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SUNRISE-3D: Sharp UNveiling of AGN feedback Regulation and its Impact on Star-formation at the cosmic noon Epoch[☆,☆☆]

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ABSTRACT

To better understand the role of AGN-driven outflows as a mechanism for heating or sweeping up gas over distances comparable to the size of the galaxy in its evolution, and to explore their physical characteristics as a function of AGN and host galaxy properties, it is necessary to have a statistical sample of AGNs selected from a uniform sample of galaxies with spectroscopic coverage of key rest-frame optical emission lines. To assess the impact of AGN-driven outflows on their host galaxies, we need to derive the mass and energy carried by the outflows, as well as correlations of these quantities with both AGN and host galaxy properties, in order to reveal their effects on the galaxy population and constrain the physical mechanisms driving the outflows. The availability of adaptive-optics-assisted 3D spectroscopy with the ELT multi-IFU instrument SHARP/VESPER enables the construction of spatially resolved outflow property maps, providing instantaneous outflow rates across the entire field of view without assuming outflow geometry, and thus significantly reducing the uncertainties compared to methods based on longslit spectroscopy. Furthermore, combining these maps with resolved star formation rate (SFR) maps allows a direct comparison between outflow properties and star-formation activity across the galaxy, providing key insights into how AGN feedback regulates star formation down to sub-kpc scales. By applying this approach to a representative sample of galaxies at cosmic noon ($1.5 < z < 2.5$), spanning a wide range of stellar masses from low-mass systems ($M_\star = 10^{8-10}\,M_\odot$) to the massive end ($M_\star > 10^{10}\,M_\odot$), we aim to systematically investigate the interplay between AGN activity, outflows, and star formation in the galaxy population as a whole.

1. Scientific rationale

Theoretical models of galaxy formation predict more stars than are actually observed: only ∼20% of the baryonic content within dark matter halos forms stellar mass (e.g. Guo et al. 2010), with the efficiency peaking in halos of $\sim10^{12}\,M_\odot$, corresponding to a stellar mass of $\sim10^{10.5}\,M_\odot$, and declining at both lower and higher masses. This implies that some mechanism must actively regulate star formation (SF) across the full mass spectrum. At the low-mass end, supernova explosions and winds from massive stars can drive outflows that redistribute gas and metals, the so-called stellar feedback (e.g. Hopkins et al. 2014), as the shallower gravitational potential makes the interstellar medium (ISM) more susceptible to energy injection. In more massive galaxies, however, the energy released by stars is insufficient to counteract the deep gravitational potential, and feedback from accreting supermassive black holes (SMBHs) becomes the dominant mechanism. Active galactic nuclei (AGN) inject energy both radiatively and kinetically into their host galaxies (e.g. Peng et al. 2010, Di Matteo et al. 2005, Pillepich et al. 2018), regulating star formation and explaining observed correlations between black hole mass and galaxy properties (see Fabian 2012 for a review). Despite significant observational progress over the past decade, from focused studies of the most luminous quasars to large statistical surveys of more typical galaxies (see Section 1.1), focusing on a single gas phase yields only a partial view of galactic outflows. A blind, spatially resolved, multi-phase census of feedback across the entire galaxy population is still missing, and the cosmic noon ($1.5 \lesssim z \lesssim 2.5$), marking the peak of both cosmic star formation and black hole accretion, represents the ideal epoch to conduct it. The Adaptive-Optics (AO)-corrected multi-IFU SHARP/VESPER, covering 1.2–2.4 μm

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at R ∼ 3000 and resolving structures down to 30 mas (≈0.3 kpc at $z \sim 2$), will simultaneously unveil the ionized and (likely) neutral gas components across the full galaxy population, making a spatially resolved, multi-phase census of this kind possible for the first time.

1.1. The role of the AGN feedback

The multi-phase nature of galactic outflows is now well established. The ionized component is probed via rest-frame optical lines such as [OIII], which traces the narrow-line region (NLR) gas (Kakkad et al., 2020), and rest-frame UV lines such as CIV, which traces winds on nuclear scales (Vietri et al., 2020, 2025); the neutral phase through blueshifted absorption features such as NaID (Rupke and Veilleux 2011, Davies et al. 2024); and the cold molecular gas via asymmetric profiles of transitions such as CO (Cicone et al., 2014).

