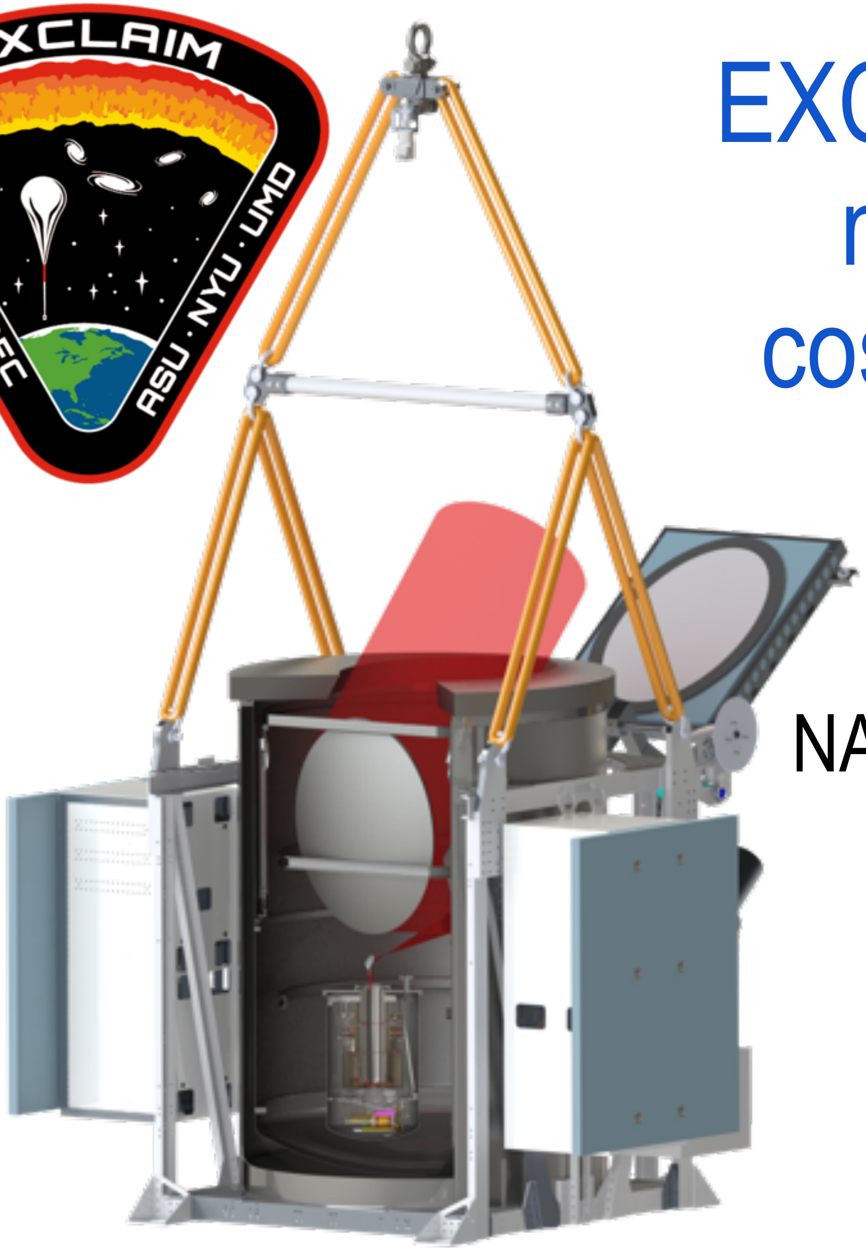


EXCLAIM: a new balloon mission to map the cosmological history of galaxies

Eric Switzer

NASA Goddard Space Flight Center

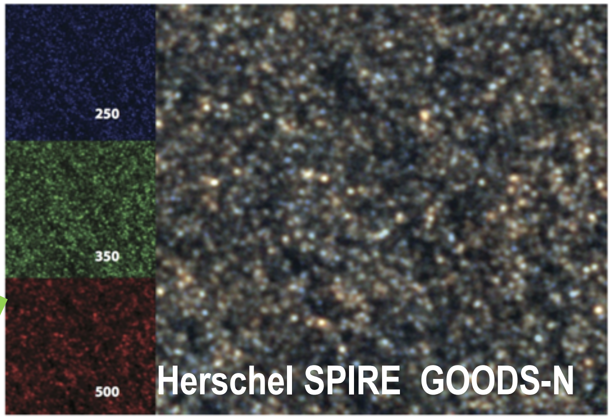
How did we get here?

Resolving cosmic backgrounds

Top down: integrals and aggregate population.

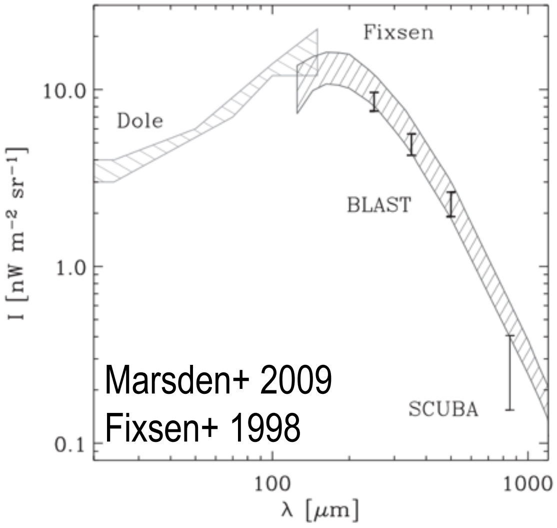
Bottom up: Specific properties of selected, bright galaxies. (ALMA, BLAST, Herschel, sub-mm)

COBE
FIRAS



Herschel SPIRE GOODS-N

Fundamental quantity: total starlight reprocessed by thermal dust emission.

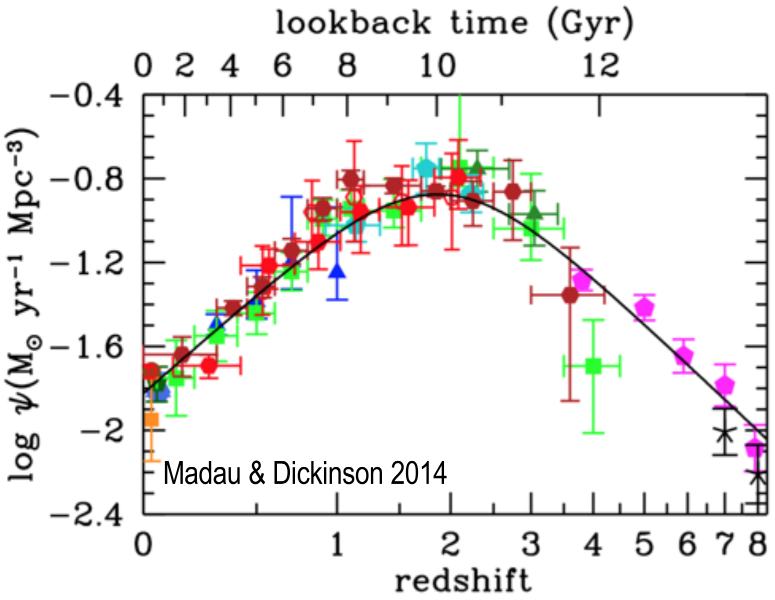


Marsden+ 2009
Fixsen+ 1998

<u>Reconciliation:</u>
<u>20 years of fruitful research.</u>

Time-resolving cosmic backgrounds

We can now observe how the universe changes over cosmic time.



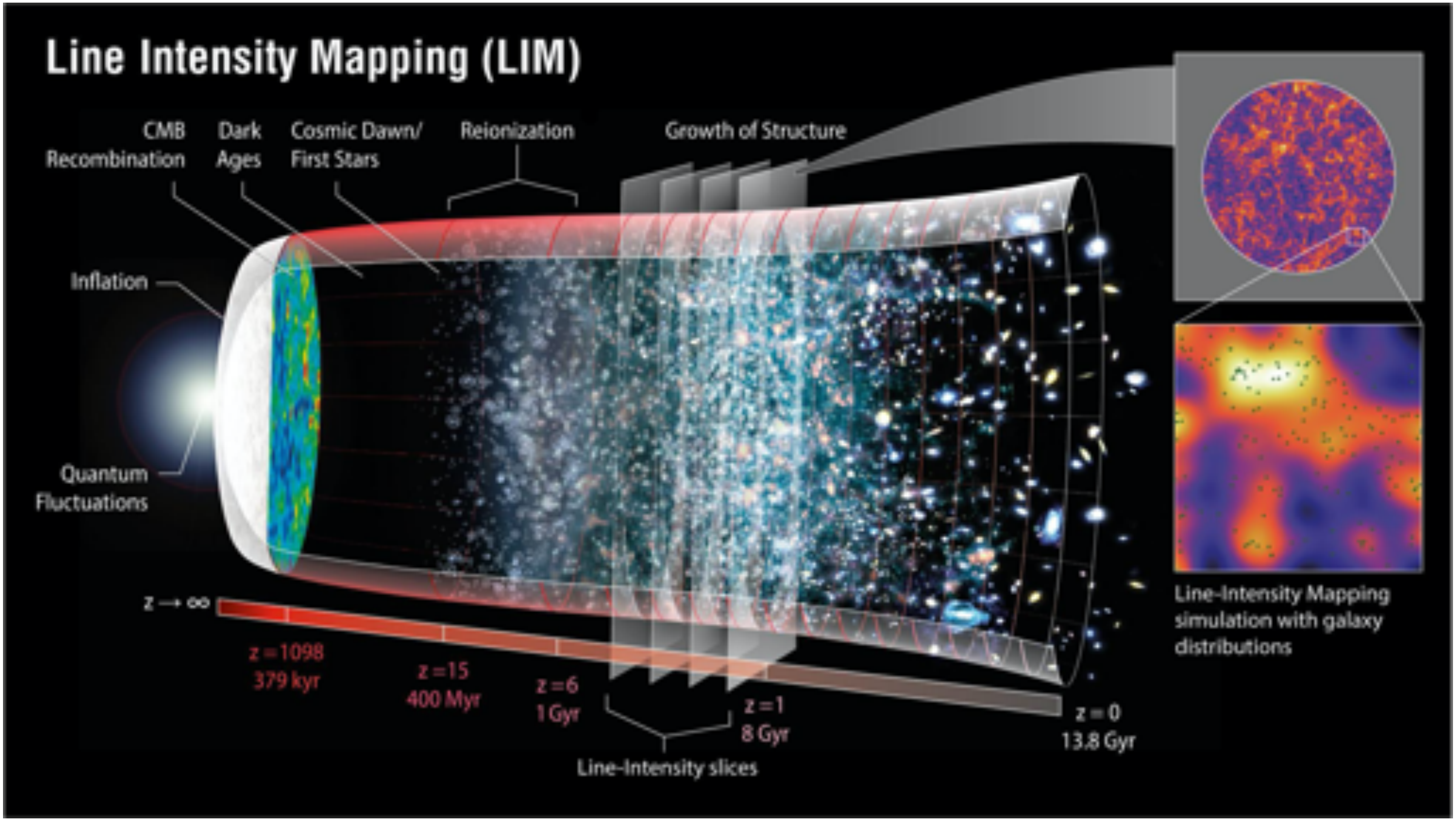
Open questions:

How much gas is available to form stars across time?

Why does the star formation rate plummet after z=2? Is the evolution in molecular gas abundance or star forming efficiency?

Is there a method to measure aggregate emission (like FIRAS) which has redshift information?

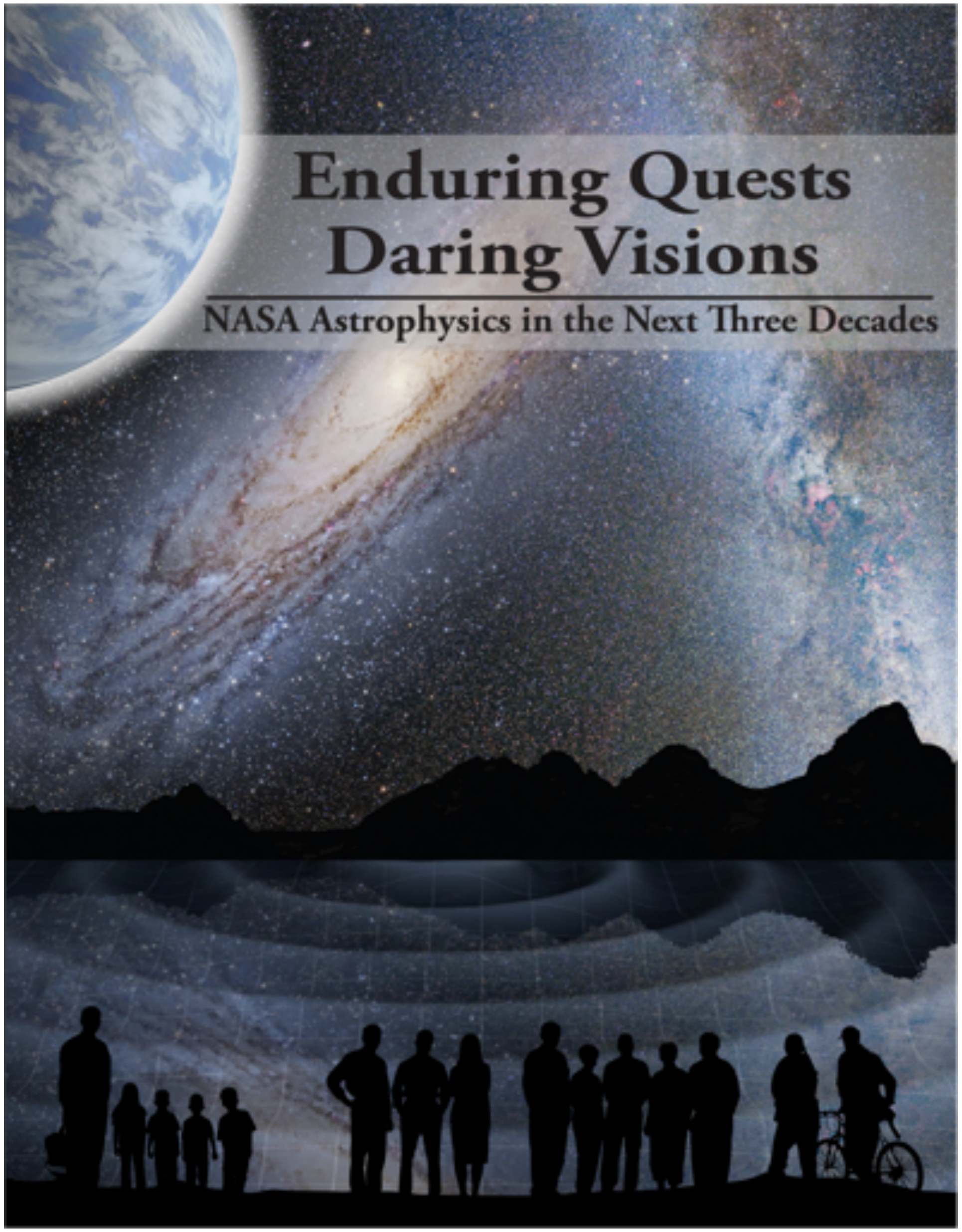
How did we get here?



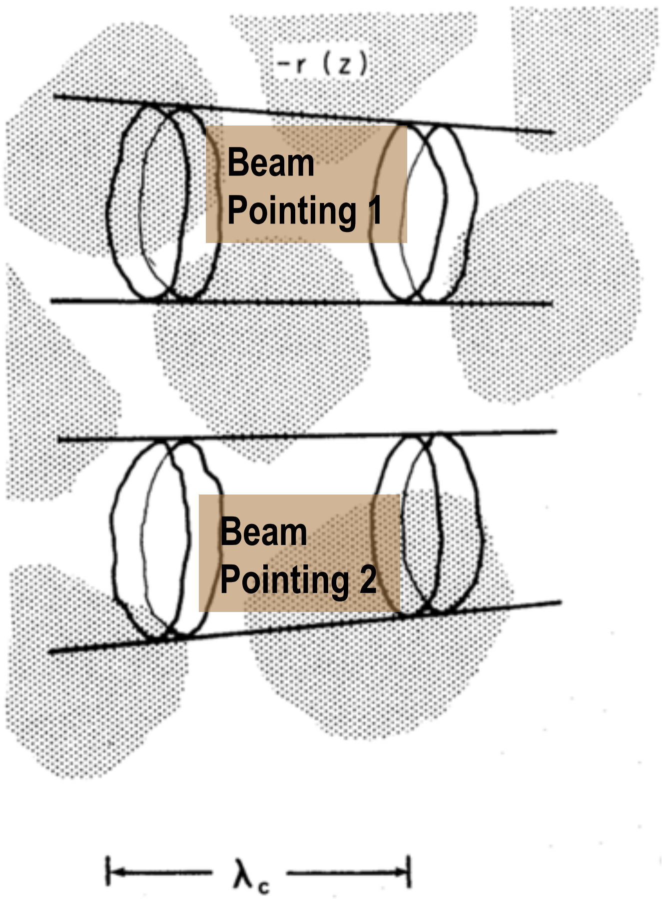
Pivotal era: How did matter organize from a highly homogeneous hydrogen/helium gas to the rich universe that we inhabit today?

Connection to agency and national goals

- Enduring Quests Daring Visions Roadmap: "completely map the content of selected volumes of space that represent slices through all of cosmic time.“
- NWNH Decadal "How do baryons cycle in and out of galaxies, and what do they do while they are there?” (Cosmic Order), "What are the connections between dark and luminous matter?" (Origins).
- IM and NASA: 1) lower requirement on aperture (which drives cost), 2) uses sensitivity from low photon backgrounds in space, 3) many frequencies of interest are not accessible from the ground.



Origins

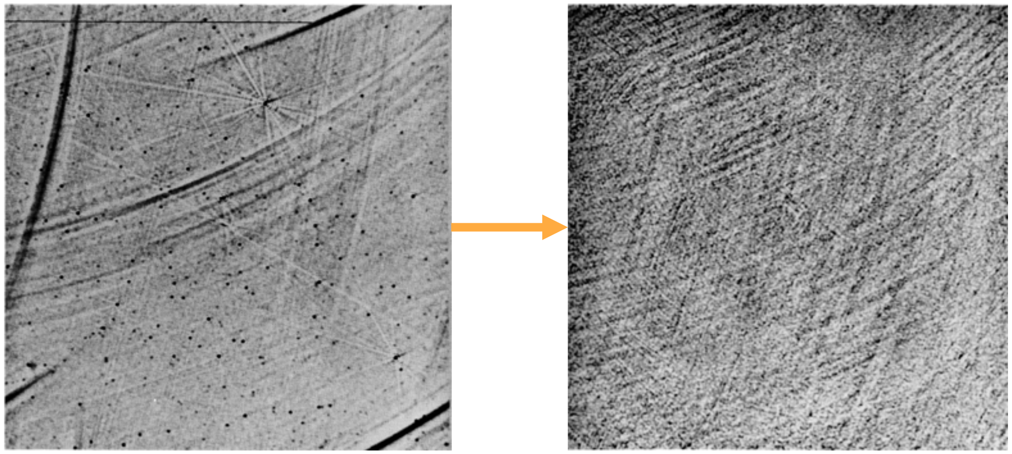


1. Measure all structure, not just the brightest objects.
2. Use narrow bands.
3. Employ the spectral structure of signal vs. continuum.

