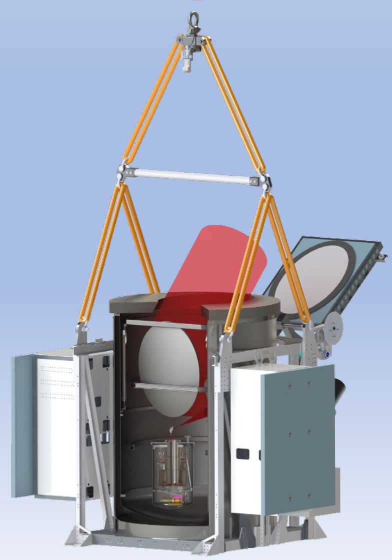
The Experiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM)

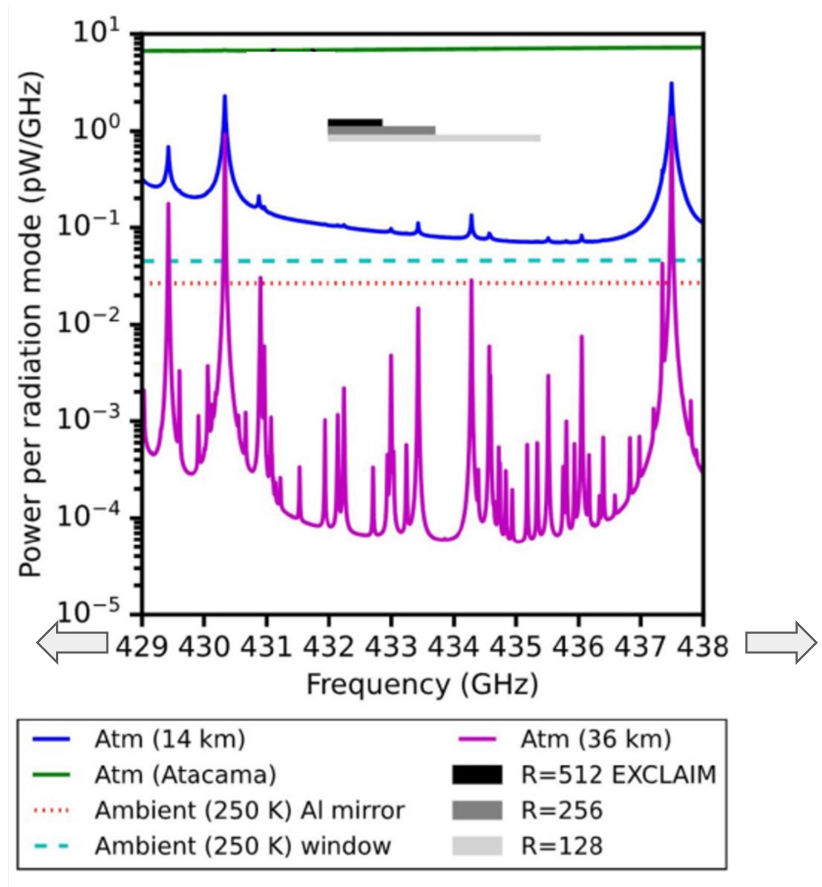
A balloon-borne, sub-mm experiment using integrated silicon spectrometers to unveil star formation history via intensity mapping



Peter Timbie - University of Wisconsin - Madison
for the EXCLAIM collaboration

EXCLAIM Mission Overview

- **Cross-correlation with BOSS for primary science**
  - **CII 2.5 < z <3.5, CO 0 < z < 1**
  - **Large area: Cross-correlation** can/should go **wide (more isotropic volume)**; vs auto-power - aims for SNR~1 per mode.
  - Access **linear scales** up to k~1 h Mpc^{-1}
- **Cryogenic telescope** for fast integration in dark atmospheric windows
- **On-chip MKID spectrometer, R=512, 420-540 GHz (555-714 um)**
- **Conventional flight** from TX or NM: well-matched to BOSS regions, simple logistics, high recovery rate, regular flight opportunities
- Start: 4/2019, Flight planned for Fall 2026
- Versatile platform for testing FIR spectrometer technology in space-like environment
- See Pullen+ 2022 for science and Switzer+ 2021 (JATIS) for mission



EXCLAIM Team

NASA Goddard
Eric Switzer (PI)
Tom Essinger-Hileman (DPI, Instrument lead)
Emily Barrentine (Spectrometer lead)

Berhanu Bulcha (Resonator design)
Jake Connors (Spectrometer)
Paul Cursey (Machinist)
Sumit Dahal (Receiver, ADR)
Negar Ehsan (Antenna design)
Jason Glenn (Receiver, MKIDs)
Larry Hess (Detector Fabrication)
Amir Jahromi (ADR)
Mark Kimball (ADR)
Alan Kogut (Gondola)
Luke Lowe (Flight Electronics)
Maryam Rahmani (Spectrometer)
Deepak Sapkota (Detector fabrication)
Joseph Watson (Mechanical)
Thomas Stevenson (Spectrometer)
Ed Wollack (Spectrometer)
Aaron Yung (Science team)

22 undergraduate interns, 12 MA/PhD, 5 PD, many early-career

NYU/CCA: Simulation and interpretation
Anthony Pullen (Science Lead)
Rachel Somerville
Shengqi Yang

SMU: Simulation and Interpretation
Patrick Breysse

UMD:
Alberto Bolatto (Galactic field, interpretation)
Carolyn Volpert (grad, spectrometer test, survey)

ASU: (Readout)
Phil Mauskopf (Readout Lead)
Adrian Sinclair (Now UBC)
Cody Roberson
Eric Weeks

UWisc: (MKID modelling, forecasting)
Peter Timbie, Faizah Siddique, Sam Kramer

U Chicago: (Silicon lens AR) Jeffrey McMahon, Joey Golec, Rahul Datta
Cardiff: (Filters) Peter Ade, Carole Tucker
U Toledo: Eli Visbal

Science goals: lines & levels

Map both [CII] and CO, R=512, 420 - 540 GHz

[CII]: BOSS QSO cross-correlation for 2.5 < z < 3.5

- **~300 deg^2**
- Definitive test of [CII] brightness in *Yang+ 2019*.
- What is the [CII]-SFR relation? See *Padmanabhan 2019*.

