Stellar Populations in the Galactic Center
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Abstract We discuss the stellar content of the Galactic Center, and in particular, recent estimates of the star formation rate (SFR). We discuss pros and cons of the different stellar tracers and focus our attention on the SFR based on the three classical Cepheids recently discovered in the Galactic Center. We also discuss stellar populations in field and cluster stars and present some preliminary results based on near-infrared photometry of a field centered on the young massive cluster Arches. We also provide a new estimate of the true distance modulus to the Galactic Center and we found $14.49 \pm 0.02$ (standard) $\pm 0.10$ (systematic) mag ($7.91 \pm 0.08 \pm 0.40$ kpc). Current estimate agrees quite well with similar photometric and kinematic distance determinations available in the literature. We also discuss the metallicity gradient of the thin disk and the sharp change in the slope when moving across the edge of the inner disk, the Galactic Bar and the Galactic Center. The difference becomes even more compelling if we take into account that metal abundances are based on young stars.

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stellar tracers (classical Cepheids, Red Supergiants, Luminous Blue Variables). Finally, we briefly outline the possible mechanisms that might account for current empirical evidence.

1 Introduction

The Galactic Bulge and the Galactic Center play a crucial role in constraining the formation and the evolution of the Galactic spheroid. Recent numerical simulations indicate that the Milky Way formed Inside-Out, this means that the bulge harbors the oldest Galactic populations [20]. This theoretical framework is soundly supported by recent photometric investigations [86] suggesting that stellar populations in the Galactic Bulge are mainly old (∼11 Gyr). On the other hand, the Galactic Center together with the super-massive black hole, harbors, very young stars (a few Myr, [71, 25]), compact star clusters and massive molecular clouds [43].

Although current knowledge of the innermost components of the Galactic spheroid is quite solid, we still lack quantitative constrains concerning their kinematic structure and their chemical enrichment history. In particular, we still lack firm estimates of the edge between the thin disk and the Galactic Bulge. Moreover and even more importantly, current predictions suggest that a presence of a bar-like structure is crucial to support the high rate of star formation present in the Nuclear Bulge. Indeed, it is the bar-like structure to drag the gas and the molecular clouds from the inner disk into the Nuclear Bulge [4, 37, 38].

A more quantitative understanding of this phenomenon will have an impact into the formation and the evolution of classical bulges and pseudo-bulges. The latter are considered disk-like stellar components slowly evolving in galaxy centers, whereas the former are considered the aftermath of galaxy mergers [39]. The chemical evolution of the thin disk in the solar circle has been investigated using different stellar tracers and optical spectroscopy (Cepheids: [45, 62], open cluster: [11]). The same outcome applies for the Galactic Bulge [5, 87]. The chemical enrichment in the Galactic Center is still in its infancy [59, 17].

In the following we discuss recent findings concerning stellar populations in the Galactic Center. In particular, we will focus our attention on recent estimates of the star formation rate (§2) and on recent findings concerning field and cluster stellar populations (§3). Moreover, we will discuss in §4 recent determinations of the distance to both the Galactic Center and the Galactic Bulge. The metallicity distribution will be discussed in §5 while in §6 we briefly outline future perspective for photometric and spectroscopic investigations.
Stellar Populations in the Galactic Center

2 Stellar populations and star formation in the Galactic Center

2.1 Star formation

The star formation rate (SFR) across the Galactic Center was estimated by [29] and more recently by [83], they found that it was constant during the last few tens of Myr. The latter investigation is based on a paramount analysis of multiband data: NIR (2MASS), MIR (SPITZER), submillimeter (SCUBA) and radio (VLA). These data were used to fit the spectral energy distribution of Young Stellar Objects and on the basis of their ages they provided solid constraints on the recent star formation rate. On the other hand, [78], by using NIR (DENIS) and MIR (ISOGAL) observations and Asymptotic Giant Branch stars as stellar tracers, found that the SFR was enhanced in the nuclear bulge more than 200 Myr ago and almost continuous till present times. By using deep NIR color-magnitude diagrams based on NICMOS at HST, [25] found that the present day enclosed mass within 30 pc of the Galactic Center, the star counts and the shape of the K-band luminosity function support a continuous star formation history with a rate of \(~0.02\, M_\odot\, yr^{-1}\). This finding is also consistent with the presence of the three young massive clusters located inside the central 50 pc. The above investigations are somehow hampered by uncertainties affecting distance determinations and by the relevant changes of the extinction across the Galactic Center. Moreover, both individual and ensemble age estimates based on the above tracers might be affected by possible systematic uncertainties. Classical Cepheids present several advantages when compared with other stellar tracers.

