The Molecular Disk of the Elliptical Galaxy NGC 5128 (Centaurus A): Using Machine Learning to Separate High from Low Star Formation Rates

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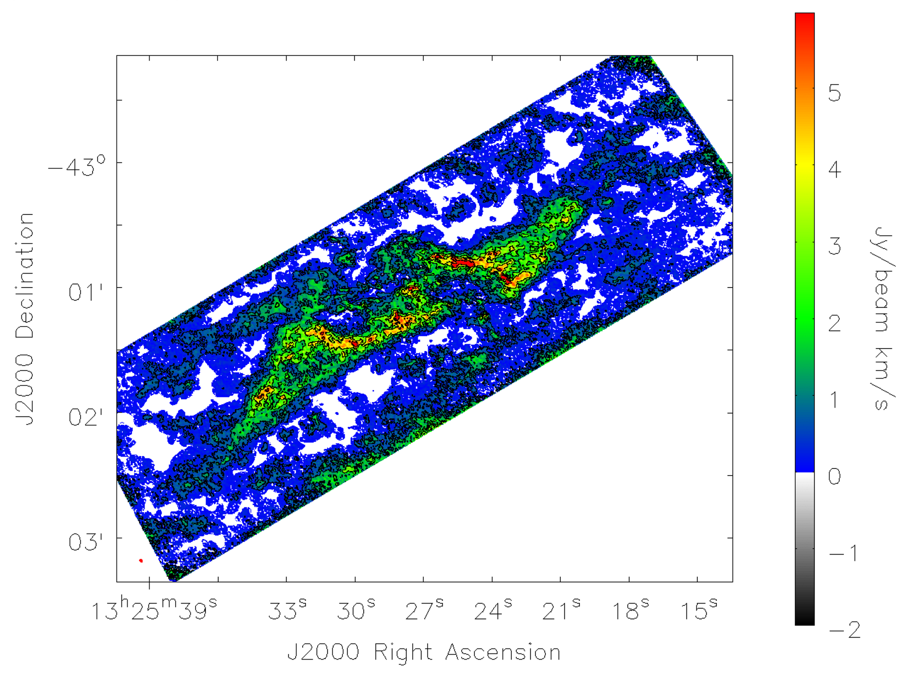
Open questions

It is still unclear what is the Kennicutt-Schmidt (KS) Star Formation (SF) Law in elliptical galaxies. Conflicting results exist in the literature, but recent studies suggest that SF is likely suppressed and the corresponding surface densities lie below the standard KS relation of late-type galaxies [Davis et al., 2014]. We aim to study:

- What are the detailed molecular gas properties in an elliptical galaxy and how it relates to the SF activity?
- What is the resolved KS SF law at giant molecular cloud (GMC) scales in an elliptical galaxy?
- High angular resolution, sensitivity, and high dynamic range observational CO studies using ALMA are essential.

NGC 5128 (Centaurus A)

Figure 1: ALMA CO(1–0) integrated intensity map (moment 0)



Cen A is, at a distance of only D $\simeq$ 3.8 Mpc (Harris et al. 2010, where 1″= 18 pc), the best target among the class of elliptical galaxies for resolved studies of the molecular gas component (Fig. 1) and relation to its SF. It has an overall SFR of about 1 $M_\odot\,yr^{-1}$, as obtained from IR data [e.g. Colbert et al., 2004]. The SF is fueled by a large amount of molecular gas mass, estimated to be $M_{\rm mol} \simeq 1.6 \times 10^9$ $M_\odot$. The gaseous component in Cen A was replenished recently (a few 10^8 yr) by gas from an external source, probably the accretion of an H I-rich galaxy [e.g. Struve et al., 2010]. Studies of this target allow us:

