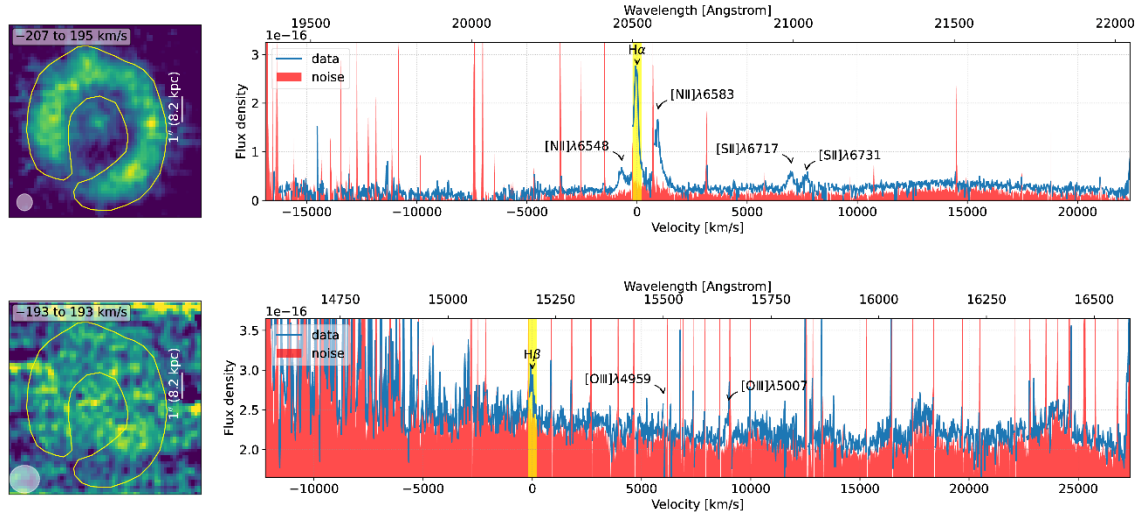


Detailed study of a rare hyperluminous rotating disk in an Einstein ring 10 billion years ago

In the format provided by the
authors and unedited

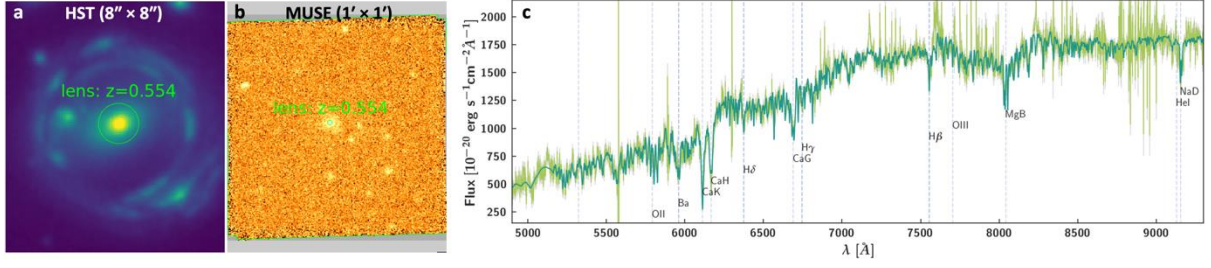
Supplementary Information

VLT ERIS IFU Science Verification Program



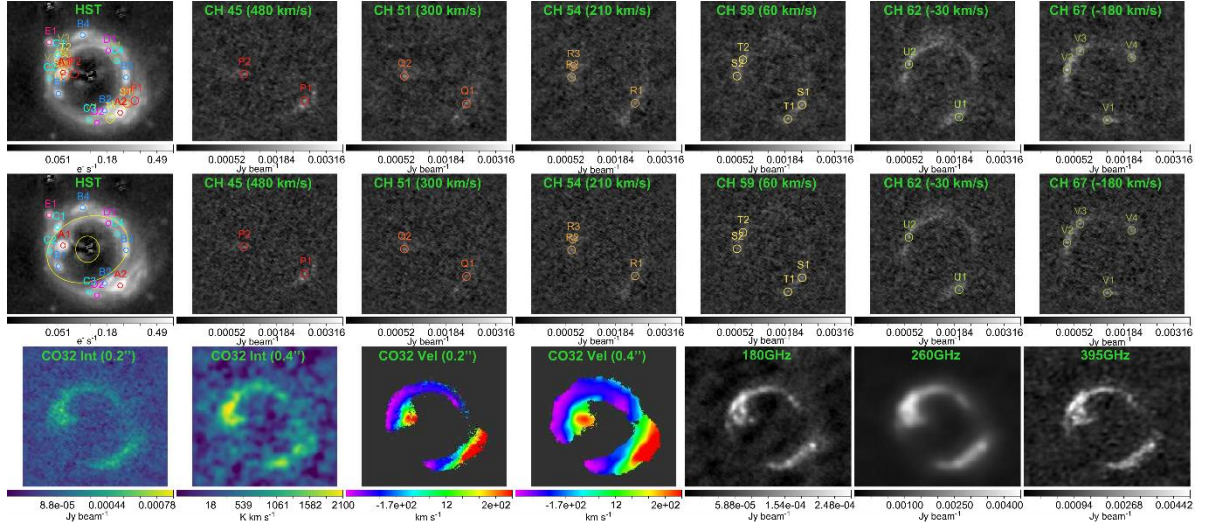
Supplementary Figure 1: ERIS IFU line-integrated map and galaxy-averaged spectra. Upper- (Lower-)left panel shows the $H\alpha$ ($H\beta$) line-integrated map. Upper- (Lower-)right panel shows the K-band spectrum (H-band) spectrum. The polygon in the left panels indicate the region from which the spectra are extracted, and the yellow highlighted channels in the right panels are integrated to make the line-integrated maps. Noise spectra are shown in red in the spectra, and the spikes indicate that there are high noise values in those channels due to atmospheric OH line contamination (e.g., Rousselot et al. 2000^[51]), which we blank out in the spectra.

