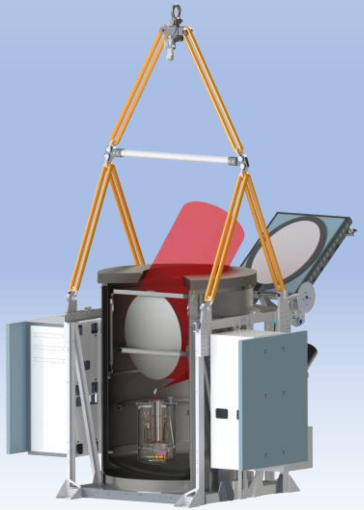
The Experiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM):

A sub-mm experiment using micro-spectrometers to unveil star formation history via intensity mapping.



Maryam Rahmani
on behalf of EXCLAIM Collaboration

Line_Intensity Mapping Workshop
April 18-21, 2023
Max Planck Institute for Astrophysics
Garching, Munich, Germany

MISSION

Science Forecasts

Map both [CII] and CO, including coverage of adjacent CO ladder emission at common z. **R=512 420-540 GHz, ~300 deg^2, BOSS Cross-correlation.**

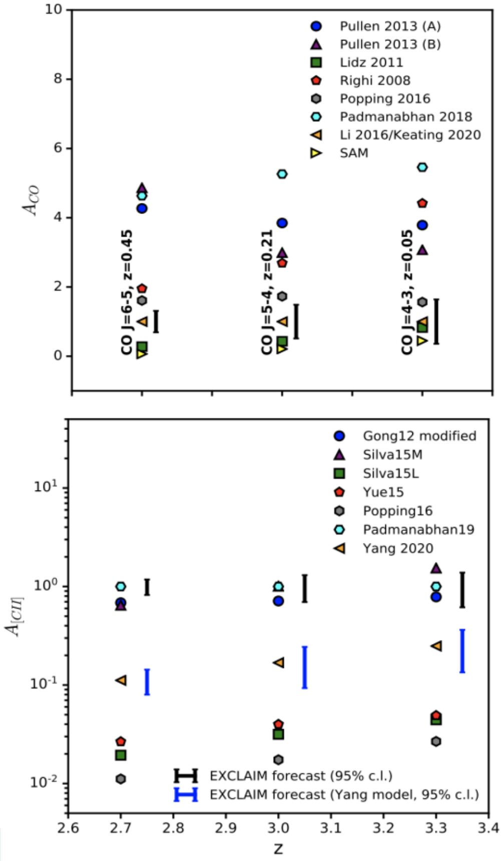
[CII]: BOSS QSO correlation for 2.5 < z < 3.5. Definitive test of [CII] brightness in *Yang+ 2019*. What is the [CII]-SFR relation? See *Padmanabhan 2019* for interpretation.

CO:

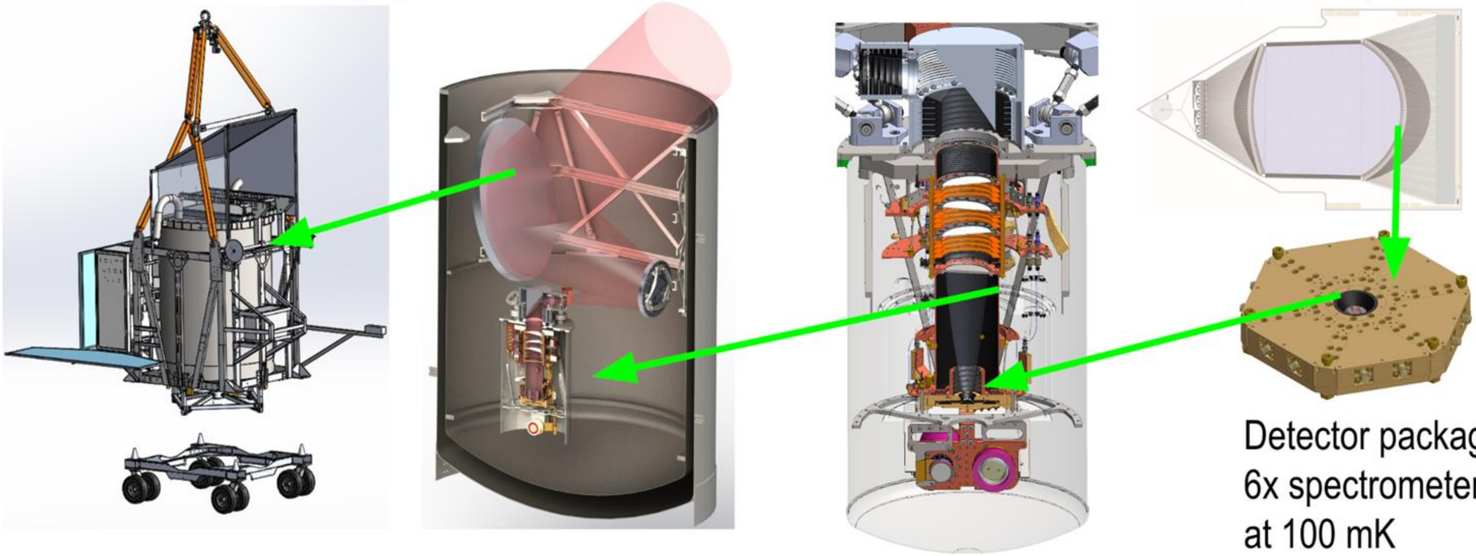
- MAIN 0 < z < 0.2 for J=5-4, J=4-3
- LOWZ 0.2 < z < 0.4 for J=6-5, J=5-4
- CMASS 0.4 < z < 0.7 for J=7-6, J=6-5
- eBOSS for z > 0.7 and higher J?

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. [CI] of interest because it contains ~⅓ of H_2 gas but no CO emission. *Wolfire+ 2010, Burton+ 2015.*



Instrument Overview



Balloon-borne cryogenic telescope

Receiver

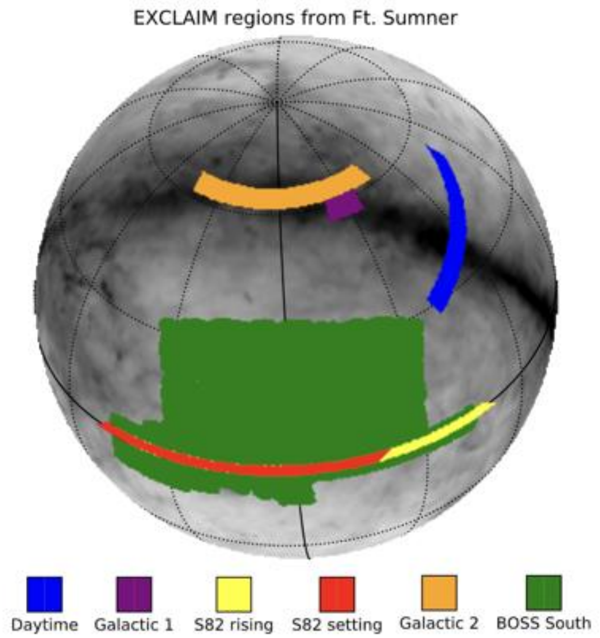
On-chip MKID spectrometer

Detector package
6x spectrometers
at 100 mK

Switzer et al., J. Astron. Telesc. Instrum. Syst. 7(4) 044004, 2021

Strategy

- **Cross-correlation with BOSS for primary science, CII z~3, CO 0<z<1.**
- Large area: Cross-correlation can/should go **wide (more isotropic volume)**; in contrast, 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**
- **Conventional flight** from TX or NM: well-matched to BOSS regions, simple logistics, high recovery rate, regular flight opportunities. Start: 4/2019, flight 2024
- **Versatile platform** for testing FIR spectrometer technology in space-like environment.

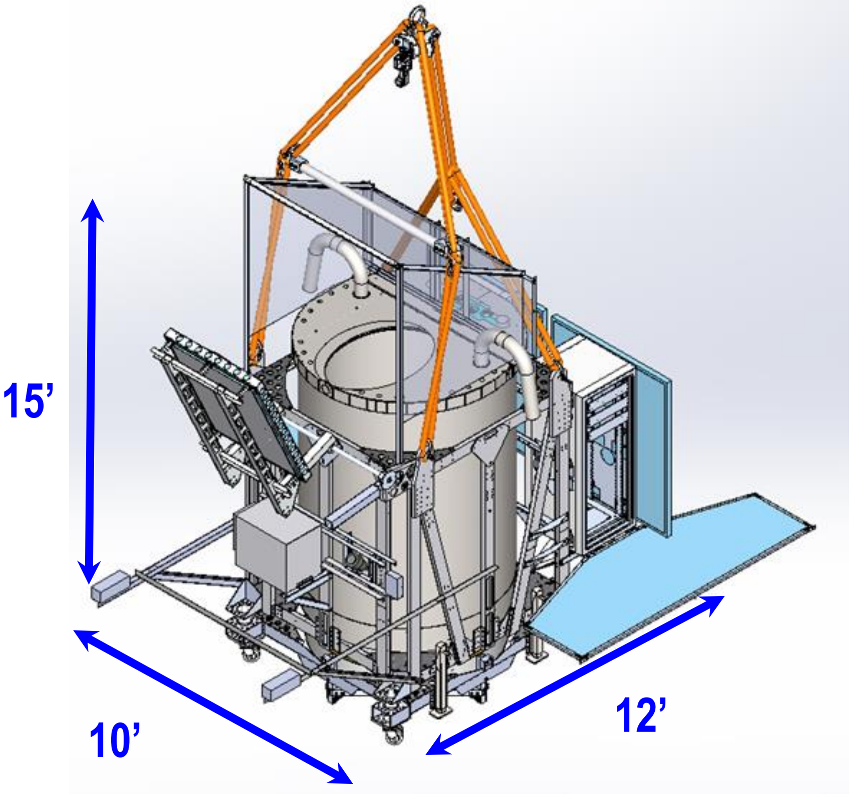


Parameter	Symbol [unit]	Value
Observed frequency range	$\nu_{\rm obs}$ [GHz]	420–540
Observed wavelength range	$\lambda_{\rm obs}$ [μm]	555–714
Spectral resolution	$R = \nu/\Delta\nu$	512
Beam FWHM at 480 GHz	$\theta_{\rm FWHM}$ [arcmin]	4.33
Sky Area (Extragalactic, GP)	Ω [deg^2]	305, 100
Number of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