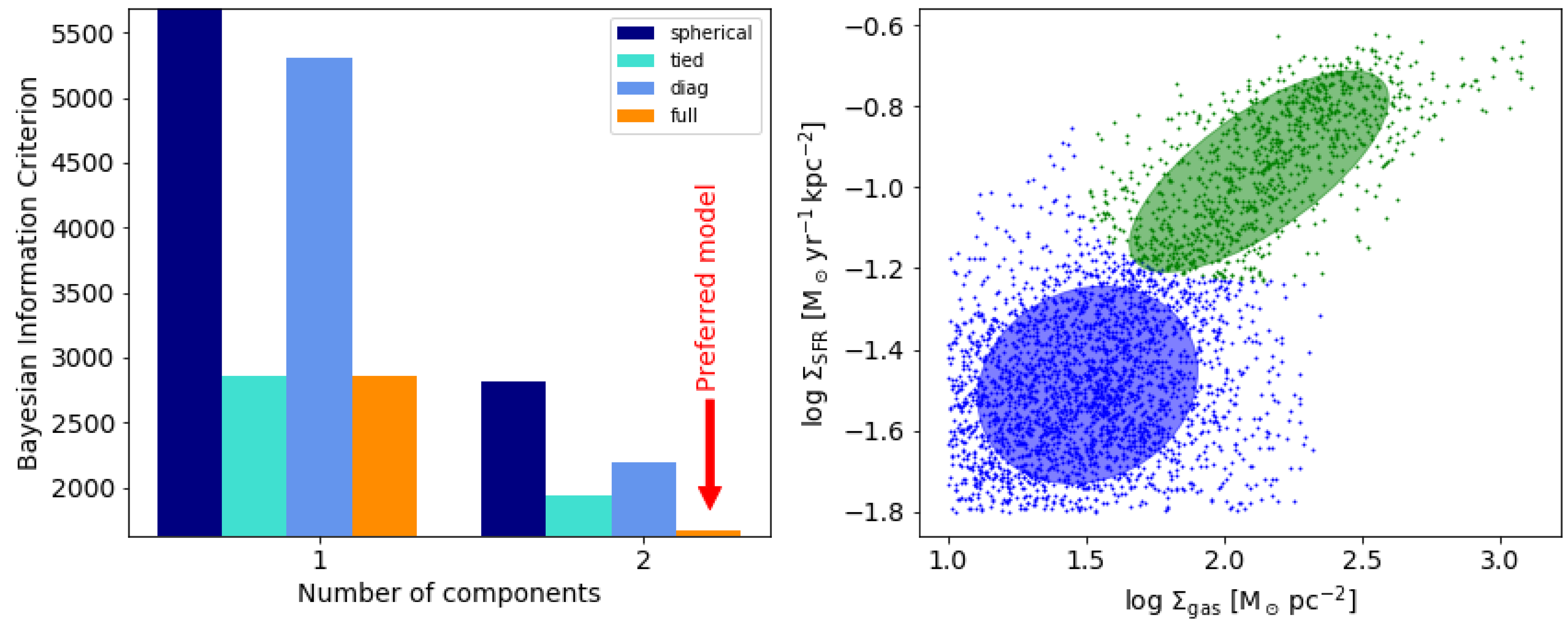
- To study with unprecedented detail the properties of the relatively stable molecular disk extending several kpc within an elliptical galaxy;
- To shed light onto the SF activities and survival of molecular gas within an elliptical galaxy before fuel is consumed or destroyed.

Conclusions

- We present the most detailed view of the SF law within an elliptical galaxy, including the circumnuclear disk ($r < 200$ pc) close to the AGN.
- We find that the global star formation rate is ~1 $M_\odot\,yr^{-1}$, which yields a star formation efficiency (SFE) of 0.6 Gyr^{-1} (depletion time $\tau = 1.5$ Gyr), similar to those in disk galaxies.
- Although on average the SFEs are similar to those of spiral galaxies, the circumnuclear disk (CND) presents SFEs of 0.3 Gyr^{-1}, lower by a factor of 4 than the outer disk. The low SFE in the CND is in contrast to the high SFEs found in the literature for the circumnuclear regions of some nearby disk galaxies with nuclear activity, probably as a result of larger shear motions and longer AGN feedback.

