Line Intensity Mapping using On-Chip Spectrometers and SPT-SLIM

Adam Anderson - Fermilab
30 November 2022
CPAD Workshop 2022

photo: Geoff Chen

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Matt Dobbs
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Dan Marrone
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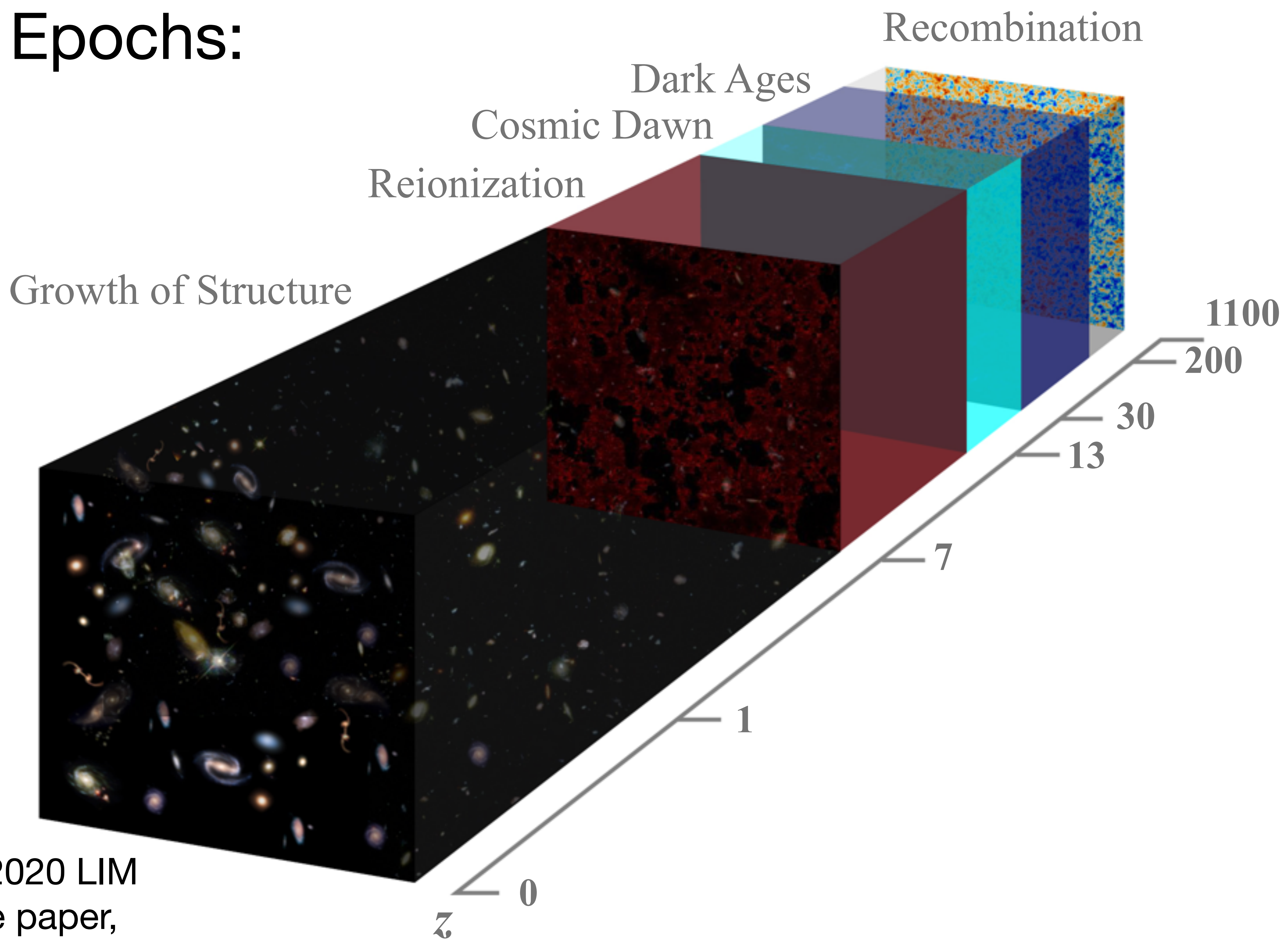
Maclean Rouble
Erik Shirokoff
+ many others

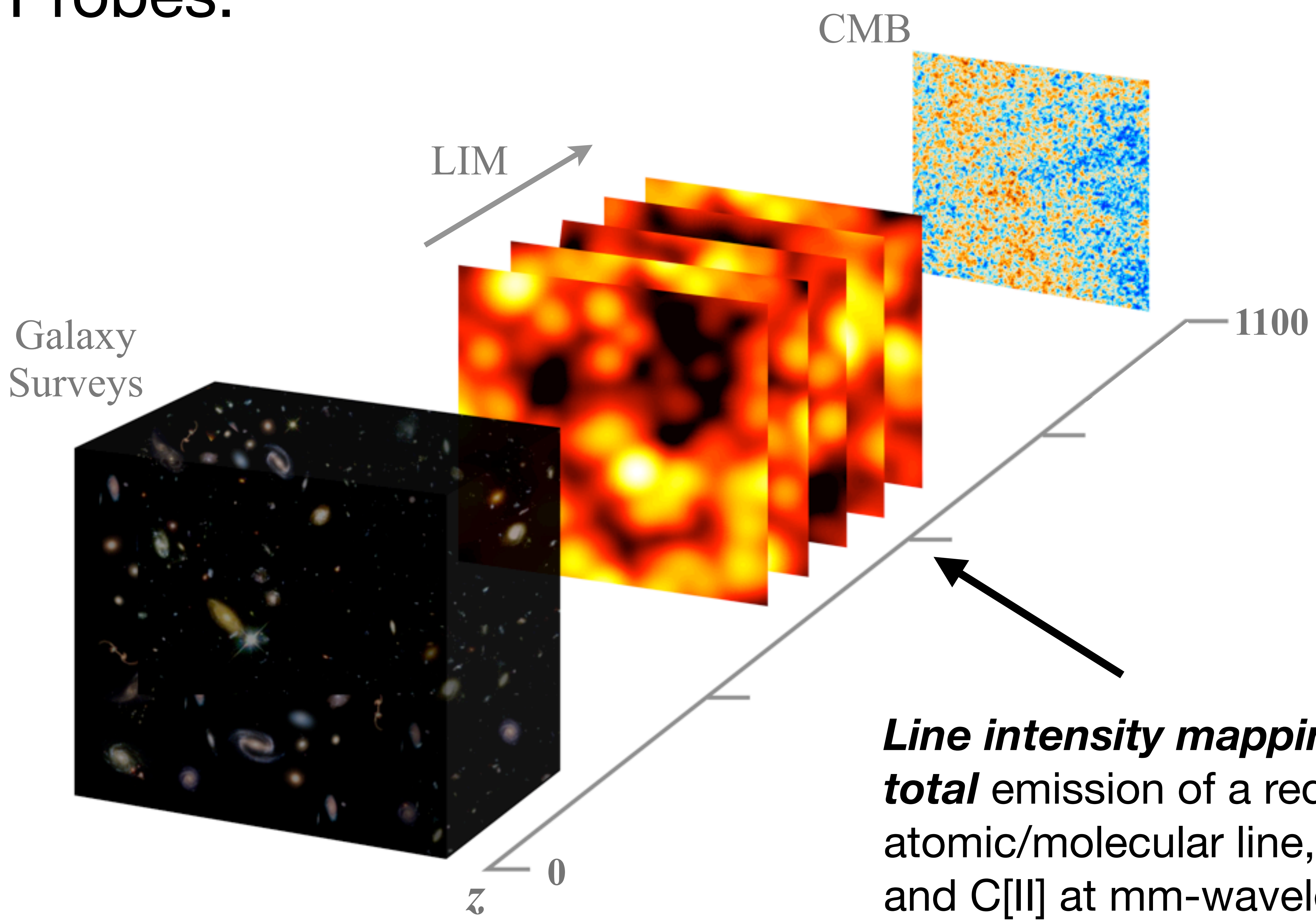
Line Intensity Mapping (LIM)

Epochs:



Astro2020 LIM white paper, 1903.04496

Probes:



Line intensity mapping - Map ***total*** emission of a redshifted atomic/molecular line, e.g. CO and C[II] at mm-wavelength

- Large redshift range $z > 3$ that is relatively unexplored: provides information on expansion history of universe, reionization, star-formation, ++
- LIM is efficient: we measure *all* sources and do not need to threshold on galaxies
- Multiple lines available across radio, millimeter, IR

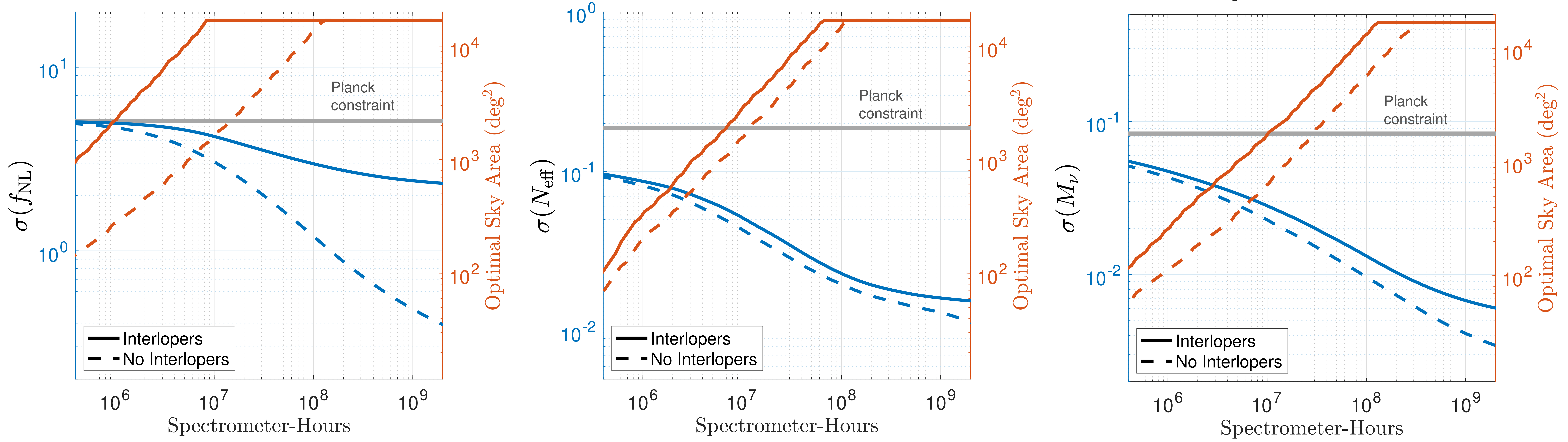
LIM Cosmology Cases

Science case	*Inflation / Primordial non-Gaussianity*	*Neutrino masses*	*Light relic particles*	*Dark energy, modified gravity*
Measurement	Scale-dependent bias in power spectrum, bispectrum	Suppression of power spectrum on small scales, expansion history	Power spectrum amplitude, phase and amplitude of BAO	Power spectrum (BAO), growth of structure
Parameter	fNL	M_ν	Neff	w_0 , w_a

Snowmass white paper on LIM, Karkare, et al. (2203.07258)

Impact on Cosmological Parameters

Snowmass white paper on LIM, Karkare, et al. (2203.07258)