Powerful outflows are predominantly observed in luminous AGN and QSOs, reaching velocities of several thousand km s^{-1} (e.g. Cano-Díaz et al. 2012; Shen and Ho 2014, Villar Martín et al. 2020). For example, in the WISE/SDSS-selected hyper-luminous quasar (WISSH) survey, 85 targets with $L_{\rm bol} > 10^{47}$ erg s^{-1} (Saccheo et al., 2023) at z = 1.5 − 4.5, the ionized component, traced for 18 QSOs by targeting the [O III] line with NIR LBT/LUCI spectrograph, shows exceptional luminosities and velocities (up to several thousand km s^{-1}), mass-outflow rates of several thousand $M_\odot$ yr^{-1} and kinetic powers amounting to a few percent of the bolometric luminosity ($L_{\rm Bol}$), demonstrating highly efficient winds that can sweep out ionized gas (Bischetti et al., 2017; Vietri et al., 2018).

By analyzing heterogeneous, large sample of AGN, Fiore et al. (2017) showed that galaxies hosting powerful AGN winds have molecular gas depletion times and gas fractions that are 3–10 times lower than those galaxies with similar star formation rates, stellar masses, and redshifts. This implies that, at high AGN bolometric luminosities, a substantial fraction of the molecular gas may be disrupted by the outflow, shifting much of it into atomic or ionized phases, though the impact appears more limited at lower stellar masses.

1.1.1. Statistical approach

Statistical studies of ionized outflows at cosmic noon became possible with the advent of near-infrared multi-object spectrographs as MOSFIRE, KMOS, and FMOS enabling observations of 500–1000 galaxies at a time and revealing the incidence and properties of galactic winds across the population.

In the MOSFIRE/MOSDEF survey, a sample of 159 AGNs at $1.4 \leq z \leq 3.8$ with $L_{\rm Bol} = 10^{44-47}$ erg/s (identified via X-ray, IR, and/or optical wavelengths) was embedded in a uniformly selected galaxy sample of both star-forming and quiescent systems spanning ∼3 orders of magnitude in stellar mass (Leung et al., 2019). Outflows were identified via Hβ, [O III], Hα and [N II] emission: detected in 17% of the AGNs, seven times more frequently than in a mass-matched sample of inactive galaxies. The outflows are fast (∼400–3500 km/s), and from 2D spectra the physical extent along the slit direction was measured to be ∼0.3–11 kpc. The incidence of outflows among AGNs was found to be independent of host-galaxy stellar mass, and outflows were found in both star-forming and quiescent galaxies. However, the absence of spatially resolved measurements introduces uncertainties, as outflows are almost certainly geometrically complex (e.g., Kakkad et al. 2020).

A complementary view comes from Förster Schreiber et al. (2019), who presented a large sample (152) of AGNs at z≈1–3, drawn from a sample of 599 galaxies observed with integral field spectroscopy (IFS) with KMOS in seeing-limited mode covering Hα, [N II], and [S II]. While the IFS data provided 2D measurements of the outflow size (reaching a spatial resolution of 4 kpc at z∼2), the [O III] and Hβ emission lines are not covered. The [O III] line is a particularly valuable tracer of NLR gas and ionized outflows because it lies far from other bright emission lines, and is less prone to contamination than [N II]. They found that ∼15% of galaxies show AGN outflows, with the incidence, strength and velocity strongly correlated with stellar mass, and independent of star-formation activity. A dedicated AGN survey, the KMOS AGN Survey at High redshift (KASHz; Harrison et al. 2016) has provided no-AO spatially resolved observations for hundreds of X-ray selected AGN, revealing ionized gas velocities that are likely indicative of outflows in about 50% of the examined sample. However, again seeing-limited observations are not sufficient to trace outflows and their properties in detail.

