THE EXPERIMENT FOR CRYOGENIC LARGE-APERTURE INTENSITY MAPPING (EXCLAIM)

Peter A. R. Ade[a], Christopher J. Anderson[b], Emily M. Barrentine[b], Nick G. Bellis[b], Patrick C. Breysse[c], Alberto D. Bolatto[d], Berhanu T. Bulcha[b], Giuseppe Cataldo[b], Jake A. Connors[b], Paul W. Cursey[b], Negar Ehsan[b], Henry Grant[d], Thomas Essinger-Hileman[b], Larry A. Hess[b], Mark K. Kimball[b], Alan Kogut[b], Alex Lamb[i], Luke N. Lowe[b], Phil Mauskopf[e], Jeff McMahon[f], Mona Mirzaei[b], S. Harvey Moseley[b], Jonas Mugge-Durum[d], Omid Noroozian[b], Ue-Li Pen[c], Anthony R. Pullen[g], Samelys Rodriguez[b], Peter J. Shirron[b], Rachel S. Somerville[h], Thomas R. Stevenson[b], Eric R. Switzer[b], Carole Tucker[a], Eli Visbal[h], C. G. Volpert[d], Edward J. Wollack[b], Shengqi Yang[g]

[a]Cardiff University, Cardiff, UK; [b]NASA-Goddard Space Flight Center, Greenbelt, MD, USA; [c]Canadian Institute for Theoretical Astrophysics, Toronto, CA; [d]University of Maryland-College Park, MD, USA; [e]Arizona State University, Tempe, AR, USA; [f]University of Michigan, Ann Arbor, MI, USA; [g]New York University, New York, NY, USA; [h]Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA, [i]Missouri University of Science and Technology, Rolla, MO, USA

ABSTRACT

The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) is a high-altitude balloon spectrometer designed to deepen our understanding of star formation in a cosmological context. Rather than identifying individual objects, as in a galaxy redshift survey, EXCLAIM will be a pathfinder to demonstrate an intensity mapping (IM) approach. EXCLAIM will operate at 421 – 540 GHz with a spectral resolution of R=512 to measure the integrated line emission from galaxies and the intergalactic medium (IGM). The instrument is ideal for observing CO and [CII] line emissions from the nearby universe out to redshifts of z~3.5. CO and [CII] line emissions are key tracers of the gas phases in the interstellar medium involved in star-formation processes. EXCLAIM will shed light on questions such as why the star formation rate declines and breaks away from the cosmological evolution of dark matter at redshifts of z~2. The instrument will employ an array of six superconducting integrated grating-analog spectrometers (μ-Spec) with superconducting microwave kinetic inductance detectors (KIDs) in an all-cryogenic telescope (1.5 K) to achieve near background-limited sensitivity. Here, we present an overview of the EXCLAIM instrument and status.

INTENSITY MAPPING (IM)

Rather than detect individual galaxies, EXCLAIM will measure the statistics of brightness fluctuations of redshifted, cumulative line emission.

