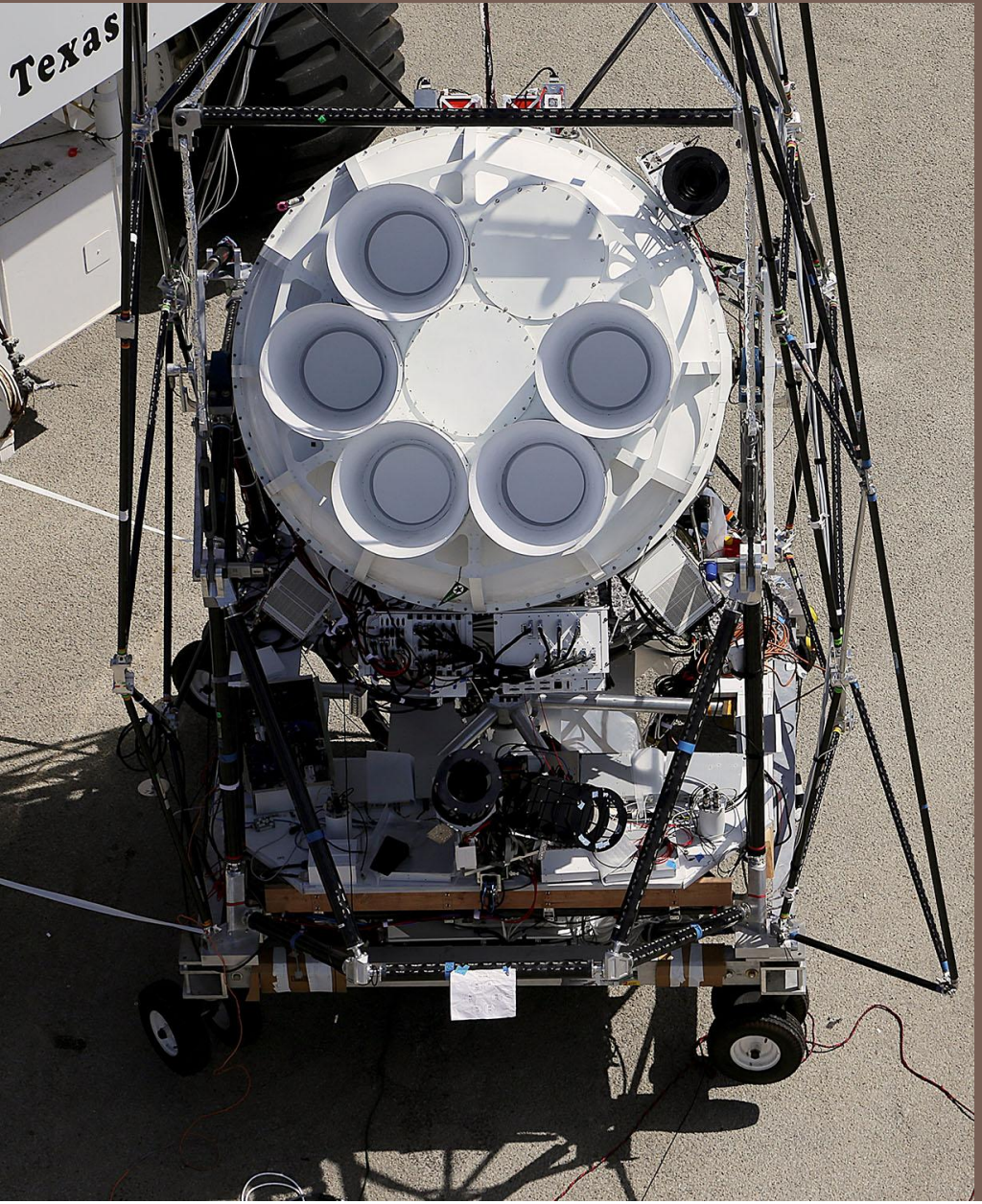


SPIDER:

A BALLOON-BORNE POLARIMETER FOR COSMIC MICROWAVE BACKGROUND OBSERVATION

June 9, 2014

Sasha Rahlin, Princeton University

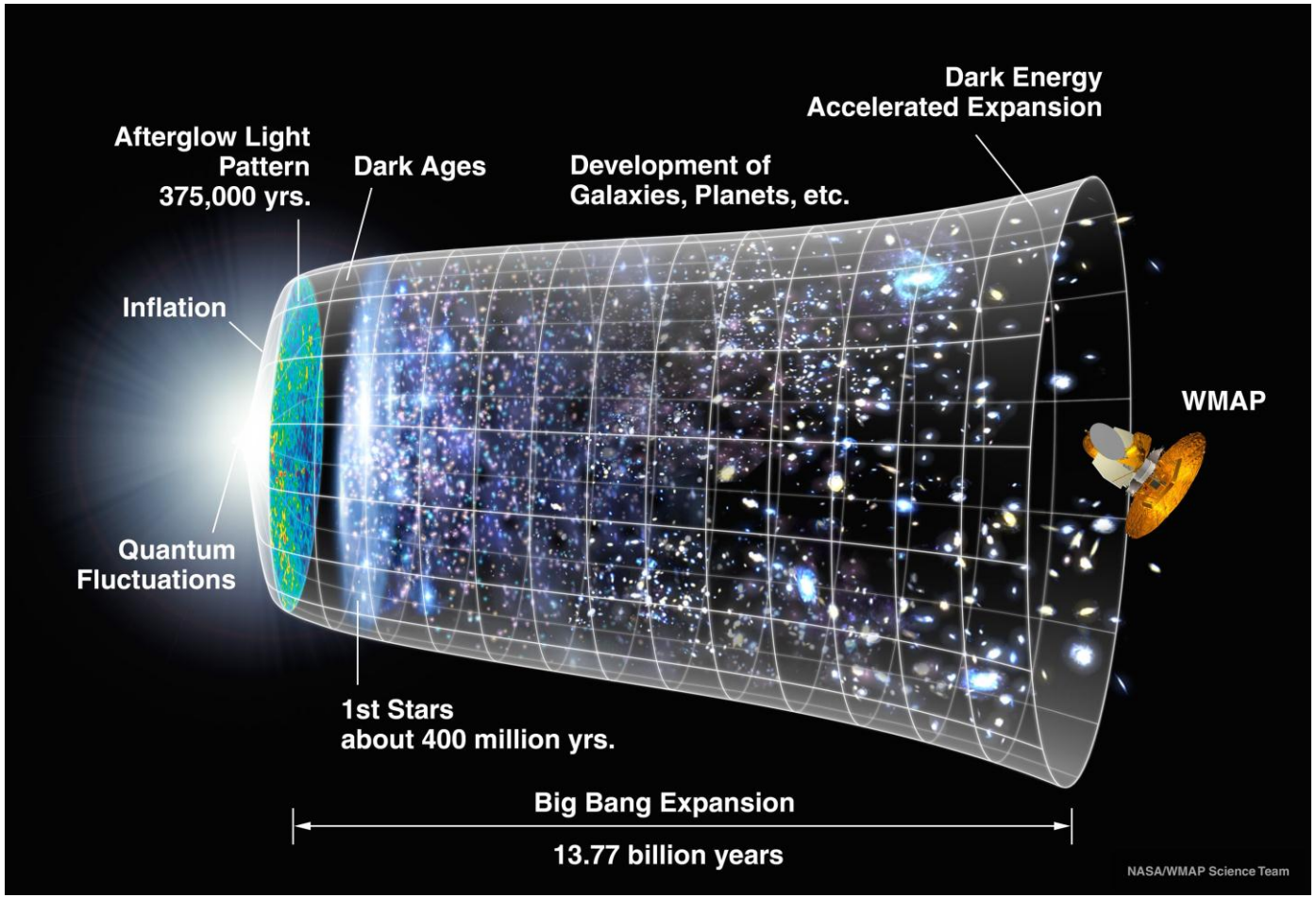
Talk Outline

- Introduction
- Instrument description
- Integration status
- Science prospects

Talk Outline

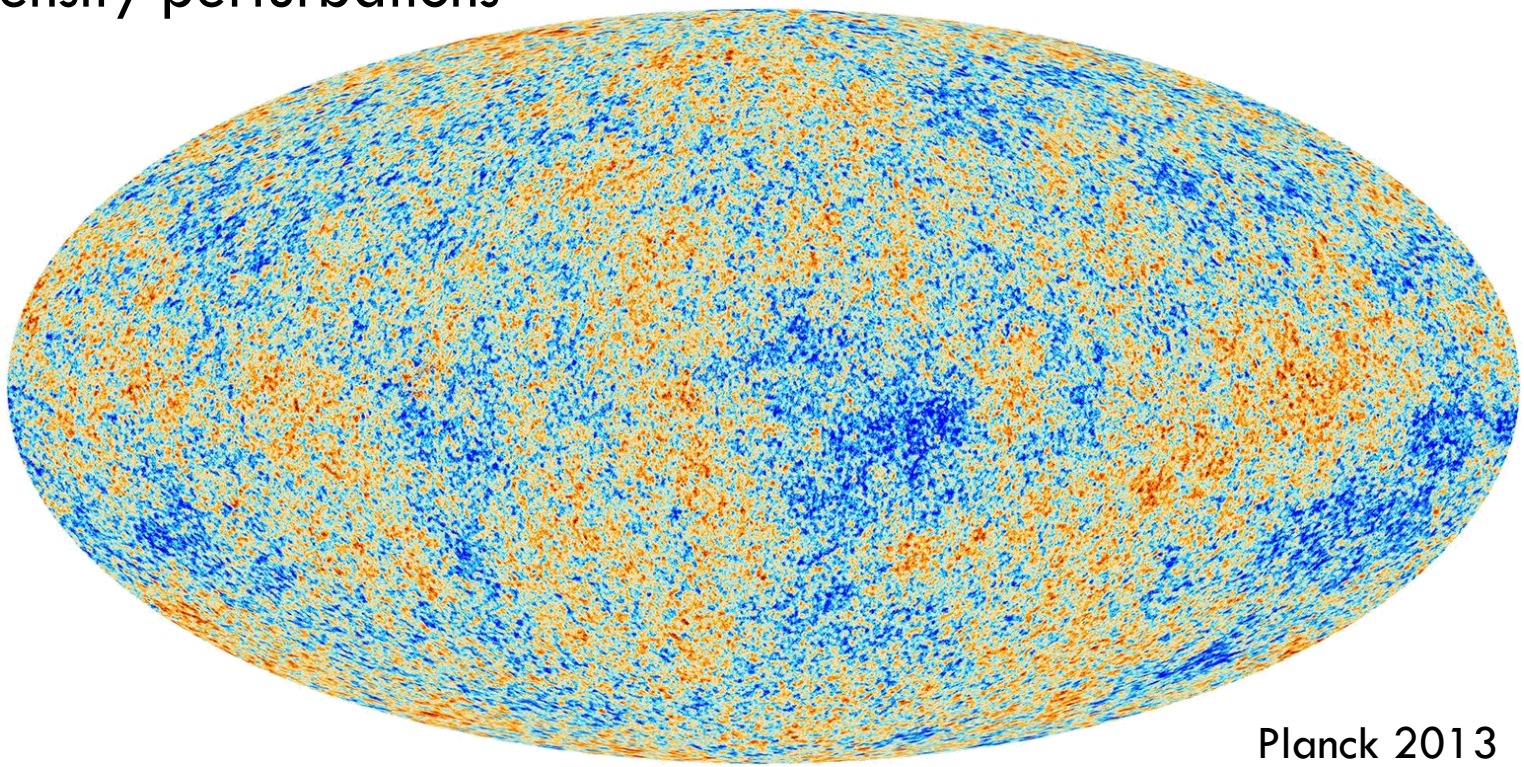
- **Introduction**
- Instrument description
- Integration status
- Science prospects

Big Bang Cosmology



Cosmic Microwave Background

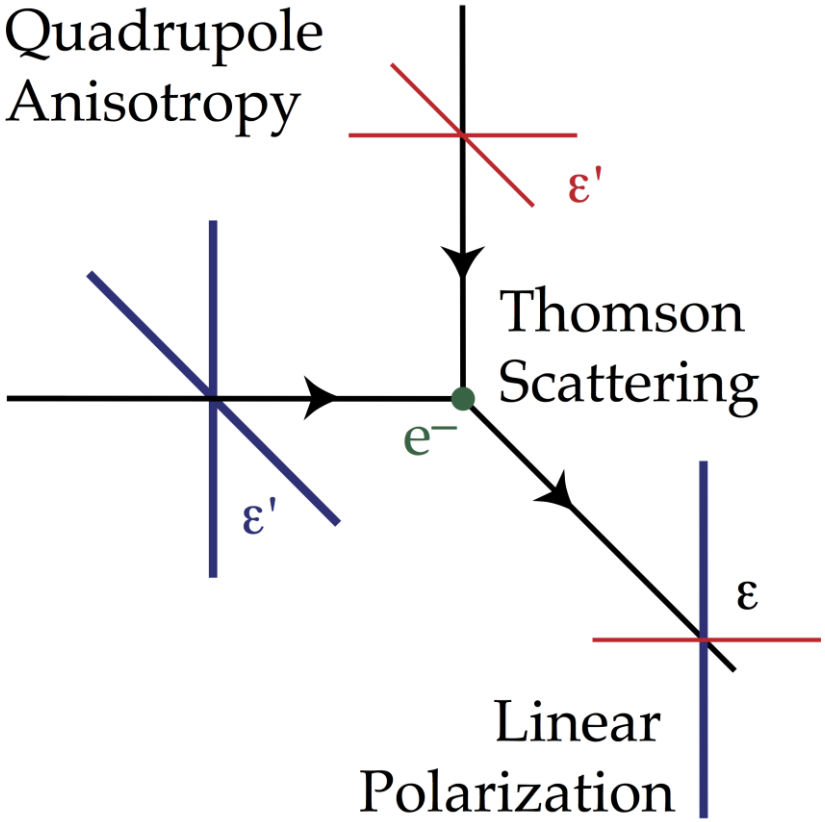
- Acoustic oscillations in photon-baryon plasma → degree-scale energy density perturbations



Planck 2013

Cosmic Microwave Background

- Acoustic oscillations in photon-baryon plasma → degree-scale energy density perturbations
- Fluid flow from hot to cold regions, velocity out of phase with density
- Thomson scattering within local quadrupole anisotropies → polarization

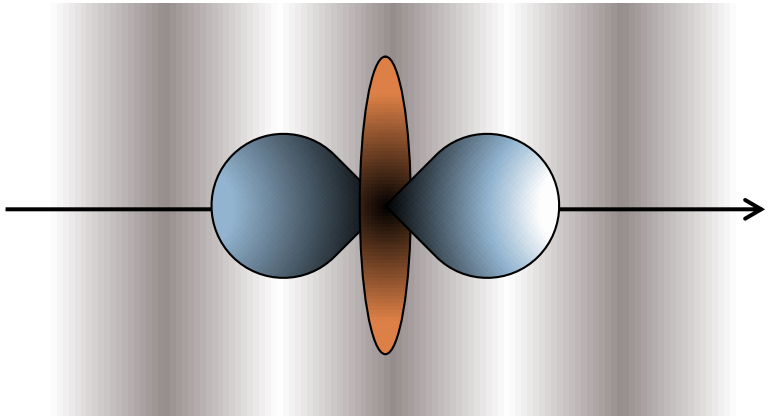


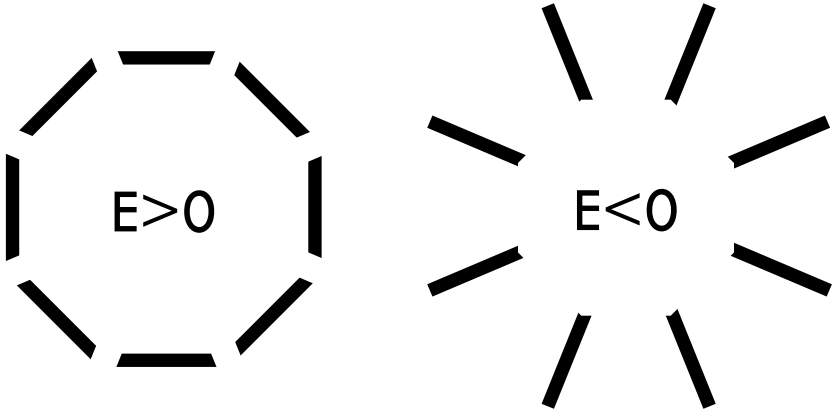
W. Hu

Cosmic Microwave Background

- Acoustic oscillations in photon-baryon plasma → degree-scale energy density perturbations
- Fluid flow from hot to cold regions, velocity out of phase with density
- Thomson scattering within local quadrupole anisotropies → polarization
- Scalar modes: T, E
- Tensor modes: T, E, B
- Ratio $r = \Delta_T / \Delta_S$