CO: Cross-correlation with galaxy surveys

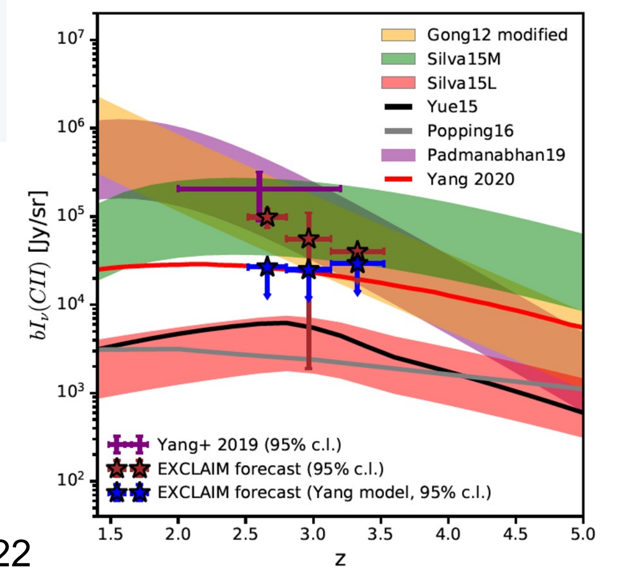
- MAIN 0 < z < 0.2 for J=5-4, J=4-3
- LOWZ 0.2 < z < 0.4 for J=6-5, J=5-4
- CMASS 0.4 < z < 0.7 for J=7-6, J=6-5
- eBOSS for z > 0.7 and higher J?

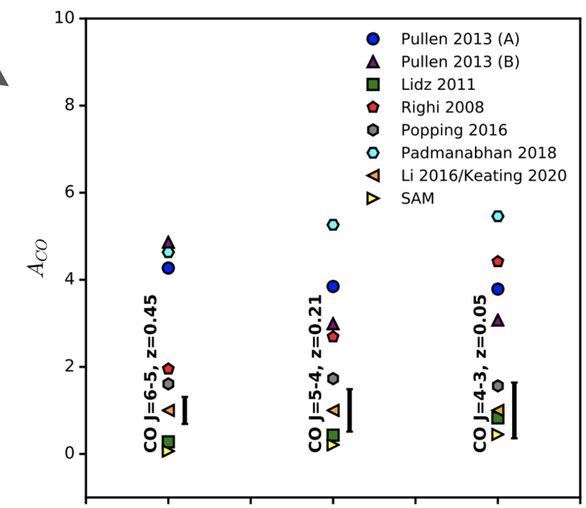
ASPECS: factor of 3 from cosmic variance. (Popping+ 2019). Confirm integral CO emission.

Galactic region: 492 GHz [CI], 460 GHz CO J=4-3, 425 GHz, 487 GHz O_2

Probe 'CO dark clouds' with [CI] - contains ~⅓ amount of H_2 gas but no CO emission: *Wolfire+ 2010, Burton+ 2015.*

Pullen & Breysse + 2022

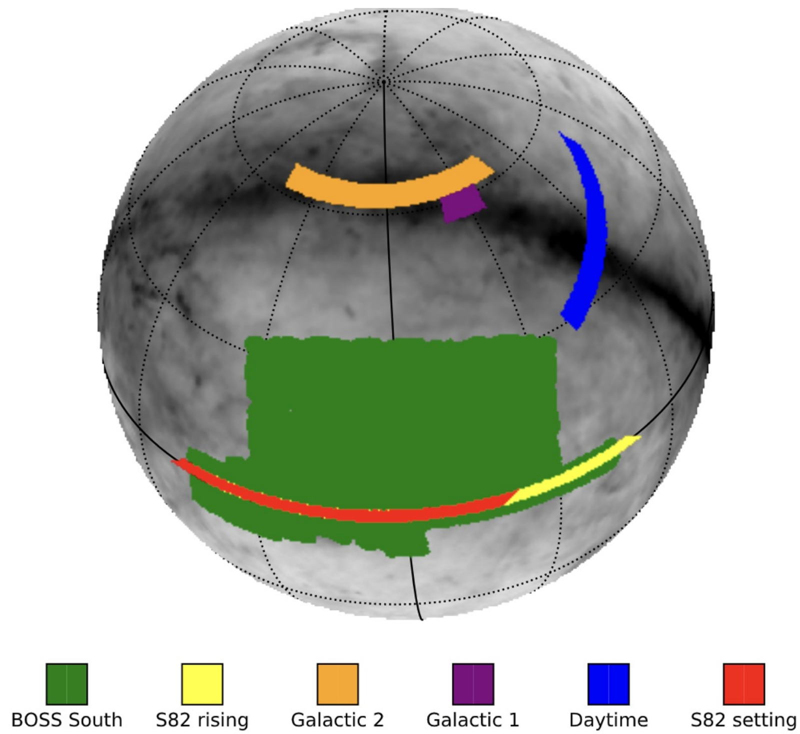




Strategy

Parameter	Symbol [unit]	Value
Observed frequency range	ν_{obs} [GHz]	420–540
Observed wavelength range	λ_{obs} [μm]	555–714
Spectral resolution	$R = \nu/\Delta\nu$	512
Beam FWHM at 480 GHz	θ_{FWHM} [arcmin]	4.33
Sky Area (Extragalactic, GP)	Ω [deg^2]	305, 100
Number of spectrometers	N_{specs}	6
Survey duration	t_{surv} [hr]	10.5

EXCLAIM regions from Ft. Sumner, NM

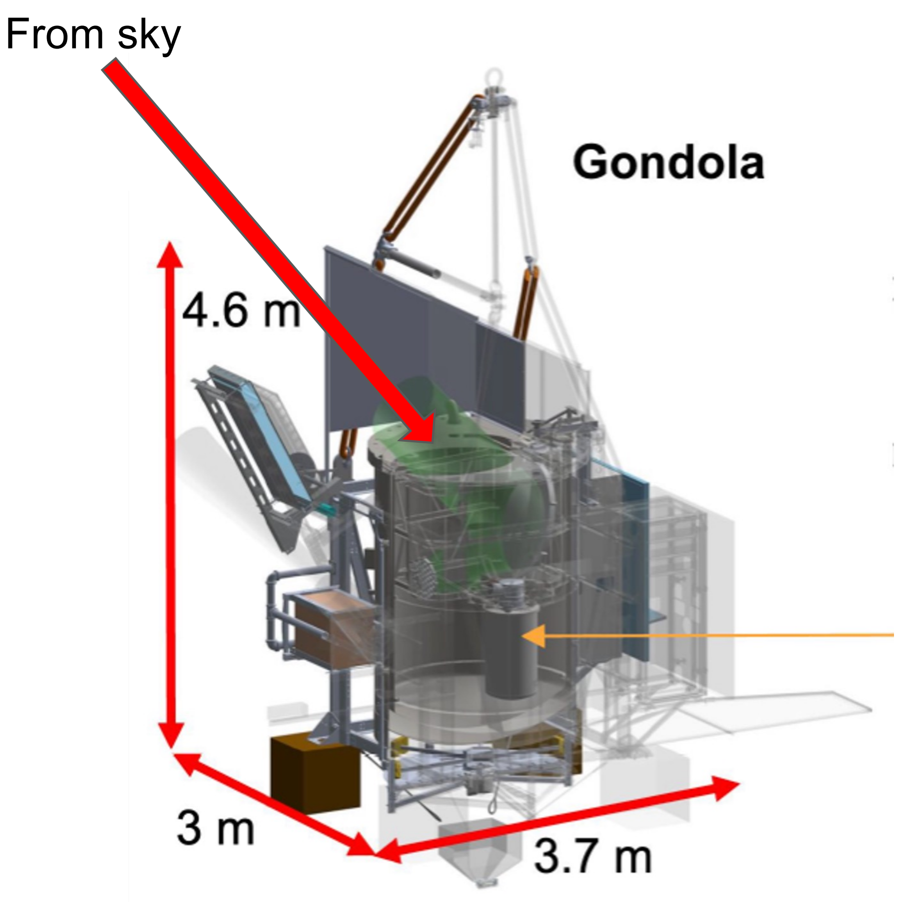


Preliminary survey plan (all local time)