Preliminary survey plan (all local time)

Daytime field anti-solar scan, 200 deg^2, crosses the galactic plan	Galactic field 1	BOSS S82 field rising 305 deg$^{2'}$	BOSS S82 field setting	Galactic field 2
3PM -6PM	6PM – 7PM	7PM – 1AM	1AM – 5:30 AM	5:30AM - 7AM

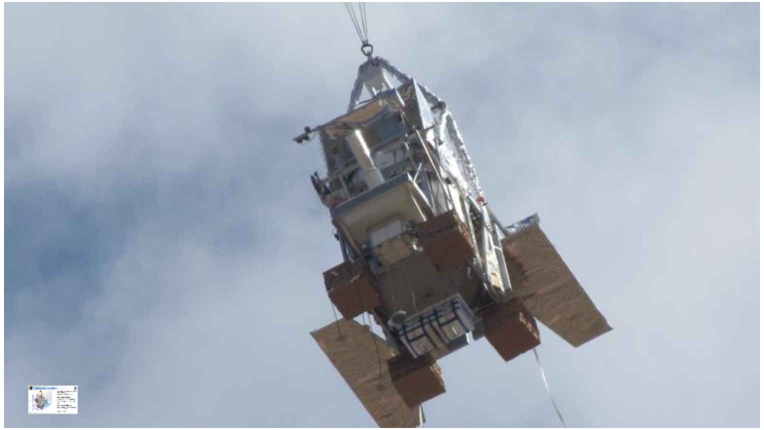
Payload and Mission Overview

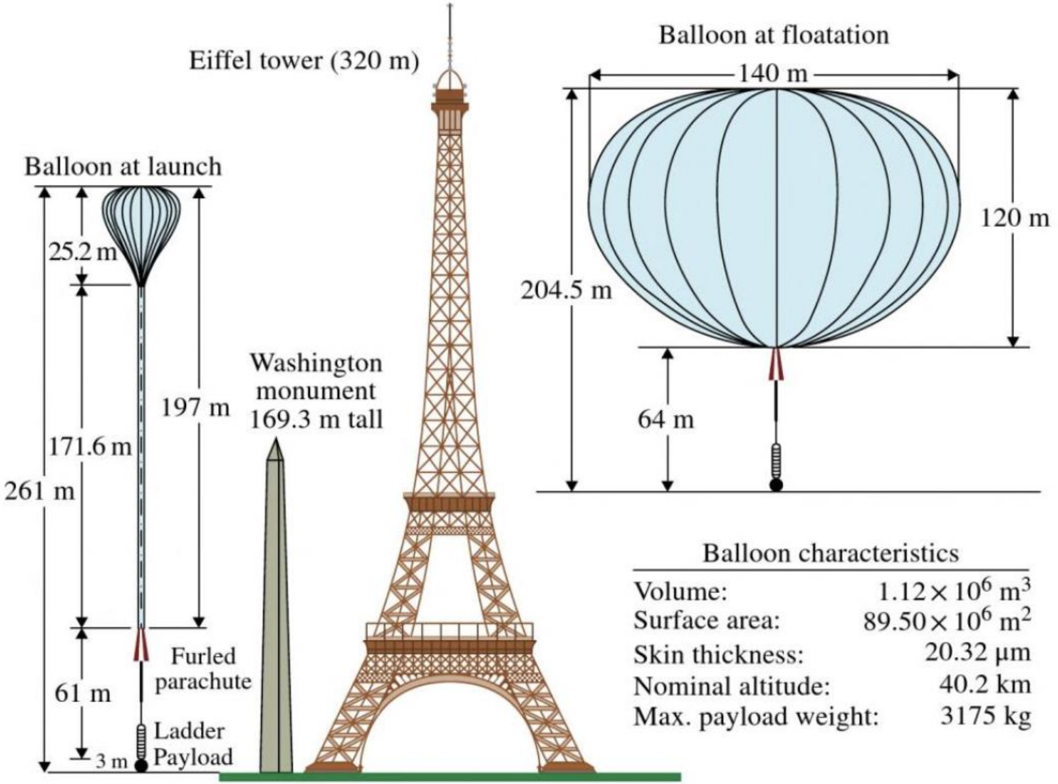


- Conventional (e.g. 1-day) flight (Ft. Sumner, NM, primary, Palestine, TX, secondary).
- 3500 l LHe Bucket dewar. Deployable cover.
- ~2400 kg dry mass, 11/34 MCF balloon.
- ~2000 l LHe fill gives 18 hr of 1.7 K operation at float.
- Superfluid fountain effect pumps cool optics to 1.7 K (Kogut+ 2021).
- 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.

BALOONING

NASA Ballooning





Balloon characteristics

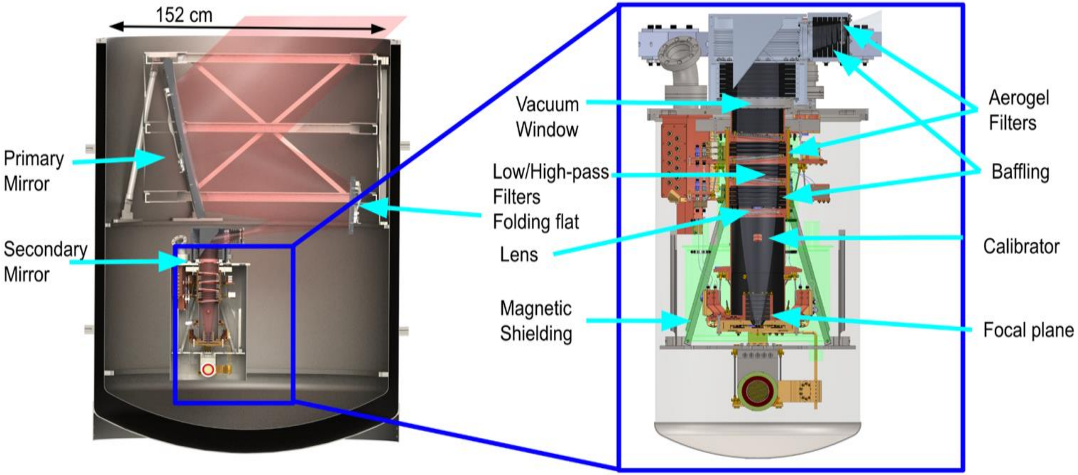
Volume:	1.12×10^6 m^3
Surface area:	89.50×10^6 m^2
Skin thickness:	20.32 µm
Nominal altitude:	40.2 km
Max. payload weight:	3175 kg

https://sites.wff.nasa.gov/code820/pages/outreach/outreach-public.html

OPTICS

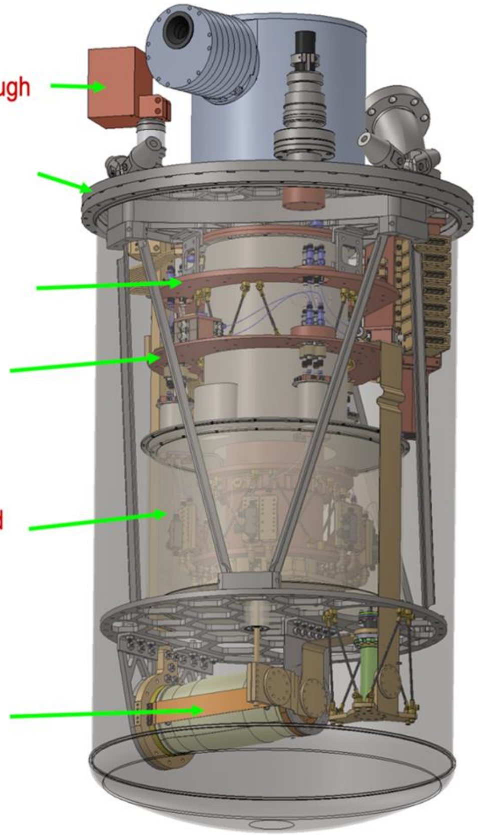
Optics

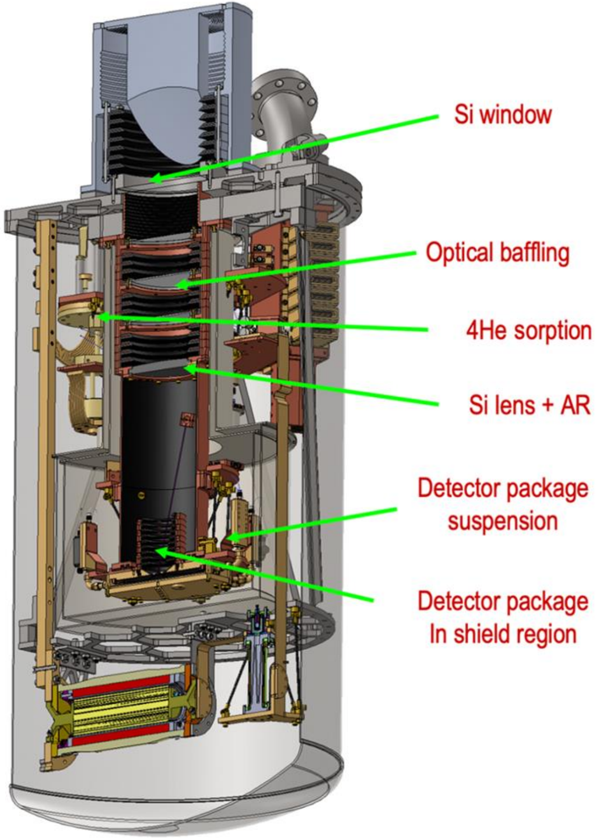
- The telescope employs a 90 cm parabolic primary mirror, 30 cm flat fold mirror, and 10 cm parabolic secondary mirror in an off-axis Gregorian configuration (all aluminum)
- The F/1.5 reflectors feed a single Si lens through a stop which couples light onto the on-chip spectrometers.
- The stop controls 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 silicon with metamaterial anti-reflective coating.