A significant advance in angular resolution came with the SUPER programme (Circosta et al., 2018), which used VLT/SINFONI in AO-assisted mode to achieve 2–4 kpc resolution at $z \sim 2$. Ionized outflows traced by [OIII] were found to be ubiquitous across the full sample of 33 X-ray selected AGN ($L_{\rm bol} = 10^{44-47}$ erg s^{-1}; 21 Type 1 and 12 Type 2) selected without any bias toward systems known to host strong winds, with spatially resolved emission in 35% of Type 1 and 86% of Type 2 sources extending over 2–10 kpc (Kakkad et al., 2020; Tozzi et al., 2024). Type 2 AGN host faster ionized outflows than their Type 1 counterparts within the same bolometric luminosity range. The velocities of ionized outflows detected in the SUPER sample are comparable to the escape speeds of their dark matter halos and are generally high enough to reach distances of 30–50 kpc from the galaxy center. These outflows can therefore expel gas from the baryonic disk and/or provide preventive-mode feedback by injecting energy and driving turbulence in the surrounding medium. In either case, they have the potential to reduce or even quench star formation.

In the low-mass regime ($M_\star < 10^{10}$ $M_\odot$), AGN have been detected in local galaxies (e.g., Sartori et al. 2015, Penny et al. 2018, Reines et al. 2020, Mezcua et al. 2023), but probing their outflow properties at higher redshifts has been challenging due to the limited sensitivity of ground-based near-infrared instruments. The launch of JWST has started to change this picture: surveys like JADES have observed [O III] and Hα emission from dwarf galaxies (52 objects) at $z \sim 3.5$–8.5 ($M_\star \sim 10^{7-9}$ $M_\odot$) using 1D multi-object spectroscopy (Carniani et al., 2024). Emission lines were detected with S/N > 5 (here S/N is defined as the ratio of the flux peak of the line and the sensitivity level of the observation at the same wavelength), and outflows were identified in roughly 25% of the sample, significantly higher than in local low-mass galaxies. These results open a new window for studying feedback in low-mass galaxies at early cosmic times, a regime that was previously inaccessible from the ground.

Recent JWST 1D spectra (R ∼1000) of individual quiescent galaxies at $z > 2$ have revealed weak ionized gas emission lines clearly linked to AGN activity, which would have been undetectable with ground-based observations (Belli et al. 2024, Carnall et al. 2023, D'Eugenio et al. 2024). Thanks to the exceptional sensitivity of JWST/NIRSpec, the Blue Jay survey (Belli et al., 2024) found that low-luminosity AGN are remarkably common in high-redshift quiescent galaxies (Bugiani et al., 2025). In this survey, 113 galaxies at $1.7 < z < 3.5$ were analyzed to study the demographics and properties of neutral gas outflows traced by NaID absorption, covering both star-forming and passive galaxies with stellar masses $M_\star > 10^{9.5}$ $M_\odot$. The results show that interstellar NaID absorption is widespread in massive galaxies ($M_\star > 10^{10}$ $M_\odot$) at $z \sim 2$, and that these neutral outflows are likely AGN-driven. This implies that powerful AGN-driven neutral gas outflows are common among massive galaxies at this epoch and may constitute a significant mechanism for rapid quenching (Davies et al., 2024).

1.1.2. Overcoming current limitations: a path forward

Despite the progress outlined above, most statistical studies of galactic outflows have so far suffered from restricted spectral coverage, often limited to Hα alone, which is challenging to model due to its proximity to [N II] and possible contamination from broad-line region emission. Longslit/1D spectra further provide only limited information on the ionized gas, severely limiting robust constraints on the geometry and true spatial extent of the outflows. Moreover, most studies have focused on a single gas phase, providing an incomplete picture of the total