- Daytime field (3-6 PM) : anti-solar scan, 200 deg^2, crosses the galactic plane.
- Galactic field 1: 6-7 PM, 45 deg^2.
- BOSS S82 field: rises 7 PM local until 1 AM. 305 deg^2, setting from 1-5:30 AM.
- Optional: Galactic field 2: 1 AM-7 AM, 220 deg^2.

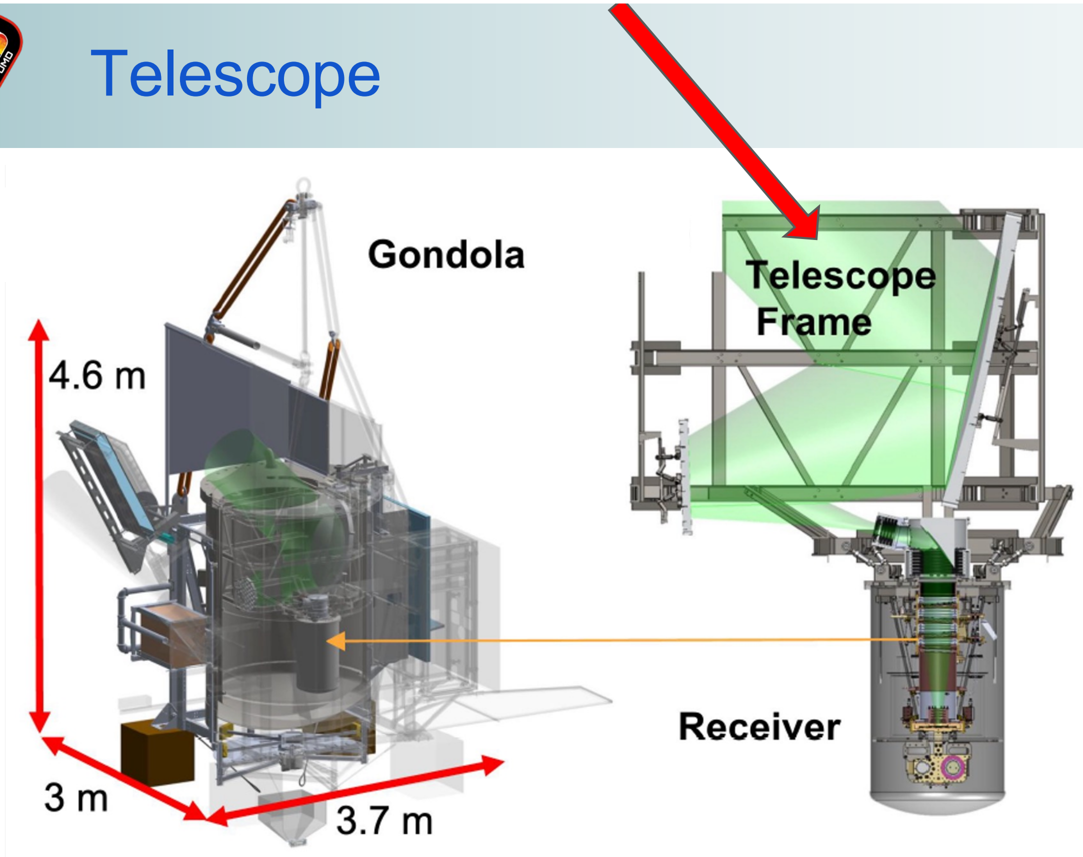
Implementation

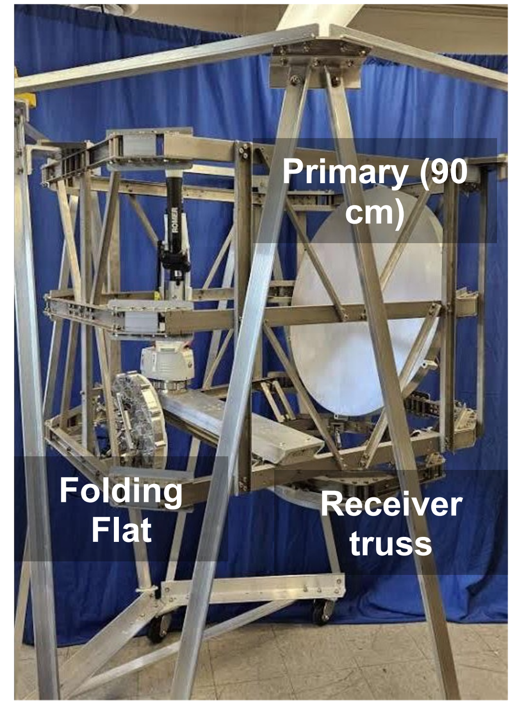
Payload and Mission Overview



- Conventional (e.g. 1-day) flight (Ft. Sumner, NM, primary, Palestine, TX, secondary).
- 3500 l LHe Bucket dewar. Deployable cover.
- ~2400 kg dry mass, 11/34 MCF balloon.
- ~2000 l LHe fill gives 18 hr of 1.7 K operation at float.
- Superfluid fountain effect pumps cool optics to 1.7 K (Kogut+ 2021).
- Scan ~7° in azimuth at fixed elevation 45°.
- Long axis of the primary is 90 cm. The 76 cm projected aperture provides ~4' FWHM.
- ARCADE/PIPER heritage.