Hogan & Rees ApJ 1979,
Sunyaev & Zel'dovich 1972, 1975

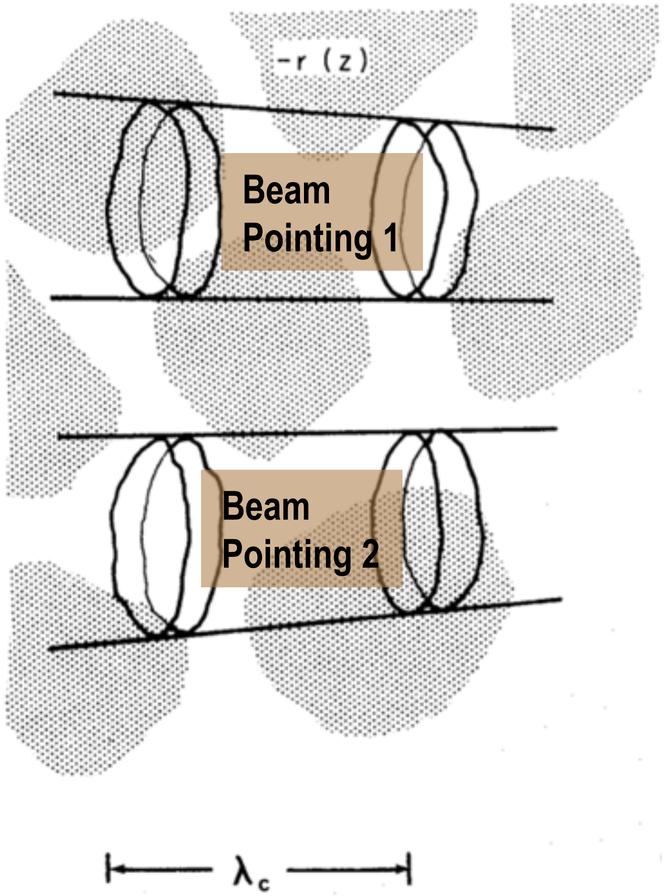
Use spectral differences to reject continuum emission.

Bebbington+ 1986: 151, 152 MHz ($z \sim 8.4$)
Surface brightness rms < 2.5 K



Why Intensity mapping?

- **Aperture**: Pushing to higher flux sensitivity and lower confusion drives large apertures. Intensity mapping measures surface brightness; sensitivity is limited by detector noise or photon background.
- **Cumulative emission**: IM is sensitive to the faintest sources (good: blind complete census) plus all other forms of radiation (bad).
- **Volume**: IM provides efficient access to large cosmological volumes and redshifts. Reduced cosmic variance.
- **Environments**: Several lines and ionization states trace different environments.
- **Clustering:** What is the cosmological context of galaxies?
- **Systematics**: There is no selection function.

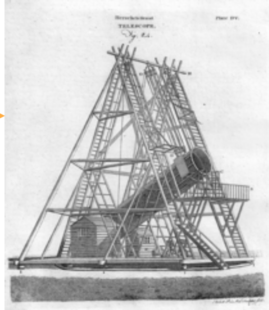


Hogan & Rees 1979

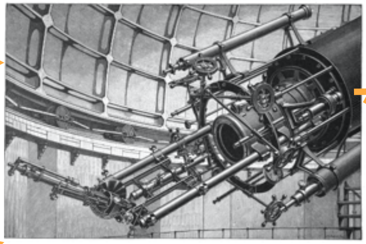
New methods break bottlenecks

Planets
Galileo 1610

Double stars
Herschel 1787



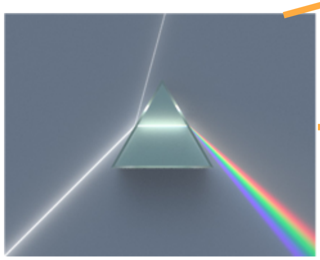
Helium
Redshift
Composition
Keeler, Brashear (Lick) 1889



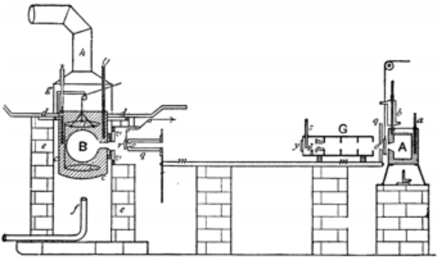
Large instruments

Intensity mapping
Smaller?

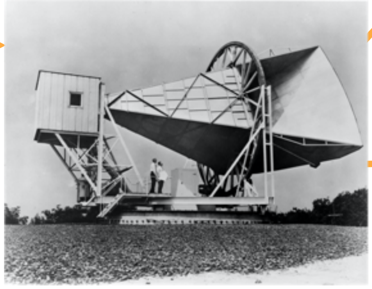
Spectroscopy



Dispersion
Newton 1666



Blackbody measurement
Kurlbaum & Lommel 1898

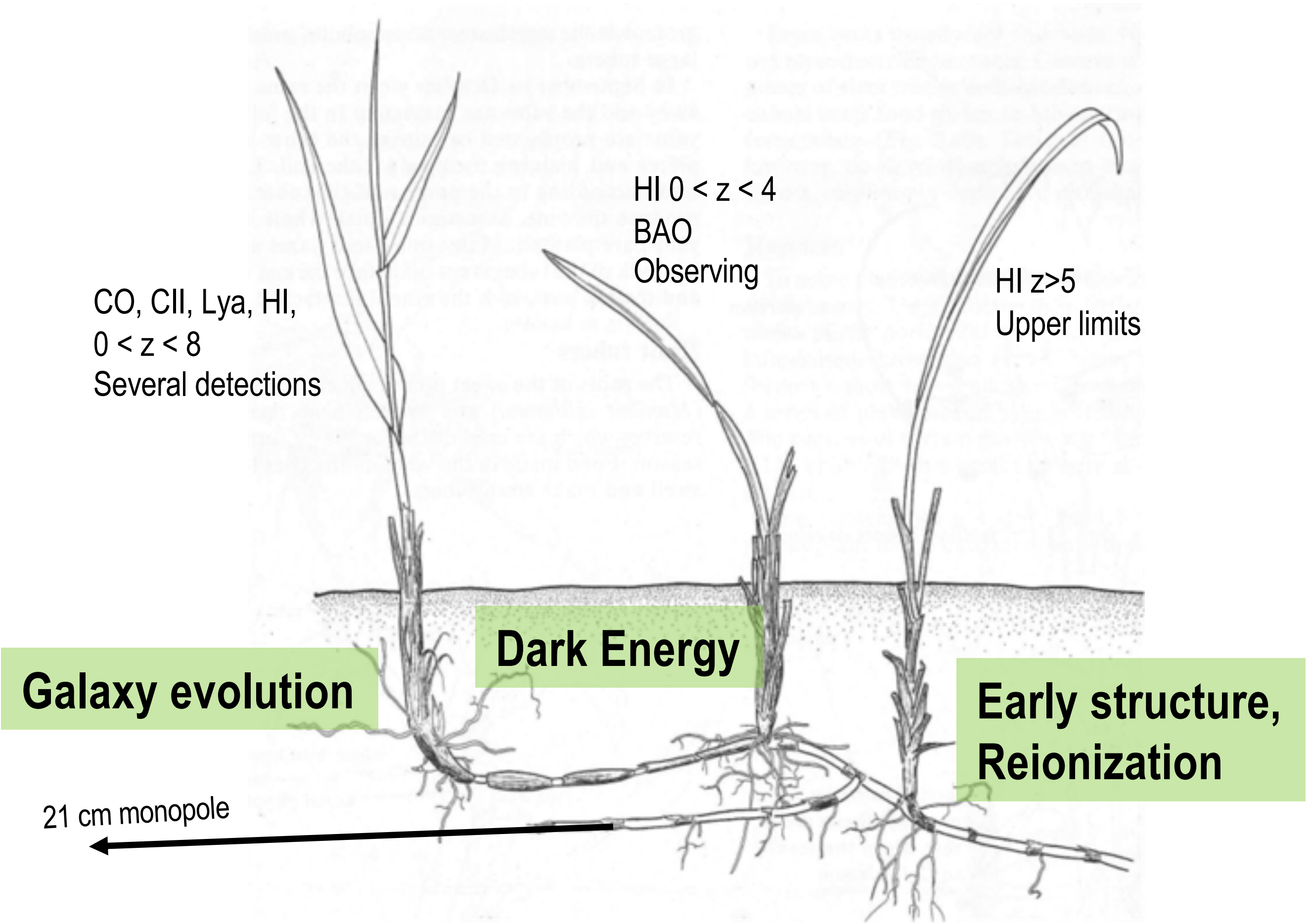


Relic radiation
Surface brightness
Penzias Wilson 1964

Large instruments

New ways of looking at nature may also find the unintended.

A path to a wide range of science



CO, CII, Lya, HI,
0 < z < 8
Several detections

HI 0 < z < 4
BAO
Observing

HI z>5
Upper limits

Galaxy evolution

Dark Energy

Early structure, Reionization

21 cm monopole

Blind, complete line surveys are expensive.
We cannot yet detect BAO in clustered line emission

←

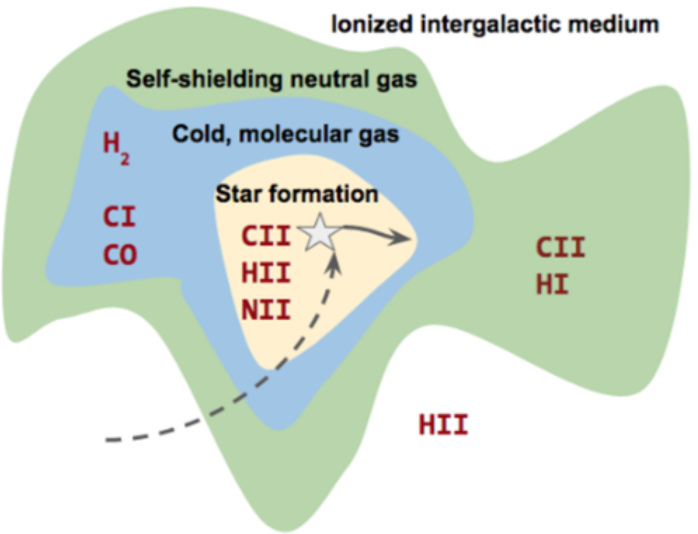
Spectroscopic samples are expensive. We cannot yet detect 21 cm structure at high redshift.

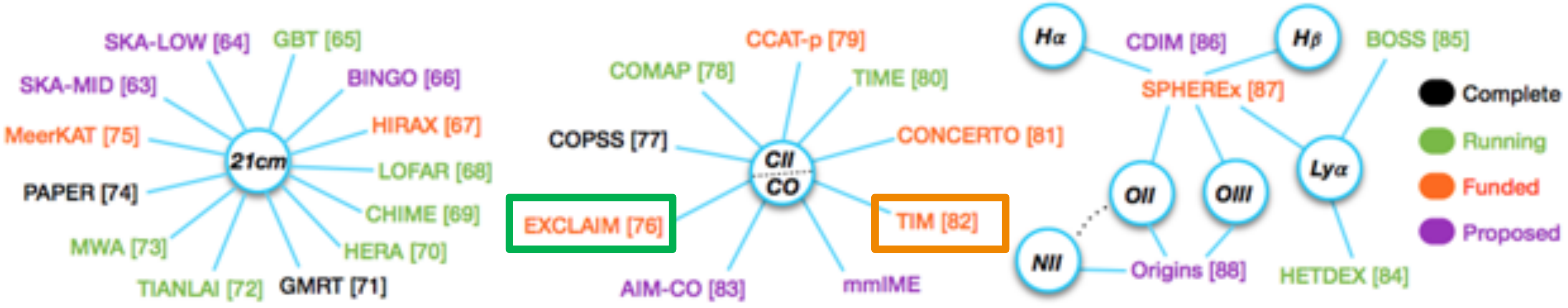
←

Flux sensitivity is expensive. We cannot resolve individual objects at high redshift.

Tracers and existing detections

- **21 cm**: traces HI in the IGM through reionization, and in galaxies after reionization. (Switzer+ 2013, GBT)
- **CO ladder at 115 * J_{upper} GHz**: traces H_2 gas. (Keating+ 2016, 2020 SZA, ACA, ALMA)
- **CII (157.7 µm)**: traces gas in several phases, is an indicator of the star formation rate (Pullen+ 2018, Planck)
- **Lyα**: traces the star formation rate and radiative transport in the IGM. (Croft+ 2018, BOSS)
- **Cosmic Infrared Background**: integrated dust emission (Fixsen+ 1998, FIRAS)

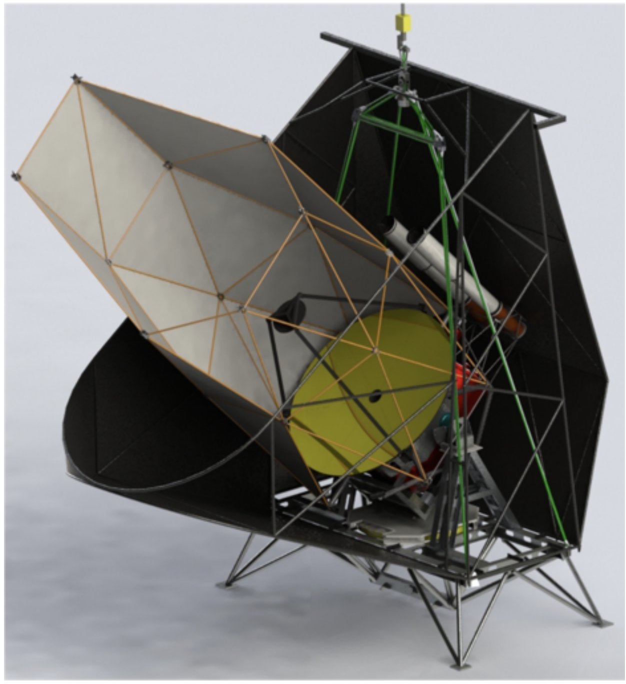




Kovetz+ 2019

An Exciting Time for Intensity Mapping

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



TIM
2 m, ambient temperature telescope
715-1250 GHz
~1 deg^2 area (deep)
Long-duration Antarctic
CII 0.5<z<1.5, NII
Auto-power, NII x CII, stacking
MKID + grating spectrometer
Direct-coupled MKID
PI: J. Vieira (UIUC)

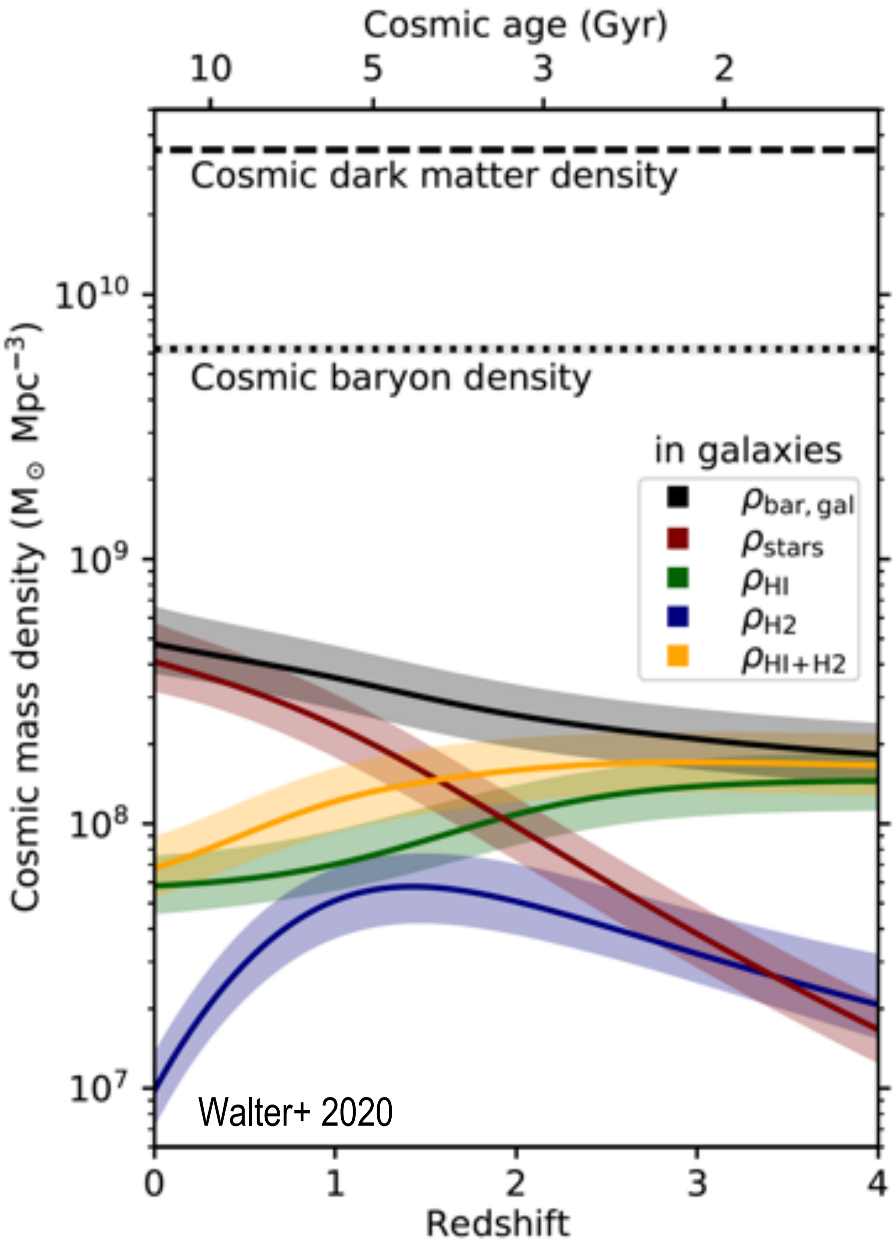
What do we know about the evolution of galaxies?

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.

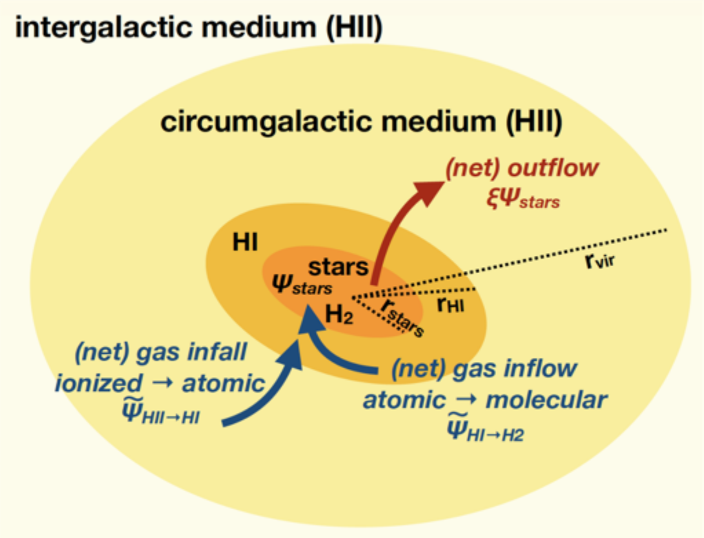
H_2 needs to be replenished:

- Depletion time H_2 density/SFR~$7\text{x}10^8$ 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.