VLT MUSE observations confirming the lens redshift



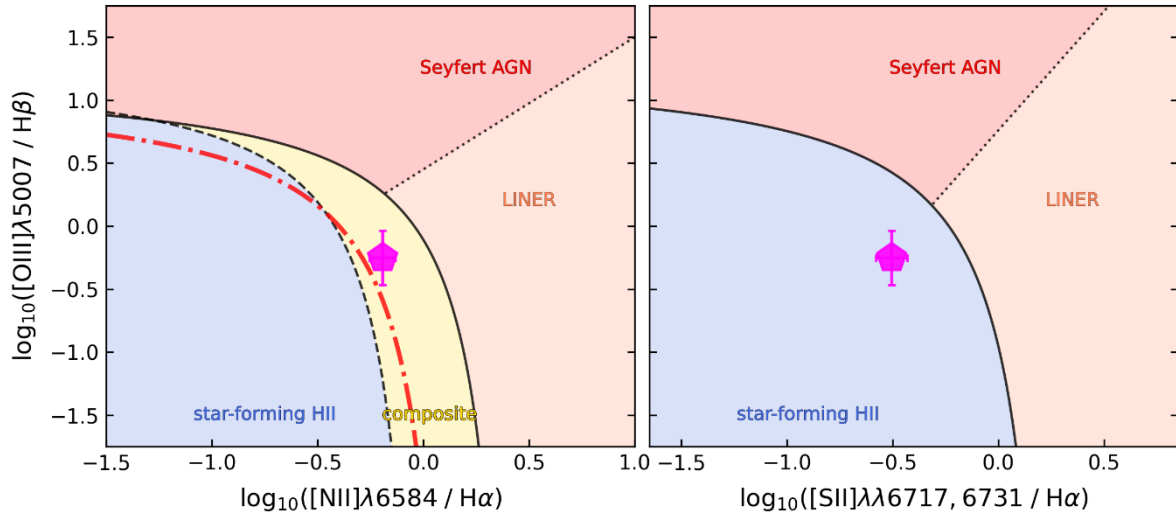
Supplementary Figure 2: VLT MUSE observation of PJ0116-24's foreground lens massive early-type galaxy. Panel **a** shows the HST image of PJ0116-24 with its foreground lens. The circle indicates the aperture to extract the MUSE spectrum in panel **c** and has a diameter of 1.3". Panel **b** shows the MUSE channel map at $\sim 7600\text{\AA}$. The extracted MUSE spectrum (light green) is overlaid by a fitted spectrum (dark green) using the `pyplatefit.fit_spec` Python software package (Bacon et al. 2023^[60]) and with identified line names labeled.

Lens modeling



Supplementary Figure 3: PJ0116-24’s lensing knots identification. **Top row:** HST and natural-weighting CO(3–2) channel maps. **Middle row:** first column is the same HST image as in the top row overlaid with the critical curves from the lens model and HST knots only, then from the second to the last columns are Briggs-weighting, higher-resolution but noisier CO(3–2) channel maps. **Bottom row:** the first and the second columns are the CO(3–2) integrated intensity image extracted from cubes at 0.2'' and 0.4'' resolutions, respectively, followed by the extracted velocity maps and dust continuum images at ~180 GHz (combined Band-3 + Band-6), 260 GHz (Band-6) and 395 GHz (Band-8). Identified HST and CO channel map emission peaks (“knots”) are marked by the colored circles with letters and numbers (the letters A–E and P–V are for HST and CO peaks, respectively; and numbers 1–4 are the lensed counterimages of the same knot).

