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

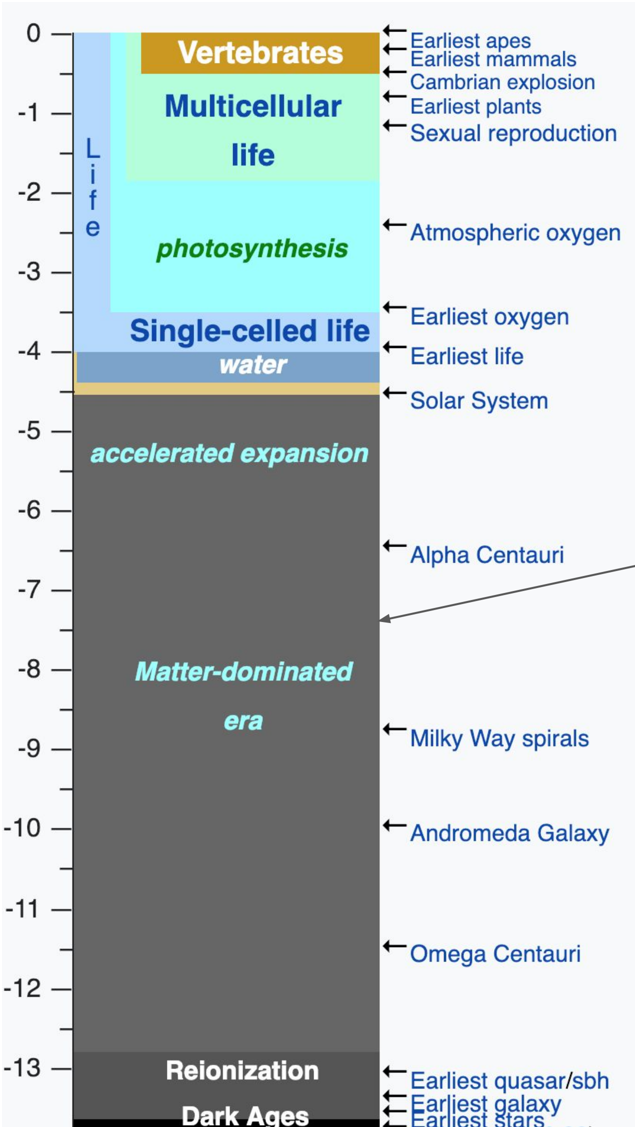
Eric Switzer
NASA GSFC

GSFC: mission lead
ASU: readout
CCA: science
CITA: science
NYU: science lead
UMD: instrument/science
UMich: instrument

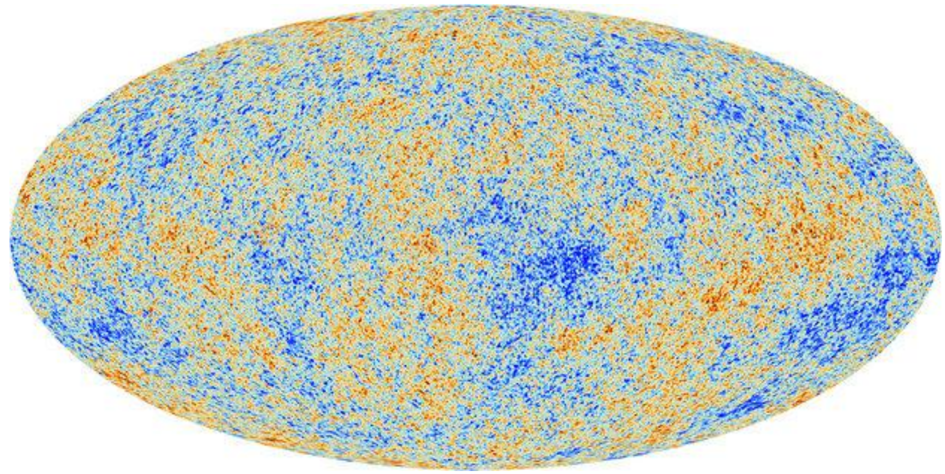
Starting now!

*Logo not final; recommendations?

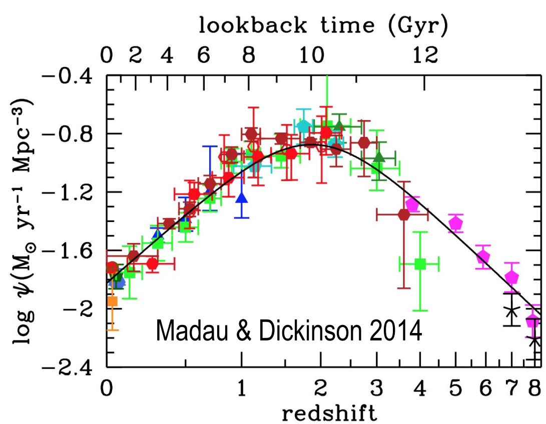
How did we get here?



wikipedia



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



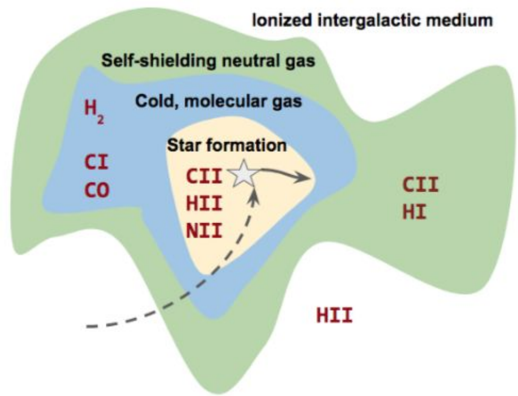
How much gas is available to form stars across time?

Pathfinder:
Can we use cooling line emission to learn about the first stars/galaxies?