1. **Easy targets**— Classical Cepheids are bright stars and they can be easily recognized by using either the Bailey diagram (luminosity amplitude vs period) or the Fourier parameters of light curves.

2. **Distance indicators**— Classical Cepheids are very robust primary distance indicators. NIR Period-Luminosity relations and Period-Wesenheit relations are marginally affected by metallicity effects and by differential reddening.

3. **Evolutionary status**— Their evolutionary status is well established. They are intermediate-mass stars during central helium burning and hydrogen shell burning. They are evolving along the so-called blue loop and obey to well defined Period-Age and Period-Color-Age relations [8]. In particular, once the chemical composition has been fixed and we neglect the width in temperature of the instability strip, longer is the pulsation period younger is the age of the Cepheid.

4. **Pulsation properties**— Their pulsation behavior is also well established [2]. They pulsate in the fundamental, first overtone and as mixed pulsators (topology of the Cepheid instability strip). They obey to well defined Period-Color relations. This means that their apparent colors can be adopted to provide an independent estimate of the reddening.

However, they are far from being ideal stellar tracers, since they also have some indisputable disadvantages.
Fig. 1 Comparison between the NIR photometry of the Galactic Center, collected with the NIR camera SIRIUS at the 1.4m telescope IRSF in South Africa, and stellar isochrones. The blue stars mark the position of the three classical Cepheids recently discovered by [55]. Solid and dashed lines display isochrones with ages ranging from 28.3 Myr (red) to 100 Myr (green) and solar chemical composition (BASTI data base). Isochrones plotted in this figure account for a mild convective core overshooting during central hydrogen burning phases. Predictions were plotted by assuming a true distance modulus of 14.5, an extinction $A_K = 2.5$ mag and the reddening law by [61].

1. **Time series**– The identification does require homogeneous time series data over time intervals ranging from a few days to more than one hundred days.

2. **Multiband observations**– The use of their mean colors does require well sampled light curves in at least two different bands.

3. **Pulsation amplitude**– Their pulsation amplitude steadily decreases when moving from the optical to the NIR bands. The difference is mainly caused by the fact that optical bands are more sensitive to temperature variations, while the NIR bands to radius variations.

On the basis of the above circumstantial evidence and on the discovery of three classical Cepheids with pulsation periods of the order of 20 days, located within 40 parsecs of the central black hole, [55] provided a solid estimate of the SFR. On the basis of the lack of classical Cepheids with shorter periods they estimated that approximately 25 million years ago the star formation rate in this region increased.
relative to the period of 30-70 million years ago. In order to further constrain the age of the newly discovered Galactic Center Cepheids, we decide to use an independent approach. Fig. 1 shows the NIR ($K_S$ vs $J - H$) Color-Magnitude Diagram of the Galactic Center region based on NIR images collected with SIRIUS at the 1.4m telescope IRIS in South Africa.

To constrain the age of the Cepheids we adopted the stellar isochrones available in the BaSTI data base\(^\text{[65, 66]}\). In particular, we selected isochrones at solar chemical composition (global metallicity, $Z=0.02$; primordial helium, $Y=0.273$) accounting for mild convective core overshooting during central hydrogen burning phases and for a canonical mass loss rate. The ages range from 28 (solid red) to 100 (dashed green) Myr. We also adopted a distance modulus of $\mu=14.5$ mag (see section 3) and the K-band extinction suggested by\(^\text{[55]}\) and the reddening law by\(^\text{[60]}\). The comparison between stellar isochrones and observed classical Cepheids (blue stars) indicate that their age is of the order of 28 Myr. This estimate agrees quite well with the age based on the Period-Age relation (20–30 Myr). It is worth mentioning that age estimates based on the comparison in the Color-Magnitude diagram (CMD) between data and isochrones do depend on uncertainties distance and reddening estimates. Moreover, they are affected by uncertainties in the treatment of mass loss rate and in the efficiency of internal mixing\(^\text{[68]}\). The age estimates based on the Period-Age relations of classical Cepheids are also affected by uncertainties affecting the mass-luminosity relation, but they appear to be more robust concerning individual age determinations\(^\text{[8]}\).

