Missing bright red giants in the Galactic center: A fingerprint of its once active state?

RAGtime 22 (Dedicated to Prof. Zdeněk Stuchlík)

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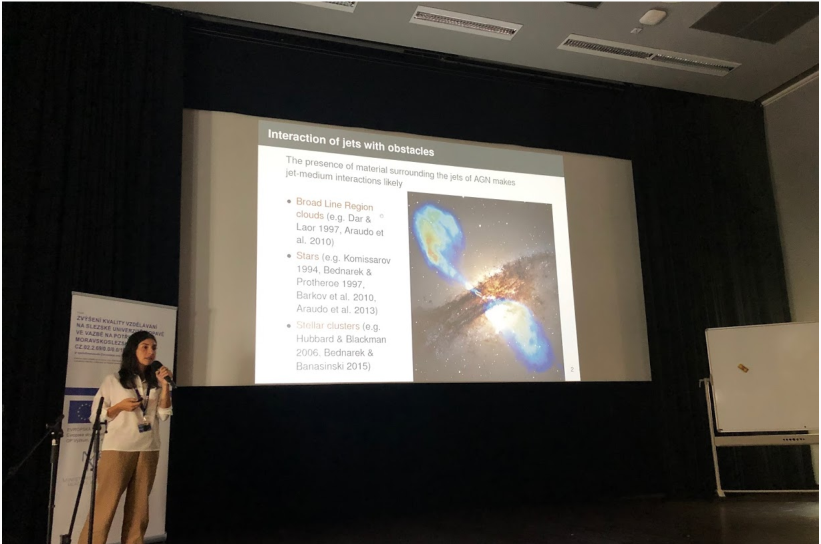
October 19, 2020

First of all: Happy Birthday! Všechno nejlepší!

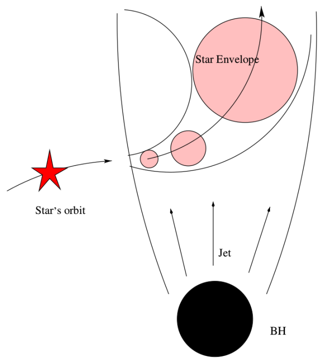
Motivation: It all started at RAGtime 21 in Opava!!!

Anabella Araudo's talk at RAGtime 21: "Truncation of AGN jets by their interaction with a stellar cluster"



Motivation: It all started at RAGtime 21 in Opava!!!

Anabella Araudo's talk at RAGtime 21: "Truncation of AGN jets by their interaction with a stellar cluster". **Anabella showed this illustration by Maxim Barkov:**



Barkov+(2012): Interaction of a red giant with a powerful AGN jet.
What happens to the star?

Discovery of missing red giants

- discovery paper of Kristen Sellgren (now Emerita Professor, Ohio State University) from 1990

THE ASTROPHYSICAL JOURNAL, **359**:112–120, 1990 August 10

VELOCITY DISPERSION AND THE STELLAR POPULATION IN THE CENTRAL 1.2 PARSECS OF THE GALAXY

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ABSTRACT

We have obtained spectra of the 2.3 μm CO band head in integrated starlight at several positions in the central 1.2 pc of the Galaxy. We find that the strength of the absorption feature declines with projected distance for projected distances less than 15″ (0.6 pc). We confirm that there is an increase in the velocity dispersion σ of the faint stars toward the Galactic center. However, within a 15″ radius of IRS 16, we find that there is no dependence of σ on projected distance. We find that $\langle \sigma \rangle = 125$ km s^{-1} and that systematic rotation of the stellar cluster is negligible in the central region. The observations are consistent with there being no CO absorption feature in the diffuse starlight within a true radius of 0.6 pc, with the observed CO feature at projected distances less than 0.6 pc arising in material at larger true radii along the line of sight. We discuss several possible explanations for the lack of CO absorption in the central 1.2 pc, including destruction of the atmospheres of late-type stars by stellar collisions, dissociation of the CO molecule in the atmospheres of the late-type stars by a central luminosity source, and a core radius for the old stellar population of 0.6 pc combined with an additional cluster of sources without CO absorption in the central parsec. Given the new information on the dependence of the strength of the CO band head on projected distance, we have reanalyzed the kinematic data presented in a previous paper (McGinn *et al.* 1989) to derive the mass distribution for radii between ~4 and ~0.6 pc. We confirm the conclusions of that paper that there is evidence for an increase in the mass–to–2 μm radiation ratio M/F_K toward the center of the Galaxy. If there is no change in M/F_K of the stellar cluster, then an unseen mass of $(5.5 \pm 1.5) \times 10^6\ M_\odot$ must be concentrated within a 0.6 pc radius of the Galactic center in order to explain the observed kinematics.