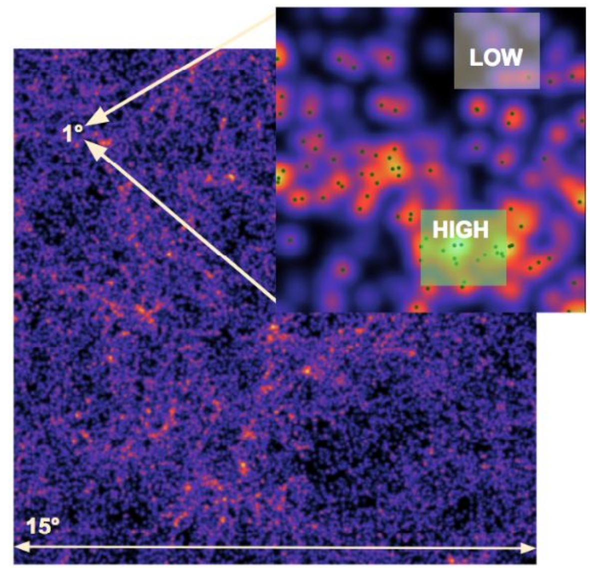
Can we economically survey large 3-D volumes of the universe to learn more of its history?

Science goals

- What factors led to the dramatic decline in star formation since z ~ 2? DM halos grow 100x while SFR declines 20x. Only 5% baryons end up in stars.
- What is the typical abundance, excitation and evolution of the molecular gas which forms stars?
- How well does CO trace H_2 in galaxies? Map CI in a Milky Way region.
- Is intensity mapping a viable approach to probe high redshifts?



- 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).



Simulation of line brightness contrast from 0.25 < z < 0.3 in a 15 deg^2 region (inset 1° region with points typical of a galaxy survey). On small scales, clustering can bias the sample (high vs. low)

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.

Science goals: lines and levels

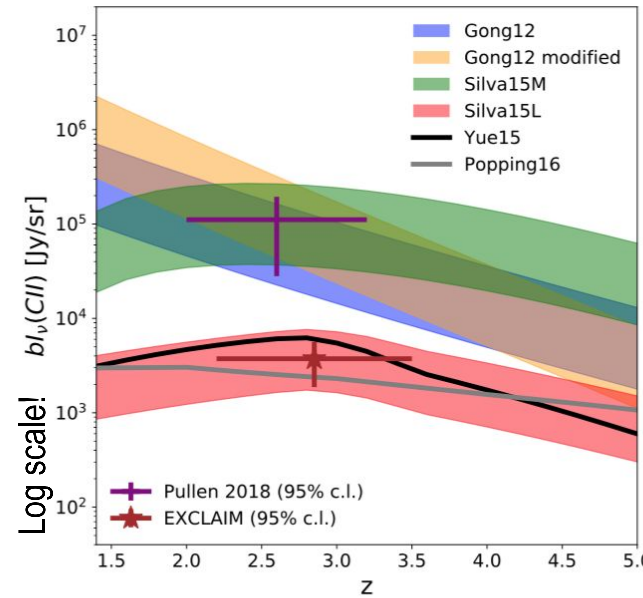
Map both CII and CO, including coverage of adjacent CO ladder emission at common z. **R=512 421-540 GHz, ~400 deg^2, BOSS Cross-correlation.**

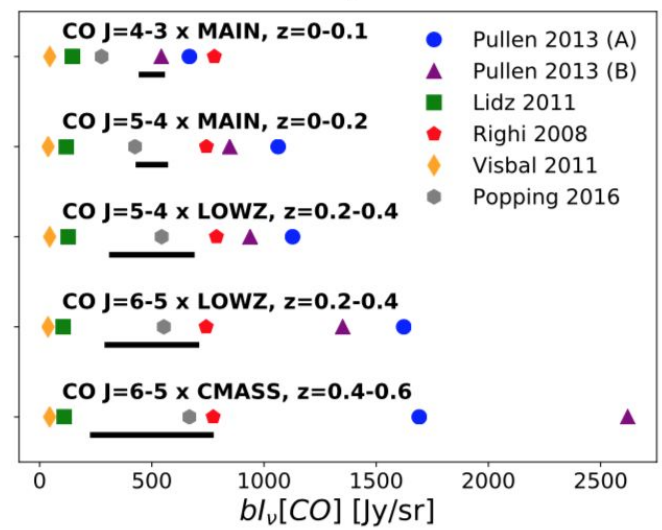
CII: BOSS QSO correlation for 2.5 < z < 3.5. Definitive test of CII brightness in *Pullen+ 2018*. What is the CII-SFR relation? See *Padmanabhan 2018* for interpretation.

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?
- Decarli+ 2016 find 3-10x decline in H_2 from z=2 to z=0. **IM is sensitive to integral emission and bias**.

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*

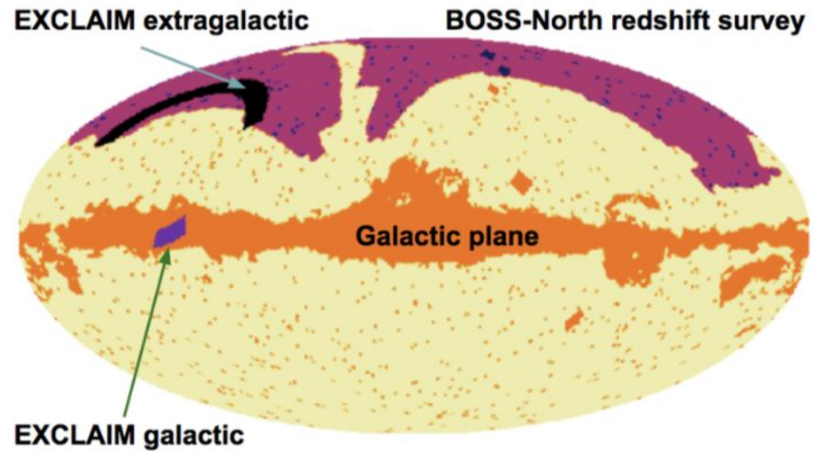




A. Pullen (Science Lead)

Strategy

- **Cross-correlation with BOSS for primary science**
- Large area: Cross-correlation can/should go **wide**; in contrast, auto-power aims for SNR~1 per mode.
- Access **linear scales** up to k~1 h Mpc^{-1}.
- **Cryogenic telescope** for faster integration in dark atmospheric windows
- **On-chip MKID spectrometer**
- **Conventional flight** from TX or NM: well-matched to BOSS-North region, simple logistics, high recovery rate, more flights.