Switzer+ 2021 JATIS DOI 10.1117/1.JATIS.7.4.044004

Receiver Overview

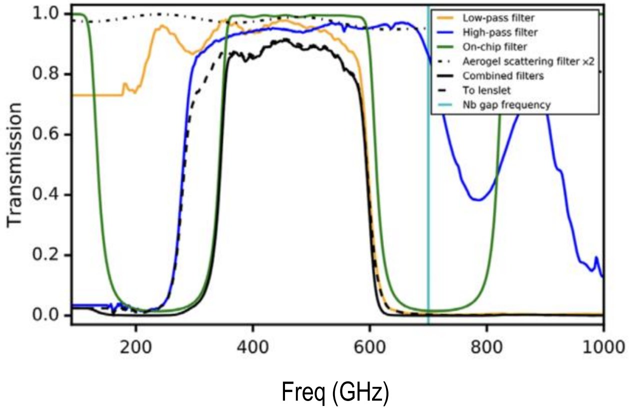


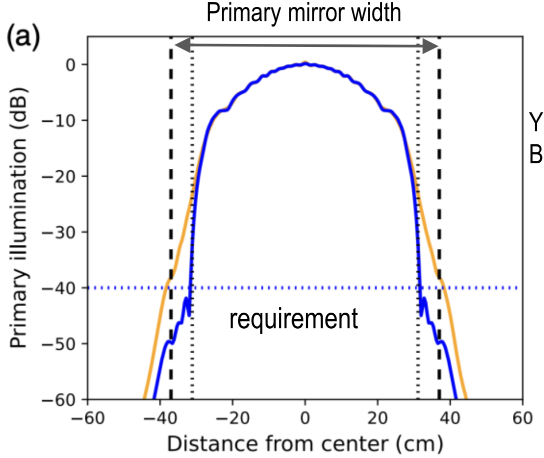


Band selection and straylight control

- Target: sensitivity to 0.1 fW signals.
- Out-of-band spectral orders controlled by Cardiff metal mesh filters and on-chip order filter.
- Aerogel filters are employed to block IR light.
- Transmission >700 GHz negligible (Nb pair-breaking makes the transmission lines opaque), but stray light coupling directly to KIDs is controlled by absorbing baffles.

- To achieve the target EXCLAIM sensitivity in dark atmospheric windows, diffracted spill onto warm surfaces must be carefully controlled (-40 dB in solid angle)
- The EXCLAIM optics were designed from the ground up with control of stray light in mind.
- Analysis by Tom Essinger-Hileman, Trevor Oxholm*, Peter Timbie, Gage Siebert*, Eric Switzer.



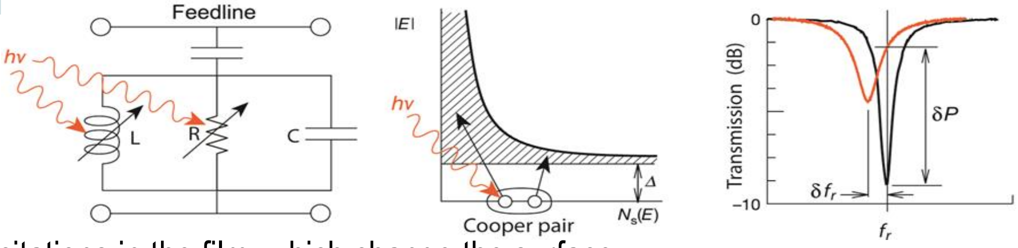


Yellow: without baffles
Blue: With baffles

Switzer+ 2021 JATIS DOI 10.1117/1.JATIS.7.4.044004

Detector

Microwave Kinetic Inductance Detectors (MKIDs)



- Microwave Kinetic Inductance Detectors (MKIDs) are superconducting thin film (microwave) resonators.
- Photons break bound 'Cooper pairs' electrons in the superconductor and create quasiparticle (normal-electron) excitations in the film, which change the surface impedance of the film. This leads to a change in resonance frequency and loss.
- They are readout out with a microwave tone on resonance via a microwave feedline. KIDs are therefore, intrinsically adapted for frequency multiplexing, and appealing for use in next-generation detector arrays.

EXCLAIM MKID Design Features

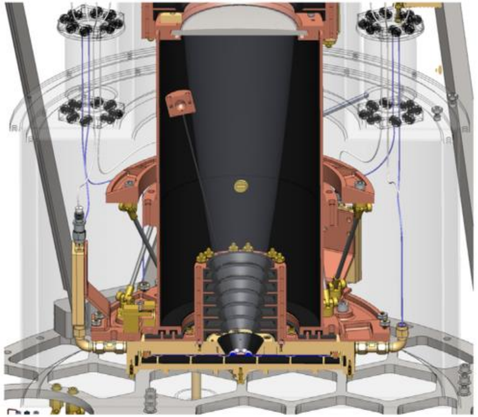
- Aluminum (top absorber) / niobium (ground plane)
- high immunity to stray light.
- Al superconducting films follow well-predicted superconducting theory.
- Lower microwave loss due to using a single-crystal-silicon rather than deposited dielectric.
- High internal microwave quality factors ~ 2-7 million fabricated in Goddard's Detector Development Laboratory (DDL)
- Sufficient high quality factor Q of the Nb films fabricated via liftoff process

EXCLAIM u-Spec

Light from collimated receiver path brought to focus at f/3 onto 6 spectrometers.

6 lenslets packed into hexagon.

Capability for single 6” wafer with 6 spectrometers or 6 individually-characterized chips.



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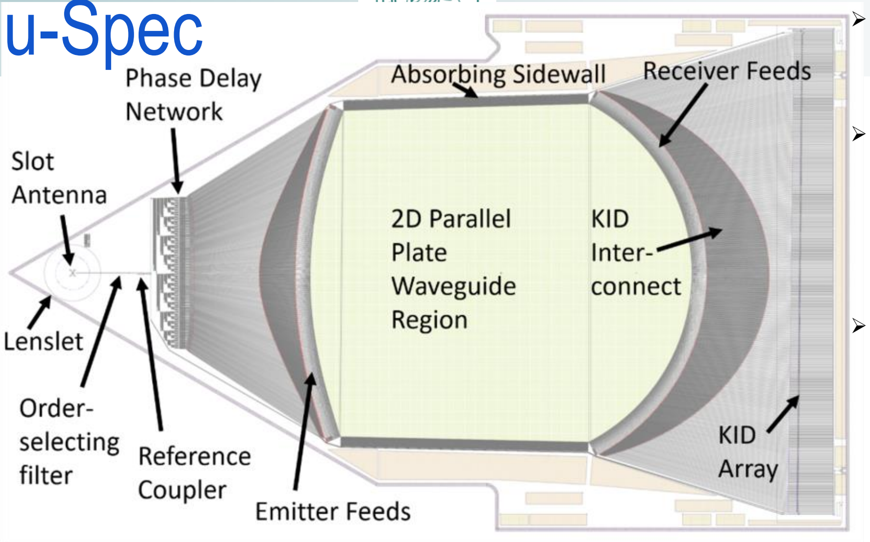
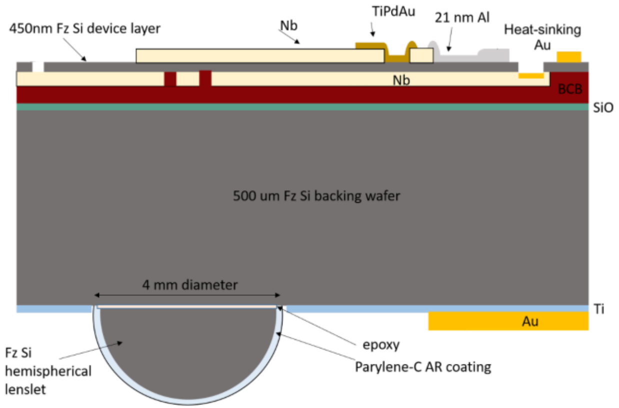


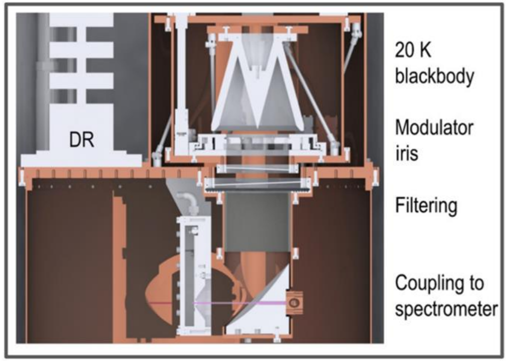


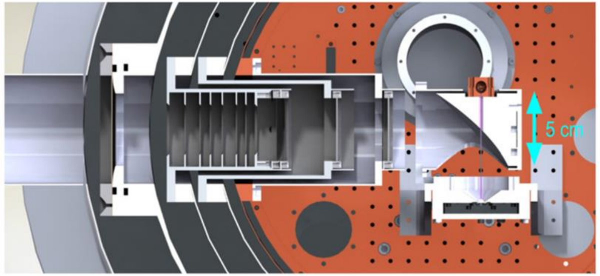
- μ-Spec integrates a Rowland grating spectrometer on a single-crystal silicon chip.
- A synthetic grating is formed from meandered Nb superconducting microstripline to introduce a linear phase delay gradient.
- A 2-D parallel plate waveguide region serves as a spatial beam combiner and focal plane.