Subject headings: galaxies: internal motions — galaxies: The Galaxy — galaxies: nuclei — infrared: spectra

Discovery of missing red giants

- discovery paper of Kristen Sellgren (now Emerita Professor, Ohio State University) from 1990

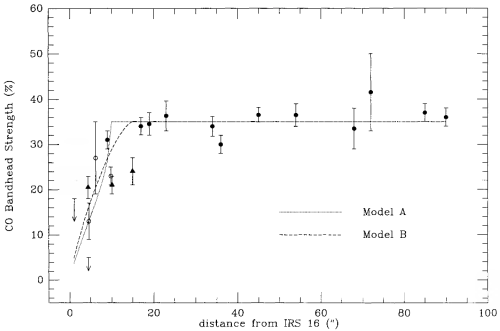


FIG. 5.—Observations of Fig. 3, compared with model calculations. The curves are model predictions for the CO absorption strength integrated along the line of sight, assuming that the density of CO absorption sources depends on true radius r as $r^{-1.8}$ outside a radius r_{CO} but changes for $r < r_{CO}$. These models assume that the density of all 2 μm sources is proportional to $r^{-1.8}$ for $r > r_{2\,\mu m}$, and is constant for $r < r_{2\,\mu m}$, where $r_{2\,\mu m}$ is the core radius for the 2 μm light. Model A (*dotted curve*): no CO absorption sources for $r < r_{CO} = 10''$; $r_{2\,\mu m} = 1''$. Model B (*dashed curve*): constant density of CO absorption sources for $r < r_{CO} = 15''$; $r_{2\,\mu m} = 1''$.

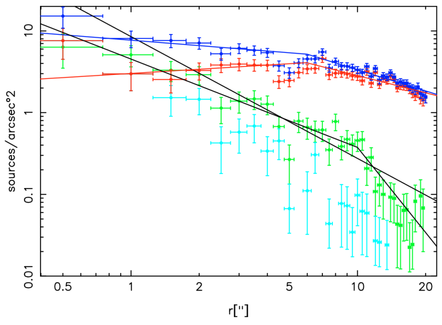
Discovery of missing red giants

- discovery paper of Kristen Sellgren (now Emerita Professor, Ohio State University) from 1990

Motivation

- **flattening of the surface-brightness profile** of brighter late-type stars
- fainter late-type stars as well as young OB stars have **cusp-like** profiles

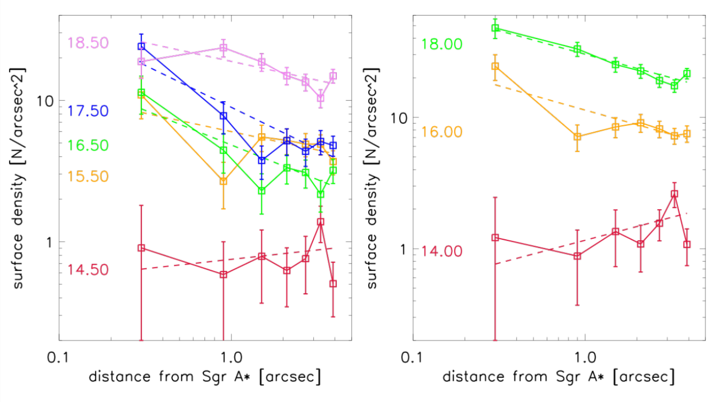
Surface density profiles of early- (green) and late-type (red) stars by Buchholz+09:



Observational results: surface-brightness profiles

- **fainter gaints** show a **cusp-like profile** (Habibi+19, Schoedel+20)
- **brighter late-type stars** of $K_{\mathrm{s}} = 14.5 - 14.0$ mag have a **flat to a decreasing surface density profile**