- Engineering flight (June 2021): one spectrometer, sky dips to verify atmospheric line model; galactic and preliminary extragalactic.
- Science flight (June 2022): 6 spectrometers
- Versatile platform for testing FIR spectrometer technology in space-like environment.

Extragalactic field: 8 PM - 4 AM, 408 deg^2 using 10° Az scan (-35° center)

Galactic region: 4 AM - 6 AM, 90 deg^2 using 10° Az scan (+30° center)

Reference mission parameters:
408 deg^2 survey in BOSS-North
90 deg^2 galactic region

Preliminary: may change with primary illumination, 1/f, scan constraints.

Interpretation

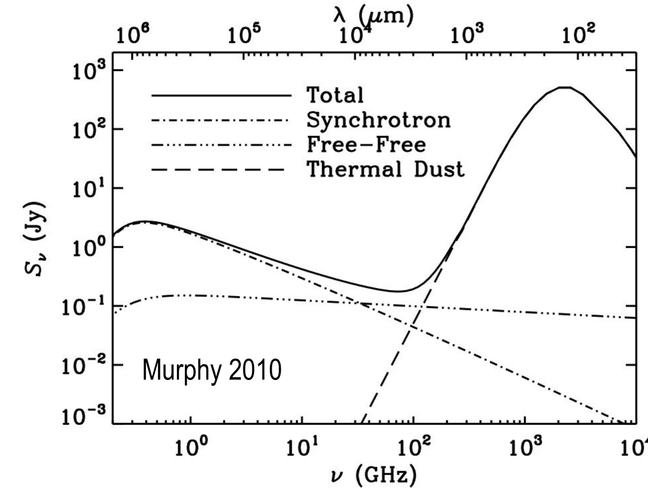
Milky Way cleaning: blind, parametric, spatial templates. **Residual MW becomes cross-power errors, not bias**: pick approach best MW suppression and least signal loss.

Correlated continuum can destroy long LOS modes, but should remain well-isolated.

Areas for work:

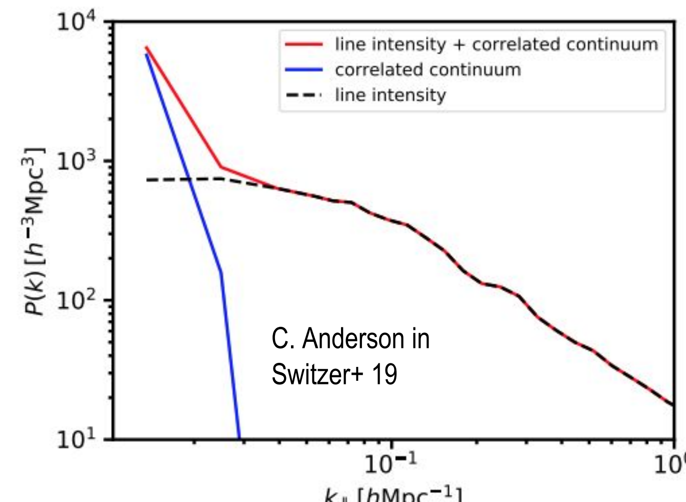
- Connecting CO and CII observations to galaxy properties and evolution (SAM).
- Grating spectrometers have sinc^2 spectral response (most analysis to-date is tophat)
- Interpretation of one-halo and shot noise scales.
- Cross-correlation against different galaxy selection? Correlated shot noise (Wolz+ 2017)?
- Galactic science: interpretation of [CI].
- Luminosity relations, scaling and evolution (Padmanabhan+ 2018):

$$L_{\rm CII}(M,z) = \left(\frac{M}{M_1}\right)^{\beta} \exp(-N_1/M) \left(\frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}}\right)^{\alpha}$$