2.2 Stellar populations

In two seminal investigations concerning the stellar populations in the Galactic Center, dating back to more than twenty years ago,\(^\text{[64]}\) and\(^\text{[57]}\) performed a NIR survey (the pixel scale was 0.278 arcsec and the filed of view $\approx 71 \times 71$ arcsec) of the central 30 pc using IRAC at 2.2m ESO/MPG telescope. They provided firm empirical constraints on the role played by the different stellar components. They found that low-mass ($M < 1 M_\odot$) stars are the main contributor to the dynamical mass (90%), while they only contribute a minor fraction of the K-band flux, namely the 6%. On the other hand, intermediate- and high-mass stars contribute with only the 6% of the dynamical mass, but with almost the 90% of the K-band flux. By using NIR, MIR, millimeter (IRAM) and radio (MPIfR) observations,\(^\text{[43]}\) confirmed the previous finding, and indeed they found that 70% of the optical-UV flux comes from massive stars. Moreover, they also provided an estimate of the dynamical mass and thy found that it is $M \approx 1.4 \times 10^9 M_\odot$.

The recent literature concerning the young massive star clusters in the Galactic Center is even more flourishing. Detailed spectroscopic investigations of high-mass stars in the Central Cluster and in Arches have been provided by using the integral

\(^1\) The interested reader is referred to http://albione.oa-teramo.inaf.it/
Fig. 2 Comparison between the NIR photometry of the young cluster Arches collected with the NIR camera SOFI at NTT/ESO in La Silla, and stellar isochrones. Note that are only plotted stars located within two arcminutes from the cluster center. The solid lines show young (30 Myr) isochrones at solar chemical composition (BaSTI data base). The adopted distance modulus of 14.5, the K-band extinction $A_K = 2.5$ mag and the reddening law are the same as in Fig. 1. The black arrow shows the reddening vector.

field spectrograph SINFONI at ESO/VLT [53, 54]. A similar analysis was recently performed by [46] for Wolf–Rayet stars along the nitrogen sequence centrally located in the Quintuplet cluster. They found that their sample is quite bright, but with relatively cool effective temperatures. Interestingly enough, they also found that these objects together with similar objects in Arches and in the Galactic Center form a distinct group in the Hertzsprung-Russell diagram. Deep NIR CMDs for Arches and Quintuplet have been provided by [23, 24] using NICMOS at HST. They reached a limiting magnitudes between 19 and 20.5 in the F160W and F205W
bands and estimated that the cluster age ranges from $2 \pm 1$ Myr (Arches) to $4 \pm 1$ Myr (Quintuplet).

A more detailed NIR photometric analysis of the Arches stellar content was recently provided by [22]. They adopted NACO Adaptive Optic camera at ESO/VLT to perform very accurate and deep photometry, they found that a Salpeter–like power law cannot be discarded for the Initial Mass Function (IMF) of Arches. This is a very interesting finding, since previous investigations [74, 36] suggested a top–heavy IMF for this cluster. The empirical scenario is becoming even more interesting due to the ongoing discoveries of new clusters. By using images collected with NCMOS at HST and low-resolution spectra with ISAAC at ESO/VLT, [19] identified a new young massive cluster located at the far end of the Galactic Bar.

In order to constrain the field and the cluster stellar populations in the Galactic Center, we started a long term project aimed at providing a detailed census of the young-, the intermediate- and the old populations. We are facing two important problems in dealing with a quantitative analysis of the stellar populations in the Galactic Center: a) heavy differential extinction affecting both field and cluster stars; b) transformations into a standard photometric system becomes a difficult problem in presence of strong reddening variations [22]. To properly address the latter problem, we performed accurate NIR photometry across the Arches cluster by using a set of $J$ (82), $H$ (45) and $K_S$ (45) images collected with SOFI at ESO/NTT. The entire data set includes both low- (0.288 arcsec/px, FoV= 4.9 x 4.9 arcmin) and high- (0.144 arcsec/px, FoV = 2.5 x 2.5 arcmin) resolution mode. The photometry was performed by using DAOPHOT and ALLFRAME ([73], and references therein). The final photometric catalog was calibrated into the 2MASS photometric system by using local standards [42]. Fig. 2 shows a preliminary $H, H-K$ CMD of the cluster region located within two arcmin from the center.