Results from Schoedel+2020: $\alpha_{14.5} = 0.13 \pm 0.32$, $\alpha_{15.5} = -0.26 \pm 0.15$, $\alpha_{16.5} = -0.49 \pm 0.14$, $\alpha_{17.5} = -0.59 \pm 0.14$, $\alpha_{18.5} = -0.27 \pm 0.11$



Motivation

- Key question: **What mechanism is responsible for a stellar cusp of fainter late-type stars and a flat, core-like profile of brighter red giants?**
- Schoedel+2020 found that 80% of the stellar mass formed > 10 Gyr ago
- two-body (non-resonant) relaxation time (in the inner parsec):

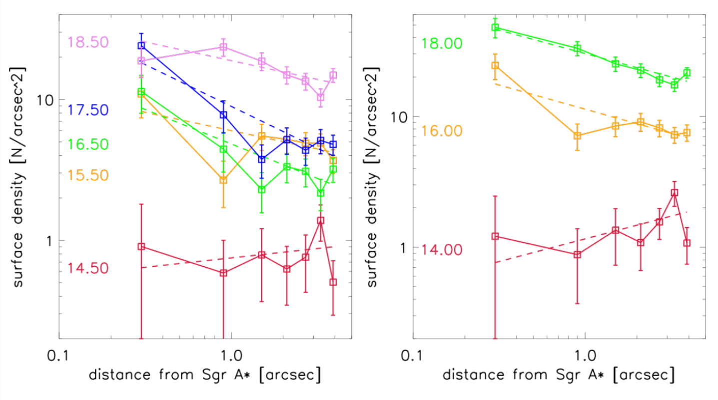
$$\tau_{\rm relax} = \frac{0.34\sigma^3}{G^2 m_\star \rho_\star \log\Lambda} \sim 1.3 \times 10^9\,{\rm yr} \tag{1}$$

- most ($\sim 80\%$) of the late-type stars are expected to be relaxed $\rightarrow$ **Bahcall-Wolf-like** cusp should be present with the **3D** slope of $\rho(r) \propto r^{-1.5}$ (Solar-mass stars) and $\gamma \approx -2$ for stellar black holes (Alexander 2017)

Observational results: surface-brightness profiles

- apart from the brightest late-type stars with $K_s = 14.5 - 14.0$ mag, fainter gaints show a cusp-like profile (Habibi+19, Schoedel+20)

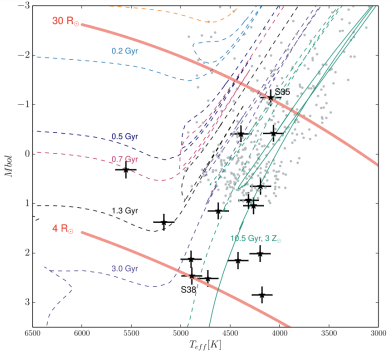
Results from Schoedel+2020: $\alpha_{14.5} = 0.13 \pm 0.32$, $\alpha_{15.5} = -0.26 \pm 0.15$, $\alpha_{16.5} = -0.49 \pm 0.14$, $\alpha_{17.5} = -0.59 \pm 0.14$, $\alpha_{18.5} = -0.27 \pm 0.11$



Observational results: surface-brightness profiles

- Habibi+19 found that $\sim 4-5$ bright giants ($K_\mathrm{s} < 15.5$) could be missing within $\sim 0.04\,\mathrm{pc}$
- Gallego-Cano+18 estimate ~ 100 missing bright giants within the inner $\sim 0.3\,\mathrm{pc}$

Habibi+19 infer that atmosphere radii of late-type stars $\lesssim 30 R_\odot$ at $\lesssim 0.2\,\mathrm{pc}$:



Explanations of the missing bright giants

- a process that **preferantially** acts upon extended, large giants and leaves smaller, fainter giants as well as young OB stars intact → alternation of spatial, temperature, and/or luminosity distribution
- **several scenarios** proposed within the last 30 years:

(a) **tidal disruption of red giants** by the SMBH (Hills 1975; Bogdanovic+2014; King 2020),