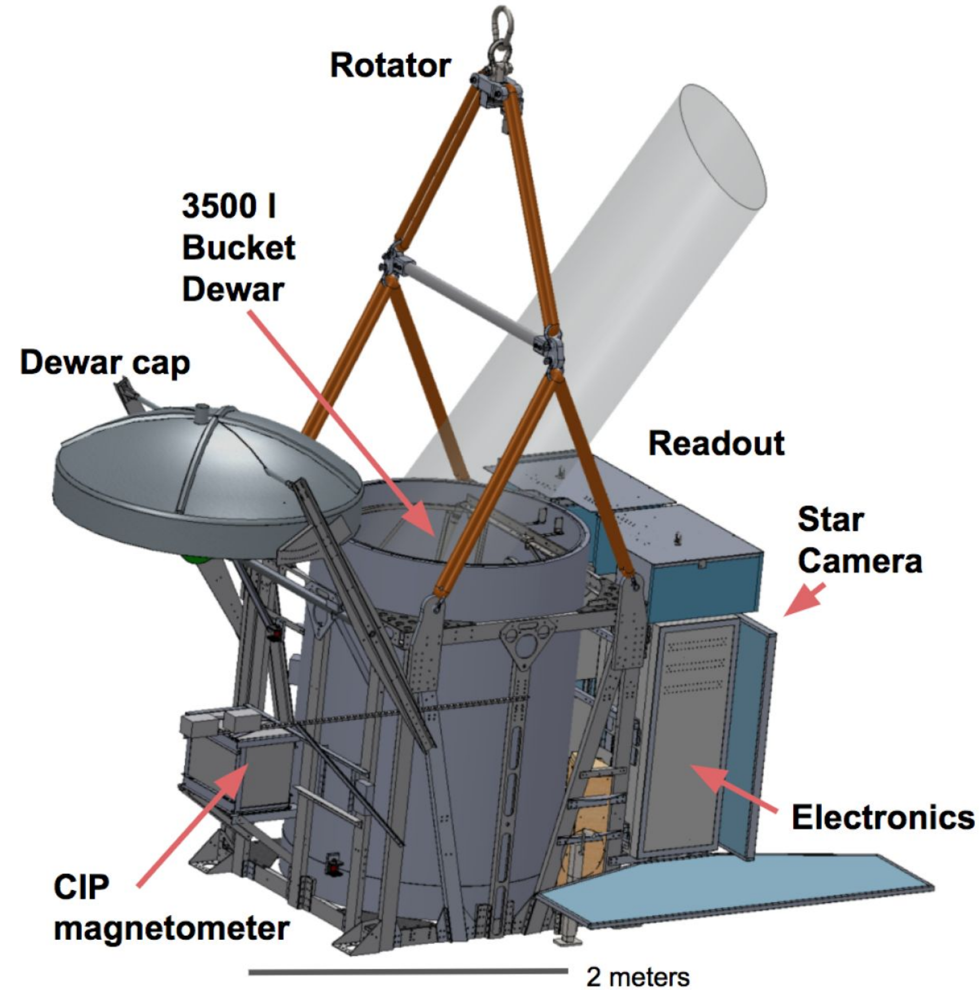


CO/CII galaxies emit continuum;
Convolution in real space is multiplication in k-space:

$$P_{\times}(k_\perp, k_\parallel) = S_L b_g \left[1 + \Delta z f_{\rm cont} \tilde{\Theta}(k_\parallel)\right] P_{\delta\delta}(k_\perp, k_\parallel)$$



Instrument overview



G. Cataldo (Mission SE)

3500 l LHe fill gives 18hr of 1.7 K operation at float.
38 km float on 34 mcf balloon; 36 km assumed.

Superfluid fountain effect pumps cool optics.

Elevation fixed (up to ~2° dither) at 50°.

Requirements: sample the beam in FWHM/3 pixels, Az rate < 2°/sec, 488 Hz readout samples the beam.

Elevation dip with cantilever mass: gondola co-moves with telescope to limit spill modulation.

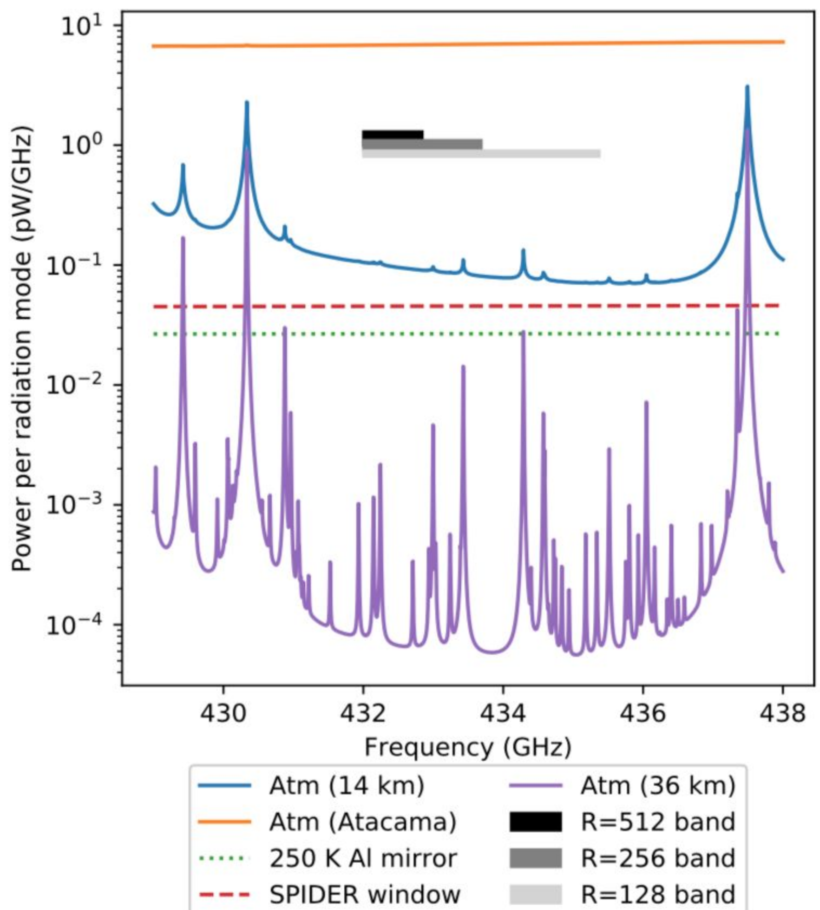
Pointing: reconstruction only, star camera + gyro, magnetometer, tilt.

Instrument	Mass	1800 kg
	Height	2.8 m
	Telemetry rate	57.6 kpbs
	Data rate	9 MB/s
	Gondola Power	600 W
	Readout Power	$\lesssim 550$ W
Telescope	Projected aperture	74 cm
	Angular resolution	3.5′ FWHM
	Edge taper	-9 dB
	Telescope $f/\#$	1.3
	Detector spacing	2.2 $f\lambda$
	Instantaneous FOV	12.5′

Physical aperture: 90 cm

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 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 A. Kogut

