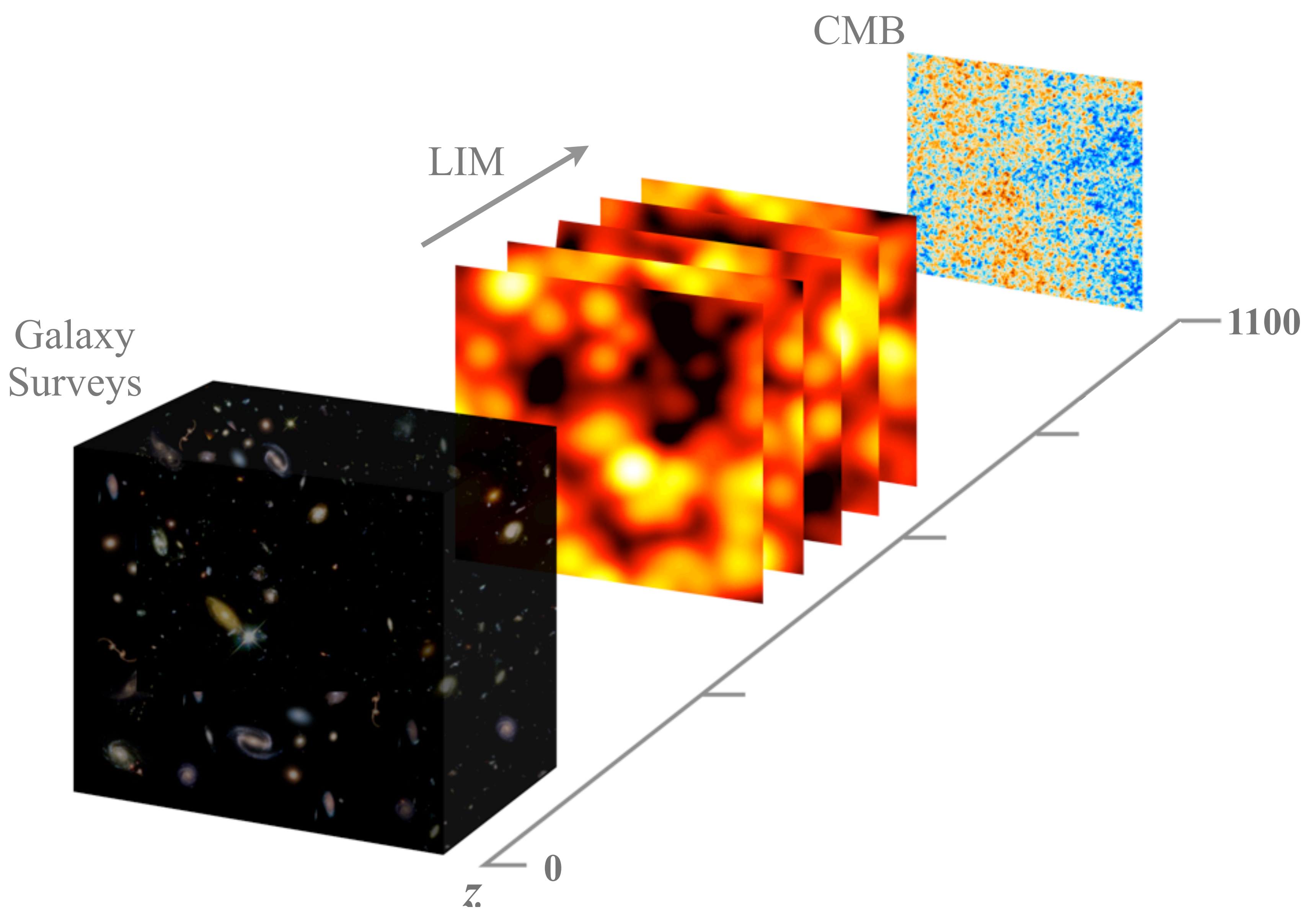
SPT-SLIM: Line-Intensity Mapping Pathfinder on the South Pole Telescope

Adam Anderson - Fermilab
mm Universe - University of Chicago
26 June 2025

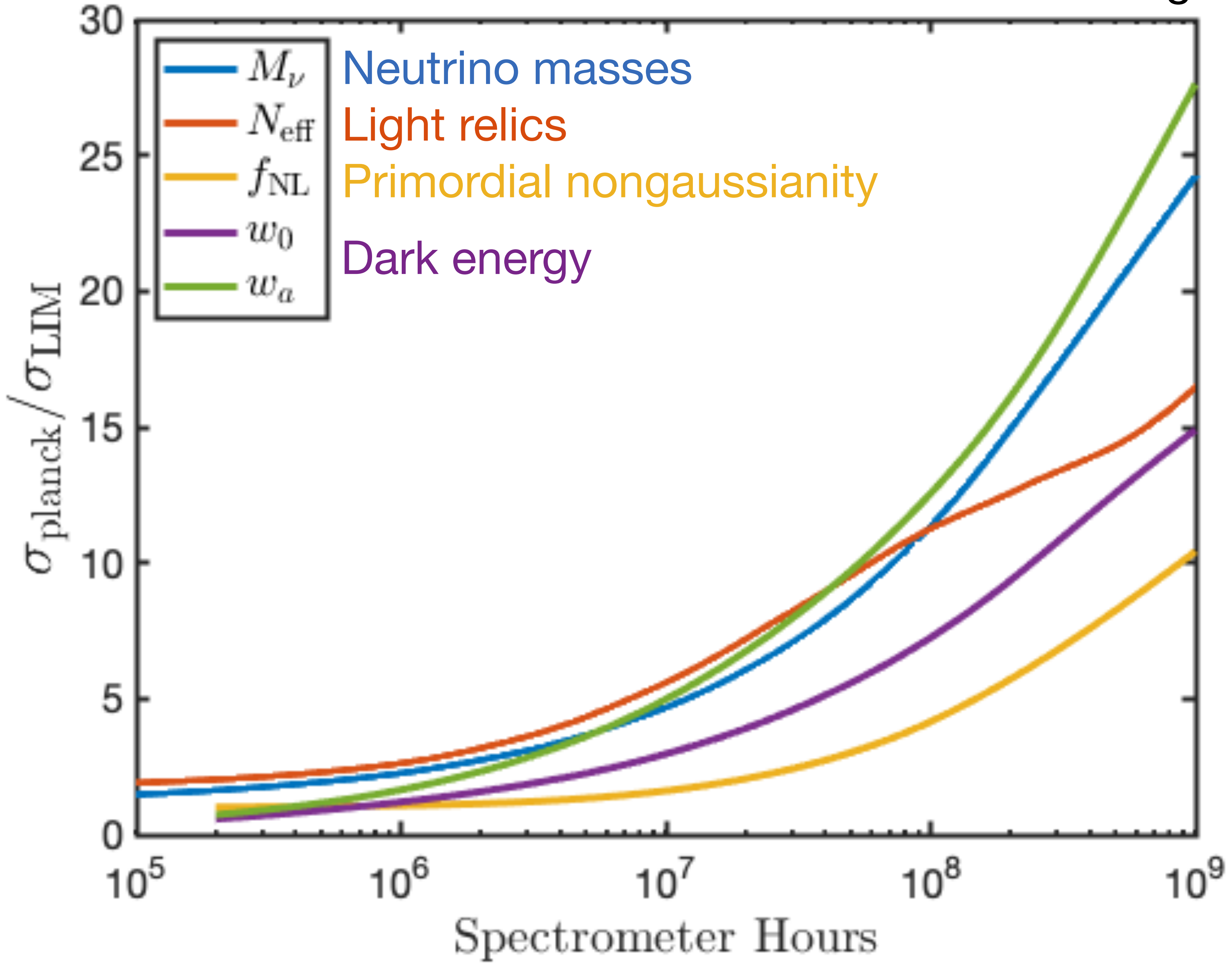
FERMILAB-SLIDES-25-0143-PPD

Cosmology with LIM

- LIM with mm tracers can, in principle, improve constraints on cosmological parameters due to:
    - Measuring more modes at higher redshifts
    - Degeneracy breaking when combined with CMB and other probes
- *Placing significant constraints on cosmology using LIM requires* ***much*** *larger arrays of detectors than currently exist* ➔ **opportunity for technology development.**



Karto Keating



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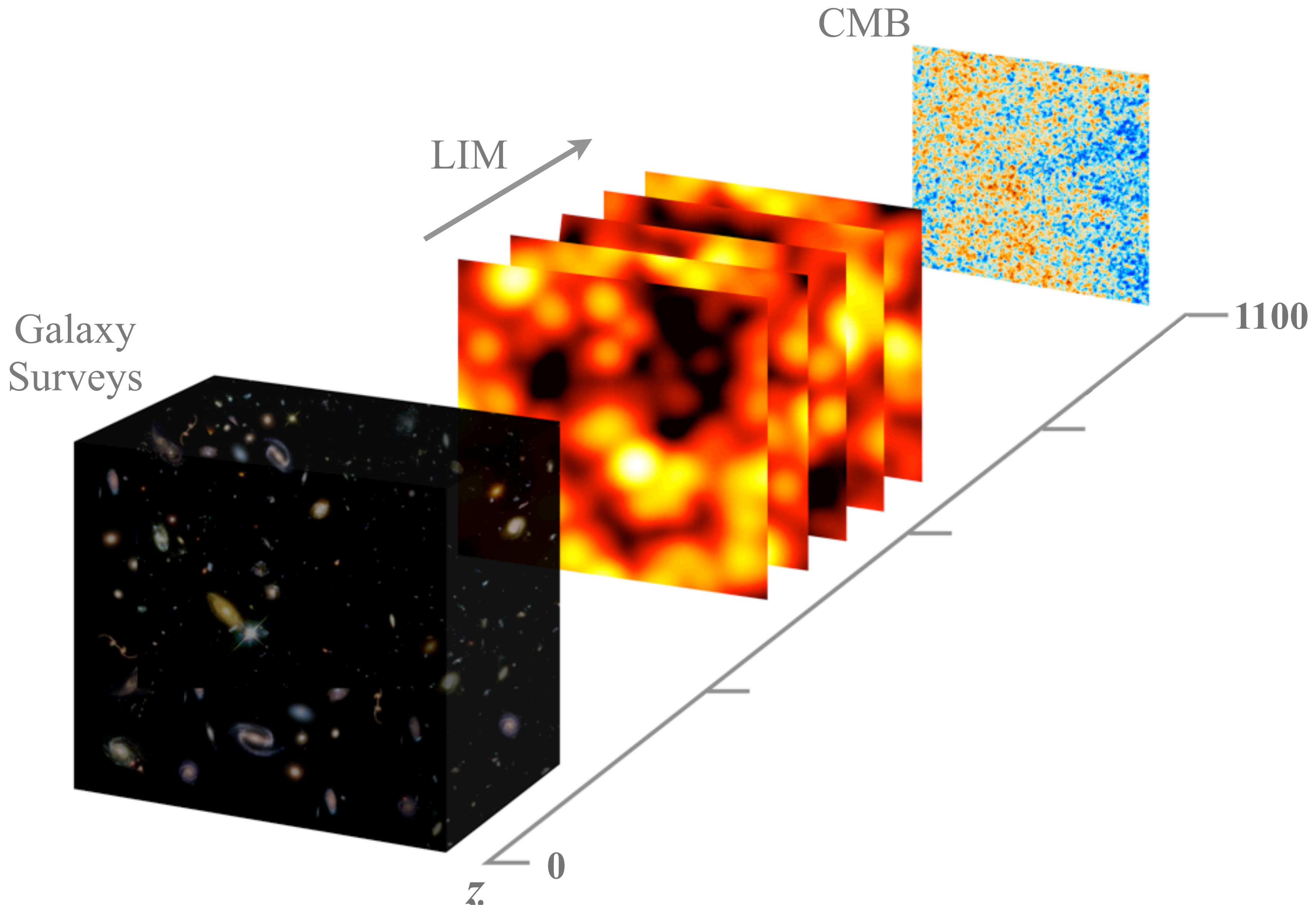

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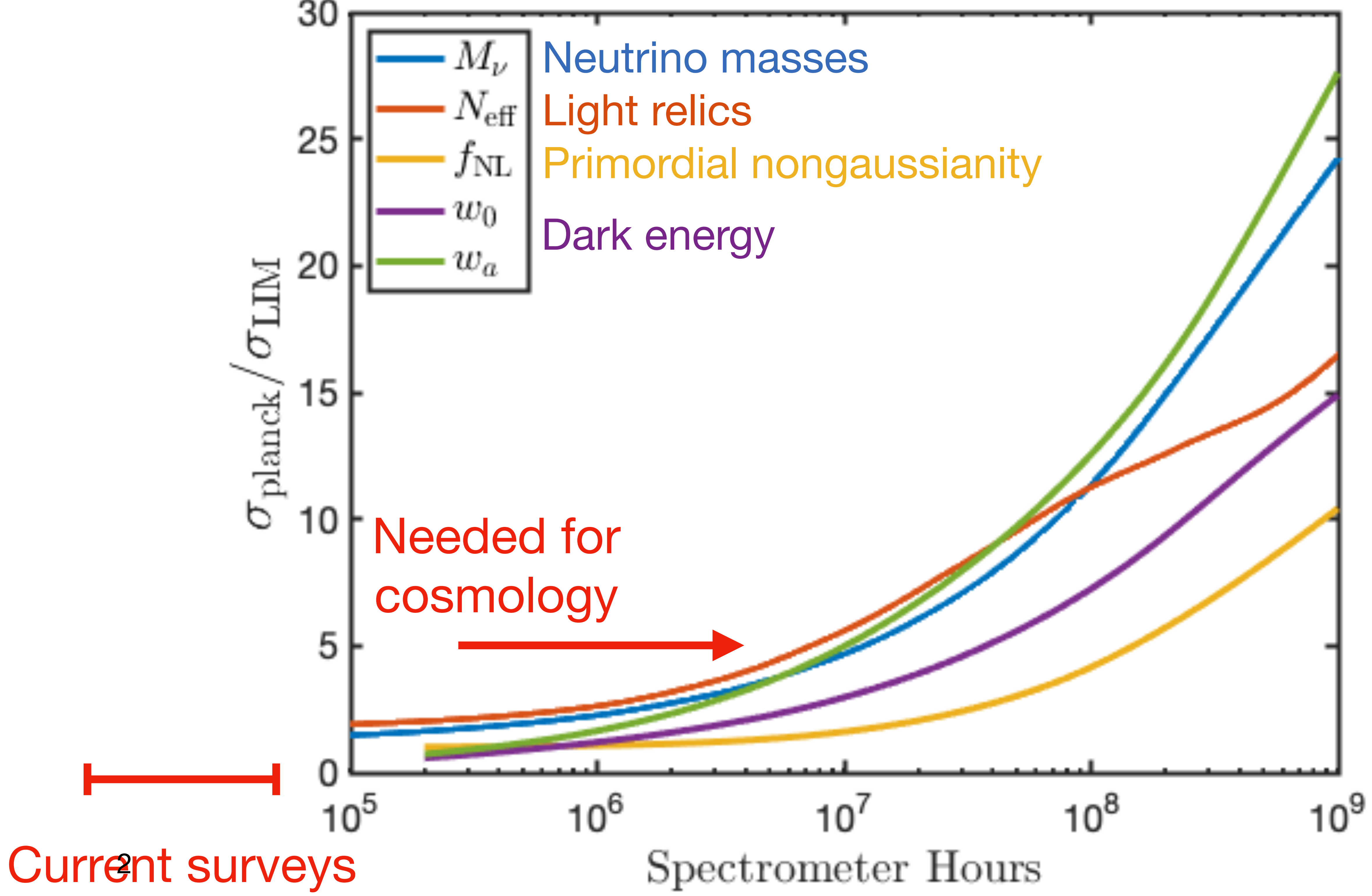
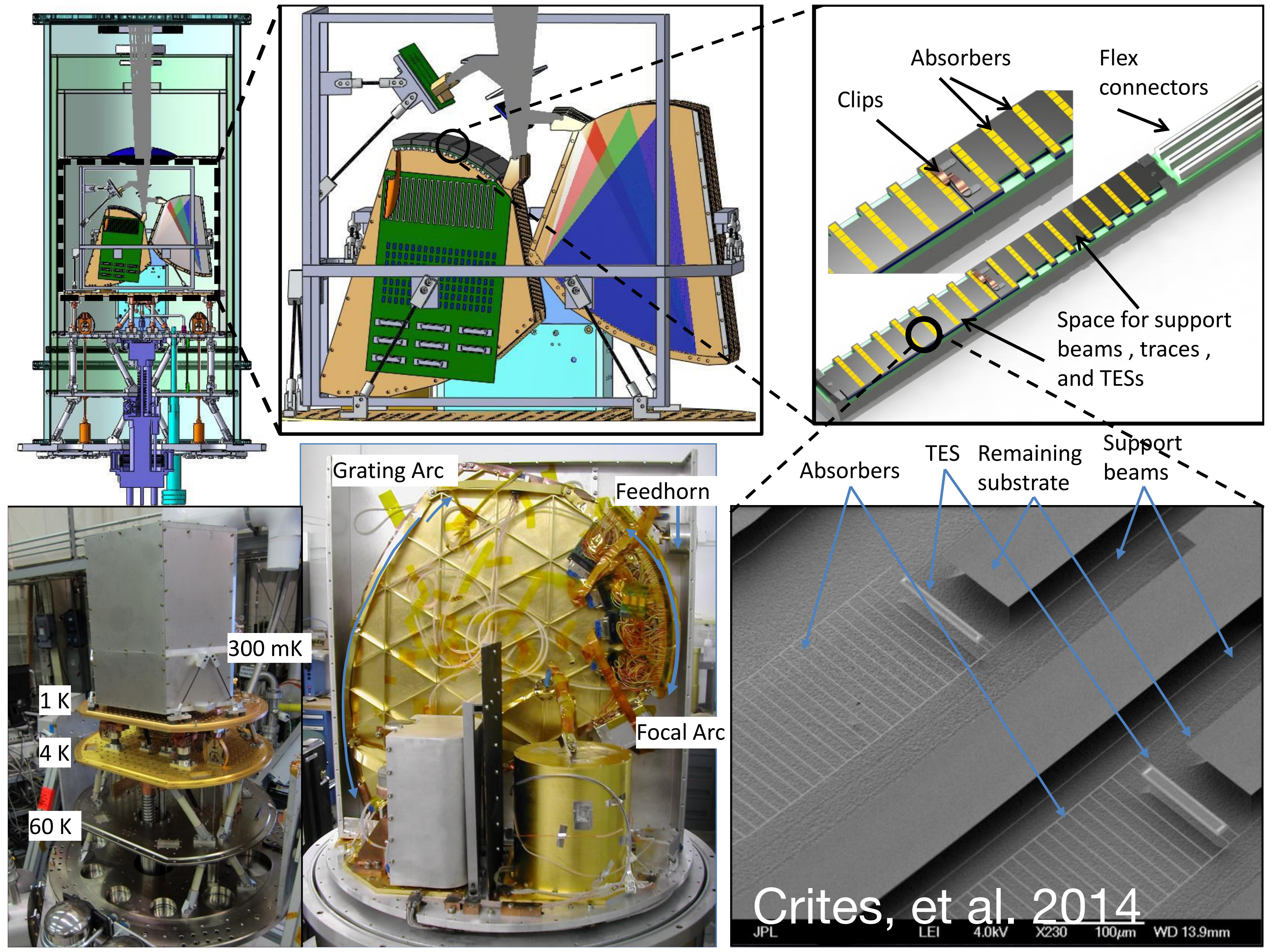