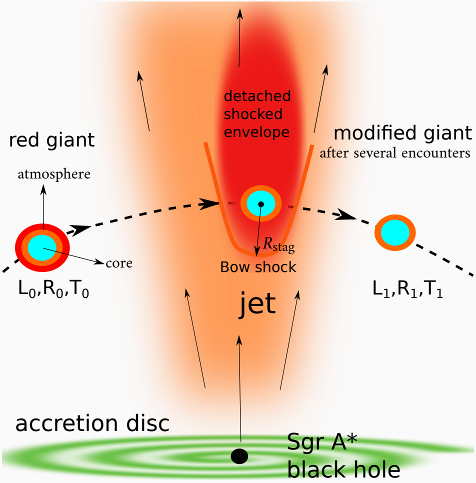
(b) **red giant–accretion disc (clumps) collisions** (Armitage+1996; Amaro-Seoane & Chen 2014; Kieffer & Bogdanovic 2016),

(c) **collisions of red giants with field stars and compact remnants** (Phinney 1989; Morris 1993; Genzel+1996),

(d) **mass segregation effects:** the infall of a secondary massive black hole (Baumgardt+2006; Merritt & Szell 2006) or the infall of a massive cluster (Kim & Morris 2003; Ernst+2009, Antonini+2012) or the dynamical segregation of stellar black holes (Morris 1993).

Novel scenario

We propose a **novel scenario**: **ablation or "shaving off" of red giants in the jet–star interactions**



Model set-up

- jet kinetic luminosity and duration based on γ-**ray Fermi bubbles/bipolar radio bubbles/X-ray chimneys** (Su+2010; Heywood+2019; Ponti+2019)
- overall energy content of $10^{56} - 10^{57}\,\mathrm{erg}$ (Bland-Hawthorn+2019)
- Guo & Mathews(2012) can reproduce the γ-ray Fermi bubbles 50° north and south of the Galactic plane by an AGN jet duration of 0.1–0.5 Myr $\rightarrow L_\mathrm{j} \approx 10^{56-57}\,\mathrm{erg}/(0.1 - 0.5\,\mathrm{Myr}) = 6.3 \times 10^{42} - 3.2 \times 10^{44}\,\mathrm{erg\,s^{-1}} \lesssim L_\mathrm{Edd} \sim 5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$
- jet active 4 ± 1 Myr due to the higher accretion activity: infall of gas cloud at least $10\,000\,M_\odot$ (Su & Finkbeiner 2012), potentially related to the observed stellar disks!? (Ali+2020)

Model set-up

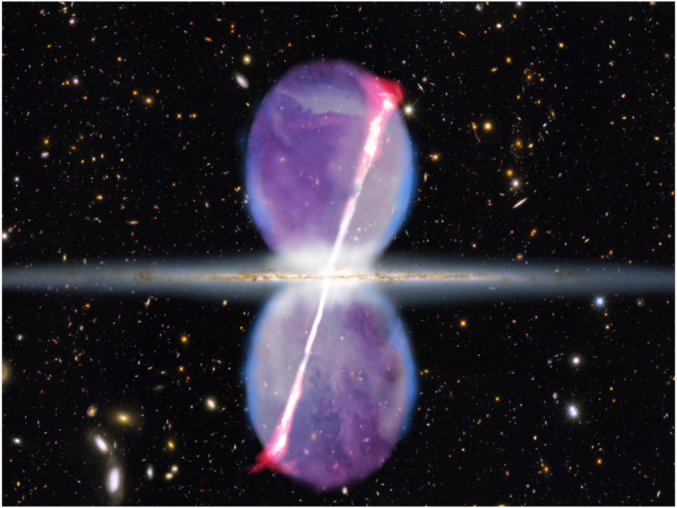


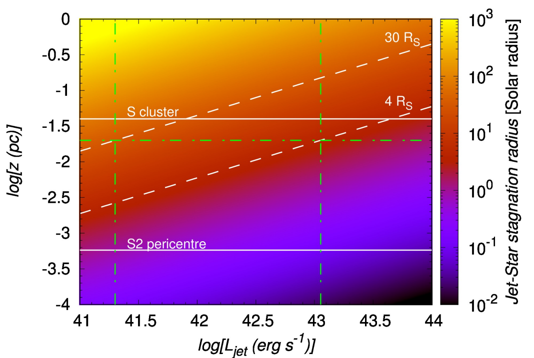
Image credit: David A. Aguilar (Harvard-Smithsonian Center for Astrophysics)