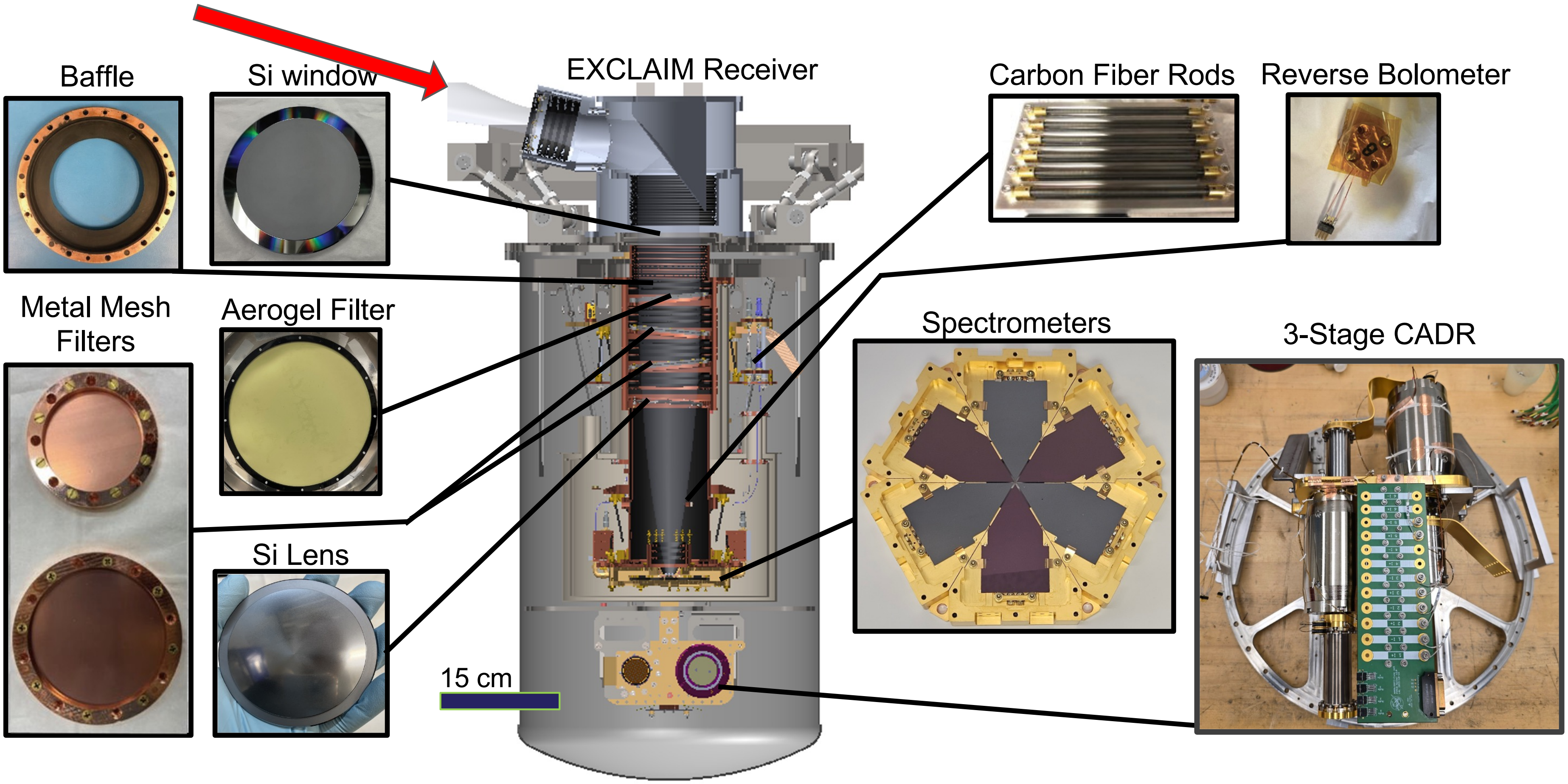
Telescope





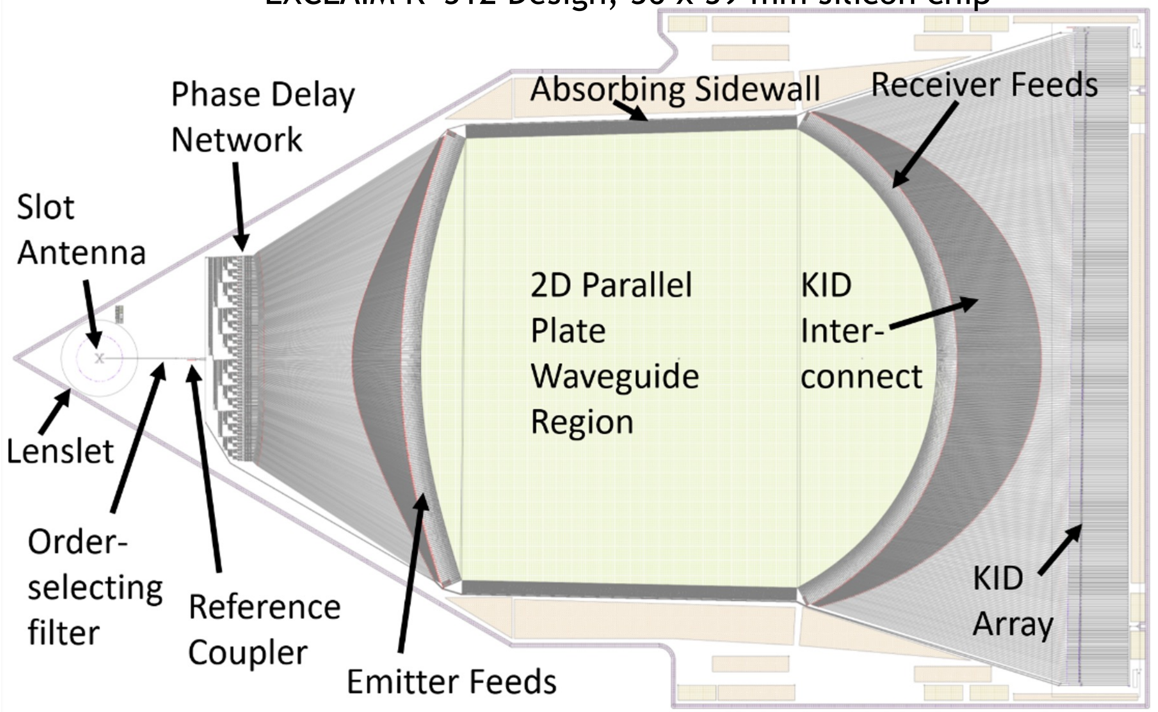
- Receiver mounted to an off-axis cryogenic telescope.
- Elevation fixed to 45 deg by telescope frame.
- Intermediate focus provides baffling region.
- Collimated section controls primary illumination, magnetic shielding, filters with low incidence angles.
- All optics aluminum and aligned with metrology arm.