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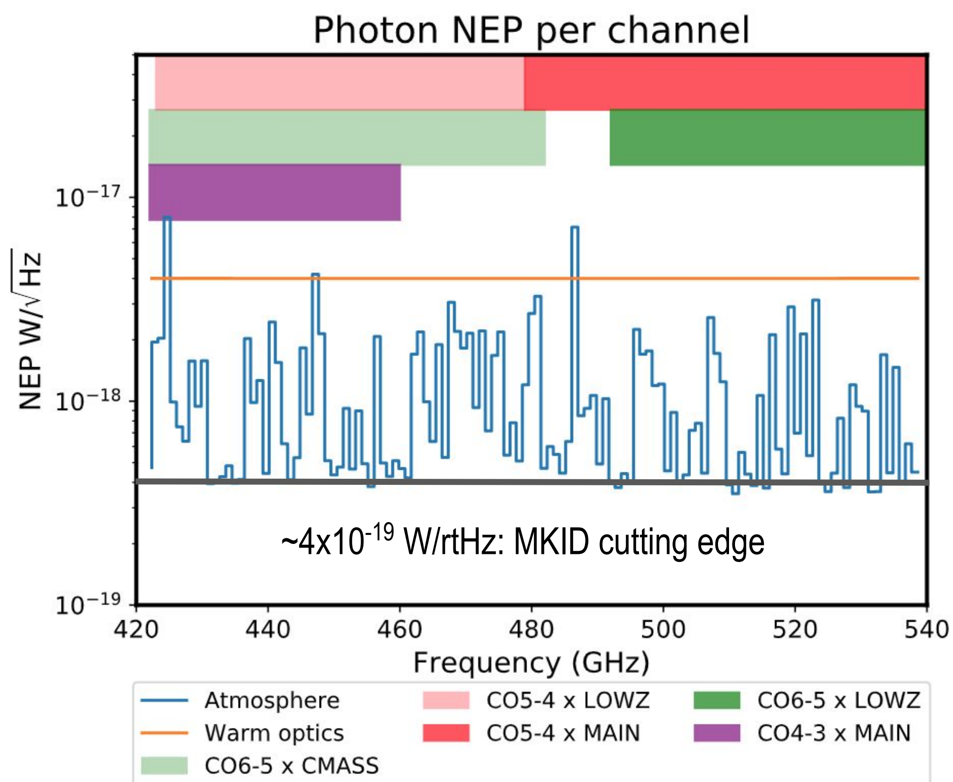
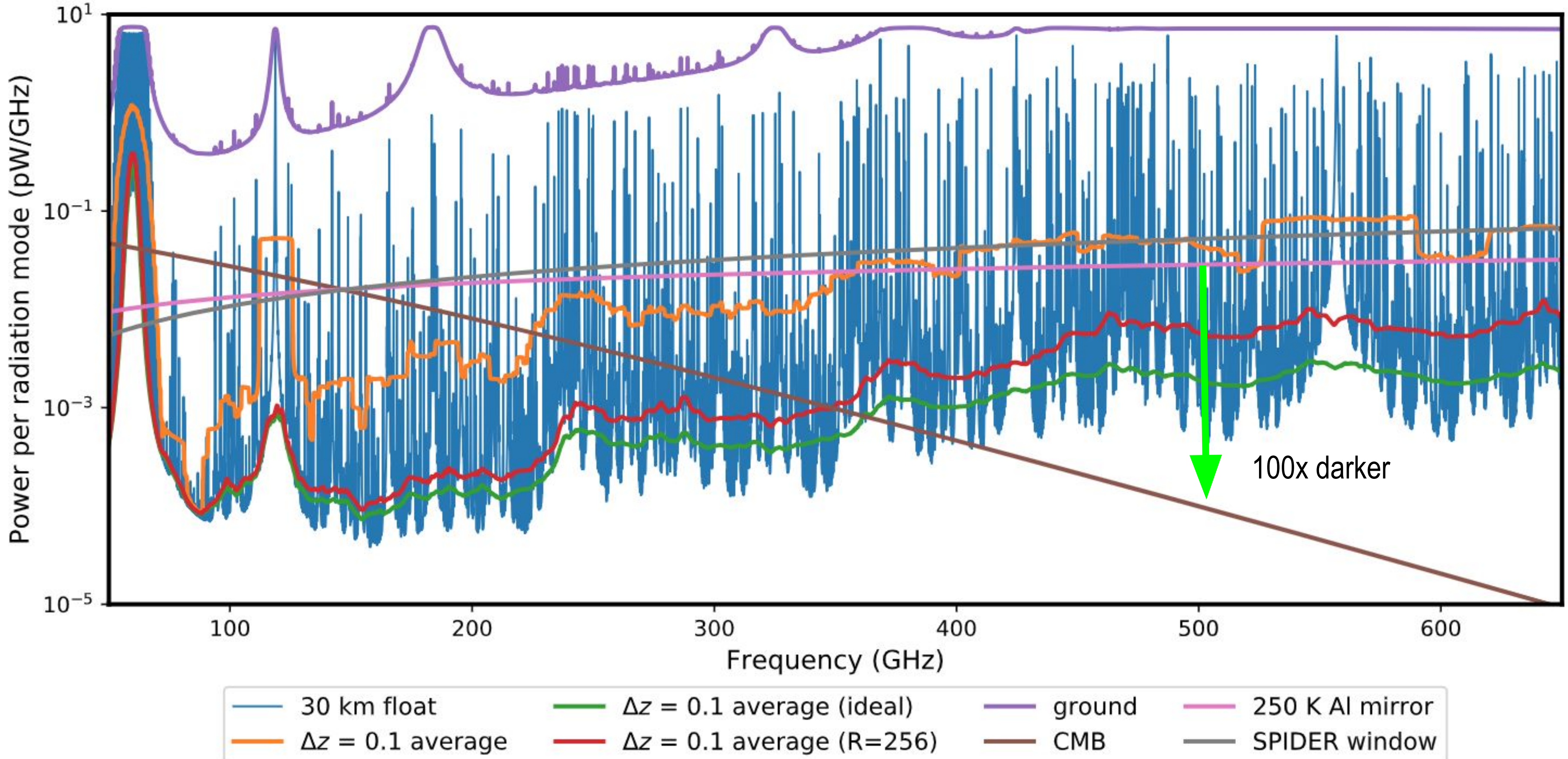


Al MKID to 10^{-19} W/rtHz level (Yates+ 2011, Baselmans+ 2017.)