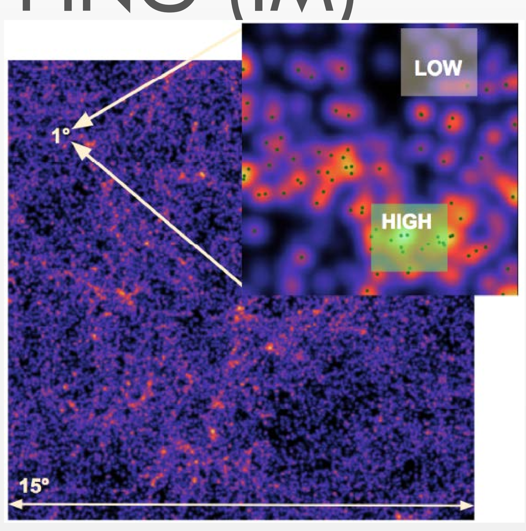


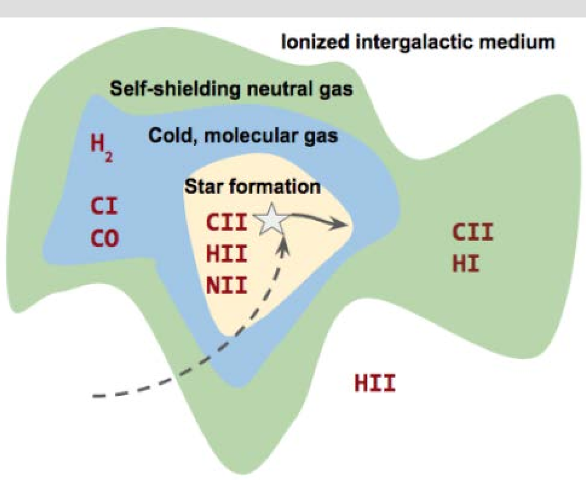
Figure: A simulation of an EXCLAIM sub-region. Most individual galaxies (green points) are not resolved, but the structure of the cosmic web is apparent on large scales. Typical small area surveys (HIGH and LOW density regions here) may not take a fair sample of galaxies.

Why Intensity Mapping?

- **Aperture**: Pushing to higher flux sensitivity and lower confusion drives large apertures. Instead, IM measures surface brightness with sensitivity limited by detector noise or photon background.
- **Cumulative emission:** IM is sensitive to the faintest sources (good! – blind complete census) but also all other radiation (bad! – but spectral differences can be used to reject continuum emission).
- **Volume:** IM provides efficient access to large cosmological volumes and redshifts, reducing cosmic variance.
- **Environments:** Lines and ionization states trace different environments.
- **Hosts:** IM measures the relative clustering of galaxies with bright line emission, which provides insight into the halos masses that host star formation.
- **Systematics:** No selection function (i.e. no dust extinction or issues such as fiber collisions from nearby galaxies).

SCIENCE

EXCLAIM will map the submillimeter emission of redshifted carbon monoxide (CO) and singly-ionized carbon ([CII]) lines in windows comprising 0 < z < 3.5. These lines trace star formation and its precursors, but have only preliminary characterization beyond the nearby universe.



EXCLAIM's Primary Science Questions:

1. What factors led to the dramatic decline in star formation since z ~ 2 in contrast to dark matter evolution?
2. What is the typical abundance, excitation and evolution of the molecular gas which forms stars?
3. How well does CO trace H2 in galaxies?
4. Is intensity mapping a viable approach to probe high redshifts?

Lines & Levels:

CO: EXCLAIM will cross-correlate with spectroscopic galaxy redshift catalogs (shown right) to constrain the total molecular CO gas abundance from 0 < z < 0.7 and potentially out to z=3.5 with extended BOSS survey releases.

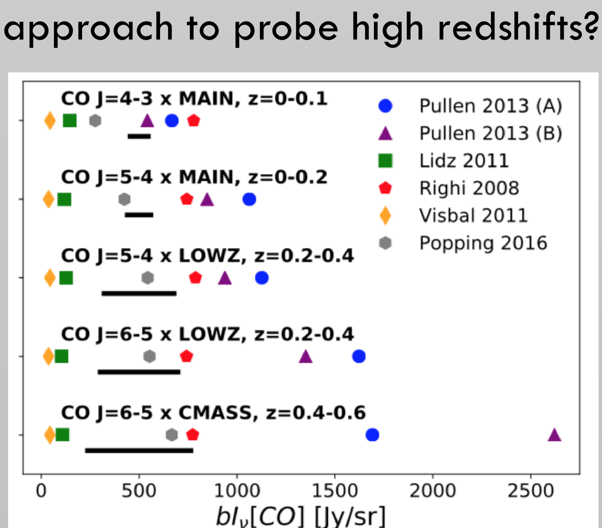


Fig.: CO total abundance from cumulative luminosity. EXCLAIM sensitivity (black line) is compared to existing models [6-10]. Here J is the transition, b is the clustering bias of the emitters and I_ν is the intensity.

CII: EXCLAIM will cross-correlate with the BOSS QSO survey from 2.5 < z < 3.5 to provide a definitive test of CII abundance (shown right) and probe the CII and the star formation rate (SFR) relation [12] determining whether it follows local relations or suggests strong evolution of the average Interstellar Medium.