Scalar Modes





Cosmic Microwave Background

- Acoustic oscillations in photon-baryon plasma → degree-scale energy density perturbations
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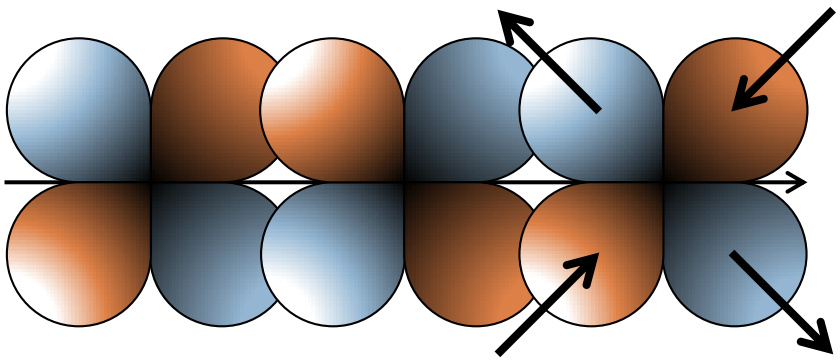
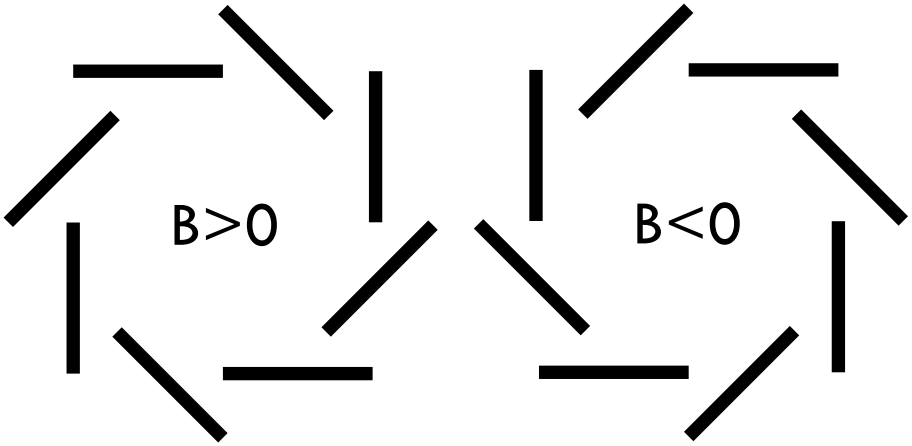
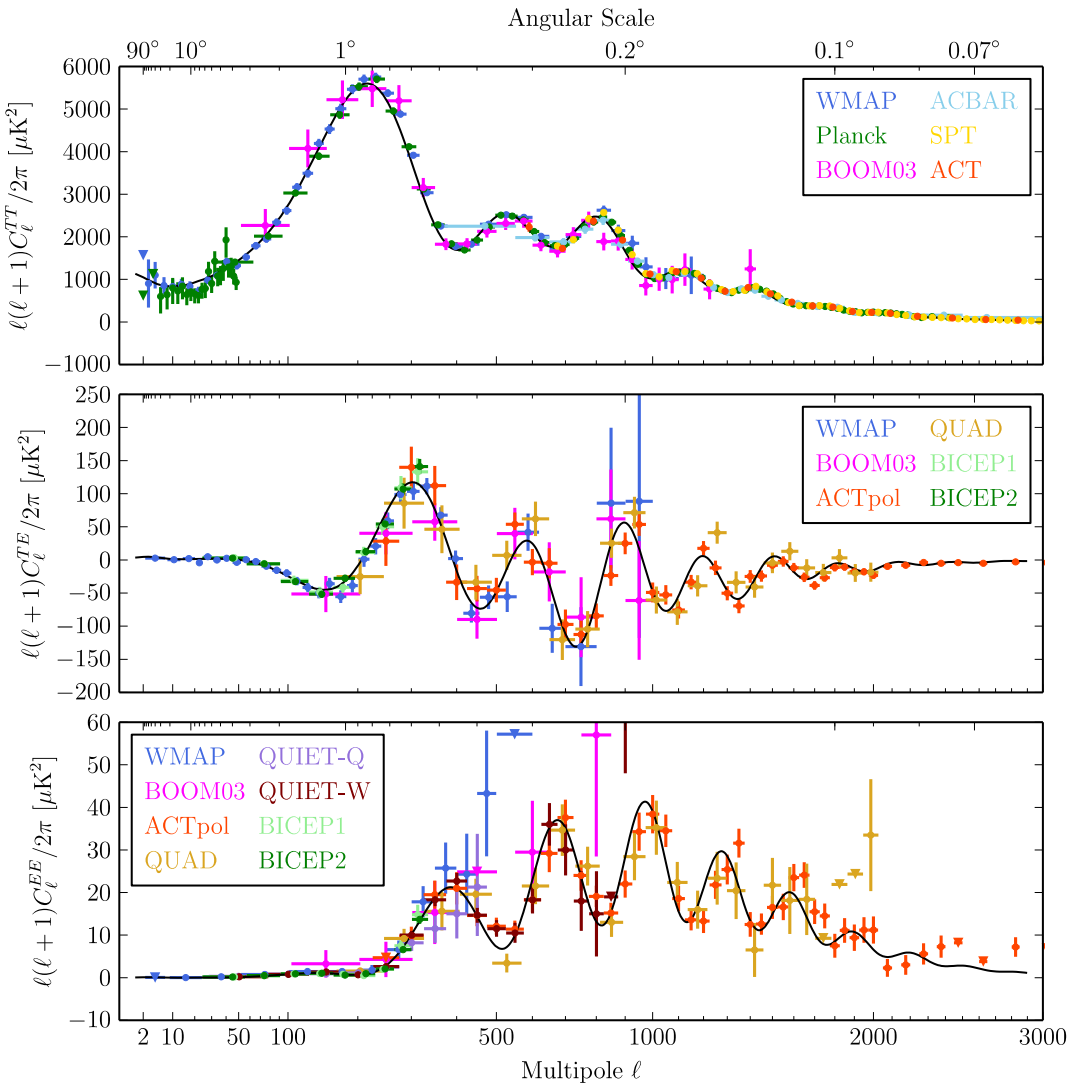
Tensor Modes



