our comparative analysis and reinforces the physical origin of the observed evolutionary trends.

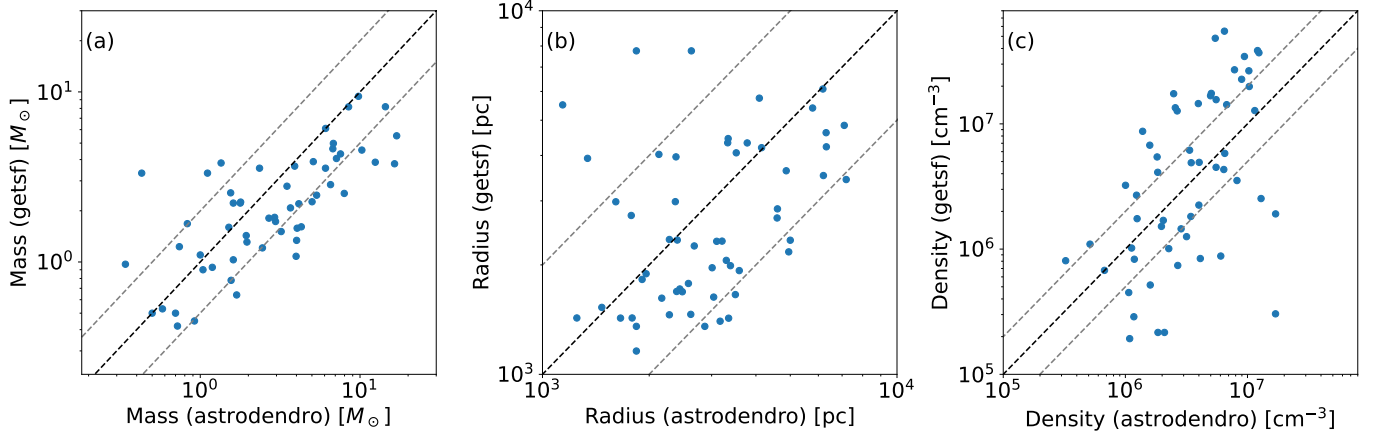


Figure 8. Masses, radii, and number densities of the 56 ASHES cores derived from *astrodendro* and *getsf*. The black dashed line represents $y = x$, while the two gray dashed lines denote $y = 0.5x$ and $y = 2x$.

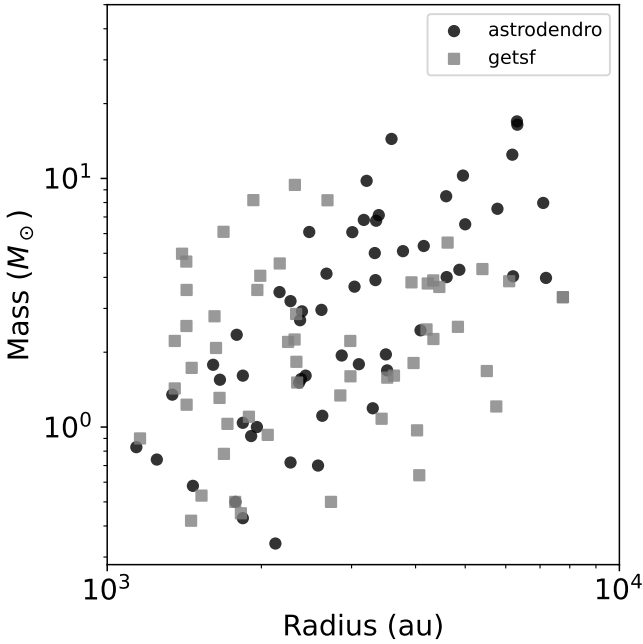


Figure 9. Mass versus radius (M - R) diagram for 56 dense cores identified from *astrodendro* (black dots) and *getsf* (gray squares).

Appendix B

Effect of Distance and Sample Number on Statistical Significance

We examine here whether the observed differences in the physical parameters (radius and mass) of starless cores between the ASHES and QUARKS samples arise from their differing clump distances and sample number or not.