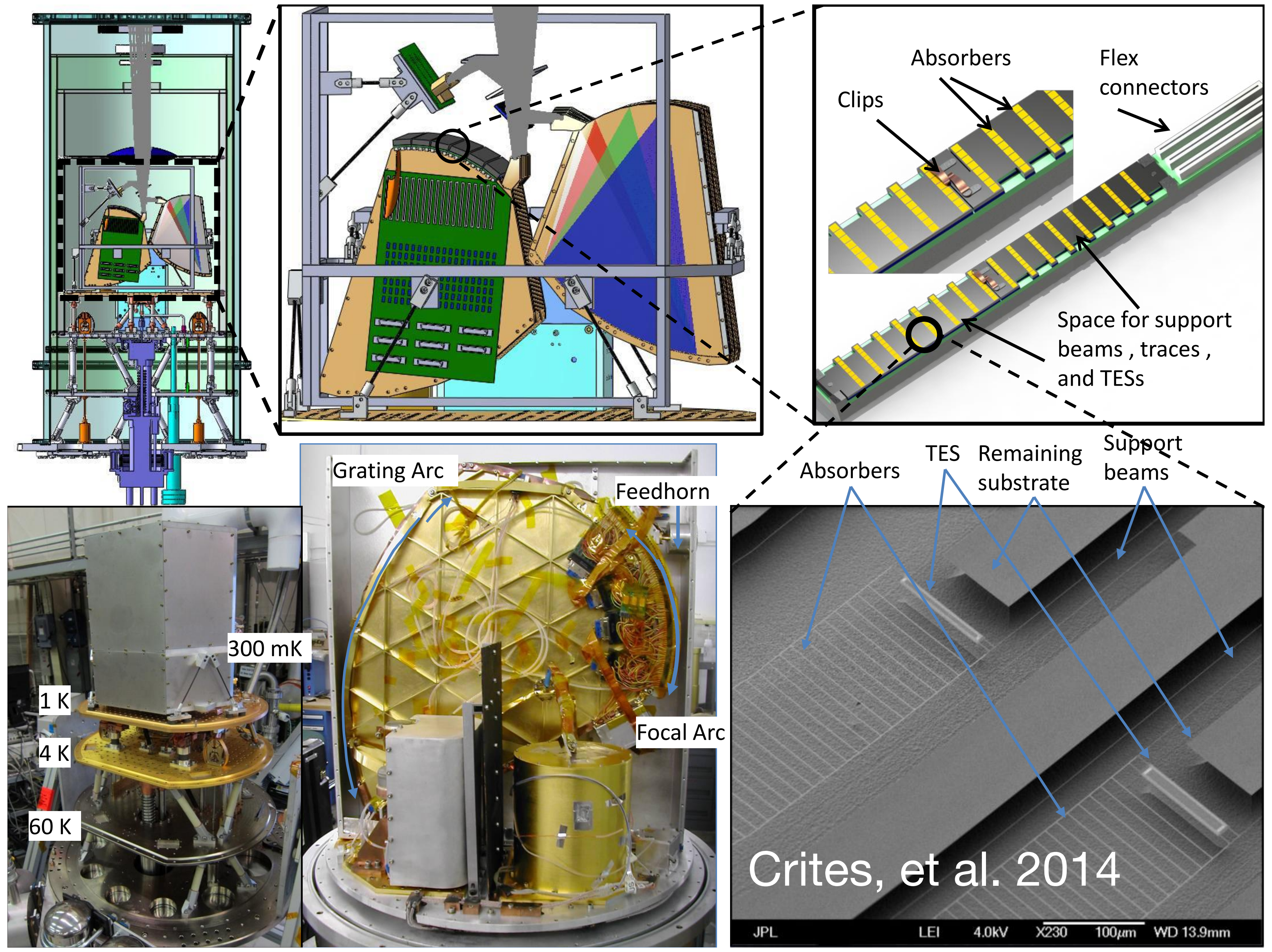
Very large experiments!! Need to start small…

- Experiment size parameterized by *spectrometer-hours*
- Significant improvement possible relative to Planck due to more modes and breaking of parameter degeneracies in CMB data

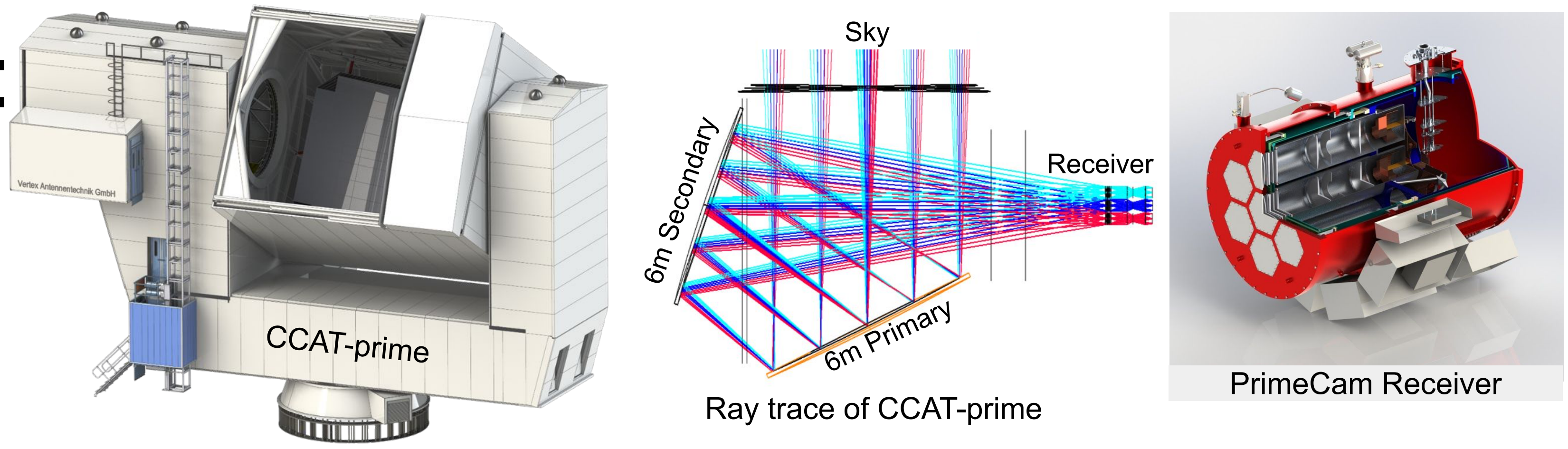
Many Lines, Many Experiments…

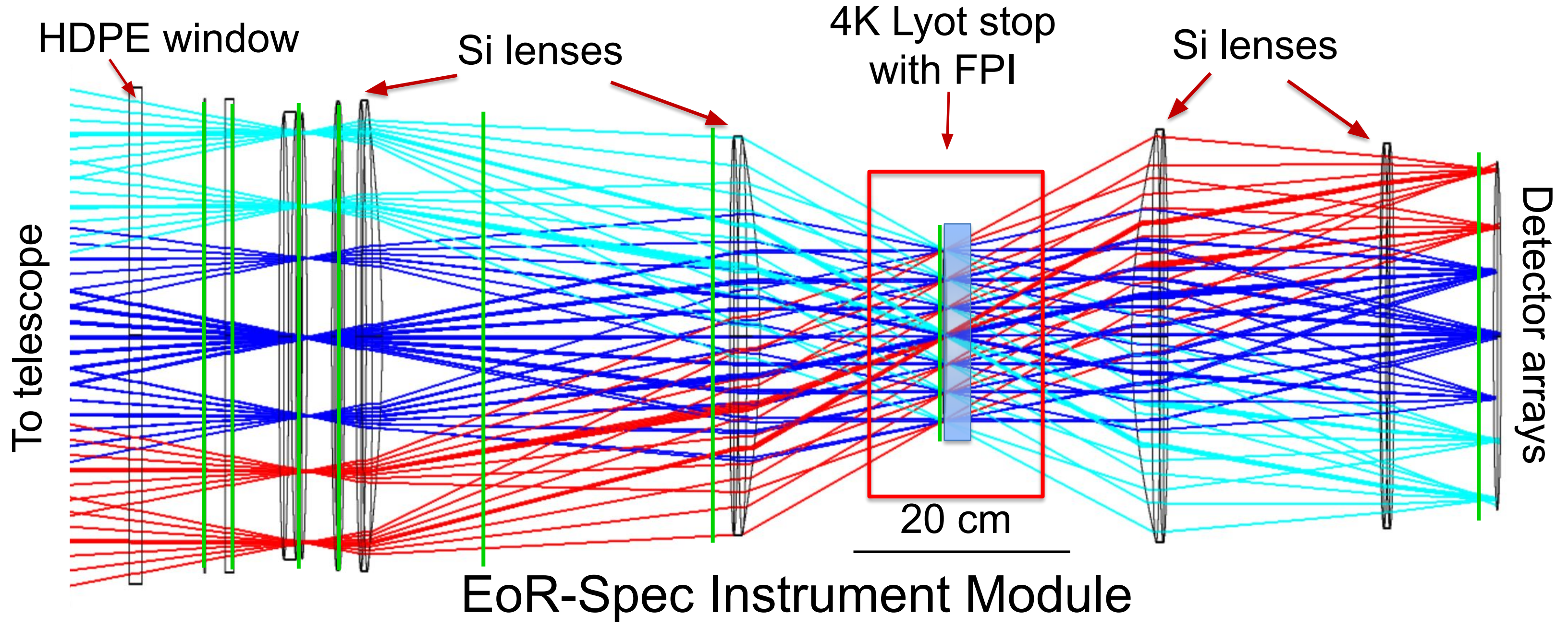
Cothard, et al. (1911.11687)

TIME:
Grating
spectrometer
C[II] 5 < z < 9



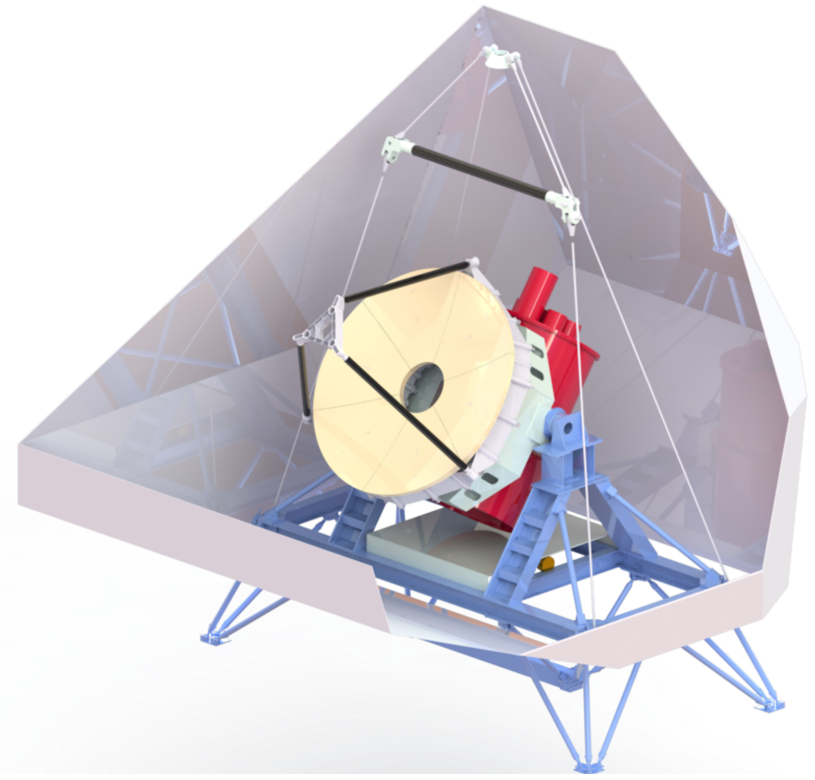
EoR-Spec / CCATp:
Fabry-Perot
C[II] 3.5 < z < 8

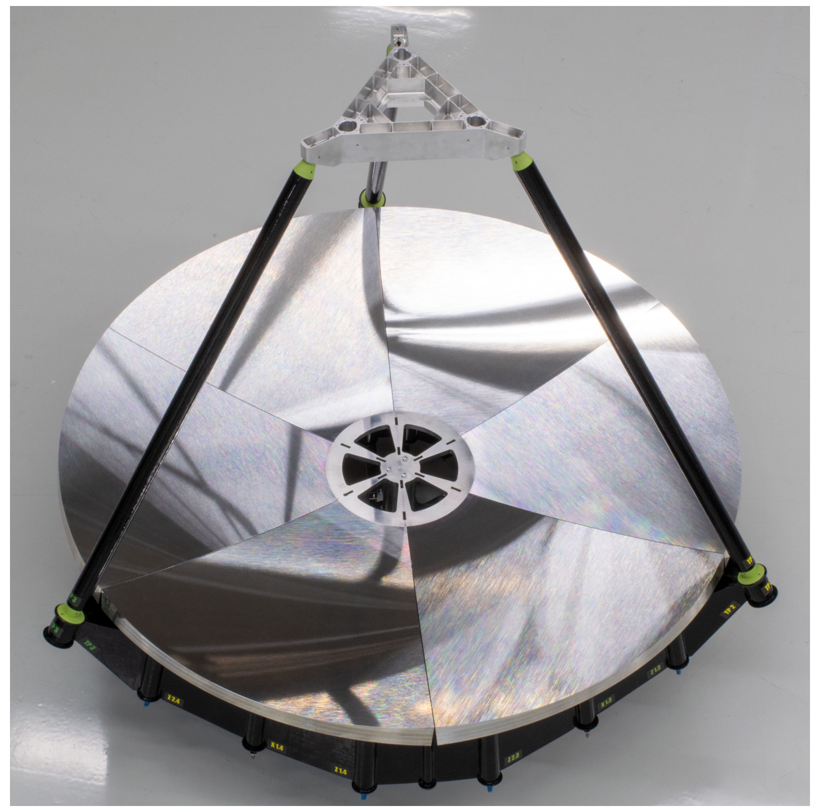




CONCERTO:
Fourier transform
spectrometer
C[II] 5 < z < 9
CO 0.3 < z < 2

TIM:
Grating
spectrometer
C[II] 0.5 < z < 1.5
N[II], O[I], O[III]