Results

- stagnation radius profile as a function of distance and jet luminosity

$$P_{\rm j} = P_{\rm sw} \rightarrow R_{\rm stag} = z \tan\theta \sqrt{\frac{\dot{m}_{\rm w} v_{\rm w} c}{4 L_{\rm j}}}$$

$$R_{\rm stag} = 27 \left(\frac{z}{0.04\,{\rm pc}}\right) \left(\frac{\dot{m}_{\rm w}}{10^{-8}\,M_{\odot}{\rm yr}^{-1}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm w}}{10\,{\rm km\,s^{-1}}}\right)^{\frac{1}{2}} \left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right)^{-\frac{1}{2}}$$

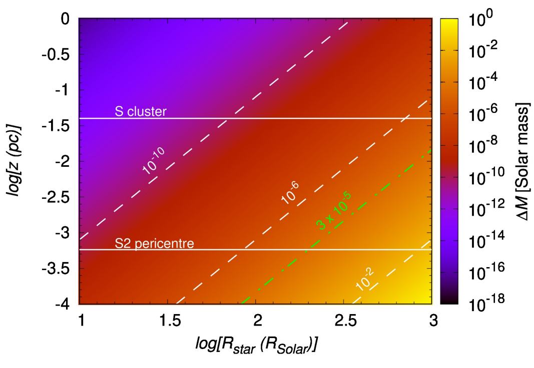


Results

- jet-induced envelope removal (single passage)

$$n_{\rm cross} = 2\frac{t_{\rm jet}}{P_{\rm orb}} \sim 2\times 10^4 \left(\frac{t_{\rm jet}}{0.5\,{\rm Myr}}\right)\left(\frac{M_\bullet}{4\times 10^6\,M_\odot}\right)^{\frac{1}{2}}\left(\frac{z}{0.01\,{\rm pc}}\right)^{-\frac{3}{2}}$$

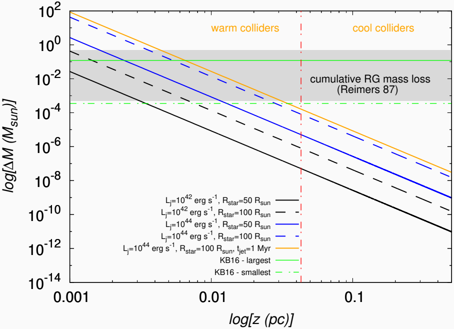
$$\frac{\Delta M_1^{\rm max}}{M_\odot} \approx 4\times 10^{-10}\left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right)\left(\frac{R_\star}{100\,R_\odot}\right)^4\left(\frac{z}{0.04\,{\rm pc}}\right)^{-2}\left(\frac{\theta}{0.22}\right)^{-2}\left(\frac{m_\star}{M_\odot}\right)^{-1}$$



Results

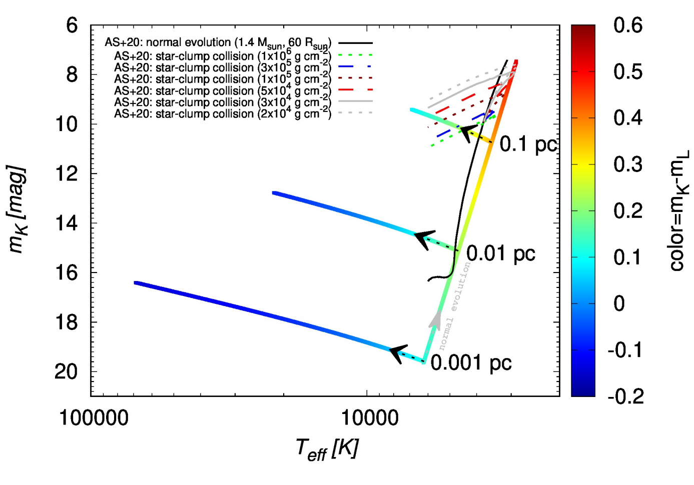
- jet-induced envelope removal – effect of multiple passages
- cumulative mass loss comparable to star–disc collisions as well as stellar-wind losses

$$\Delta M \sim n_{\rm cross}\Delta M_1$$
$$\approx 10^{-4}\left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right)\left(\frac{R_\star}{100\,R_\odot}\right)^4\left(\frac{z}{0.01\,{\rm pc}}\right)^{-\frac{7}{2}}\times$$
$$\left(\frac{\theta}{0.22}\right)^{-2}\left(\frac{m_\star}{M_\odot}\right)^{-1}\left(\frac{t_{\rm jet}}{0.5\,{\rm Myr}}\right)\left(\frac{M_\bullet}{4\times10^6\,M_\odot}\right)^{\frac{1}{2}}$$