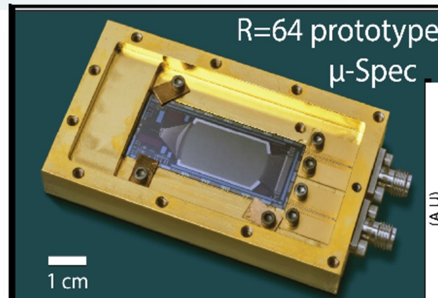
Receiver Components

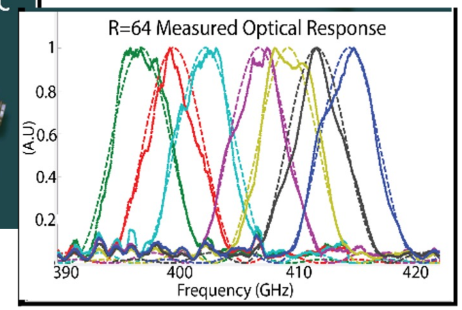


μ-Spec Integrated Spectrometer Technology

EXCLAIM R=512 Design, 36 x 59 mm silicon chip







G. Cataldo, Applied Optics, 53(6), 1094, 2014
O. Noroozian et al., 26th Intern. Symp. Space THz Tech., 2015

- μ-Spec integrates a Rowland grating spectrometer on a single-crystal silicon chip.
- A synthetic grating is formed from meandered Nb superconducting microstripline to introduce a linear phase delay gradient.
- A 2-D parallel plate waveguide region serves as a spatial beam combiner and focal plane.

Design Lead: Emily Barrentine/NASA Goddard

Current NASA Goddard μ-Spec Team::
Berhanu Bulcha, Giuseppe Cataldo, Jake Connors, Nick Costen, Negar Ehsan, Tom Essinger-Hileman, Jason Glenn, Jim Hays-Wehle, Larry Hess, Vilem Mikula, Mona Mirzaei, Jonas Mugge-Durum, Omid Noroozian, Trevor Oxholm/U-Wisconsin, Maryam Rahmani, Samelys Rodriguez, Thomas Stevenson, Eric Switzer, Carolyn Volpert, Ed Wollack

Concept: S. Harvey Moseley 2011-2019

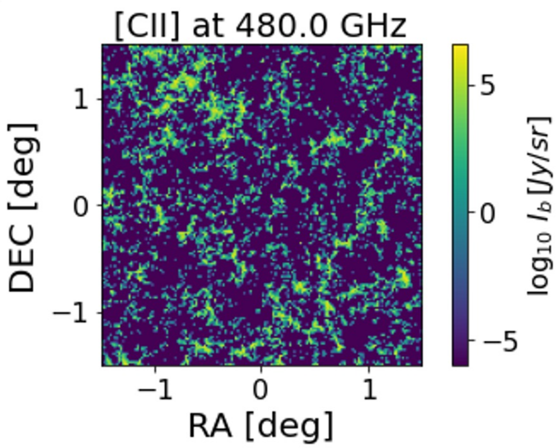
Simulation Pipeline:

Time-ordered-data to Mapmaking

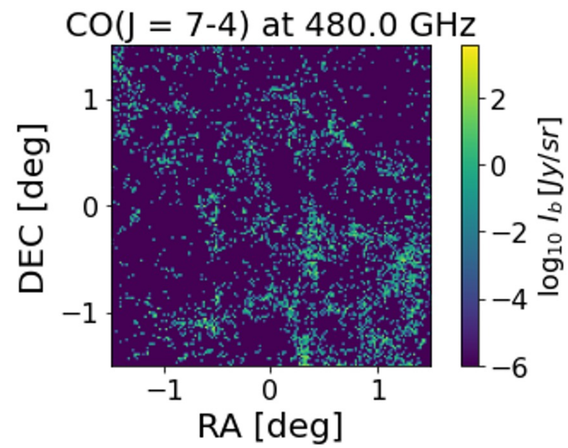
Faizah Siddique
Physics PhD student
University of Wisconsin Madison

Theory Science Maps

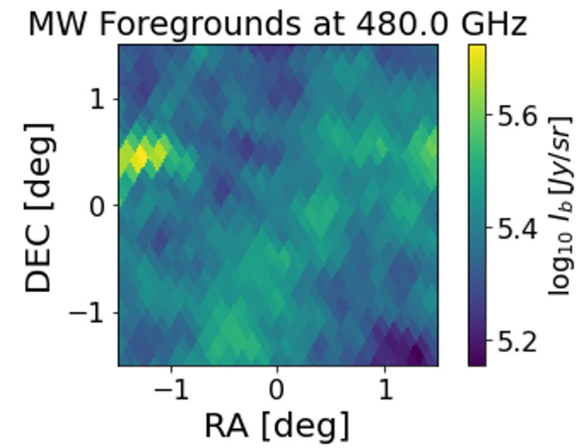
(z = 2.5 - 3.5)

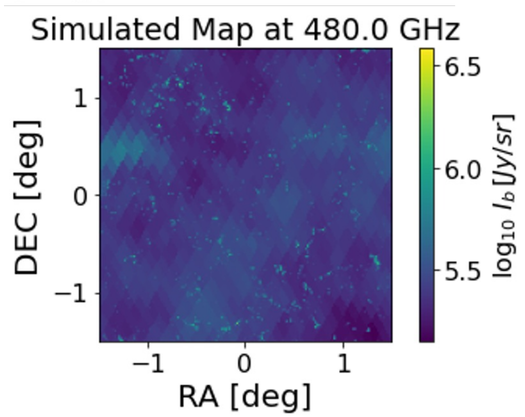


(z = 0.1 - 1.0)
CO(7-4) = CO(7-6) + CO(6-5) + CO(5-4)



(Planck data)