Marrone, et al. 2022

LIM with Millimeter-Wavelength Tracers

- The CII line and the CO rotational ladder over $1 < z < 10$ redshift to the ground-based CMB observing frequencies

- CMB community has invested decades in R&D on detectors, cryogenic optics, and survey design for observing in the 20-300 GHz range

- ***Transfer our CMB expertise to line intensity mapping***

- Many small experiments (TIME, COMAP, CONCERTO, EXCLAIM, TIM, …) trying this with extremely diverse approaches: coherent detectors vs. bolometers; grating spectrometers vs. fourier transform spectrometers vs. …

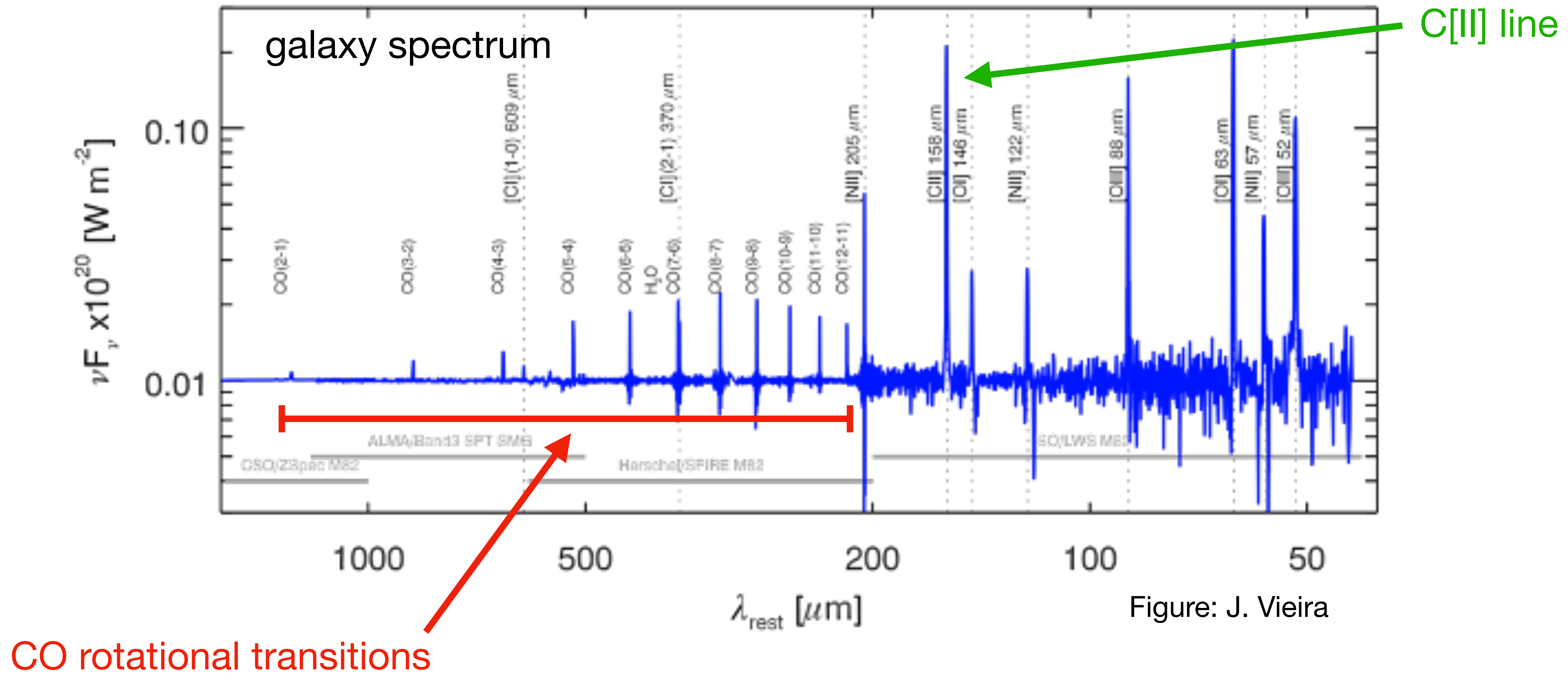


Figure: J. Vieira

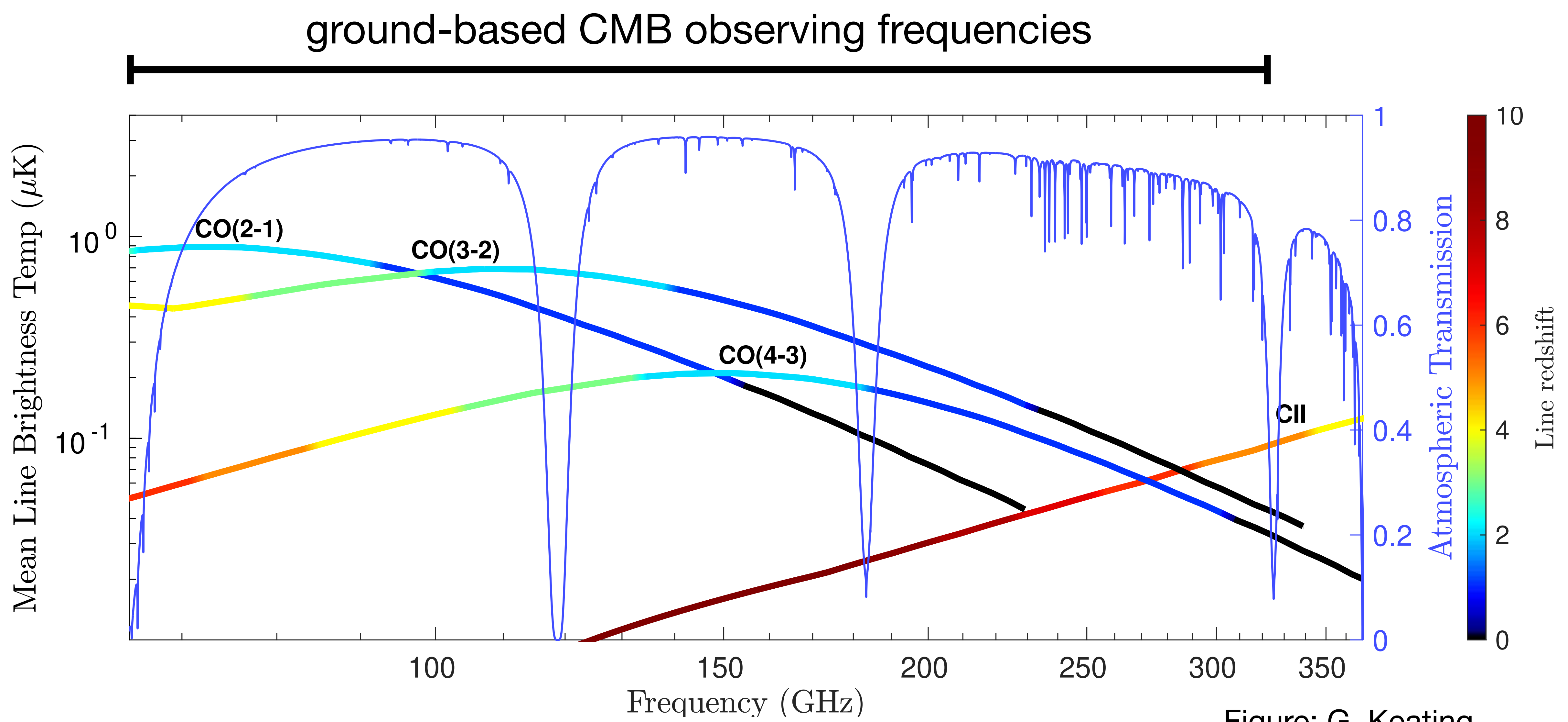
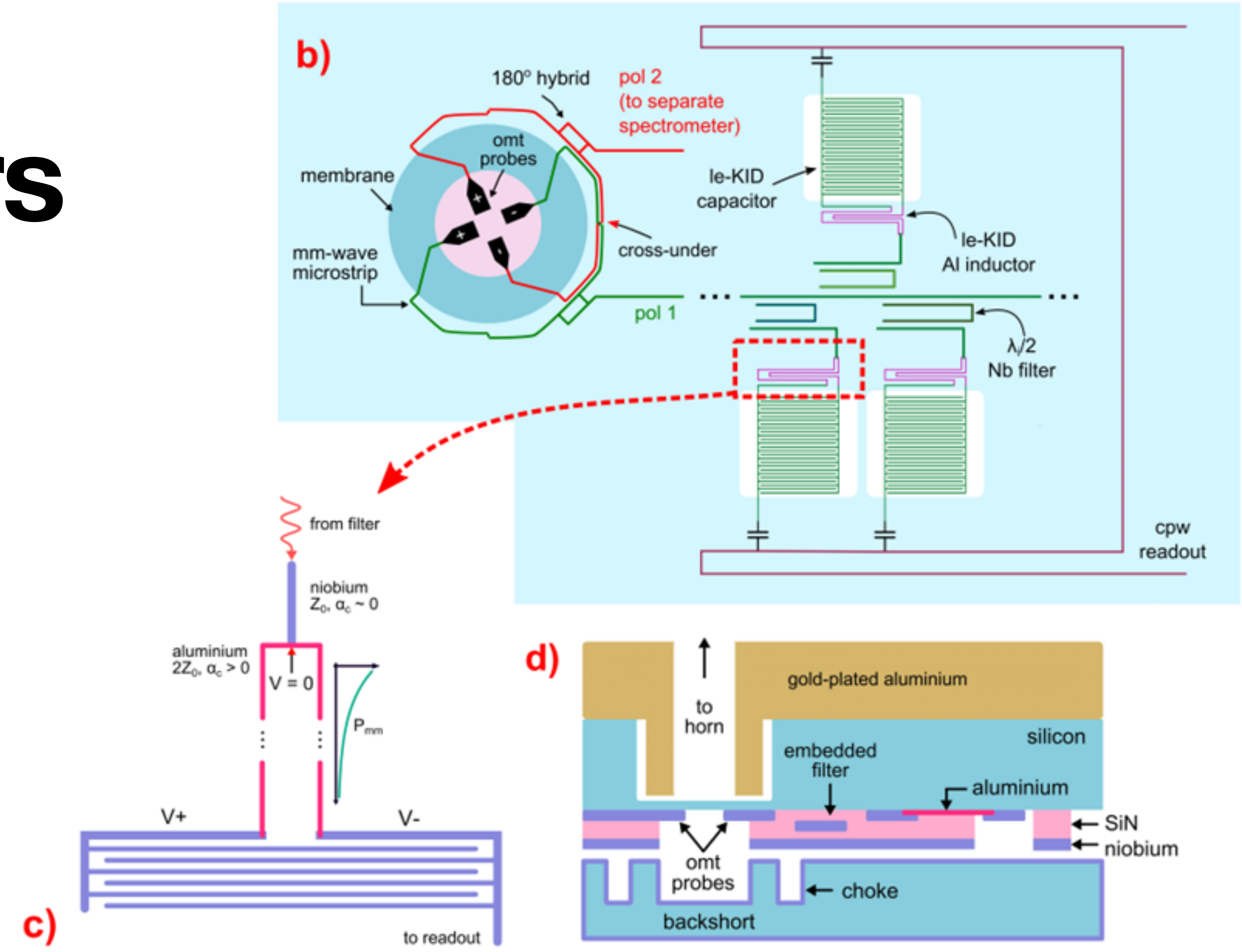
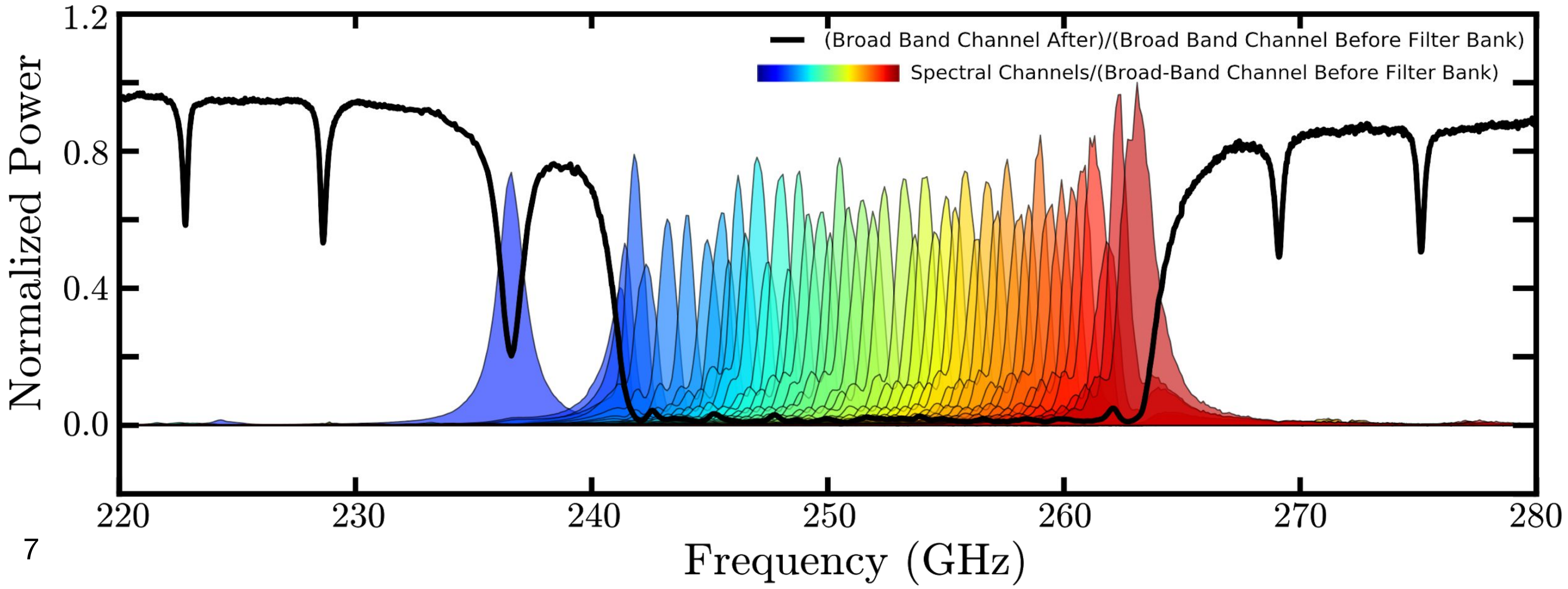