Single spectrometer test package and mechanical test chip

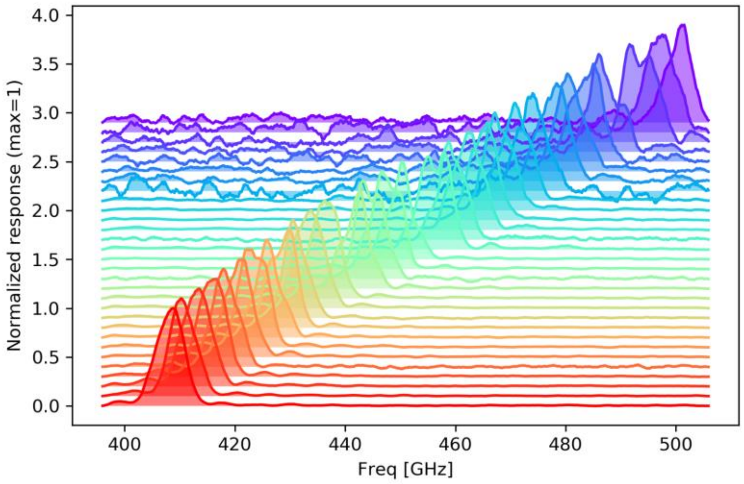
Spectrometer characterization

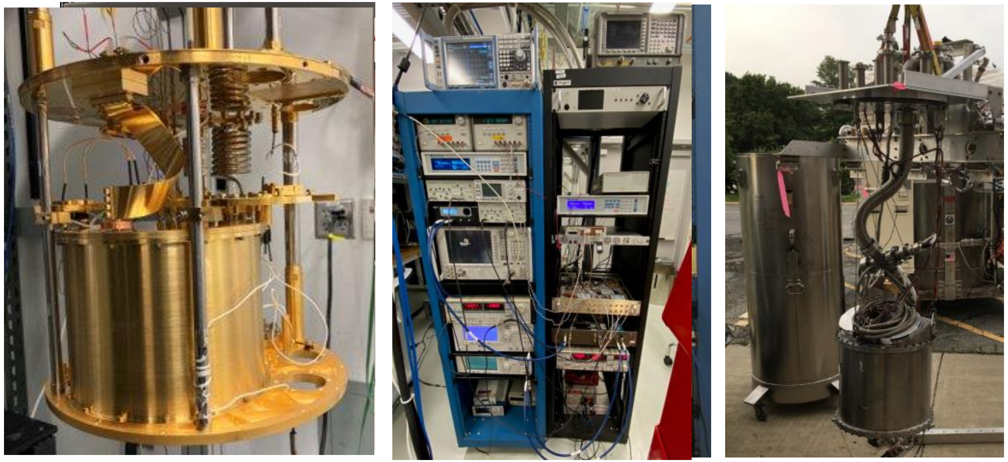
- Spectrometers characterization and qualified in dilution refrigerator.
- Blackbody source measures efficiency and NEP. Photomixer measures spectral response.
- ROACH+IF and VNA characterizing resonators.
- Integrated receiver testing in flight-like (superfluid bath)
- Perform characterization of R64 prototype:





Optical coupling to photomixer swept-line source.



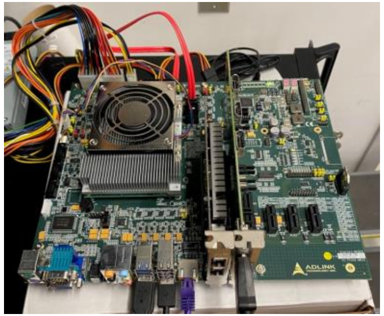


BB integrated into DR system, readout rack and flight-like test facility (PIPER test)

ELECTRONICS

Flight electronics and ADCS

- Power and survival heater control boxes
- Star camera field test with flight software; fixing star solutions on sky
- Packaged magnetometer and clinometer reading out.
- Flight software implements closed loop control in mission-level simulator.
- Proto-flight computer uses flight processing unit, primary system running detector readout and ADCS.
- Rotator and reaction wheel support frame.

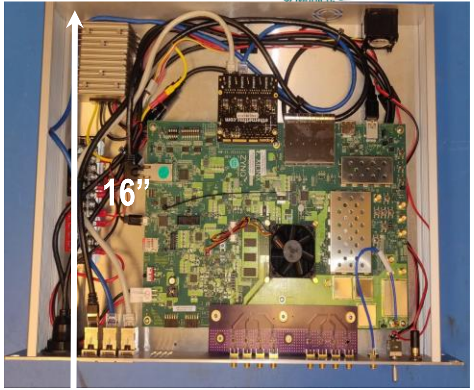


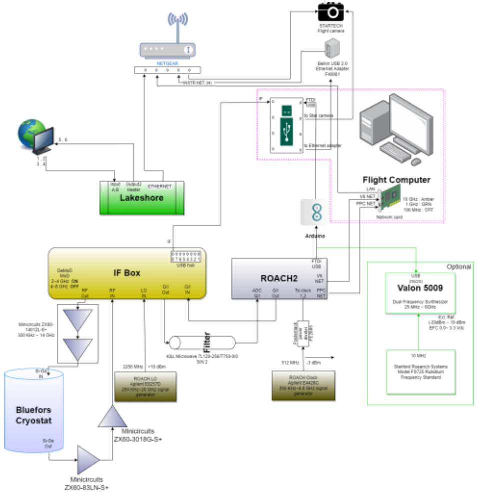
Readout

Line-intensity mapping (LIM)
April 18-21, 2023
Garching, Munich, Germany

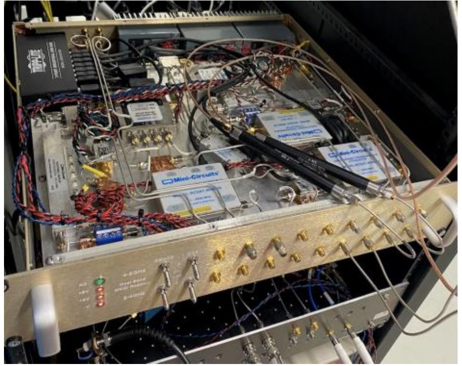
ASU’s RFSoC readout ETU, 1x Xilinx RFSoC ZCU111, reads two spectrometers.

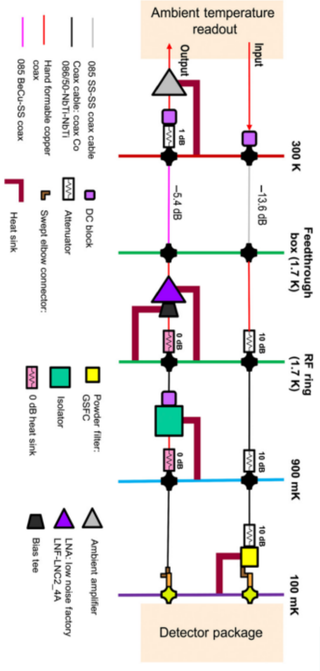
- The readout process utilizes an IF-Box, a cold prototype u-Spec (R64) mounted in a DR, the ASU’s RFSoC / ROACH2
- The resonance frequency of the resonators in the lab are identified by a VNA frequency sweep.
- After tuning the power levels, a 1000 tone comb is generated and measures the resonator Qs.





IF-Box 2~4 GHz , 4~8 GHz





Bluefors Dilution Refrigerator

summary

EXCLAIM Team

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

Berhanu Bulcha (Resonator design)
Paul Cursey (Machinist)
Negar Ehsan (Antenna design)
Jason Glenn (Receiver, MKIDs)
Larry Hess (Fabrication)
Amir Jahromi (ADR)
Mark Kimball (ADR)
Mona Mirzaei (Fabrication)
Alan Kogut (Gondola)
Luke Lowe (Flight Electronics)
Jacob Nellis (ADR)
Joseph Watson (Mechanical)
Thomas Stevenson (Spectrometer)
Ed Wollack (Spectrometer)
Aaron Yung (Science team)

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

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

ASU: (Readout)
Phil Mauskopf (Readout Lead)
Adrian Sinclair
Kate Okun
Cody Roberson

UWisc: (MKID modelling, forecasting)
Trevor Oxholm, Gage Siebert
Peter Timbie

U Chicago: (Silicon lens AR) Jeffrey McMahon
Cardiff: (Filters) Peter Ade, Carole Tucker
NIST: Jake Connors
UToledo: Eli Visbal

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

Summary

- 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 especially smaller instruments, 3) provides a complementary view of integrated populations and cosmological clustering.
- Intensity mapping has provided insights into HI, CO, and CII emission using existing and (increasingly) new dedicated instruments.
- Ballooning and integrated spectrometers provide a niche for testing technology for future space applications and also conducting intensity mapping surveys.
- EXCLAIM employs a Rowland-analog integrated spectrometer from a balloon-borne cryogenic telescope, and is designed to make definitive follow-up of early indications of CII emission from Planck data.

