From Rings to Bulges: Evidence for Rapid Secular Galaxy Evolution at z ~ 2 from Integral Field Spectroscopy in the SINS Survey

Genzel et al 2008, ApJ 687, 59

We present Hα integral field spectroscopy of well-resolved, UV/optically selected z~2 star-forming galaxies as part of the SINS survey with SINFONI on the ESO VLT.

Our laser guide star adaptive optics and good seeing data show the presence of turbulent rotating star-forming outer rings/disks, plus central bulge/inner disk components, whose mass fractions relative to the total dynamical mass appear to scale with the [N II]/Hα flux ratio and the star formation age.

We propose that the buildup of the central disks and bulges of massive galaxies at z~2 can be driven by the early secular evolution of gas-rich proto-disks.

The Jeans length in a gravitationally unstable gas disk with is

$$L_{\rm Jeans} = \frac{\pi}{\sqrt{2}}\left(\frac{\sigma_0}{v_d}\right) R_r Q_{\rm Toomre}, \qquad (2)$$

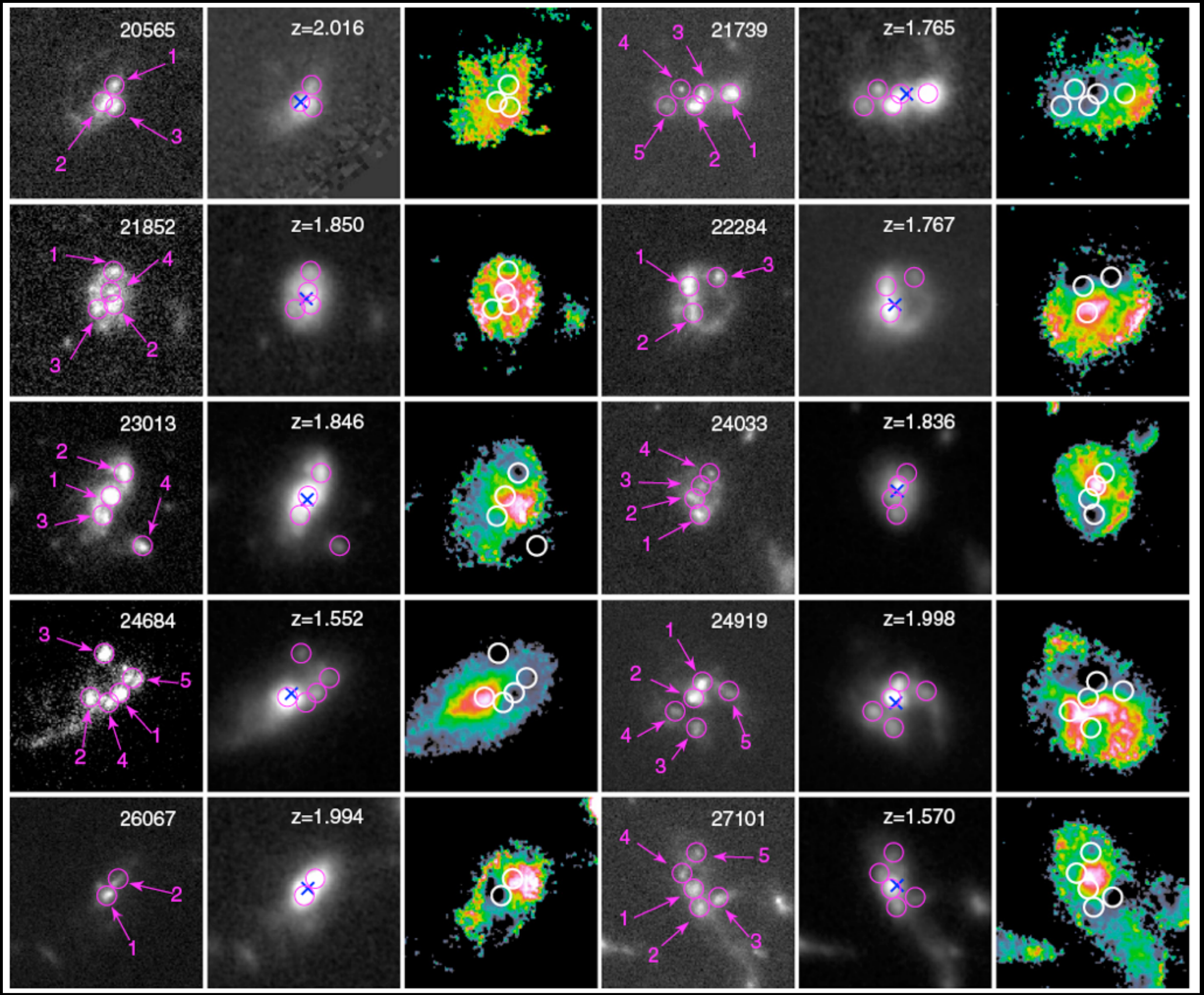
which yields L_{Jeans} =2.5 kpc or 0.3" for the parameters appropriate for the galaxies in Tables 2 and 3. The observed sizes of the giant Hα clumps/star forming complexes in the clumpy galaxies are consistent with the Jeans lengths inferred from the galaxies' kinematics properties. The Hα clumps thus may be initially close to virial equilibrium.

