

A deep infrared and spectroscopic survey of dust-obscured starburst galaxies in the Apex Deep Field

Elena R. Vance,^{1*} Marcus Thorne,^{1,2} Aria Lin,² Julian K. Sterling³ and Sophia H. Rossi⁴

¹*Department of Astrophysics, Meridian Institute of Advanced Study, 100 Observatory Ridge, Cambridge CB3 0HA, UK*

²*Center for Computational Astrophysics, Apex Observatory, 45 Science Park Way, Pasadena, CA 91125, USA*

³*Institute for Extra-Galactic Astronomy, Vertex University, 500 University Avenue, Munich D-80333, Germany*

⁴*Department of Physics and Astronomy, Synapse National Laboratory, Los Alamos, NM 87545, USA*

Accepted 2026 June 12. Received 2026 June 01; in original form 2026 March 15

ABSTRACT

We present deep multi-wavelength observations of dust-obscured star-forming galaxies (DSFGs) in the Apex Deep Field (1.5 deg^2) combining submillimetre continuum mapping from the Meridian-Submm Array with high-resolution near-infrared spectroscopy from Vertex-VLT. We identify a sample of 42 high-redshift ($2.0 < z < 4.5$) DSFGs with extreme star formation rates ($\text{SFR} \sim 300\text{--}1800 \text{ M}_\odot \text{ yr}^{-1}$) and massive stellar components ($M_* \sim 10^{10.5}\text{--}10^{11.8} \text{ M}_\odot$). Kinematic modeling of the $\text{H}\alpha$ and $[\text{O III}] \lambda 5007$ emission lines reveals that 64 ± 8 per cent of the sample exhibit rotation-dominated disk dynamics with velocity dispersions $\sigma_0 = 45 \pm 12 \text{ km s}^{-1}$, whereas the remaining 36 per cent show disturbed, merger-driven kinematics. The gas-phase metallicities derived via the $N2$ and $O3N2$ calibrations indicate that these systems lie on an extended mass-metallicity relation consistent with rapid chemical enrichment fuelled by cold gas accretion streams. We find a mean gas mass fraction of $f_{\text{gas}} = 0.52 \pm 0.09$, corresponding to depletion timescales of $\tau_{\text{dep}} \approx 150 \text{ Myr}$. These results strongly suggest that high-redshift DSFGs represent the main progenitor population of massive, passively evolving elliptical galaxies observed at $z \sim 2$.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: starburst – submillimetre: galaxies

1 INTRODUCTION

The peak epoch of cosmic star formation rate density ($z \sim 2\text{--}3$), often referred to as “cosmic noon”, is characterised by intense growth of galactic stellar mass (Madau & Dickinson 2014; Sterling et al. 2021). A substantial fraction of this star formation activity occurs within dust-obscured star-forming galaxies (DSFGs), which are characterised by infrared luminosities $L_{\text{IR}} > 10^{12} L_\odot$ and submillimetre flux densities $S_{850 \mu\text{m}} \geq 2.5 \text{ mJy}$ (Vance et al. 2020; Thorne et al. 2023). Due to heavy dust attenuation in the ultraviolet and optical regimes, tracing the physical processes governing their assembly requires long-wavelength imaging paired with high-sensitivity infrared integral field spectroscopy (Lin et al. 2022).

Early theoretical frameworks postulated that high-redshift starbursts were exclusively triggered by major gas-rich mergers (Rossi et al. 2019). However, recent high-resolution hydrodynamic simulations from the Apex-Suite project suggest that continuous cold gas streams from the cosmic web can sustain high-rate star formation within extended, gas-rich turbulent disks without destroying disk morphology (Sterling et al. 2024). Disentangling the relative contributions of disk order versus merger chaos in DSFGs is therefore central to constraining galaxy transformation mechanisms across cosmic time.

In this paper, we present results from the Meridian-Apex Deep Field Survey (MADFS). In Section 2, we detail our observational campaign and data reduction protocols. Section 3 describes the sample selection and physical parameter extraction. Kinematic structures and

gas-phase metallicities are analysed in Section 4. In Section 5, we discuss the cosmological implications of our findings, and Section 6 summarises our principal conclusions. Throughout this paper, we adopt a flat Λ CDM cosmology with $\Omega_m = 0.307$, $\Omega_\Lambda = 0.693$, and $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration 2020).