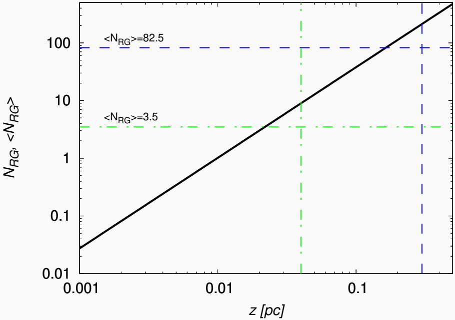
Results

- ablated red giants become warmer/"bluer" $T_{\rm abl} = T_0(R_0/R_{\rm abl})^{1/2}$
- ablated red giants become fainter in the NIR domain $L_{\rm abl} \approx L_0(R_{\rm abl}/R_0)^{3/2}$



Results

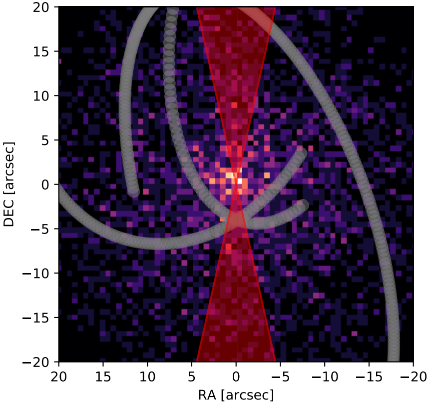
- a number of red giants crossing the jet per orbital period consistent with the inferred number of missing bright red giants at 0.04 and 0.3 pc: 4-5 (Habibi+2019) and 100 (Gallego-Cano+2018), respectively



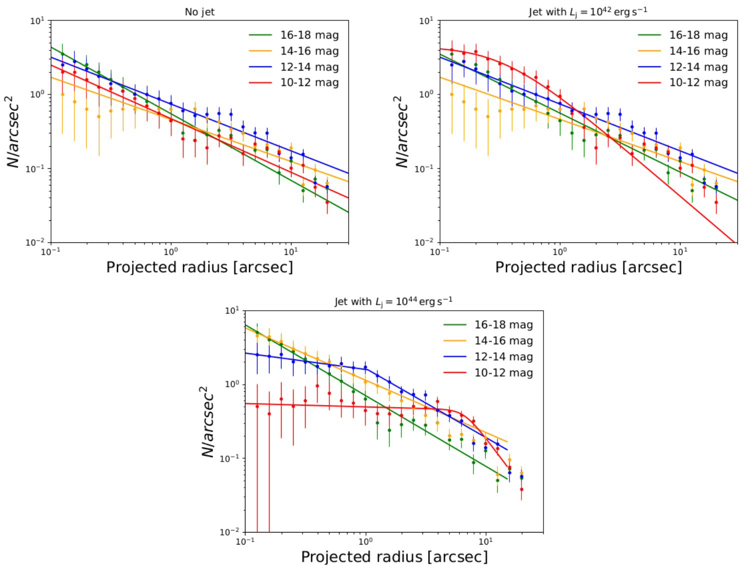
Distance	$L_{\rm j} = 10^{42}\,{\rm erg\,s^{-1}}$	$L_{\rm j} = 10^{44}\,{\rm erg\,s^{-1}}$
$0.04\,{\rm pc}$	$R_\star = 27\,R_\odot,\ m_{\rm abl} = 11.7,\ \eta = 1.27\%$	$R_\star = 2.7\,R_\odot,\ m_{\rm abl} = 16.1,\ \eta = 26.5\%$
$0.5\,{\rm pc}$	$R_\star = 338\,R_\odot,\ m_{\rm abl} = 6.95,\ \eta = 0.05\%$	$R_\star = 33.8\,R_\odot,\ m_{\rm abl} = 11.3,\ \eta = 0.95\%$