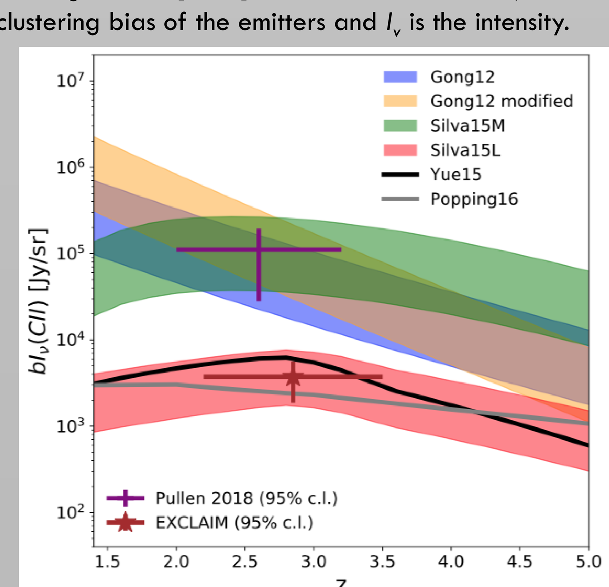
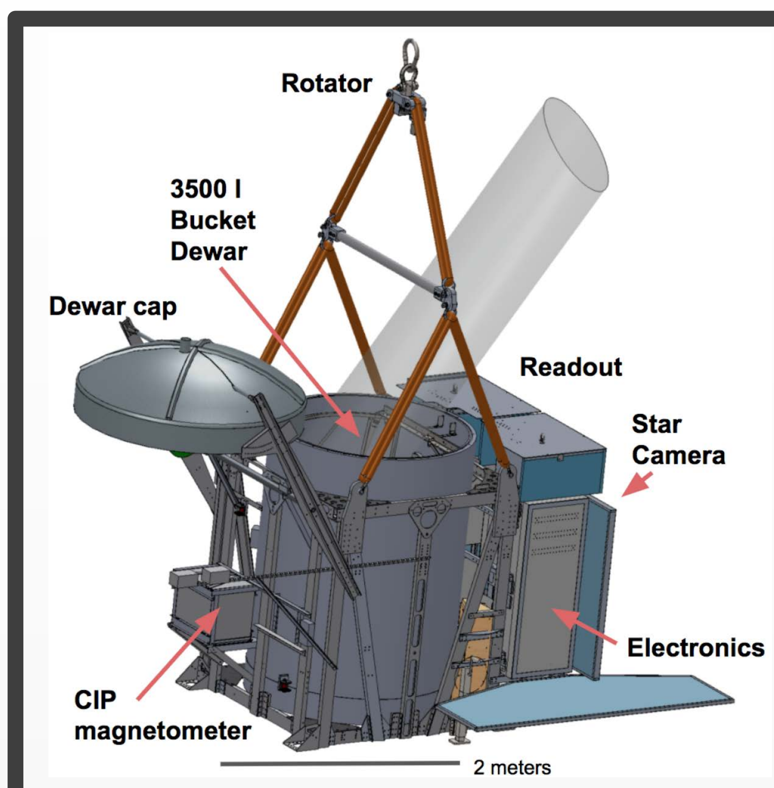


Fig.: CII total abundance from cumulative luminosity vs. redshift. EXCLAIM sensitivity (red star) is compared to existing models [7,13-15] and preliminary measurements [11]. Here b is the clustering bias of the emitters and I_ν is the intensity.

INSTRUMENT OVERVIEW



Cryogenic Balloon-Borne Instrument:

- 3500 liters of liquid helium gives ~24 hrs of operation at 1.7 K at float altitude.
- 4-stage Continuous Adiabatic Demagnetization Refrigerator (CADR) provides 10 μW cooling at 100 mK with 4.3 K (ground) to 1.7 K (float) bath temperature.
- 38 km elevation at float on a 34 mcf balloon; 36 km is assumed.
- Superfluid He pumps distribute the liquid He to cool the optics.
- The pointing elevation is fixed at 50°.
- We sample the beam in FWHM/3 pixels, at an azimuthal rate of < 2°/sec
- Elevation dip is achieved with a cantilevered mass. The gondola co-moves with the telescope to limit spill modulation.
- Pointing: reconstruction only, star camera + gyro, magnetometer, tilt.
- Heritage: Primordial Inflation Polarization ExploreR (PIPER). Uses gondola, housekeeping electronics, software, and CADR designs.