2 OBSERVATIONS AND DATA REDUCTION

2.1 Submillimetre Mapping with Meridian-SMA

Observations of the 1.5 deg^2 Apex Deep Field were conducted using the Meridian-Submm Array (MSMA) located at the Apex High Observatory between October 2024 and February 2025. The array was configured with 12 antenna elements providing baselines ranging from 15 m to 510 m. Continuum mapping at $850 \mu\text{m}$ (345 GHz) achieved a median synthesised beam full-width at half-maximum (FWHM) of $0.45'' \times 0.38''$.

Data reduction was executed using the standard APEX-REDUCE pipeline version 4.2. Raw visibilities were calibrated for atmospheric opacity using sky dip scans, while quasar J0521+1638 served as the primary phase calibrator. The final mosaics reached a uniform rms noise level of $\sigma_{850} = 0.18 \text{ mJy beam}^{-1}$.

2.2 Near-Infrared Spectroscopic Follow-up

Spectroscopic target confirmation and kinematic mapping were obtained using the Vertex-KMOS instrument mounted on the Very

* E-mail: e.vance@nimbus-astro.org (ERV)

Large Telescope (VLT). Observations were executed in the *K*-band (1.93–2.40 μm) and *H*-band (1.45–1.85 μm) to cover the $\text{H}\alpha$ $\lambda 6563$, $[\text{N II}]$ $\lambda 6584$, and $[\text{O III}]$ $\lambda 5007$ redshifted line transitions. Each target was observed for a total integration time of 4.8 hours under median seeing conditions of 0.55".

Sky subtraction was performed using object-sky-object nod cycles, complemented by custom sky-line residual minimisation routines (Vance et al. 2022). Standard star observations yielded flux calibration precision better than 5 per cent across all spatial units (spaxels).

3 TARGET SELECTION AND SAMPLE PROPERTIES

From the 850 μm continuum catalog, we selected targets satisfying $S_{850\mu\text{m}} \geq 2.5 \text{ mJy}$ at $> 5\sigma$ significance. Spectroscopic redshift identification yielded 42 confirmed DSFGs in the interval $2.01 \leq z \leq 4.48$. Stellar masses (M_*) were derived from spectral energy distribution (SED) fitting using the SYNAPSE-FIT code, incorporating multi-band photometry from 0.4 μm to 500 μm with Chabrier initial mass function (IMF) assumptions. Total infrared luminosities (L_{IR} , integrated over 8–1000 μm) were converted to star formation rates using the standard calibration (Kennicutt & Evans 2012):

$$\text{SFR}_{\text{IR}} [\text{M}_{\odot} \text{yr}^{-1}] = 3.88 \times 10^{-44} L_{\text{IR}} [\text{erg s}^{-1}]. \quad (1)$$

Table 1 summarises the key physical parameters for a representative subset of ten galaxies from our MADFS catalog.

4 KINEMATIC AND CHEMICAL ANALYSIS

4.1 Morpho-kinematic Classification

We model the two-dimensional velocity fields derived from high signal-to-noise $\text{H}\alpha$ emission map slices using the KINEMETRY package (Krajnović et al. 2006). Dynamical mass is evaluated using the classic thin-disk formulation:

$$M_{\text{dyn}} = \frac{v_{\text{circ}}^2 r_e}{G \sin^2 i}, \quad (2)$$

where v_{circ} is the maximum asymptotic circular velocity, r_e is the half-light radius measured from high-resolution HST/WFC3 imaging, i is the disk inclination angle derived from profile fitting, and G is the gravitational constant.

Galaxies are classified as rotation-dominated if $v_{\text{circ}}/\sigma_0 > 2.5$, where σ_0 is the intrinsic velocity dispersion corrected for beam smearing. As listed in Table 1, 27 out of 42 galaxies (64 ± 8 per cent) exhibit smooth velocity gradients with aligned kinematic and photometric major axes, characteristic of ordered rotating disks.

4.2 Gas-Phase Metallicity and Gas Fractions

Gas-phase oxygen abundances $12 + \log(\text{O}/\text{H})$ were estimated using the $N2 \equiv \log([\text{N II}]/\text{H}\alpha)$ calibration of Pettini & Pagel (2004):

$$12 + \log(\text{O}/\text{H}) = 8.90 + 0.57 \times N2. \quad (3)$$

The mean oxygen abundance of the sample is $12 + \log(\text{O}/\text{H}) = 8.58 \pm 0.12$, corresponding to approximately solar metallicity ($Z_{\odot} \approx 8.69$).