Balmer decrements in the literature for comparison



Supplementary Figure 4: PJ0116-24's [NII]-BPT and [SII]-BPT diagrams. Star-forming, composite, low-ionization emission region (LINER) and Seyfert AGN regimes are divided by the lines from bottom left to the top/bottom right, respectively. Error bars indicating observational uncertainties (mean values $\pm$ SD) of PJ0116-24's global line ratios. The dashdot line in the left panel shows the best-fit relation of MOSDEF $z \sim 2$ SFGs (Shapley et al. 2015^[84]).

AGN Activity

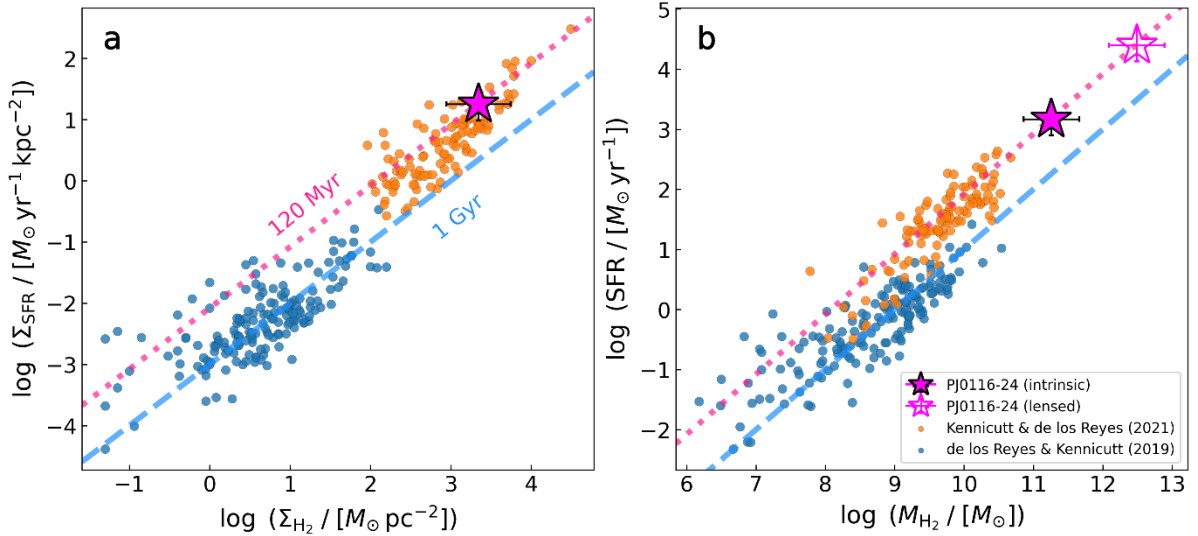
An AGN is identified via X-ray and radio at the center of PJ0116-24 by Wang et al. (2024)^[36] and Kamieneski et al. (2024)^[6], respectively. The former work modeled the *XMM-Newton* X-ray spectroscopic data with a high-mass X-ray binary (HMXB) component and an AGN component, finding that the AGN has a mild X-ray luminosity $\log(\mu L_{X,AGN}/[\text{erg s}^{-1}]) = 44.23^{+0.33}_{-1.90}$ (rest-frame 0.5–8.0 keV;). The latter work obtained VLA 6GHz observations at 0.4'' resolution and found that PJ0116-24 has a radio emission peak coinciding with the HST emission peak at the galaxy center. The total inferred 1.4GHz luminosity is $\log(\mu L_{3\text{GHz}}/[\text{W Hz}^{-1}]) = 24.9 \pm 0.1$, and thus the far-IR-to-radio ratio is $q_{FIR} = 2.3 \pm 0.2$. This global q_{FIR} is far away from the $q_{FIR} < 1.8$ criterion for radio AGNs, and is in line with our ERIS spectroscopic finding. Spatially resolved q_{FIR} at the galaxy center will likely be closer to the AGN's q_{FIR} threshold and will be analyzed in future work.

Given these pieces of observational evidence, we can infer that PJ0116-24 only has a mild AGN, like nearby low-luminosity Seyfert galaxies. On the one hand, the X-ray emission from the aforementioned X-ray spectroscopic modeling, corrected for the magnification of $\mu_{AGN} \sim 12$, is of the order of $\sim 10^{43} \text{ erg s}^{-1}$. On the other hand, its supermassive black hole (SMBH) mass can be very roughly estimated as $\sim 10^{7-8} M_{\odot}$ ($\sim 10^{7.75} M_{\odot}$ if using the BH mass–stellar mass relation from Greene et al. (2020)^[144], or $\sim 10^{7.61} M_{\odot}$ if adopting the BH mass–bulge mass relation from Kormendy et al. (2013)^[145], where the bulge mass is from our kinematic modeling; see [Methods “Dynamical modeling with DysmalPy+Lensing”](#)). The Eddington ratio is thus $\lambda_{\text{Edd}} \sim 0.005$ (although with a large uncertainty), lower than most X-ray detected AGNs in Rojas et al. (2020)^[146].