References

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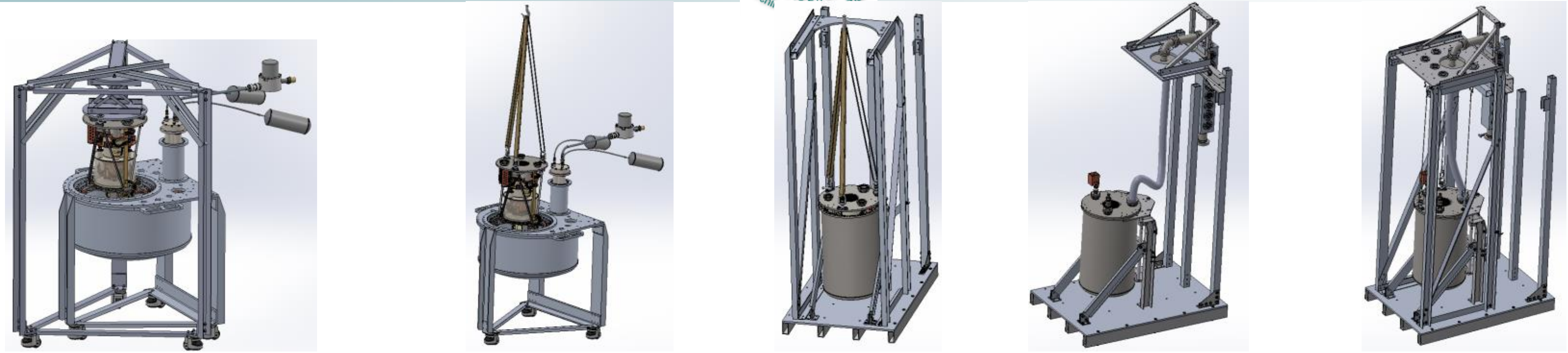
[11] Rahmani, Maryam, et al. "Optical characterization and testbed development for µ-Spec integrated spectrometers." Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave. Vol. 12180. SPIE, 2022.

Thank YOU!

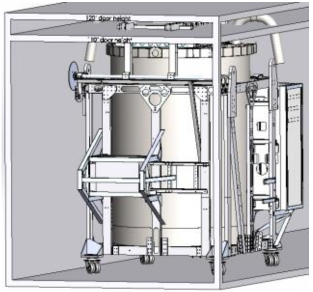
INTEGRATION & TESTING

I&T sequence

Transition to flight-like test

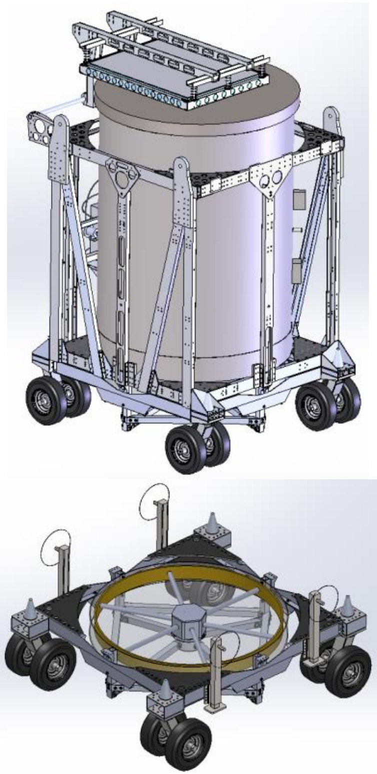


Transition to flight

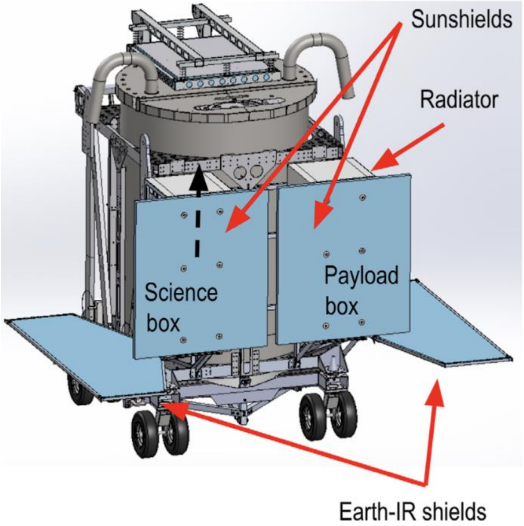


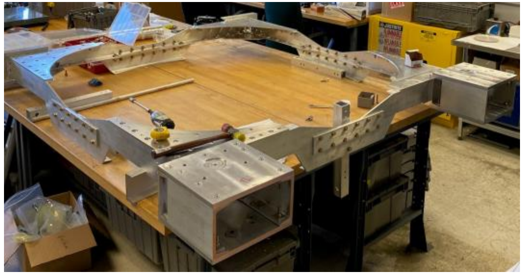
Roll onto truck for shipment and rapid field integration

Flight preparation sequence

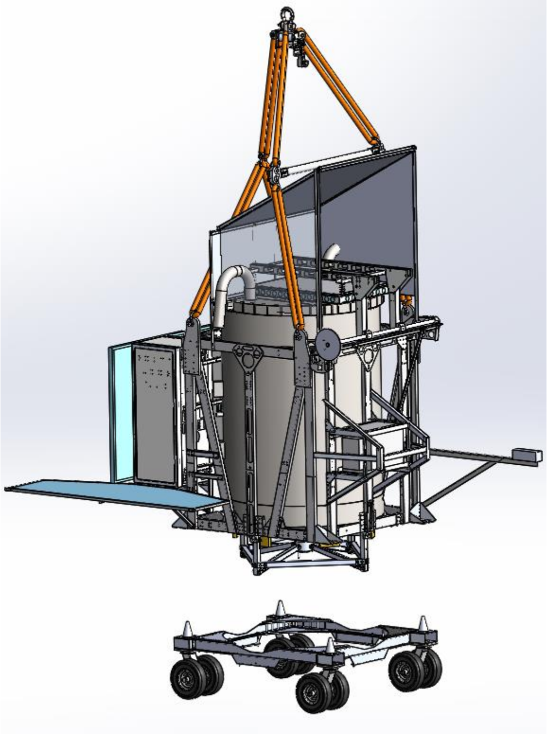


Combine the gondola with reaction wheel and field cart





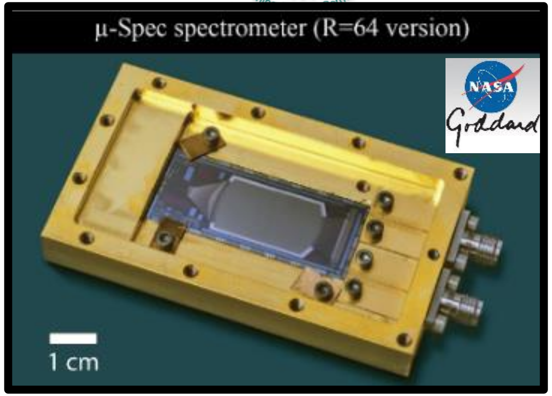
Prepare for flight, fill with cryogens



Lift onto flight train, leaving cart base

Current-generation spectrometers

- On-chip spectrometers integrate all the spectrometer optical elements with detectors, on a silicon-based chip with planar transmission lines, using microfabrication techniques.
- This reduces spectrometer size by at least an order of magnitude compared to free-space spectrometer designs.