The comparison between theory and observations was performed by using young cluster isochrones at solar chemical composition. The solid lines show isochrones with ages ranging from 30 to 100 Myr. The isochrones were computed using evolutionary tracks that account for mild convective core overshooting. The isochrones were plotted by adopting a true distance modulus of $14.48 \pm 0.13$ mag, an extinction in the K-band of $A(K_S)=2.5$ mag and the reddening law by [60]. A glance at the data plotted in this figure shows that the blue stars located at $H - K_S \sim 1.4$ are cluster young main sequence stars (see Fig. 4 in [26]). However, a detailed comparison between theory and observations does require an appropriate subtraction of field stars by using nearby control fields.

3 The distance to the Galactic Center

In the recent literature distance estimates to the Galactic Center are often mixed with distance determinations to the Galactic Bulge. However, current evaluations concerning the edge of the inner disk suggest $d \sim 5 \pm 1$ kpc. Photometric and astrometric distances to the Galactic Center have been recently reviewed by [50] and
They found that both photometric and kinematic estimates cluster around 8kpc. This means that distance determinations to the Galactic Bulge do depend on the density profile and on the radial distribution of the adopted standard candle. It is plausible to assume that the two sets of distance determinations may differ at the 20% level.

In order to provide a quantitative estimate of the difference we decided to provide a new distance determination to the Galactic Center by using NIR and MIR Period-Wesenheit relations for the three new classical Cepheids in the Galactic Center. The use of the PW relation has several indisputable advantages when compared with Period-Luminosity relations [9].

1. **Reddening uncertainty**– The PW relations are independent of uncertainties affecting reddening estimates.
2. **Instability strip topology**– The PW relations are independent of the pulsator distribution inside the instability strip, since they account for the width in temperature.
3. **Linearity** – They are almost linear over the entire period range [35], since they mimic a PLC relation.
4. **Mixing length**– The dependence of the PW relations (slope and zero-point) on the adopted mixing-length parameter is negligible.
5. **Chemical composition**– The slopes of both NIR and optical-NIR PW relations appear to be independent of chemical composition for metallicities ranging from Z=0.004 (Small Magellanic Cloud) to Z=0.02 (Milky Way). The adopted helium content Y, at fixed metallicity and mass-luminosity relation, only affects the zero-point of the PW relations.

However, the PW relations also have some indisputable disadvantages.

1. **Reddening law**– The Wesenheit magnitudes rely on the assumptions that the reddening law is universal [34]. Thus, distance estimates based on PW relations do depend on the reddening law adopted to estimate the extinction coefficients.
2. **Multiband photometry**– The PW relations require time series data in two different bands.

### Table 1 Nuclear Bulge Cepheid Distances

| Star | $\mu_{\text{JK}}^0$ | $\mu_{\text{JH}}^0$ | $\mu_{\text{HK}}^0$ | $\mu_{\text{mean}}^b$ |
|------|----------------|----------------|----------------|----------------|
| a    | 14.69 ± 0.05  | 14.55 ± 0.05  | 14.53 ± 0.05  | 14.57 ± 0.03  |
| b    | 14.51 ± 0.05  | 14.32 ± 0.05  | 14.30 ± 0.05  | 14.46 ± 0.03  |
| c    | 14.53 ± 0.05  | 14.48 ± 0.05  | 14.41 ± 0.05  | 14.42 ± 0.03  |

* $^a$ Distance modulus based on the zero-point calibration obtained by the predicted FU PW relations for Galactic Cepheids provided by [52]. The associated error is the standard deviation from the theoretical PW relation. The color coefficients of the adopted PW relations are the following: $k_{J-K_S} = 0.50; \Delta \mu_{JK} = 1.42; \Delta \mu_{JH} = 1.44$; [60].