ASHES clumps are located at approximately 2.9–5.4 kpc, while the QUARKS sample spans a wider range of 1.2–11.6 kpc. To evaluate bias due to distance variation, we

restricted the QUARKS starless core sample to the same distance range as ASHES (2.9–5.4 kpc), which produces a subset of 70 cores. We compared the radii of the starless cores in the subset of the QUARKS sample and the ASHES sample (Figure 10(a)). A two-sided K-S test yields a p -value > 0.05 , suggesting that the radii are drawn from the same distribution—a result consistent with previous findings (see Section 3.1). Similarly, we did the comparison for the mass parameter (Figure 10(b)). The systematic differences in the mass distribution still hold, where a median mass ratio between the two samples is ~ 2.6 ($1.66/0.63 M_{\odot}$). A one-sided K-S test yields a p -value $\ll 0.05$, indicating that these QUARKS cores are also significantly more massive than those of ASHES. Therefore, we suggest that the disparity in mass between the ASHES and QUARKS samples is not driven by the clump distance.

In addition, to evaluate potential biases arising from the differing sample number between the QUARKS and ASHES samples, we performed a resampling analysis. Specifically, we repeatedly drew random subsamples of 127 (counts of QUARKS starless cores) cores from the full set of 197 ASHES starless cores, conducting 1000 iterations of this process. Across all iterations, the median mass of the ASHES starless cores fell within the range of ~ 0.5 – $0.8 M_{\odot}$, with a median of $\sim 0.6 M_{\odot}$ over all randomly generated subsamples, as shown in Figure 10(c). Importantly, each randomly selected subset of the ASHES sample yielded a median mass significantly lower than that of the QUARKS sample (i.e., $1.66 M_{\odot}$), with one-sided K-S tests consistently returning p -values $\ll 0.05$. These results are consistent with our earlier findings (see Section 3.1), indicating that the difference in sample sizes is not responsible for the observed disparity in the mass distribution between the ASHES and QUARKS starless cores.

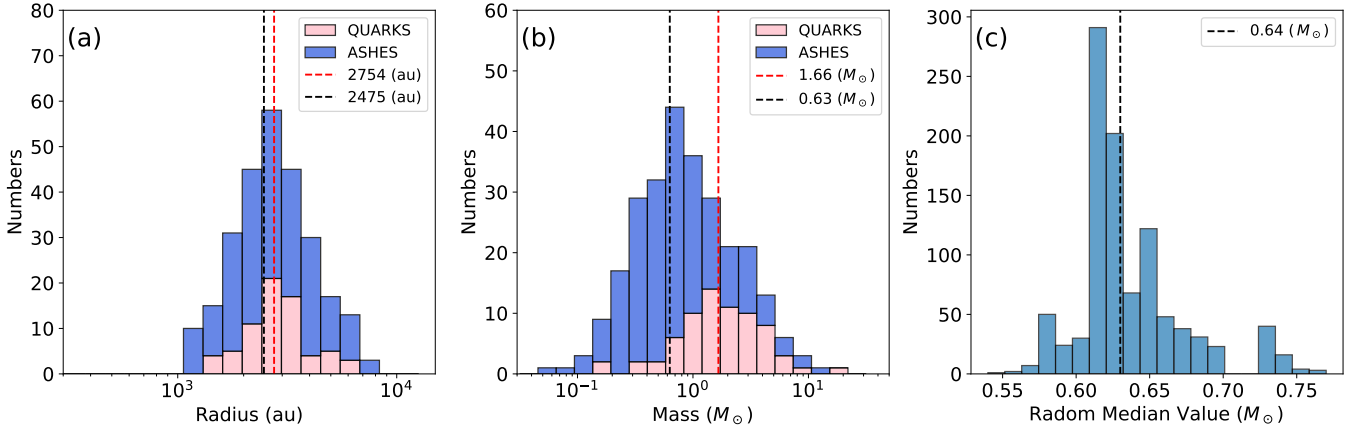


Figure 10. Distributions of the radius (panel (a)) and mass (panel (b)) of the starless cores in the subset of the QUARKS sample and the ASHES sample, both of which are imposed to the same distance range. Distribution of median core mass obtained from 1000 random resamplings for ASHES starless cores (panel (c)). The dashed lines in all panels indicate the median values for the corresponding distributions.