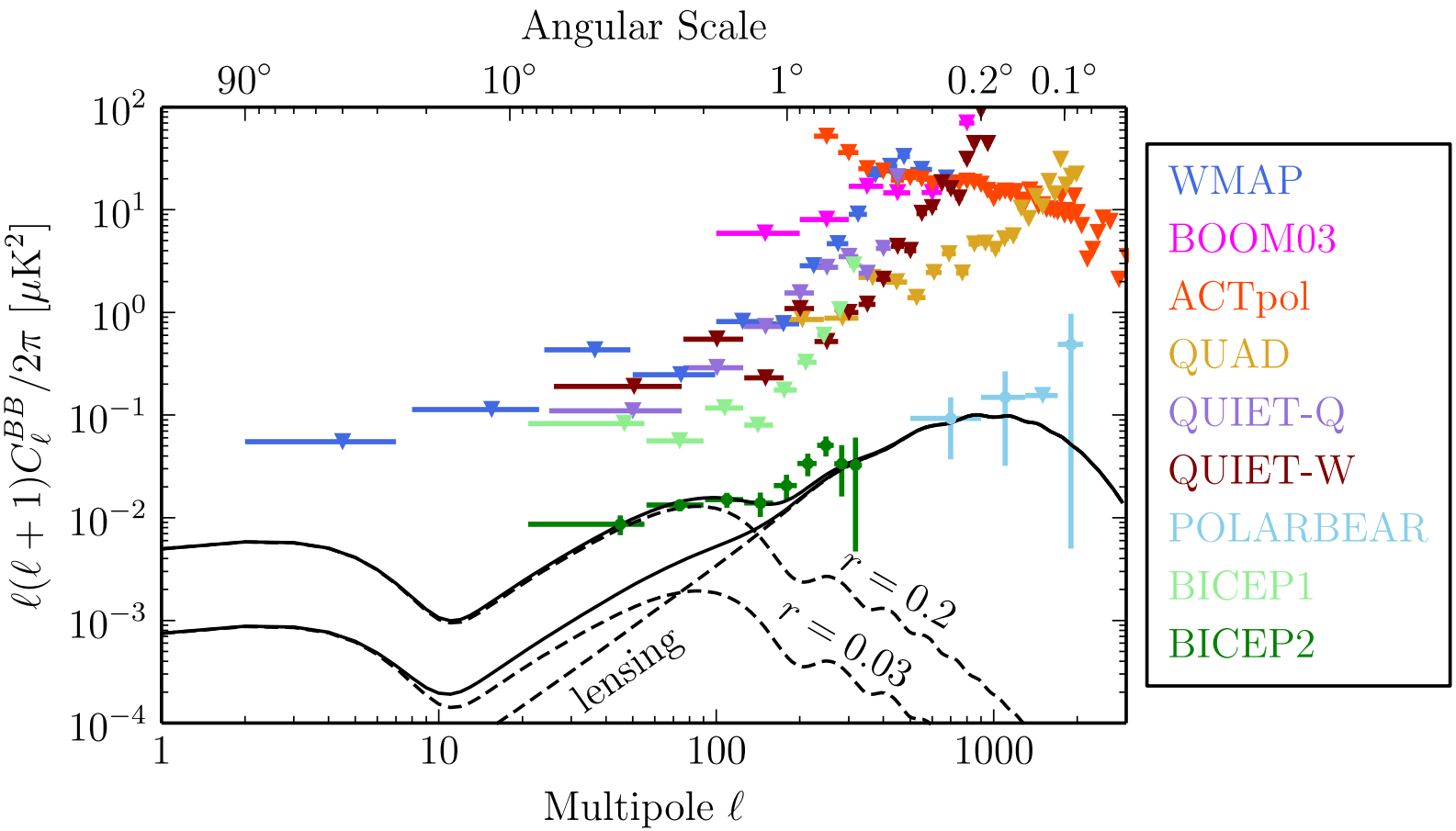


CMB Measurements



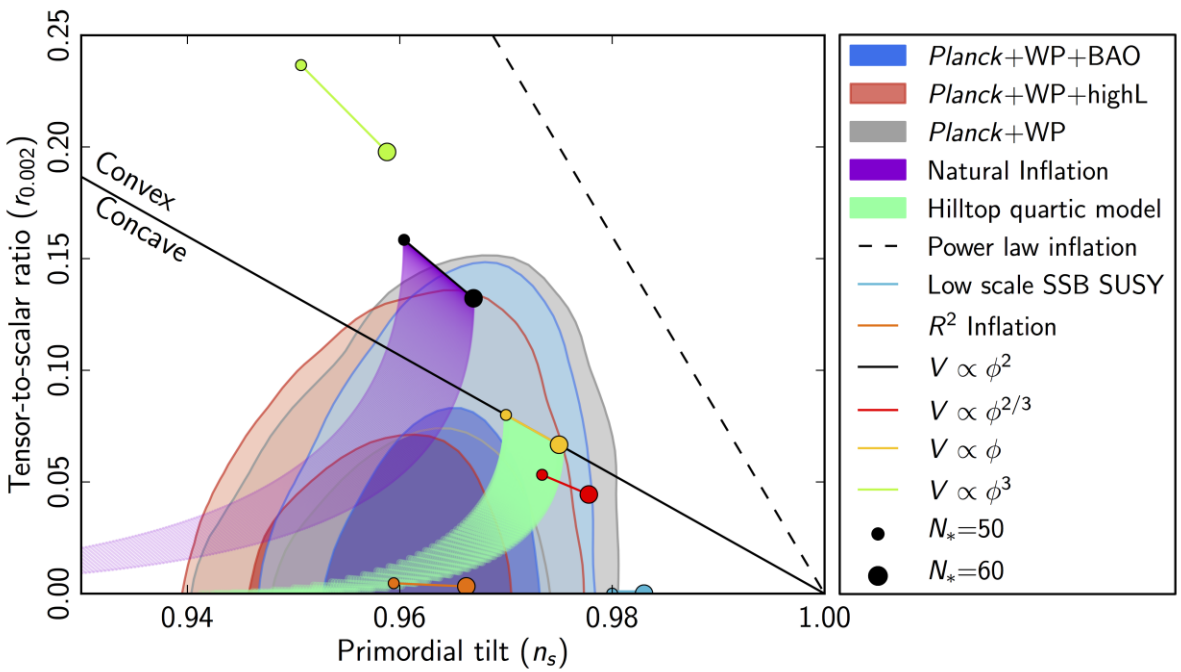
Consistent with six-parameter ΛCDM

CMB Measurements



Inflationary Paradigm

- Generic Predictions:
  - Near homogeneity, isotropy, flatness
  - Nearly scale invariant perturbations ($n_s < 1$)
  - Gravitational waves: $r \sim V(\phi) / (10^{16}\ \mathrm{GeV})^4$



$r < 0.11$
(95% CL)

Planck XXII

SPIDER Overview

- Instrument: balloon-borne microwave polarimeter
- Goals: Primordial B-modes, foreground characterization
- The good:
  - Frequency coverage
  - Pol angle coverage
  - Sky coverage
- The difficult:
  - Mass/power constraints
  - One shot at quality data
  - Recovery
- The ugly:
  - Government shutdowns…

Frequencies	94 / 150 GHz
Beam FWHM	42 / 30 arcmin
Visible sky	8%
Flight 1	Dec. ~~2013~~ 2014, McMurdo Station
Observation time	10-20 days
Pol modulation	Stepped HWP
# detectors	2400, 85% yield
NET/det	110 – 140 uK-rts
Map depth	12 / 10 uK-arcmin

BICEP2: 5 uK-arcmin

SPIDER Collaboration

Caltech
J. J. Bock
B. P. Crill
O. Doré
J. P. Filippini
S. Golwala
W. Holmes
V. V. Hristov
P. V. Mason
L. Moncelsi
T. A. Morford
M. C. Runyan
A. Trangsrud
R. S. Tucker
A. D. Turner

Cambridge
C.J. MacTavish

Cardiff
P. Ade
C. Tucker

CWRU
J.E. Ruhl
S. Bryan
J. Nagy

Imperial College
C.R. Contaldi

NIST
G. Hilton
C. Reintsema

Princeton
W.C. Jones
A. Fraisse
A. Gambrel
J.E. Gudmundsson
M. Hasselfield
Z. Kermish
A.S. Rahlin
E. Young

Stanford
K.D. Irwin
C.L. Kuo

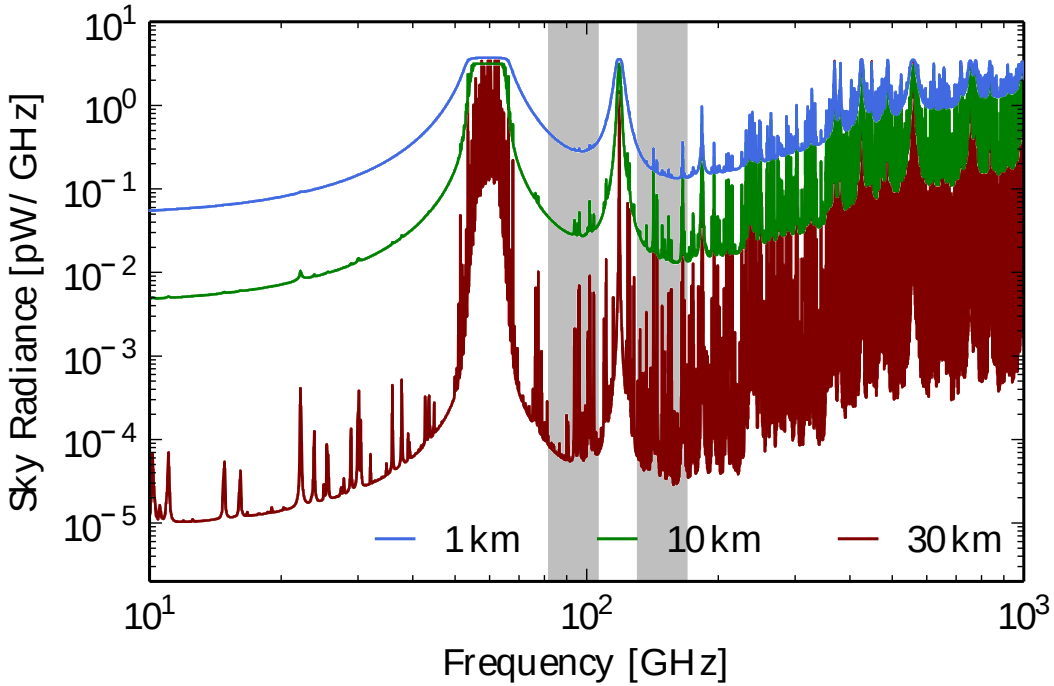
UBC
M. Halpern
M. Amiri
D. Wiebe

UKZN
H.C. Chiang

U. Toronto/CITA
C.B. Netterfield
J.R. Bond
S.J. Benton
M. Farhang
L.M. Fissel
N.N. Gandilo
I. Padilla
J.A. Shariff
J.D. Soler