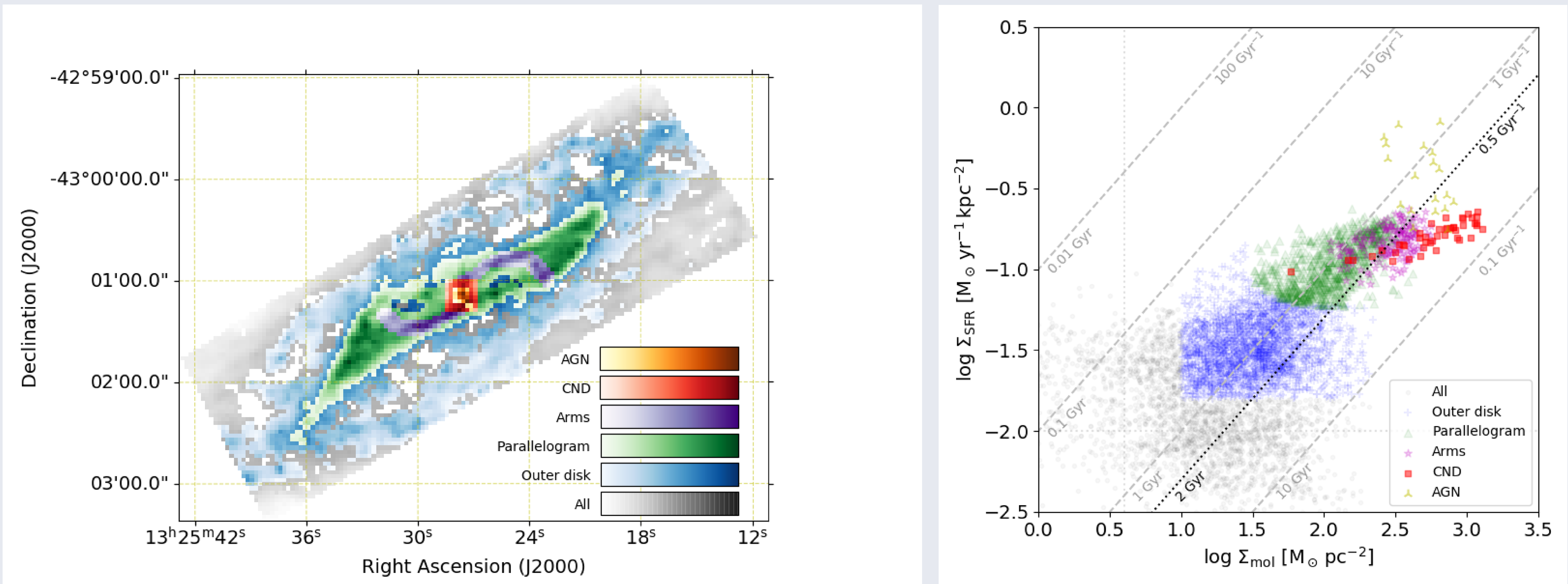
Machine learning to separate star formation into components

Figure 2: Bayesian Information Criterion and Gaussian mixture model (GMM)



We present in Fig. 2 the spatially resolved KS SF law plot (i.e. $\Sigma_{\rm SFR}$ versus $\Sigma_{\rm mol}$) along the dust lane of Centaurus A. The scatter is large, but by visual inspection it is clear that there are two main clusters of data points, one cluster at high $\Sigma_{\rm mol}$ and $\Sigma_{\rm SFR}$, and another centered at $\Sigma_{\rm mol}$ and $\Sigma_{\rm SFR}$ about 1 dex smaller. We used a machine learning technique to separate the dataset in the $\log \Sigma_{\rm SFR} - \log \Sigma_{\rm mol}$ parameter space (see Fig. 2, right panel) into clusters. We first remove the 19 points corresponding to the AGN to focus only on separating the low and high components in this parameter space. We use a Gaussian mixture model (GMM), based on an iterative expectation - maximization algorithm, to extract a mixture of multi-dimensional Gaussian probability distributions that best model our dataset [VanderPlas, 2016]. To separate our dataset into two components, random initializations are used, and we tested several covariance options (diagonal, spherical, tied, and full covariance matrices). A Bayesian Information Criterion (BIC) selects the best model, which is the one obtained with the full covariance matrix, allowing each cluster to be modeled by an ellipse with arbitrary orientation.

Spatially Resolved Kennicutt-Schmidt Star Formation Law



The right panel shows the spatially resolved SF law using the ALMA CO(1–0) data as a tracer of the molecular gas surface densities ($\Sigma_{\rm mol}$) and the Spitzer 8 μm maps for the SFR surface densities ($\Sigma_{\rm SFR}$). Dashed lines indicate constant SFEs expressed in Gyr, and the dotted lines (vertical and horizontal) show the estimated sensitivity limits. The left panel shows the location of the different regions using the same color codes as in the right panel. Regions with high $\Sigma_{\rm SFR}$ ($\log(\Sigma_{\rm SFR}$ [$M_\odot$ yr^{-1} kpc^{-2}]) > –0.8) are indicated as green circles in the right panel, the spiral arms [Espada et al., 2012] in magenta star symbols, and the circumnuclear disk (CND, $r < 200$ pc, Espada et al. 2009, 2017) in red squares. The outer parts of the disk are marked in blue.