Figure: G. Keating

On-Chip Spectrometers

- Couple antenna to an RF filter-bank to achieve tunable narrow-band response, filling the atmospheric frequency “windows” used for ground-based observations
- Couple a microwave kinetic indutance detector (MKID) to each filter channel
- Demonstrated in few-pixel field tests (e.g. SuperSpec, DESHIMA), but not in monolithic arrays needed for future surveys
- Development of on-chip mm spectrometers for large-scale structure surveys endorsed by *DOE Basic Research Needs Study on HEP Detector Research and Development* (2020)





SPT-SLIM: South Pole Telescope Summertime Line Intensity Mapper

Argonne:
T. Cecil
C. Chang
Z. Pan

Cardiff:
P. Barry
G. Robson

Harvard / CfA:
G. Keating

Fermilab:
A. Anderson
B. Benson
S. Simon
M. Hollister

McGill:
M. Dobbs
M. Rouble

U. Arizona:
D. Kim
D. Marrone

U. Chicago:
K. Karkare
R. McGeehan
J. McMahon
E. Shirokoff

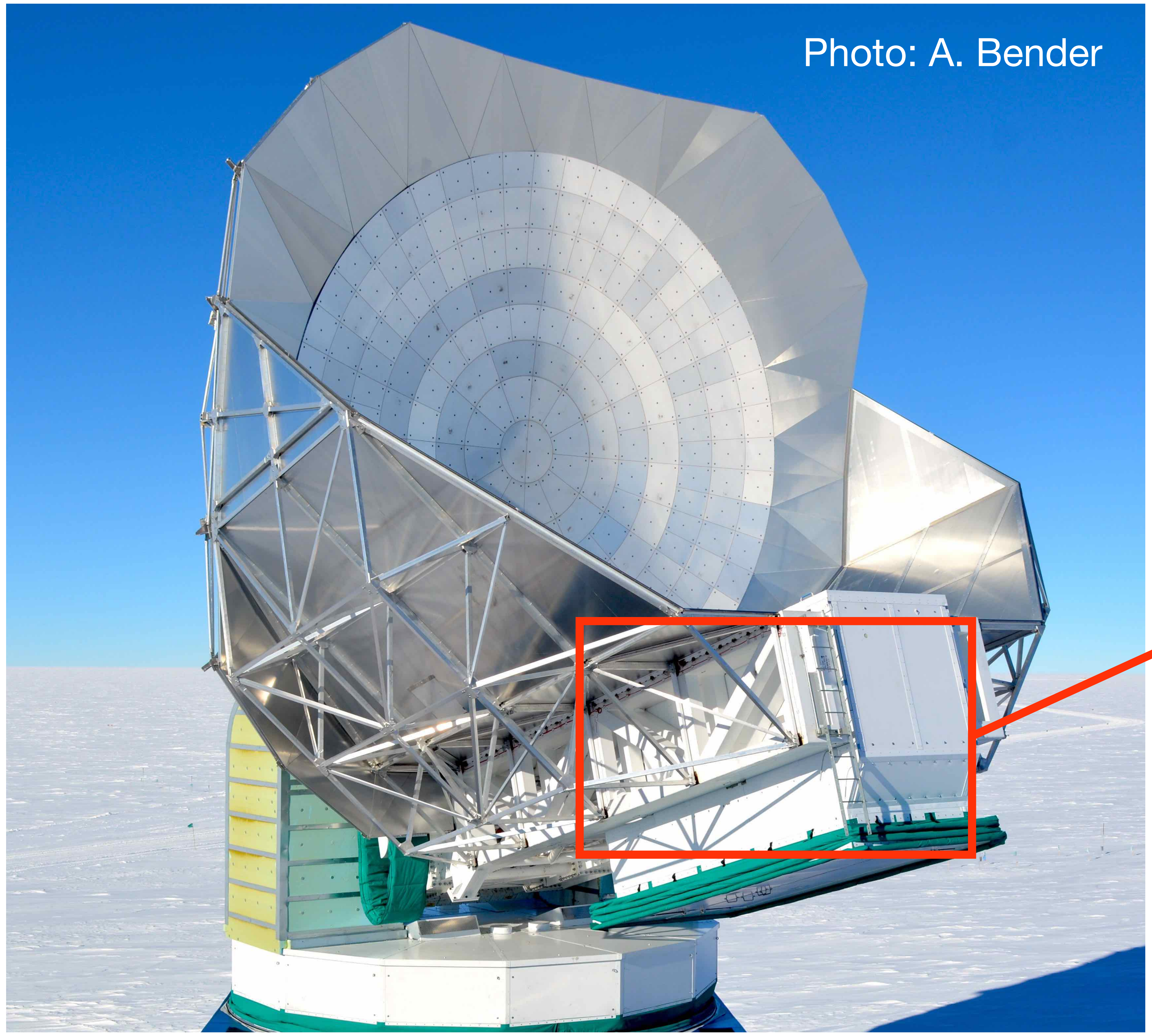
Three-Speed Logic
G. Smecher

SPT-SLIM Experimental Concept

South Pole Telescope is 10-m CMB telescope observing at 90/150/220 GHz during both austral winter *and summer*

SPT optics include mount point for optional receiver, used by Event Horizon Telescope (EHT) during 2017-present

SPT-SLIM - Replace EHT cryostat with on-chip spectrometers and observe for one summer season



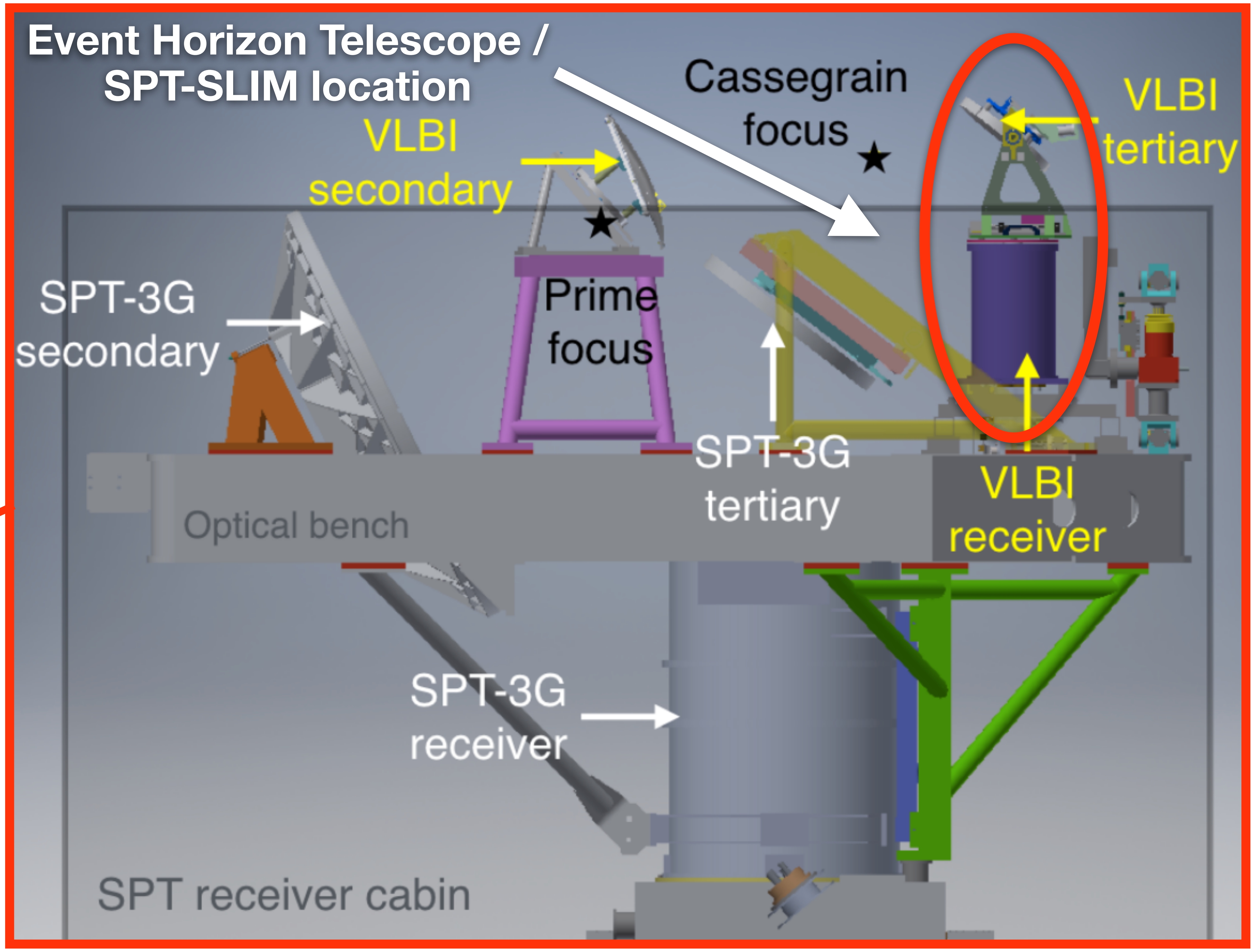
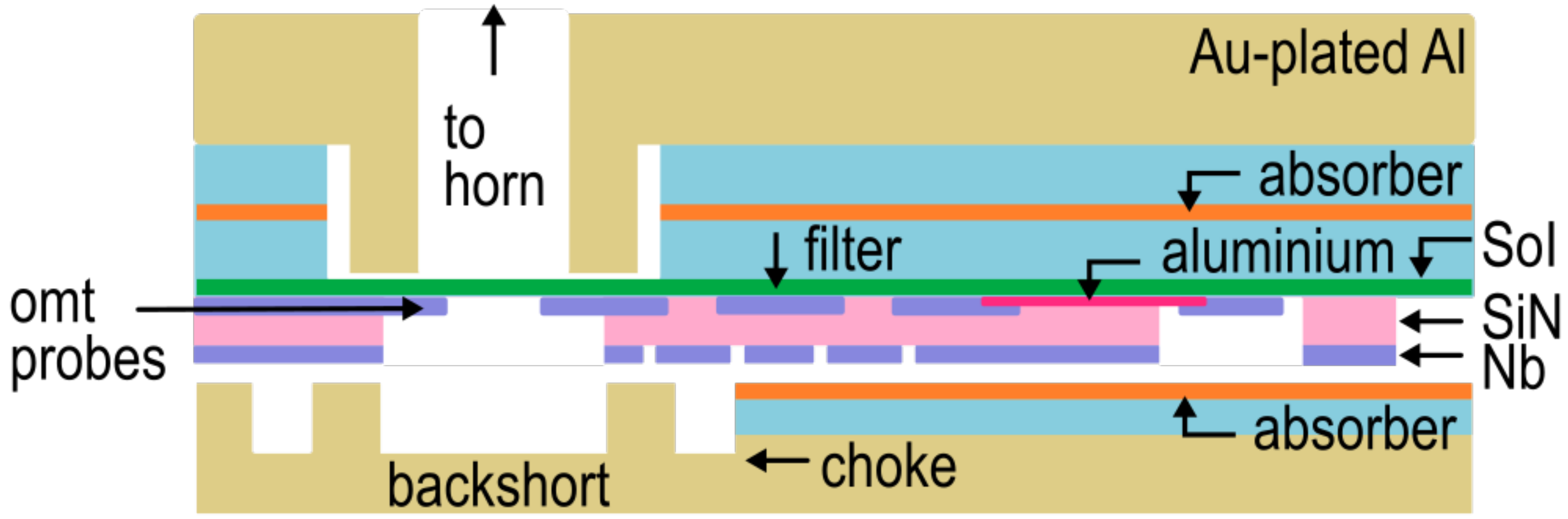