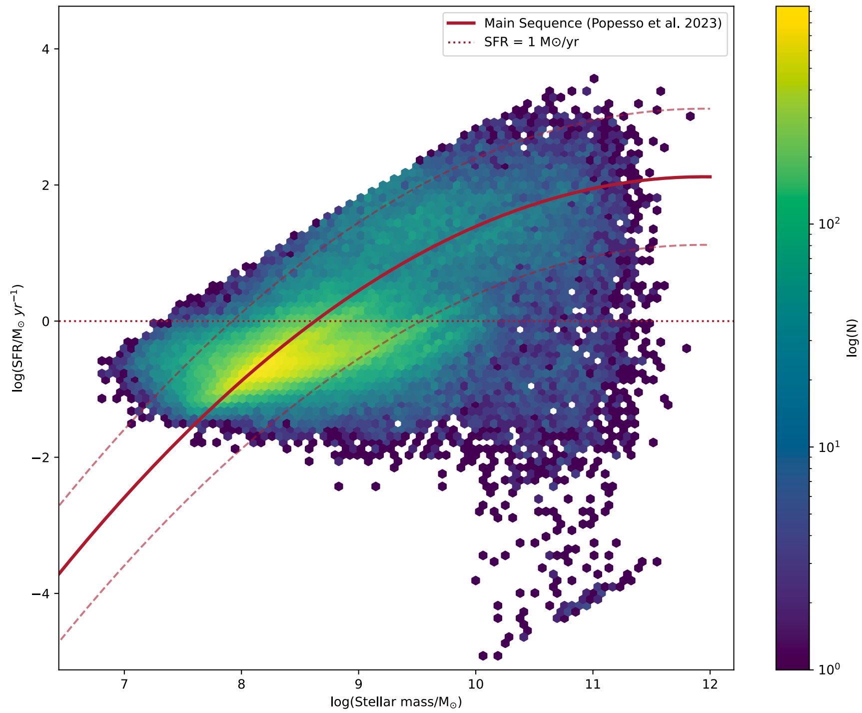

Fig. 1. Star formation versus stellar mass for COSMOS-Web galaxies at 1.5 < z < 2.5 (Shuntov et al., 2025). The star-forming main sequence at z∼2 from Popesso et al. (2023) is also shown as solid red curve, with a dispersion of ± 1 dex. The adopted observational SFR limit of 1 $M_{\odot}$/yr is indicated by the red dotted horizontal line.

outflow impact. The AO-corrected multi-IFU SHARP/VESPER, covering 1.2–2.4 μm at R ≈3000, overcomes these limitations within a single setup: the simultaneous coverage of [O III]+Hβ, Hα+[N II]+[S II], and Na I D enables the study of feedback mechanisms through ionized and neutral outflows at $1.5 < z < 2.5$ in a statistical sample of both low- and high-mass galaxies. By simultaneously tracing star formation via Hα and the neutral and ionized gas phases through the Na I D and [O III] lines, respectively, we will be able to characterize outflows in unprecedented detail. The VESPER spaxel size (31 mas ≈300 pc at $z \approx 2$) will resolve star-forming clumps and outflow substructures with unmatched precision, enabling robust conclusions on the global impact of AGN-driven feedback on the galaxy population.

2. Objectives

The multi-IFU capability of VESPER (N = 12), combined with the collecting power of the ELT, will provide the S/N required to detect even the faintest galactic winds in a statistical sample of galaxies spanning the full mass range, from low-mass systems ($M_{\star} = 10^{8-10}\,M_{\odot}$) to the massive end ($M_{\star} > 10^{10}\,M_{\odot}$). This will allow us to spatially resolve both neutral and ionized gas and to achieve the following goals:

• **Obtaining a spatially resolved view of the ionized and neutral outflows.** For the ionized phase, spaxel-by-spaxel analysis of the [O III] line profile will yield the centroid, velocity shift, width, and luminosity of both systemic and broad/blueshifted components, and outflow distance, allowing us to reconstruct the outflow kinematics and geometry. The ionizing source will be identified through the BPT diagnostic diagram ([O III]/Hβ vs. [N II]/Hα; Baldwin et al. 1981), complemented by multi-band photometric AGN identification (see Section 2.1), separating AGN-driven from stellar ionization. Electron densities will be primarily estimated from the spatially resolved [S II]$\lambda\lambda$6716,6731 doublet ratio, sensitive over the range $n_e \approx 10^2$–$10^{3.5}$ cm^{-3}, though this diagnostic is known to underestimate the true outflow density in AGN-photoionized gas (Davies et al., 2020). We will therefore complement it with the ionization-parameter method of Baron and Netzer (2019), which derives n_e from the [O III]/Hβ and [N II]/Hα line ratios combined with the spatially resolved outflow distance, all quantities accessible within a single SHARP/VESPER setup. Together, these measurements will allow us to derive key physical quantities such as the mass outflow rate and kinetic power, thereby constraining the efficiency of the winds in influencing their host galaxies. By constructing spaxel-by-spaxel mass outflow rate maps with spatially variable density and velocity, we will derive instantaneous outflow rates across the full field of view without assuming a global outflow geometry, avoiding the large biases that affect single-aperture or longslit-based estimates (Kakkad et al., 2022). For the neutral component, the relative weakness of the NaID absorption feature requires either analysis of the integrated spectrum or Voronoi binning of the 3D data cube to enhance the S/N (see Section 2.1.1 for further details).