Pixel-to-Pixel Star Formation Efficiency (SFE)

Figure 3: SFE plot along the disk of Cen A

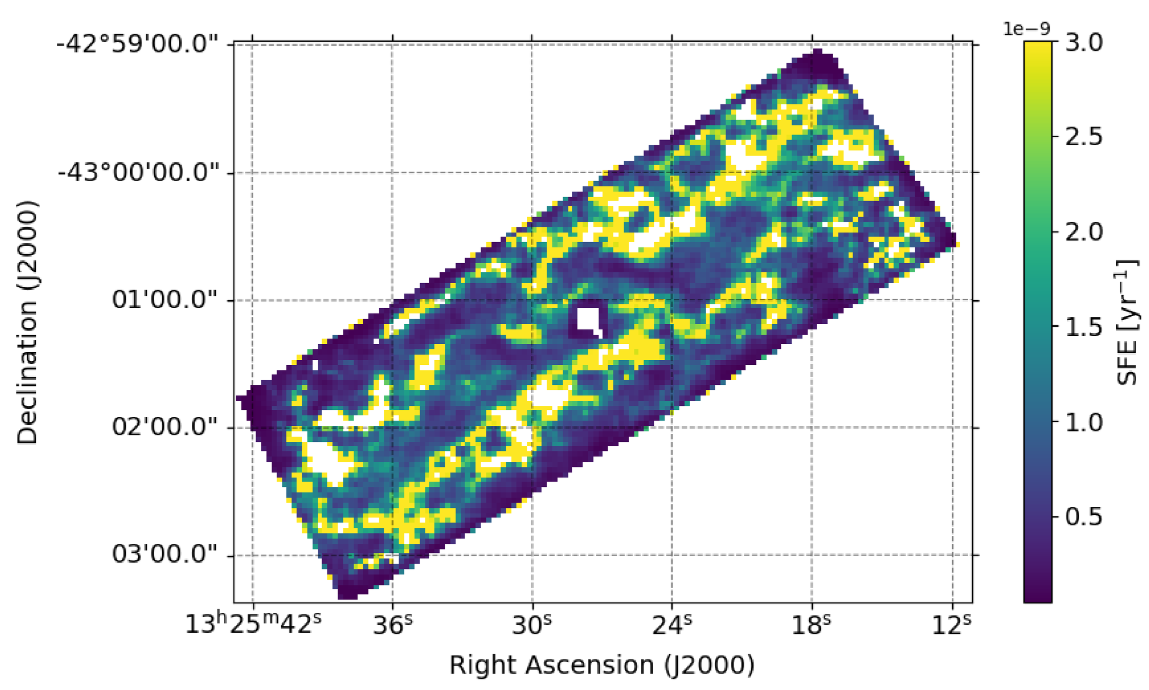


Fig. 3 presents a pixel-to-pixel plot of the star formation efficiency (SFE = $\Sigma_{\rm SFR}$ / $\Sigma_{\rm mol}$) along the dust lane of Cen A.

- In the pixel-to-pixel (40 pc) analysis we see that the mean/median SFEs (and standard deviations) for the different regions increase as a function of radius. The CND presents on average a lower SFE (0.3 Gyr^{-1}) by a factor of four than that in the outskirts of the molecular disk. This is compatible with the range (0.4 – 1.6 Gyr^{-1}) observed in nearby disk galaxies.
- The global star formation efficiency (SFE) is 0.6 Gyr^{-1} (depletion time $\tau = 1.5$ Gyr), similar to that in star forming galaxies.
- Cen A shows that not in all cases is the SFE suppressed in early-type galaxies after gas-rich minor mergers. However, regions with low SFE can also be found within the molecular disk of Cen A such as in the CND of Cen A where strong shear and shocks together with AGN activity are likely preventing SF.

Accepted for publication in the Astrophysical Journal:
Espada et al., ApJ, 2019 *(arXiv: 1906.01237)*