Figure: J. Kim, et al. 1805.09346

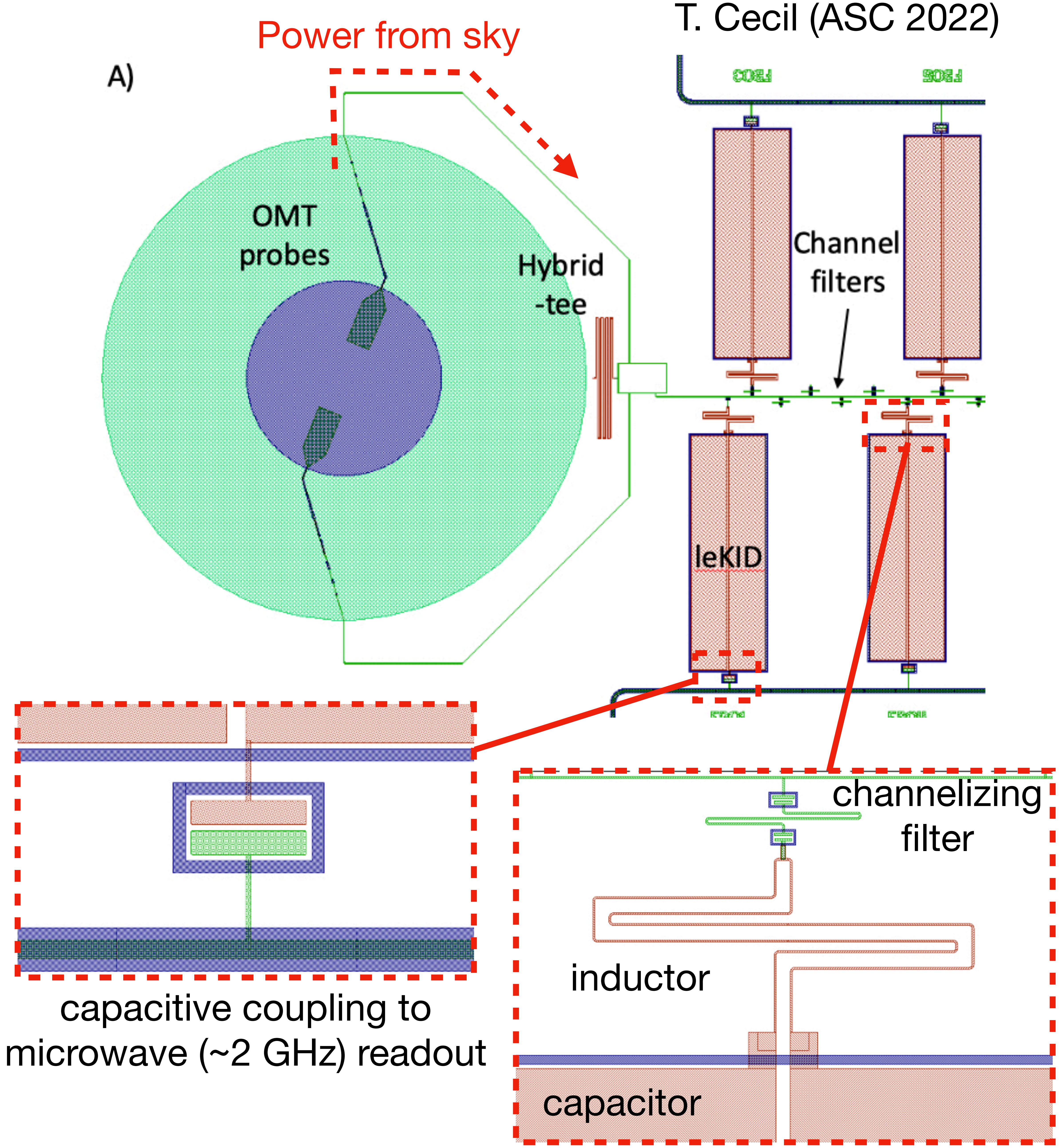
Detector Architecture

- Millimeter-wave (~150 GHz) light from telescope is coupled via feedhorn to orthomode transducer (OMT).
- Narrow-band filters channelize the broadband power feeding lumped-element kinetic inductance detector (leKID).
- Power breaks Cooper pairs in Al inductor and LC resonator is coupled to microwave (~2GHz) feed line.
- Inverted microstrip design reduces microwave losses.



P. Barry++ (2111.04633)

T. Cecil (ASC 2022)



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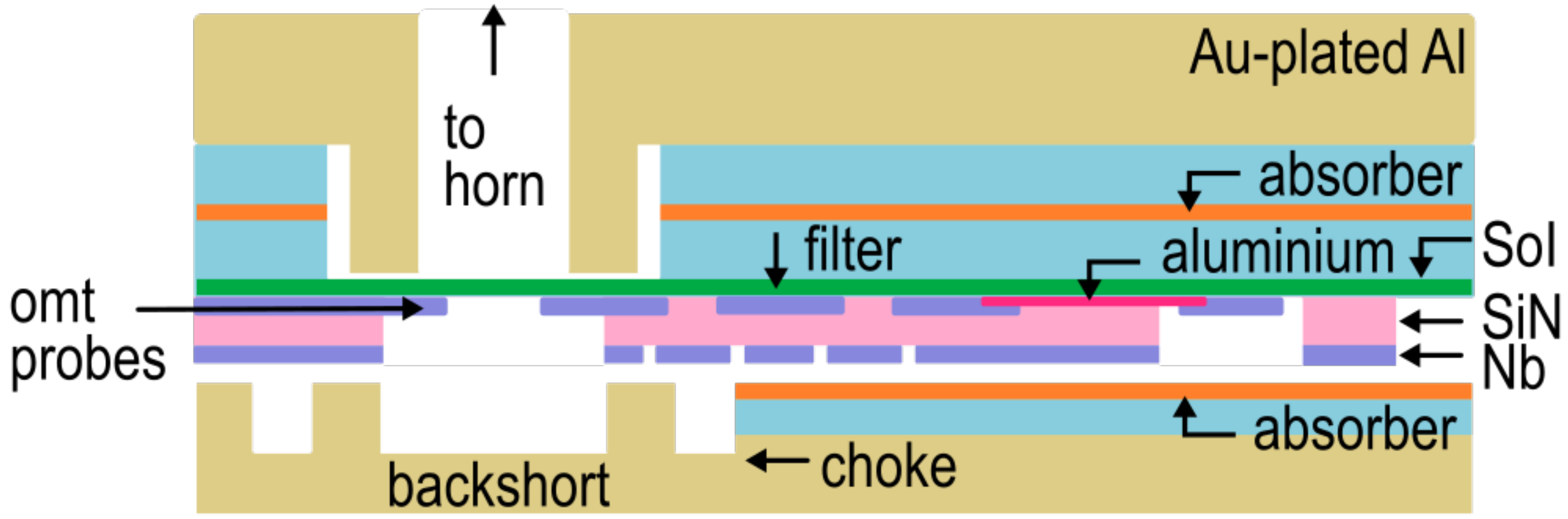

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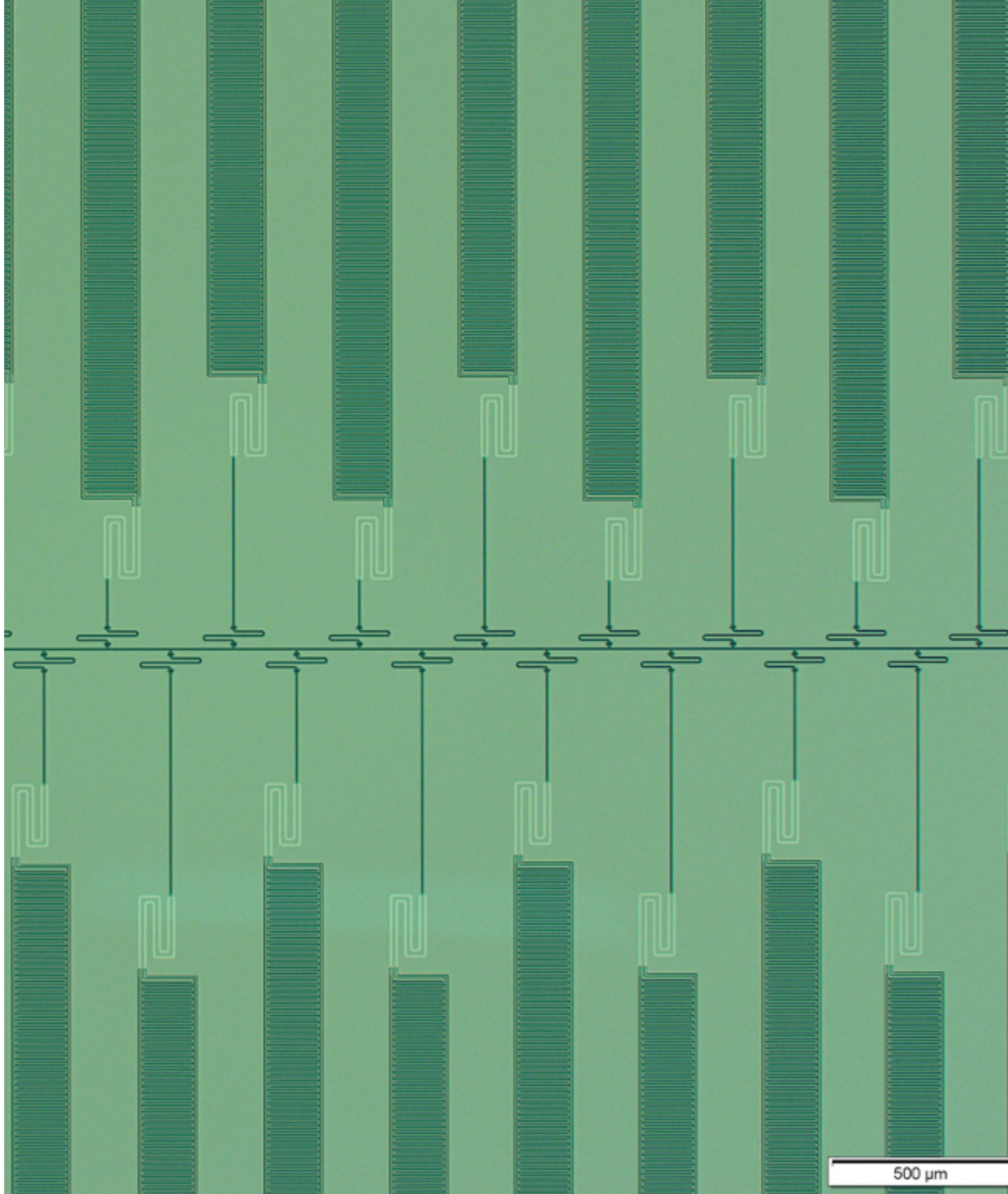
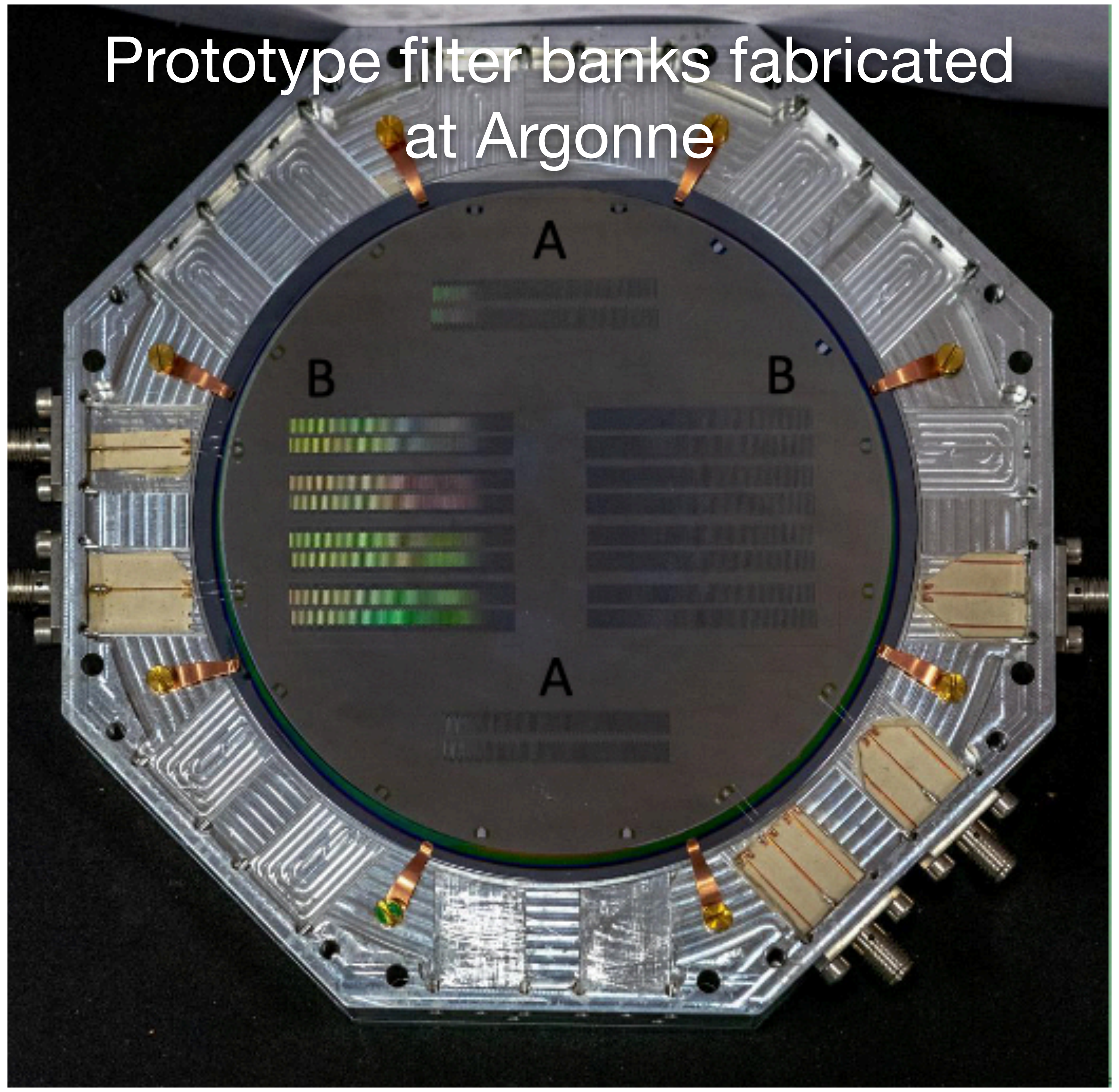