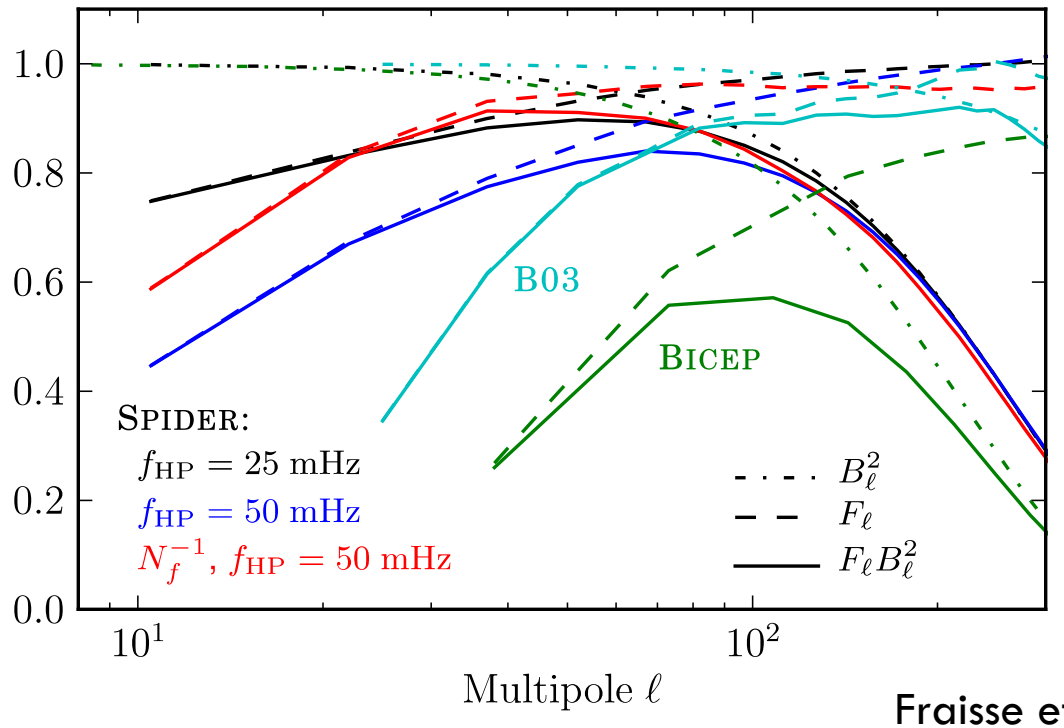
Why Ballooning?

- Avoid the atmosphere
  - Reduced loading → achieve high SNR quickly
    - Weeks on a balloon = years on the ground
    - Frequencies > ~220 not feasible from the ground



Why Ballooning?

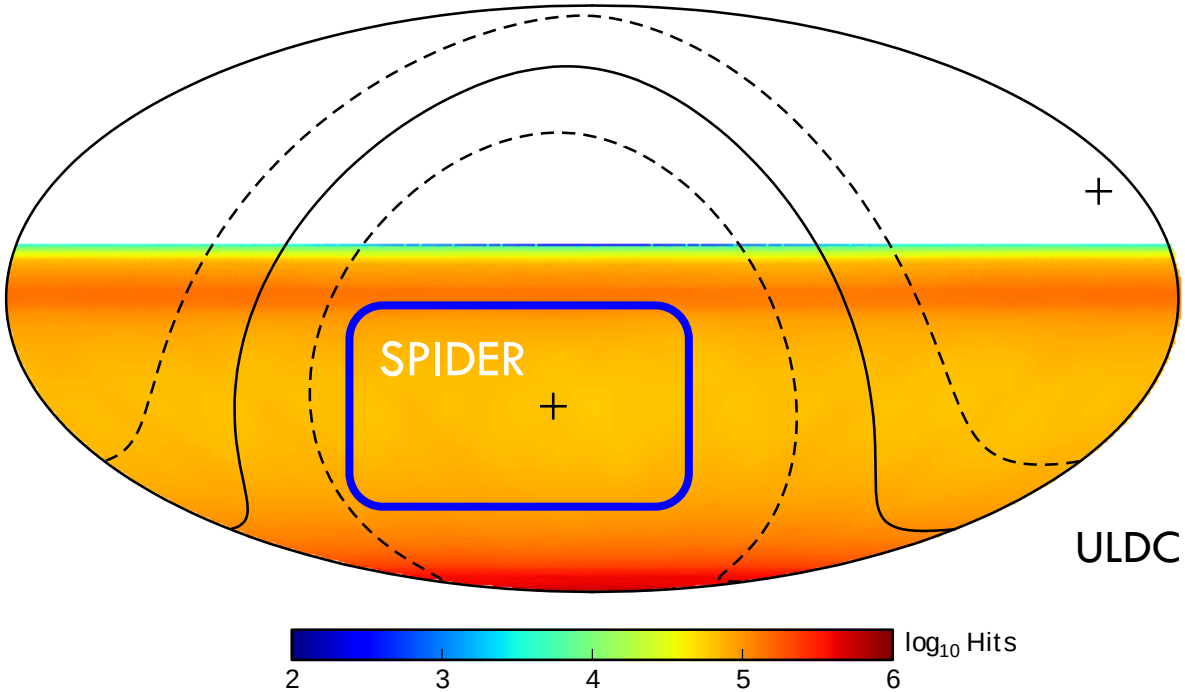
- Avoid the atmosphere
  - Reduced 1/f → access to larger scales



Fraisse et al 2011

Why Ballooning?

- Access to lots of sky
  - Mid-latitude 100-day flights soon feasible
  - Space-quality data