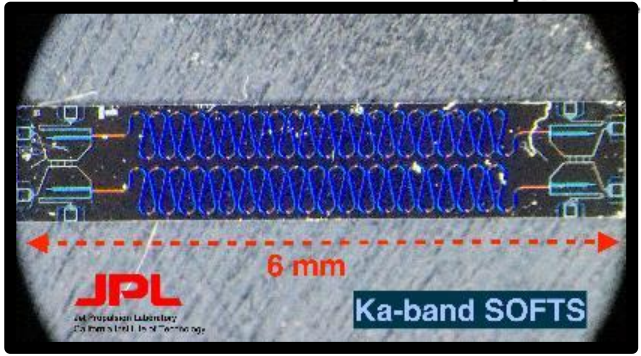


Photo courtesy Ritoban Basu Thakur/Caltech

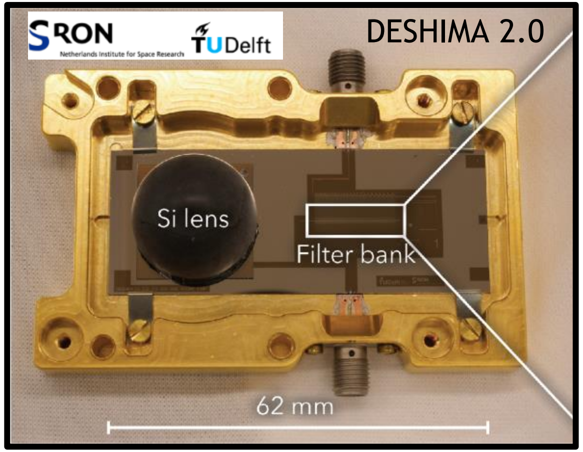


Photo courtesy Jochem Baselmans/SRON

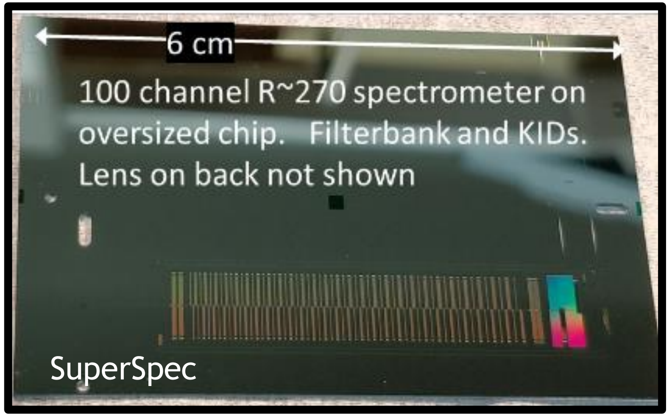


Photo courtesy Matt Bradford & Joseph Redford/Caltech

Integrated spectrometer designs

1. Taniguchi et al., arXiv:2110.14656 (2021)
2. A. Endo et al, Nature Astronomy Letters, Vol.3, 989-996 (2019)
3. Endo et al., J. Astron. Telesc. Instrum. Syst. 5(3), 035004 (2019)
4. Karkare et al. J. Low Temp. Phys. Vol. **199** (2020)
5. Redford et al. Proc. SPIE, Vol. 10708.(2018).
6. Wheeler et al. J. Low Temp. Phys. 193 (2018): 408-414.
7. Wheeler, et al., Proc. SPIE, Vol. 9914 SPIE (2016)
8. Hailey-Dunsheath et al., J. Low Temp. Phys., Vol.**184** (2016)
9. G. Robson et al., https://arxiv.org/pdf/2111.04632.pdf (2021)
10. Karkare, K. S. et al. J. Low Temp. Phys. (2022),
11. Thomas et al, https://arxiv.org/abs/1401.4395 (2014)
12. Zheng et al, Proc. 27th Intern. Symp. Space THz Tech.(2016)
13. Switzer et al., J. Astron. Telesc. Instrum. Syst. 7(4) 044004 (2021) and references therein.
14. Basu Thakur, R. et al., https://arxiv.org/abs/2111.06558 (2021)
15. Basu Thakur, R. et al. J Low Temp Phys 200, 342-352 (2020).
16. Faramarzi, F. B, et al, J. Low Temp. Physics, 199:867-874 (2020)

	Design Approach	R	Wavelength Range [µm]	Transmission Line Materials	Optical Coupling	# in focal plane	# of KIDs per spectrometer	Near Term Science Instruments/ Current Status
DESHIMA [1-3]	Filterbank	380	799-908	NbTiN	Lens-Slot Antenna	1	49 Al KIDs	Atacama Submillimeter Telescope Experiment (ASTE) / First light in telescope in 2017
		500	681-1363	NbTiN & Amorphous Si	Lens-Slot Antenna	1	347 Al KIDs	Atacama Submillimeter Telescope Experiment (ASTE) / In characterization for telescope
SuperSpec [4-8]	Filterbank	270	1000-1500	Nb & SiN	Lens-Slot Antenna	6	100 TiN KIDs	Large Millimeter Telescope (LMT) / Deploying in telescope
SPT-SLIM [9-10]	Filterbank	300	1874-2141 1666-2498	Nb & SiN	Feedhorn-Probe Antenna	36	200 Al KIDs	South Pole Telescope Summertime Line Intensity Mapper (SPT-SLIM) / In development for telescope
CAMELS [11-12]	Filterbank	3000 (design)	2630-2911	NbN & SiO	Waveguide -Probe Antenna	2	256 Ta KIDs	Greenland Telescope (GLT) / In development for telescope
µSPEC [13]	Grating-Analog	512 (design)	555-715	Nb & Si	Lens-Slot Antenna	6	355 Al KIDs	EXCLAIM Balloon / In fabrication for mission
SOFTS [14-16]	FTS	Tunable up to 10,000	2725-11103 150-400 (optical coupling)	NbTiN & SiN NbN & Amorphous Si MgB_2 & SiN	Waveguide -Probe Antenna	60 (balloon design)	2 (KID or TES)	Proposed OLIMPO Balloon / Laboratory prototypes currently in progress

E. Barrentine (EXCLAIM spectrometer lead)

Resolving atmospheric emission

- **Pressure broadening** ~10 MHz/Torr. Spacing between bright lines ~5 GHz. To be in the wings of emission between lines (down 50x FWHM) need < 10 Torr, or >100000 ft altitude. Lines also drop in brightness with increasing altitude.
- To be able to resolve these windows at ~500 GHz, **need R > 500 GHz / 5 GHz = 100.** EXCLAIM goal is a margin of 5, or **R=512**. Flight >120,000 ft (36 km).
- We truncate at 540 GHz to avoid bright ortho-H_2O at 557 GHz.
- A factor of 10 in photon background is 100 in time; 8 hour conventional flight with cryogenic telescope comparable to 33 day flight with warm telescope (LDB).
- ARCADE, PIPER heritage (A. Kogut)

Instrumental niche 350 GHz -1.1 THz (273 um-856 um):

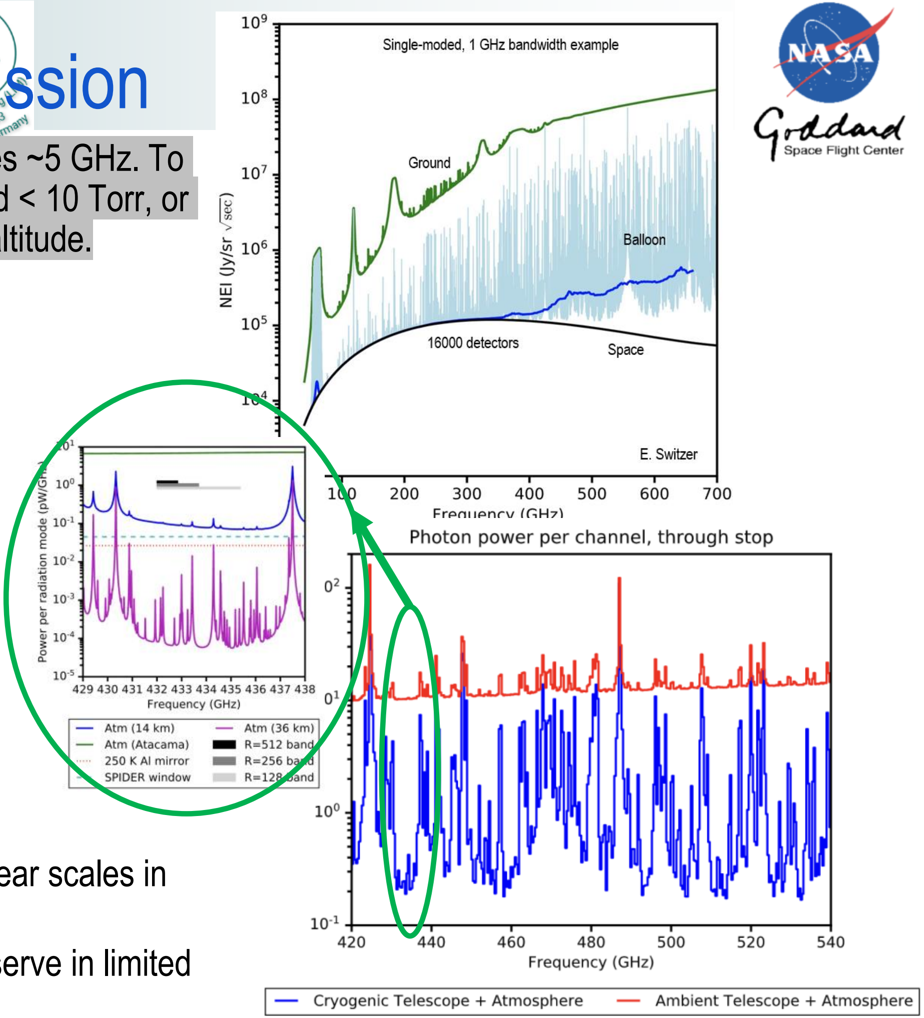
•MKID Materials: NbTiN < 273 um (1.1 THz), Al > ~90 GHz. Note: [CII] 1.9 THz. FTS/Gratings not limited.

•Space optical background dropping off > 300 GHz

•Aperture limits: < 2m budget, implies >200 um prone to confusion, making IM effective alternative for longwave.

•CMB surveys tend to naturally by nearly full-sky, which is ideal for linear scales in IM, cosmic census of gas.

•Ground-based instrument can have many detectors, but may still observe in limited windows. From space: multiple lines over range of redshift.



Significant benefit for cryogenic telescope

Science goals: lines and levels

Map both [CII] and CO, including coverage of adjacent CO ladder emission at common z. **R=512 420-540 GHz, ~300 deg^2, BOSS Cross-correlation.**

[CII]: BOSS QSO correlation for 2.5 < z < 3.5. Definitive test of [CII] brightness in *Yang+ 2019*. What is the [CII]-SFR relation? See *Padmanabhan 2019* for interpretation.