Star formation efficiency / gas depletion time

We use the SED-derived global SFR and updated ISM mass of PJ0116-24 to estimate its star formation efficiency ($SFR/M_{\text{mol. gas}}$) or gas depletion time ($M_{\text{mol. gas}}/SFR$) and inspect whether it is different from normal star-forming or starburst galaxies. Averaged over the disk of PJ0116-24 ($R_{\text{eff}} \sim 3.6$ kpc), the extreme SFR and large gas mass turn into moderately-high SFR and gas mass surface densities, indicating a gas depletion time of ~ 120 Myr, which is typical of starburst galaxies (Tacconi et al. 2018^[147]; Liu et al. 2019^[148]).

Supplementary Figure 5 shows PJ0116-24's location in the *Kennicutt-Schmidt* diagram, compared with about two hundred local star-forming and starburst galaxies^{91,42}. PJ0116-24 is among the most massive systems, and is well within the regime of starburst galaxies in the surface-brightness relation (panel a) but not substantially above the local starburst population. It stands out only when plotting the integrated values (panel b), given its extended galaxy disk radius ($R_{\text{eff}} \sim 3.6$ kpc) and intrinsically large amount of gas and star formation.



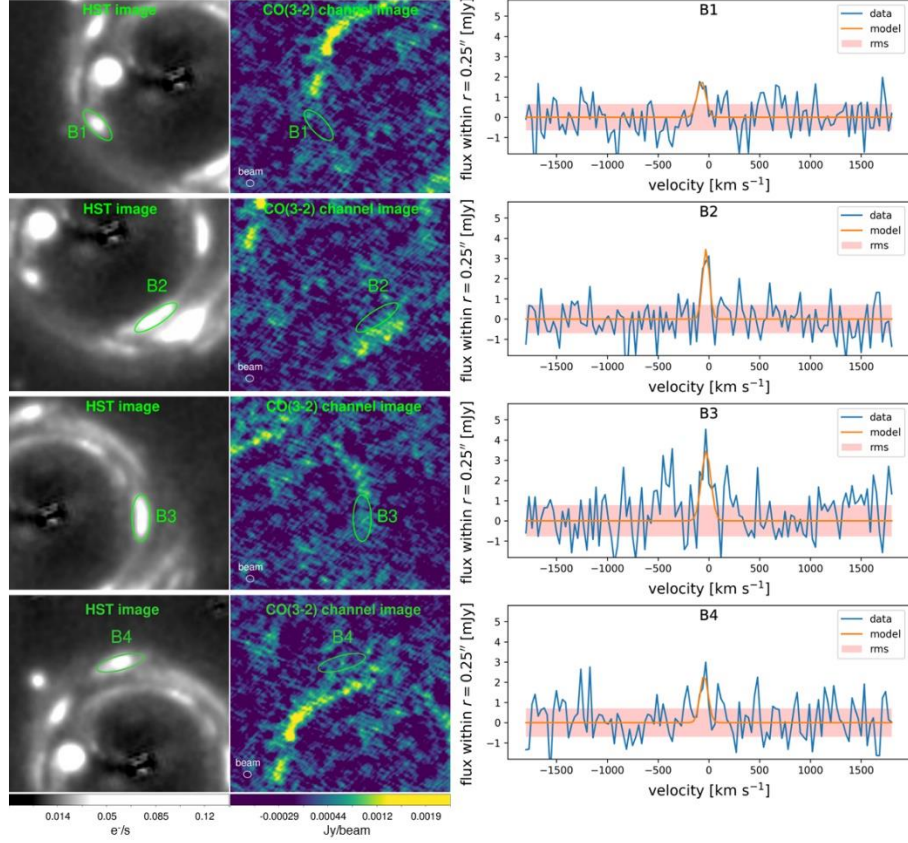
Supplementary Figure 5: The Kennicutt-Schmidt relation between molecular gas and star formation rate. The surface densities relation (averaged over entire galaxies) is shown in panel **a**, and the globally integrated relation is shown in panel **b**. Local star-forming spiral, dwarf and low surface brightness galaxies are from de los Reyes & Kennicutt (2019)^[149], and local starburst (luminous and ultra-luminous infrared) galaxies are from Kennicutt & de los Reyes (2021)^[42]. The PJ0116-24 intrinsic (i.e., corrected for lensing magnification) and apparent (i.e., lensed) values are shown as the solid and open stars, respectively, with error bars indicating observational uncertainties (mean values $\pm$ SD). The dashed and dotted lines, both with a slope of unity, indicate a constant gas depletion time ($\Sigma_{\text{ISM}}/\Sigma_{\text{SFR}}$) of 1 Gyr and 120 Myr, respectively.