* $^b$ The weighted average of the three distance modulus estimations.
The distance of the Cepheids in the Galactic Center are derived using the PW relations in the three NIR bands ($JHK_s$). We have defined the three Wesenheit magnitudes adopting the color coefficients given in Tab. 1. By using the theoretical models provided by [52], we have computed the following PW relations:

\[
W(JK_s) = -(2.802 \pm 0.002) - (3.205 \pm 0.002) \times \log P
\]

\[
W(JH) = -(2.971 \pm 0.00) - (3.361 \pm 0.007) \times \log P
\]

\[
W(HK_s) = -(2.714 \pm 0.003) - (3.123 \pm 0.003) \times \log P
\]

with standard deviations of 0.03, 0.01 and 0.04 mag.

The mean $JHK_s$ magnitudes of the Cepheids are given in [55]. The difference between the predicted and the observed value of the Wesenheit magnitude gives the true distance modulus of each Cepheid. The distance moduli obtained in each band and the error-weighted average are listed in Tab. 1. The associated error is due to the standard deviation from the theoretical PW relation and also to the error on the total-to-selective extinction ratio, as given in [60]. The derived distances agree quite well with the independent determinations provided by [55]. Our results are independent of the extinction correction, therefore, we obtain a mean distance modulus for the three Cepheids in the Galactic Center of 14.49$\pm$0.02 (standard)$\pm$0.10 (systematic) mag with a small intrinsic error. The systematic error accounts for uncertainties in the zero-point of the NIR PW relations and in the reddening law [35]. Thus, we found a mean distance of 7.91$\pm$0.08$\pm$0.40 kpc to the Galactic Center that is in very good agreement with the distance to the Galactic Center based on the S2 orbit around the central black hole (8.28$\pm$0.35 kpc, [30]) and with the parallax of Sgr B (7.9$\pm$0.8 kpc, [70]).

4 Metallicity distribution in the Galactic Center

The iron and the $\alpha$-element abundance gradients across the Galactic disk are fundamental observables to constrain the chemical enrichment of disk stellar populations [3, 49, 45, 62, 50, 51]. They also play a key role in constraining the physical assumptions adopted in chemical evolution models [67, 15, 13]. The most recent theoretical and empirical investigations brought forward three open issues:

1. **Stellar tracers** – Empirical evidence indicates that different stellar tracers do provide different slopes. Metallicity gradients based on Cepheids, provide slopes ranging from $-0.05$ dex kpc$^{-1}$ [48, 12, 44, 41, 2, 49, 80] to $-0.07$ dex kpc$^{-1}$ [45]. More recently, [62] using iron abundances for 265 classical Cepheids – based either on high-resolution spectra or on photometric metallicity indices – and Galactocentric distances ranging from $R_G \sim 5$ to $R_G \sim 17$ kpc, found an iron gradient of $-0.051 \pm 0.004$ dex kpc$^{-1}$. By using an even more large sample of over 400 classical Cepheids, [51] found a gradient of $-0.062 \pm 0.002$ dex kpc$^{-1}$. A similar gradient was also found by [28] by using a sample of 40 open clus-
ters located between the solar circle and $R_G \sim 14$ kpc, namely $-0.06$ dex kpc$^{-1}$. On the other hand, [10] by using new metallicities for five old open clusters located in the outer disk ($12 \leq R_g \leq 21$ kpc) and the sample adopted by [28] found a shallower iron gradient: $-0.018$ dex kpc$^{-1}$. The slope of the metallicity gradient based on oxygen abundances of HII regions—with Galactocentric distances ranging from 5 to 15 kpc— is similar to the slope based on Cepheids ($-0.04$ dex kpc$^{-1}$, [21]). The difference between the different tracers, might be due to the age difference between the different tracers (young vs intermediate-age).

2. **Linear slope**—By using a sample of 76 open clusters with distances ranging from 6 to 15 kpc, it was suggested by [76] that a proper fit to the metallicity distribution does require two zones. The inner disk for Galactocentric distances ranging from 6 to 10 kpc and the outer disk for distances larger than 10 kpc. This hypothesis was supported by [12, 48, 3]. More recently, [62] found for the two zones a slope of $-0.130 \pm 0.015$ dex kpc$^{-1}$ for the inner disk ($R_G < 8$ kpc) and a slope of $-0.042 \pm 0.004$ dex kpc$^{-1}$ for the outer disk. Data plotted in Fig. 3 support the above results. We adopted the same abundances provided by [62], but we used new individual distances based on NIR Period-Wesenheit relations [35] instead of NIR Period-Luminosity relations. Current findings indicate that young tracers do show evidence of a sharp steepening of the slope in the inner disk and a mild flattening of the gradient in the outer disk.