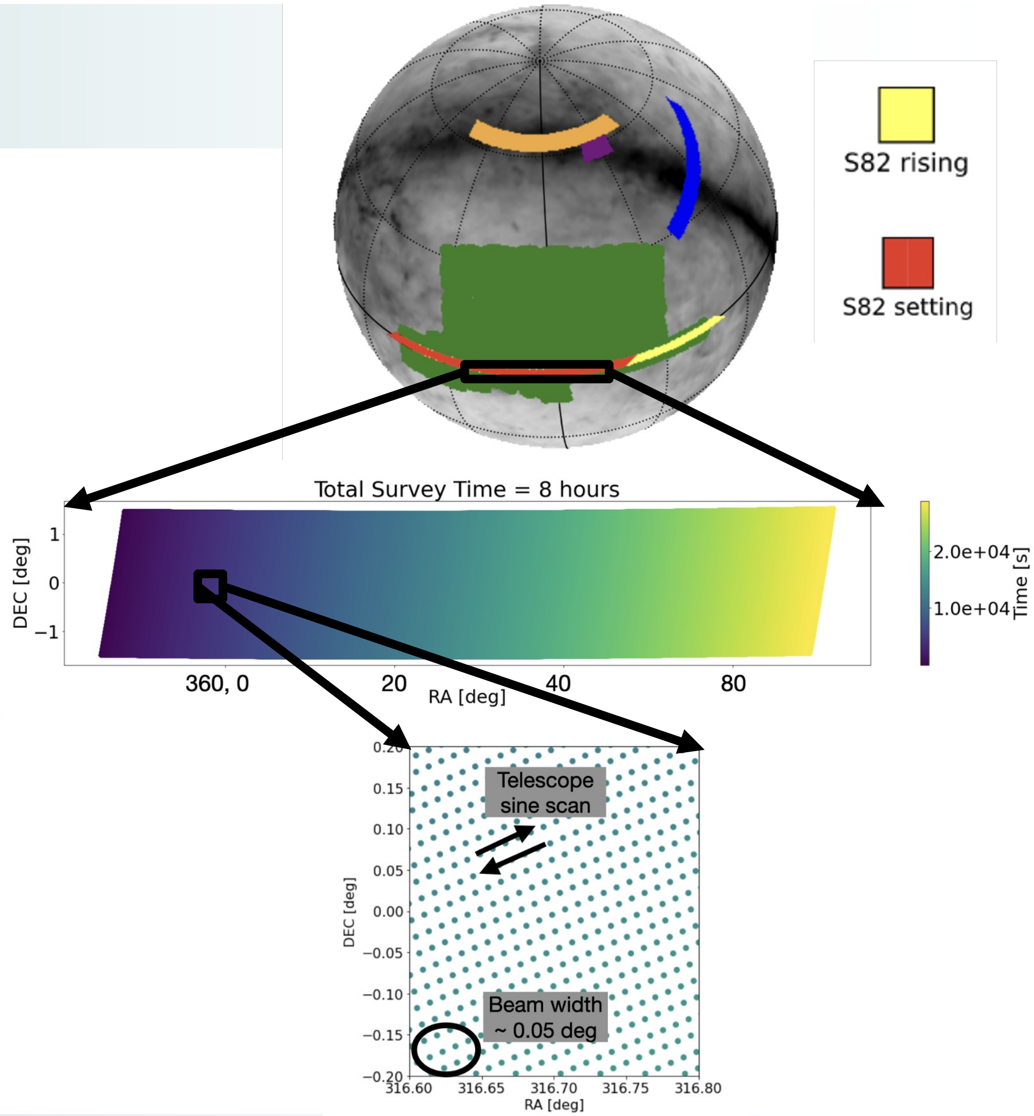


Maps generated using limlam-mocker - A package for LIM mapping (G.Stein, D. Chung):

- mass-Peak Patch halo catalogues from CITA (G. Stein 2018, D. Chung)
- Min halo mass ~2.5e10 M-solar
- [CII] → (Padmanabhan 2019)
- CO → (Li 2016 / Keating 2020)
- Generally, $I_{[CII]} > I_{CO}$ over 420 - 540 GHz

Survey Strategy

- **Generate a time-series** (beam pointing location at each sample step).
- **Scan strategy:** sine scanning pattern with a 7-deg peak-to-peak throw with a period of 14-sec as it drifts in the azimuthal direction at fixed elevation.
- **Sampling rate:** 488 Hz.
- **Beam-width:** Gaussian beam of 3.5 arcmin (~0.05 deg).
- **Used in calculating a pointing matrix M,** which is needed for mapmaking.



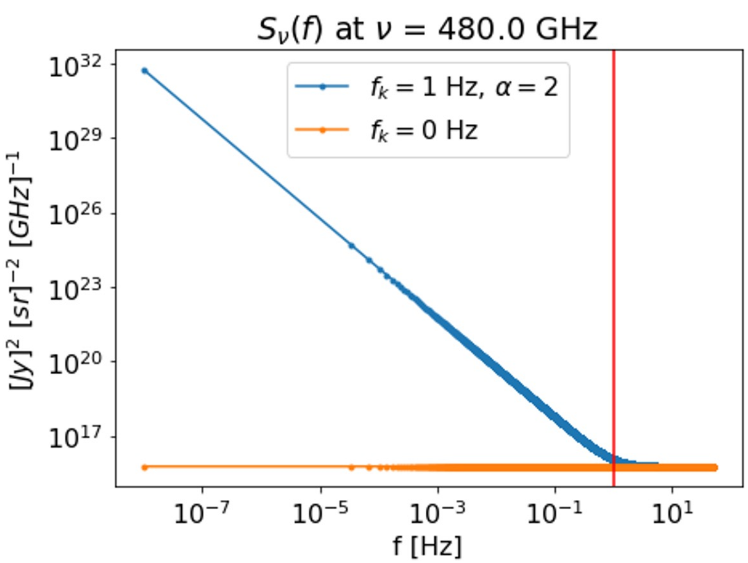
Simulated region: 8 hour observing time covering approx. 300 deg^2 overlapping Stripe-82, ±1.5 deg in DEC, and ~315 deg < RA < 90 deg.

Calculate Noise Timestream (white + 1/f)

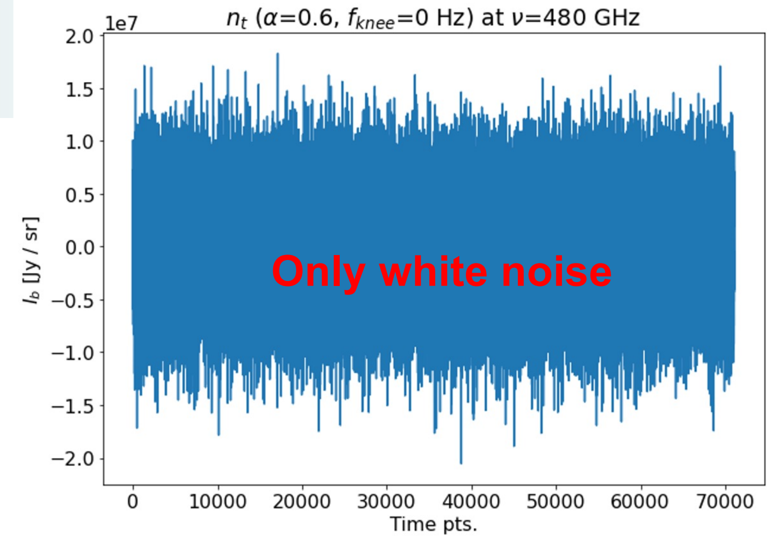
A simple model for the noise that assumes a diagonal $C_{\nu\nu'}$ (modified from (Li et al. 2023)):