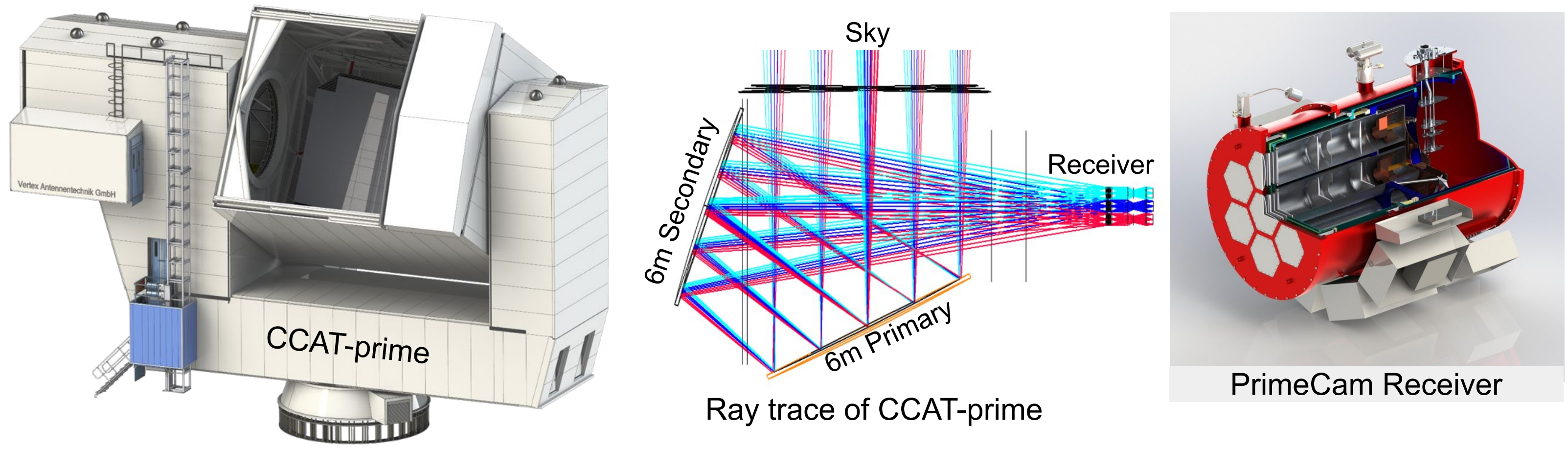
Many Lines, Many Experiments…

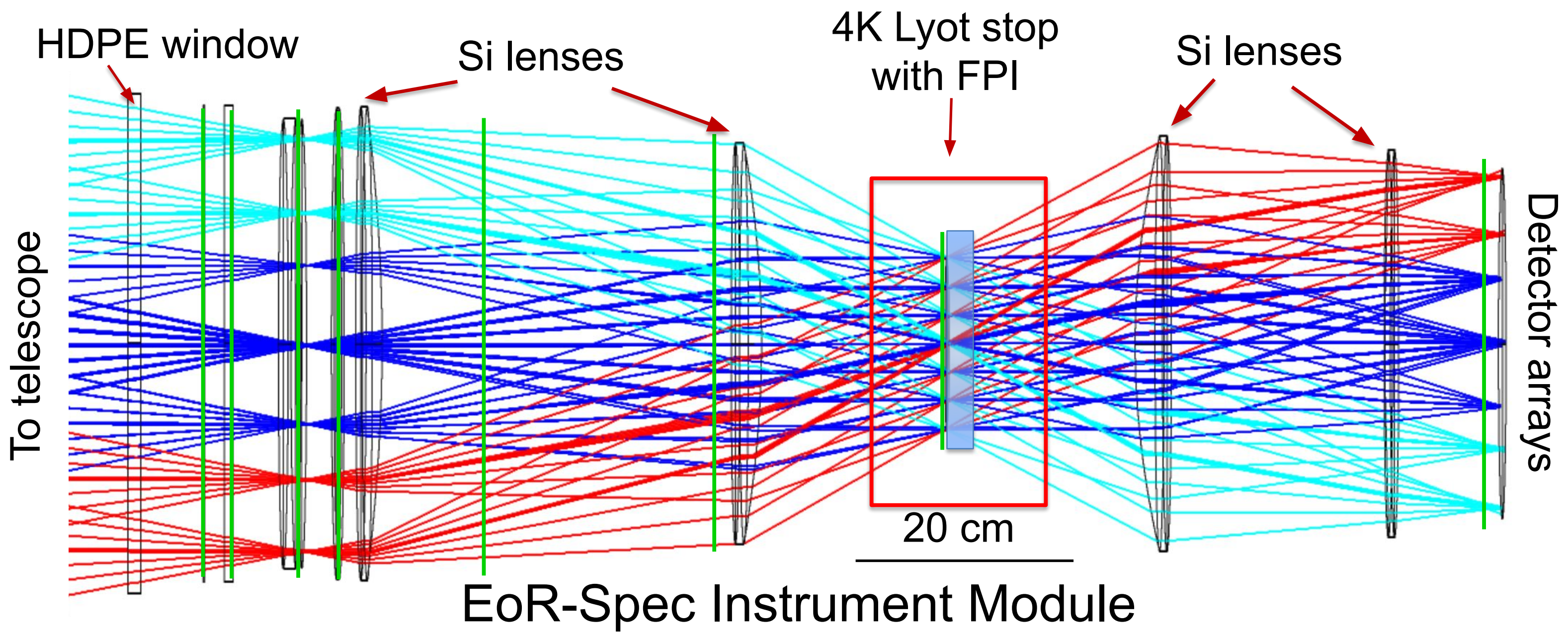
Cothard, et al. (1911.11687)

TIME:
Grating spectrometer
CII 5 < z < 9
(180–320 GHz)

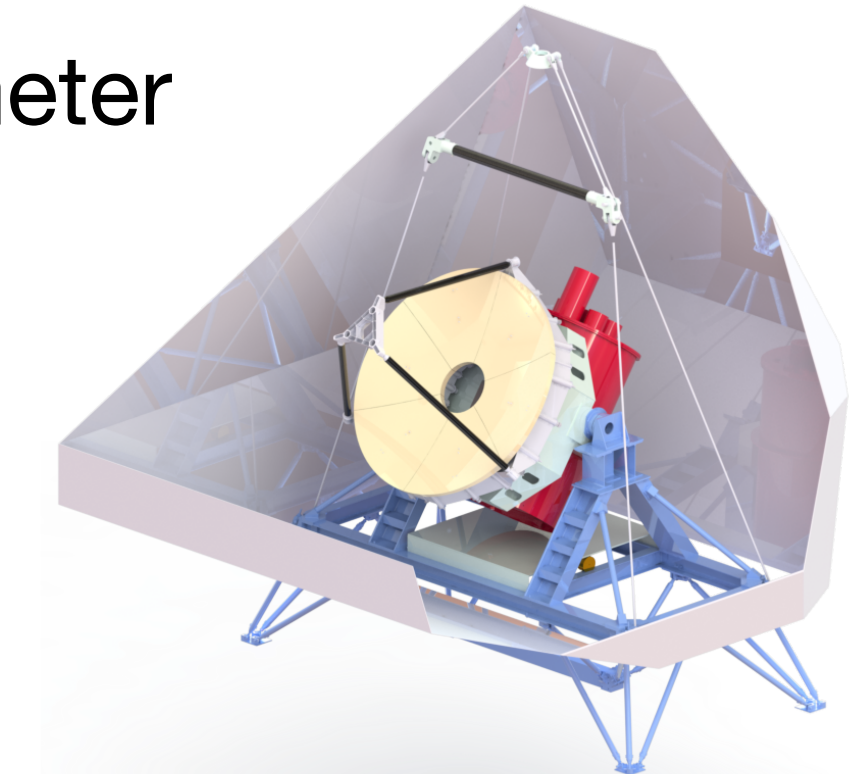


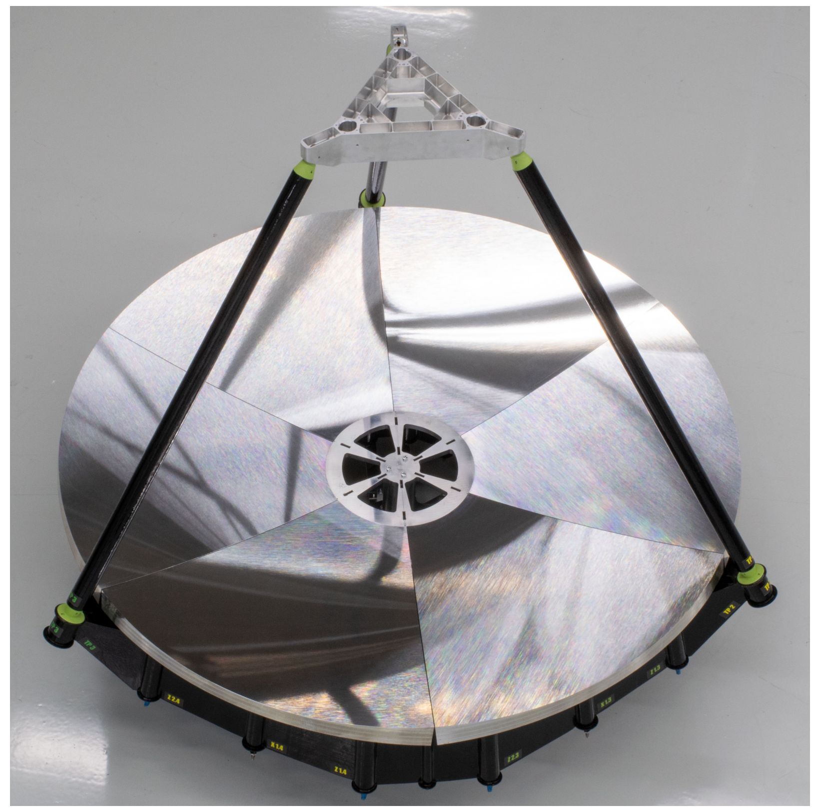
EoR-Spec / CCATp:
Fabry-Perot
CII 3.5 < z < 8
(210-420 GHz)





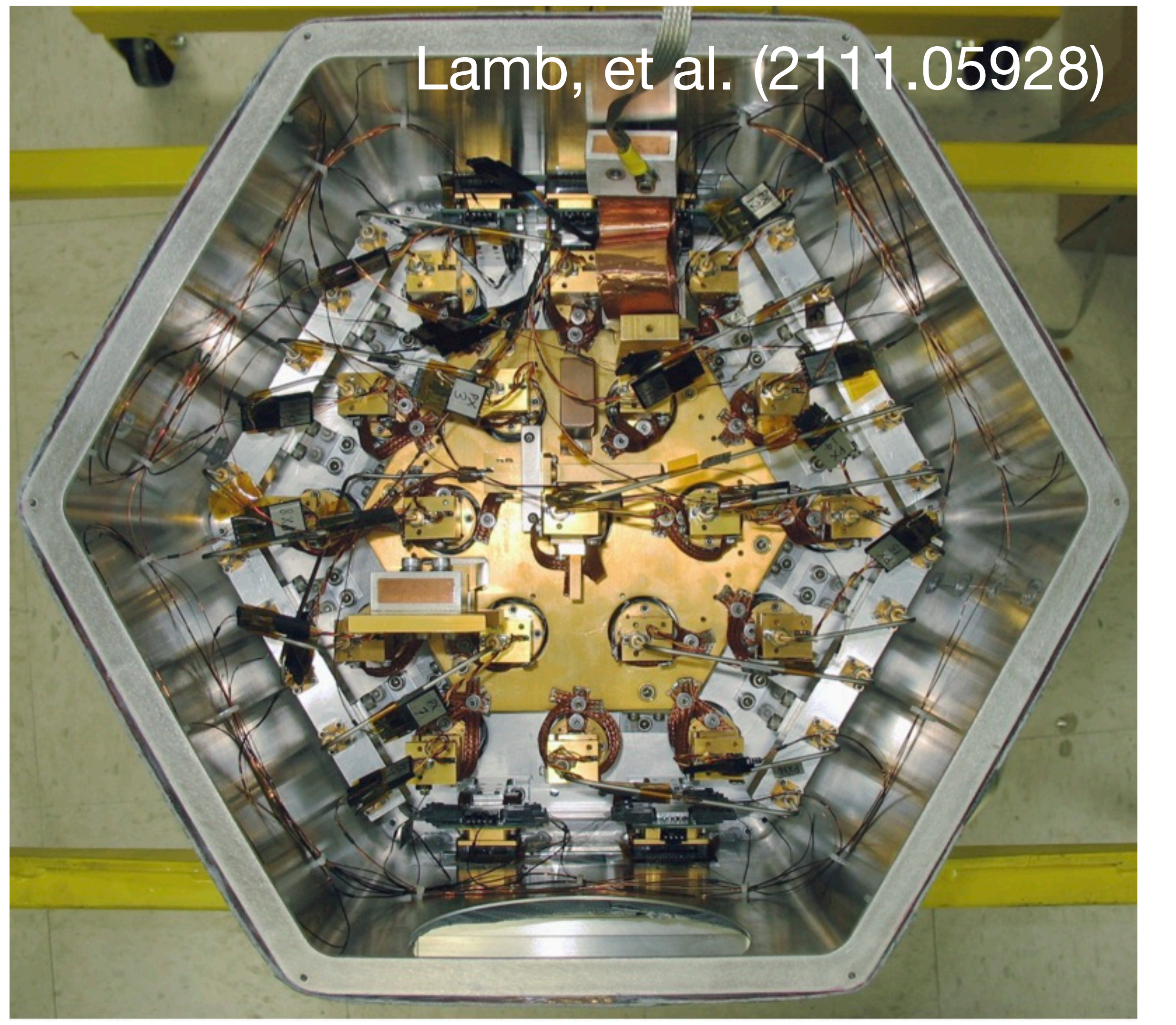
TIM:
Grating spectrometer
CII 0.5 < z < 1.5
NII, OI, OIII
(240-420 μm)





Marrone, et al. 2022

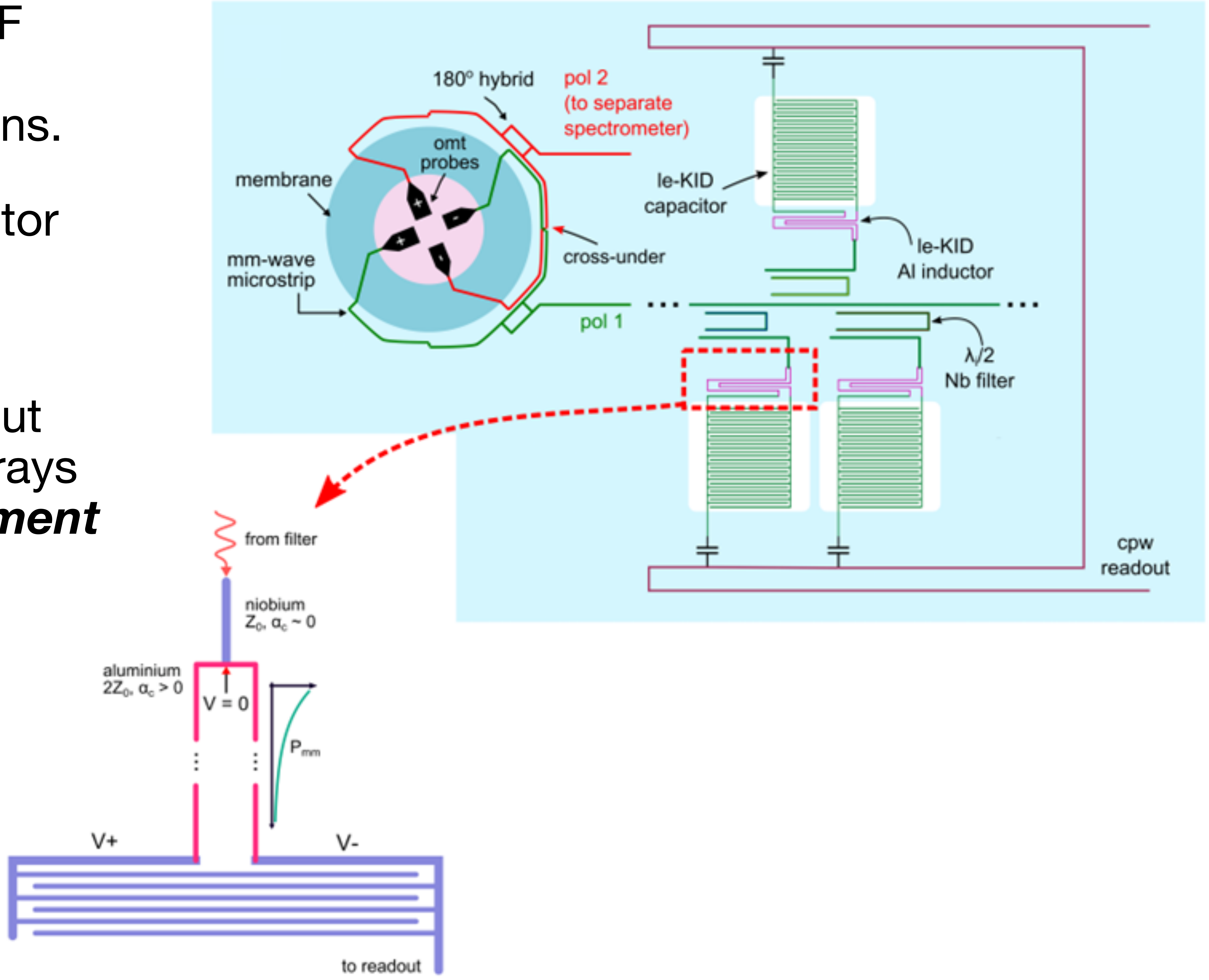
COMAP:
Coherent detectors
CO(1-0) 2.4 < z < 3.4
CO(2-1) 6 < z < 8
(26–34 GHz)

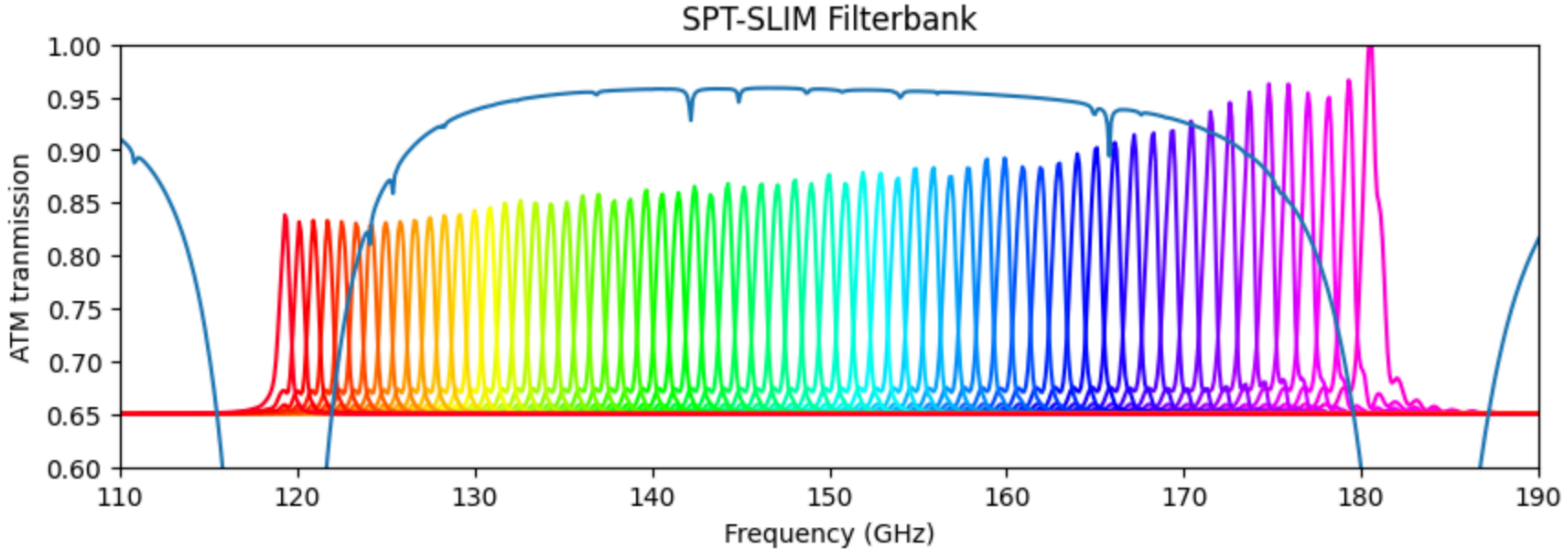


On-Chip Spectrometers: Principle of Operation

Peter Barry (Cardiff)

- Couple antenna to an bank of narrow-band RF filters, filling the atmospheric frequency “windows” used for ground-based observations.
- Couple a microwave kinetic inductance detector (MKID) to each filter channel.
- Multiple groups are pursuing on-chip spectrometers (e.g. SuperSpec, DESHIMA), but demonstrations are currently on very small arrays of detectors. ***Scaling is an important instrument R&D problem.***





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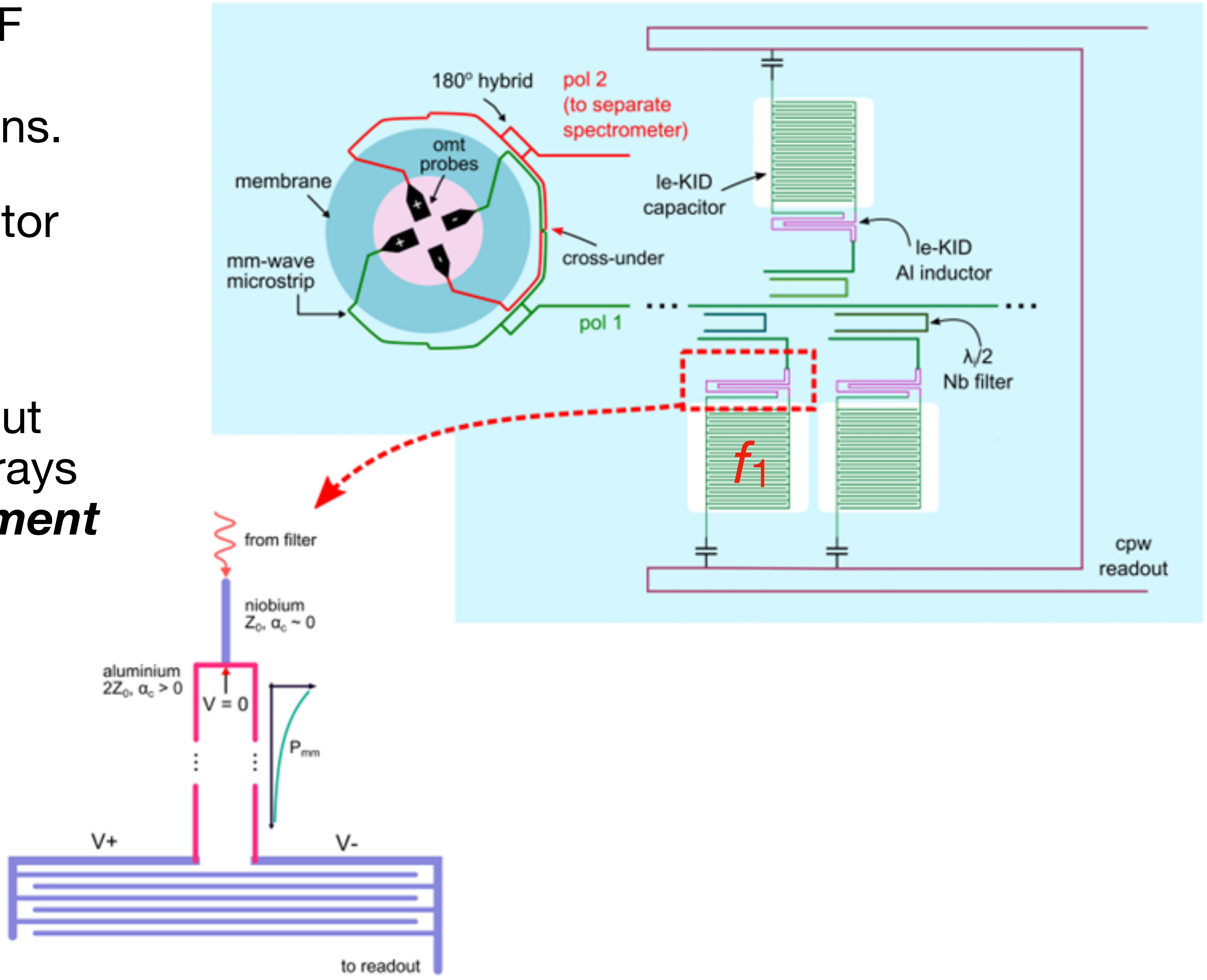