MULTI-WAVELENGTH VIEW OF KILOPARSEC-SCALE CLUMPS IN STAR-FORMING GALAXIES AT $z \sim 2$

Yicheng Guo, Mauro Giavalisco, Henry C. Ferguson, Paolo Cassata, and Anton M. Koekemoer ApJ 757, 120, 2012

This paper studies the properties of kiloparsec-scale clumps in star-forming galaxies at $z \sim 2$ through multi-wavelength broadband photometry. A sample of 40 clumps is identified from *Hubble Space Telescope* (*HST*)/Advanced Camera for Surveys (ACS) z-band images through auto-detection and visual inspection from 10 galaxies with $1.5 < z < 2.5$ in the Hubble Ultra Deep Field, where deep and high-resolution *HST*/WFC3 and ACS images enable us to resolve structures of $z \sim 2$ galaxies down to the kiloparsec scale in the rest-frame UV and optical bands and to detect clumps toward the faint end.

The physical properties of clumps are measured through fitting spatially resolved seven-band (*BVizYJH*) spectral energy distribution to models. On average, the clumps are blue and have similar median rest-frame UV–optical color as the diffuse components of their host galaxies, but the clumps have large scatter in their colors. Although the star formation rate (SFR)–stellar mass relation of galaxies is dominated by the diffuse components, clumps emerge as regions with enhanced specific star formation rates, contributing individually ~10% and together ~50% of the SFR of the host galaxies. However, the contributions of clumps to the rest-frame UV/optical luminosity and stellar mass are smaller, typically a few percent individually and ~20% together. On average, clumps are younger by 0.2 dex and denser by a factor of eight than diffuse components. Clump properties have obvious radial variations in the sense that central clumps are redder, older, more extincted, denser, and less active on forming stars than outskirt clumps. Our results are broadly consistent with a widely held view that clumps are formed through gravitational instability in gas-rich turbulent disks and would eventually migrate toward galactic centers and coalesce into bulges. Roughly 40% of the galaxies in our sample contain a massive clump that could be identified as a proto-bulge, which seems qualitatively consistent with such a bulge-formation scenario.



Montage of our 10 clumpy star-forming galaxies at $z \sim 2$. Each row shows images of two galaxies. For each galaxy, the panels from left to right show the z-band, H-band, and $z-H$ maps. Galaxy IDs are shown in the z-band images, while redshifts are shown in their H-band images. Small circles (magenta in the z-band and H-band images, and white in the $z-H$ maps) show the identified clumps. The blue "X"'s in the H-band images show the light-weighted centers.