Talk Outline

- Introduction
- **Instrument description**
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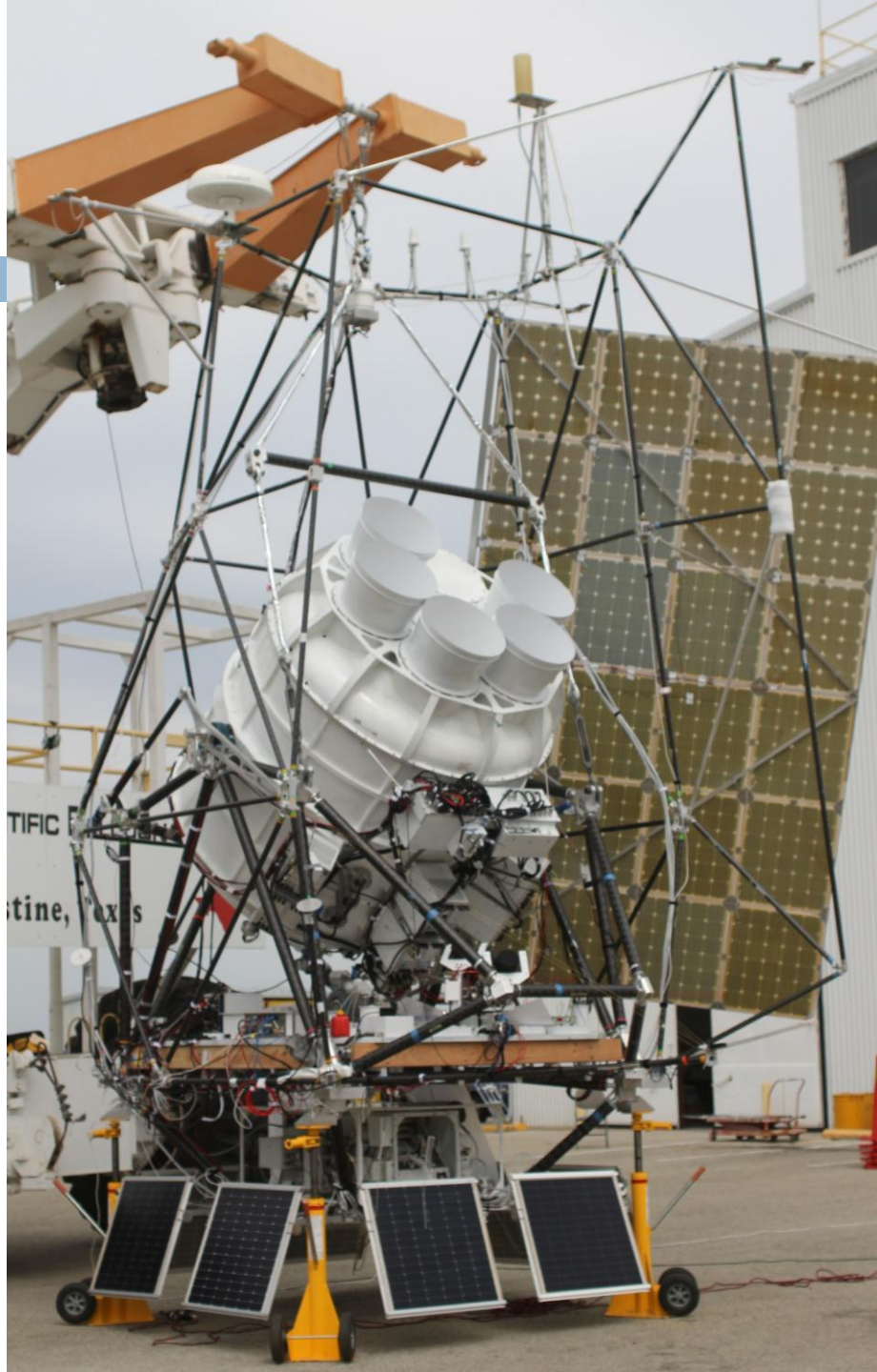
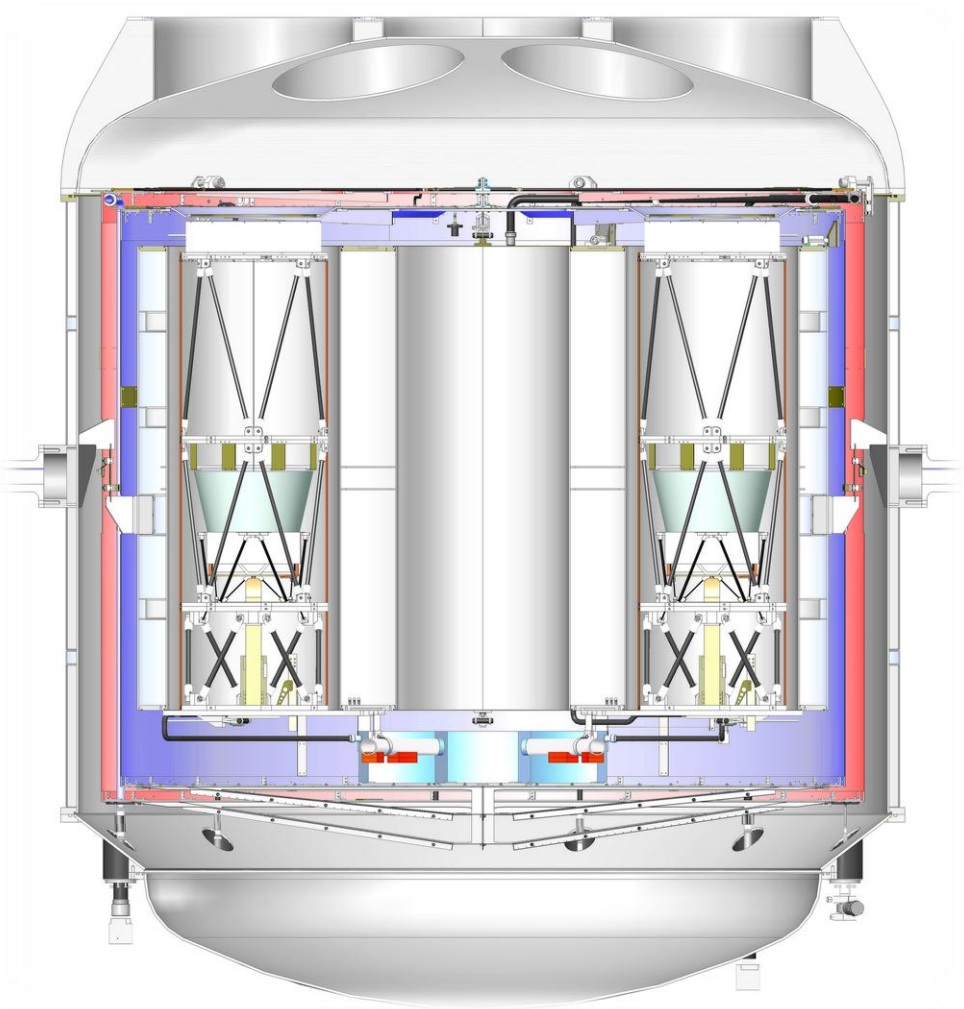
System Overview

- 6 independent telescopes
- Single cryogenic/vacuum environment
- Lightweight carbon fiber gondola
- ~5000 lb payload



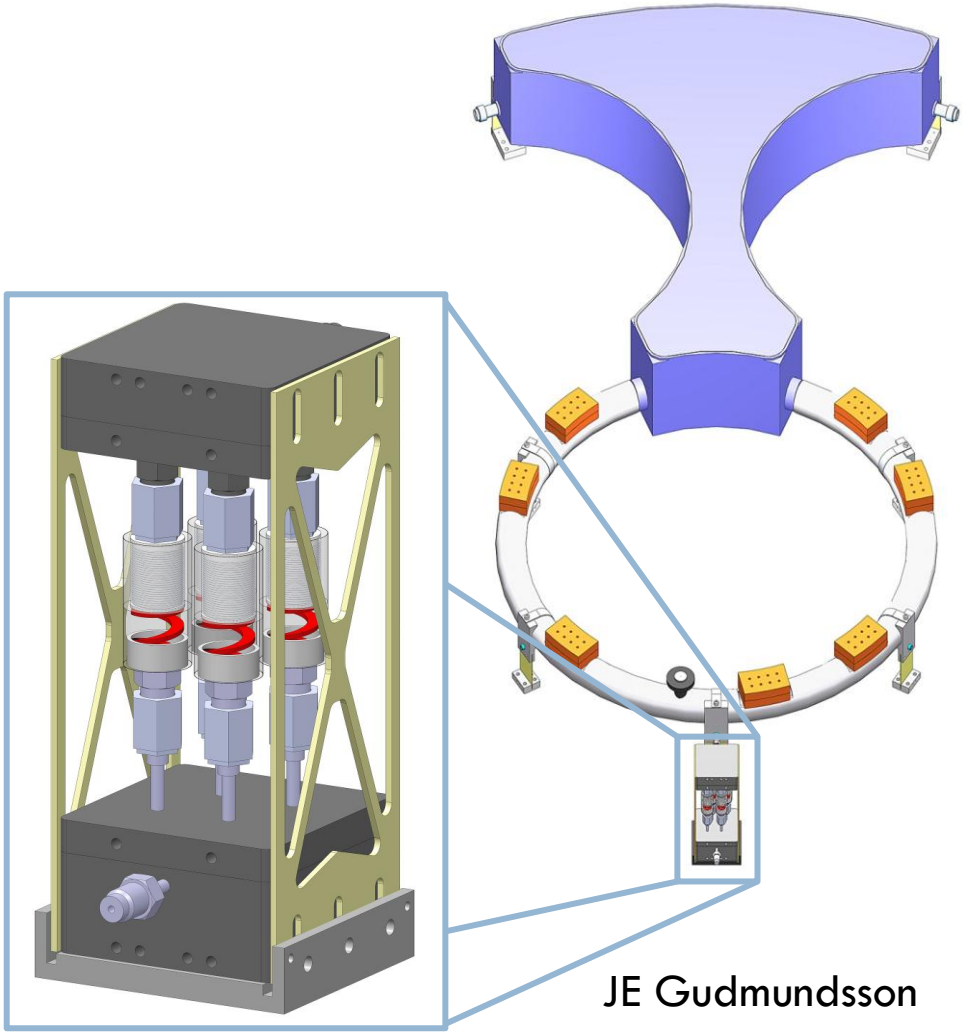
Cryogenic System

- Lightweight (850 kg)
- 1300-L LHe4 cryostat (4K)
- Two vapor cooled shields (30K, 150K)
- Capillary-fed 20-L superfluid LHe4 tank (1.5K)
- Closed-cycle He3 adsorption fridge per telescope (300mK)
- Two weeks from close up to cold detectors
- Baselined for 25 day hold time



Superfluid System

- Pumped SF tank
  - 1.5K condensation point
  - 16L volume
  - 5 torr at float
- Capillary system
  - Continuous LHe flow
  - 3x 0.0035” ID parallel
  - Mott filters reduce clogging
  - ~100 mW cooling
  - Compact and modular