Environment

PJ0116-24 has no submillimeter-bright companion within the field of view (FWHM $\sim 15''$ – $50''$; or projected distances of ~ 60 – 200 kpc from the galaxy center) of the dust continuum images at 110–395 GHz. The sensitivity of the Band-3+Band-6 combined dust image at ~ 180 GHz is $1\sigma \sim 12$ μ Jy/beam at the phase center, or twice larger at the field of view FWHM. Assuming a graybody dust spectral energy distribution with $T_{dust} = 50$ K and $\beta = 1.8$, the 3σ dust emission detection limit at ~ 180 GHz corresponds to an IR luminosity of $L_{IR, lim} \sim 1.3 \times 10^{12} L_{\odot}$ and dust mass $M_{dust, lim} \sim 5 \times 10^7 M_{\odot}$, which is sufficient to detect any companion dusty star-forming galaxies with an $SFR \gtrsim 130 M_{\odot} yr^{-1}$ and $M_{ISM} \gtrsim 5 \times 10^9 M_{\odot}$ (mass ratio $\gtrsim 1:20$).

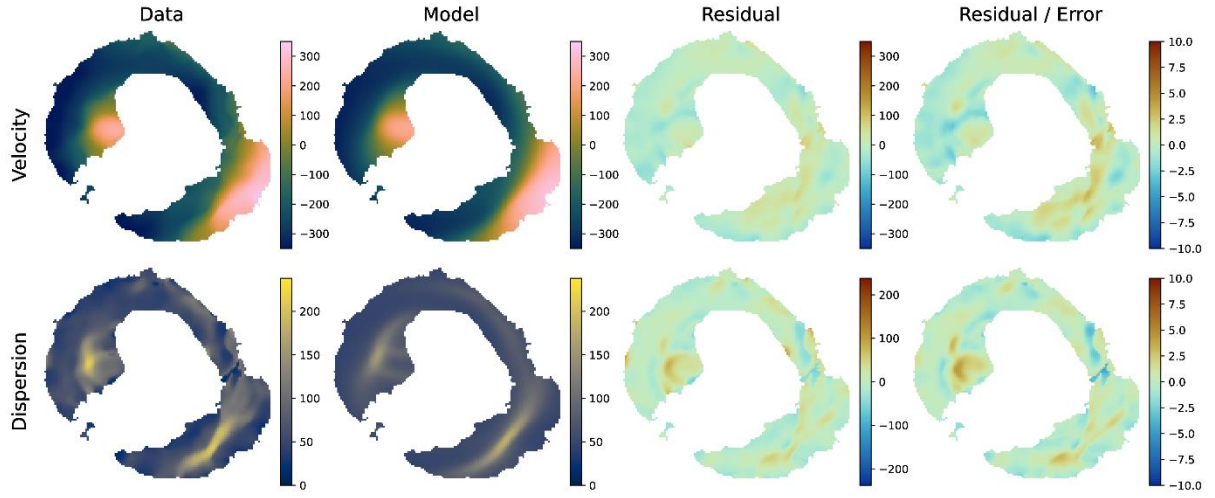
The MUSE data are from shallow filler program thus are insufficient to detection the rest-frame UV lines from PJ0116-24 or line emitters at $z \sim 2$ that could be used to study the environment of PJ0116-24. However, the HST *H*-band image and the ground-based Gemini-South *r'* and *z'* images together provide some preliminary photometric/color information for high-*z* galaxies in the field near PJ0116-24. Future work will explore the environments together with other PASSAGES HyLIRGs. Based on this work, it is likely that PJ0116-24 does not clearly have a massive companion nor is it undergoing a major merger event or in a dense environment. These speculations lead us to more believe that the source B is a giant star-forming clump typically formed in high-*z* turbulent disks (see the next subsection) instead of a merging dwarf.