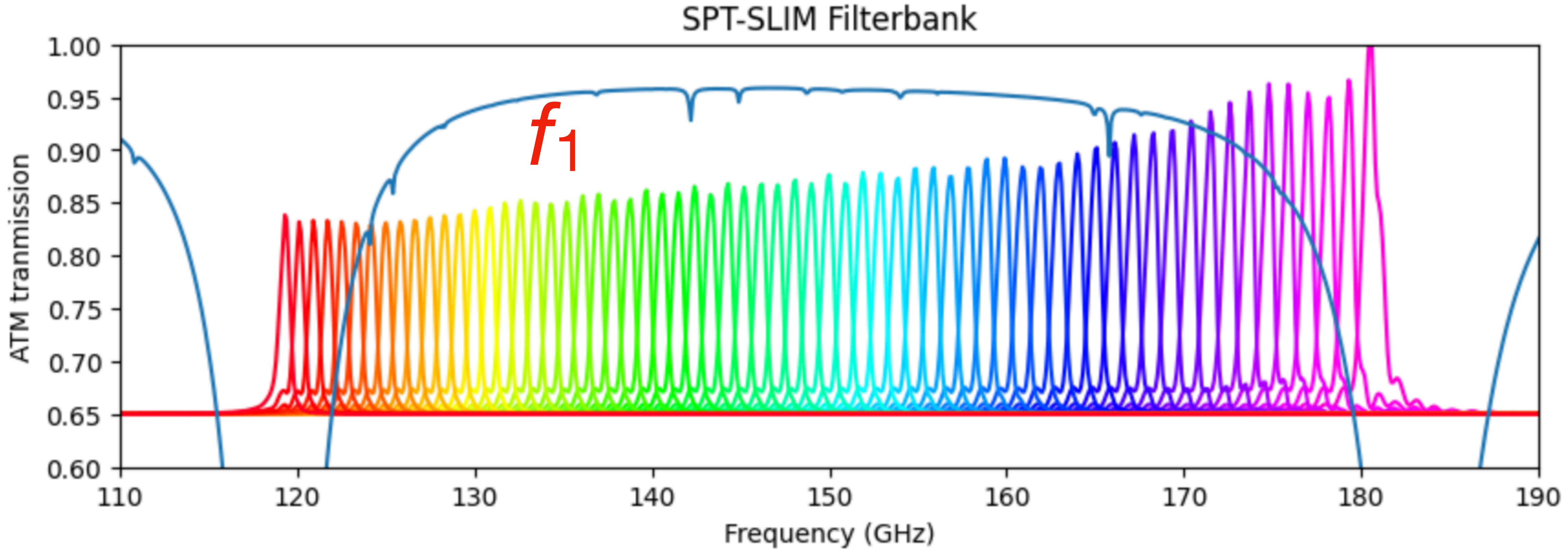

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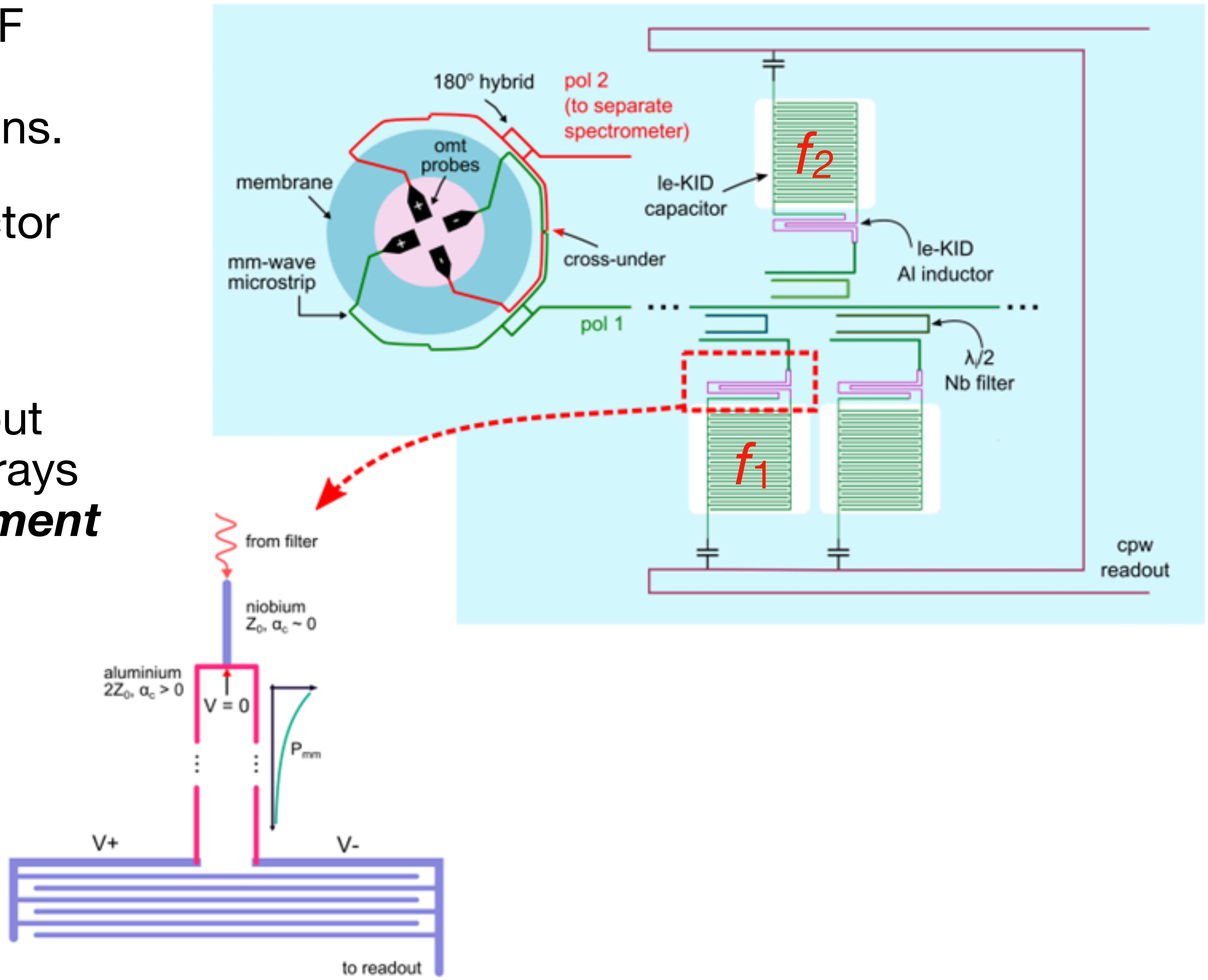

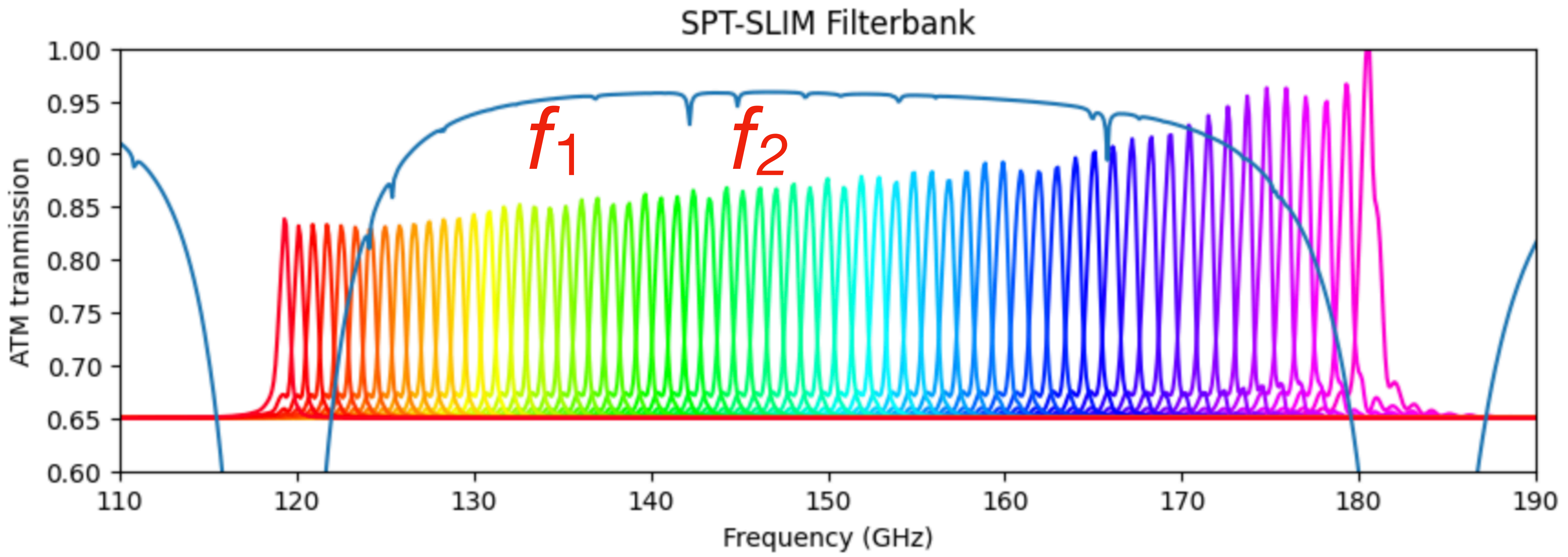

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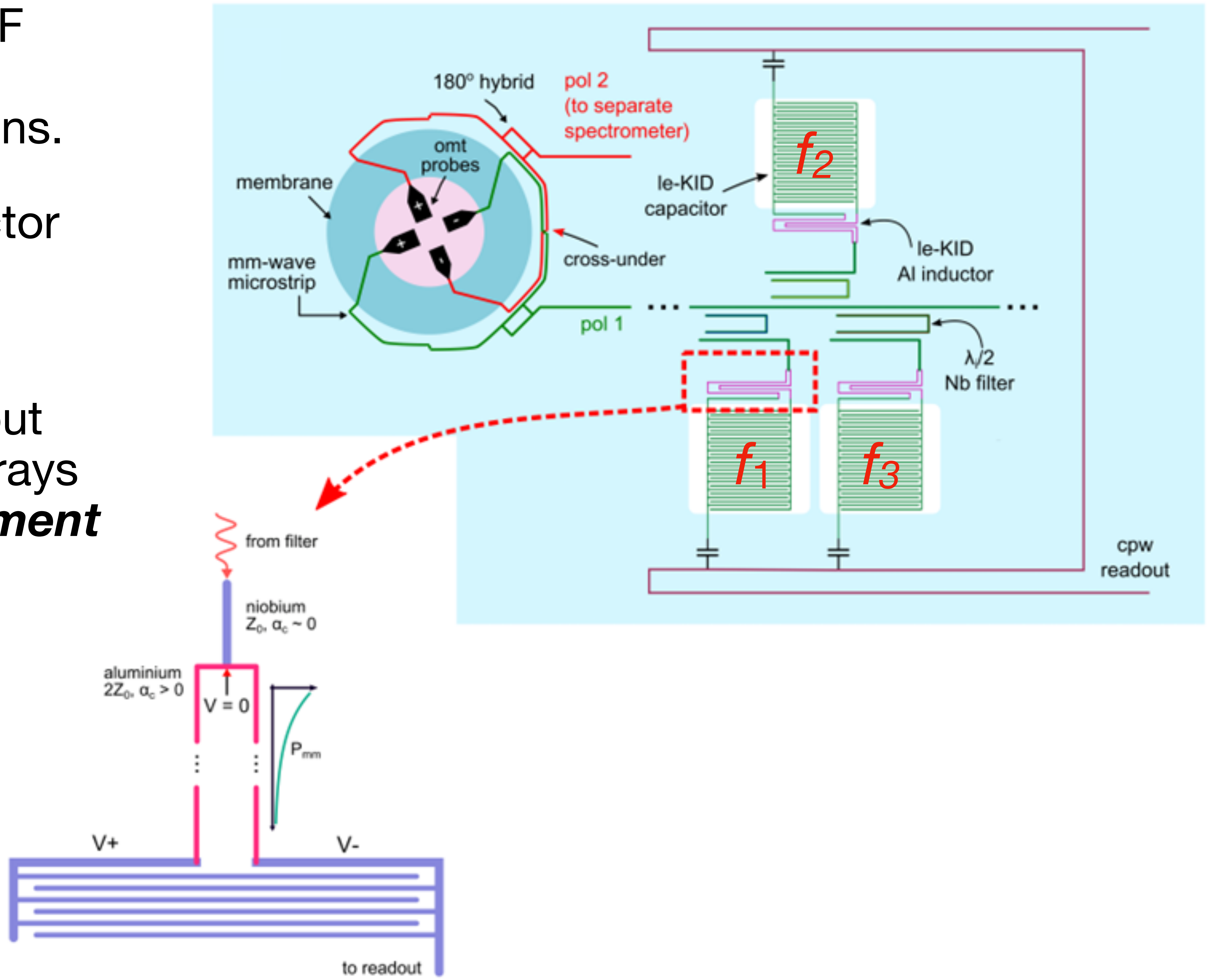
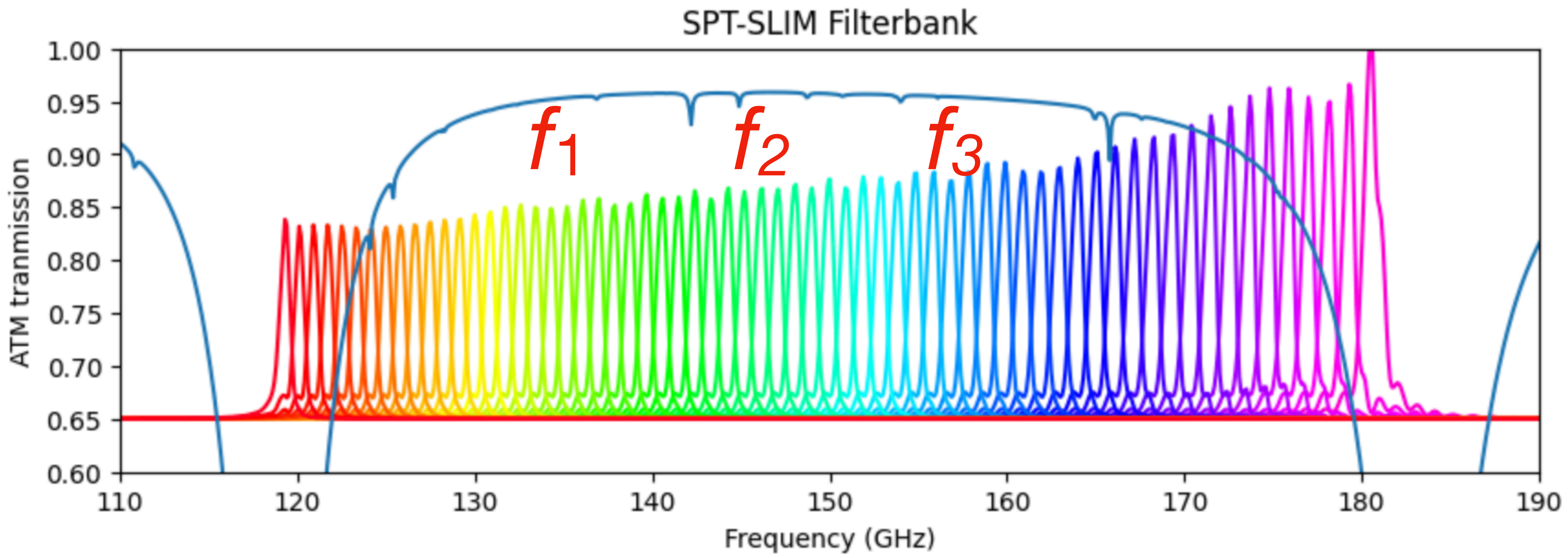
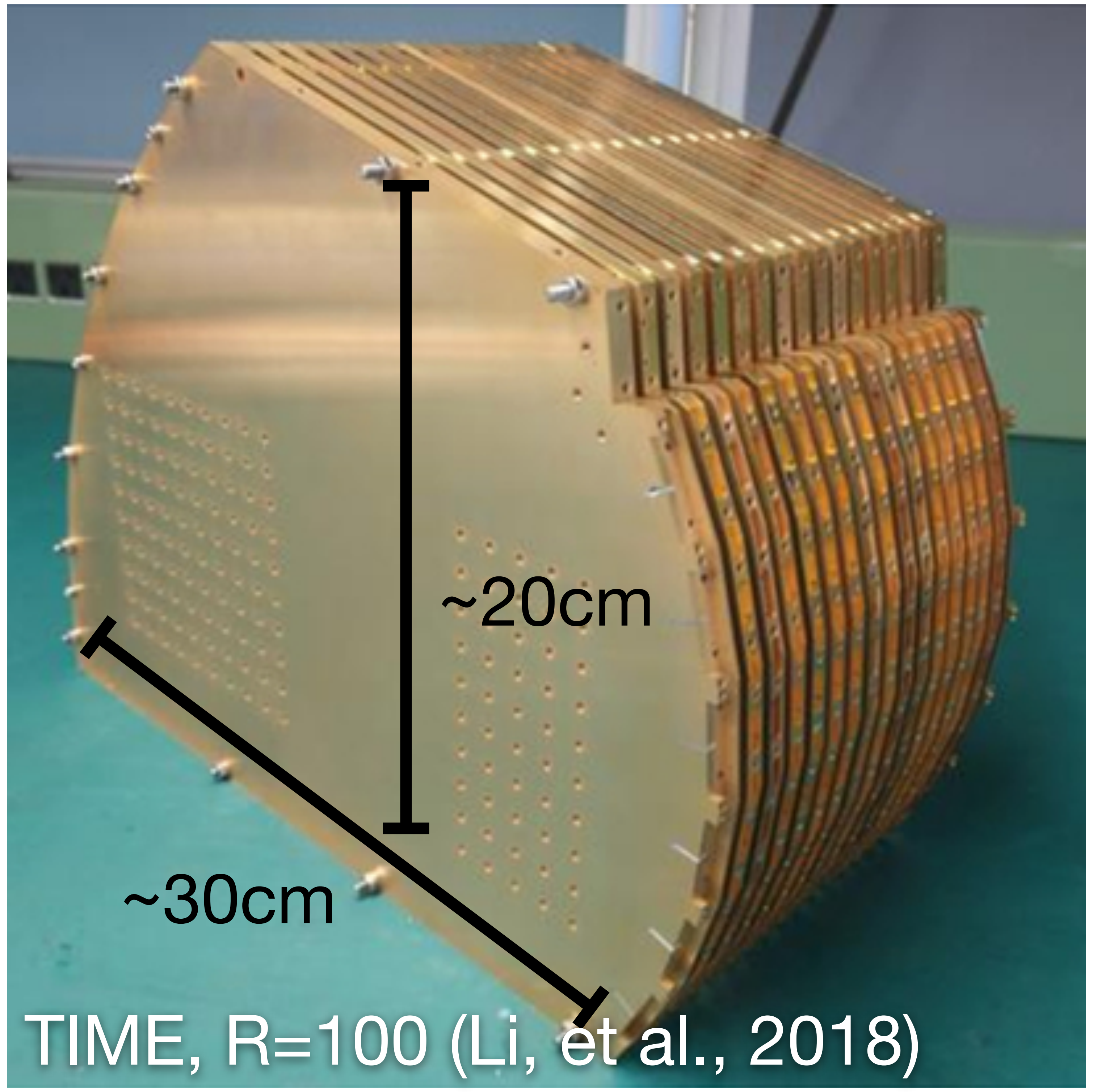