Appendix C Effect of Dust Temperature

We investigate here the impact of dust temperature assumptions on the derived mass distributions of the two starless core samples. Using an MC approach, we simulated the mass distributions for both the ASHES and QUARKS starless cores by sampling dust temperatures over the specific ranges: 7.0–22.8 K for ASHES (based on NH_3 line-derived temperatures) and 10–30 K for QUARKS (reflecting the assumed range around the fiducial value of 20 K). Specifically, for each simulation, we assigned a random temperature uniformly drawn from the respective range to every core in the sample and recalculated its mass accordingly. A total of 1000 independent MC realizations were run.

Note that we adopted a uniform sampling of dust temperatures in MC simulations, rather than sampling from a narrow distribution centered on a fixed value. This approach better accounts for potential temperature gradients within a clump—particularly relevant for IRBCs, which often harbor luminous protostars and H II regions capable of inducing significant thermal structure across the clump. By uniformly sampling the full temperature range, we can evaluate whether assuming a single representative dust temperature introduces systematic biases in the derived temperature-dependent parameters (mass, surface density, and number density) for QUARKS starless cores. As shown in Figure 11, we directly

compare the parameter distributions obtained using a fixed $T_{\text{dust}} = 20$ K versus those derived from randomly assigned temperatures drawn uniformly from the 10–30 K range. The resulting distributions are nearly indistinguishable, with highly consistent median values between two types of calculation for all three parameters. Quantitatively, two-sided K-S tests yield p -values of ~ 0.81 (mass), ~ 0.18 (surface density), and ~ 0.56 (number density), indicating no statistically significant difference between the two sets of distributions. We therefore suggest that the use of a single dust temperature for all QUARKS starless cores does not introduce appreciable systematic uncertainties in the analysis of temperature-dependent parameters in this study.

Across all simulations, the median mass of QUARKS starless cores varies between 1.32 and $2.12 M_{\odot}$, while that of ASHES cores ranges from 0.57 to $0.83 M_{\odot}$ (Figure 12(a)). This yields a median mass ratio (QUARKS/ASHES) between ~ 1.84 and 3.42, with a median value of 2.48 ± 0.25 (Figure 12(b)). Furthermore, in every realization, a one-sided K-S test comparing the two mass distributions returns a p -value $\ll 0.05$ (not shown here), indicating that the QUARKS cores are consistently more massive than their ASHES counterparts at high statistical significance, regardless of the adopted temperature uncertainty. We therefore conclude that the observed disparity in core mass distributions between the two samples is robust and not an artifact of dust temperature assumptions.