The scenario of a giant star-forming clump

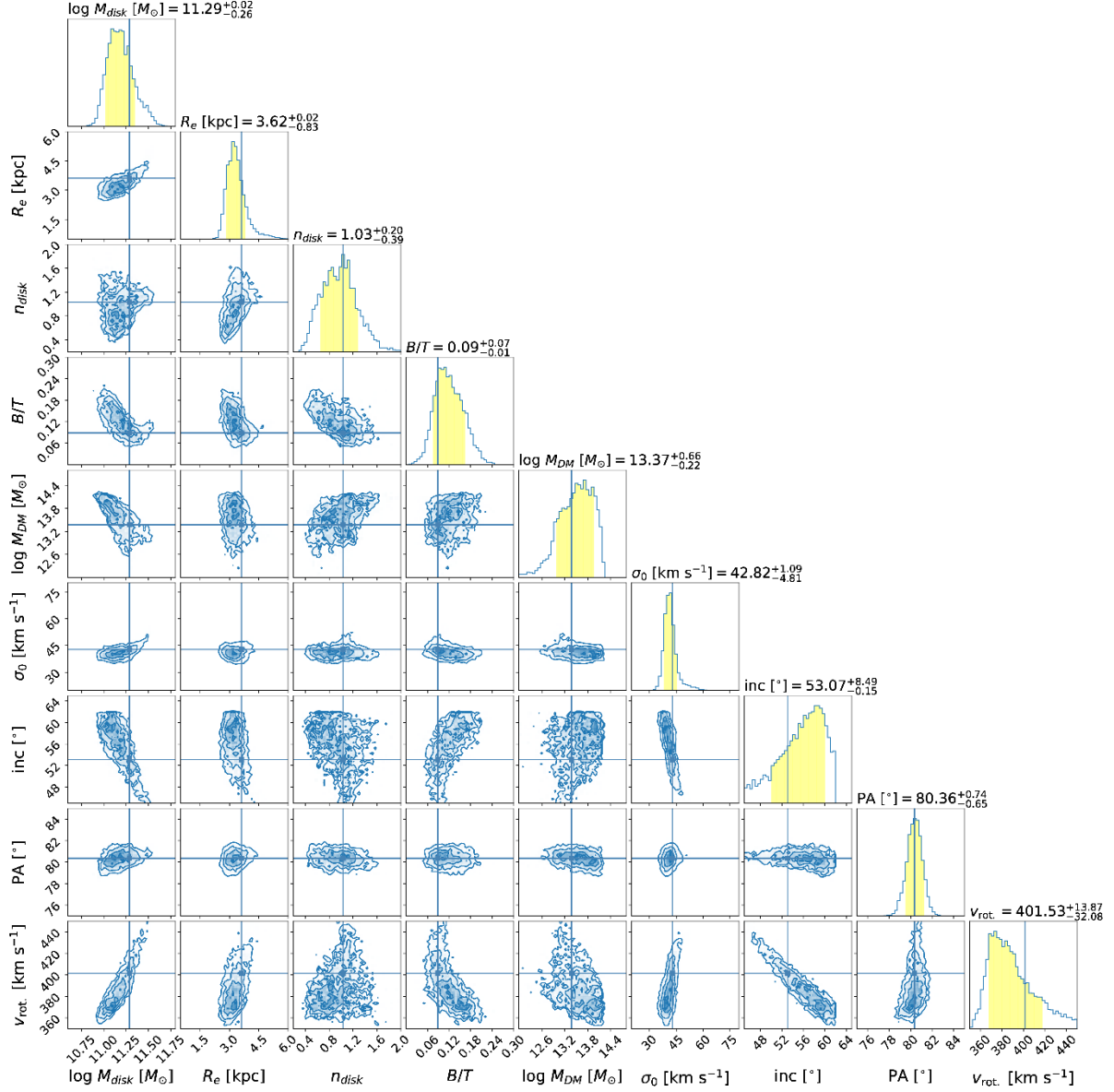


Supplementary Figure 6: Zoomed-in view of the stellar and CO emission and spectra for the clump B1–B4. HST emission maps are shown in the left panels, ALMA CO(3–2) channel maps (-45 km s^{-1} to -15 km s^{-1}) are shown in the middle panels, and the CO(3–2) spectra are shown in the right panels (extracted within apertures as shown in the left panels). The CO(3–2) beam (FWHM $\sim 0.19'' \times 0.16''$) is shown at the bottom left of middle panels. A 1-D Gaussian line model is fitted to each spectrum as shown in the right panels.

Dynamical modeling with DysmalPy+Lensing



Supplementary Figure 7: *DysmalPy+Lensing* kinematic fitting results based on the 0.4'' angular resolution smoothed CO(3–2) data. Upper panels show the 2D projected, image-plane velocity map of the data, best-fit model, the residual of data subtracting the model, and the residual divided by the error, from left to right, respectively. Lower panels show the data, model, residual and residual/error images for the velocity dispersion (after correcting for line spread function broadening). Color bars in the upper and lower panels indicate the velocity and velocity dispersions, respectively, in units of km s^{-1} .



Supplementary Figure 8: Markov-Chain Monte Carlo (MCMC) parameter constraints from the *DysmalPy*+*Lensing* kinematic fitting. Contours are the 2-D posterior probability distributions of each pair of parameters. Best-fit values (i.e., maximum likelihood) are indicated by the crosses in the contour plots. Histograms in the top panels are the 1-D posterior probability distributions of each parameter, with 1σ (16th to 84th percentiles) highlighted in yellow.