JE Gudmundsson

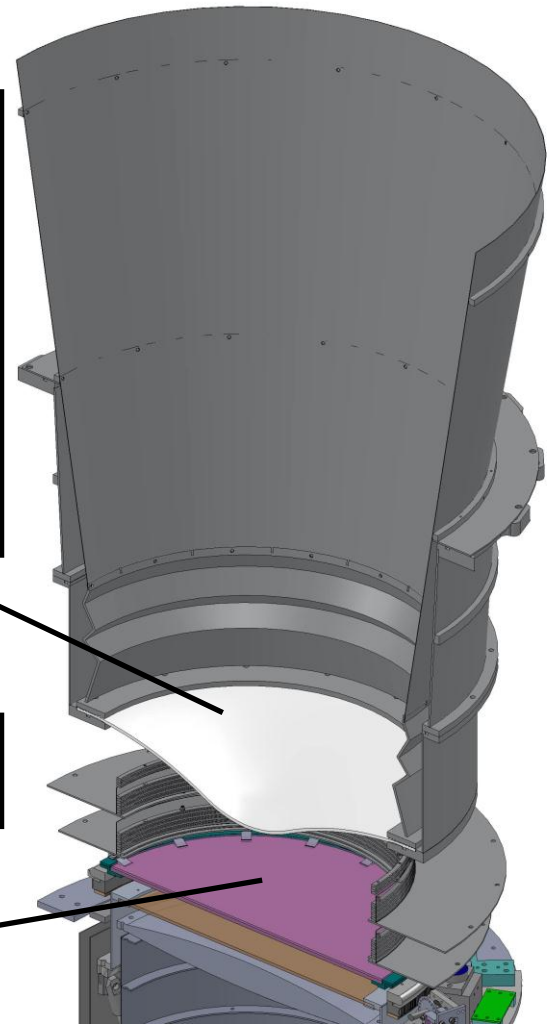
Telescope Insert

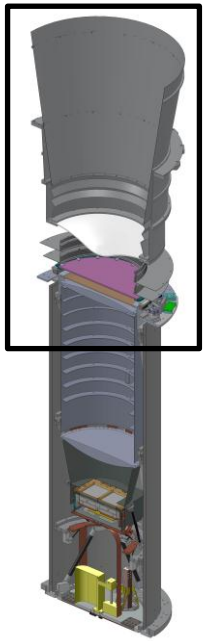
Reflective baffle

Recessed window
1/8” UHMWPE, AR-coated

Filter stack: single- and
multi-layer metal mesh

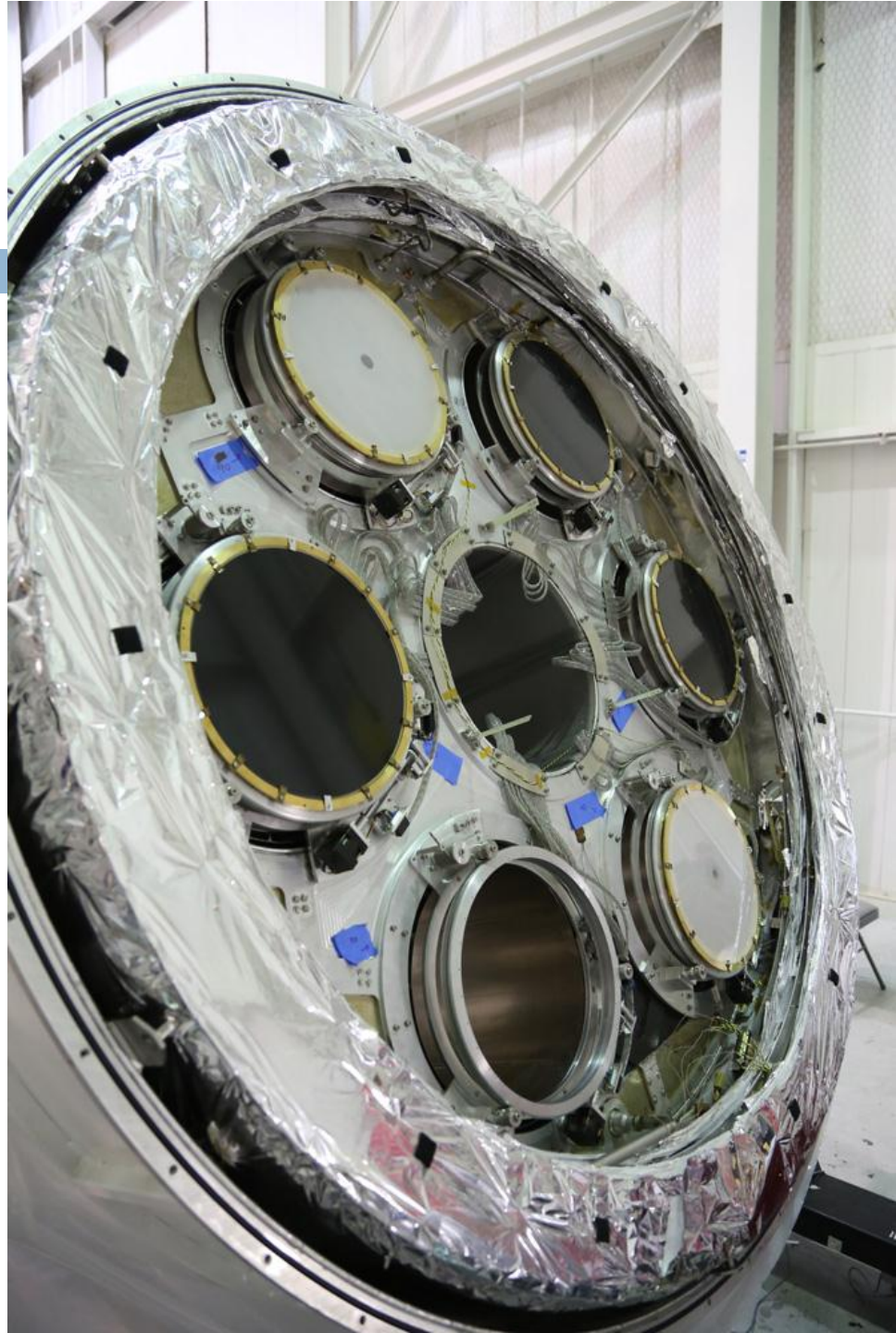
Sapphire HWP (4K)



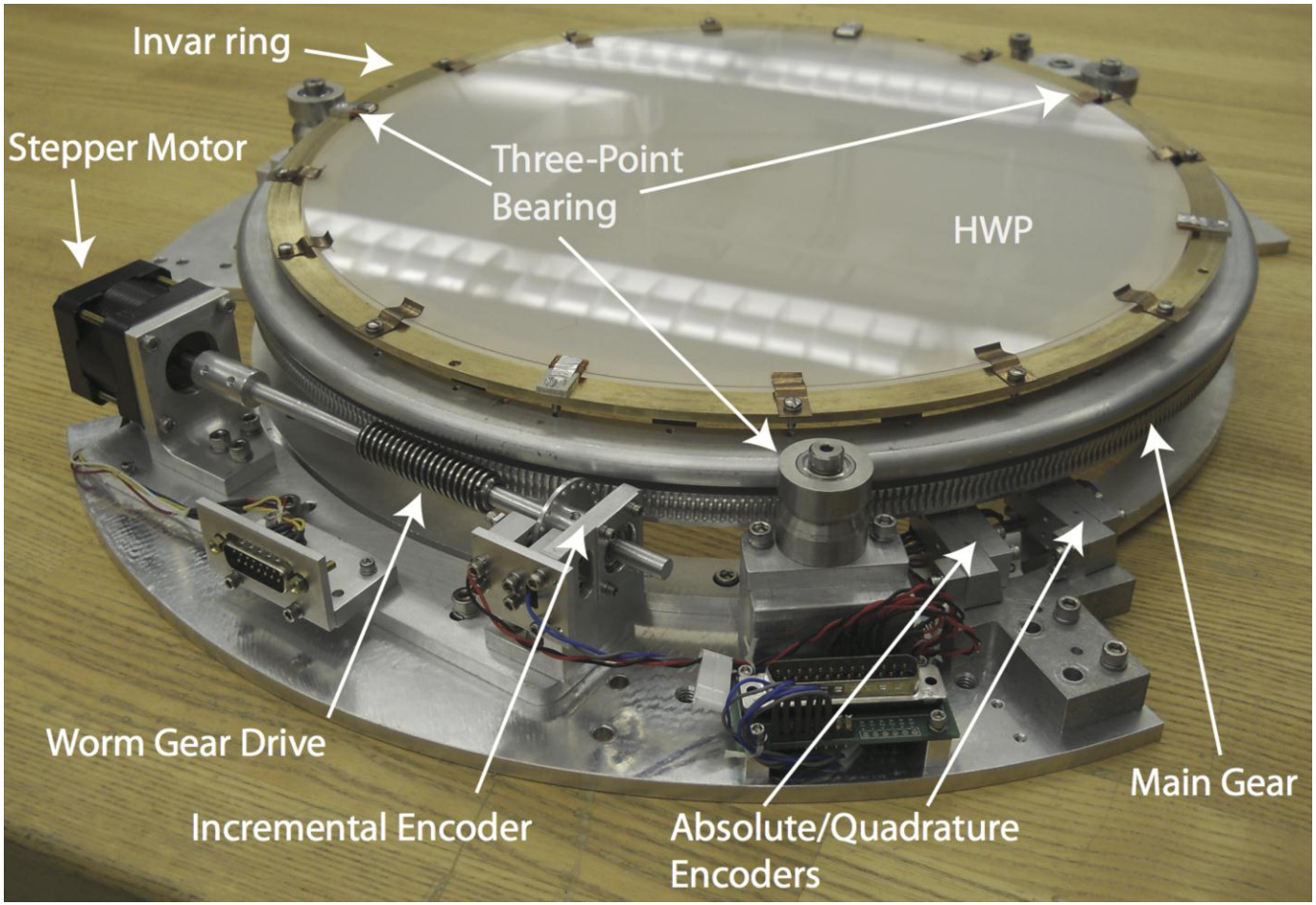


Half-Wave Plate

- Sapphire with quartz (90 GHz) and Cirlex (150 GHz) bonded AR coatings
- Custom worm gear mechanism does not bind at 4K
- Stepped daily to modulate polarization
- Custom absolute and relative encoders to reconstruct HWP angle to better than 0.1°