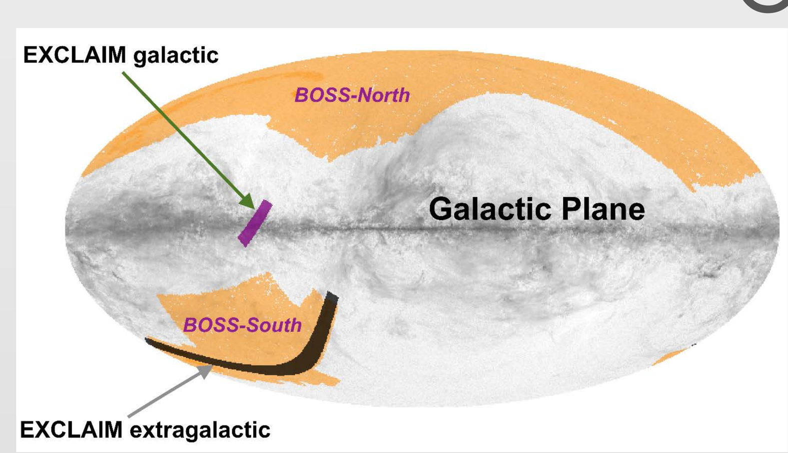
EXCLAIM Instrument & Telescope Parameters

Mass	1800 kg
Height	2.8 m
Telemetry rate	57.6 kpbs
Data rate	9 MB/s
Gondola Power	600 W
Readout Power	≤ 550 W
Projected aperture	74 cm
Physical aperture	90 cm
Angular resolution	3.5' FWHM
Edge Taper	-9 dB
Telescope f/#	1.3
Detector spacing	2.2 f λ
Instantaneous FOV	12.5'

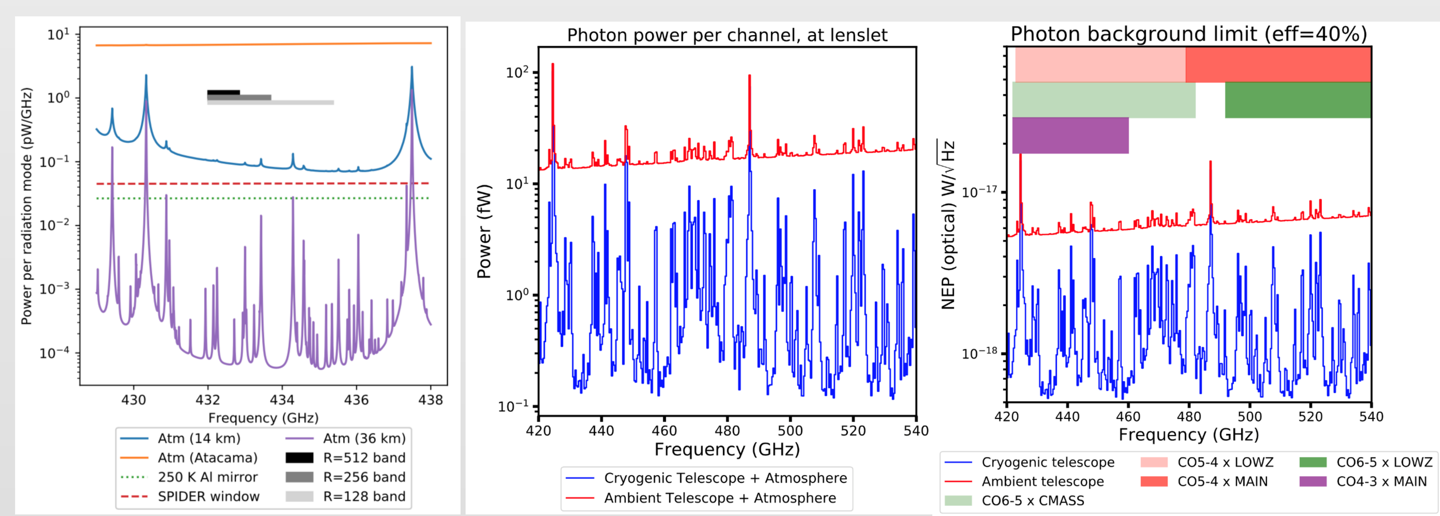
EXCLAIM Spectrometer & MKID Parameters

Spectrometer Design	μ-Spec, antenna-coupled diffraction-grating analog, Rowland configuration
Number of spectrometers	6
Spectral Range	421-540 GHz
Spectrometer Grating Order	2 (operates over a single order)
Resolving Power, R = λ/Δλ	512
Spectrometer Efficiency	~40% (from Si lens input to the MKIDs)
Spectrometer materials	Nb planar transmission line, single-crystal Si dielectric
MKIDs per spectrometer	355
MKID materials	20 nm thick Al microstrip, single-crystal Si dielectric, ground plane Nb
MKID Readout Band	2 – 2.5 GHz
NEP	< 3x the photon background limit at the spectrometer input (Photon NEP ~ 6 x 10^{19} W/√Hz in the darkest atmospheric channels)
Operating temperature	100 mK
LNA Noise Temperature	≤ 5 K