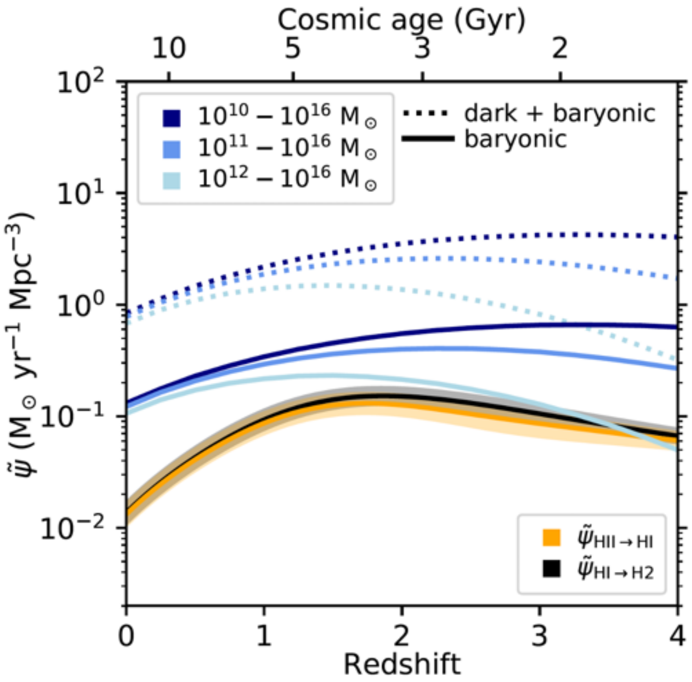
Walter+ 2020 synthesis

- **Infall:** ionized IGM/CGM to extended HI reservoir. **Inflow:** HI reservoir to H_2.
- Galaxies grow through smooth accretion (dominates) and distinct mergers. Dense filaments in halos produce cold streams to replenish reservoir (“cold-mode accretion”) in the free-fall time 10^8 yr.
- HI reservoir: 50 kpc from disk. CGM 50-300 kpc bound to halo, decoupled from Hubble flow (10^4-10^6 K) time to cool 10^4 K CGM is comparable to dynamical time ~10^8.



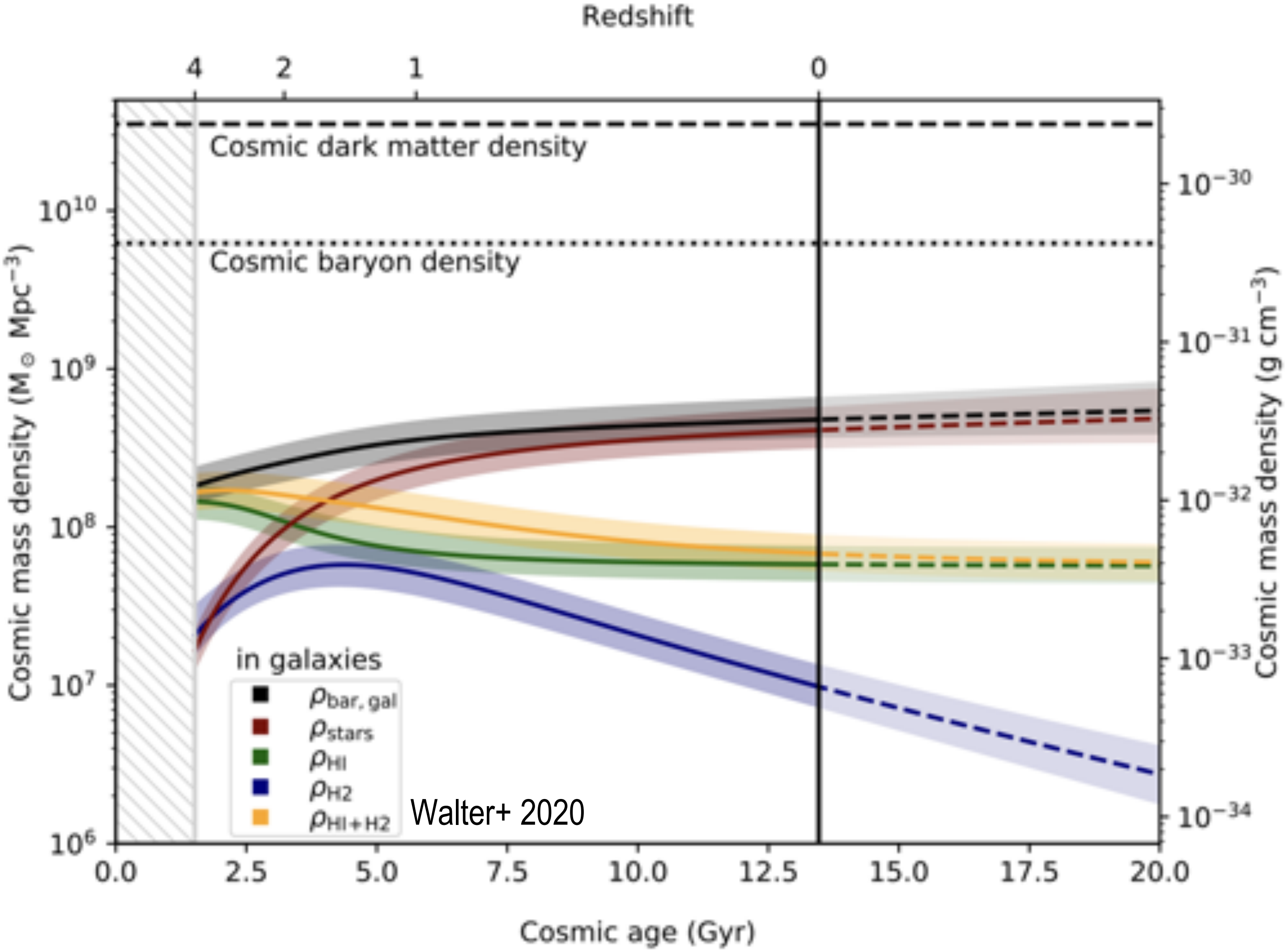
Simulations show:

- Decline in mass rate is due to an expanding universe (not accelerated expansion) and decreasing available accretable matter.
- Cosmological mass accretion brings in sufficient matter for star formation.
- Additional feedback processes dominate dynamics.



Walter+ 2020

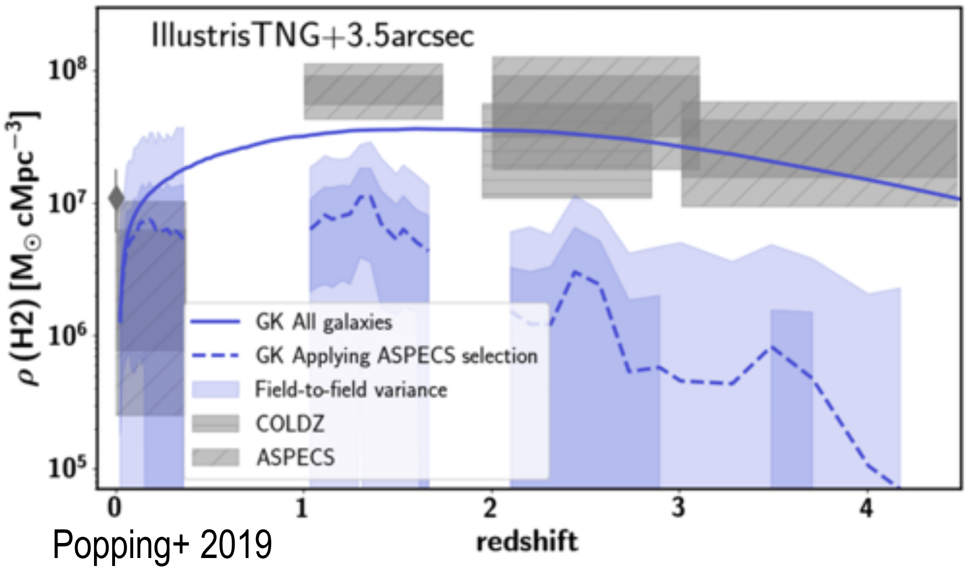
Future evolution of galaxies



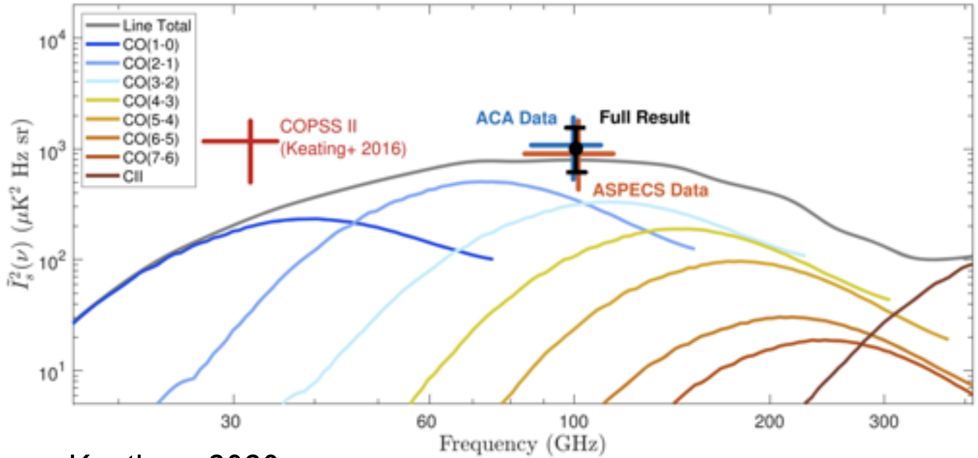
The densest IGM filaments have already fallen in to galaxy wells, and remaining gas will expand and dilute away.

Tensions and limitations of existing measurements

- **Tension:** Model of H_2 mass of z>1 galaxies vs. stellar mass 2–3x lower than ASPECS, especially in H_2 rich galaxies.
- **Field size:** ASPECS 4.6 arcmin^2: high-field to field scatter. z<1 is of particular interest for falling SFR, but scatter significant due to smaller volumes
- **Selection:** from Illustris TNG, At z=1 ASPECS misses 30% of emission. At z>2 misses 90% or even more.
- **Intensity mapping**: ASPECS and ACA auto-power (Uzgil+ 2019, Keating+ 2020). Largely consistent with ASPECS source catalog.
- **Challenges:** measures total line-like emission at all redshifts at 100 GHz, in small region. Must rule out other sources of emission. Does not measure clustering bias (relation of galaxies to DM halos).

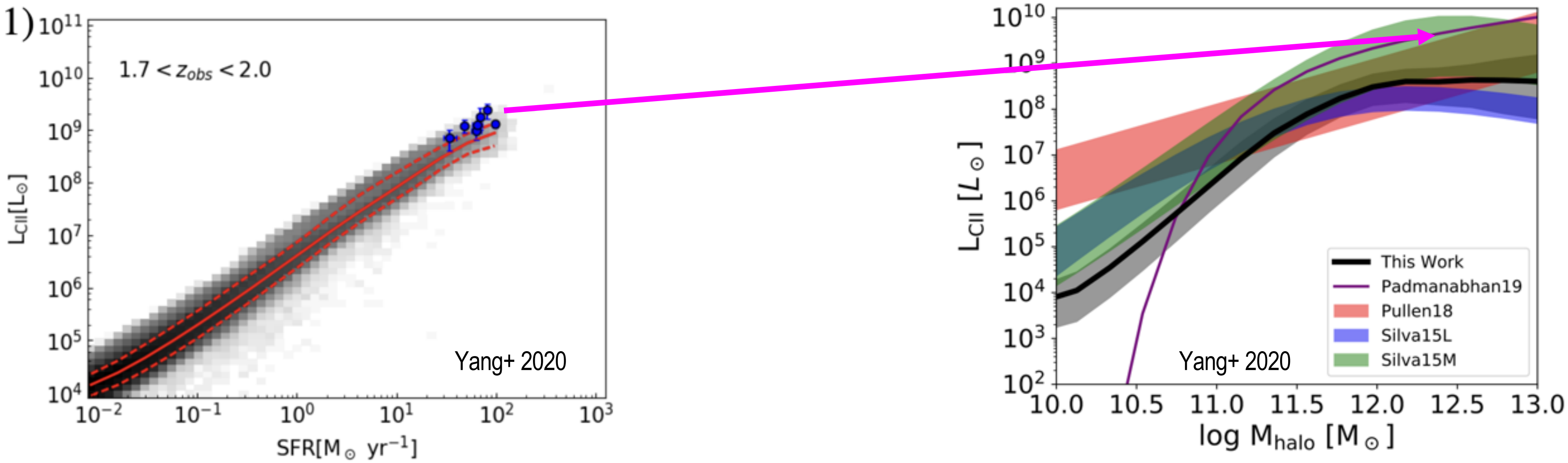


Popping+ 2019



Keating+ 2020

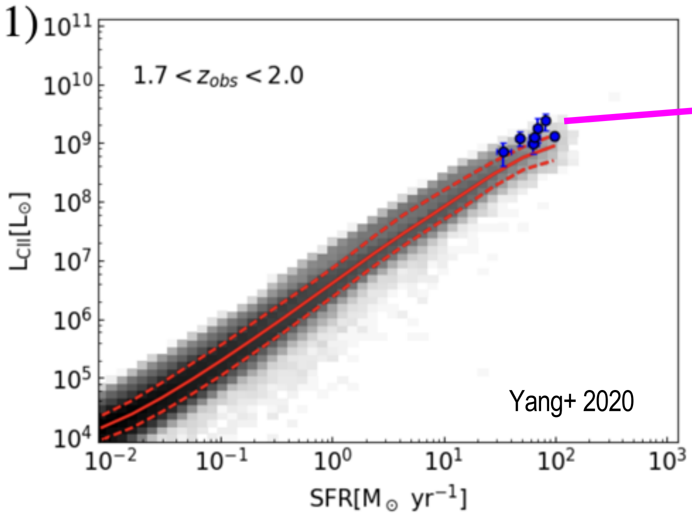
Line emission models and observations

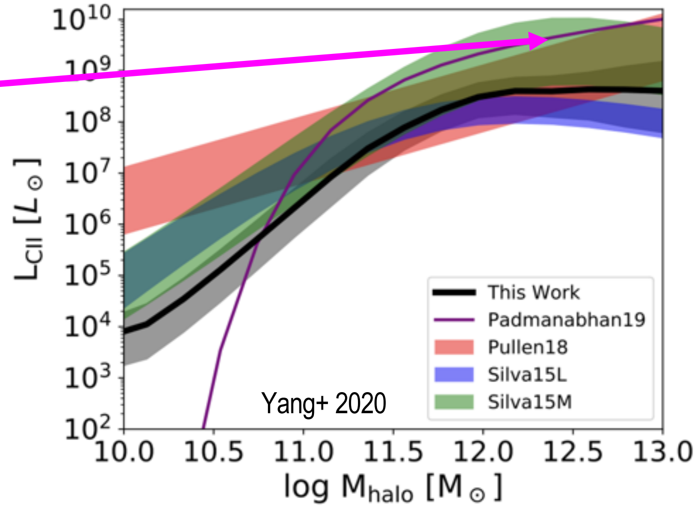


Discrete measurements: tip of the iceberg
Data: Zanella+ 2018, [CII] at z~2 from ALMA
Model: Yang+ 2020 SAM for line emission

Models: informed by local relations, galaxy models, feedback parametrics.

Line emission models and observations

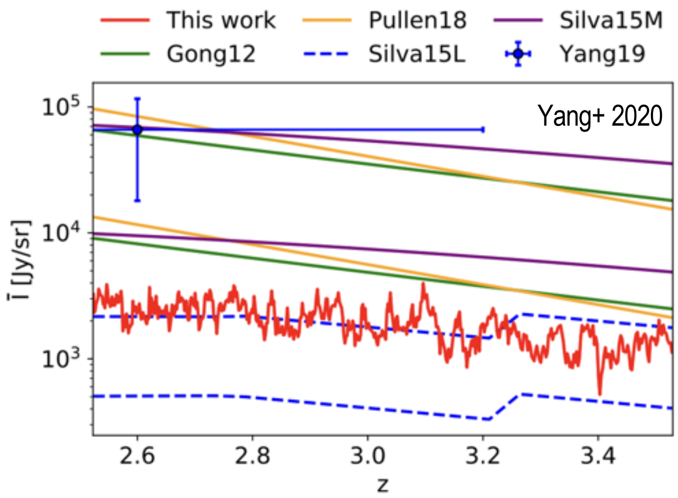




Discrete measurements: tip of the iceberg
Data: Zanella+ 2018, [CII] at z~2 from ALMA
Model: Yang+ 2020 SAM for line emission

Models: informed by local relations, galaxy models, feedback parametrics.

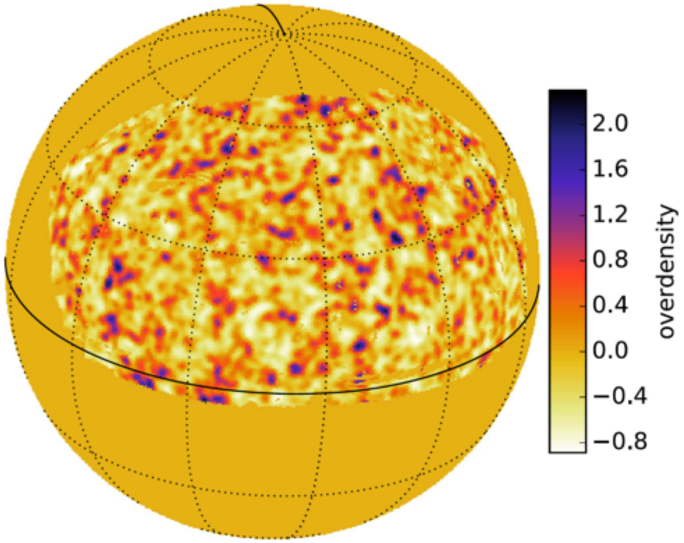
The result:
Great uncertainty in the total emission.



1. **Nowhere near resolving [CII] emission into constituents.**
2. **Limited constraints at low mass, where feedback can play a critical role.**
3. **New instruments are needed; we have pushed the limits of Planck 545 GHz.**

What's needed?