Integration time ~ power^2

Approach from A. Kogut

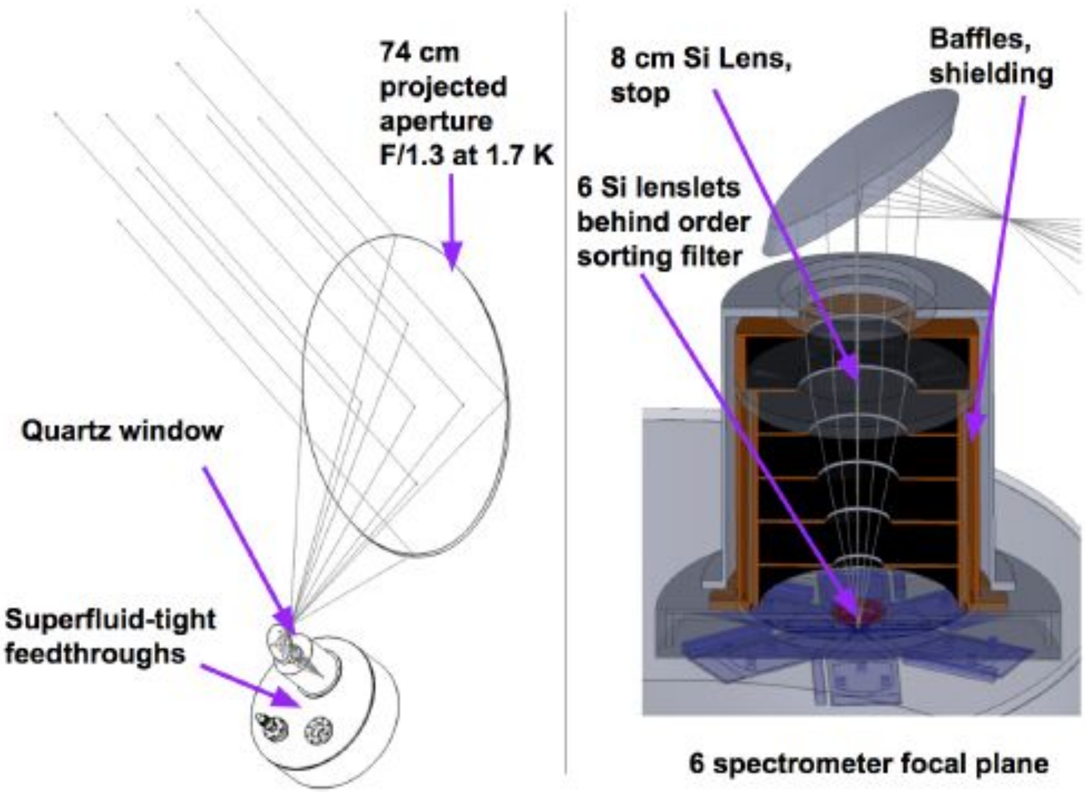
Resolving atmospheric emission: big picture

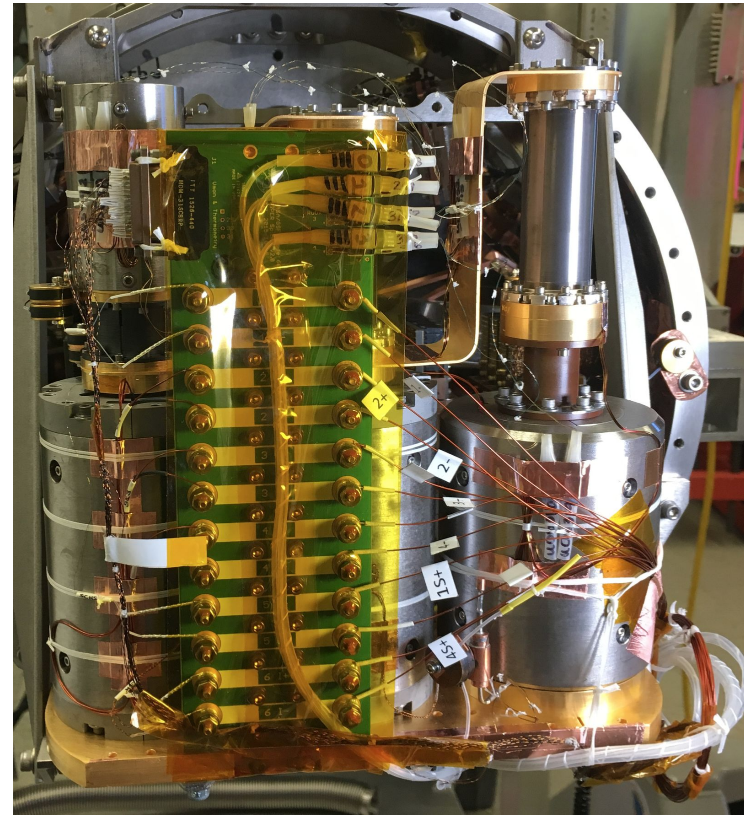


SPIDER ⅛" UHMWPE @ 300 K background limited in broad bands with a warm window -- at lower frequency.

Balloon float atmosphere in broad bands ~ bounce from warm mirror ~ transmission through warm window.
With warm optics, also need to control stray light to emissive surfaces.

Optics and receiver





Windows: quartz (teflon AR) or silicon (metamaterial AR)

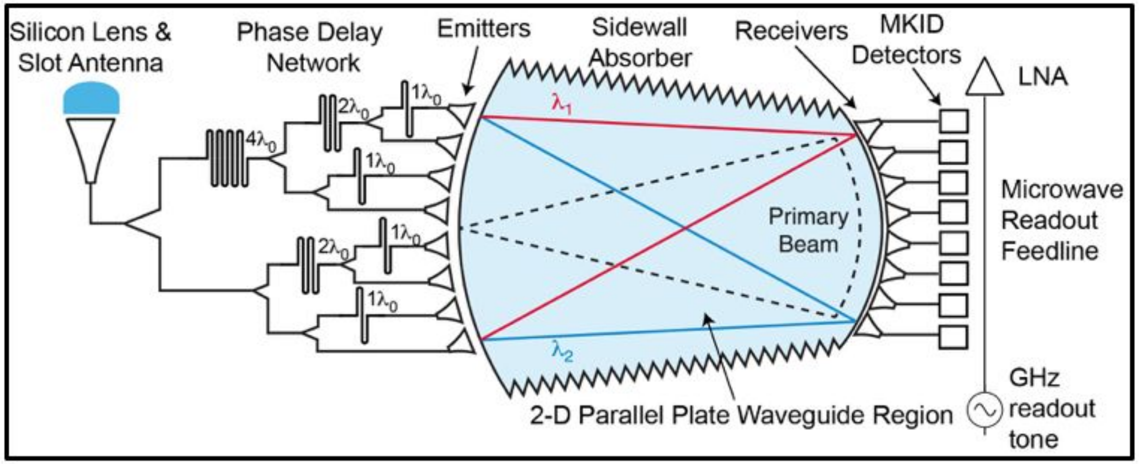
Lenses: silicon (metamaterial AR)