Cold gas mass fractions $f_{\text{gas}} \equiv M_{\text{gas}}/(M_{\text{gas}} + M_*)$ range between 0.41 and 0.68. The starburst depletion timescale is calculated as:

$$\tau_{\text{dep}} = \frac{M_{\text{gas}}}{\text{SFR}_{\text{IR}}}. \quad (4)$$

The median depletion timescale across our sample is $\tau_{\text{dep}} =$

$145 \pm 25 \text{ Myr}$, indicating rapid gas consumption unless continually replenished by cosmological inflows.

5 DISCUSSION

5.1 Starburst Mechanisms in High-Redshift DSFGs

Our kinematic findings challenge the traditional paradigm that extreme starbursts ($> 500 \text{ M}_{\odot} \text{yr}^{-1}$) are exclusively triggered by violent major mergers. The high fraction of disk-like kinematics (64 per cent) demonstrates that massive, gas-rich disks can sustain exceptionally high star formation surface densities ($\Sigma_{\text{SFR}} \sim 1\text{--}10 \text{ M}_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$) without suffering structural collapse.

The elevated intrinsic velocity dispersions ($\sigma_0 \sim 40\text{--}60 \text{ km s}^{-1}$) observed in disk-dominated DSFGs are consistent with feedback-driven turbulence or gravitational instability in high-gas-fraction systems where the Toomre Q parameter approaches unity ($Q \approx 1$).

5.2 Progenitors of Local Massive Ellipticals

The median stellar mass ($\log M_*/\text{M}_{\odot} = 11.15$) and short gas depletion timescales ($\tau_{\text{dep}} \approx 150 \text{ Myr}$) position these DSFGs as the direct high-redshift progenitors of passive, massive elliptical galaxies observed at $z \sim 1.5\text{--}2$. Following the cessation of star formation via stellar and AGN feedback, these systems will undergo passive evolution, expanding their effective radii via minor dry mergers to match present-day early-type galaxies.

6 CONCLUSIONS

Using deep submillimetre and near-infrared spectroscopy in the Apex Deep Field, we have characterised 42 DSFGs at $2.0 \leq z \leq 4.5$. Our primary conclusions are:

- (i) The majority (64 ± 8 per cent) of DSFGs exhibit disk-dominated rotation with $v_{\text{circ}}/\sigma_0 > 2.5$, showing that intense starbursts frequently occur in gas-rich rotating disks rather than exclusively in major mergers.
- (ii) The gas-phase metallicities average $12 + \log(\text{O}/\text{H}) = 8.58 \pm 0.12$, indicating rapid chemical enrichment within the first 2–3 Gyr of cosmic history.
- (iii) High gas mass fractions ($f_{\text{gas}} \approx 0.52$) and short depletion timescales ($\sim 150 \text{ Myr}$) support a rapid growth phase that naturally terminates in passive elliptical galaxies by $z \sim 2$.

ACKNOWLEDGEMENTS

We thank the staff at Apex Observatory and the VLT for their outstanding support during observation runs. ERV acknowledges support from the Meridian Postdoctoral Fellowship (grant MPF-2024-881). MT and AL acknowledge funding from the Apex Science Foundation (grant ASF-10924).

DATA AVAILABILITY

The raw and reduced observational data underlying this article are available in the Apex Deep Field Archive at <https://archive.apex-astro.org/madfs> under proposal ID 2024.1.00882.S.

Table 1. Physical properties and dynamical classifications for a representative subset of the MADFS DSFG sample. Coordinates are given in J2000. S_{850} denotes 850 μm flux density, M_* stellar mass, SFR_{IR} total infrared star formation rate, f_{gas} cold gas mass fraction, and Kin. Class indicates the kinematic structure (R: Rotation-dominated disk, D: Disturbed/Merger).