1. Large area survey. Currently: Field variance from HDF/GOODS.
2. Measure integral of emission. Currently: individual CO detections are biased toward large galaxies and hot gas.
3. Cross-correlation in intensity mapping to isolate redshifts.
4. Cosmological context (clustering bias)
5. Diagnostics of multiple J from same redshift. Highly dependent on ISM and selection effects in ordinary surveys.
6. Simulations for CO/CII, not just H_2



BOSS CMASS z~0.5 smoothed to 1.7 deg FWHM to show large-scale overdensity (Switzer 2017)

The EXCLAIM Mission

See recent SPIE 2020 proceedings for more details:

G. Cataldo, “Overview and status of EXCLAIM, the experiment for cryogenic large-aperture intensity mapping” Proc. SPIE, Vol 11445, 1144524 (2020)

T. Essinger-Hileman, “Optical Design for the Experiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM),” Proc. SPIE, Vol 11453, 114530H (2020)

M. Mirzaei, “μ-Spec Spectrometers for the EXCLAIM Instrument,” Proc. SPIE, Vol 11453, 114530M (2020)

EXCLAIM Team

NASA Goddard

Eric Switzer (PI)
Tom Essinger-Hileman (DPI, Instrument lead)
Giuseppe Cataldo (Mission SE)
Emily Barrentine (Spectrometer lead)

Chris Anderson (Map analysis, JHU coop)
Alyssa Barlis (SECP, optical test design)
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)
Omid Noroozian (MKID design and test)
Tatsat Parekh (Mechanical)
Samelys Rodriguez (Wirebonding)
Peter Shirron (ADR)
Thomas Stevenson (Spectrometer)
Ed Wollack (Spectrometer)

Interns (spring 2021):
Jim Fouquet (ISAE-SUPAERO)
Alberto Marrtinez Gonzalez (ISAE-SUPAERO)
Trevian Jenkins (UMD)
Mathias Ramirez (ASU)

NYU/CCA: Simulation and interpretation

Anthony Pullen (Science Lead)
Rachel Somerville
Eli Visbal
Shengqi Yang
Aaron Yung (starting at GSFC)

UMD:

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

ASU: (Readout)

Phil Mauskopf (Readout Lead)
Jacob Glasby
Adrian Sinclair
Sasha Sypkens

Funded partners

UWisc: (MKID modelling, forecasting)

Trevor Oxholm, Gage Siebert
Peter Timbie

CITA: Simulation and interpretation

Ue-Li Pen
Patrick Breysse

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

Science goals: lines and levels

Map both [CII] and CO, including coverage of adjacent CO ladder emission at common z. **R=512 421-540 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 2018* for interpretation.

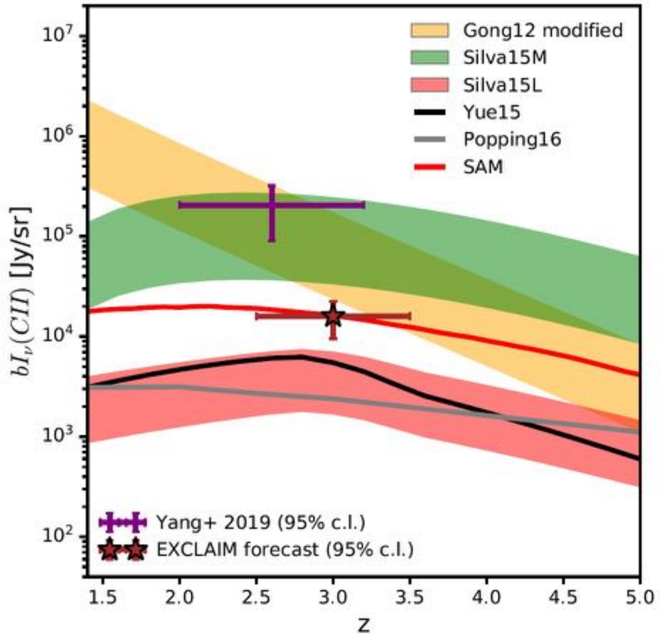
CO:

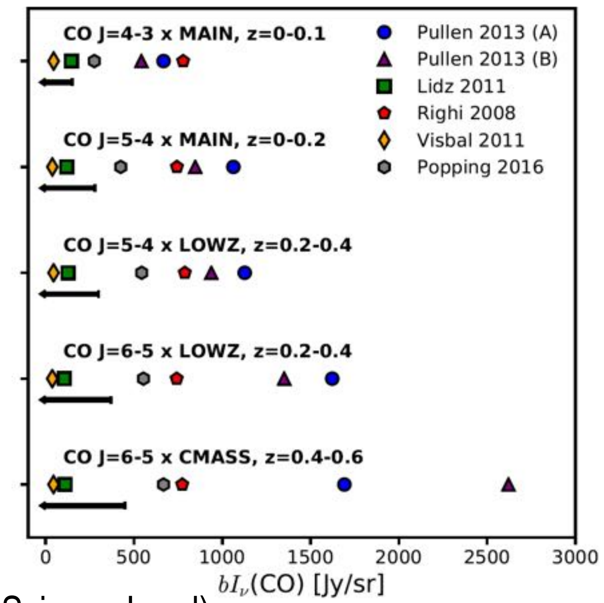
- MAIN 0 < z < 0.2 for J=5-4, J=4-3
- LOWZ 0.2 < z < 0.4 for J=6-5, J=5-4
- CMASS 0.4 < z < 0.7 for J=7-6, J=6-5
- eBOSS for z > 0.7 and higher J?

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!



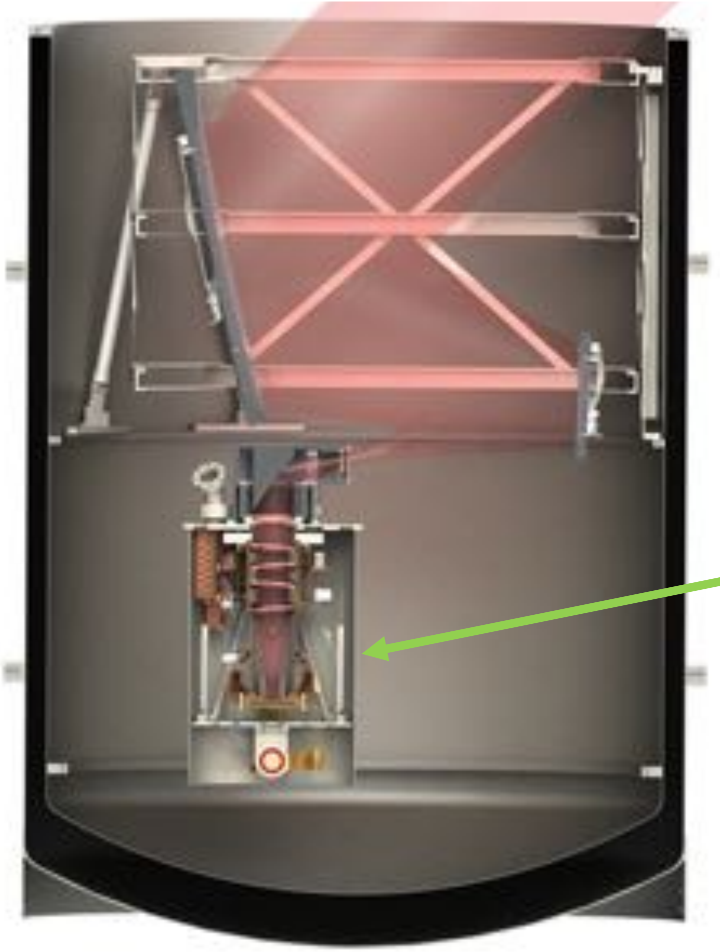


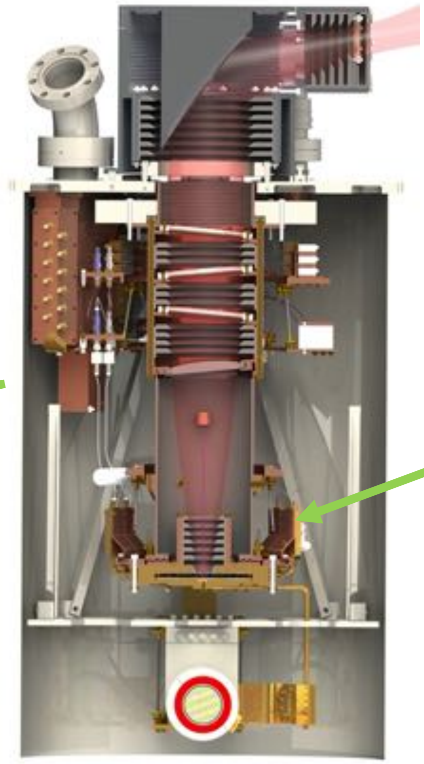
Anthony Pullen (Science Lead)

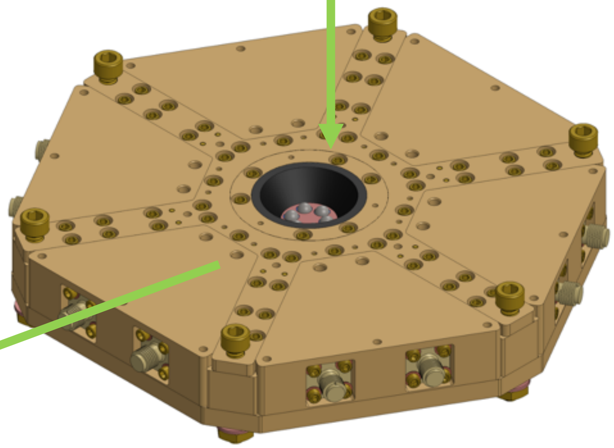
Mission System Overview

Balloon-borne
Cryogenic
Telescope

On-chip MKID
spectrometer







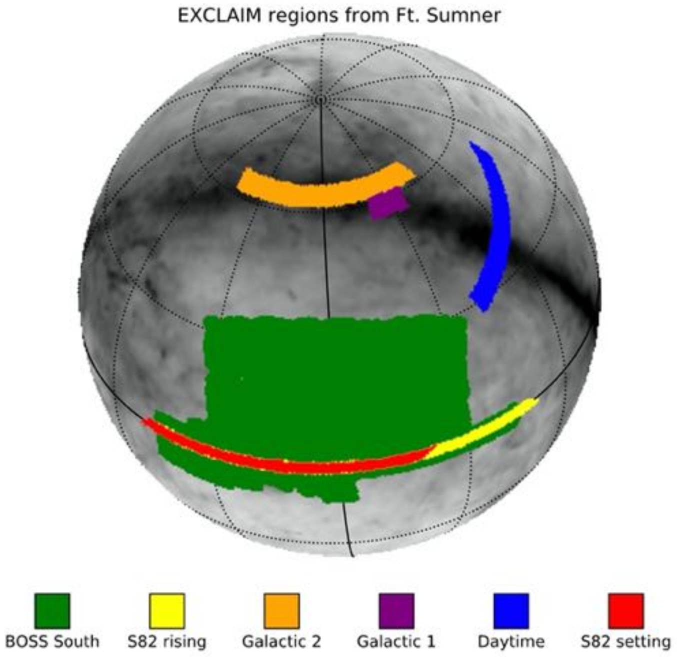
Detector package
6x spectrometers
at 100 mK

Receiver

Strategy

- **Cross-correlation with BOSS for primary science**
- 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.

- Project start: 4/2019
- Engineering flight (2022): one spectrometer, sky dips to verify atmospheric line model; galactic and preliminary extragalactic.
- Science flight (2023): 6 spectrometers
- Versatile platform for testing FIR spectrometer technology in space-like environment.



Preliminary survey plan

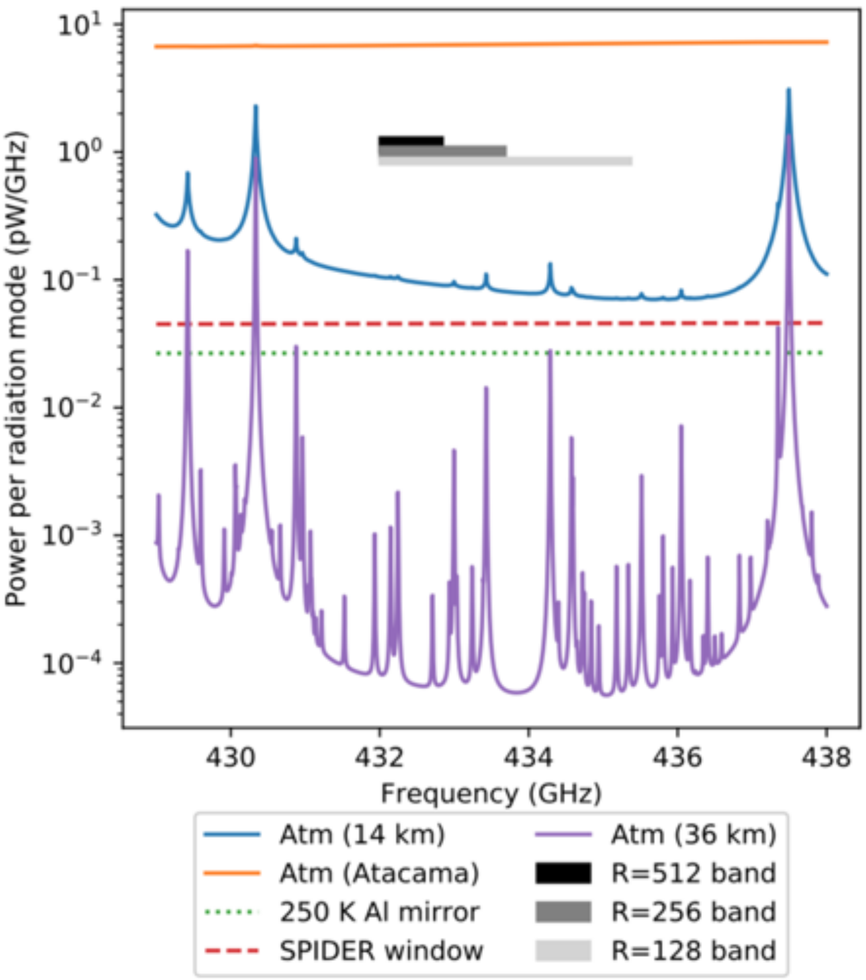
Engineering flight:

- Daytime field: anti-solar scan, 300 deg^2, crosses the galactic plan. 3-7 PM local.
- Galactic field 1: 7-8 PM. 50 deg^2.
- BOSS S82 field: rises 8 PM local until 2 AM. 320 deg^2.
- Galactic field 2: 2 AM-7 AM, 200 deg^2.

Science flight observes S82 setting from 2-5 AM: 9 hours total.

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).

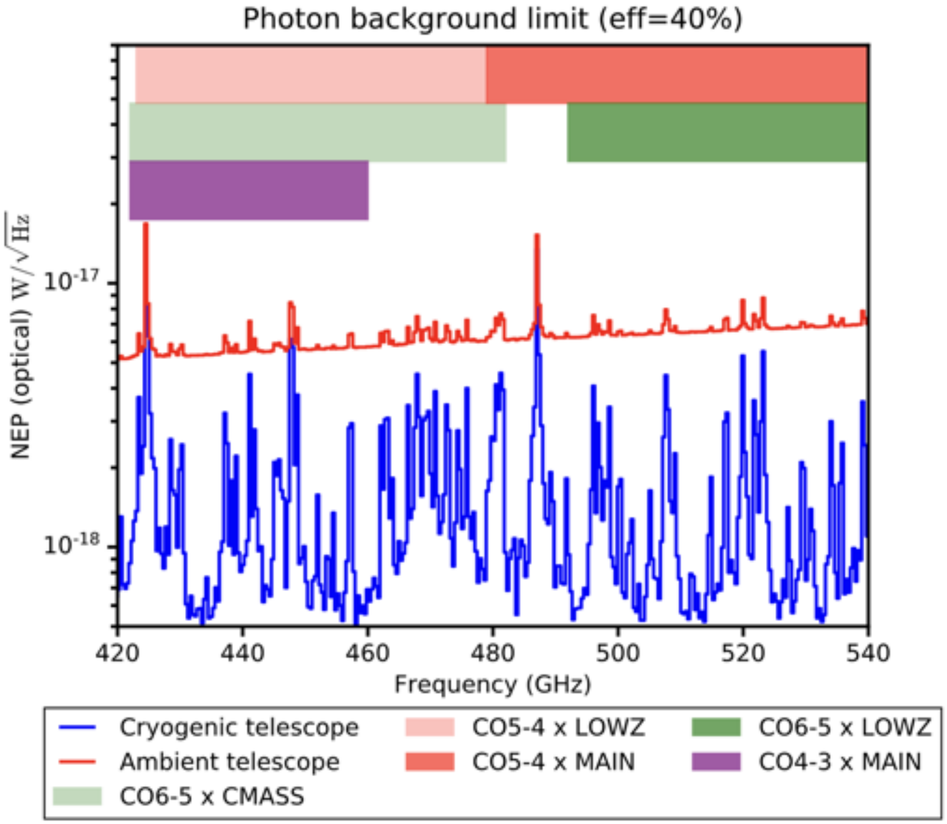


Integration time ~ power^2

Approach from Al Kogut

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).



Al MKID to 10^{-19} W/rtHz level (Yates+ 2011, Baselmans+ 2017.)

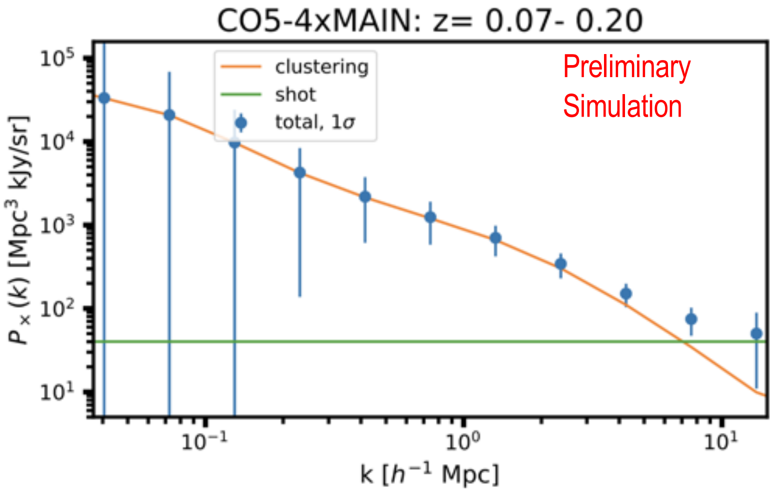
Background limit includes MKID recombination noise.