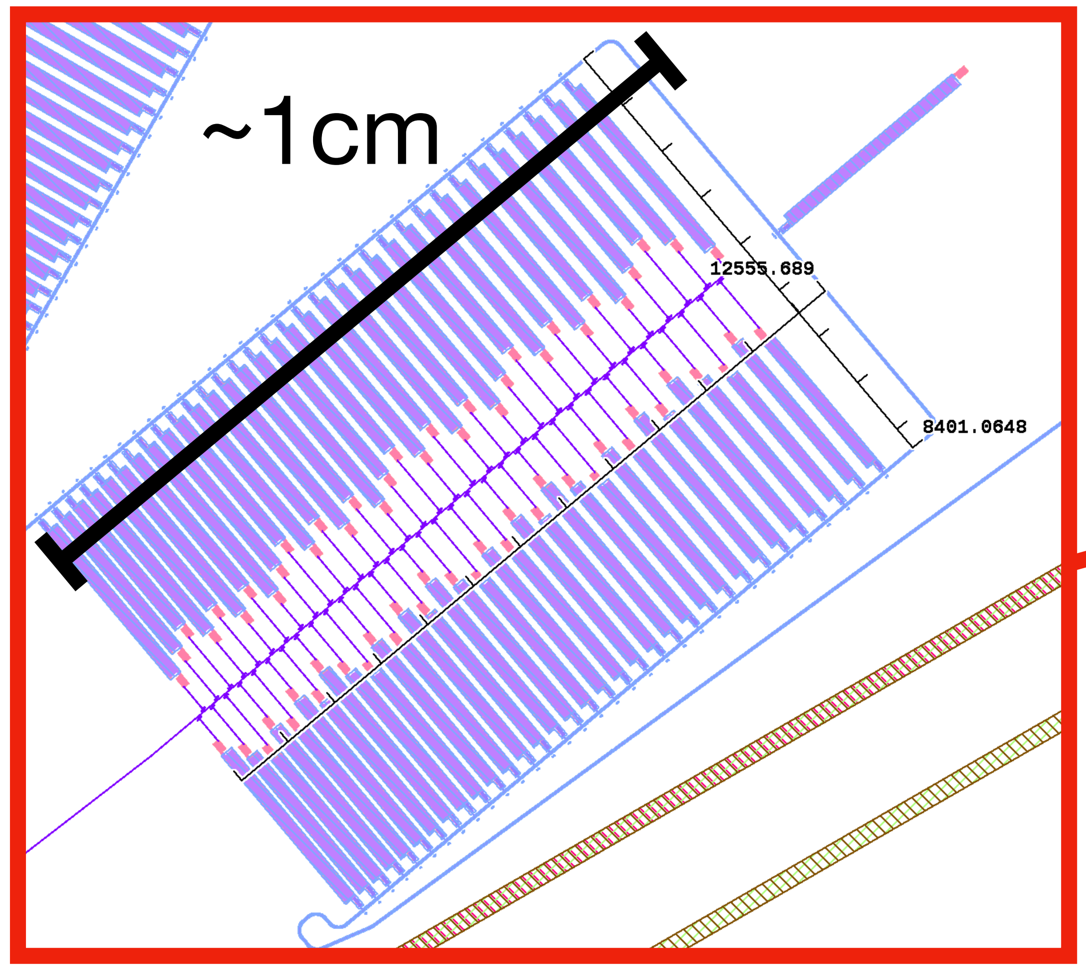


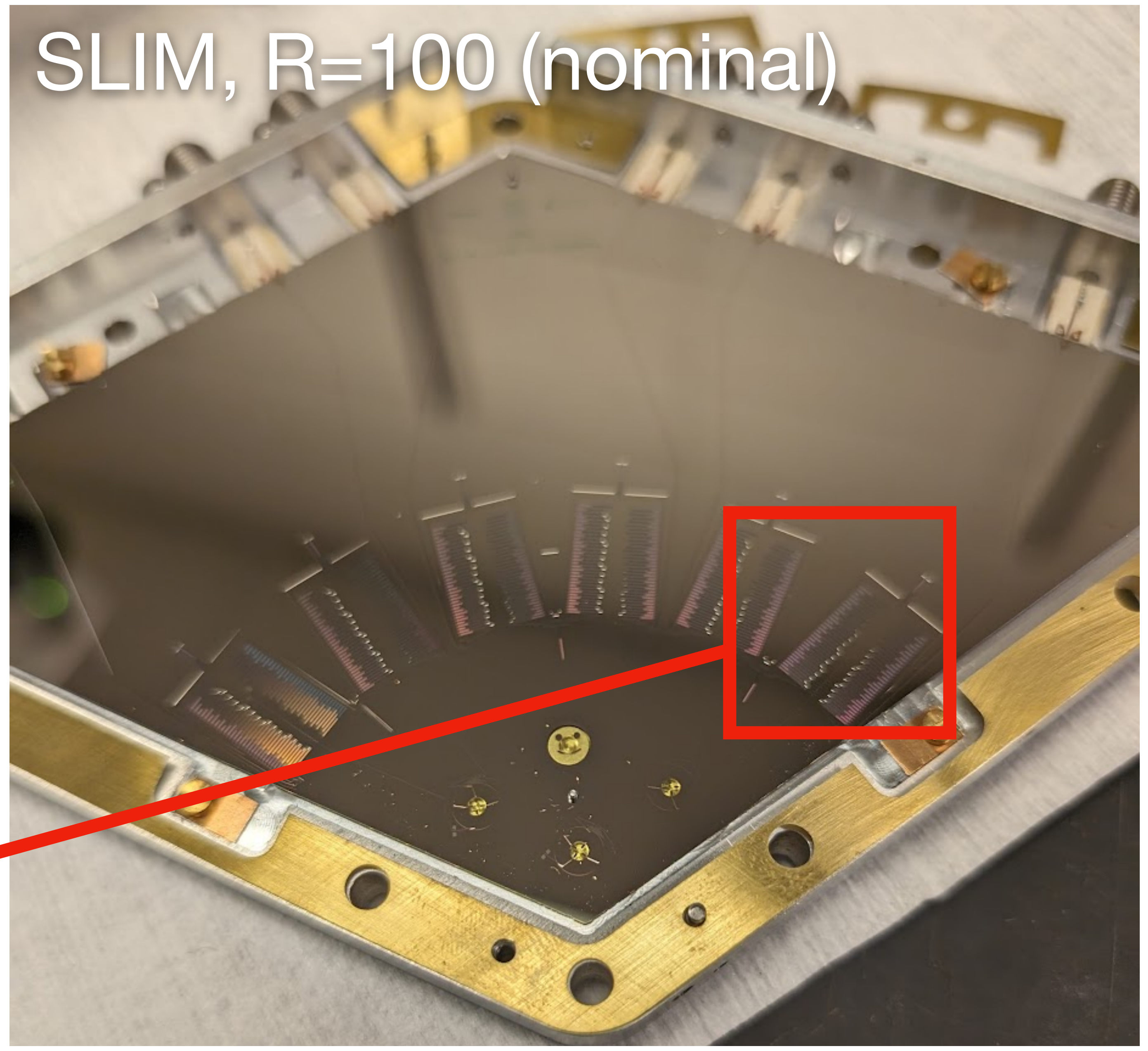
On-Chip Spectrometers: Potential Advantages

- ***Compactness:*** On-chip spectrometers are more compact that e.g. grating spectrometers, which may make scale-up to large arrays easier.

- ***Programmatic economies of scale:*** Fully drop-in compatible with cryostats used for CMB detectors, which may open up more time on telescopes and reduce duplicative effort.





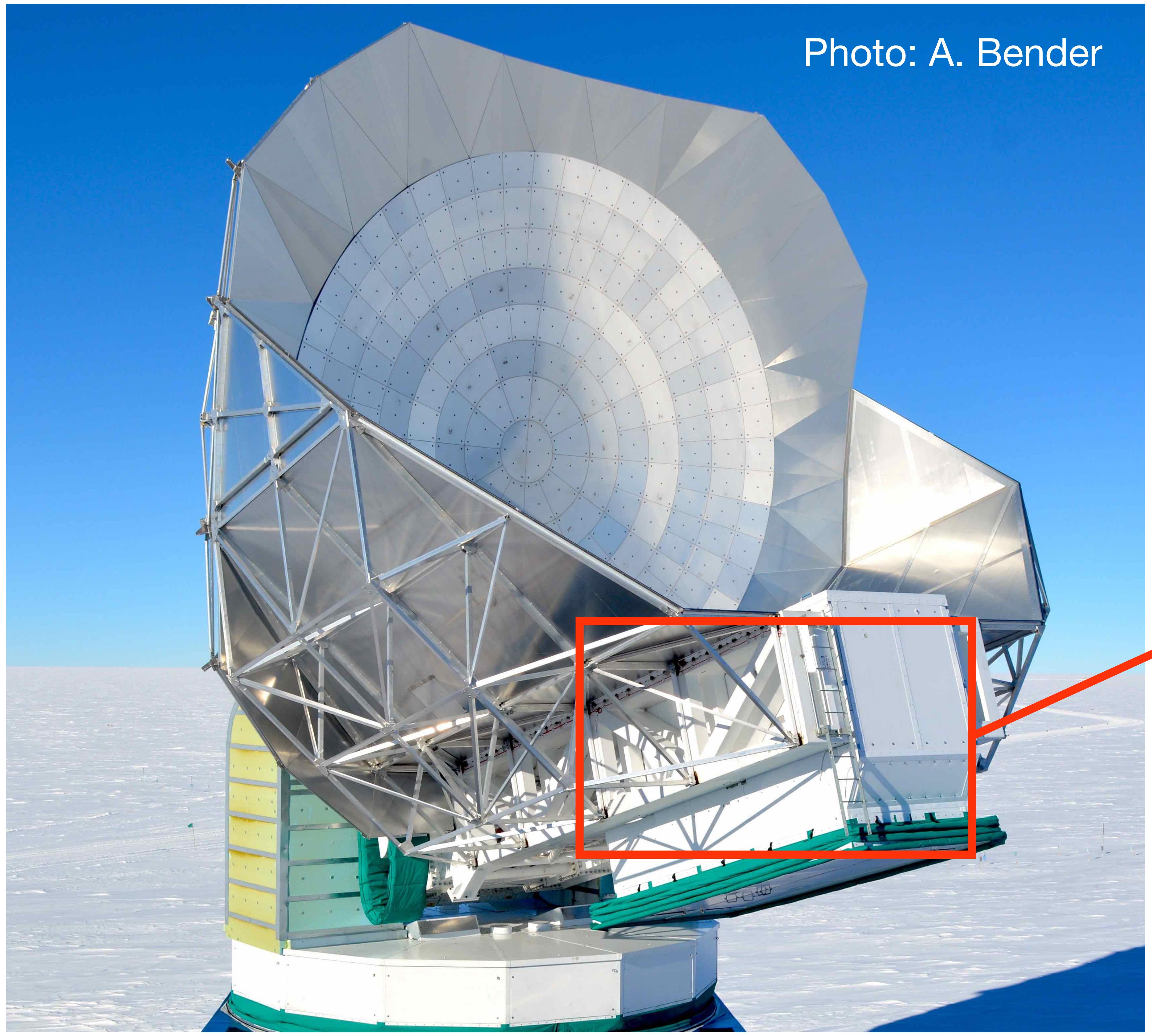


SPT-SLIM Pathfinder Concept

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 during austral summers.



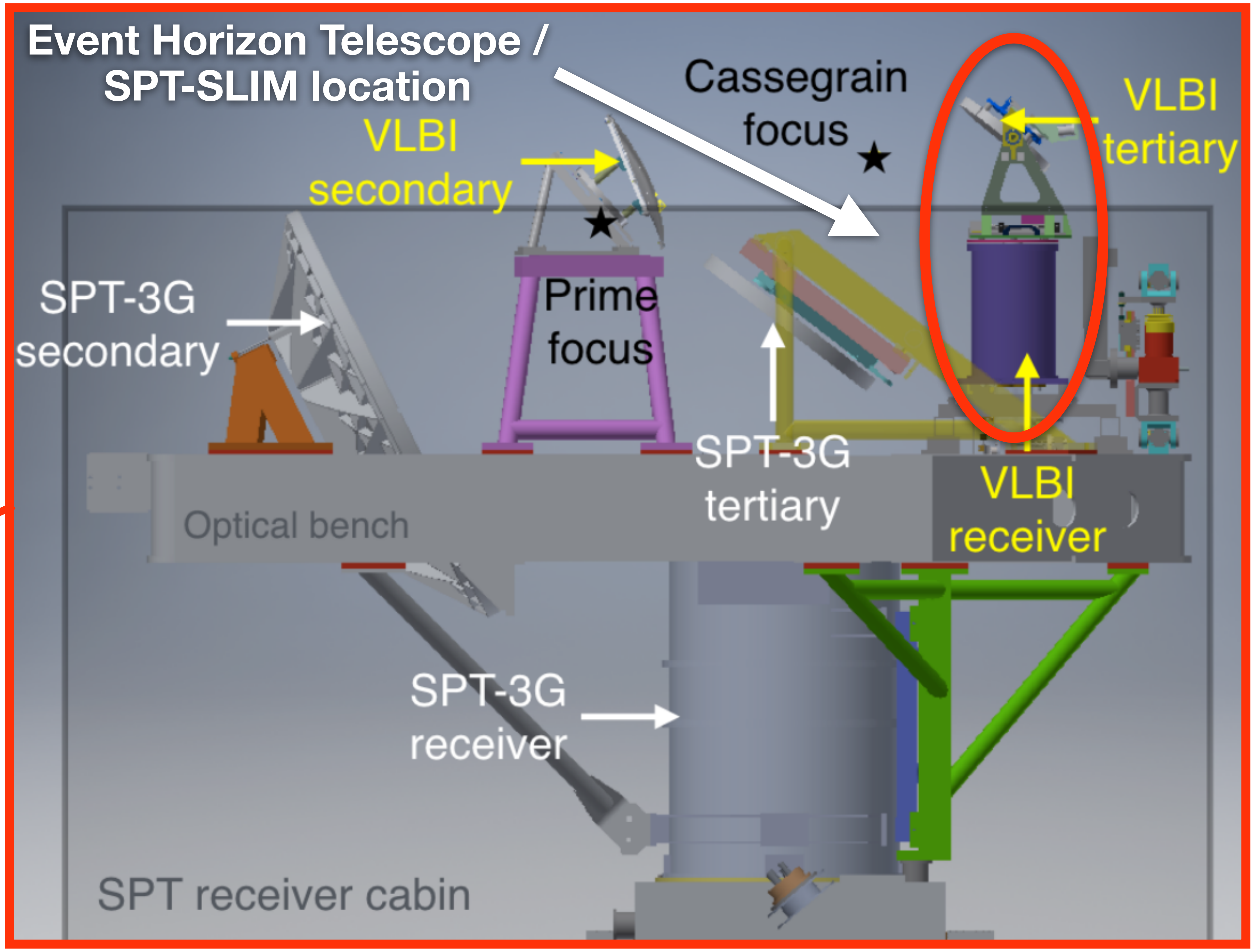


Figure: J. Kim, et al. 1805.09346

SPT-SLIM: SPT ~~Summertime~~ Shirokoff Line Intensity Mapper

Argonne:
T. Cecil
C. Chang
M. Lisovenko
V. Yefremenko
C. Yu

Boston University
K. Karkare
A. Lapuente

Cardiff:
P. Barry
C. Benson
G. Robson

Fermilab:
A. Anderson
B. Benson
M. Young

Harvard:
G. Keating

McGill / t0:
M. Adamic
M. Dobbs
J. Montgomery
M. Rouble
G. Smecher

U. Arizona:
D. Kim
H. Tailor
D. Marrone

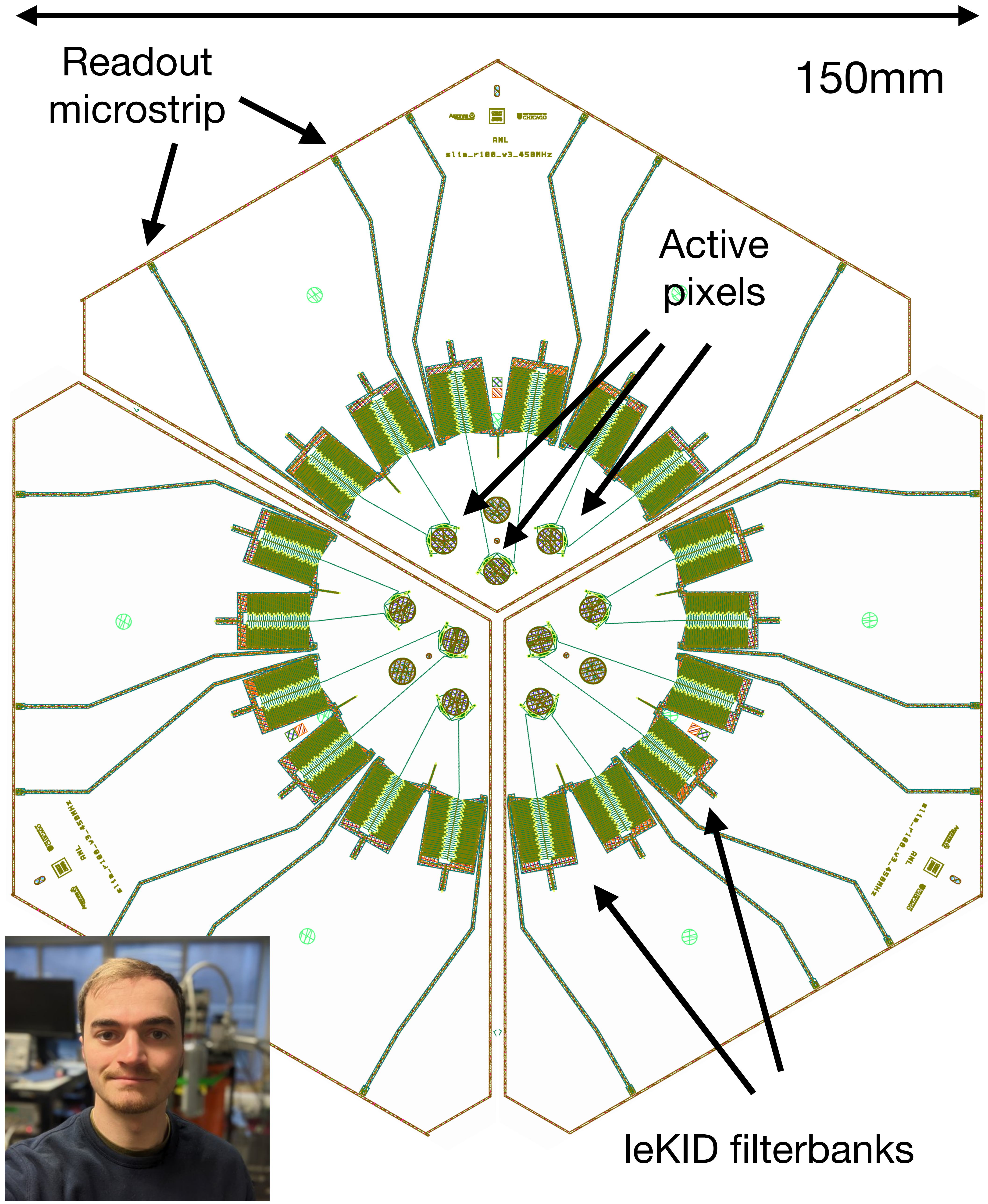
SLAC
C. Zhang

U. Chicago:
J. Carlstrom
K. Dibert
K. Fichman
T. Natoli
A. Rahlin
J. Zebrowski

Erik Shirokoff (Chicago)

Detector Architecture

- Focal plane design consists of 9 optical pixels, split between 3 submodules, each coupled to two R=100 filterbanks:
  - 65 detectors / filterbank
  - 18 filterbanks ➔ 1170 KIDs
  - Designed observing band: 120-180 GHz
- Detectors fabricated at Argonne National Laboratory.
- Feedhorn / orthomode-transducer-coupling of light to detectors using machined aluminum parts.



G. Robson (Cardiff)

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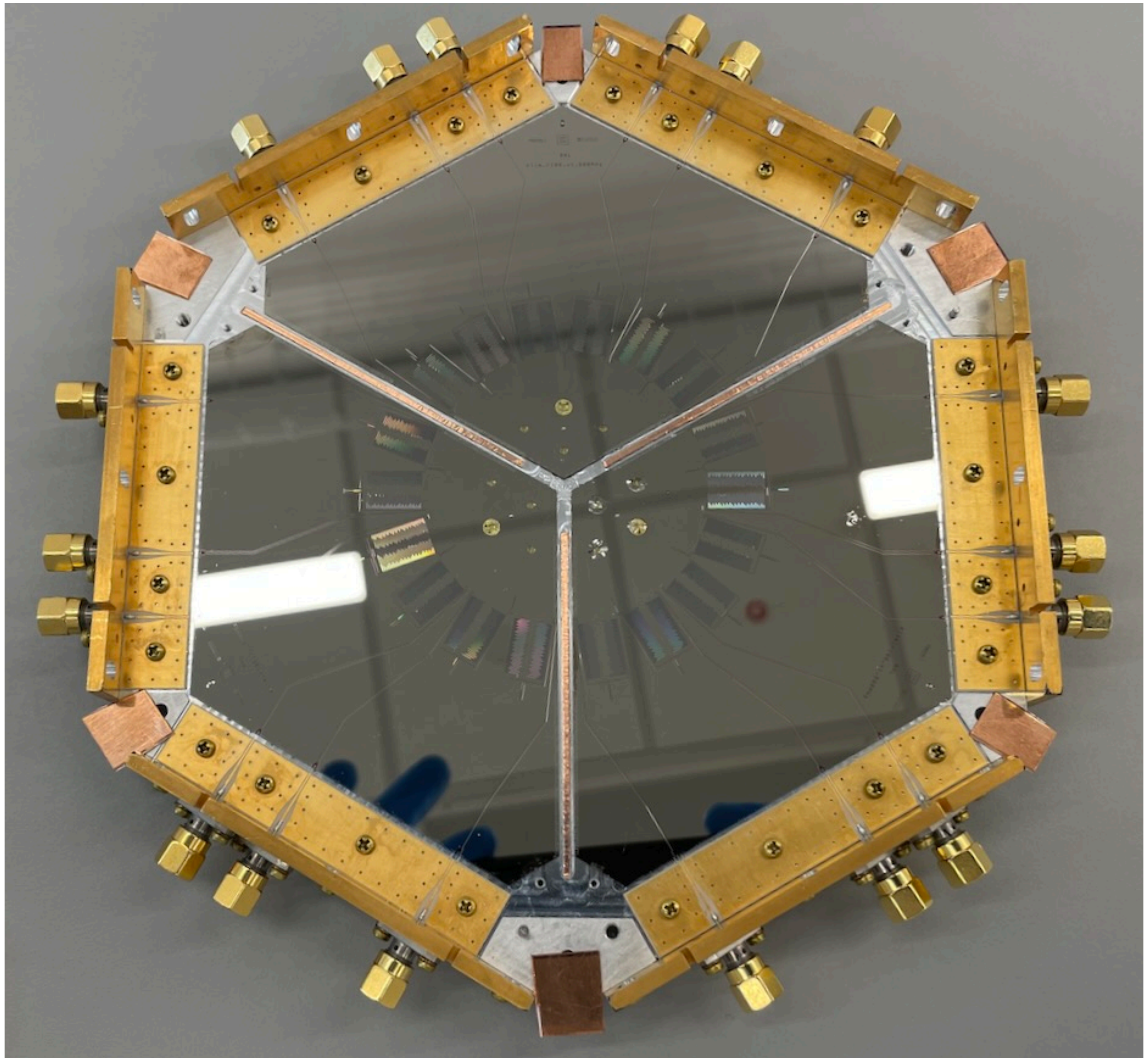