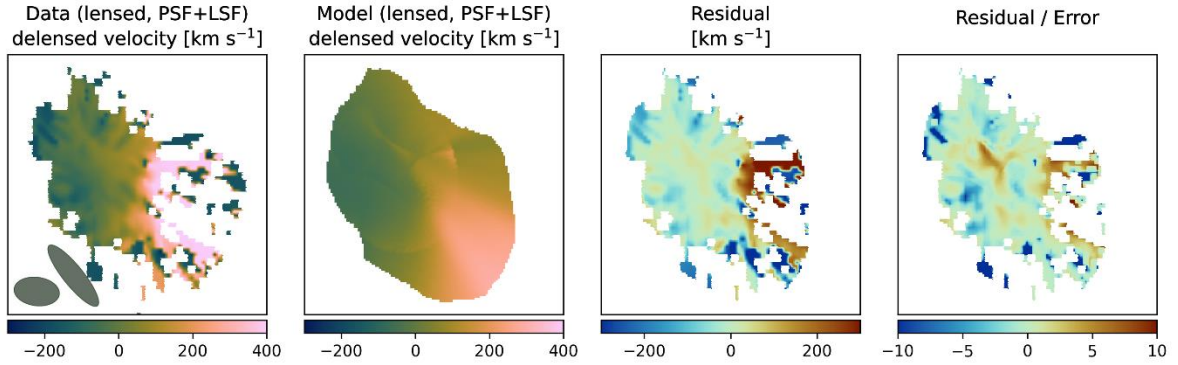
Validating the consistency of CO and H-alpha kinematics

To examine whether the CO and H α have consistent intrinsic velocity fields, we use a forward-modeling approach to overcome the effect of different angular and spectral resolution. We take the CO-based best kinematic model and forward-model it to match the angular resolution and line spread function of the ERIS H α data using DymalPy+Lensing, obtaining the image-plane mock model cube with the same PSF and LSF as the ERIS data. Then we delense the model cube to the source plane as for the data (using the adaptive mesh interpolation and coadding code developed in Liu et al. 2023^[61]). Then a pixel-by-pixel 1D Gaussian line fitting is performed for the reconstructed source-plane mock model cube, which is also the same approach used for the data as shown in Figure 2.

We compare the source-plane ERIS H α line velocity map and the reconstructed mock model H α line velocity map in Supplementary Figure 9. The residual of the two maps, when normalized by the error from 1D Gaussian fitting, have 16-th, 50-th and 84-th percentiles of -1.9 , -0.0 and $+1.3$. Ideally, this ratio should be below or close to unity if the errors represent the true uncertainties. Here the errors are likely underestimated given the effect of delensing from beam-smeared data and the deviation of line profiles from Gaussian. Although the residual/error ratios are larger than unity, these deviations are not substantial high and do not indicate an inconsistency. Given the coarse angular resolution of the H α data, our delensing approach using adaptive mesh may be severely affected by smeared light scattered into different mesh grids, causing artifacts near the caustic in the source plane (as seen in the second panel of Supplementary Figure 9) whilst our intrinsic velocity model is a perfect axisymmetric rotating disk. Moreover, different gas tracers like CO and H α may actually have different intrinsic PA (e.g., due to inflow/outflow and thickness of the gaseous disk) and σ_0 hence rotation curves (e.g., see discussion in Genzel et al. 2023^[111], Sect. 3.1). Therefore, the differences between the reconstructed H α velocity and that of a CO-based forward-modelled mock cube do not impose a strong inconsistency.

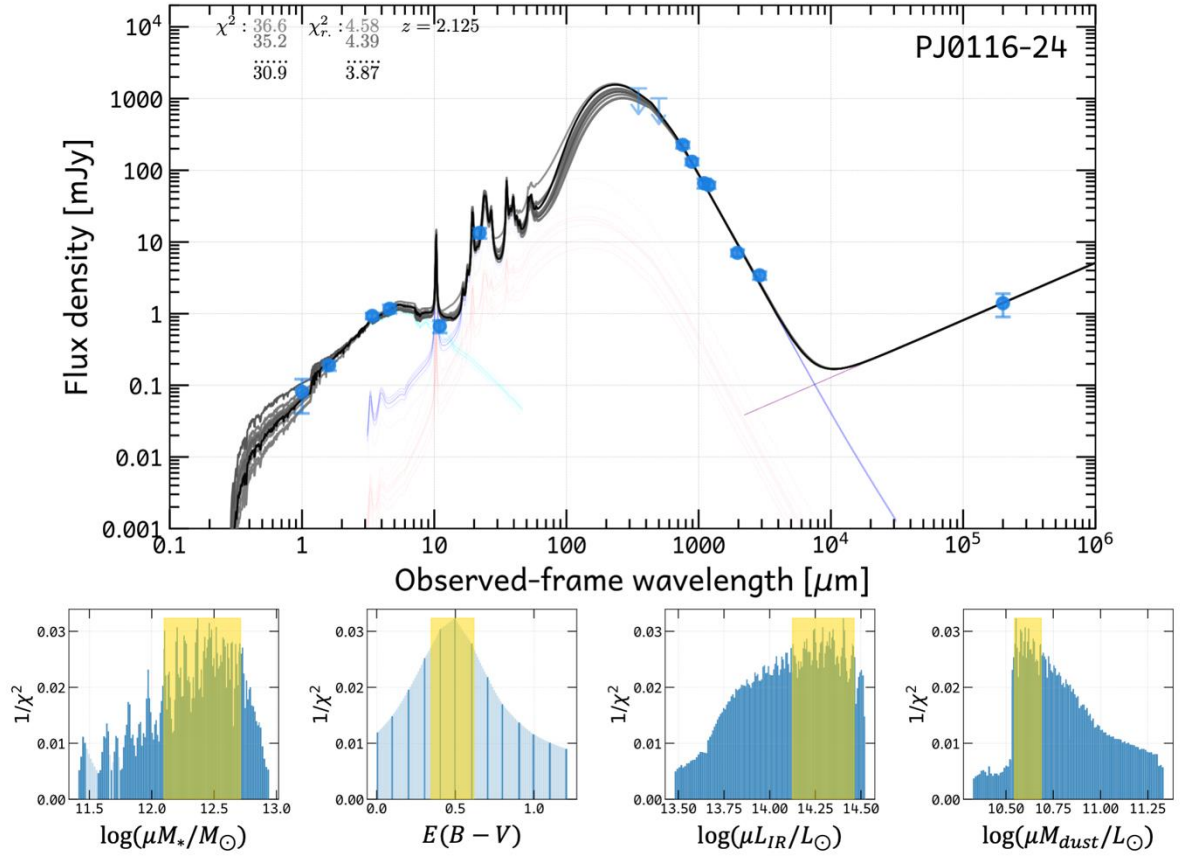
Directly comparing the image-plane velocity maps of H α and that of a resolution-degraded CO mock model also leads to a reasonable agreement. The residual/error ratios have 16-th, 50-th and 84-th percentiles of -2.4 , $+0.0$ and $+1.7$, respectively. Any subtle differences may await higher-resolution ERIS observations to further understand.