Approach from Al Kogut

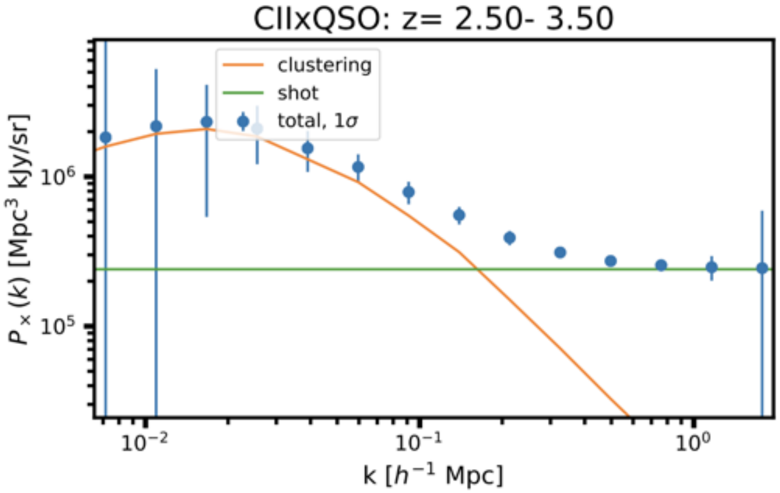
EXCLAIM x BOSS forecasts

Ingredients:

- **LSS:** Matter power spectrum, spectroscopic survey density, bias.
- **Multiple tracers:** Correlated shot noise (Wolz+ 2017): fraction of total line emission from the galaxies in spectroscopic sample.
- Angular and spectral resolution (Li+ 2016, Lidz).
- Spectral response per channel is diffractive, not a top-hat. (true for any diffractive spectrometer design)
- Inhomogeneous noise in frequency.
- MKID Quasi-particle shot noise, photon shot and bunching noise.
- 1/f in raster scan (Crawford 2007).
- Fast 3D mode counting agrees with likelihood on $C_l(z,z')$. **See future work by C. Anderson.**


CO5-4xMAIN: z= 0.07- 0.20

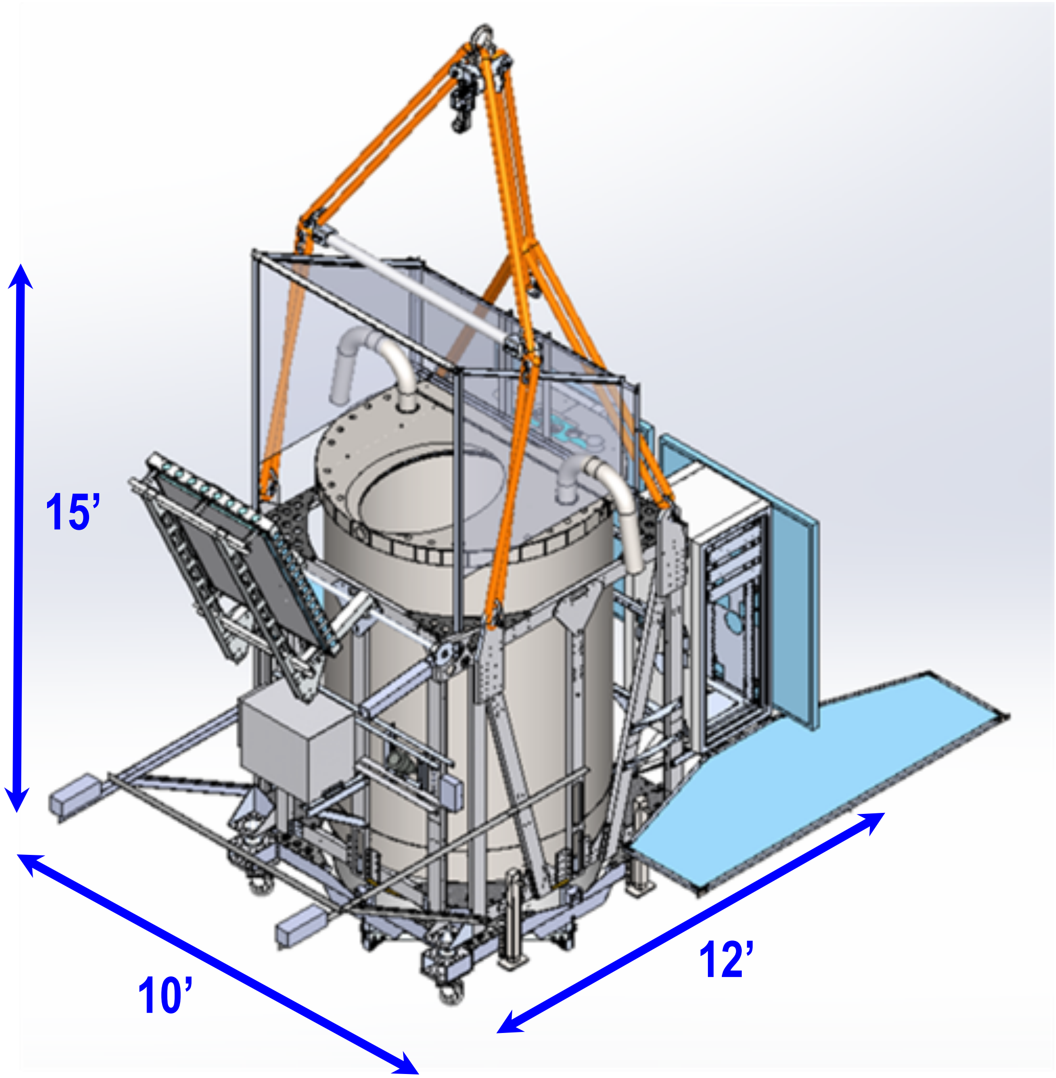
Preliminary Simulation


CIIxQSO: z= 2.50- 3.50

Assuming MKID noise 3x background limit, baseline sensitivity.

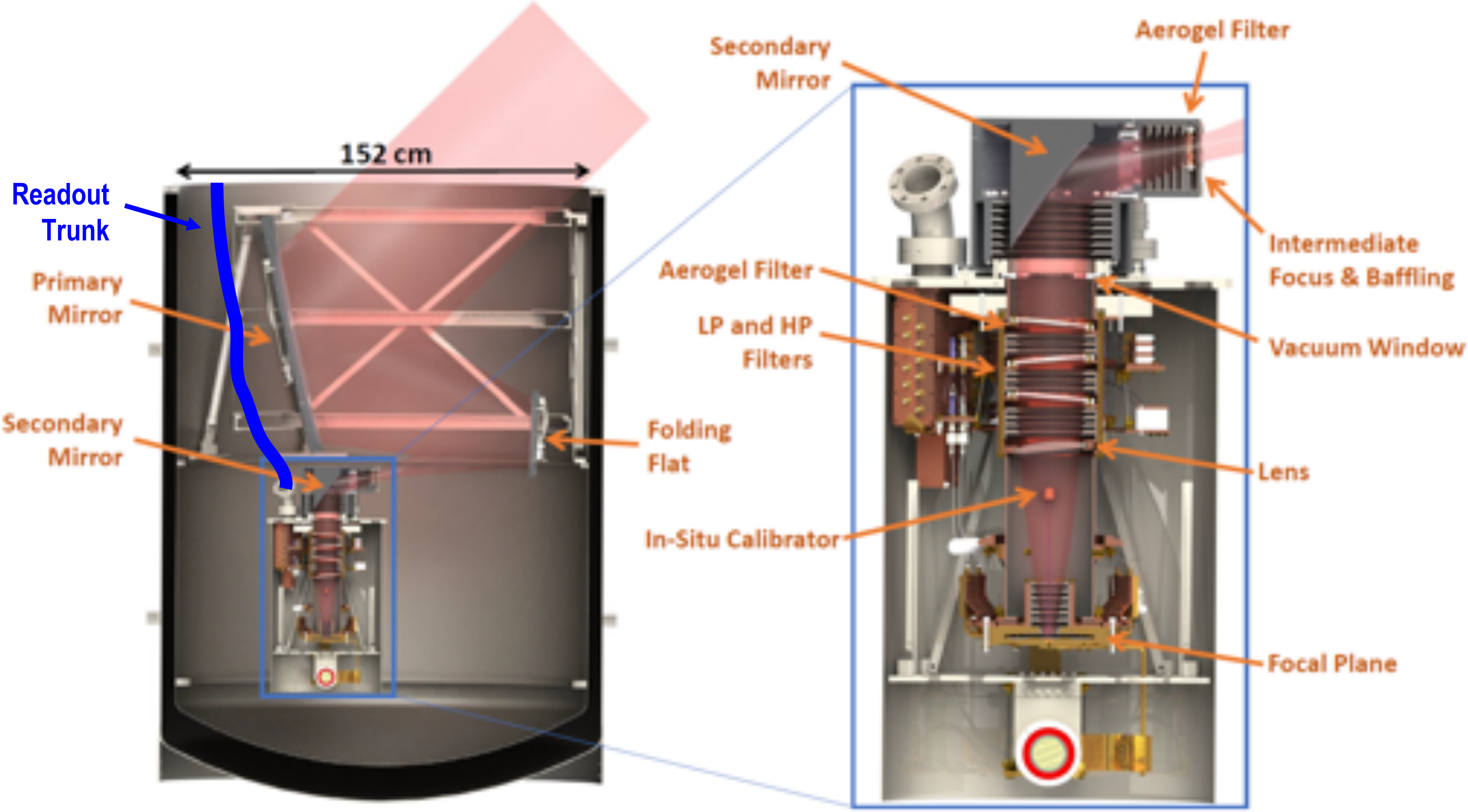
EXCLAIM Technical Approach

Payload and Mission Overview



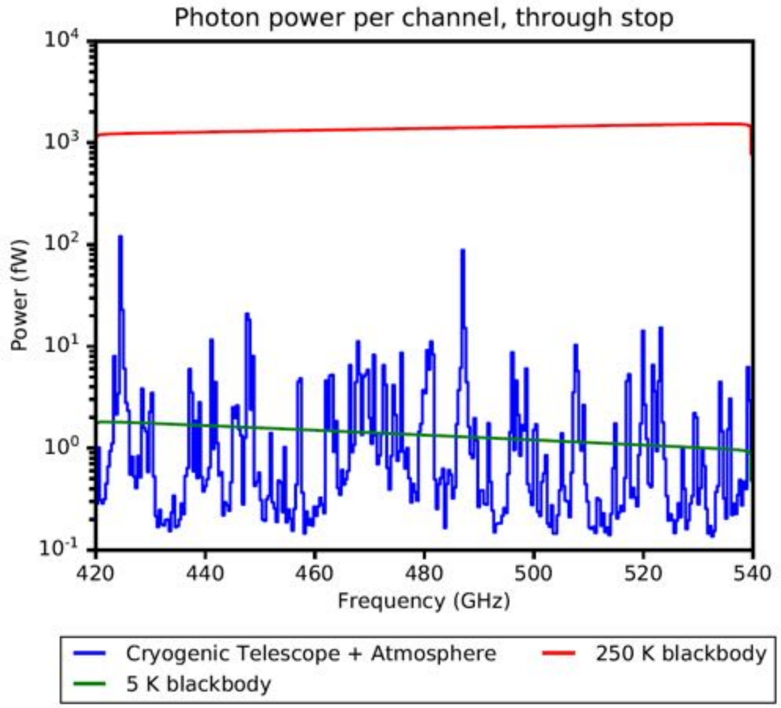
- Conventional (e.g. 1-day) flight (Ft. Sumner, NM, primary, Palestine, TX, secondary).
- 3500 l LHe Bucket dewar
- ~2400 kg dry mass, 34 MCF balloon.
- ~2000 l LHe fill gives 18 hr of 1.7 K operation at float.
- Superfluid fountain effect pumps cool optics to 1.7 K.
- Scan ~7° in azimuth at fixed elevation 45°.
- Long axis of the primary is 90 cm. The 76 cm projected aperture provides ~3’ FWHM.
- ARCADE/PIPER heritage.

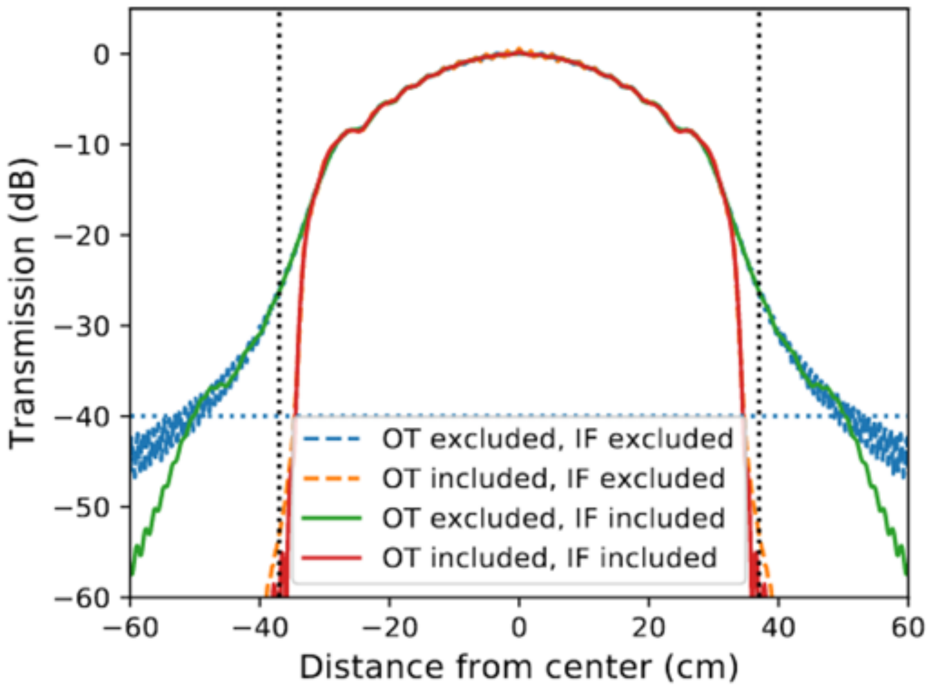
Optics Design



Diffraction Analysis

- To achieve the target EXCLAIM sensitivity in dark atmospheric windows, diffracted spill onto warm surfaces must be carefully controlled.
- The EXCLAIM optics were designed from the ground up with control of stray light in mind.
- Analysis of diffraction in the EXCLAIM optics is on-going with a mixture of:
  - Analytical calculations of an on-axis analog system with POPPY (python code developed for JWST, fast, allows iteration of baffle designs)
  - Physical optics finite-element analysis using Microwave CST Studio.





PIPER Cryogenic telescope operation

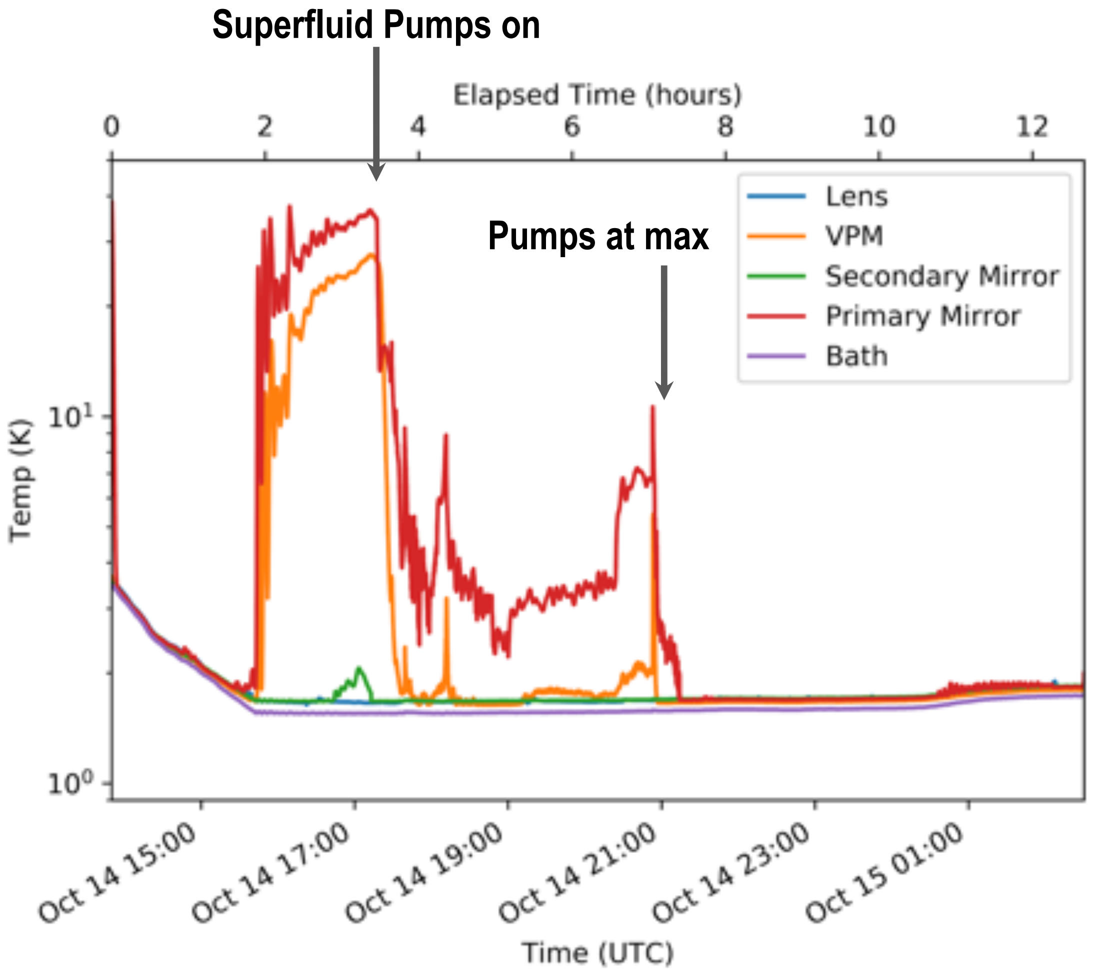
Primary starts ~90 K.

Receiver ~6 K
Sitting out of LHe initially.

Primary cooled by rapid gas flow: ~½ LHe boils on ascent.

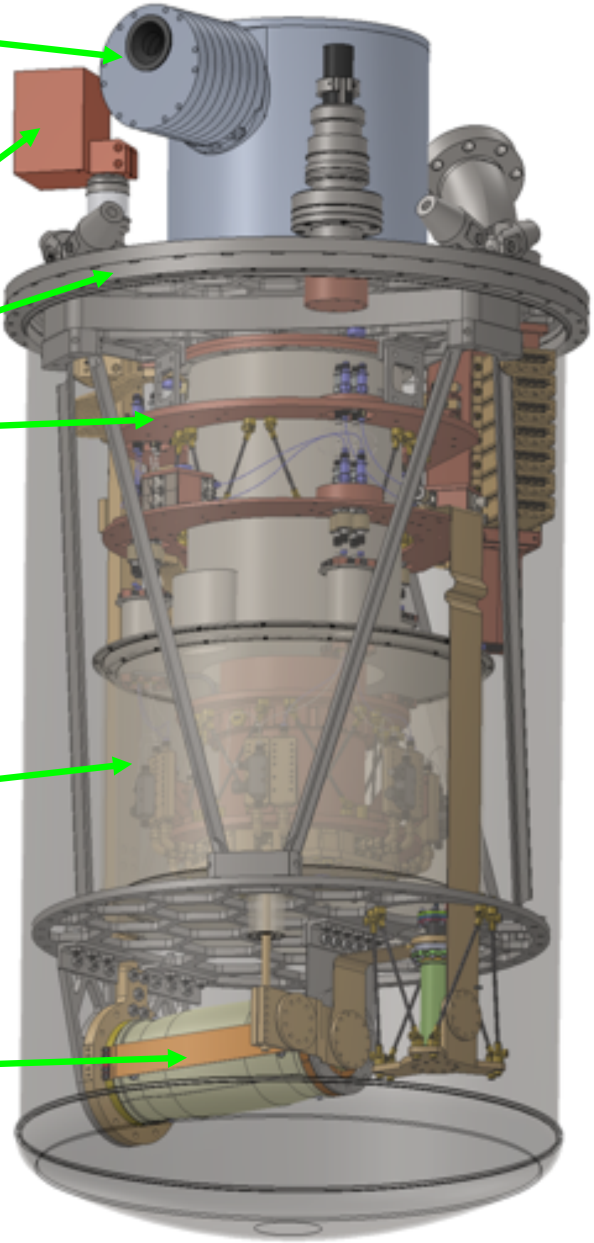
Gradually stratifies, low atmospheric pressure gives poor conduction.

Low temperature -> Low heat capacity, rapid warming.