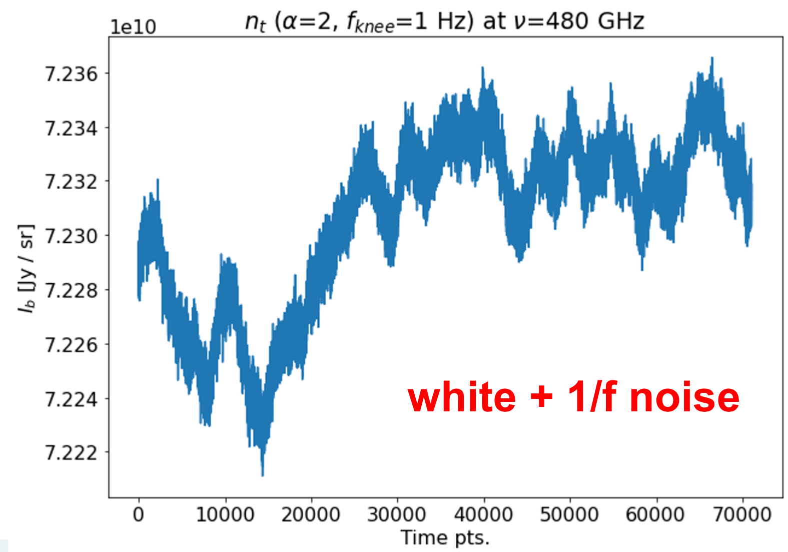
$$\left\langle \delta X_\nu(f) \middle| \delta X_{\nu'}(f') \right\rangle = S_{\nu\nu'}(f)\delta(f-f')$$

$$S_\nu(f) = \frac{C_{\nu\nu'}}{\delta\nu}\left(1+\left(\frac{f_k}{f}\right)^\alpha\right)$$



https://arxiv.org/pdf/2302.02683





Forecasting Science Results from Simulated Maps

Sam Kramer
Physics PhD student
University of Wisconsin-Madison

Simulation & Analysis Considerations

Complete simulations and real data include:

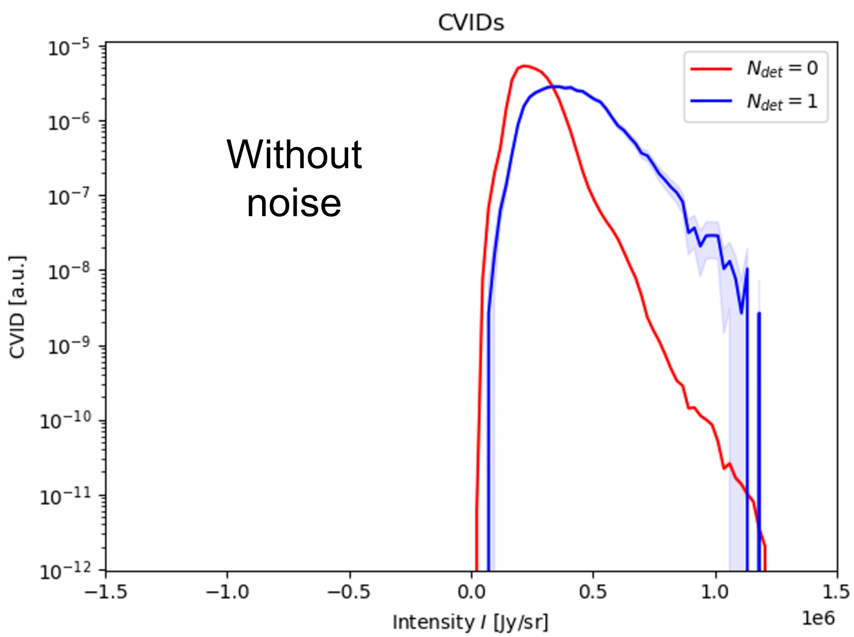
- Interloper lines (~10^4 Jy/sr)
  - CO, [CI], O_2, etc.
  - Small scale clustering
- Galactic foregrounds (~10^5 Jy/sr)
  - Continuum emission from Milky Way
  - Large scales
- Instrument noise
  - Likely overpowers the signal

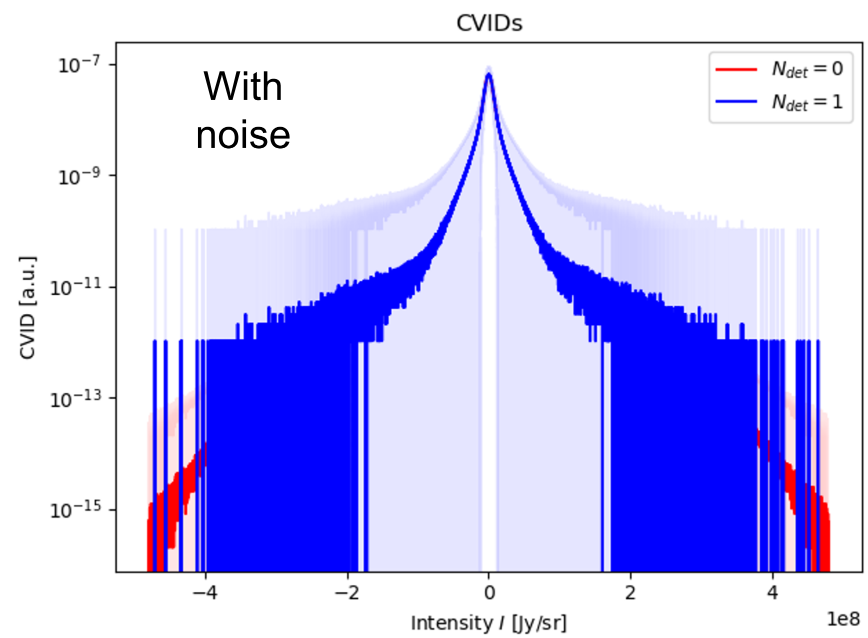
How do we isolate the [CII] signal (~10^6 Jy/sr)?

- Cross-correlation with (e)BOSS quasar survey
- Quasars correspond to halos hosting galaxies most likely to be bright in [CII] due to mass
- Techniques
  - **Conditional voxel intensity distribution**
  - **Stacking**
  - **Cross power spectrum**
- Can also be applied to CO as signal, likely much weaker

Conditional Voxel Intensity Distribution (CVID)

$$\mathcal{P}(I|N_{\rm det}) = \mathcal{P}_{\rm CII}(I|N_{\rm det}) \circ \mathcal{P}_{\rm CO}(I)$$