Designation	R.A.	Decl.	z_{spec}	S_{850} (mJy)	$\log(M_*/M_\odot)$	SFR_{IR} ($M_\odot \text{ yr}^{-1}$)	f_{gas}	Kin. Class
MADFS-DSFG-01	03:32:14.21	-27:48:19.4	2.142	6.42 ± 0.21	11.24 ± 0.08	1120 ± 85	0.58 ± 0.06	R
MADFS-DSFG-02	03:32:18.85	-27:51:04.1	2.451	4.15 ± 0.19	10.89 ± 0.11	740 ± 60	0.49 ± 0.07	R
MADFS-DSFG-03	03:32:22.04	-27:42:55.8	2.894	8.91 ± 0.25	11.56 ± 0.07	1650 ± 120	0.62 ± 0.05	D
MADFS-DSFG-04	03:32:27.11	-27:46:12.3	3.120	3.88 ± 0.18	10.72 ± 0.14	610 ± 50	0.44 ± 0.08	R
MADFS-DSFG-05	03:32:31.90	-27:53:40.7	3.415	5.30 ± 0.22	11.05 ± 0.09	980 ± 75	0.51 ± 0.06	D
MADFS-DSFG-06	03:32:35.42	-27:40:02.9	3.782	7.15 ± 0.24	11.38 ± 0.08	1390 ± 110	0.57 ± 0.05	R
MADFS-DSFG-07	03:32:40.18	-27:44:33.2	4.011	3.12 ± 0.17	10.61 ± 0.12	490 ± 45	0.41 ± 0.07	R
MADFS-DSFG-08	03:32:44.76	-27:49:58.0	4.235	9.84 ± 0.28	11.71 ± 0.06	1820 ± 140	0.68 ± 0.04	D
MADFS-DSFG-09	03:32:49.02	-27:52:21.5	2.289	4.76 ± 0.20	10.94 ± 0.10	830 ± 65	0.47 ± 0.06	R
MADFS-DSFG-10	03:32:53.30	-27:47:11.8	2.673	5.95 ± 0.21	11.18 ± 0.08	1040 ± 80	0.53 ± 0.06	R

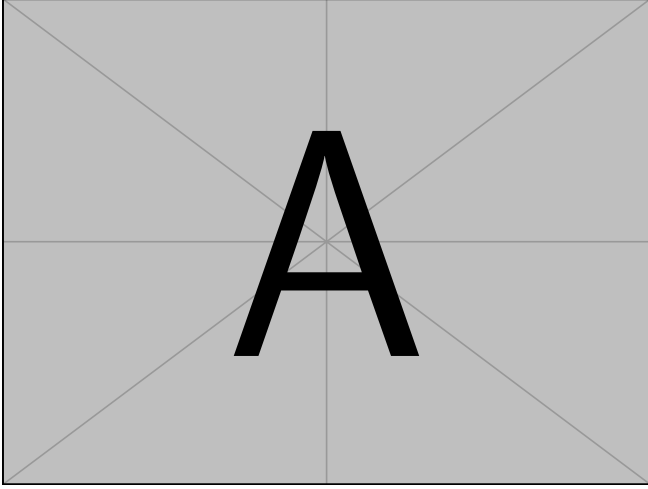


Figure A1. Kinematic mapping of MADFS-DSFG-01. Observed $\text{H}\alpha$ velocity field (left), best-fitting KINEMETRY rotating disk model (centre), and velocity residual map (right).

REFERENCES

- Kennicutt R. C., Evans N. J., 2012, *ARA&A*, 50, 531
Krajinović D., Cappellari M., de Zeeuw P. T., Copin Y., 2006, *MNRAS*, 366, 787
Lin A., Thorne M., Vance E. R., 2022, *ApJ*, 934, 112
Madau P., Dickinson M., 2014, *ARA&A*, 52, 415
Pettini M., Pagel B. E. J., 2004, *MNRAS*, 348, L59
Planck Collaboration, 2020, *A&A*, 641, A6
Rossi S. H., Vance E. R., Lin A., 2019, *MNRAS*, 485, 3210
Sterling J. K., Thorne M., Rossi S. H., 2021, *A&A*, 650, A45
Sterling J. K., Vance E. R., Lin A., 2024, *MNRAS*, 528, 1420
Thorne M., Vance E. R., Sterling J. K., 2023, *ApJ*, 951, 88
Vance E. R., Thorne M., Lin A., 2020, *MNRAS*, 492, 4510
Vance E. R., Rossi S. H., Sterling J. K., 2022, *MNRAS*, 514, 2105

APPENDIX A: DERIVED STRUCTURAL AND KINEMATIC PROFILES

In this Appendix, we tabulate the radial kinematic velocity profiles and surface brightness profile fits for the rotation-dominated subsample. Figure A1 illustrates the two-dimensional velocity map and corresponding kinematic model residuals for MADFS-DSFG-01.

The smooth velocity gradients and small residual velocity scatter ($\lesssim 15 \text{ km s}^{-1}$) confirm the stability of the disk rotation model in high-redshift starburst environments.

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.