PIPER 2019 Flight

Receiver Overview



Optical baffling

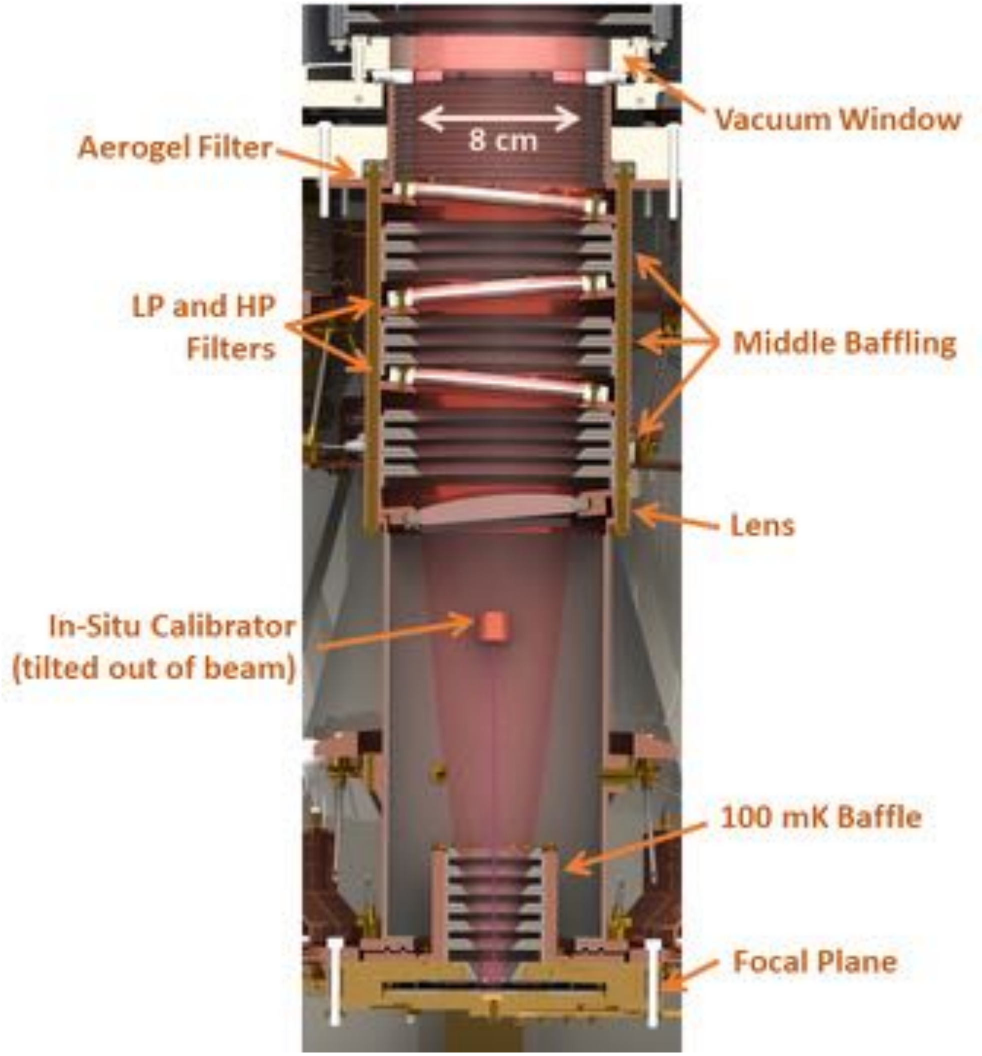
Thermal feedthrough

Superfluid seal

4K RF: LNAs

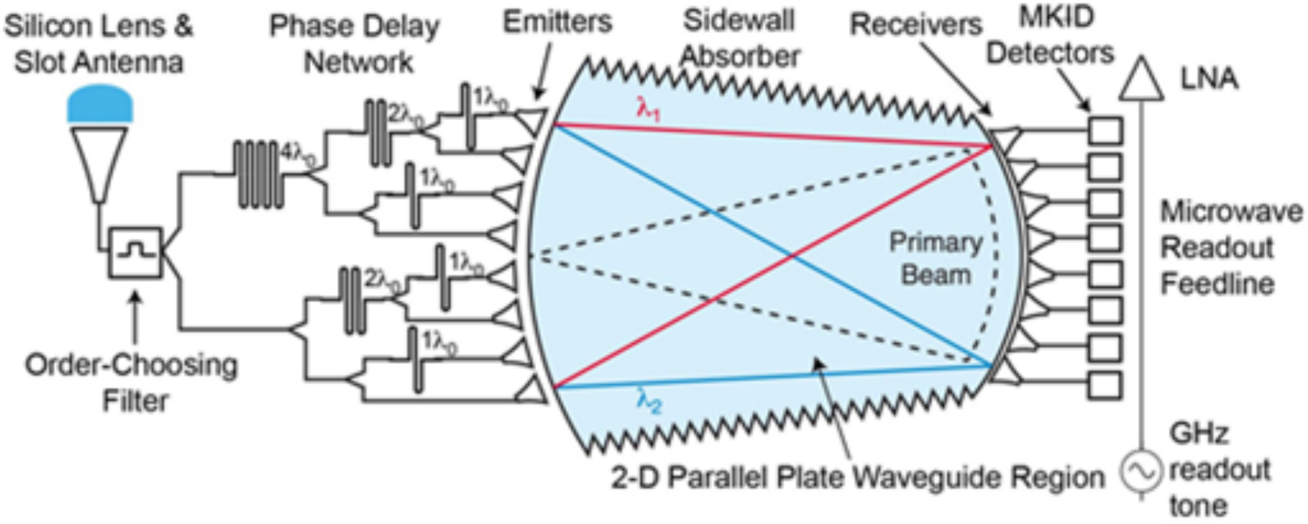
Two-layer
Amnueal shield
~10000x

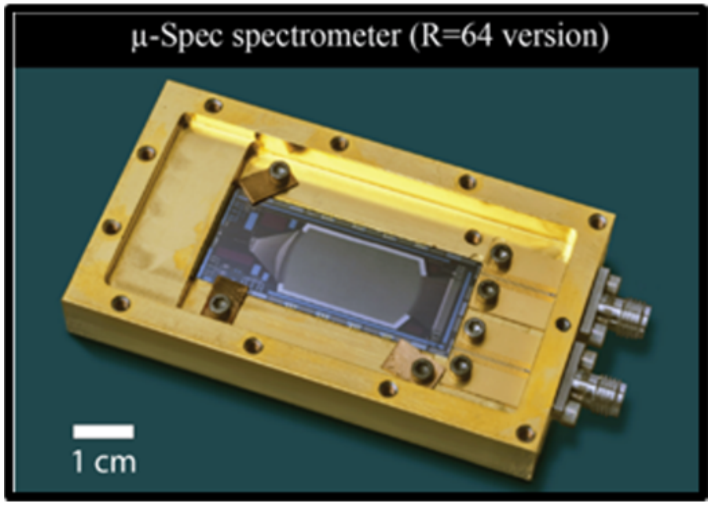
ADR (100 mK)



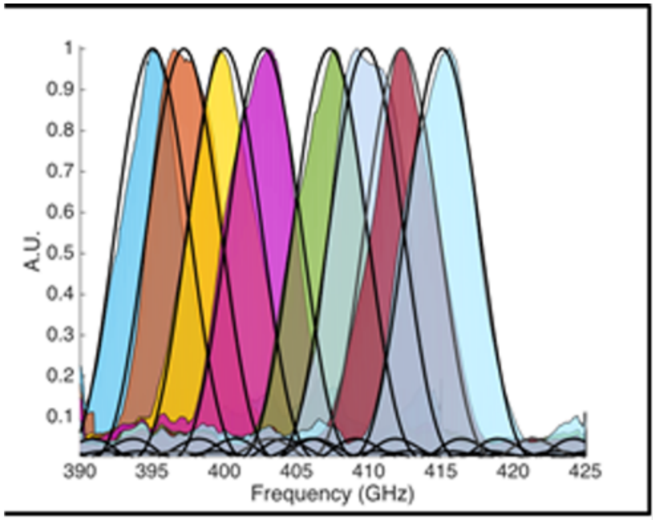
Alex Lamb and Jonas Mugge-Durum (interns)

μ-Spec: An Integrated Grating-Analog Spectrometer



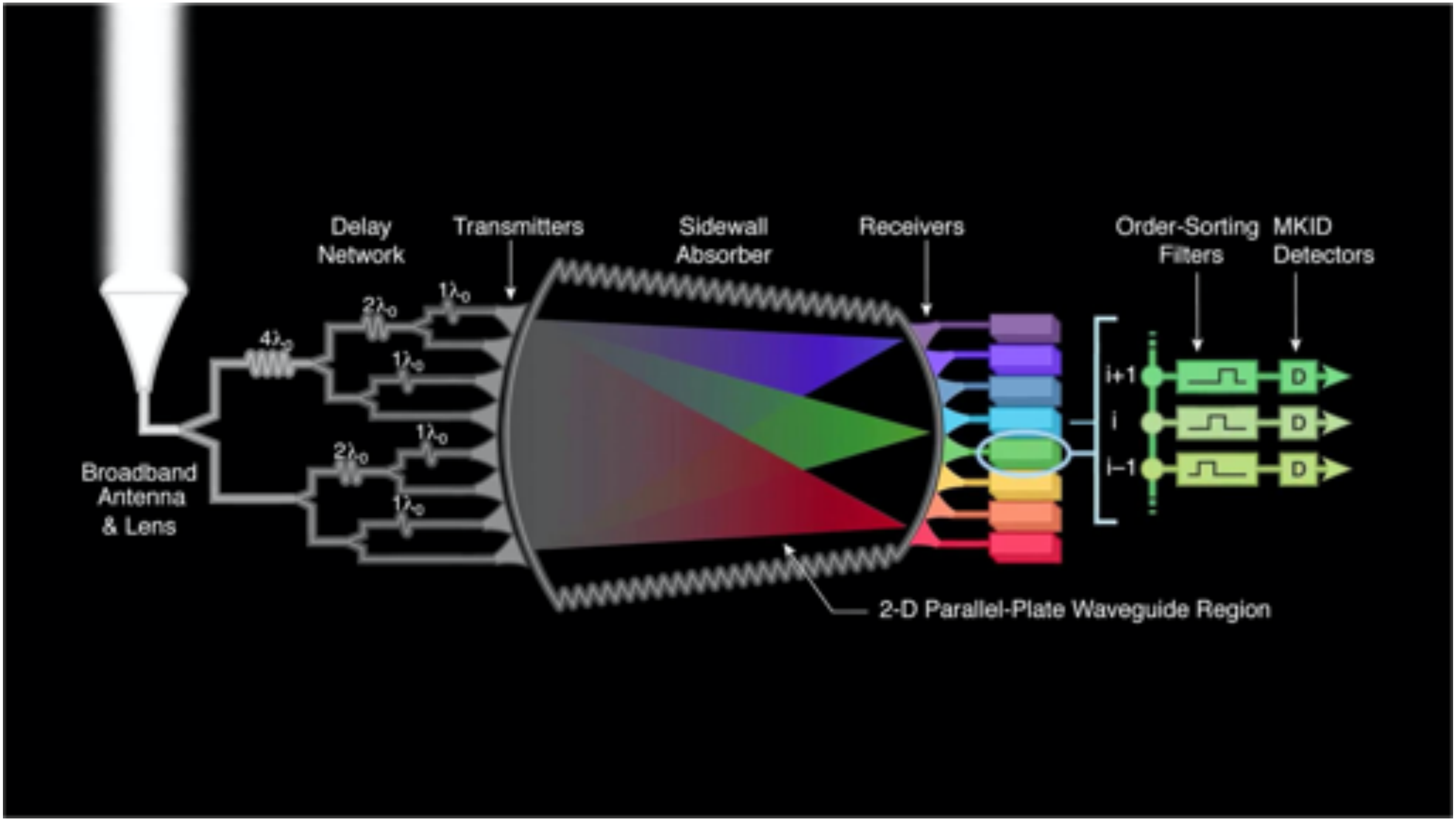

μ-Spec spectrometer (R=64 version)

- μ-Spec integrates all the elements of a grating spectrometer on a single silicon chip, providing order of magnitude reduction in size.
- Phase delay is introduced by a synthetic ‘grating’ consisting of a meandered superconducting niobium microstrip transmission lines on a single-crystal silicon substrate.
- The high index of refraction of silicon allows us to introduce the required phase delay in a compact space.
- The low-loss of single-crystal silicon and the superconducting transmission lines provides high efficiency and resolution.
- We use Microwave Kinetic Inductance Detectors (KIDs) due to their intrinsic multiplexing capability and capability to reach ultra-low sensitivity.

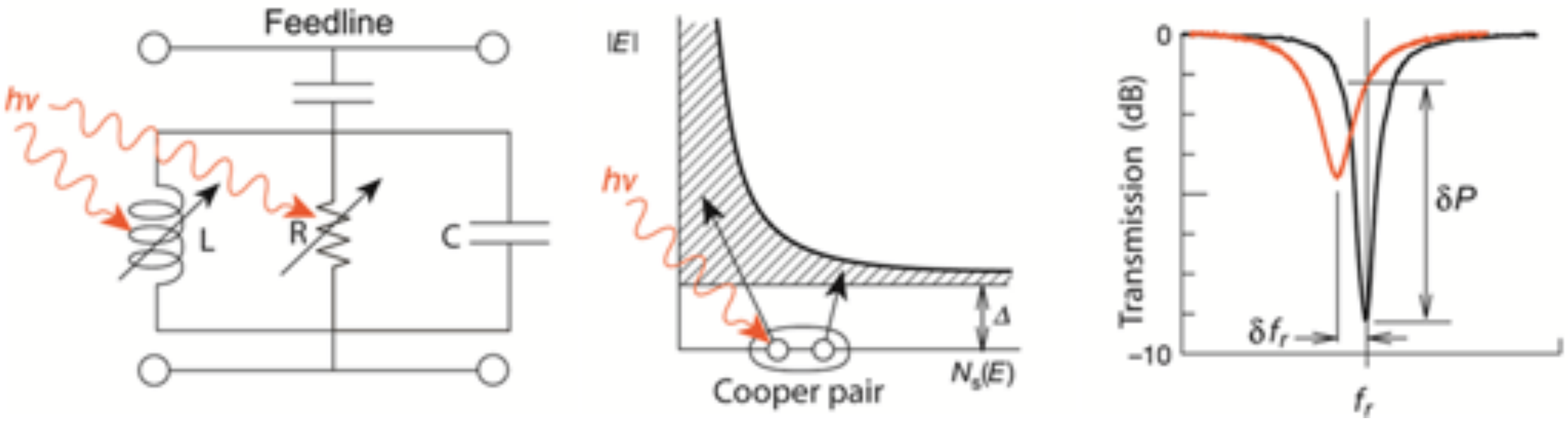


Heritage: ROSES APRA R=64 development & demo (PI: S. Harvey Moseley)

µ-Spec operation

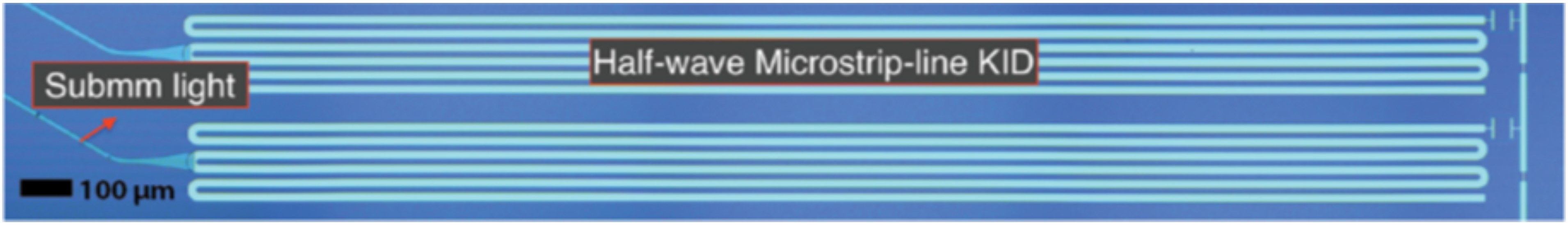


Microwave Kinetic Inductance Detectors (MKIDs)



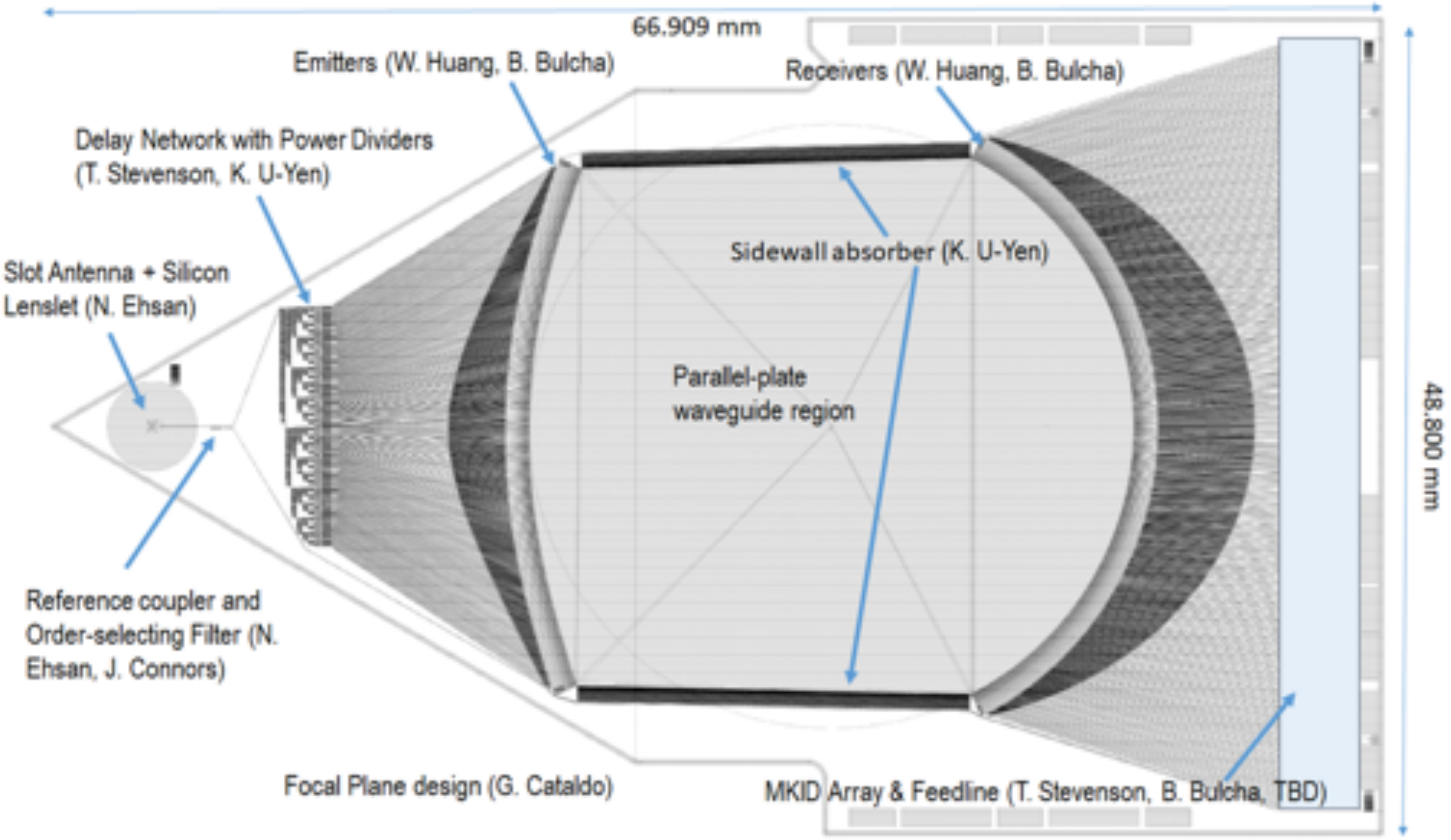
- Microwave Kinetic Inductance Detectors (MKIDs) are superconducting thin film (microwave) resonators.
- Photons break bound 'Cooper pairs' electrons in the superconductor and create quasiparticle (normal-electron) excitations in the film, which change the surface impedance of the film. This leads to 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