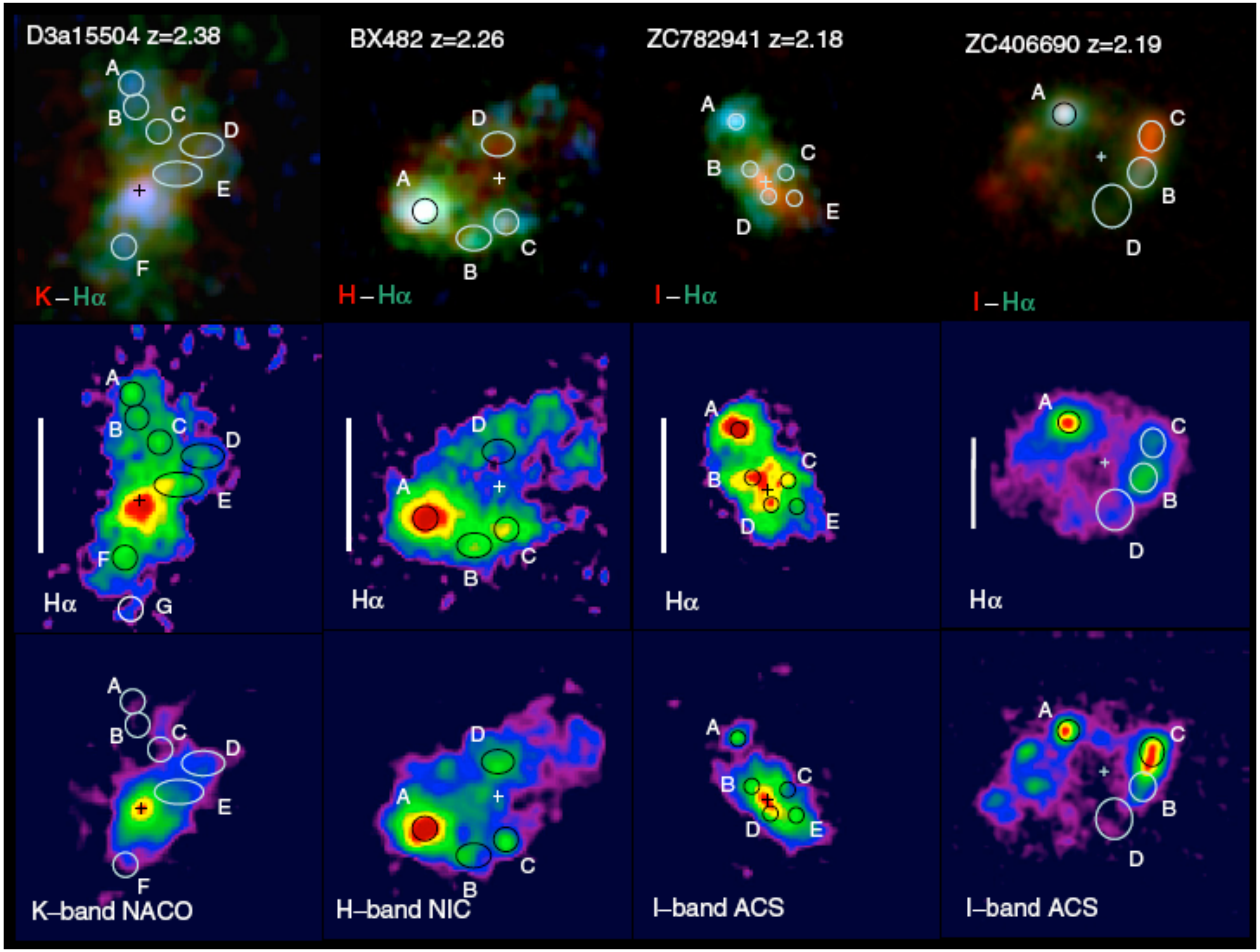
The Sins Survey of z ~ 2 Galaxy Kinematics: Properties of the Giant Star-forming Clumps