In addition to this verification, we also performed DysmalPy+Lensing fittings to the $H\alpha$ data, one by fixing all dynamical parameters to the best-fit values from the CO modeling but allowing the $H\alpha$ intrinsic velocity dispersion to vary ($\sigma_{0, \text{ion. gas}}$; which represents the intrinsic velocity dispersion of the ionized gas), and another by keeping the same MCMC free parameters as for the CO fitting but fixing the inclination and PA to the CO-based best-fits (due to their degeneracy at the much lower angular resolution of the $H\alpha$ data). With the former fitting, we find $\sigma_{0, \text{ion. gas}} \sim 69 \pm 8 \text{ km s}^{-1}$, a value after accounting for the lensing effect, projection, circular rotation, beam smearing and line spread function. The relatively large $\sigma_{0, \text{ion. gas}}$ and the contrast between $\sigma_{0, \text{ion. gas}}$ and the CO intrinsic velocity dispersion ($\sigma_{0, \text{mol. gas}} \sim 43 \pm 5 \text{ km s}^{-1}$) are consistent with those found in $z \sim 2$ massive galaxies^{120,121,61}. With the latter fitting, we verified that the $M_{\text{disk+bulge, dyn}}$, M_{DM} and v_{rot} parameters from the independent fittings of the CO and $H\alpha$ data are consistent with their $1\text{--}2\sigma$ uncertainties, and the $\sigma_{0, \text{ion. gas}} \sim 87 \pm 8 \text{ km s}^{-1}$ from the $H\alpha$ -based MCMC fitting also agrees within 2σ of that from the all-fixed fitting of the $H\alpha$ data.



Supplementary Figure 9: Validation of the consistency of $H\alpha$ and CO kinematics. This figure compares the $H\alpha$ line velocity map reconstructed directly from the ERIS data (first panel) and that reconstructed from the CO-based best kinematic model. In the first panel, the $H\alpha$ velocity map is extracted from the delensed data cube of the $\sim 0.68''$ -angular-resolution ERIS image-plane data cube. The source-plane PSFs are shown at the bottom left. In the second panel, the $H\alpha$ velocity map is obtained by first modeling the CO-based best kinematic model at the angular and spectral resolution of the ERIS data, included the lensing, then delensing the mock cube and extracting the velocity map as for real data. The residual of the first and second panel images is shown in the third panel. The residual-to-error ratio map is shown in the last panel.

SED fitting



Supplementary Figure 10: SED fitting results of PJ0116-24 with the MiChi² code (Liu et al. 2021^[94]). Upper panel shows the photometry data points of PJ0116-24 (upper limits are shown as down arrows, and error bars indicate observational uncertainties as mean values $\pm$ SD). Solid bold lines are SEDs that are within 1σ probability range (as highlighted in yellow in the lower panels). Dashed/thin lines from left to right in wavelength are the stellar, PDR dust, ISRF dust, and radio components, respectively (the mid-infrared AGN component is fitted to be negligible and is therefore not shown here in the best-fit SED). Lower panels show the $1/\chi^2$ distribution of the apparent stellar mass, dust attenuation $E(B - V)$, IR luminosity and dust mass.

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146. Rojas, A. F., et al. BAT AGN Spectroscopic Survey - XIX. Type 1 versus type 2 AGN dichotomy from the point of view of ionized outflows. *MNRAS* 491, 5867 (2020).
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