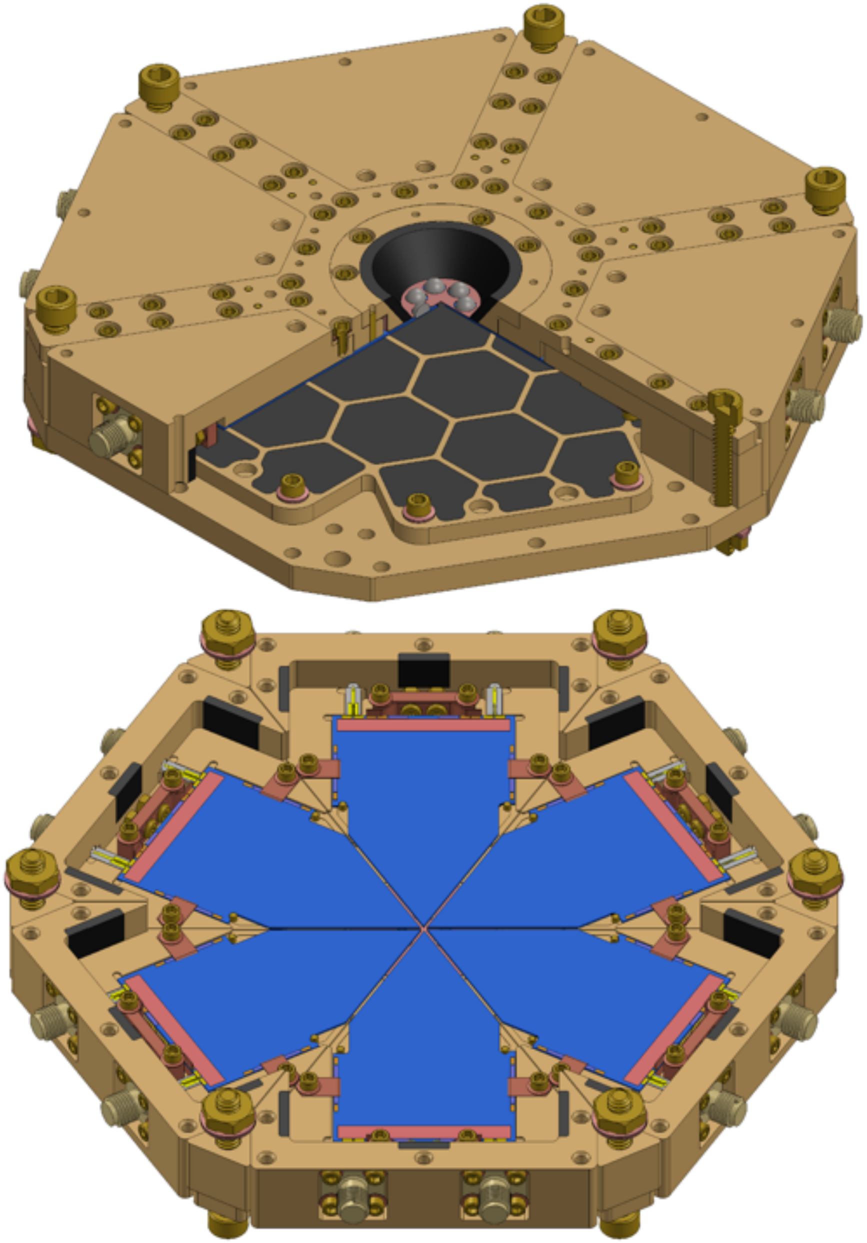
- Aluminum (top absorber) / niobium (ground plane) film in a microstrip transmission line resonator design.
- The microstrip architecture (like the rest of the spectrometer design) provides high immunity to stray light.
- Unlike nitride superconducting films (another popular choice for MKIDs), Al films follow well-predicated superconducting theory.
- Microwave loss in the film and dielectric systems (often dominated by two-level systems in amorphous dielectrics on the surfaces) is an important detector performance parameter:
  - The single-crystal silicon dielectric provides lower loss than deposited dielectrics.
  - Thin Al films (10-20 nm thick) fabricated in Goddard’s Detector Development Laboratory (DDL) have world record high internal microwave quality factors ~ 2-7 million (O. Noroozian, A. Brown, E. Barrentine, C. Volpert)
  - Nb films fabricated via liftoff process also have sufficiently high quality factors Q (L. Hess, E. Barrentine).

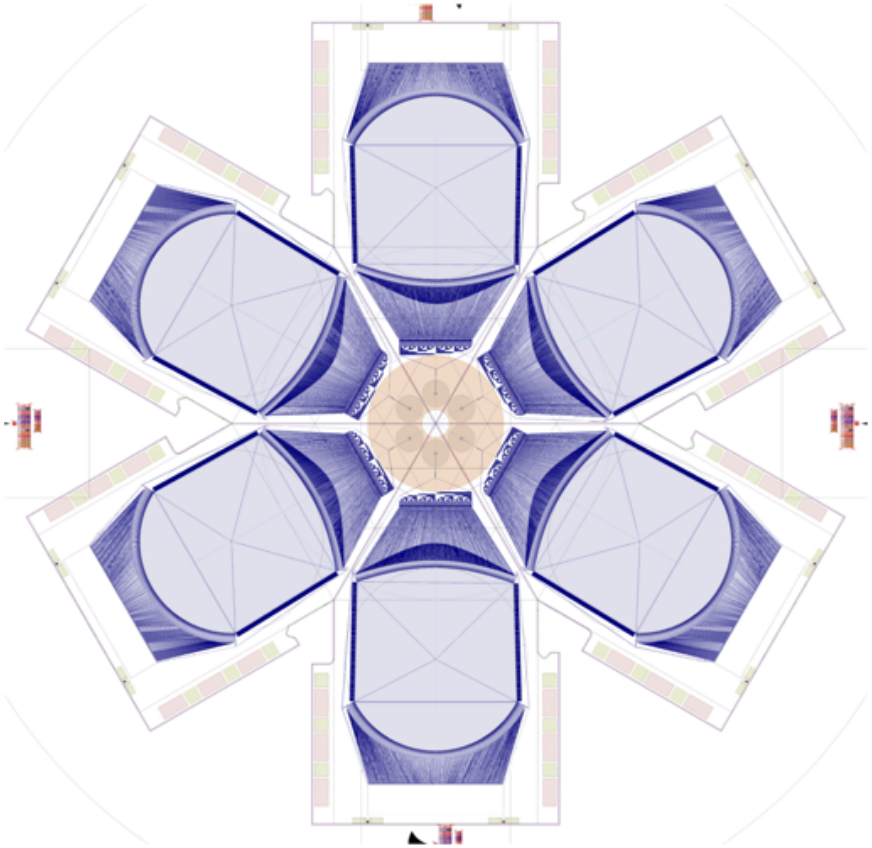
EXCLAIM Spectrometer Design (Mask Layout)



Lead: Emily Barrentine

Detector package



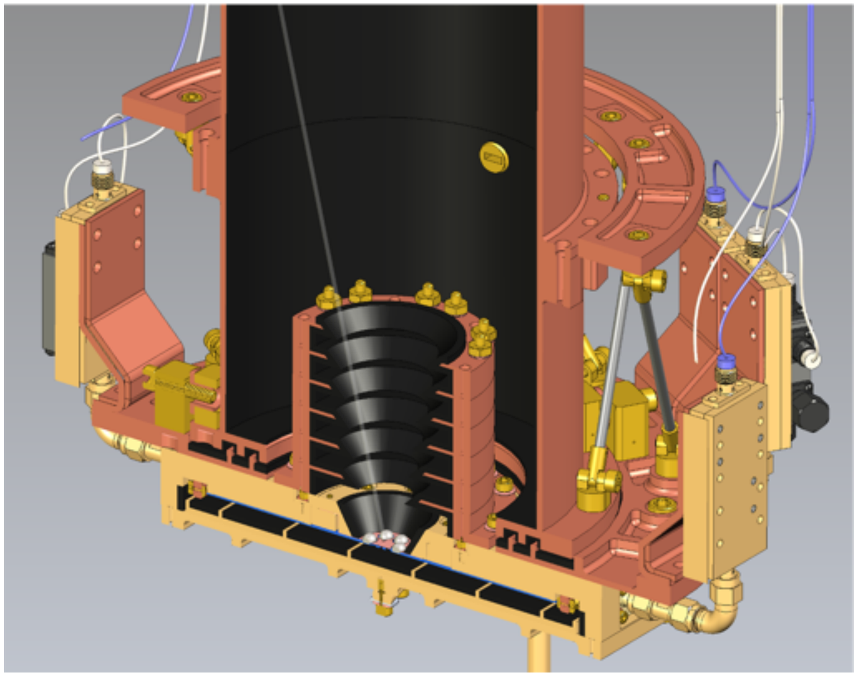


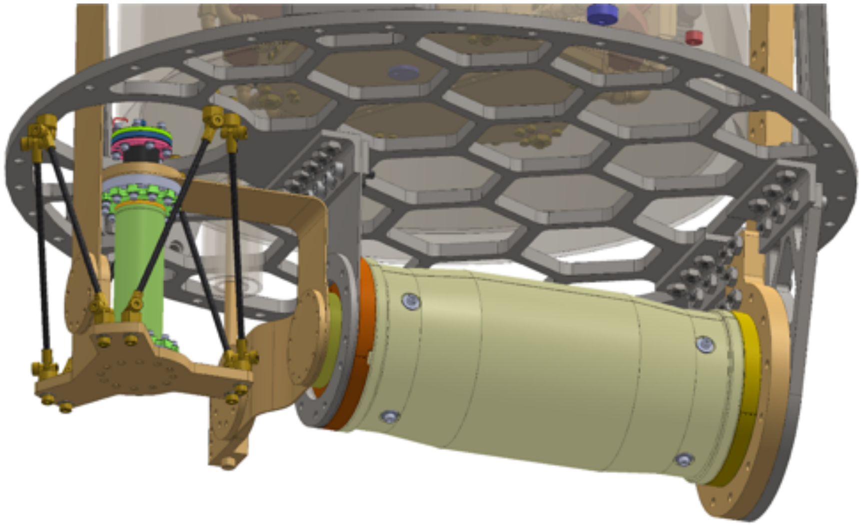
- 6 lenslets packed into hexagon.
- Capability for single 6” wafer with 6 spectrometers or 6 individually-characterized chips.

Emily Barrentine, Tom Essinger-Hileman, Jonas Mugge-Durum (intern)

Focal plane cooling

- Thermal generation noise is exponentially activated
- For aluminum resonators, maintain temperature below 125 mK: negligible contribution.
- Focal plane cooled to ~100 mK using adiabatic demagnetization refrigerator with heritage from Hitomi (prev. Astro-H).
- Receiver interior is maintained at pumped LHe bath ~1.7 K.
- Carbon fiber for thermal isolation from bath provides highly rigid support of detector package.
- Intermediate 900 mK stage (^{4}He adsorption cooler) allows for long hold time with single-stage ADR.



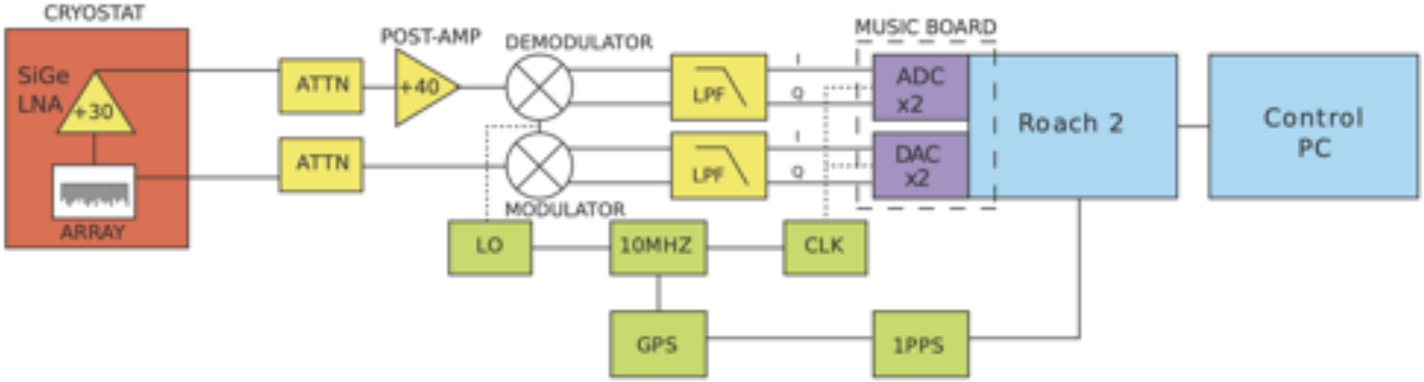


Jonas Mugge-Durum (intern)

Readout

- Readout from ASU with balloon heritage in BLAST-TNG and OLIMPO. Pursuing RFSoC (SAT).
- Prototype of integrated IF board for 3 GHz resonators.

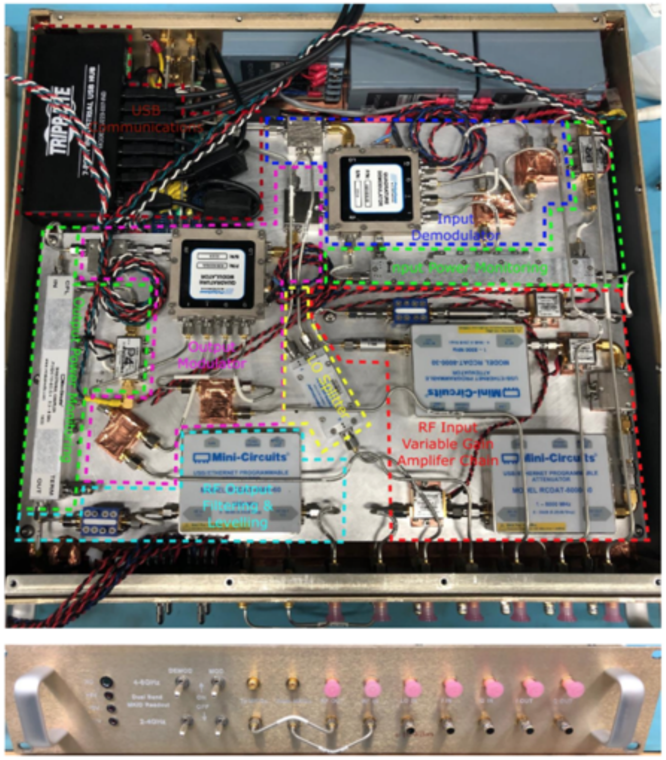
P. Mauskopf (BLAST-TNG)



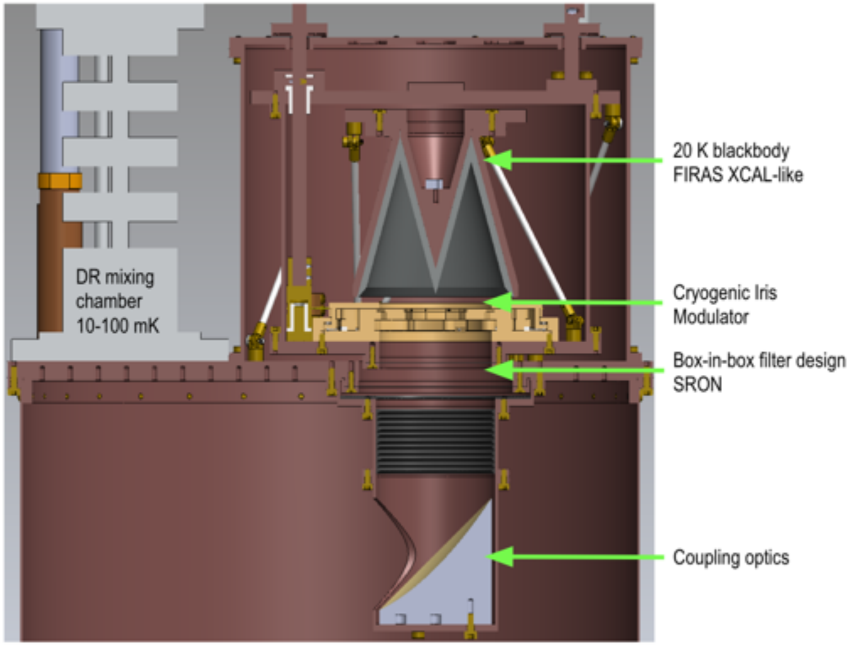
Gordon+ 2016

Detector test facility

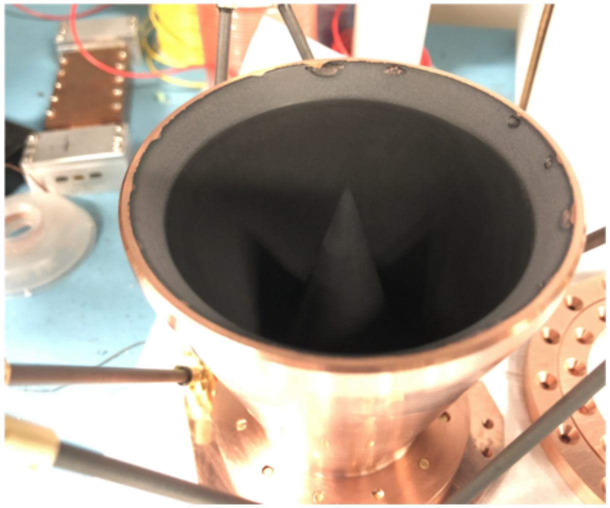
- VNA + direct sample for individual MKID characterization.
- Single-spectrometer (lab test) intermediate frequency (IF) electronics.