Genzel et al 2011, ApJ 2011, 733, 101

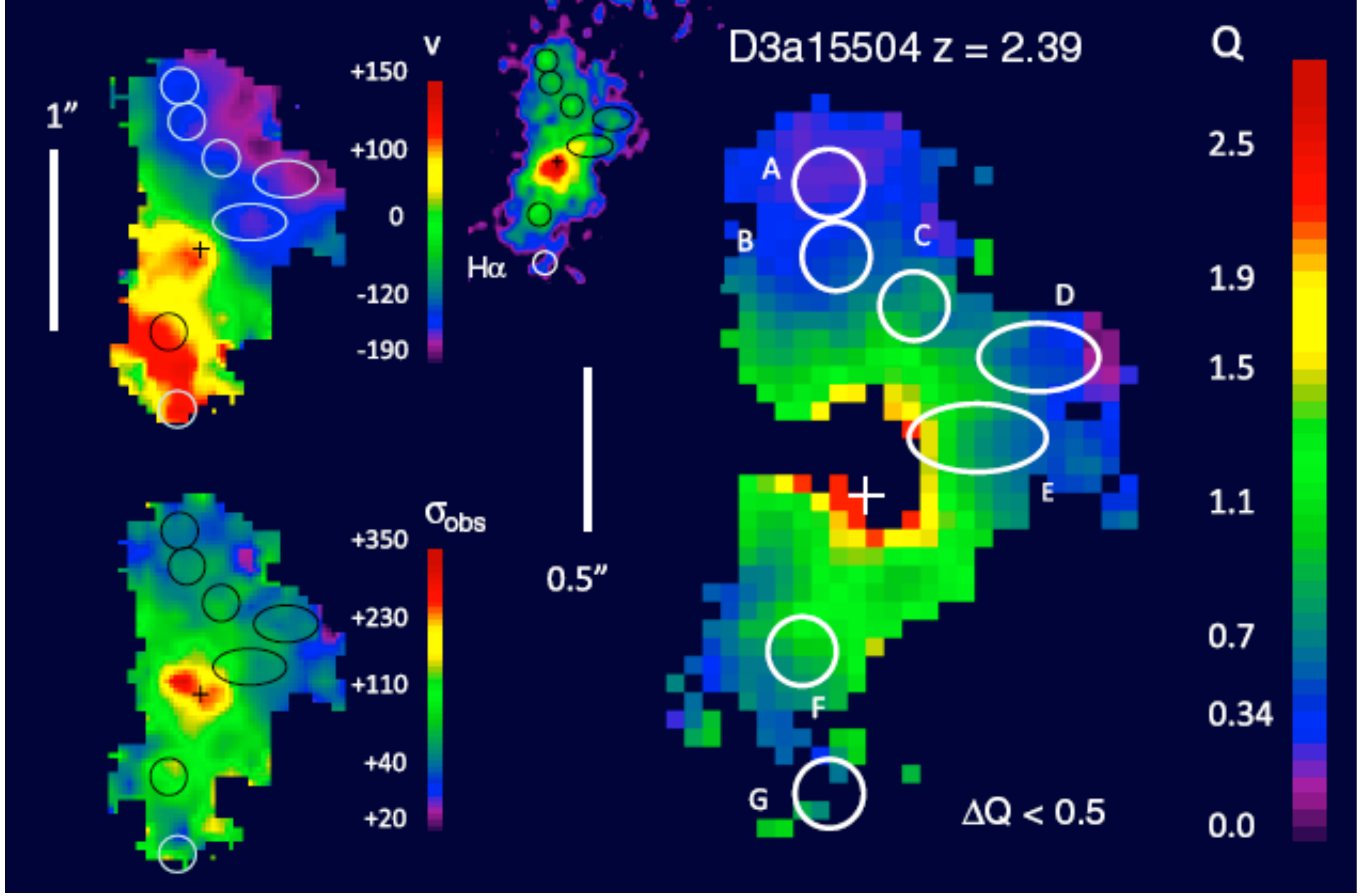
We have studied the properties of giant star-forming clumps in five z ~ 2 star-forming disks with deep SINFONI AO spectroscopy at the ESO VLT. The clumps reside in disk regions where the Toomre Q-parameter is below unity, consistent with their being bound and having formed from gravitational instability.
Broad Hα/[N II] line wings demonstrate that the clumps are launching sites of powerful outflows. The inferred outflow rates are comparable to or exceed the star formation rates, in one case by a factor of eight. Typical clumps may lose a fraction of their original gas by feedback in a few hundred million years, allowing them to migrate into the center. The most active clumps may lose much of their mass and disrupt in the disk.
The clumps leave a modest imprint on the gas kinematics. Velocity gradients across the clumps are 10-40 km s^{-1} kpc^{-1}, similar to the galactic rotation gradients. Given beam smearing and clump sizes, these gradients may be consistent with significant rotational support in typical clumps.