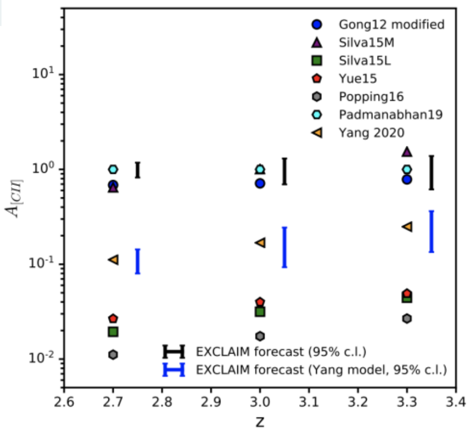
CO:

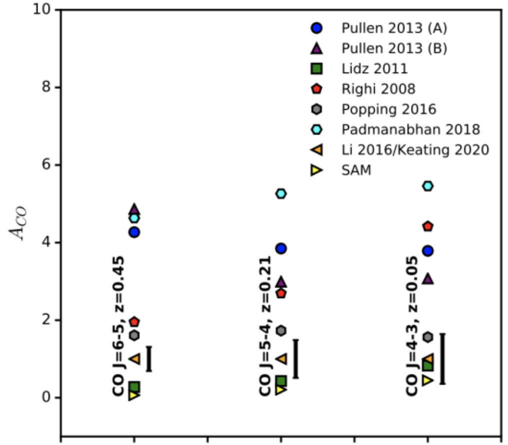
- MAIN 0 < z < 0.2 for J=5-4, J=4-3
- LOWZ 0.2 < z < 0.4 for J=6-5, J=5-4
- CMASS 0.4 < z < 0.7 for J=7-6, J=6-5
- eBOSS for z > 0.7 and higher J?

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

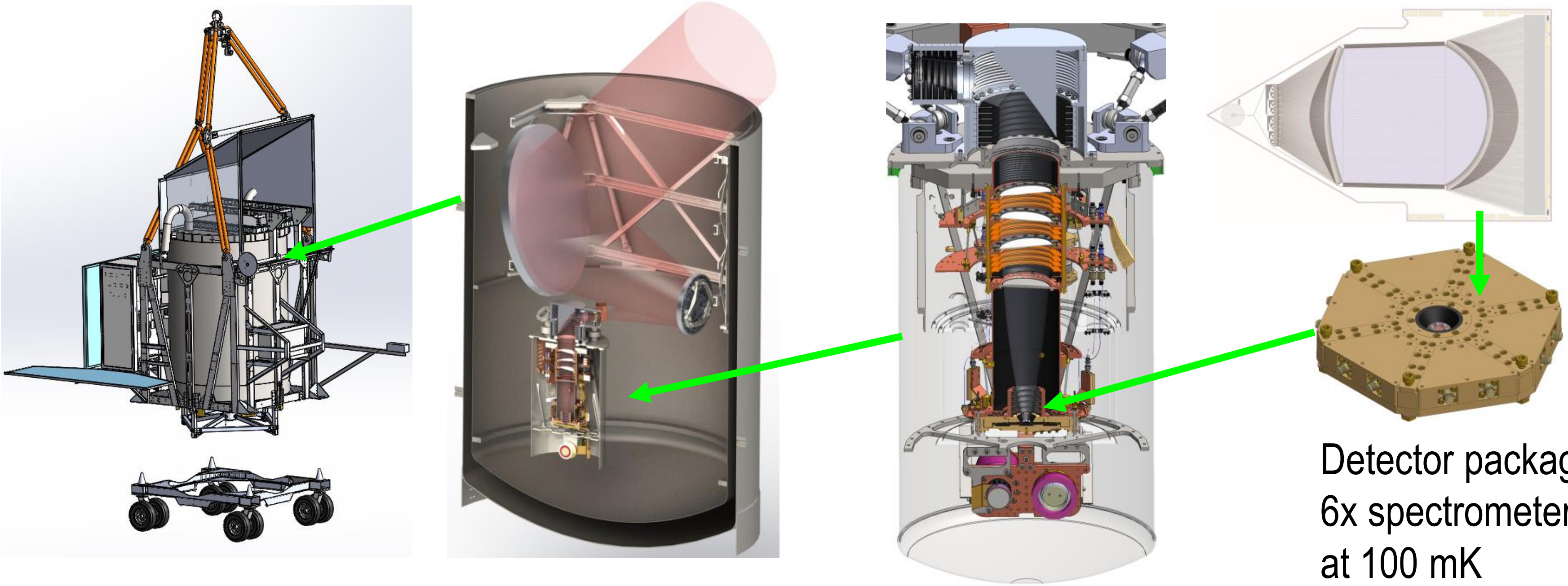
Galactic region: 492 GHz [CI], 460 GHz CO J=4-3, 425 GHz, 487 GHz O_2. [CI] of interest because it contains ~⅓ of H_2 gas but no CO emission. *Wolfire+ 2010, Burton+ 2015.*

Log scale!





Mission System Overview



Balloon-borne cryogenic telescope

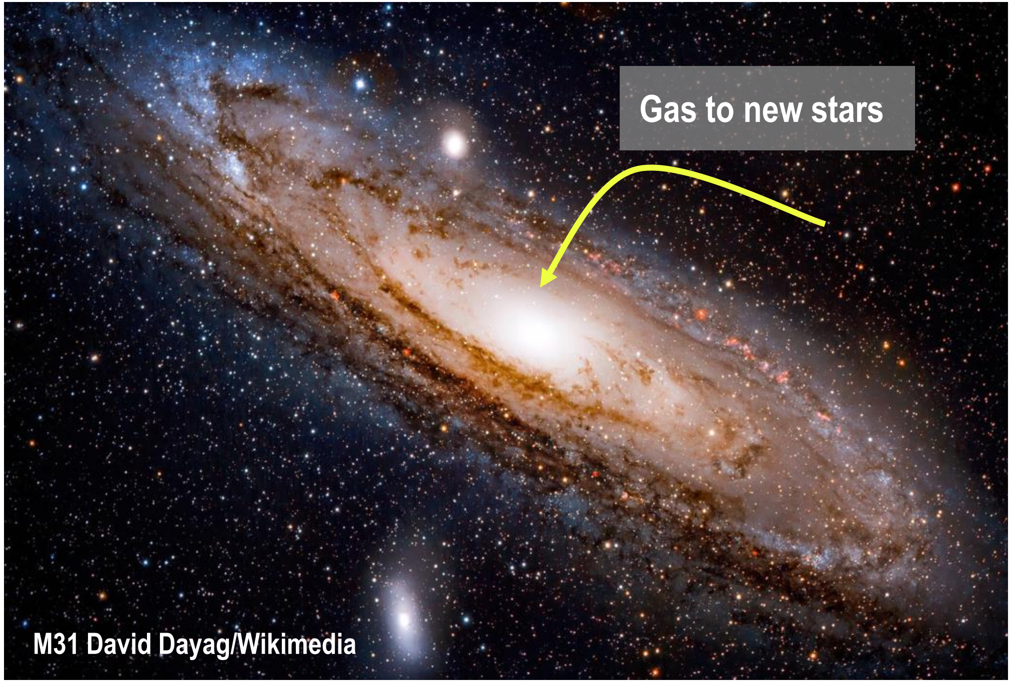
Receiver

On-chip MKID spectrometer

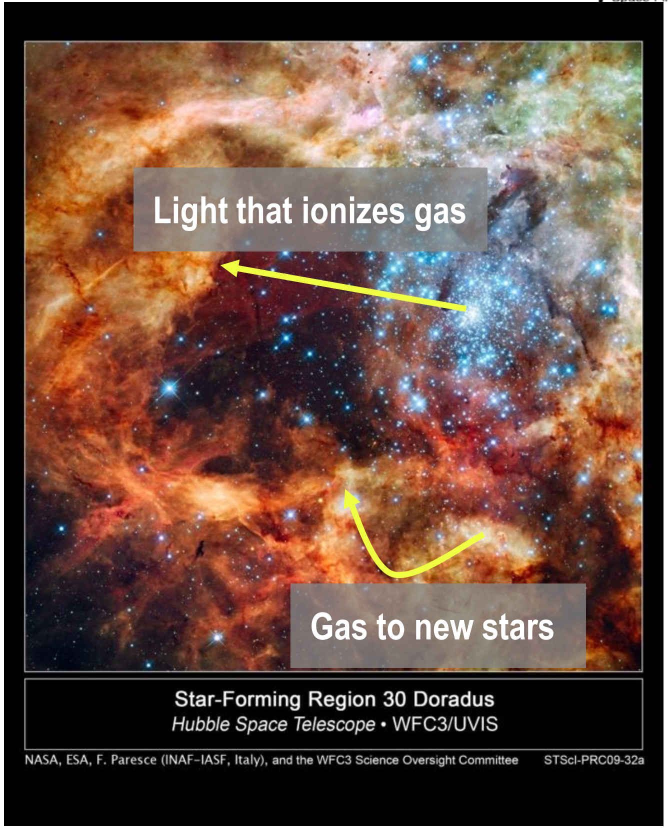
Detector package
6x spectrometers
at 100 mK