• **Obtaining a spatially resolved view of star formation** over ∼10 Myr timescales, comparable to those of the outflow. By disentangling SF-associated Hα emission from AGN contributions, we will construct SFR maps and compare them directly with the ionized and neutral outflow maps, searching for spatial signatures of negative and positive AGN feedback. A spatial anti-correlation between outflow and SFR on a spaxel-by-spaxel basis, i.e. the suppression of star formation precisely where the outflow is detected, constitutes direct evidence of negative feedback (Cresci et al., 2015), while positive feedback may manifest as an enhancement at the outflow edges where gas compression triggers new star formation (Cresci et al., 2015; Cresci and Maiolino, 2018). We acknowledge that Hα traces SF on ∼10 Myr timescales while AGN activity varies on much shorter timescales; any causal interpretation will therefore be discussed in the context of the relevant timescale uncertainties.

• **Estimating the incidence of ionized and neutral outflows as a function of host galaxy properties.** By probing the ionized phase through [OIII] and the neutral phase through NaID, we will establish how outflow occurrence depends on stellar mass and SFR, and whether it is causally linked to ongoing star-forming activity as traced by Hα. A delayed-feedback scenario, in which outflows preferentially occur in high-SFR systems at fixed stellar mass (Woo et al., 2017), will be directly testable with our dataset.

• **Investigating the scaling relations.** Simulations predict that AGN feedback correlates more strongly with black hole mass than with instantaneous bolometric luminosity, pointing to a dependence on integrated rather than current AGN activity (Piotrowska et al., 2022). Testing this requires measuring outflow properties (e.g., velocity, distance) against L_{Bol}, estimated from spectral energy distribution (SED) fitting or bolometric corrections to the continuum at 5100 Å, and black hole mass, derived directly for Type 1 AGN via Balmer lines (Shen, 2013) or indirectly for Type 2 AGN (Baron and Ménard, 2019).

2.1. The SUNRISE sample

Fields with deep multi-wavelength coverage are the natural choice for a programme of this kind. The COSMOS field, with its extensive photometric data from X-ray to radio (Marchesi et al. 2016, Weaver et al. 2022), provides the ideal foundation: its source density of ∼200000 objects over 2 deg^2 at $1.5 < z < 2.5$ implies ∼10–15 galaxies per VESPER/SHARP pointing of $24 \times 70\,\mathrm{arcsec}^2$, making it perfectly matched to the multi-IFU capability of VESPER. From this dataset, stellar masses and integrated SFRs can be derived through SED fitting, while AGN can be identified via X-ray, MIR/radio, or optical selection, all without pre-selecting galaxies in a particular evolutionary stage or with unusual properties. Using MCAO-assisted observations, we will achieve angular resolutions of ∼30 mas for high-SFR galaxies, while for low-SFR systems the data quality will be comparable to NIRSpec@JWST (∼100 mas).