Results - Demonstration on the surface stellar profiles

- we generated a mock nuclear stellar cluster with the initial $n_{\mathrm{RG}} = n_0(z/z_0)^{-\gamma}$ with $\gamma \sim 1.43$ according to Gallego-Cano+2018 (4000 late-type stars in total)

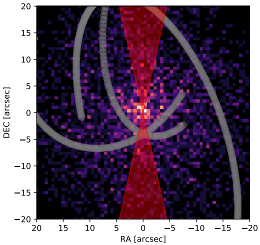


Results - Demonstration on the surface stellar profiles



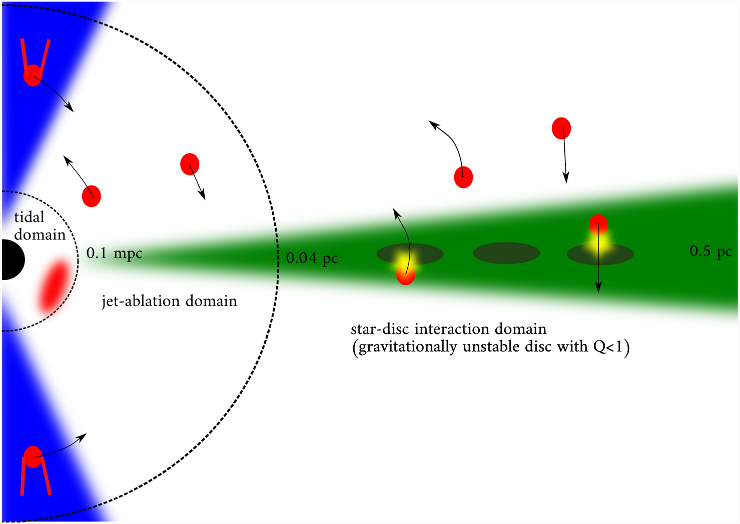
Results - Main conclusions

- in comparison with the **no-jet scenario**, the **active** Seyfert-like **jet flattens the surface profile of the brightest red giants** (10-12 mag, intrinsic), starting within the inner arcsecond (0.04 pc)
- for the most luminous jet ($10^{44}\,\mathrm{erg\,s^{-1}}$), the core-like profile extends up to 0.4 pc for the brightest gianst
- fainter giants ($>$ 14 mag, intrinsic) keep the cuspy profile within the S cluster for all jet luminosities
- young OB stars are left intact because of their powerful winds



Results - Unification scheme

- tidal disruption of red giants, jet-ablation, and star-disc collisions **coexisted likely simultaneously** but on different spatial scales



Results - Paper Accepted by ApJ

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Depletion of bright red giants in the Galactic center during its active phases

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ABSTRACT

Observations in the near-infrared domain showed the presence of the flat core of bright late-type stars inside $\sim 0.5\,$pc from the Galactic center supermassive black hole (Sgr A*), while young massive OB/Wolf-Rayet stars form a cusp. Several dynamical processes were proposed to explain this apparent paradox of the distribution of the Galactic center stellar populations. Given the mounting evidence about a significantly increased activity of Sgr A* during the past million years, we propose a scenario based on the interaction between the late-type giants and a nuclear jet, whose past existence and energetics can be inferred from the presence of γ-ray Fermi bubbles and bipolar radio bubbles. Extended, loose envelopes of red giant stars can be ablated by the jet with kinetic luminosity in the range of $L_{\rm j} \approx 10^{41}$–$10^{44}\,{\rm erg\,s^{-1}}$ within the inner $\sim 0.04\,$pc of Sgr A* (S cluster region), which would lead to their infrared luminosity decrease after several thousand jet-star interactions. The ablation of the atmospheres of red giants is complemented by the process of tidal stripping that operates at distances of $\lesssim 1\,$mpc, and by the direct mechanical interaction of stars with a clumpy disc at $\gtrsim 0.04\,$pc, which can explain the flat density profile of bright late-type stars inside the inner half parsec from Sgr A*.

Keywords: Galaxy: center — stars: supergiants — galaxies: jets — stars: kinematics and dynamics