Extreme clumps may not be rotationally supported; either they are not virialized or they are predominantly pressure supported. The velocity dispersion is spatially rather constant and increases only weakly with star formation surface density.

The large velocity dispersions may be driven by the release of gravitational energy, either at the outer disk/accreting streams interface, and/or by the clump migration within the disk. Spatial variations in the inferred gas phase oxygen abundance are broadly consistent with inside-out growing disks, and/or with inward migration of the clumps.



FWHM ~ 0.2 Hα *an*d rest-frame UV/*op*tical continuum images of four massive luminous z ~ 2 SFGs. All maps have been re-binned to 0.025 pixels. Top row: three-color composites of integrated Hα li*ne* emission (red), and continuum (blue–green) images, along with the most prominent clumps identified by labels A, B,. . .. *Mi*ddle: integrated SINFONI Hα em*is*sion. All four images are on the same angular scale, with the white vertical bar marking 1 (~8.4 kpc). Bottom. HST NI*C* *H*-band*,* ACS I-band*,* or NACO-VLT AO Ks-ban*d* images of the program galaxies, at about the same resolution as the SINFONI Hα maps. The color scale is linear and autoscaled.



H*α* Gaussian fit velocities (top left), H*α* Gaussian fit dispersion (bottom left), and inferred Toomre *Q*-parameter (right, Equation (2)) for D3a15504. Shown in the top center is also the map of H*α*-integrated flux from Figure 2. The locations of the main clumps (Figure 1) found in the individual velocity channel maps are denoted by circles/ellipses. The H*α*, velocity, and velocity dispersion maps (resolution 0.18 FWHM) were re-binned to 0.025 pixels. For construction of the Q-map, the data were smoothed to 0.25 FWHM. The typical uncertainties in the Q-values are ±0.05 to ±0.3 (1σ) throughout most of the disk of D3a15504.

We estimated molecular surface densities (and masses, including a 36% helium contribution) from Equation (8) of Kennicutt et al. (2007), modified for the Chabrier IMF used here,

$$\log\left(\frac{\Sigma_{\rm mol-gas}}{M_\odot\,{\rm pc}^{-2}}\right) = 0.73\log\left(\frac{\Sigma_{\rm star-form}}{M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2}}\right) + 2.91. \quad (2)$$

Equation (2) is based on Hα, 24 μm, and CO observations of M51 and is similar to results for larger samples of $z \sim 0$ SFGs (e.g., Equation (4) in Kennicutt 1998a, and Figure 4 of Genzel et al. 2010). It has the added advantage

$$Q_{\rm gas} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{\rm gas}} = \left(\frac{\sigma_0}{v_c}\right)\left(\frac{a\left(v_c^2 R_{\rm disk}/G\right)}{\pi R_{\rm disk}^2 \Sigma_{\rm gas}}\right)$$
$$= \left(\frac{\sigma_0}{v_c}\right)\left(\frac{a M_{\rm tot}}{M_{\rm gas}}\right) = \left(\frac{\sigma_0}{v_c}\right)\left(\frac{a}{f_{\rm gas}}\right).$$

Here the constant a takes on the value of $1, \sqrt{2}, \sqrt{3},$ and 2 for a Keplerian, constant rotation velocity, uniform density and solid body disk; $f_{\rm gas}$ is the gas fraction within $R_{\rm disk}$. If the disk consists of molecular ($H_2 + He$), atomic ($H\,{\rm I} + He$), and stellar (*) components, $Q_{\rm tot}{}^{-1} = Q_{\rm H2}{}^{-1} + Q_{\rm HI}{}^{-1} + Q_*{}^{-1}$ if all components have similar velocity dispersions. If there is a (young) stellar