Focal Plane and Prototypes

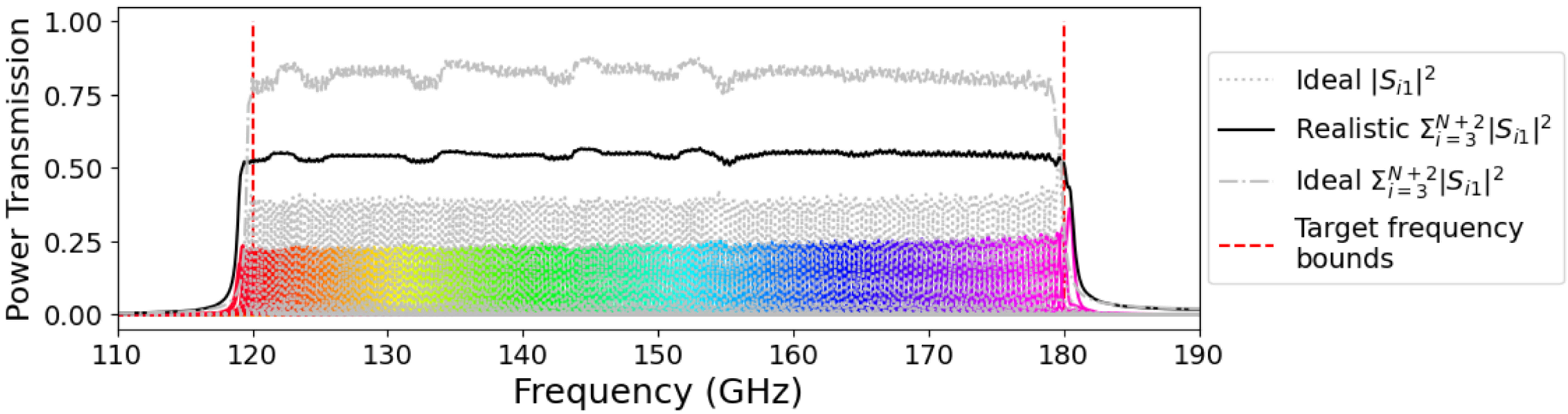
- Baseline 18 dual-pol pixels with R~300 = ***8640 detectors (240 detectors / pixel)***
- Use 118-186 GHz atmospheric window, sensitive to CO(2-1), CO(3-2), CO(4-3) in 0.5 < z < 2.1
- Filter banks are much larger than 1 pixel, so array them around perimeter on segments of 3x 4-inch wafers and read out KIDs from perimeter
- Oversampling of millimeter-wave spectrum boosts total optical efficiency of system

P. Barry (Cardiff)

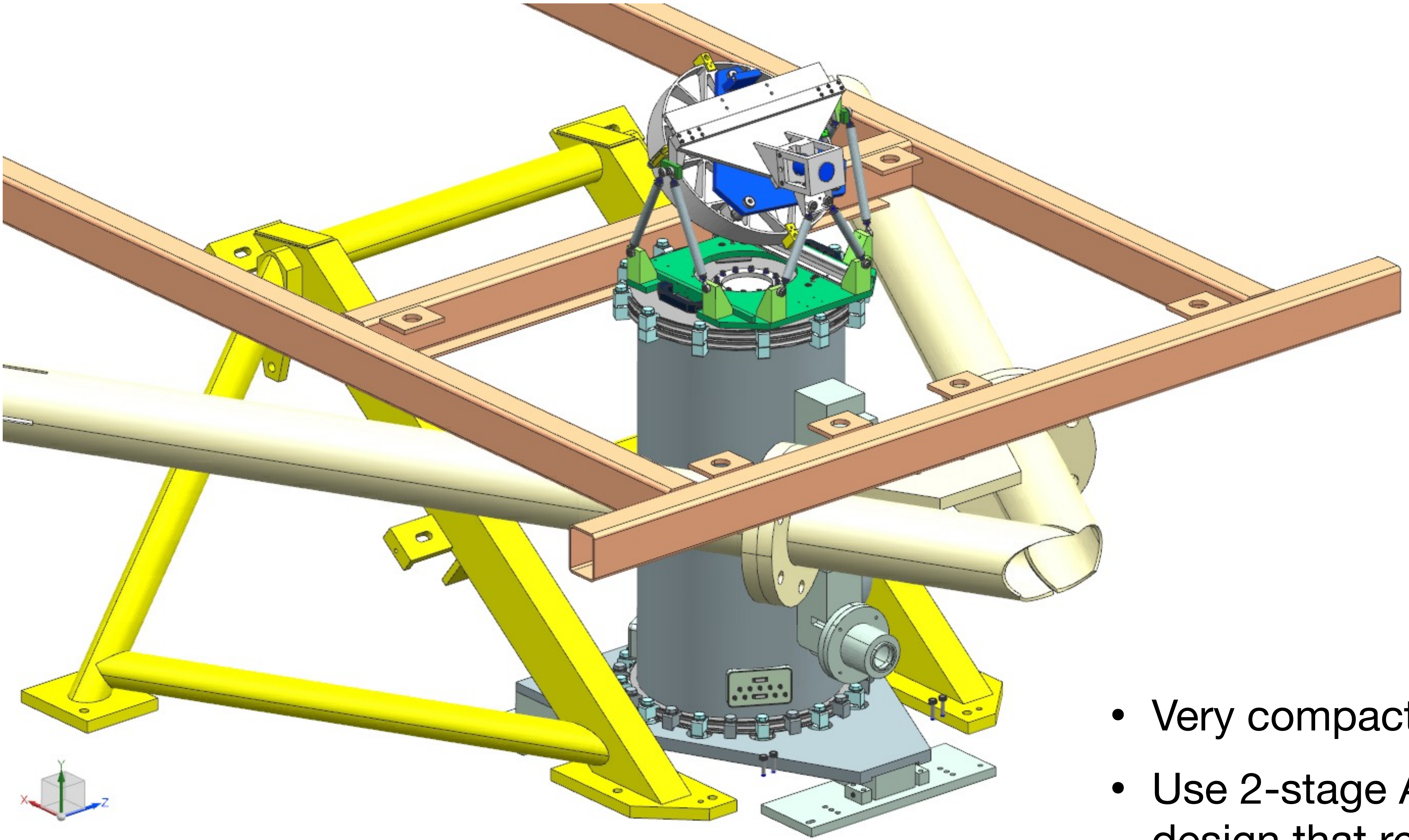
T. Cecil (Argonne), G. Robson (Cardiff)