Switzer et al., J. Astron. Telesc. Instrum. Syst. 7(4) 044004, 2021

Star formation within galaxies



M31 David Dayag/Wikimedia



Star-Forming Region 30 Doradus
Hubble Space Telescope • WFC3/UVIS

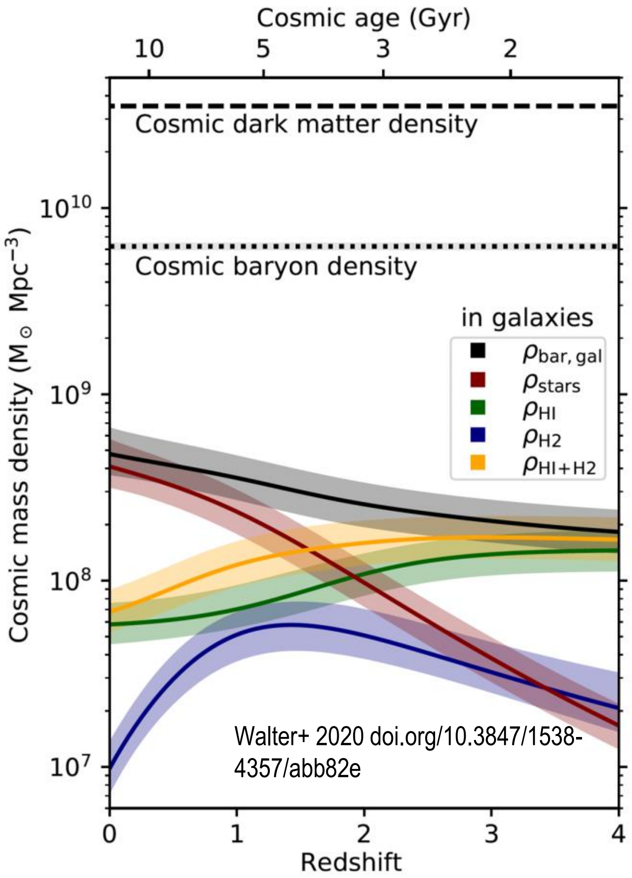
NASA, ESA, F. Paresce (INAF–IASF, Italy), and the WFC3 Science Oversight Committee STScI-PRC09-32a

Evolving components

- Phenomenological model from **Walter+ 2020** based on all current measurements.
- H_2 decreases ~6x from z~1.5 to z=0 while HI remains roughly constant.

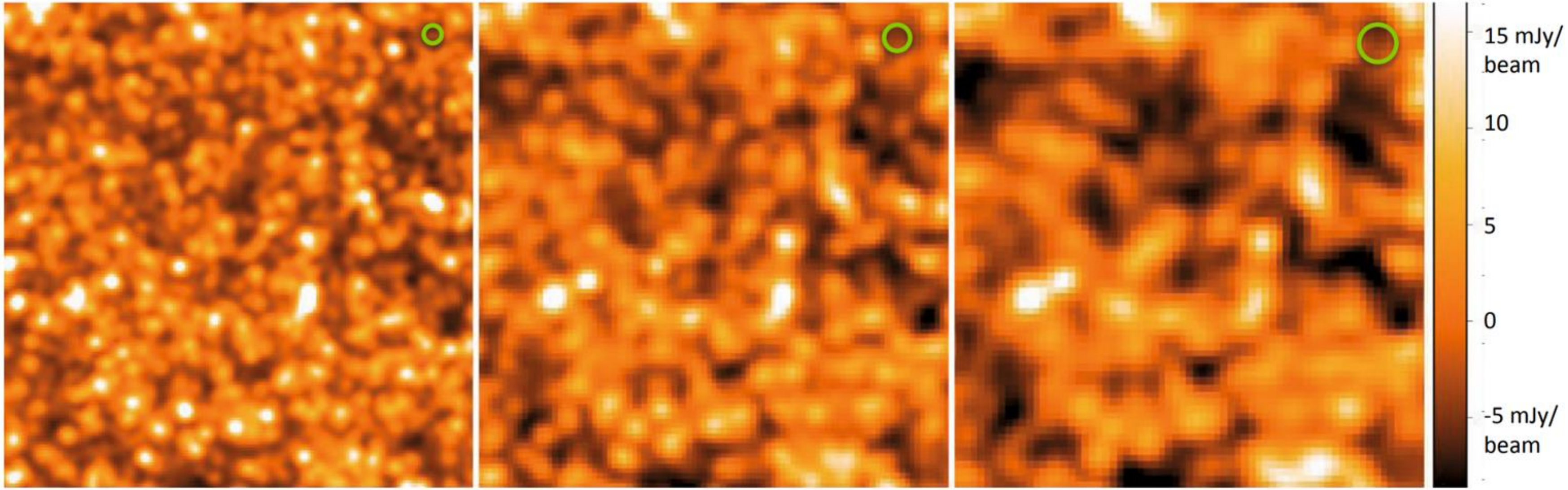
H_2 needs to be replenished:

- Depletion time H_2 density/SFR~7x10^8 yr.
- Assuming that all H_2 ends up in stars since z~1.5 only explains ~20% of the stellar density. SFR is not “using up” a fixed H_2 reservoir.



Walter+ 2020 doi.org/10.3847/1538-4357/abb82e

The confusion limit



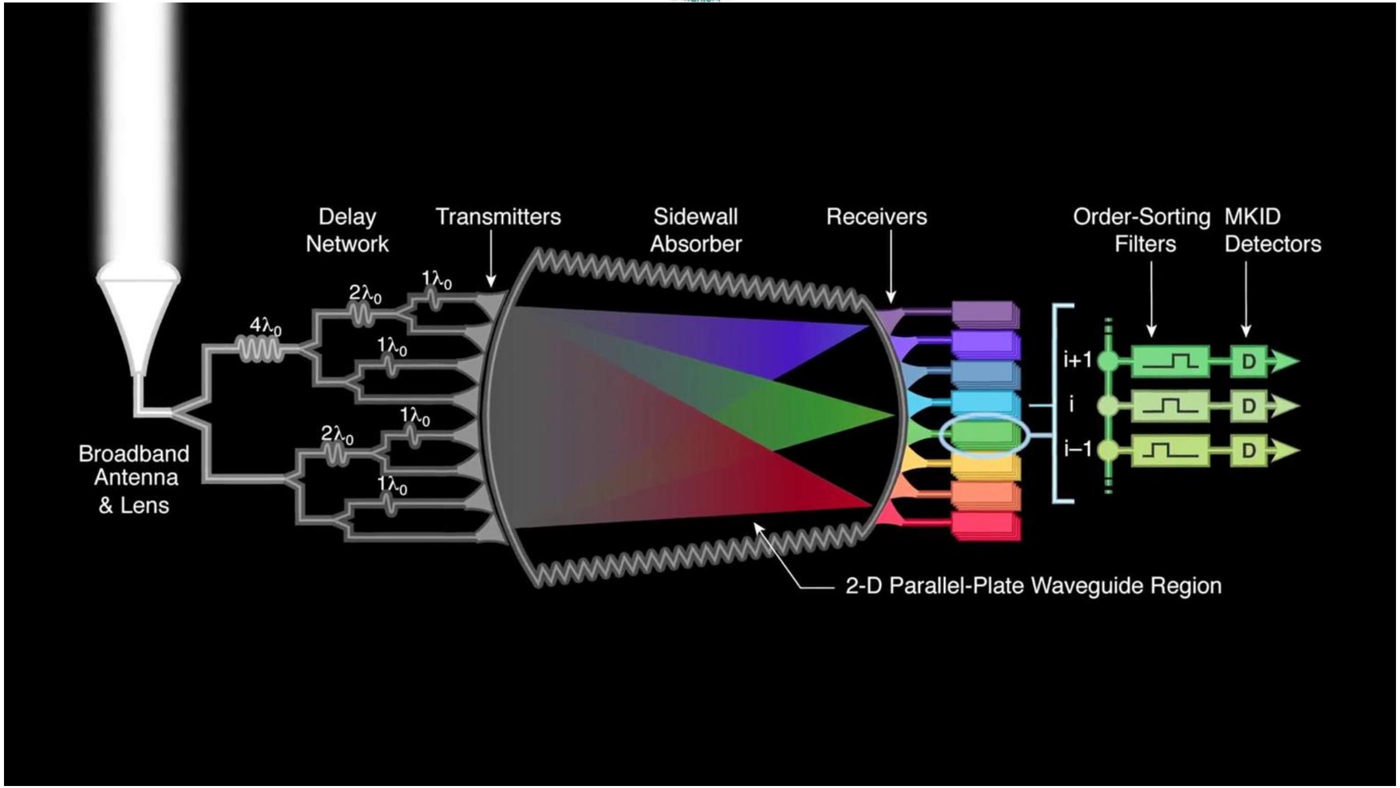
Herschel SPIRE; HerMES GOODS-N over 16’ for 250, 350, and 500 um

doi.org/10.1051/0004-6361/201014680 Nguyen+ 2010

The dense distribution of galaxies produces an irreducible noise floor.

Confusion limits increase at longer wavelengths/smaller apertures.

μ-Spec operation



What's needed & what's possible?

1. **Large area survey.** Currently: Field variance from HDF/GOODS. Evade cosmic variance? [Seljak 2008].
2. **Intensity mapping:** Work beyond the confusion limit in the longwave far-IR
3. **Measure integral of emission**. Currently: individual CO detections are biased toward large galaxies and hot gas.
4. **Cross-correlation** in intensity mapping to isolate redshifts.
5. Cosmological context (clustering bias)
6. Diagnostics of multiple J from same redshift. Highly dependent on ISM and selection effects in ordinary surveys.
7. Simulations for CO/CII, not just H_2

EXCLAIM
0.75 m, cryogenic telescope
420-540 GHz
~300 deg^2 area (wide)
Conventional flight
CO 0<z<0.6+, CII 2.5<z<3.5
BOSS cross-correlation
MKID on-chip spectrometer
Antenna-coupled MKID
NASA-GSFC