Fabrication: T. Cecil, C. Chang, M. Lisovenko, V. Yefremenko (Argonne)

Argonne NATIONAL LABORATORY

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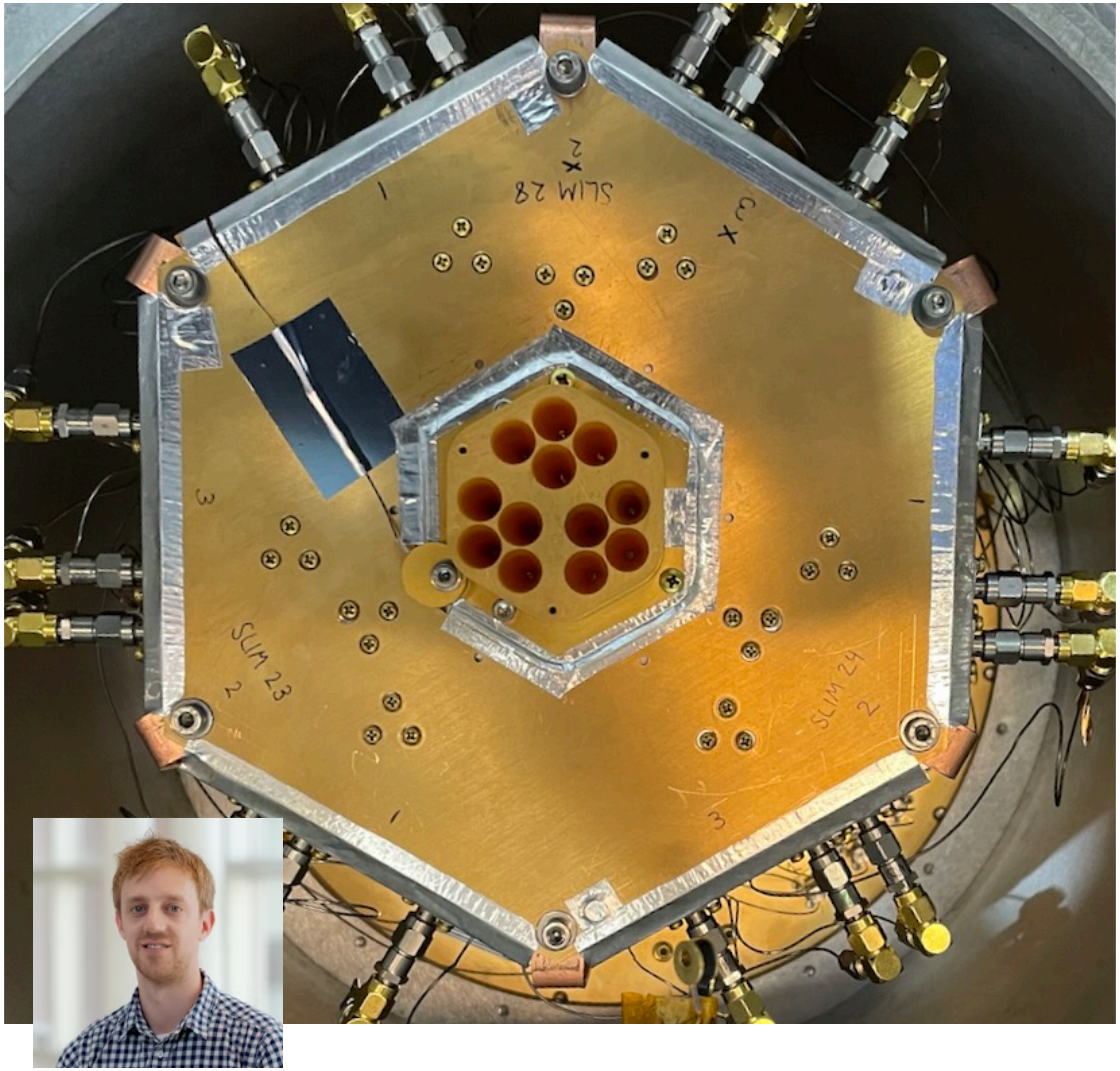
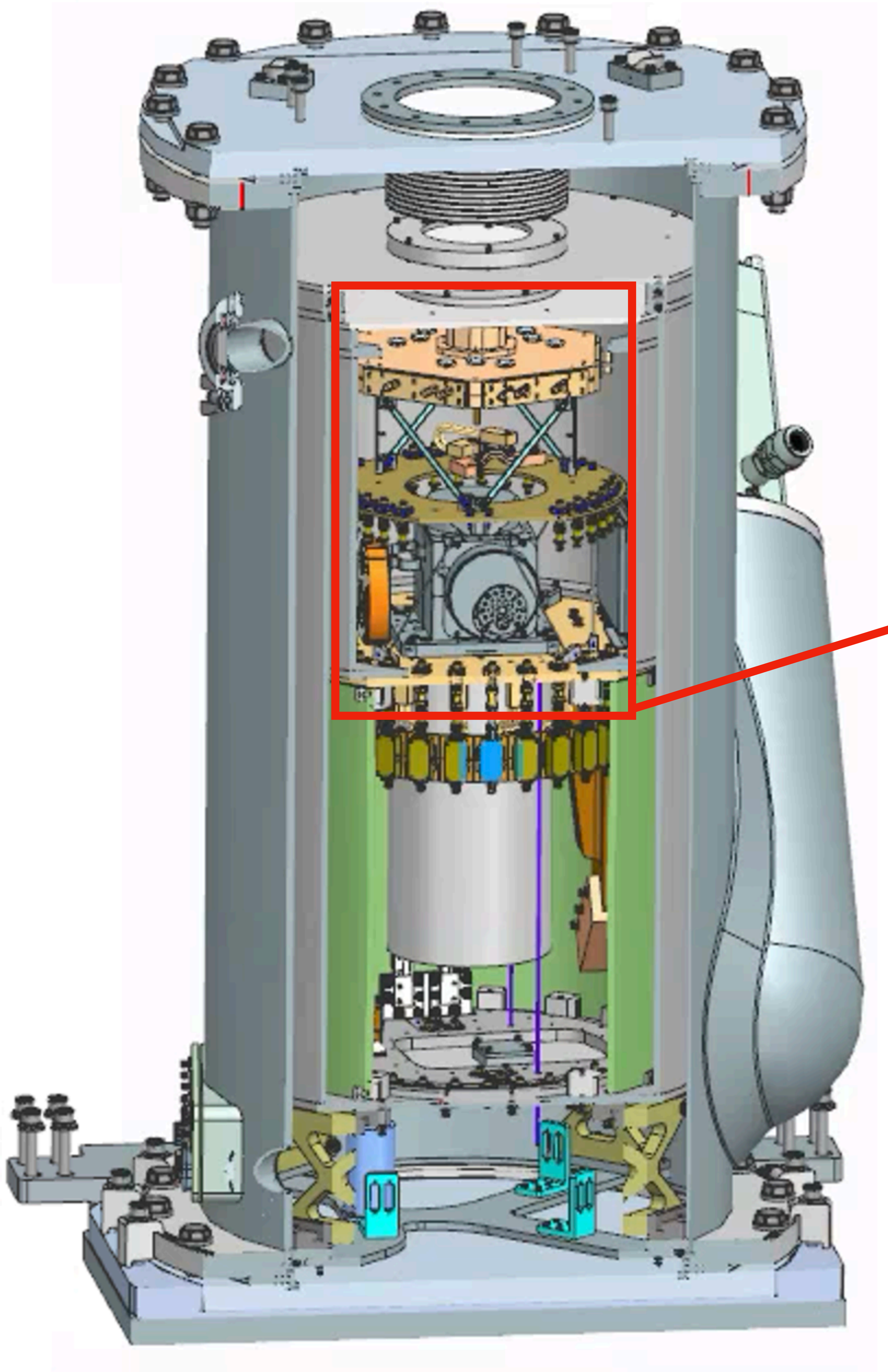
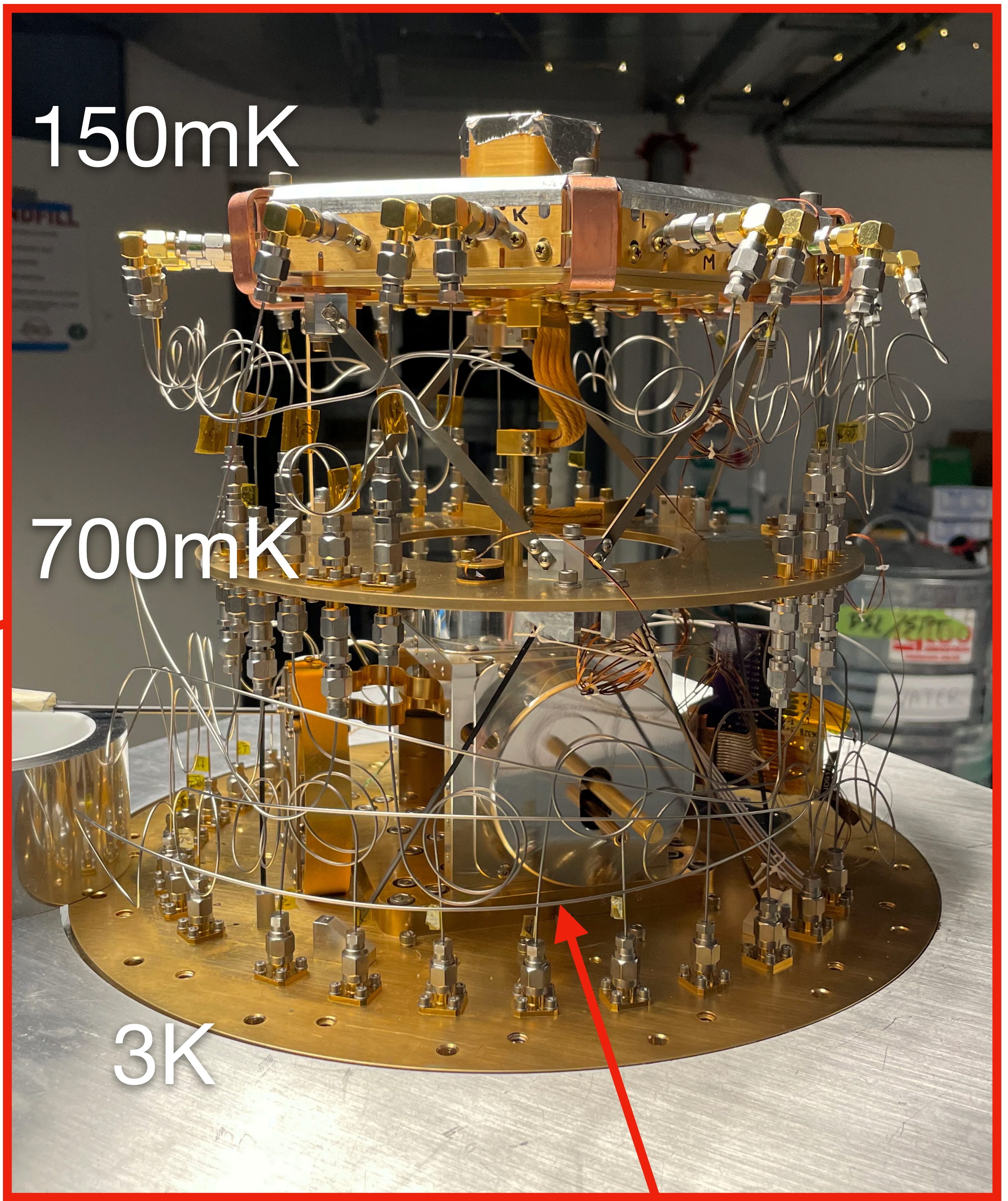


P. Barry (Cardiff)

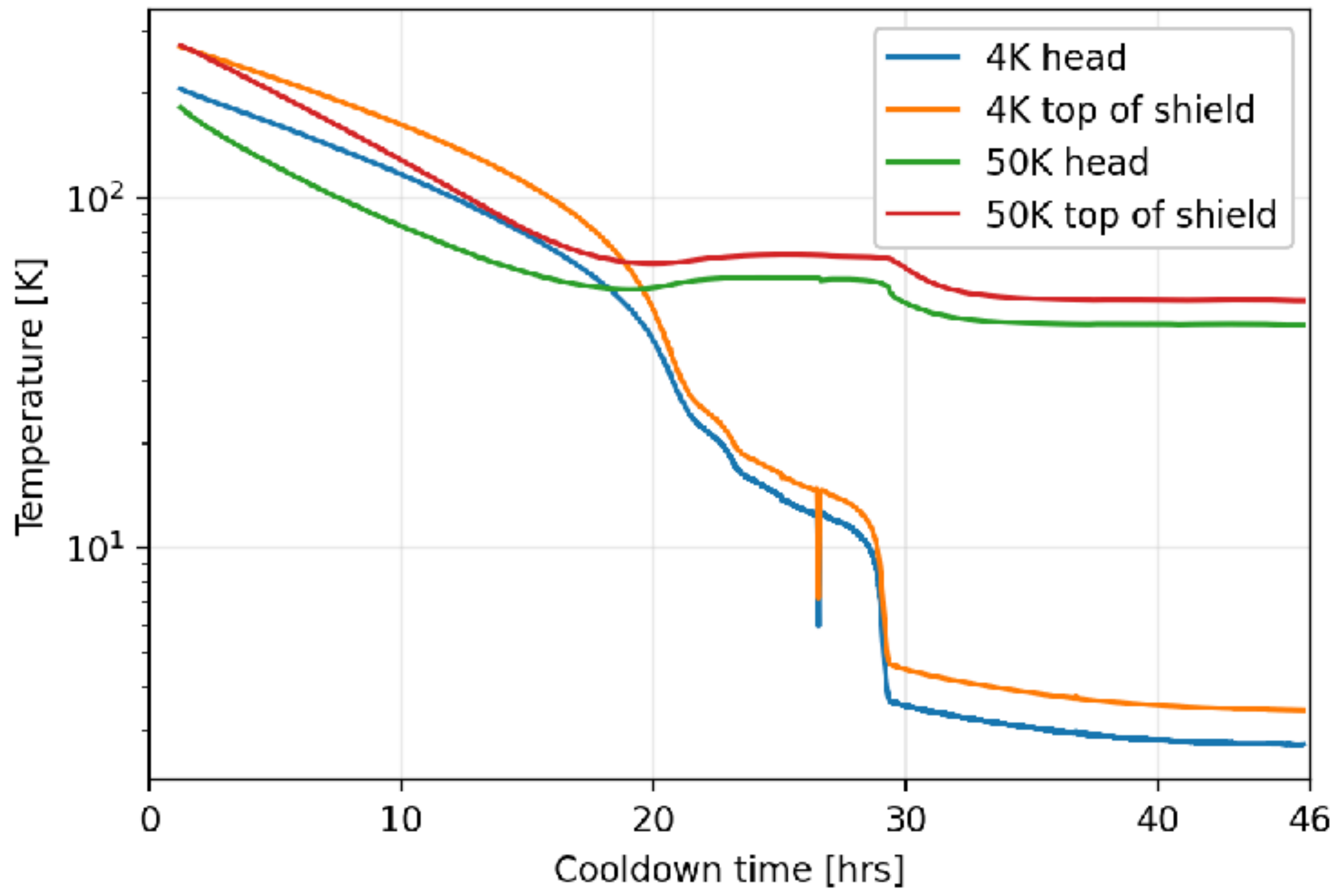
Cryostat Assembly at Pole





Adiabatic demagnetization refrigerator (ADR)

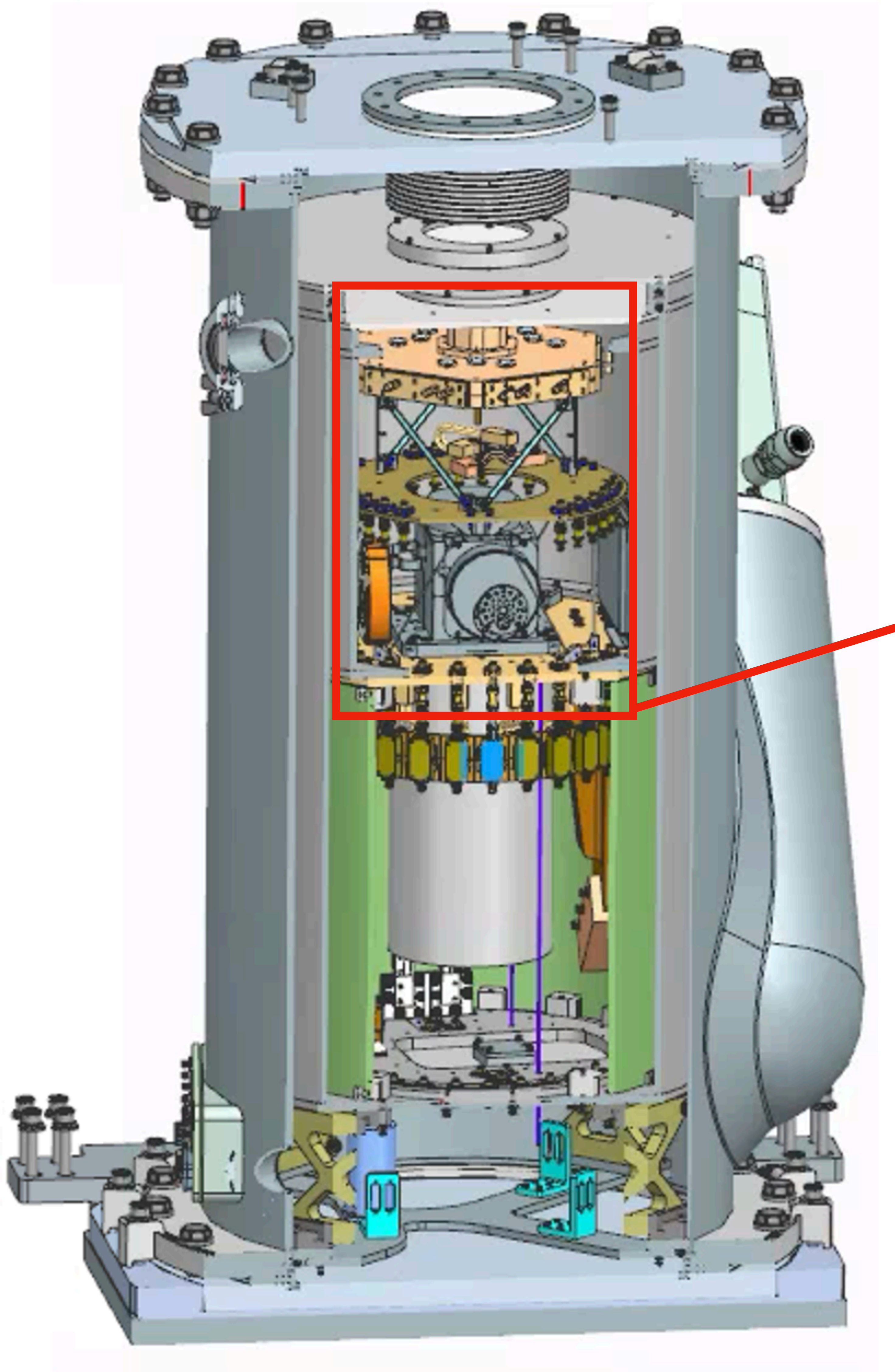
300K to 3K in 46 hours

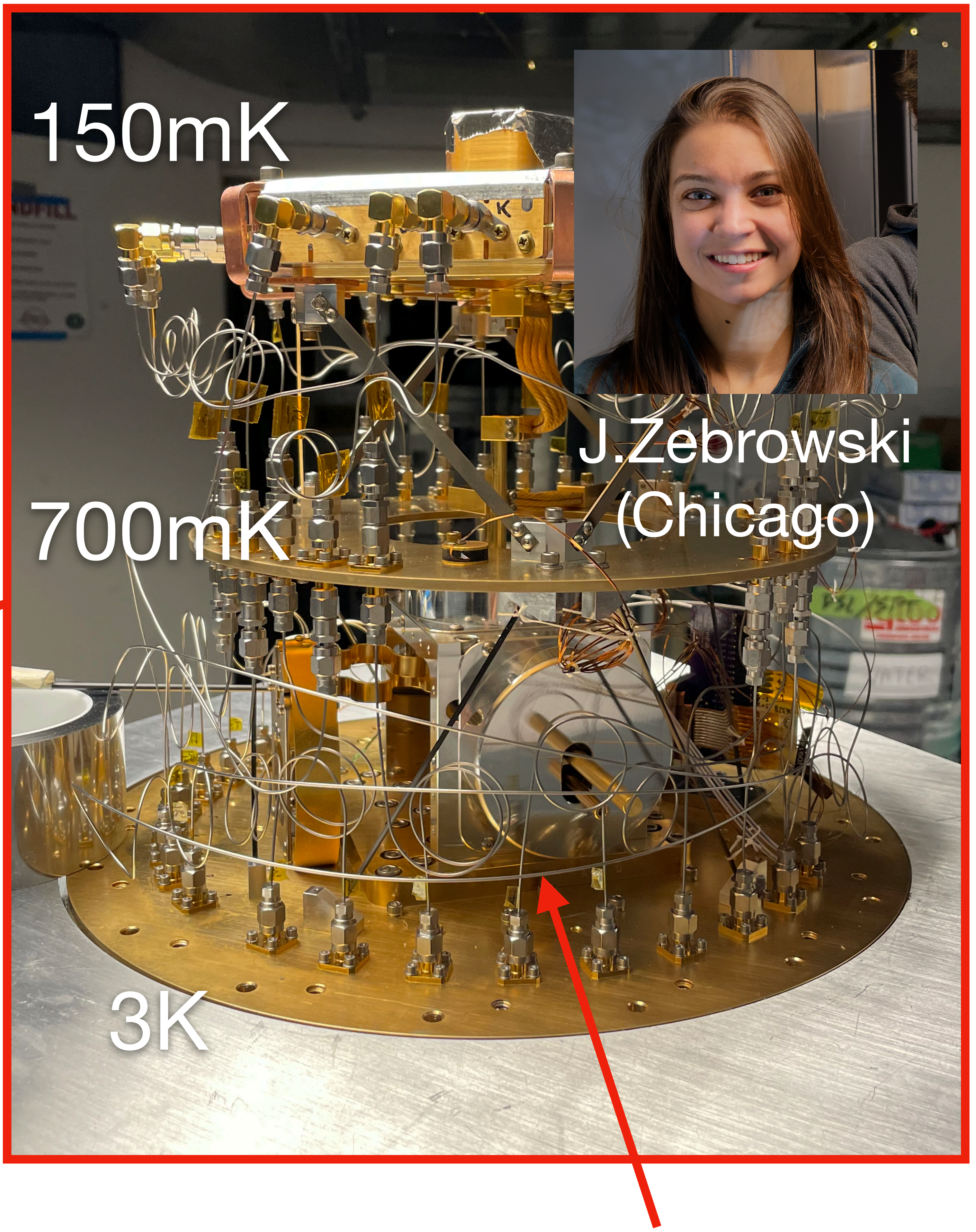


Stage	Thermal load (modeled)	Thermal load (measured)
50K	14.5 W	15 W
4K	0.11 W	0.10 W
700mK	15 uW	17 uW
100mK	1.5 uW	1.7 uW