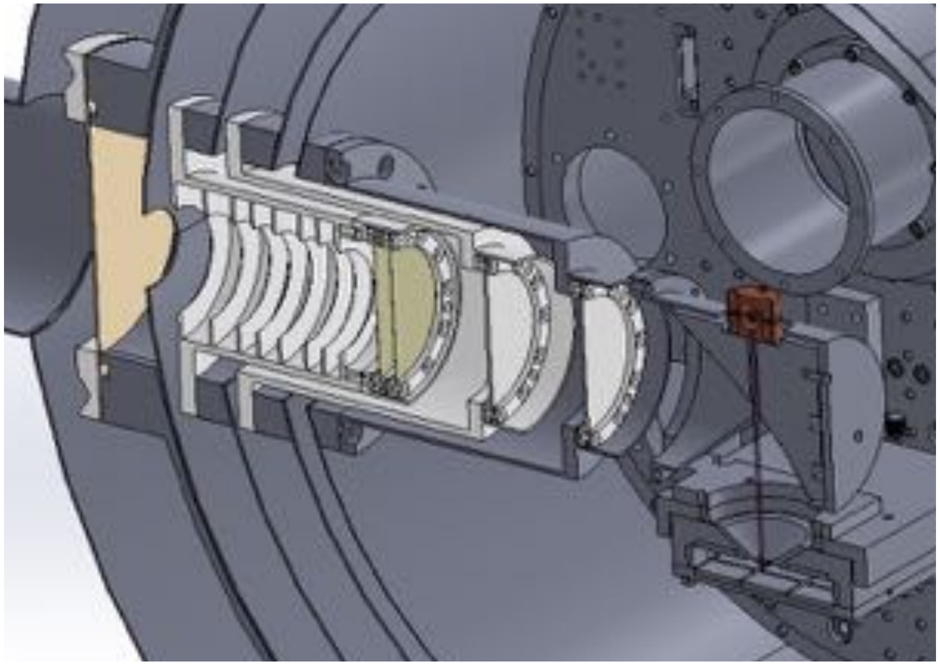


Spectrometer Characterization: Blue Fors DR

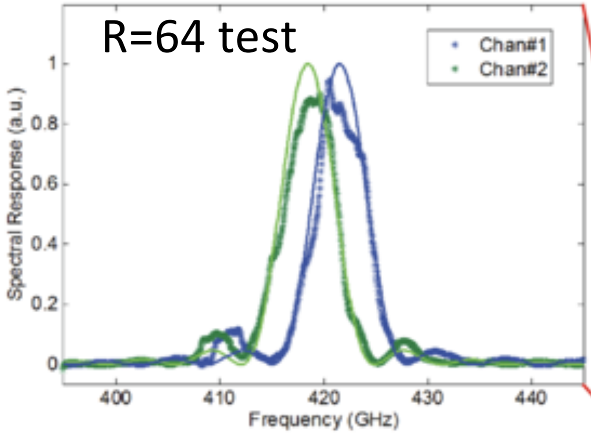


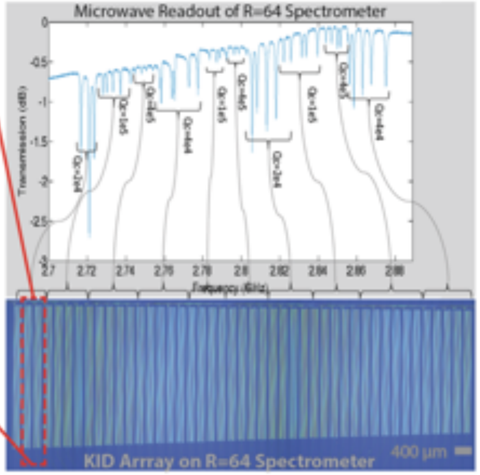
Commissioning Blackbody source (NEP, eff)





External coupling to Toptica photomixer (operating) or Virginia Diodes source (new). Measurement of spectral response.





Receiver test facilities

Long-term integrated test of receiver core in cryocooler lab system.

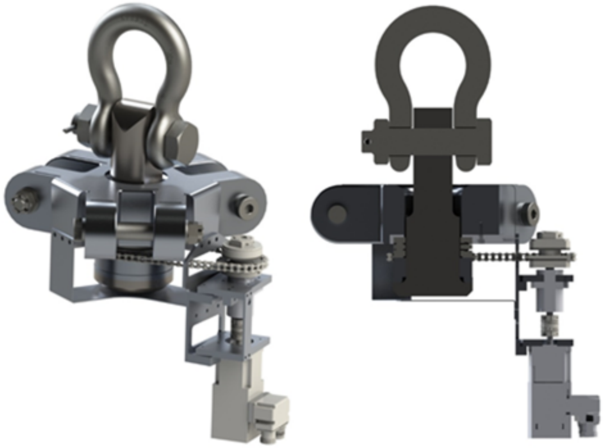
Commissioning phase (all parts in-hand).

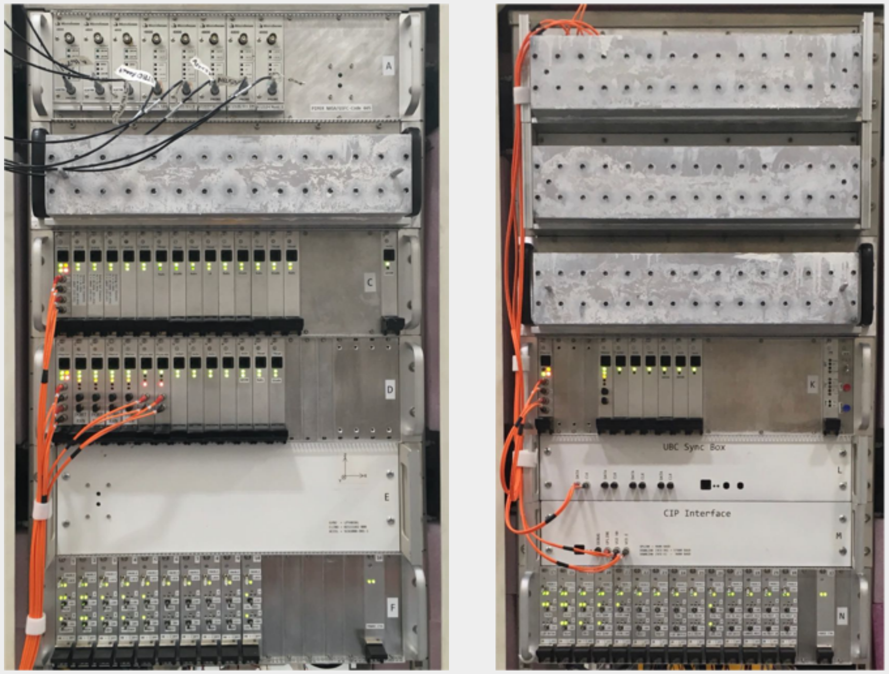
~2 weeks of test in a person-sized dewar with high-throughput pump to simulate float.

Test as you fly. (PIPER heritage)

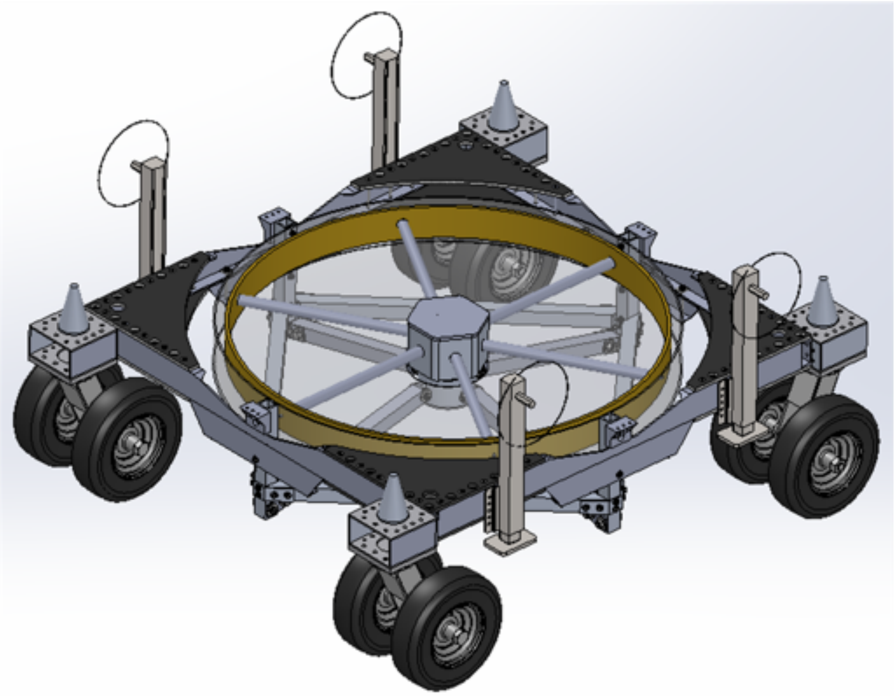
Electronics and attitude control

- Attitude control system based on SPIDER.
- Rotator design based on PIPER.
- Mission survey plan, scan strategy defined
- Mass model has high fidelity from heritage
- Flight electronics largely built to print from PIPER.

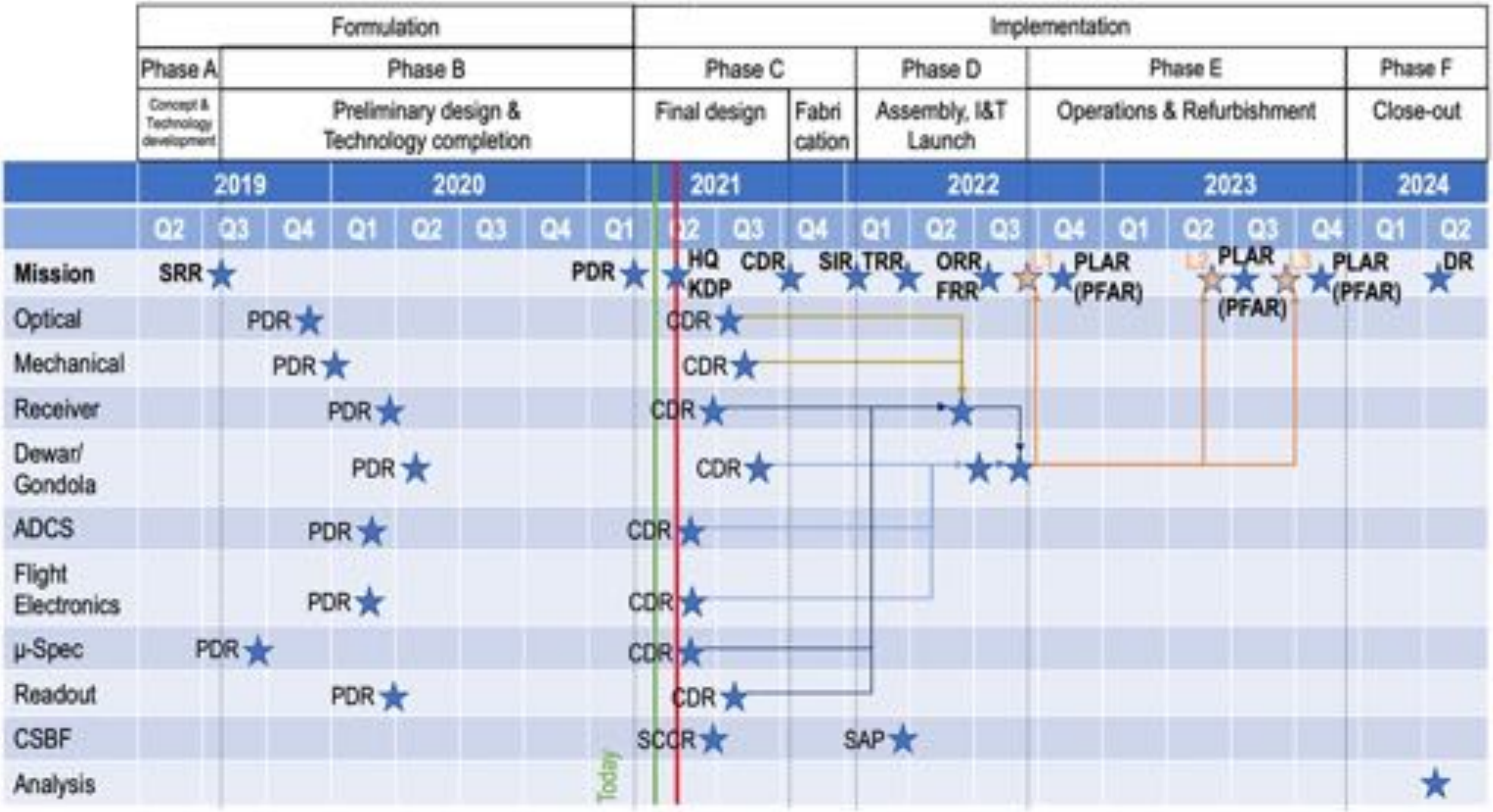




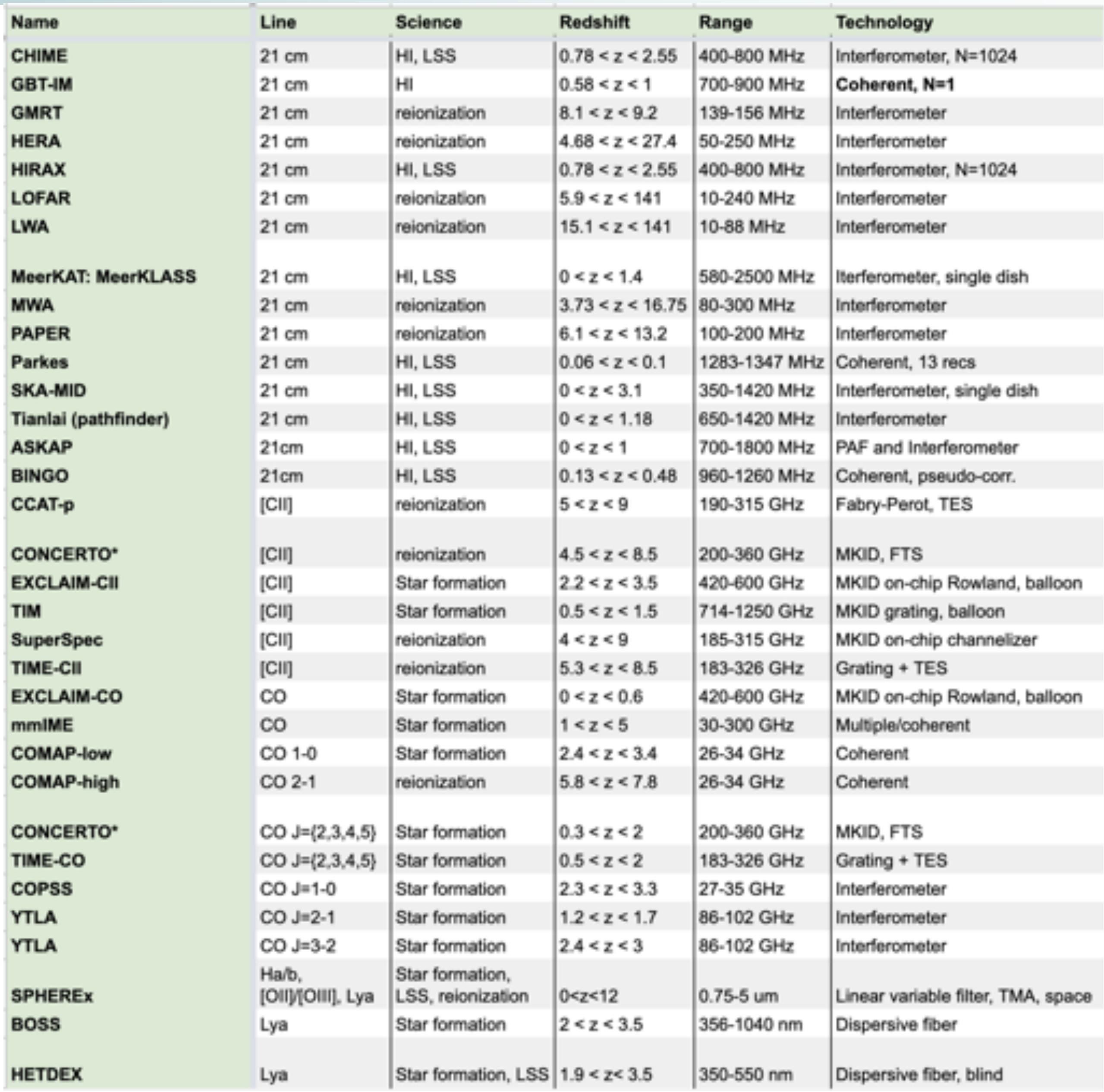
PIPER flight electronics



EXCLAIM mission life cycle



Current and future efforts



Name	Line	Science	Redshift	Range	Technology
CHIME	21 cm	HI, LSS	0.78 < z < 2.55	400-800 MHz	Interferometer, N=1024
GBT-IM	21 cm	HI	0.58 < z < 1	700-900 MHz	**Coherent, N=1**
GMRT	21 cm	reionization	8.1 < z < 9.2	139-156 MHz	Interferometer
HERA	21 cm	reionization	4.68 < z < 27.4	50-250 MHz	Interferometer
HIRAX	21 cm	HI, LSS	0.78 < z < 2.55	400-800 MHz	Interferometer, N=1024
LOFAR	21 cm	reionization	5.9 < z < 141	10-240 MHz	Interferometer
LWA	21 cm	reionization	15.1 < z < 141	10-88 MHz	Interferometer
MeerKAT: MeerKLASS	21 cm	HI, LSS	0 < z < 1.4	580-2500 MHz	Iterferometer, single dish
MWA	21 cm	reionization	3.73 < z < 16.75	80-300 MHz	Interferometer
PAPER	21 cm	reionization	6.1 < z < 13.2	100-200 MHz	Interferometer
Parkes	21 cm	HI, LSS	0.06 < z < 0.1	1283-1347 MHz	Coherent, 13 recs
SKA-MID	21 cm	HI, LSS	0 < z < 3.1	350-1420 MHz	Interferometer, single dish
Tianlai (pathfinder)	21 cm	HI, LSS	0 < z < 1.18	650-1420 MHz	Interferometer
ASKAP	21cm	HI, LSS	0 < z < 1	700-1800 MHz	PAF and Interferometer
BINGO	21cm	HI, LSS	0.13 < z < 0.48	960-1260 MHz	Coherent, pseudo-corr.
CCAT-p	[CII]	reionization	5 < z < 9	190-315 GHz	Fabry-Perot, TES
CONCERTO*	[CII]	reionization	4.5 < z < 8.5	200-360 GHz	MKID, FTS
EXCLAIM-CII	[CII]	Star formation	2.2 < z < 3.5	420-600 GHz	MKID on-chip Rowland, balloon
TIM	[CII]	Star formation	0.5 < z < 1.5	714-1250 GHz	MKID grating, balloon
SuperSpec	[CII]	reionization	4 < z < 9	185-315 GHz	MKID on-chip channelizer
TIME-CII	[CII]	reionization	5.3 < z < 8.5	183-326 GHz	Grating + TES
EXCLAIM-CO	CO	Star formation	0 < z < 0.6	420-600 GHz	MKID on-chip Rowland, balloon
mmIME	CO	Star formation	1 < z < 5	30-300 GHz	Multiple/coherent
COMAP-low	CO 1-0	Star formation	2.4 < z < 3.4	26-34 GHz	Coherent
COMAP-high	CO 2-1	reionization	5.8 < z < 7.8	26-34 GHz	Coherent
CONCERTO*	CO J={2,3,4,5}	Star formation	0.3 < z < 2	200-360 GHz	MKID, FTS
TIME-CO	CO J={2,3,4,5}	Star formation	0.5 < z < 2	183-326 GHz	Grating + TES
COPSS	CO J=1-0	Star formation	2.3 < z < 3.3	27-35 GHz	Interferometer
YTLA	CO J=2-1	Star formation	1.2 < z < 1.7	86-102 GHz	Interferometer
YTLA	CO J=3-2	Star formation	2.4 < z < 3	86-102 GHz	Interferometer
SPHEREx	Ha/b, [OII]/[OIII], Lya	Star formation, LSS, reionization	0<z<12	0.75-5 um	Linear variable filter, TMA, space
BOSS	Lya	Star formation	2 < z < 3.5	356-1040 nm	Dispersive fiber
HETDEX	Lya	Star formation, LSS	1.9 < z< 3.5	350-550 nm	Dispersive fiber, blind

Summary

- Intensity mapping has numerous applications and significant experimental effort.
- The EXCLAIM mission seeks to measure CO, [CII] emission from $0<z<3.5$, and Milky Way lines.
- EXCLAIM uses a compact on-chip spectrometer coupled to a cryogenic telescope. This provides sufficient sensitivity for cross-correlation with BOSS in a conventional flight.