3. **Local inhomogeneities**—There is mounting empirical evidence that abundance inhomogeneities are present not only across Galactic quadrants, but also on smaller spatial scales. [62] found that the iron abundance of the Cepheids belonging to the two overdensities located in the second and in the fourth quadrant, covers a range in metallicity similar to the range in metallicity covered by the global gradient (see also [49, 44, 50]).

Fig. 3 shows the position of bright supergiants in two Galactic Center young clusters—Arches and Quintuplet—by [58, 59] (cross) and Galactic Center field supergiants by [17] (open square). The open diamonds display the position of the two Scutum Red Supergiant clusters by [18]) located at the end of the Galactic Bar. A glance at the data plotted in this figure discloses that stars located in the Galactic Center have a solar iron abundance, whereas the average iron abundances are subsolar by $0.2-0.3$ dex for the stars located along the Galactic Bar. This means that we are facing a stark discrepancy between the metallicity gradient based on classical Cepheids and the above iron abundance. Plain leading arguments based on the extrapolation of both the global and the inner disk metallicity gradient would imply a super-solar iron abundances approaching the Galactic Center [17]). This discrepancy has already been noted in the literature and [10] suggested that the slope of the metallicity gradient should become shallower for Galactocentric distances smaller than 5 kpc. In principle there is no plausible reason why it should be extrapolated from the inner disk to the Galactic Center. Solid empirical evidence

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2 The interested reader is referred to the Table 2 of [17] for a detailed list of the most recent metallicity estimates of the Galactic Center.
suggest that the Galactic Bulge is dominated by an old (11 Gyr) stellar population with a secondary intermediate-age (a few Gyr) stellar component \[86\]. Moreover and even more importantly, recent spectroscopic investigations based on high-resolution spectra indicates that the stellar populations in the Galactic Bulge range from metal-intermediate ($[\text{Fe/H}] \sim -1$) to super solar ($[\text{Fe/H}] \sim +0.5$) with a broad main peak $[\text{Fe/H}] \approx 0.2$ \[86, 87, 32\].

4.1 Transition between the Galactic Bulge and the Galactic Center

Quantitative constraints concerning the edge between the inner disk and the Bulge and the edge between the Bulge and the Galactic Center are hampered by lack of accurate distance determinations (see Fig. 4). The above scenario is further complicated by the possible presence of the Galactic Bar. We are facing the evidence that the region located between the Galactic Center and the inner disk is characterized by the lack of star forming regions, of giant HII regions and of young open clusters \[17\]. On the other hand, Galactic Legacy Mid-Plane Survey Extraordinaire (GLIMPSE) survey based on 30 million mid-infrared (SPITZER) sources identified a linear bar passing through the Galactic Center with half-length $R_{\text{bar}} = 4.4 \pm 0.5$ kpc.

Theoretical \[4, 27\] and observational \[85, 1, 84\] investigations indicate that the abundance gradient in barred galaxies is shallower than in unbarred galaxies. The typical explanation for this trend is that the bar is dragging gas from the inner disk into the Galactic Center \[37\]. The pileup of the new fresh material triggers an ongoing star formation activity till the dynamical stability of the bar. In passing we note that the three new Cepheids discovered by \[55\] in the inner disk is supporting the evidence that star formation events might have occurred on an area broader than the near end of the Galactic Bar. A more quantitative understanding of this phenomenon has an impact into the formation and the evolution of classical bulges and pseudobulges. The latter are considered disk-like stellar components slowly evolving in galaxy centers, whereas the former are considered the aftermath of galaxy mergers \[39, 40, 55\].