Performance matches design goals: 81% ADR efficiency

Cryostat Assembly at Pole





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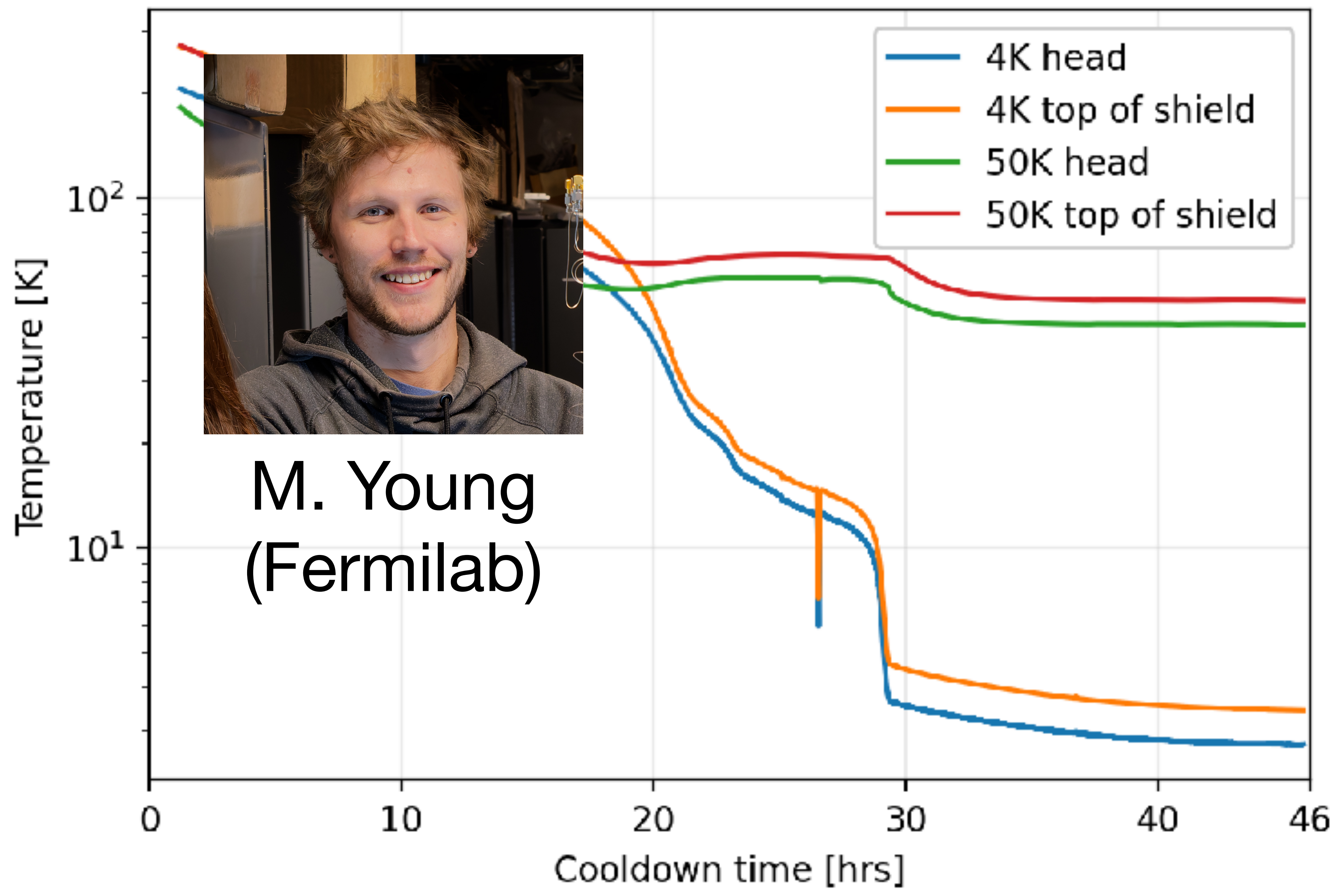

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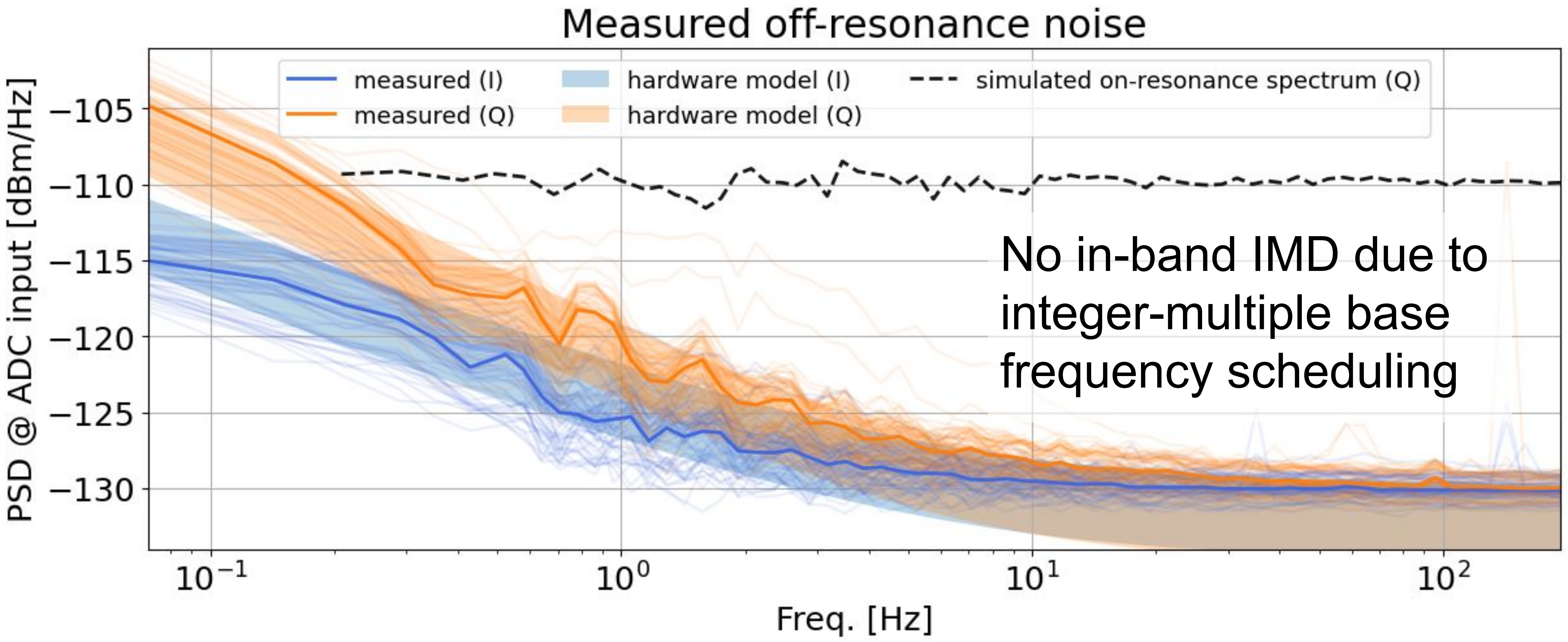
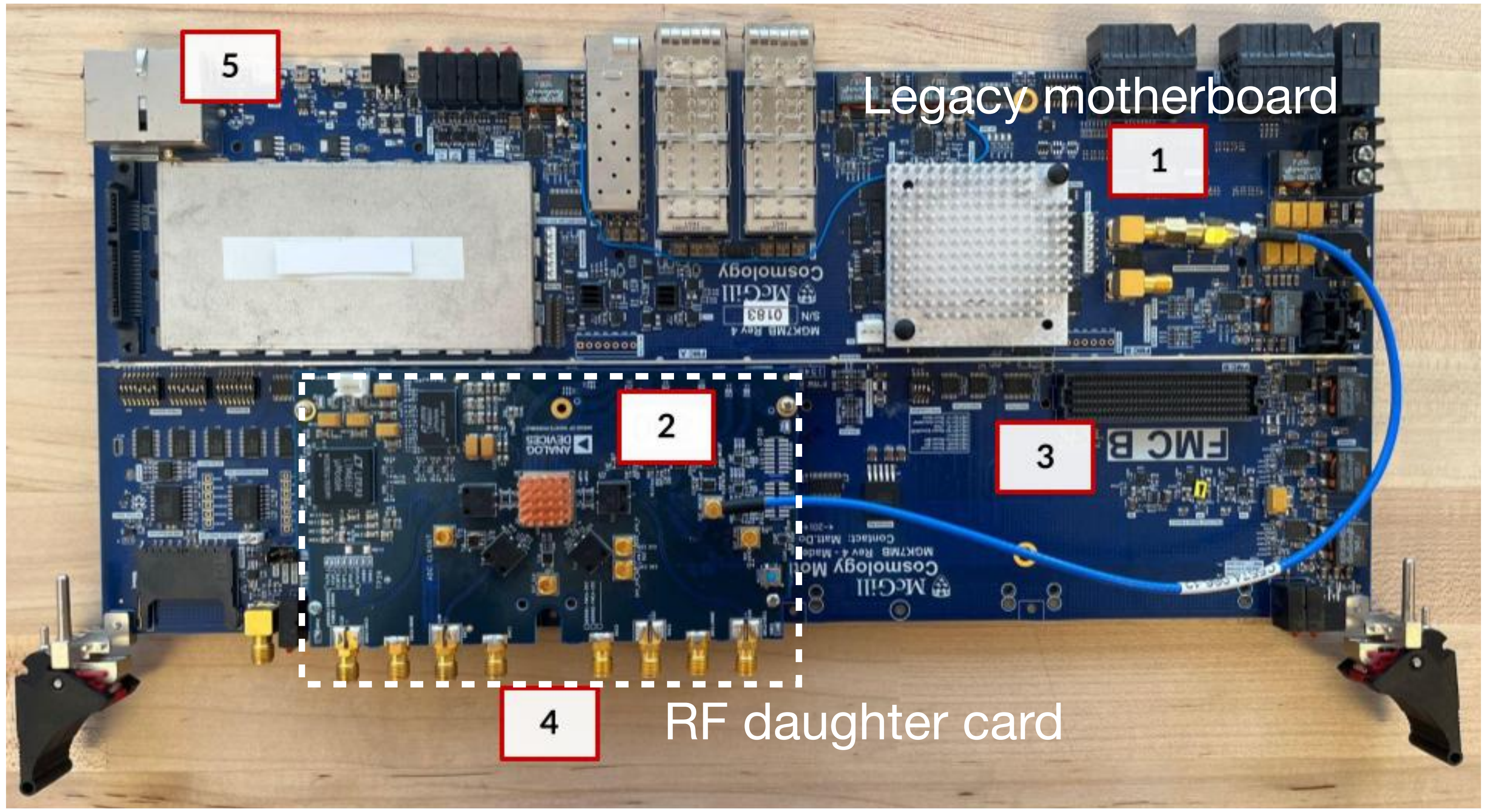
Performance matches design goals:
81% ADR efficiency

Readout Electronics

- RF-ICE: Adapted "ICE" platform developed by McGill for readout of TESs in SPT-3G and radio receivers in CHIME.
- 1024x multiplexing x 2 RF chains / board in 500 MHz bandwidth.
- Excellent readout noise performance integrated with cold system, in good agreement with hardware-based model.
- Commercially available from Canadian company t0.



M. Rouble (McGill)



Rouble++, Proc SPIE 12190 (2022)

Photo: J. Zebrowski

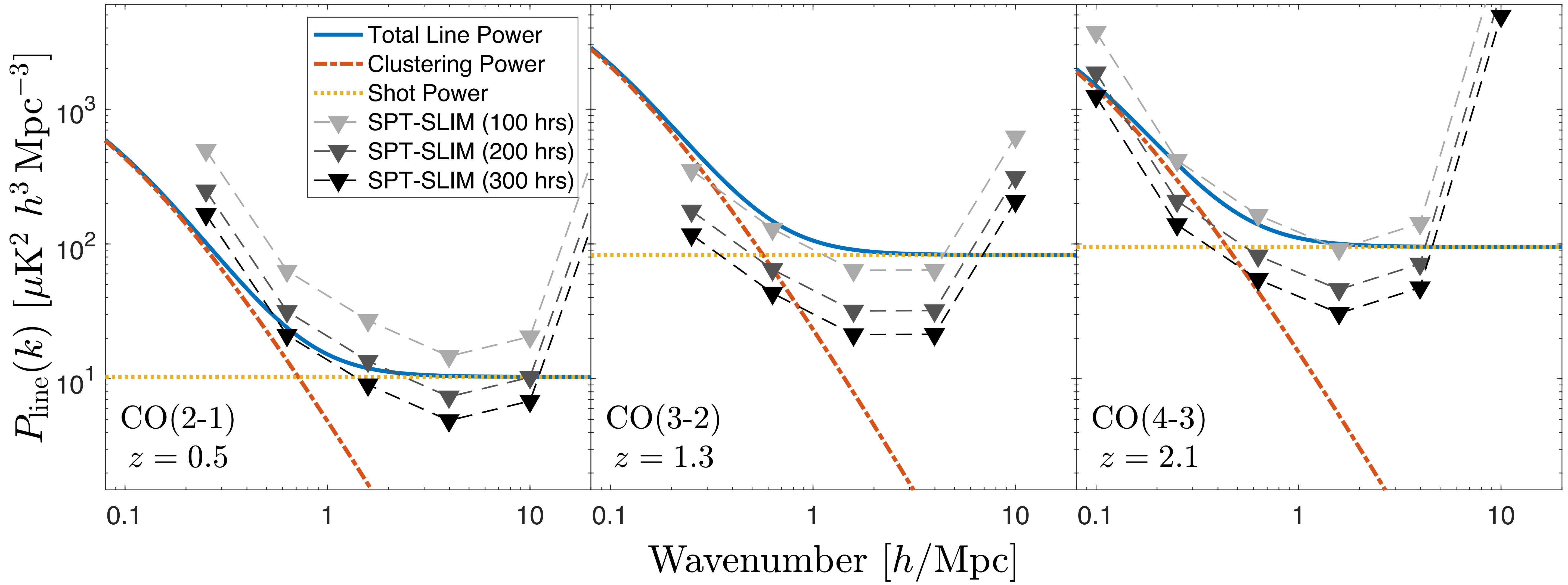
Deployment in Theory…

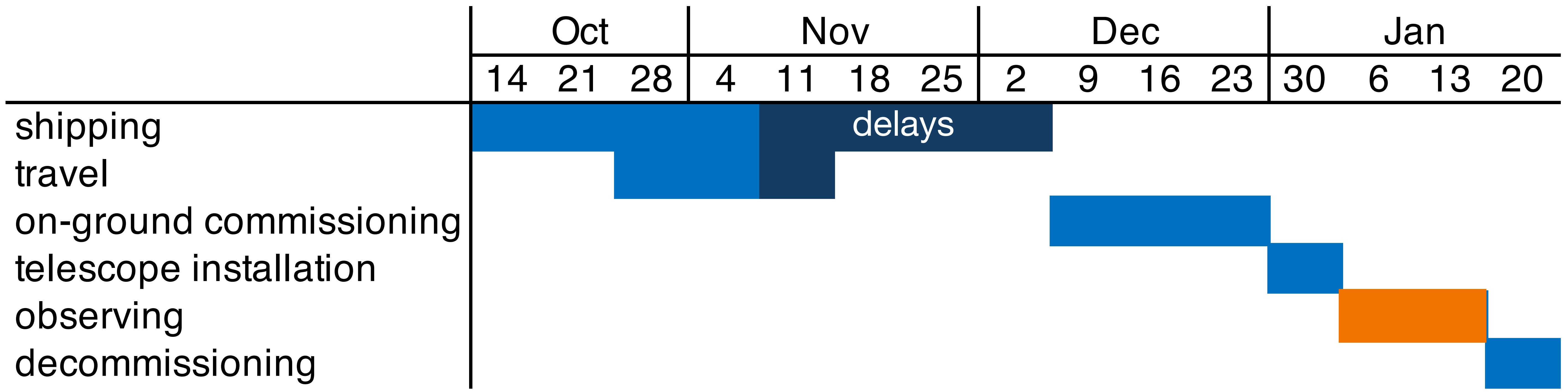
- On-paper sensitivity of a SLIM-like instrument may be sufficient to measure CO power spectrum with low S/N in few 100 hours…

- But real-world effects are important:
  - Short summer season limits available time on-sky, and transport delays are significant.
  - Detectors are not as sensitive as designed.

- ***Goal for 1st deployment:*** Test end-to-end performance of integrated system, debug problems, and characterize “real world effects”.

Karto Keating (CfA)



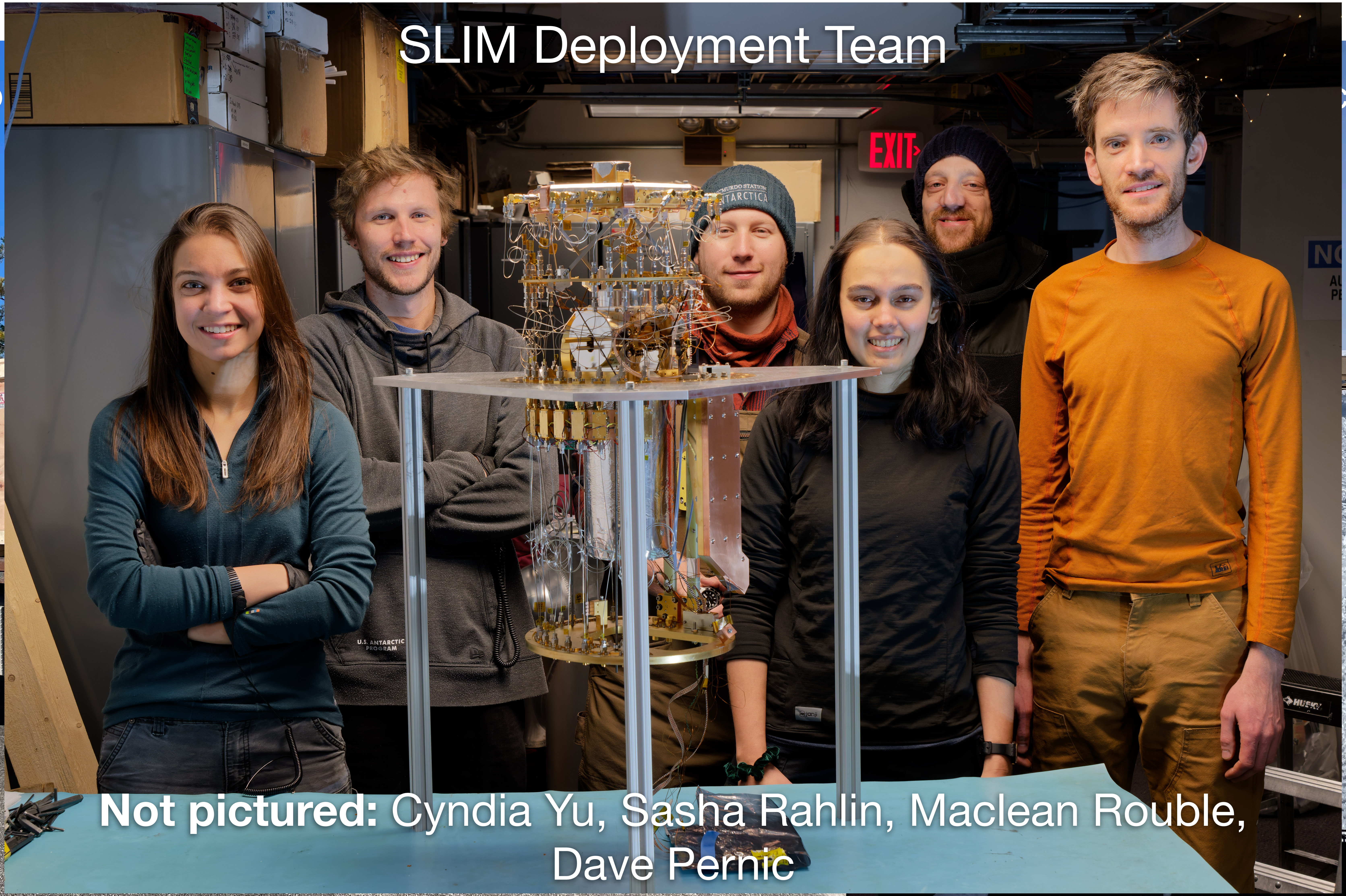


Deployment in Practice

Departing Fermilab, 14 October, 2025

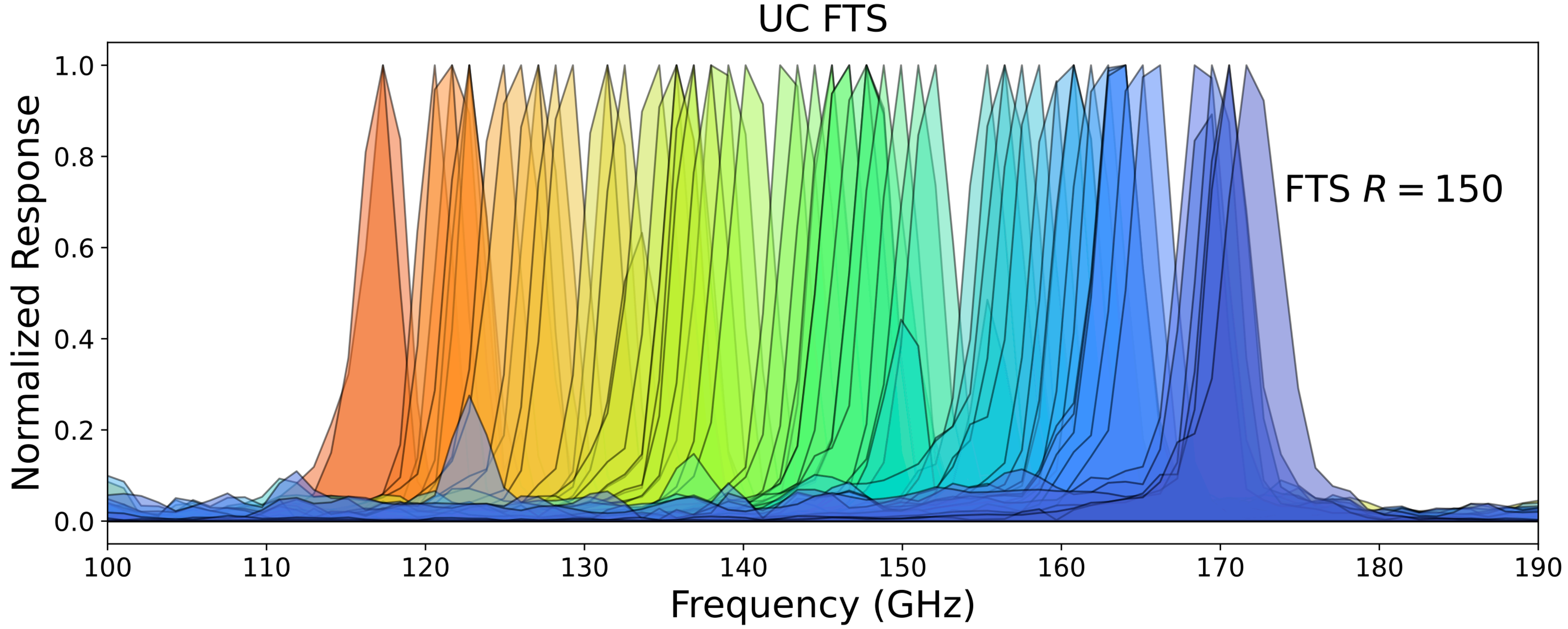
Arriving South Pole, 6 December, 2025
(4 weeks late…)