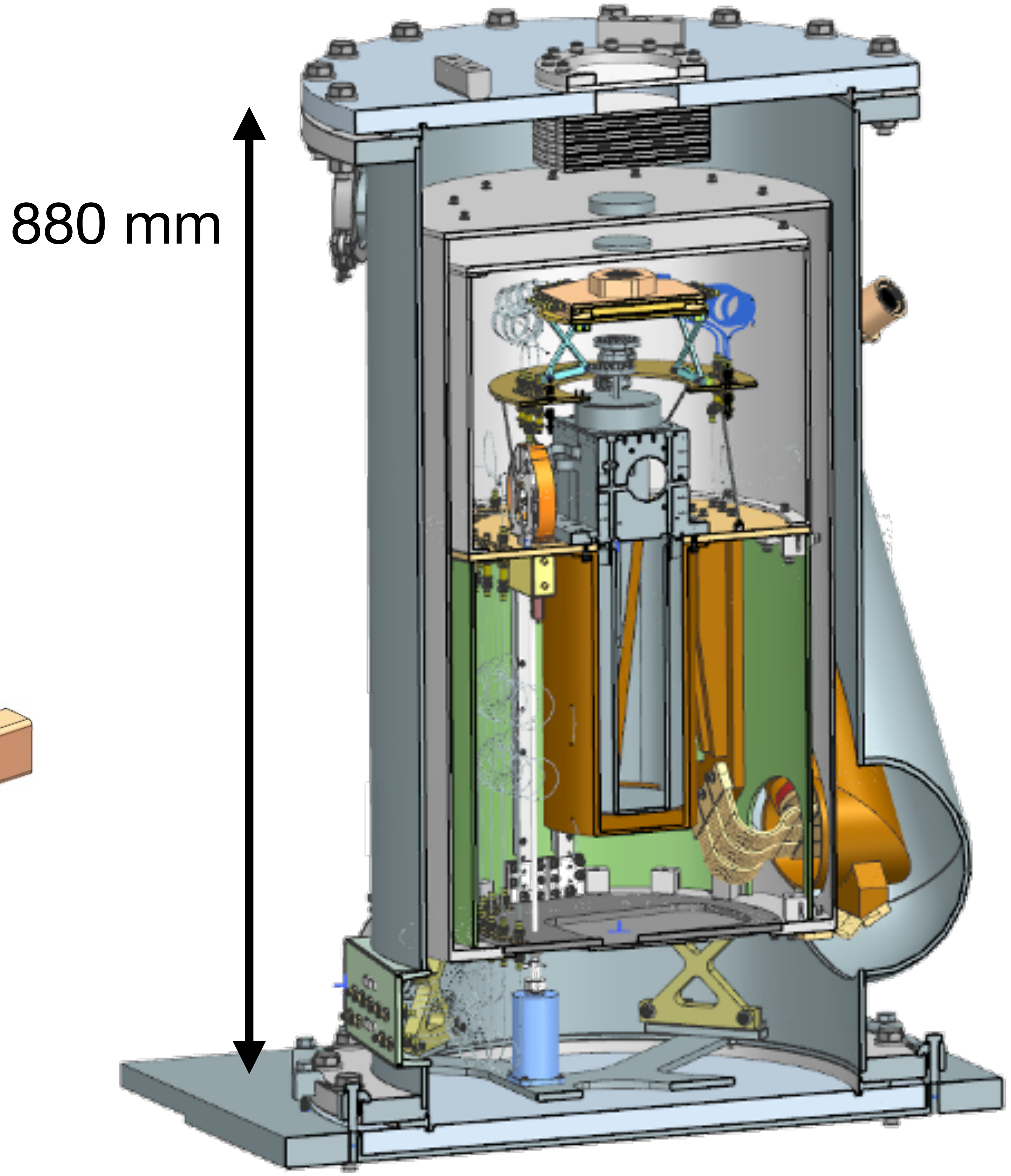


G. Robson++ (2111.04632)



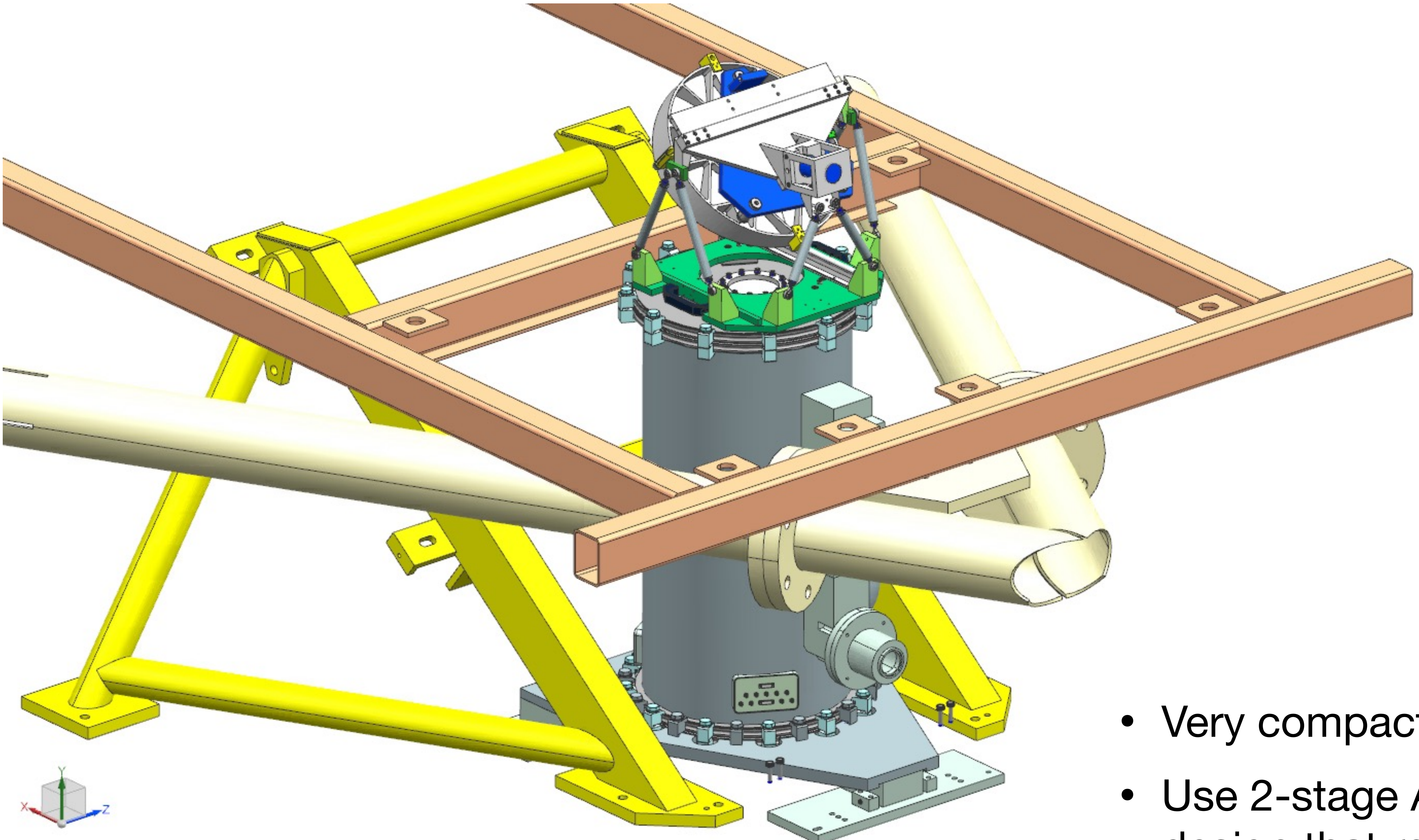
SPT-SLIM Cryostat

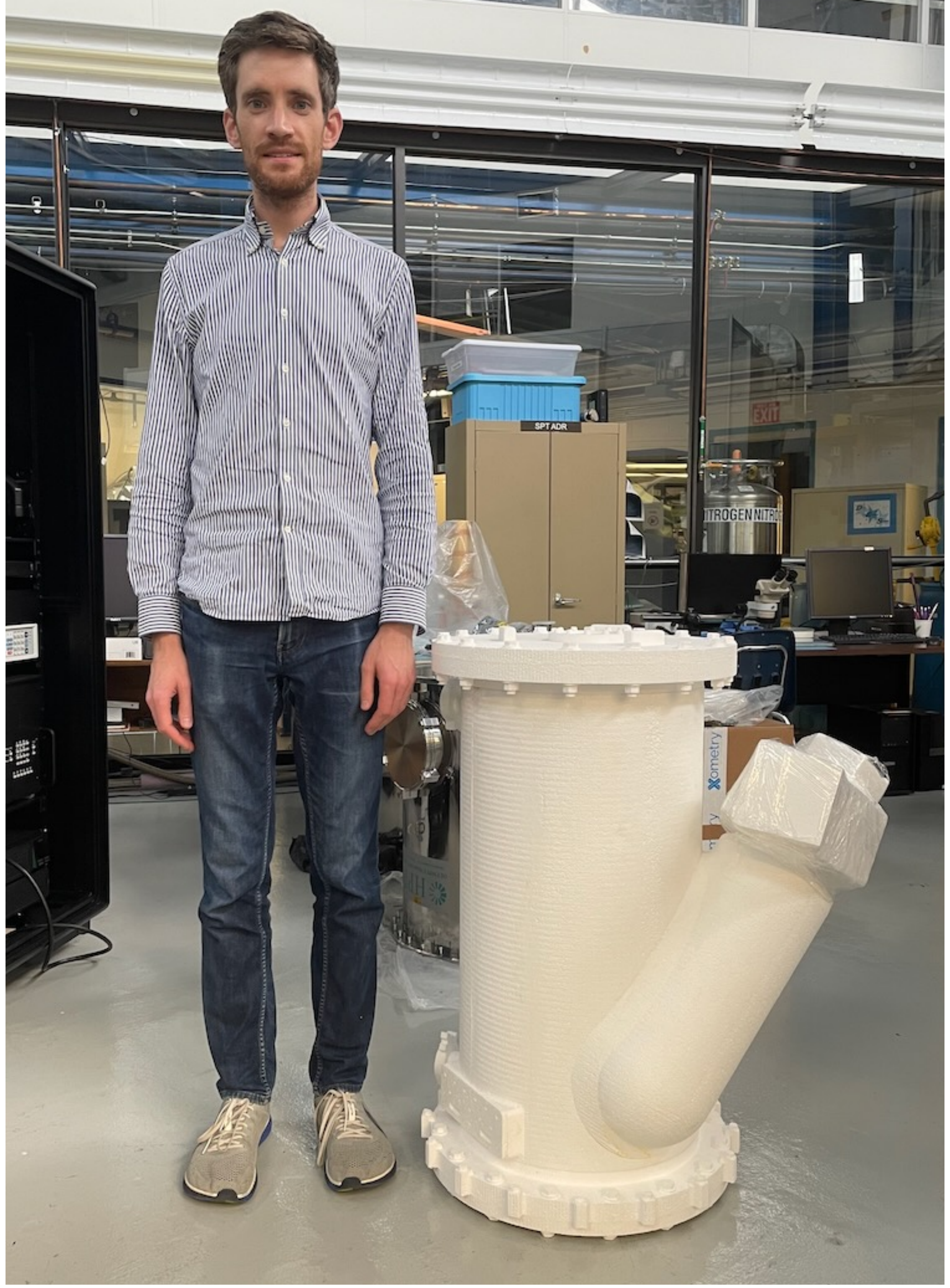




- Very compact design required to fit in SPT receiver cabin
- Use 2-stage ADR backed by PTC operated at 100mK—design that requires strict control of thermal loading