One of the key consequences of the above scenario is that the typical metallicity distribution along the Galactic Bar and in the Galactic Center should be quite similar to the metallicity distribution in the inner disk. The main advantage in current analysis is that we are using stellar tracers with similar ages, since both Supergiants, Luminous Blue Variables (LBVs) and Cepheids are either massive or intermediate–mass stars. Their evolutionary lifetime is typically shorter than 100 Myr. This evidence seems to support the hypothesis that the occurrence of the bar might not be the main culprit in shaping the metallicity gradient between the inner disk and the Galactic Center. Indeed, current numerical simulations suggest that the timescale within which the radial motion of the gas smooths the actual abundance gradient is of the order of a few hundred Myrs. Part of the azimuthal variations currently observed across the Galactic disk might be caused by changes in the abundance patterns between the spiral arms and the inter-arm regions \[37\] and by the clumpiness...
of the star formation episodes. However, the kinematics of the above stellar tracers is quite limited, since they evolve in situ. This working hypothesis is supported by a very large set of Cepheid abundances provided by [50, 51]. They found no evidence of azimuthal variations in an annulus of 1 kpc around the sun. The statistics concerning the Galactic Cepheids located in the inner disk is quite limited, and indeed only a handful of Cepheids are known with Galactocentric distances smaller than 6 kpc. However, in a recent investigation [63] by using high-resolution, high S/N ratio spectra confirmed the super metal-rich nature of four of them [3]. The hypothesis suggested by [17] that the wind of metal-intermediate bulge stars might mix with metal-rich gas present along the bar and the Galactic Center to produce a chemical mixture close to solar appears also very promising. However, to our knowledge we still lack firm empirical evidence on how the winds of bulge stars might fall in the Galactic Center. The infall of metal-poor gas in the Galactic Center appears an even
more plausible channel to explain current abundance patterns [79, 47]. This is the so-called biased infall scenario [14] in which the infall of gas takes place more rapidly in the innermost than in the outermost regions (inside-out disk formation).

The abundance pattern of $\alpha$-elements is even more puzzling, since accurate measurements indicate solar abundances, and therefore consistent with typical thin disk stars [18]. However, different tracers (B-type stars, red supergiants, classical Cepheids, HII regions) do provide slightly different mean values, suggesting a broad distribution ([17], and references therein). In this context, it is worth mentioning another piece of evidence concerning the thin disk. Accurate abundance estimates of $\alpha$-elements in a sizable sample of classical Cepheids indicates that the $\alpha$(Ca, Mg, Si)-to-iron ratio attains, within the errors, a constant value across the disk [49, 44]. This evidence once confirmed has two relevant implications:

1. **Chemical enrichment**– the chemical enrichment in the last few hundred Myrs across the Galactic disk seems to be driven by core collapse supernovae.
2. **Galactic Center**– the same outcome applies to the Galactic Center, since current estimates suggest a solar composition for both the iron and the $\alpha$-elements.

### 5 Future perspectives

The content of the previous sections further underline the paramount effort undertaken by the astronomical community both from the theoretical and the observational point of view to constrain the stellar populations, the star formation rate and the chemical enrichment of the Galactic Center. During the last few years the multi-wavelength approach also provided a comprehensive picture of the physical mechanisms driving the formation and the evolution of disks and bulges [40, 31].

However, we still lack firm constraints concerning the geometry and the kinematics at the interface between inner disk, Bulge and Center. The quoted properties of stellar populations in the Bulge and in the Center bring forward that old stellar tracers, such as RR Lyrae, appear to be solid beacons to trace the 3D structure of the innermost Galactic regions. A detailed map of the RR Lyrae in the Galactic Bulge has been performed by OGLE [75], but we still lack a detailed census of RR Lyrae variables in the Galactic Center.

Moreover, we still lack detailed kinematic constraints concerning outer and the inner Lindblad resonance and of the corotation radius [81, 82, 43]. Recent estimates are mainly based on gas kinematics [6, 33, 69], but estimates based on stellar tracers are not available yet. The occurrence of peculiar radial motions at the ending points of the Galactic Bar would also provide the optimal target selection to constrain the chemical enrichment of these regions. It is clear that the second generation instruments at ESO/VLT, such as the KMOS spectrograph [72], appear to be an optimal facility to constrain the kinematics in crowded and highly reddened fields. The field of view is slightly larger than 7 arcmin in diameter and are available 24 integral field units (IFU). The wavelength coverage ranges from 0.8 to 2.5 $\mu$m with
A medium spectral resolution ($R \sim 3500$). This new observing facility will provide detailed kinematic maps for both cluster and field stars and chemical abundances for a relevant fraction of the Galactic Center. In this context the next generation of Extremely-Large-Telescopes (European-ELT [E-ELT], the Thirty Meter Telescope [TMT] and the Giant Magellan Telescope [GMT]) will also play a key role due to their high spatial resolution and high NIR sensitivity. The same applies for JWST.

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