Indium seals on superfluid-tight submarine

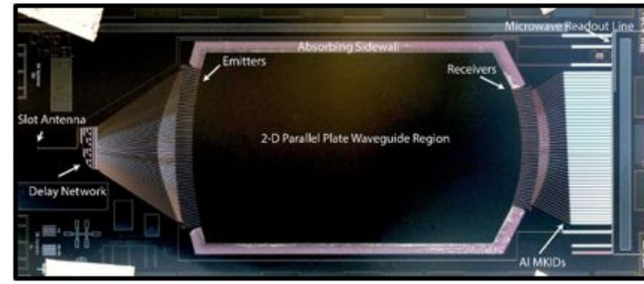
4-stage Continuous Adiabatic Demagnetization Refrigerator (GSFC) provides 100 mK from a bath: 4.3 K (ground) to 1.7 K (float).

T. Essinger-Hileman (Instrument Lead)

μ-Spec: An Integrated Grating-Analog Spectrometer



- μ-Spec integrates all the elements of a grating spectrometer - the dispersive elements and detectors - on a single silicon wafer. Phase delay is introduced by a synthetic 'grating' consisting of a meandered delay network made of superconducting niobium microstrip transmission lines on a low-loss single-crystal silicon substrate. The high index of refraction of silicon allows us to introduce the required phase delay 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).
- 10-25 nm Al CPW demonstrated at Q_{int}=(1-4)x10^6 and ~1 ms quasiparticle lifetime, Nb Q_{int}=(5-8)x10^5 (Noroozian+ 2017). On low-loss single-crystal Si, enabling up to R=1000 operation.
- Antenna-coupled Nb-Al limited to 120-700 GHz, but design is compatible with NbTiN process for up to 1.1 THz.



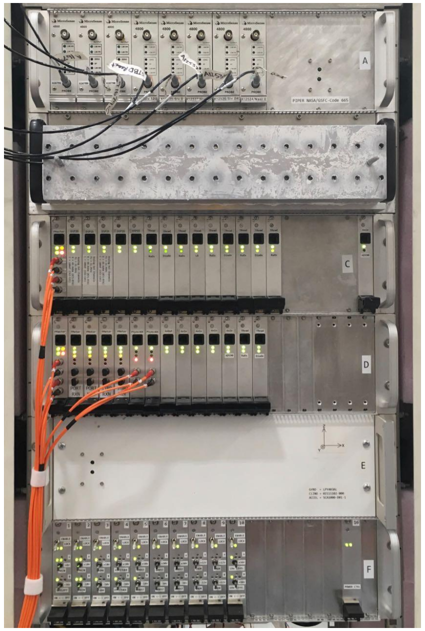
R=64 Prototype. Focal plane design reported in G. Cataldo et al., Applied Optics, 53(6), 1094, 2014

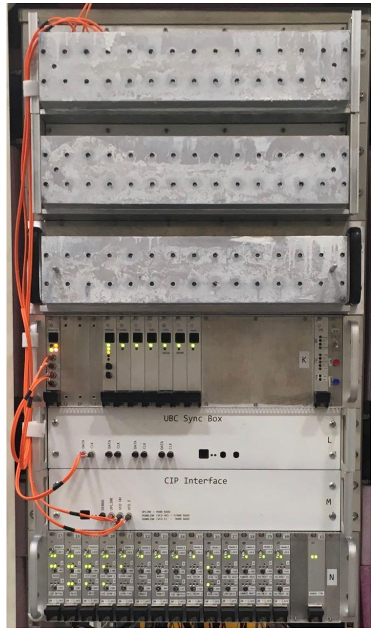
Aluminum MKIDs

Spectrometer	Spectrometer architecture	Rowland on-chip
	Number of spectrometers	6 single-pol
	Spectral range [GHz]	421-540 GHz
	Spectrometer efficiency	$53-63\%$
	Resolving power	$\mathrm{R}=512$
	Spectrometer order	2
	Spectrometer dimensions	4×8 cm
	Detectors per spectrometer	349
	Emitters per spectrometer	256
Detectors	Time constant	<1 ms
	MKID Al film thickness	20 nm
	MKID NEP $10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$	3
	Detector bath	100 mK CADR
	MKID Readout Band	$2.64-3.36$ GHz
	HEMT Noise Temp.	5 K

E. Barrentine (Detector Lead)

Heritage: gondola, flight electronics, software





L. Lowe (Electronics Lead)

The EXCLAIM payload draws heavily upon **PIPER** and ARCADE heritage (A. Kogut):

- Bucket dewar providing cold (~1.7K) optics
- Gondola mechanical design
- Flight electronics
- Submarine receiver with super-fluid tight window

Readout electronics based on BLAST-TNG (ASU)