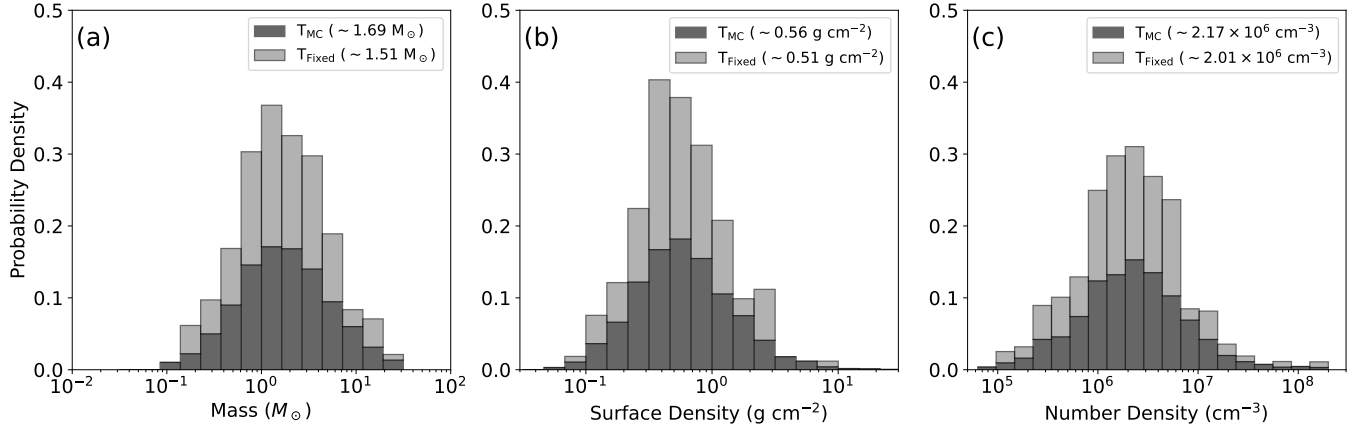


Figure 11. Histograms of the relevant physical parameters for QUARKS starless cores, derived using a fixed dust temperature (T_{Fixed}) of 20 K (gray) and from MC simulations where the dust temperature (T_{MC}) was randomly sampled from a range of 10–30 K (black). Median values for each distribution are given in parentheses.

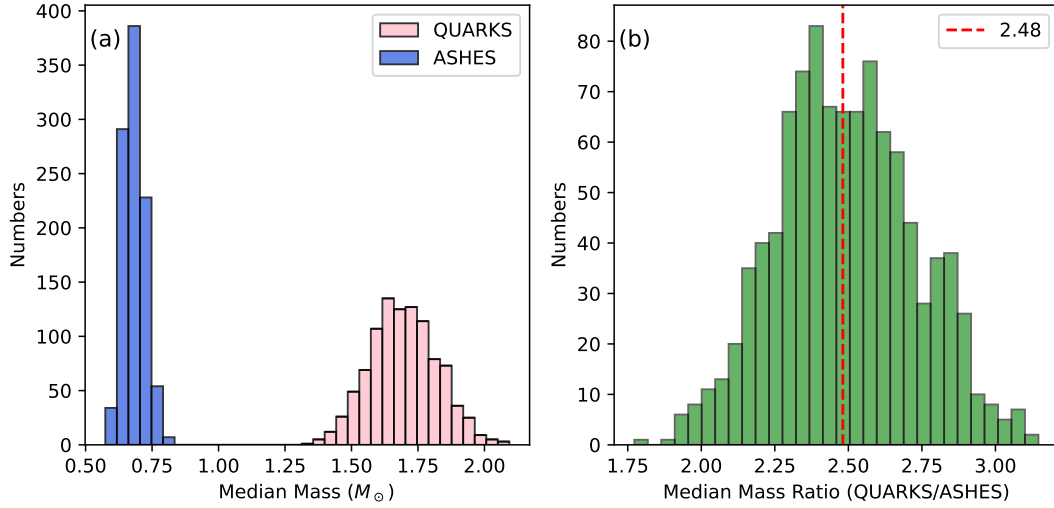


Figure 12. Simulated mass distributions for both the ASHES and QUARKS starless cores (panel (a)) and the median mass ratio distribution between the simulated QUARKS and ASHES samples (panel (b)). The dashed line indicates the median value.

Appendix D

Parameters of Molecular Line Emission from the QUARKS Starless Cores

Table D1 presents the relevant Gaussian-fit parameters of H_2CO , DCN , N_2D^+ , and H^{13}CO^+ detected in the QUARKS starless cores.