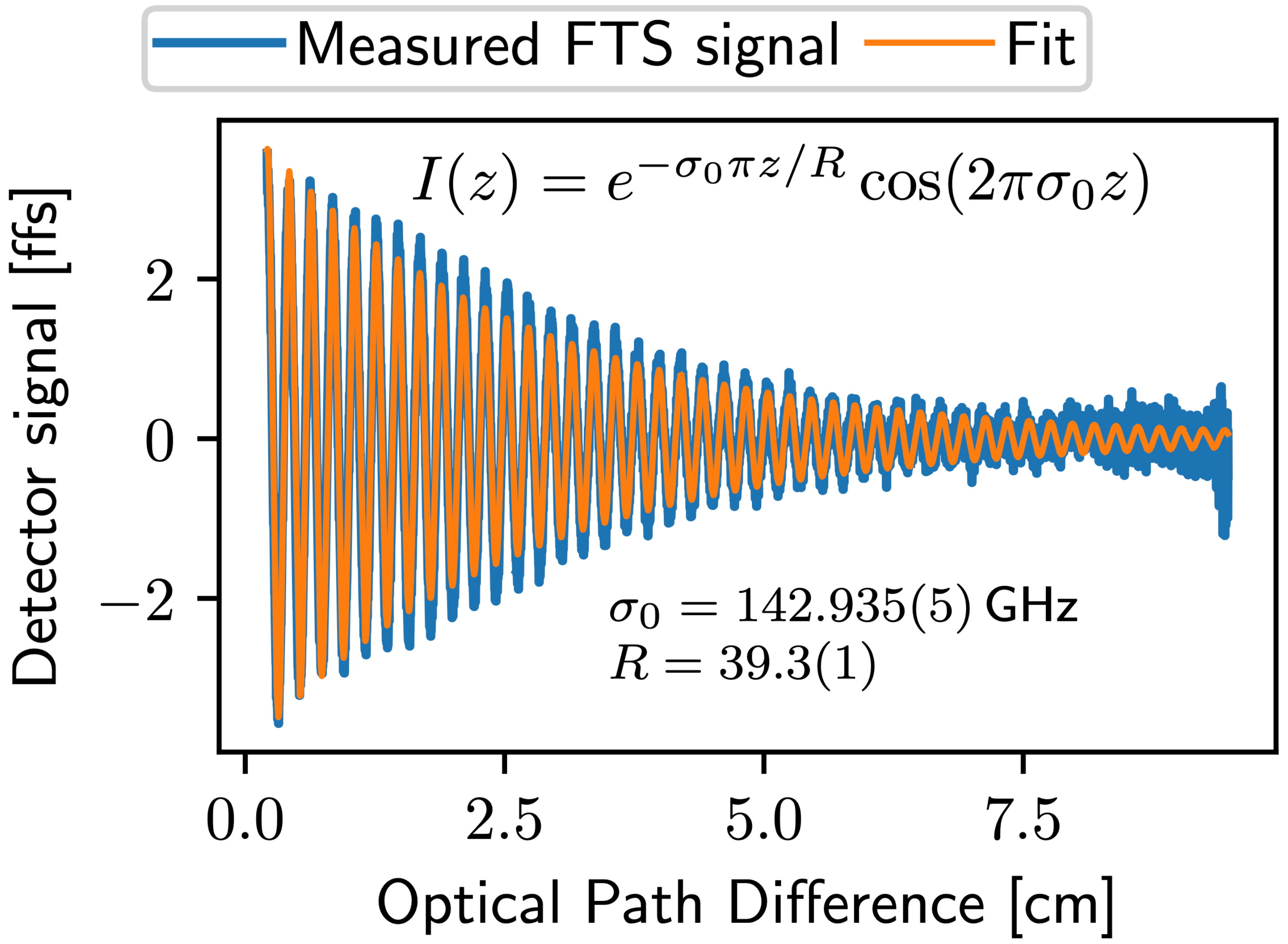
Deployment in Practice

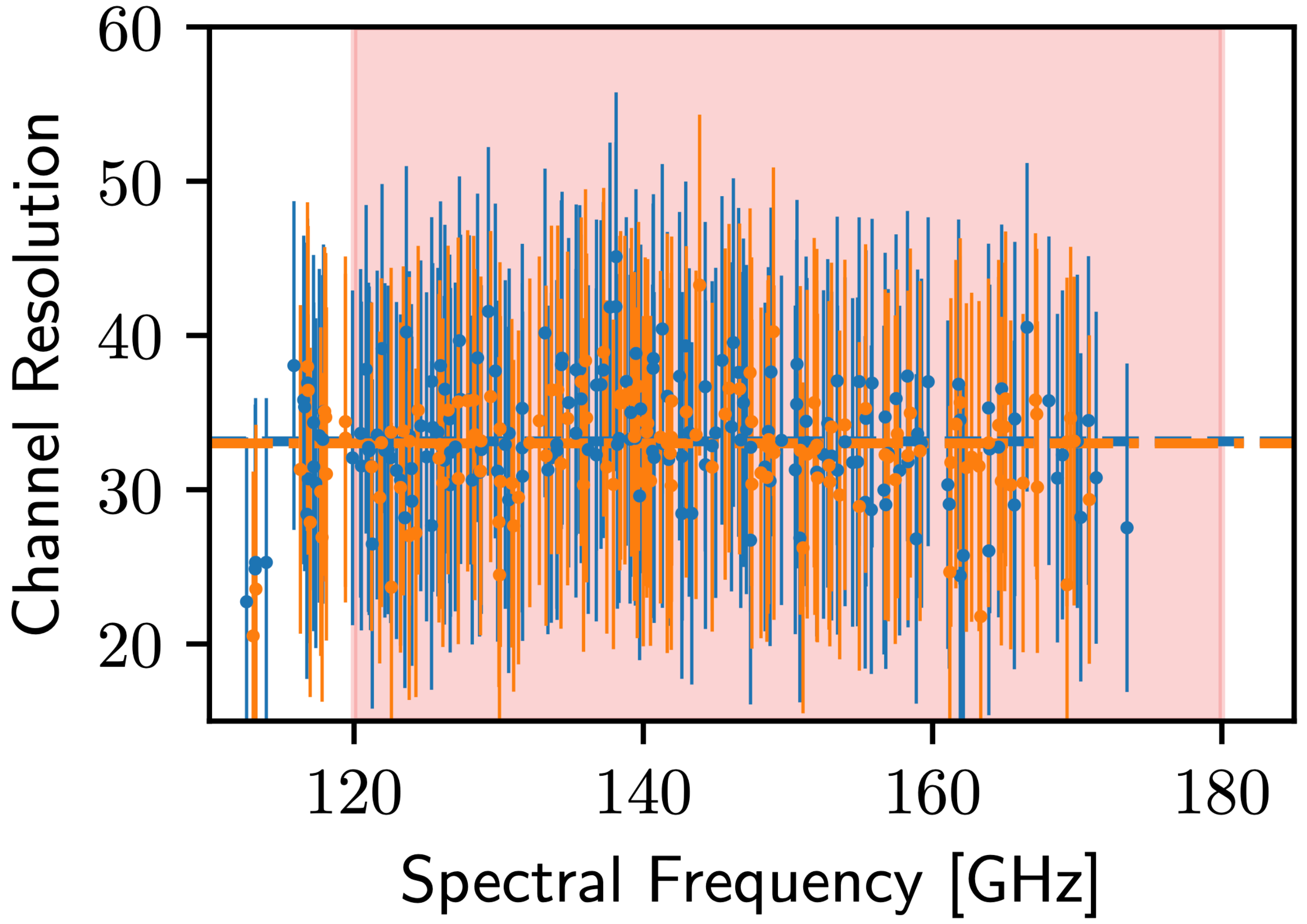


On-Site Characterization

- Spectrometer channel frequencies, measured with Fourier Transform Spectrometer (FTS) are in good agreement with design.
- Template-fitting method used to extract unbiased measurement of spectral resolution from FTS data.
- Resolution is low (R~35 vs. R~100 design), implying extra dielectric loss and/or impedance mismatch in filterbank design.







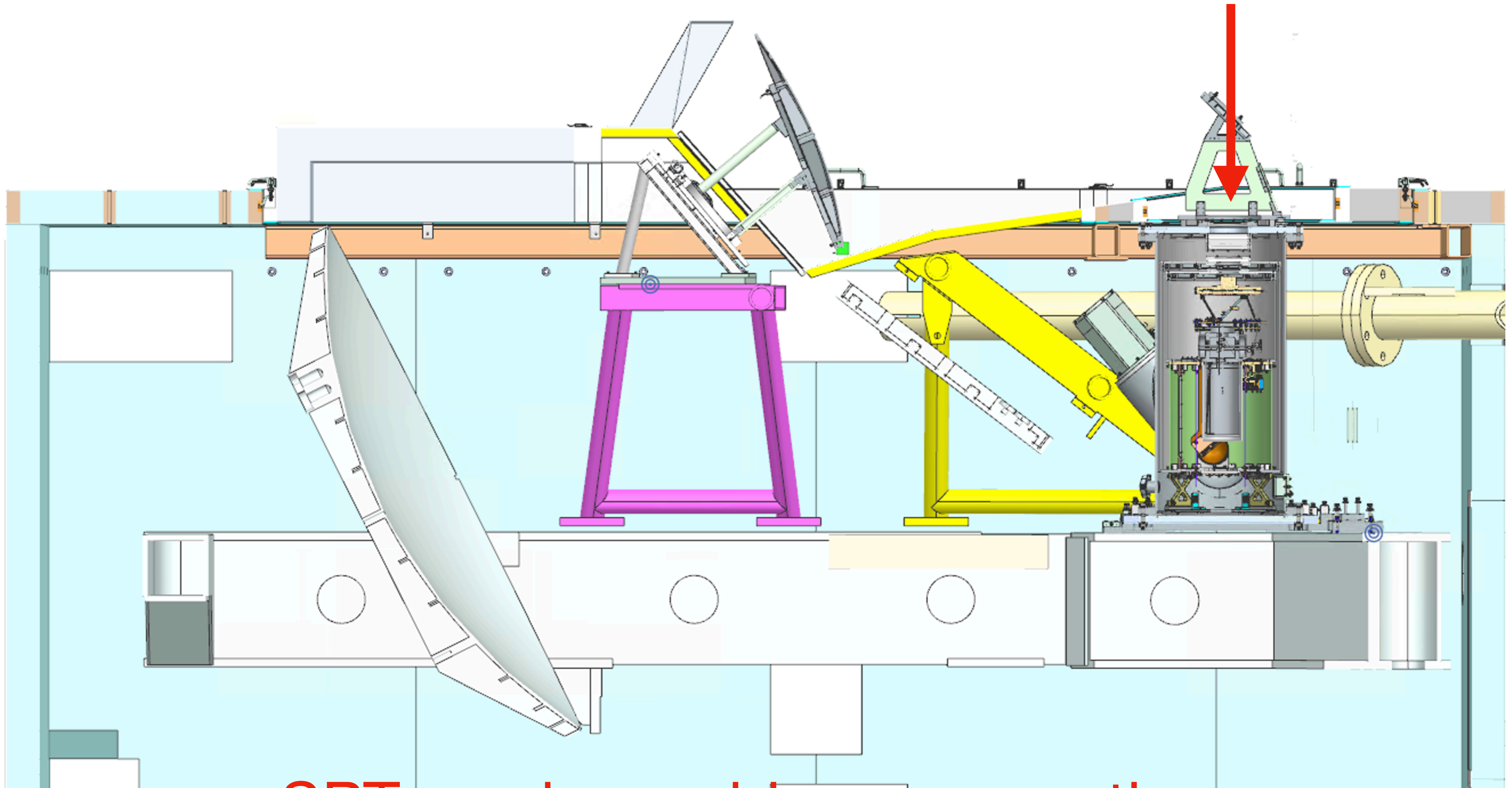

C. Benson
(Cardiff)


K. Fichman
(Chicago)


K. Dibert
(Chicago ➔ Caltech)

Installation

- SPT-SLIM cryostat is onto the roof of the SPT receiver cabin and lowered into position.



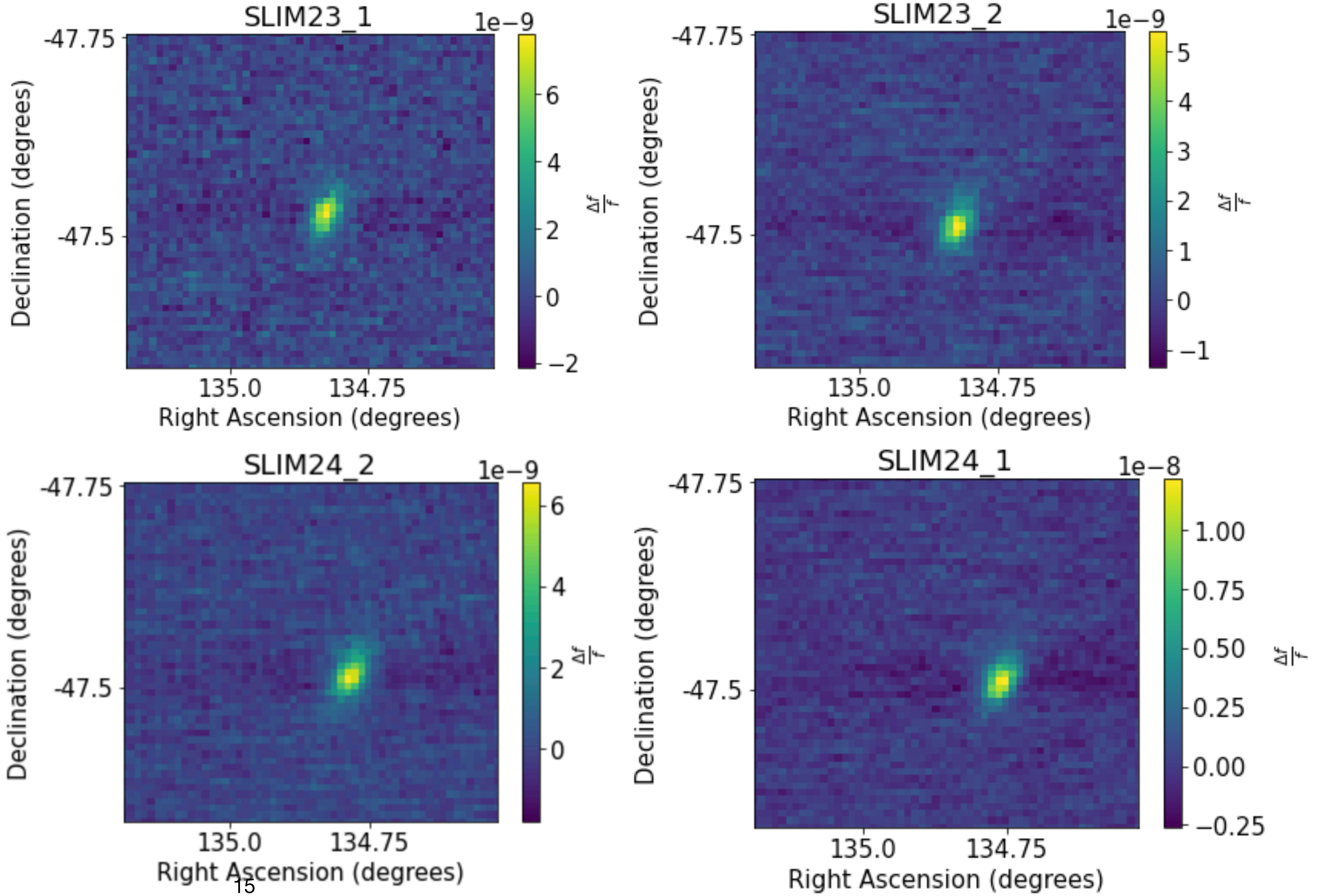
SPT receiver cabin cross section

First Light - 15 January, 2025

J. Zebrowski (Chicago)

A. Rahlin (Chicago)

- Observed HII region RCW38, a bright mm-wavelength source.
- High S/N in per-pixel coadded maps, with minimal filtering.
- Observed other bright mm sources in the galaxy:



Atmospheric Calibration

- Motivated by similar study with early DESHIMA data (Takekoshi, et al. 2001.05151).

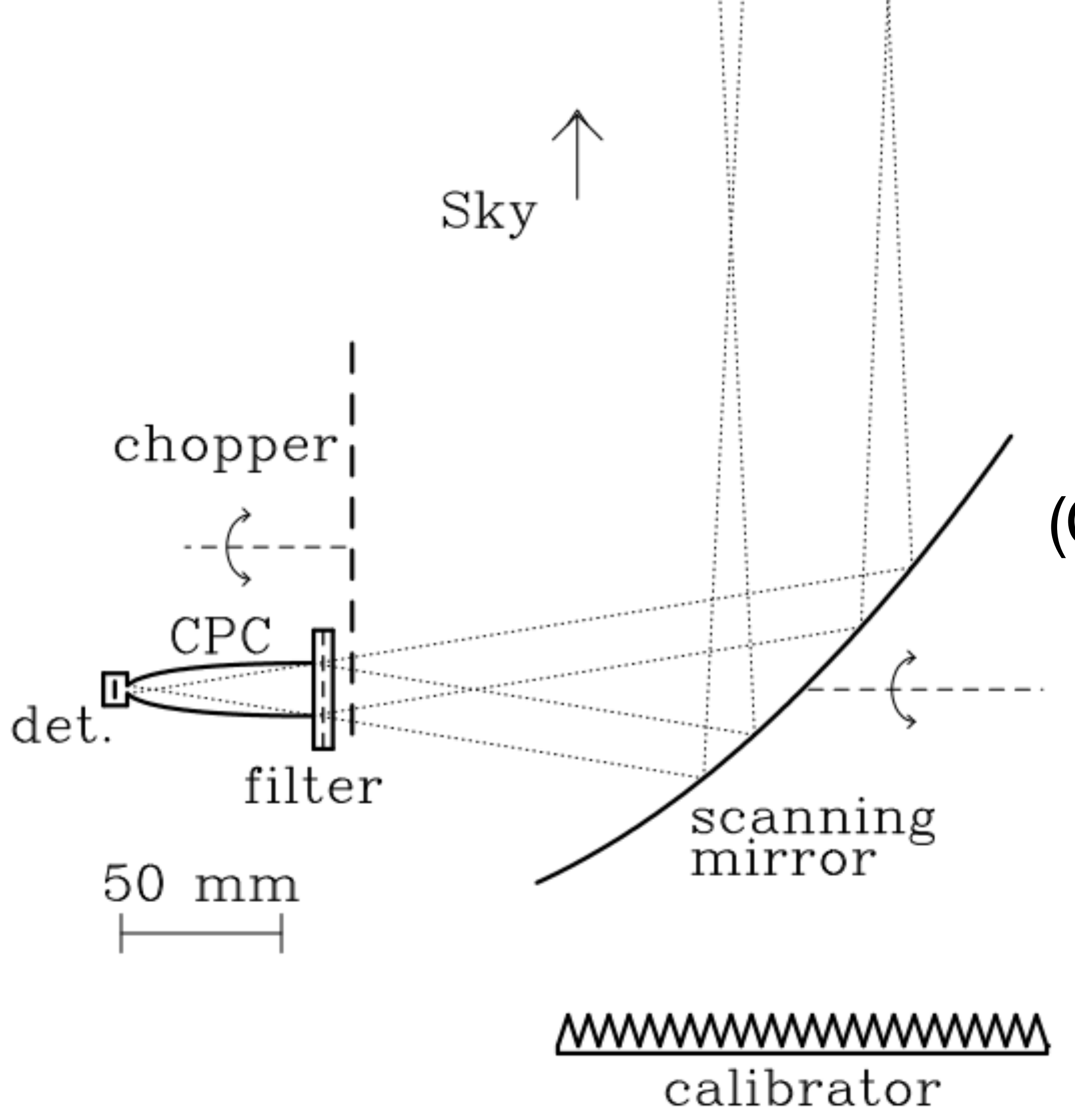
- Use continuous monitoring of atmospheric opacity with 850 GHz radiometer to parameterize am atmospheric model and estimate optical power, given measured bandpass per-detector.