PIPER engineering flight 2017

Lofting a 3000 liter dewar of LHe to 100,000 ft

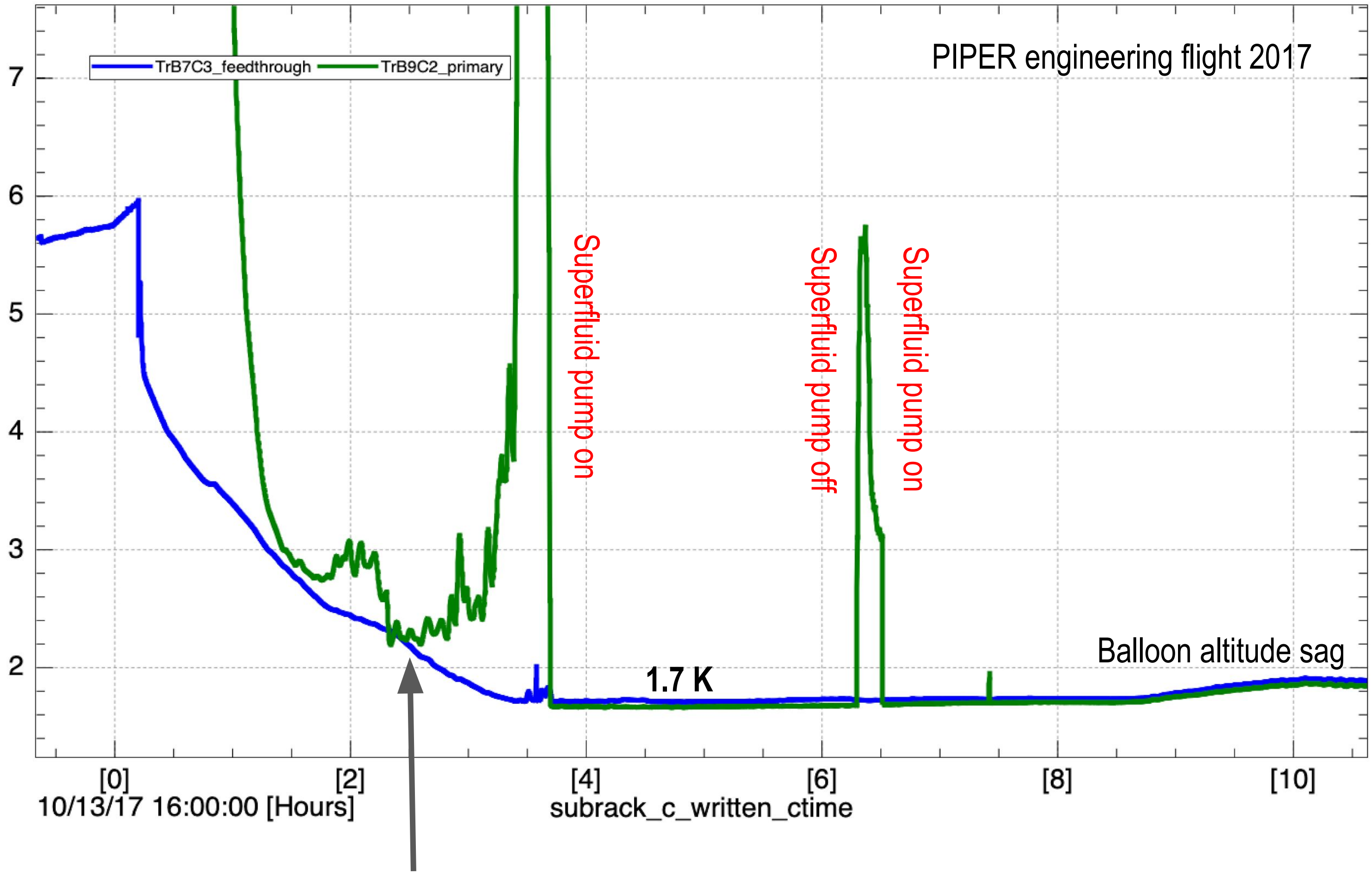
40 cm Primary starts ~90 K (Green line)

Receiver ~6 K
Sitting out of LHe initially
(Blue line)

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

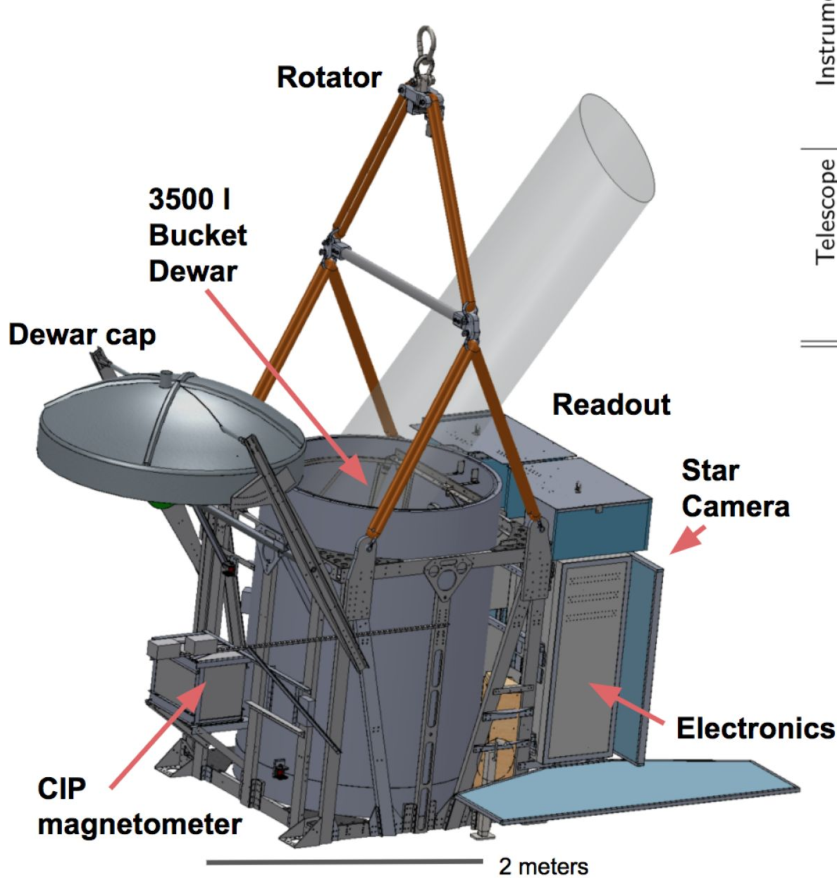
Gradually stratifies, low atmospheric pressure gives poor conduction.

Low temperature -> Low heat capacity, rapid warming.



Superfluid transition ~2.2 K, ~80 kft

EXCLAIM Summary



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