2.1.1. ETC calculation

Our goal is to investigate 3D outflow and star-formation properties, extending down to low-mass ($M_\star < 10^{10}\,M_\odot$) systems and up to the passive population at the high-mass end. We aim to take advantage of the flux limits achievable with the ELT/SHARP–VESPER instrument. From Fig. 1, which shows the distribution of COSMOS-Web galaxies in the instantaneous SFR–stellar mass plane (Shuntov et al., 2025), a SFR limit of $\sim 1\ M_\odot\ \mathrm{yr}^{-1}$ is indicated, representing the threshold above which galaxies can be followed up within a reasonable observing time. Indeed, by converting the expected SFR into Hα emission line fluxes, we estimate that a SFR $\sim 1\ M_\odot\ \mathrm{yr}^{-1}$ corresponds to an Hα flux of $\sim 7 \times 10^{-18}$ erg s^{-1} cm^{-2} (assuming a Chabrier IMF) at $z = 2$ (Kennicutt, 1998). We used the SHARP ETC (v0.5) to simulate a galaxy with $M_\star$=10^9 $M_\odot$ at $z \sim 2.35$ with $f_{\mathrm{H}\alpha} \sim 7\times10^{-18}$ erg s^{-1} cm^{-2}, FWHM = 500 km/s (∼37 Å) at $\lambda = 22000$ Å, and a Sersic radius of $R_e = 250$ mas (Shuntov et al., 2025). An integration time of ∼20 hours per source is required to achieve S/N ∼6 (after binning 7 spectral pixels, corresponding to 20 Å∼270 km/s) for the Hα line at its peak in the central pixel, and S/N ∼ 1.5 at 0.3 arcsec, assuming a spatial resampling of 3×3 pixels (100 mas). These exposure times should also permit spatially resolved [O III] outflow measurements. The feasibility of detecting the NaID absorption feature instead depends critically on the S/N achieved on the continuum rather than on emission line fluxes. The NaID doublet is an intrinsically weak absorption feature, and its detection at $z \sim 2$ has so far been demonstrated only in integrated 1D spectra of massive galaxies ($M_\star \gtrsim 10^{10}\,M_\odot$) using deep JWST/NIRSpec observations (Davies et al., 2024; Bugiani et al., 2025). We therefore expect the NaID analysis to be feasible for the high-mass end of our sample, where the continuum S/N will be sufficient for individual detections or modest Voronoi binning of the SHARP/VESPER data cubes. For lower-mass systems ($M_\star < 10^{10}\,M_\odot$), we will rely on the integrated spectrum of each galaxy, or on spectral stacking across sub-samples, to place statistical constraints on the neutral gas outflow properties.

For brighter targets in terms of SFR or outflows, higher S/N can be reached with such exposure times by adopting the native angular resolution of SHARP (∼30 mas), allowing us to probe sub-kpc scales.

3. Comparison with other facilities

The ELT will host several first- and second-generation instruments designed to probe galaxy evolution at high redshift. For the specific goal of conducting a statistical, spatially resolved study of AGN-driven feedback at cosmic noon, a combination of multiplexing, angular resolution, and broad near-infrared spectral coverage is required. In this context, VESPER provides instrumental capabilities that are well matched to the scientific objectives of this programme.

Compared to ELT/HARMONI, which provides single-IFU integral-field spectroscopy over a contiguous field of view, VESPER enables the simultaneous IFU observation of up to 12 galaxies within a single pointing, making it particularly well suited for building statistically significant samples of galaxies and AGN at z∼2 within realistic observing times.

The wavelength coverage of VESPER (1.2–2.4 μm) is optimally matched to the key rest-frame optical diagnostics at $1.5 < z < 2.5$, including [OIII], Hβ, Hα, [NII], [SII], and NaID. Access to these emission and absorption lines within a single instrumental setup enables a self-consistent, multi-phase characterization of ionized and neutral gas.

Relative to JWST/NIRSpec, VESPER provides a factor of ∼3–4 improvement in angular resolution thanks to the ELT aperture and adaptive optics correction, reaching spatial scales of ∼30 mas (≈300 pc at $z \sim 2$). This resolution is critical for resolving the spatial structure and kinematics of galactic outflows, which are otherwise blurred together at the angular resolution of JWST.

4. Conclusions

AGN-driven outflows are widely invoked as a key mechanism regulating star formation and driving the co-evolution of galaxies and supermassive black holes, yet their global impact and physical coupling to the host galaxy remain poorly constrained, particularly at the peak epoch of galaxy assembly. Current observational limitations have restricted most studies to small samples, single gas phases, or seeing-limited spatial resolutions, preventing a comprehensive and statistically robust assessment of feedback processes.

The SUNRISE programme, enabled by the multi-IFU, AO-assisted capabilities of ELT/VESPER, will overcome these limitations by providing the first blind, spatially resolved, multi-phase census of AGN-driven outflows in a representative galaxy population at cosmic noon. By simultaneously mapping ionized and neutral gas outflows together with star formation on sub-kpc scales, this survey will allow us to directly test how and where AGN feedback operates, whether it suppresses or potentially triggers star formation, and how its efficiency depends on galaxy mass and AGN properties.

CRediT authorship contribution statement

Giustina Vietri: Writing – original draft, Methodology, Conceptualization. **Susanna Bisogni:** Writing – review & editing, Investigation. **Enrico Piconcelli:** Writing – review & editing, Investigation. **Federica Ricci:** Writing – review & editing, Investigation. **Paolo Franzetti:** Software. **Adriana Gargiulo:** Writing – review & editing, Investigation. **Chiara Mancini:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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