- Use large-angle sky dip with SPT-SLIM to fit model of resonator frequency shift:

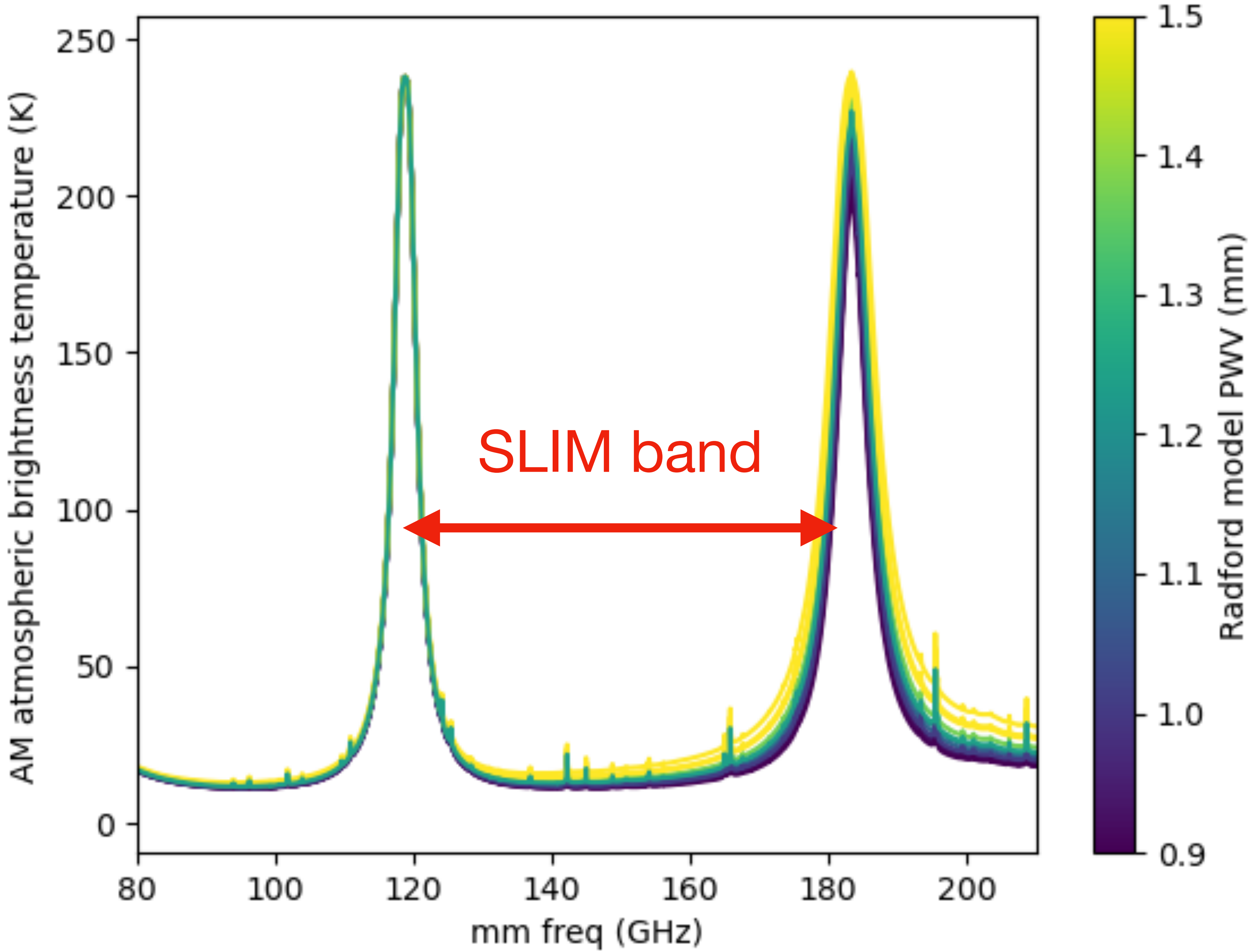
$$R_x(P_{\mathrm{sky}}) = \frac{d}{dP_{\mathrm{sky}}}\left(\frac{\delta f}{f_0}\right) = \frac{A}{2f_0}\frac{1}{\sqrt{P_{\mathrm{sky}}}}$$

- Compare with observed response from observations of moon. Spectrum agrees with expectation, after accounting for transmission of the atmosphere, including expected suppression from oxygen line.

S. Radford & J. Peterson, 1602.08795



K. Dibert
(Chicago ➔ Caltech)



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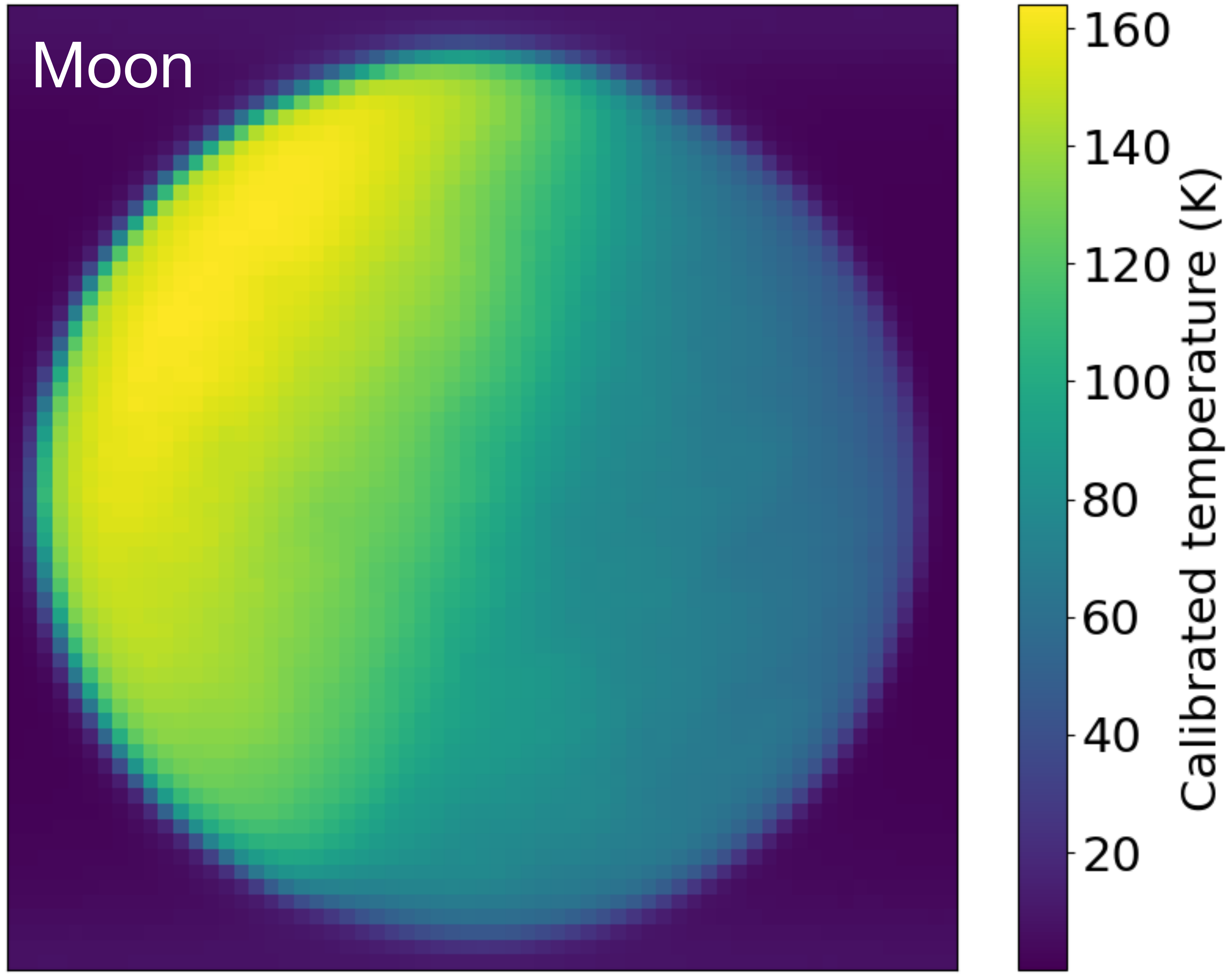
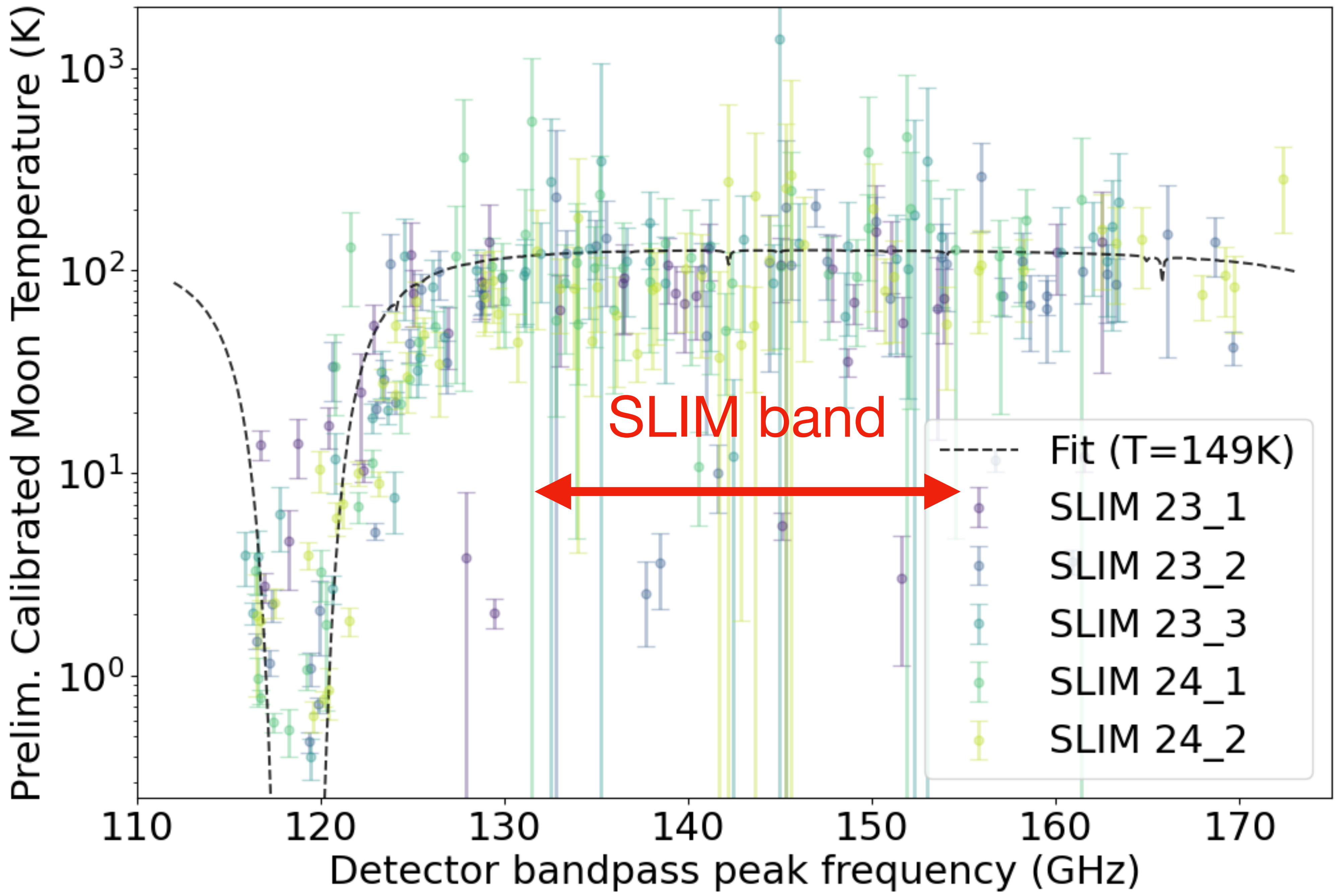
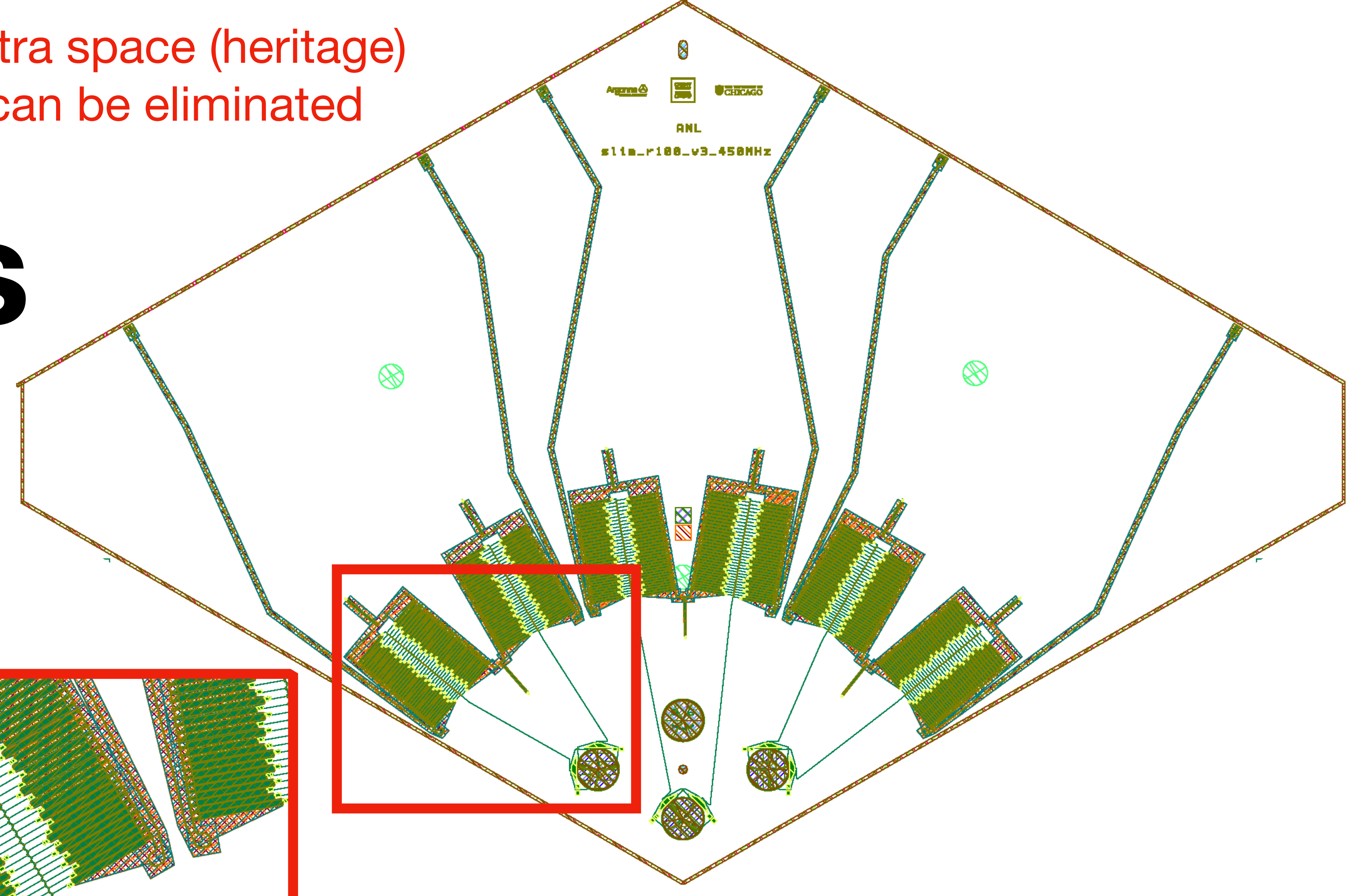
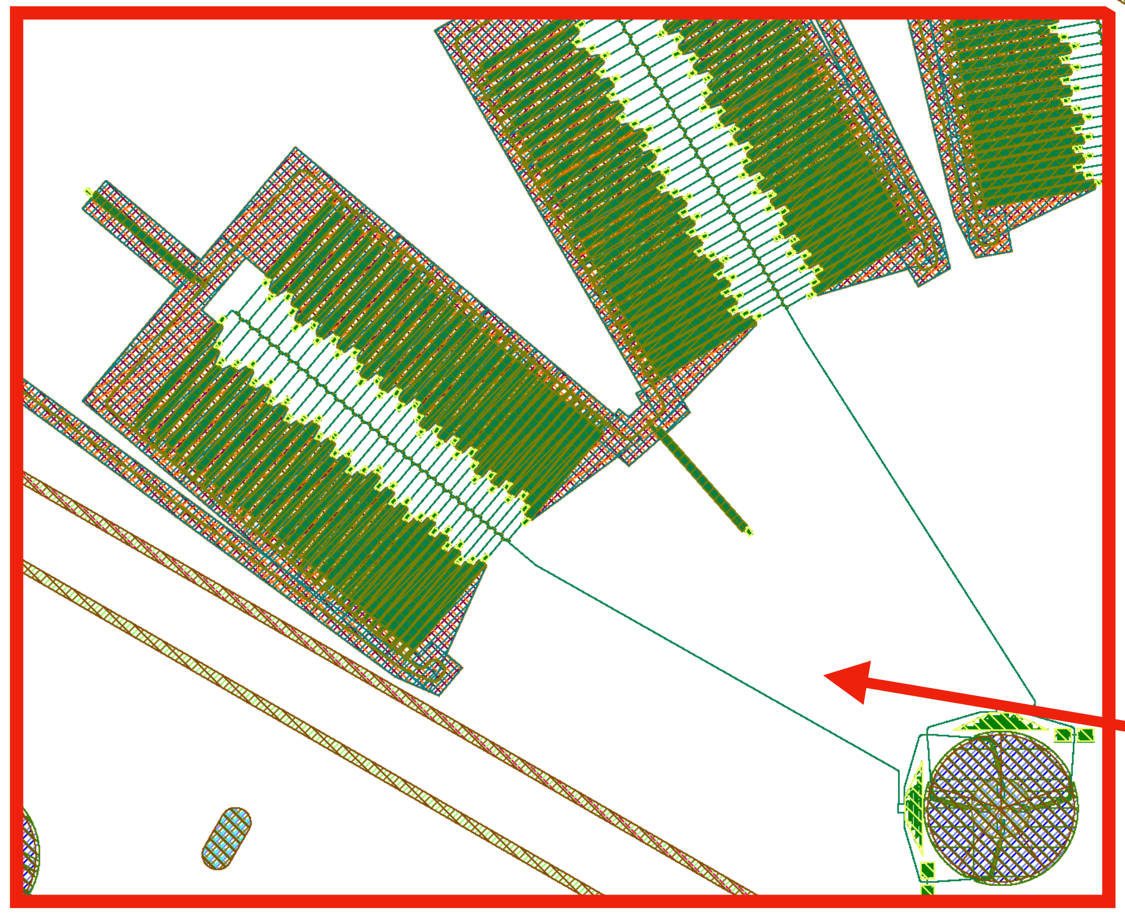




Lessons Learned and Next Steps

- Readout, detectors, cryostat, and optics were assembled and worked as an integrated system.
- Main issues are: microwave loss on the detector wafer, which limits optical efficiency; cryogenic cabling.
- Left cryostat in storage at South Pole. Can be commissioned and installed in ~2 weeks in future season (no shipping delays!).
- ***Deploy in 2025-2026 summer season for rework + another 2-3 week observing campaign. 2026-2027 also possible!***

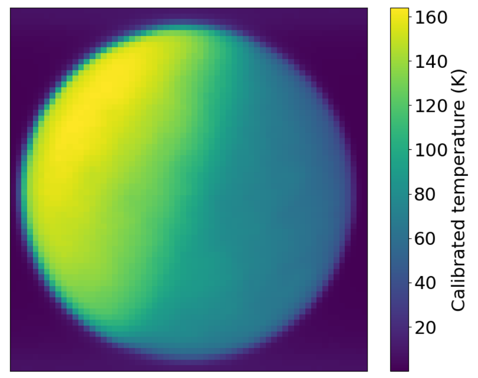




P. Barry (Cardiff)

C. Chang++ (Argonne)

2024	2025	2026	2027	
• 1st deployment • First-light • Demonstrate technical approach	• New detectors + rework • First LIM survey observations	• Continue LIM survey observations (pending telescope availability)	Larger detector arrays?	



Conclusions

- First commissioning observations with SPT-SLIM were performed during the 2024-2025 austral summer season.
- Successfully observed bright mm-wavelength sources in the galaxy with the integrated system. Analysis of data is currently ongoing.
- Work is underway now to fabricate detectors with improved optical efficiency.
- Plan to deploy again for a second campaign in the 2025-2026 summer season with a goal of conducting LIM observations!