OBSERVING STRATEGY



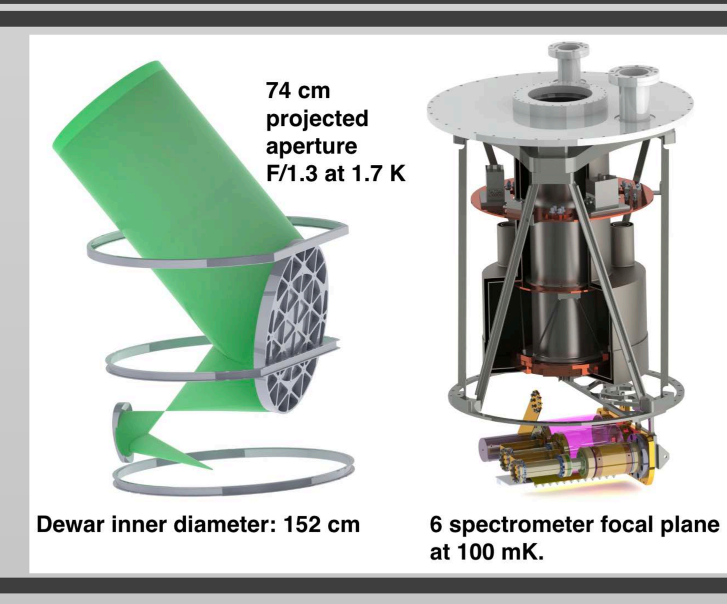
- •We cross-correlate with the Baryon Oscillation Spectroscopic Survey (BOSS) Stripe 82 for primary science – a reference survey is shown above.
- •Large area: Cross-correlation can go wide (more isotropic volume); in contrast, auto-power aims for SNR~1 per mode.
- •Access linear scales up to k~1 hMpc^{-1}.
- •Plan for a conventional flight from Texas or New Mexico, as it is well matched to the BOSS-North/South region, and has simple logistics, high recovery rate, and frequent flight opportunities.



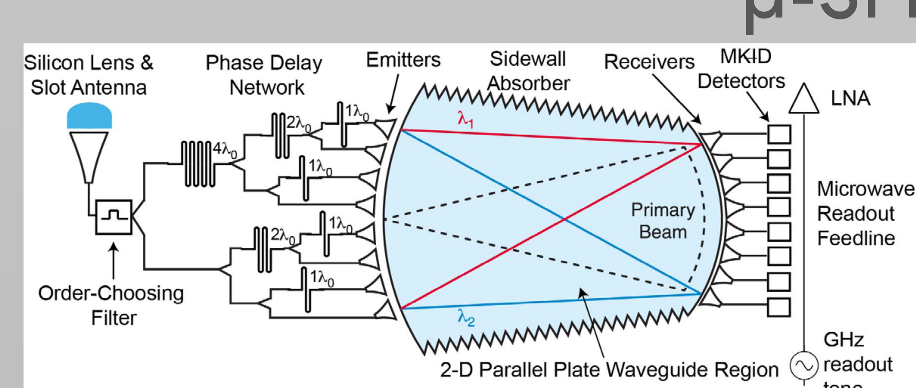
- •The spacing between bright atmospheric emission lines is ~5 GHz. Pressure broadens these lines, following the relation ~10 MHz/Torr. Thus, to observe between these lines requires < 10 Torr, or >100000 ft altitude. EXCLAIM will fly at >120,000 ft (36 km).
- •To resolve these windows at ~500 GHz requires R > $\frac{500\ GHz}{5\ GHz}$ = 100. The EXCLAIM goal is R=512.
- •We truncate at 540 GHz to avoid the bright ortho-H_2O line at 557 GHz.
- •A factor of 10 in photon background is a factor of 100 in time. An 8 hour conventional flight with a cryogenic telescope thus is comparable to a 33 day flight with a warm telescope.