Table D1
Parameters of Molecular Line Emission from the QUARKS Starless Cores

Source	Core	H ₂ CO				DCN				N ₂ D ⁺				H ¹³ CO ⁺			
		Detc.	<i>T</i> (K)	<i>V</i> _{LSR} (km s ⁻¹)	<i>σ</i> _{obs} (km s ⁻¹)	Detc.	<i>T</i> (K)	<i>V</i> _{LSR} (km s ⁻¹)	<i>σ</i> _{obs} (km s ⁻¹)	Detc.	<i>T</i> (K)	<i>V</i> _{LSR} (km s ⁻¹)	<i>σ</i> _{obs} (km s ⁻¹)	Detc.	<i>T</i> (K)	<i>V</i> _{LSR} (km s ⁻¹)	<i>σ</i> _{obs} (km s ⁻¹)
I08448-4343	9	1	4.8	2.22	0.79	1	0.68	3.16	0.59	1	1.57	2.8	0.9	2	1.76	2.73	0.87
I08448-4343	20	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I09002-4732	8	1	4.1	6.32	0.54	1	5.39	6.52	0.81	...	...	...	...	...	...	...	...
I09094-4803	6	1	1.19	76.93	0.8	...	...	...	...	...	...	...	...	1	1.8	76.64	0.86
I09094-4803	7	1	1.14	76.87	0.71	...	...	...	...	...	...	...	...	...	...	...	...
I09094-4803	9	1	1.23	75.13	1.32	...	...	...	...	...	...	...	...	1	0.91	75.55	0.97
I12572-6316_2	3	...	...	...	...	...	...	...	...	...	...	...	...	1	1.78	30.64	0.82
I12572-6316_2	4	1	1.53	28.32	0.9	1	0.26	28.5	0.81	1	0.25	29.1	0.89	1	0.78	29.51	0.99
I13079-6218	5	1	1.7	-41.19	1.56	1	0.49	-40.8	0.73	...	...	...	...	1	0.92	-41.24	0.4
I13079-6218	6	1	0.72	-39.8	0.86	1	0.62	-40.6	0.62	...	...	...	...	1	2.26	-40.4	0.8
I13111-6228	11	...	...	...	...	...	...	...	...	...	...	...	...	1	2.16	-38.9	0.8
I13134-6242	3	...	...	...	...	1	0.61	-29.6	0.57	...	...	...	...	2	1.53	-30.19	0.67
I13140-6226	12	...	...	...	...	...	...	...	...	1	0.71	-34.51	0.63	1	1.67	-34.49	0.95
I13291-6229	10	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I13291-6229	12	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I13291-6229	13	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I13295-6152	7	1	0.52	-46.1	1.3	...	...	...	...	...	...	...	...	1	2.5	-44.77	0.96
I13295-6152	10	1	0.95	-44.16	0.91	...	...	...	...	...	...	...	...	1	2.81	-44.47	0.83
I14050-6056	7	1	0.74	-48.7	0.83	...	...	...	...	...	...	...	...	...	...	...	...
I14050-6056	9	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I14206-6151	2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I14206-6151	5	...	...	...	...	...	...	...	...	1	1.16	-48.91	0.78	1	3.22	-49.0	0.38
I14206-6151	6	1	1.22	-50.97	0.62	...	...	...	...	...	...	...	...	2	2.39	-48.89	0.48
I14212-6131	5	1	0.72	-50.51	0.55	...	...	...	...	1	0.91	-51.05	0.68	1	3.4	-50.19	1.14
I14212-6131	11	...	...	...	...	...	...	...	...	...	...	...	...	1	2.45	-50.85	0.8
I15384-5348	6	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I15384-5348	8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I15384-5348	9	1	0.59	-43.0	0.87	...	...	...	...	...	...	...	...	...	...	...	...
I15384-5348	10	1	0.6	-42.8	0.78	...	...	...	...	...	...	...	...	...	...	...	...
I15384-5348	15	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I15411-5352	15	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
I15437-5343	2	1	0.45	-82.7	1.9	1	0.38	-81.6	0.9	1	0.38	-82.3	0.6	1	0.92	-82.34	0.38
I15437-5343	5	1	0.99	-84.86	0.6	1	0.39	-84.7	0.54	...	...	...	...	2	1.73	-83.23	0.51

(This table is available in its entirety in machine-readable form in the [online article](#).)

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