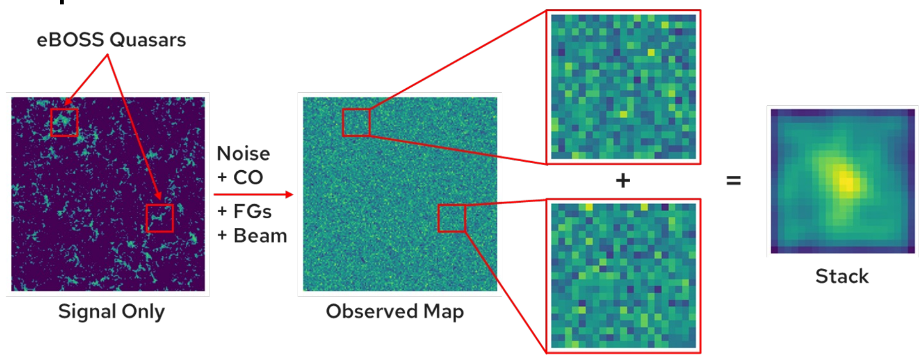


- Using ratio of Fourier-transformed CVIDs, one can remove uncorrelated fields (Breysse + 2019)
  - Simulation forecast under construction/review

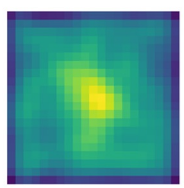
Stacking

EXCLAIM stacking steps:

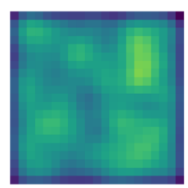
1. Stack using eBOSS quasars



1. Sum luminosities of central voxels
2. Detect [CII] by comparing quasar stacks to random stacks:



vs.

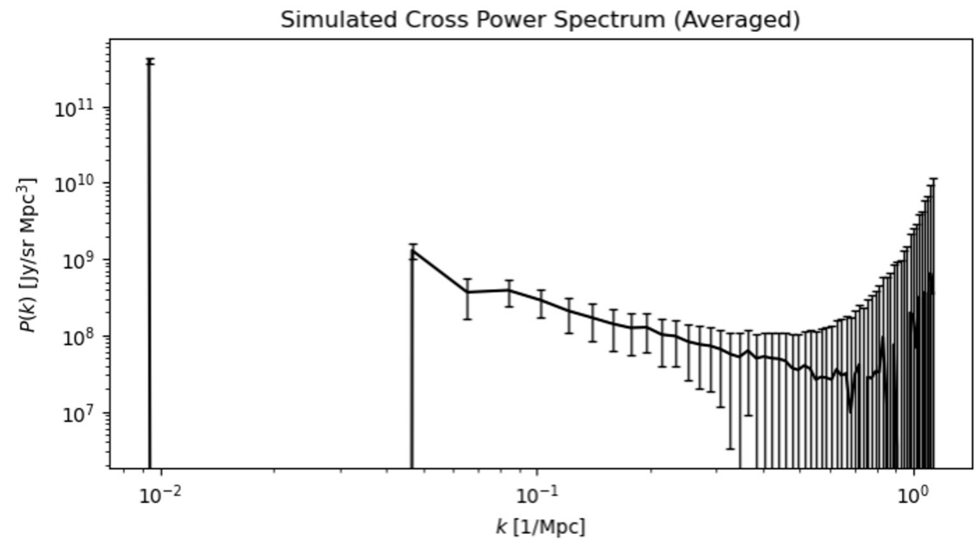


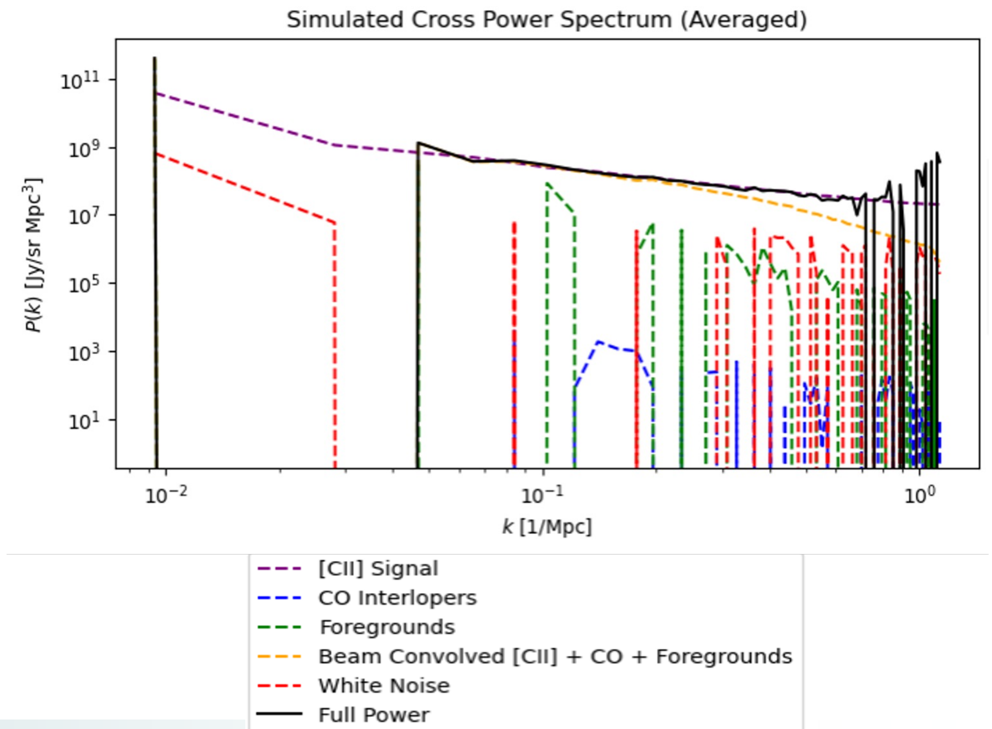
⇒ SNR = 3-5 (preliminary)

1. Constrain [CII] emission models through MCMC, currently under construction

Cross Power Spectrum

- Cross-correlate with BOSS quasars
- ~40 2.5° × 3° patches across full S82 with individual power spectra
- Preliminary simulation forecast SNR: <15





Summary

- Ballooning and integrated spectrometers provide a niche for testing technology and survey approaches for future space applications, including intensity mapping surveys.
- EXCLAIM employs a Rowland-analog integrated spectrometer (420-540 GHz, R=512) from a balloon-borne cryogenic telescope and is designed to make a definitive follow-up of early indications of [CII] emission (z = 2.5-3.5) from Planck data, as well as constraining CO (z<1).
- EXCLAIM plans a conventional (1-day) flight from Ft. Sumner, NM in Fall 2025. Key hardware is being fabricated and integrated now.
- Studies of emission lines over the history of the universe illuminate the complex evolution of stars and galaxies in the background cosmology.
- Intensity mapping 1) provides a means to study line emission when individual galaxy detection is not possible, 2) increases the reach of smaller instruments, 3) provides a complementary view of integrated populations and cosmological clustering.
- Simulating [CII] and CO intensity maps is an important step towards preparing for the flight. These maps are made using simulated time-ordered-data (which includes [CII], CO, Galactic Foregrounds, and noise) and mapmaking.
- Using cross-correlation techniques like stacking, the CVID, and cross power spectra, EXCLAIM seeks to detect [CII] and CO and constrain their emission models.