OPTICS AND RECEIVER

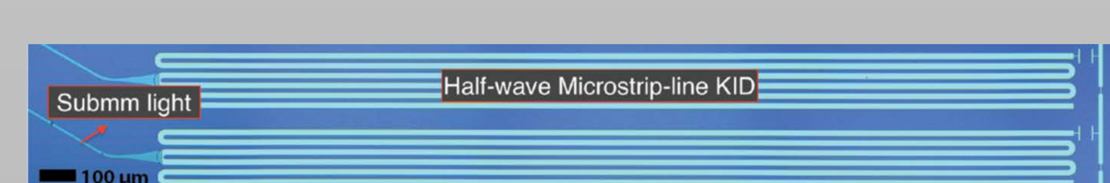
- The telescope is an open Dragone configuration with 90 cm parabolic primary mirror and 10 cm ellipsoidal secondary mirror, both machined of aluminum.
- The F/1.3 reflectors feed a single Si lens through a stop. This Si lens couples light onto the on-chip spectrometers.
- The stop controls illumination of the primary and terminates stray light onto blackened cold baffles.
- Si lenses are anti-reflection coated with metamaterial.
- The superfluid-tight vacuum window is quartz with a PTFE anti-reflection coating.



μ-SPEC & READOUT



- μ-Spec integrates all the elements of a grating spectrometer - the dispersive element, filters, and detectors - on a single chip.
- Phase delay is introduced by a synthetic grating made of superconducting Nb microstrip lines patterned on both sides of a single-crystal Si substrate (450 nm thick) [1]. The high index of refraction of Si allows us to do so in a compact space.
- A 2-D parallel plate waveguide region in a Rowland circle architecture serves as a spatial beam combiner and focal plane (which Nyquist-samples the spectral response).
- For EXCLAIM, an order-choosing filter selects the design order.
- We uses superconducting Microwave Kinetic Inductance Detectors (MKIDs) for easy multiplexing and to reach ultra-low sensitivity. We implement thin film Al in a microstrip half-wave resonator design with a Nb ground plane.



- **Heritage:** R=64 μ-Spec prototype demonstration [2]. Demonstration of Coplanar Waveguide (CPW) resonators of 10-25 nm thick Al with Q_{int}≥1x10^6 [3] and Nb with Q_{int}≥5x10^5 [4].
- **Readout:** EXCLAIM will use a Reconfigurable Open Architecture Computing Hardware (ROACH)-derived readout system developed by ASU [5], which is the most mature MKID readout system for balloon platforms.

REFERENCES

[1] Patel, A., et al., *IEEE Trans. Appl. Supercond.*, 23.3 (2013): 2400404.
[2] Noroozian, O., et al., *International Symposium on Space Terahertz Technology*, (2015).
[3] Noroozian, O., et al., *American Astron. Soc. Meeting Abstracts*, 231 (2018).
[4] Hess, L., et al., *J. Low Temp. Phys.*, in prep., (2019).
[5] Gordon, S., et al., *J. Astron. Instrum.*, 5.04 (2016): 1641003.
[6] Lidz, A., et al., *Astrophys. J.*, 741.2 (2011): 70.
[7] Popping, G., et al., *Mon. Notices Royal Astron. Soc.*, 461.1 (2016): 93-110.
[8]Pullen, A. R., et al., *Astrophys. J* 768.1 (2013): 15.
[9]Righi, M. et al., Astron. Astrophys., 489.2 (2008): 489-504.
[10]Visbal, E., et al., *J. Cosmol. Astropart. Phys.*, 2011.08 (2011): 010.
[11]Pullen, A. R., et al., *Mon. Notices Royal Astron. Soc.*, 478.2 (2018): 1911-1924.
[12] Padmanabhan, H., *arXiv preprint arXiv:1811.01968* (2018).
[13] Y. Gong, et al., *Astrophys. J*, 745:49 (2012).
[14] M. Silva, et al., *Astrophys. J*, 806:209 (2015).
[15] Yue, B., et al., *Mon. Notices Royal Astron. Soc*, 450.4 (2015): 3829-3839.
[16] Li, Tony Y., et al., *Astrophys. J*, 817.2 (2016): 169.

ACKNOWLEDGEMENT

We gratefully acknowledge funding provided by the NASA Astrophysics Research and Analysis (APRA) Program.

CURRENT STATUS

The EXCLAIM program began in April 2019 and is in a requirements definition stage, with subsystem designs in progress. The engineering flight is expected in 2021, and a science flight in 2022.