SPT-SLIM Cryostat





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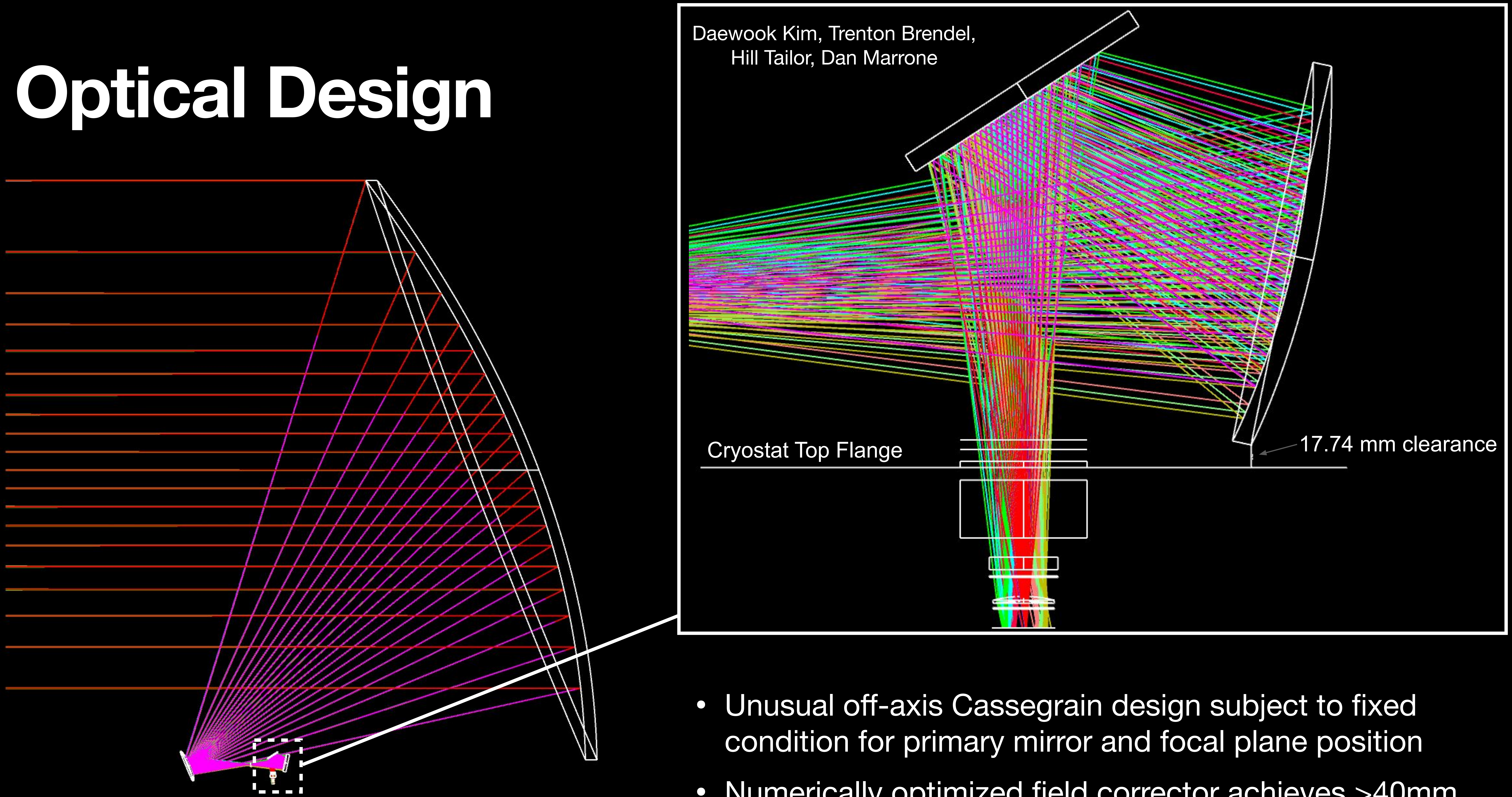
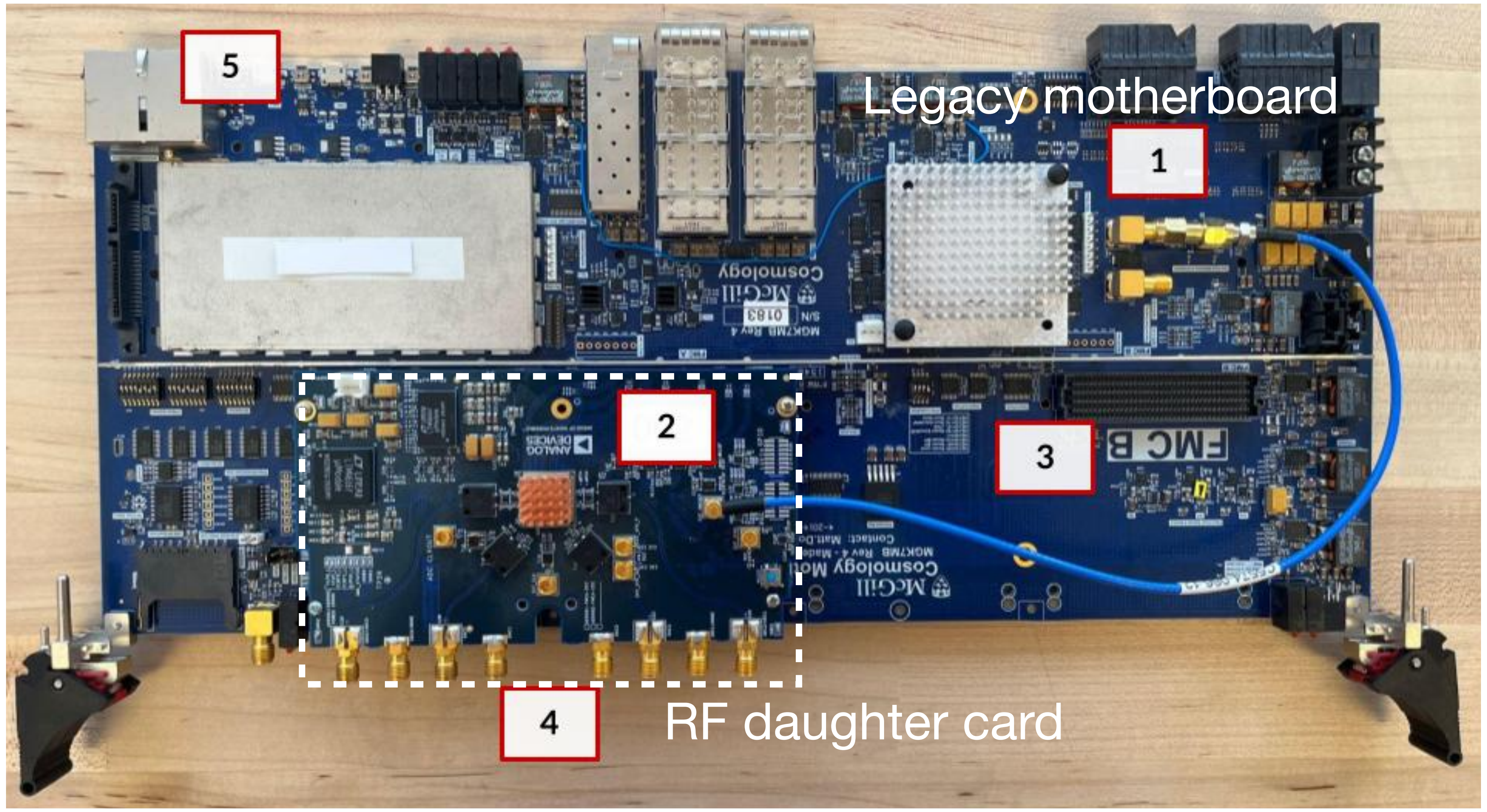
Optical Design



- Unusual off-axis Cassegrain design subject to fixed condition for primary mirror and focal plane position
- Numerically optimized field corrector achieves >40mm diameter usable focal plane at f/2.5

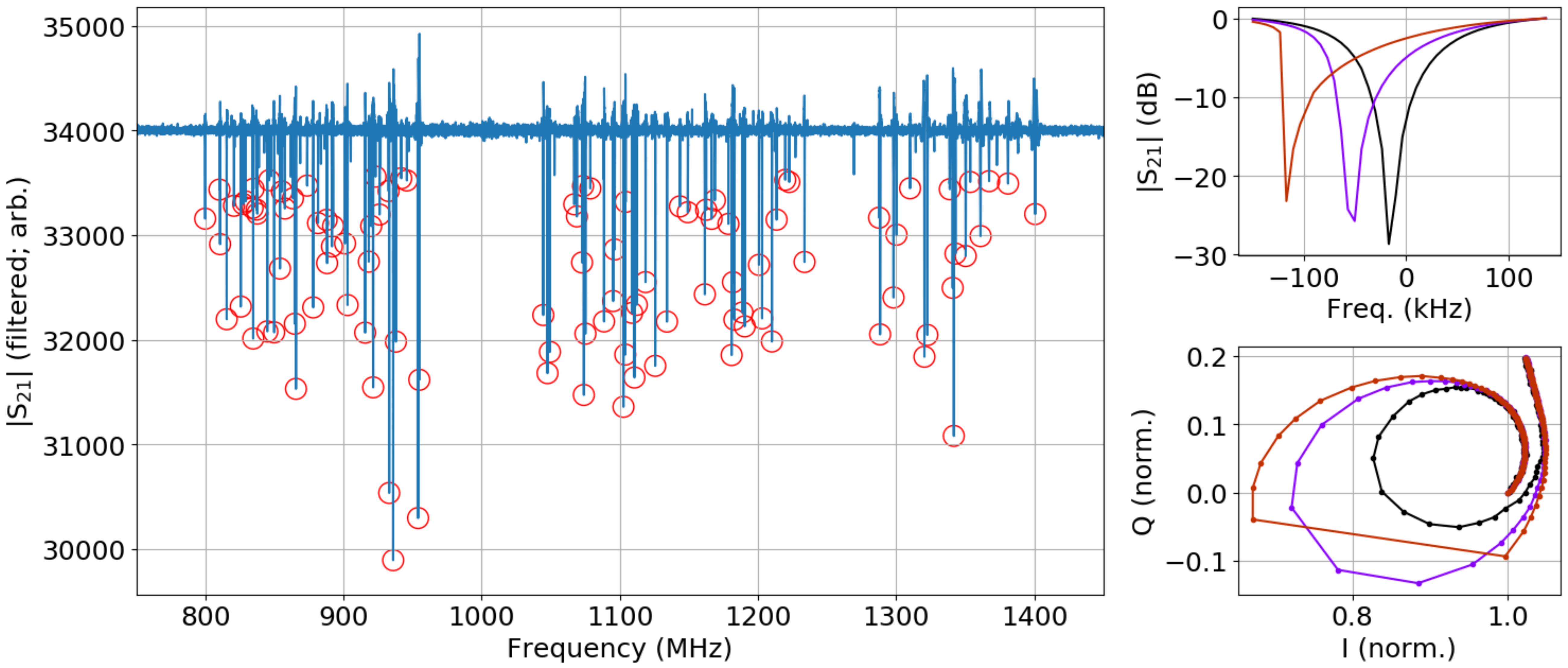
Next-Generation Microwave Readouts

- Adapting “ICE” platform developed by McGill for readout of TESs in SPT-3G and radio receivers in CHIME
- Maintain legacy motherboards while swapping RF mezzanine based on the AD9082 chip:
    - 4x DACs (12 GSPS) and 2x ADCs (6 GSPS) per board, supporting 2048x multiplexing at baseband
- Enables reuse of full software stack developed for SPT-3G TESs: major reduction in effort!
- Upgrade path with RFSoC FPGAs: McGill spin-off company called t0 developing board for KIDs and quantum readout and controls using adapted RF-ICE firmware
- FNAL has also developed prototype KIDs readout firmware for RFSoC demo board (ZCU111)



Rouble++, Proc SPIE 12190 (2022)

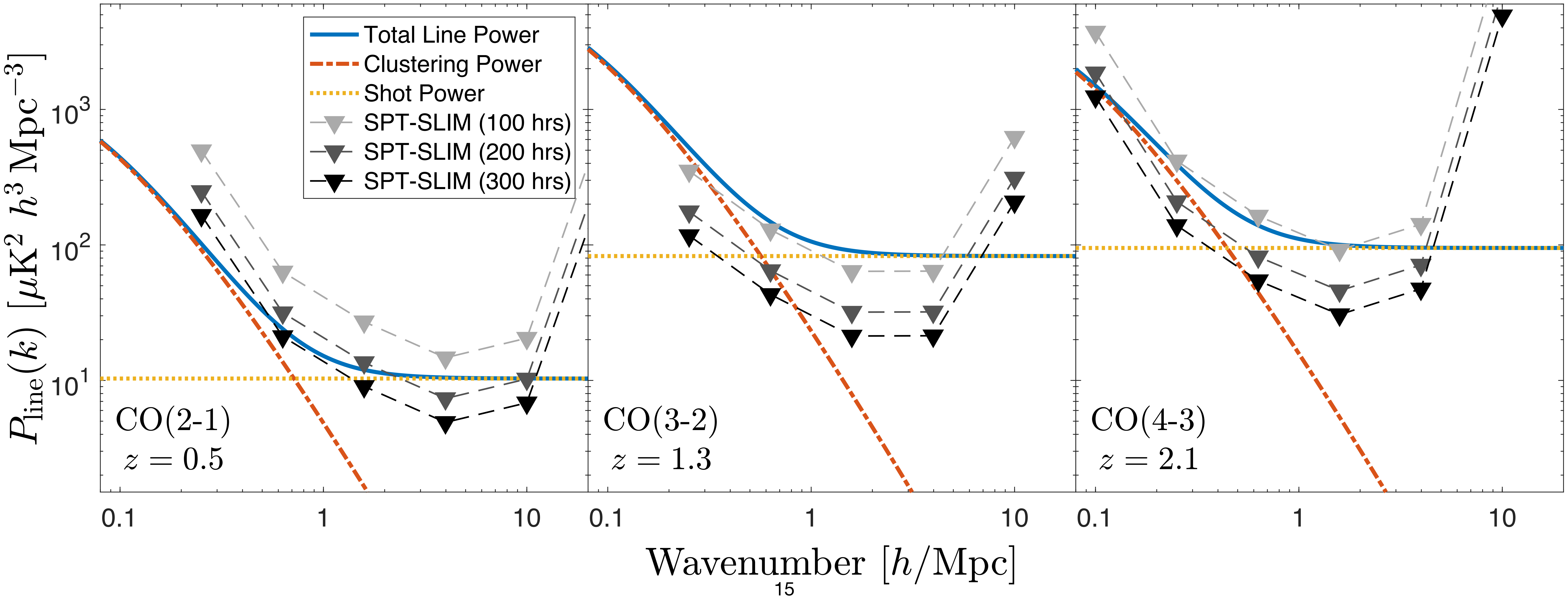
Example outputs from RF-ICE prototype MKID wafer characterization routine



Forecast and Experimental Outlook

- Conservatively expect 50-75% total observing efficiency for ~4 weeks, so >300 hours on-target time is realistic
- Raw sensitivity of SPT-SLIM could be sufficient for a first detection of the CO power spectra (0.5 < z < 3) with high significance in a single summer season

with Karto Keating, Kirit Karkare



Conclusions

- SPT-SLIM is funded by internal Fermilab LDRD funds and NSF, and target deployment to South Pole is 2023-2024 austral summer
- Demonstration of scaling the on-chip spectrometer technology from single pixels to a full array
- High-significance detection of CO power spectrum is possible even with a small technology demonstrator