Half-Wave Plate



SA Bryan

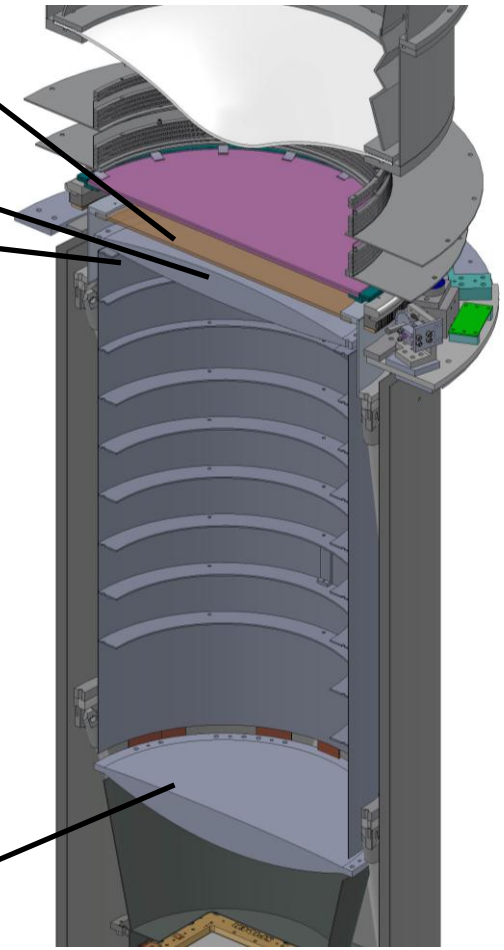
Telescope Insert

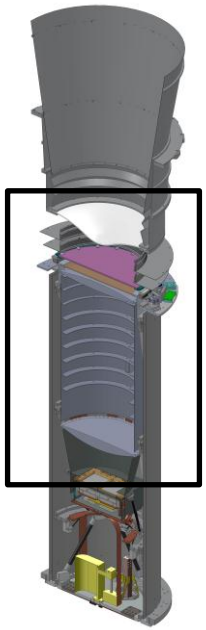
AR-coated Nylon
+ metal mesh filters

Objective Lens (4K)
Lyot Stop

2K optics sleeve
Blackened with steelcast
Baffle rings

Eyepiece Lens (4K)





Telescope Insert

A4K Spittoon

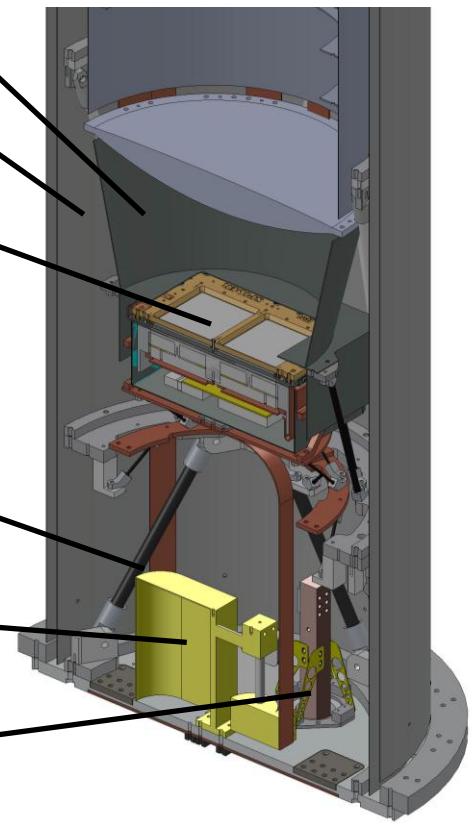
Cryoperm Shell

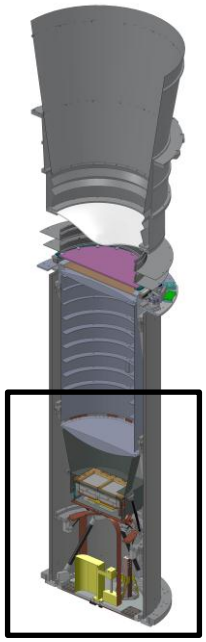
Focal Plane (300 mK)
TDM SQUID Readout

Carbon fiber truss

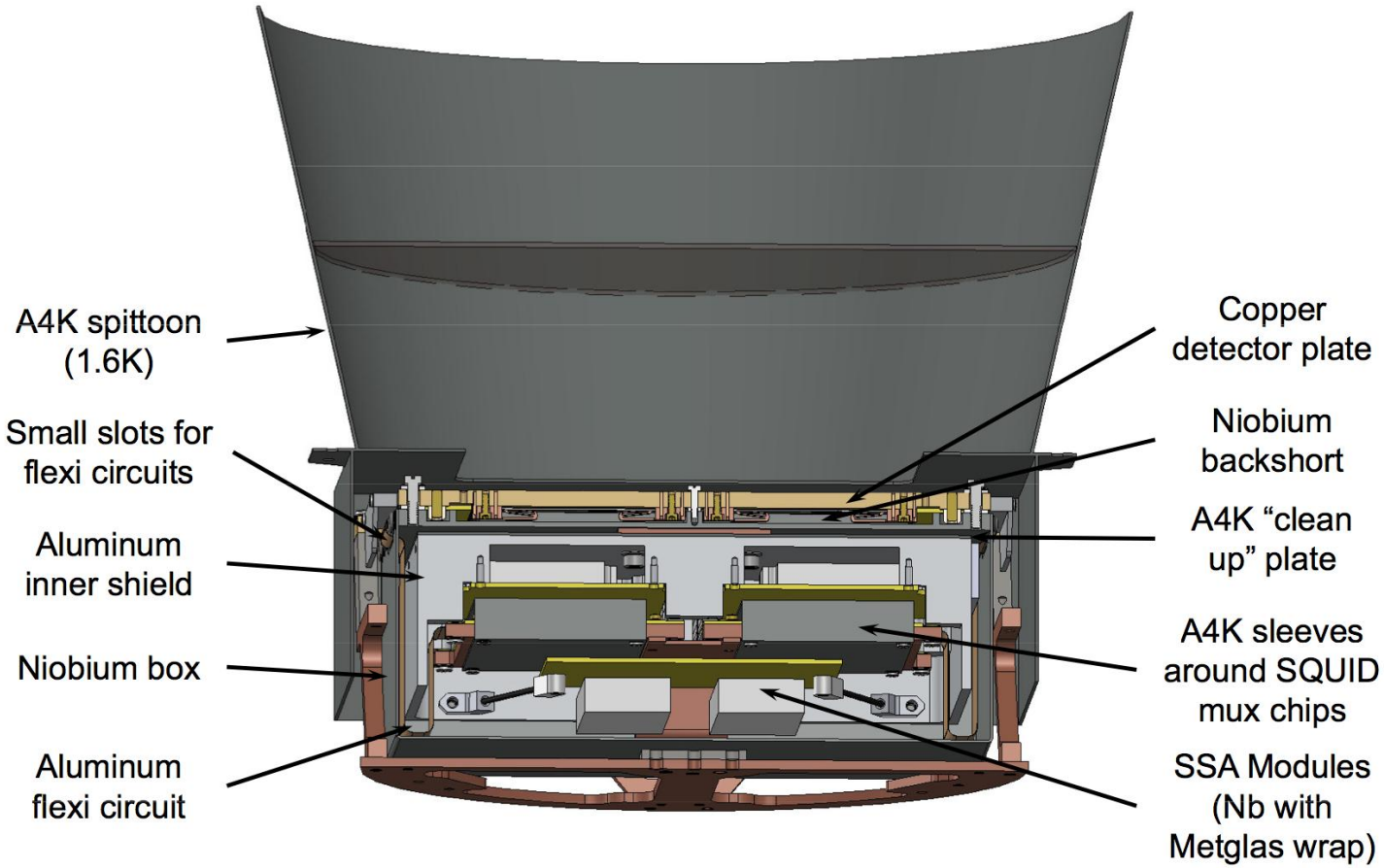
He-3 adsorption fridge

Aux post (2K)

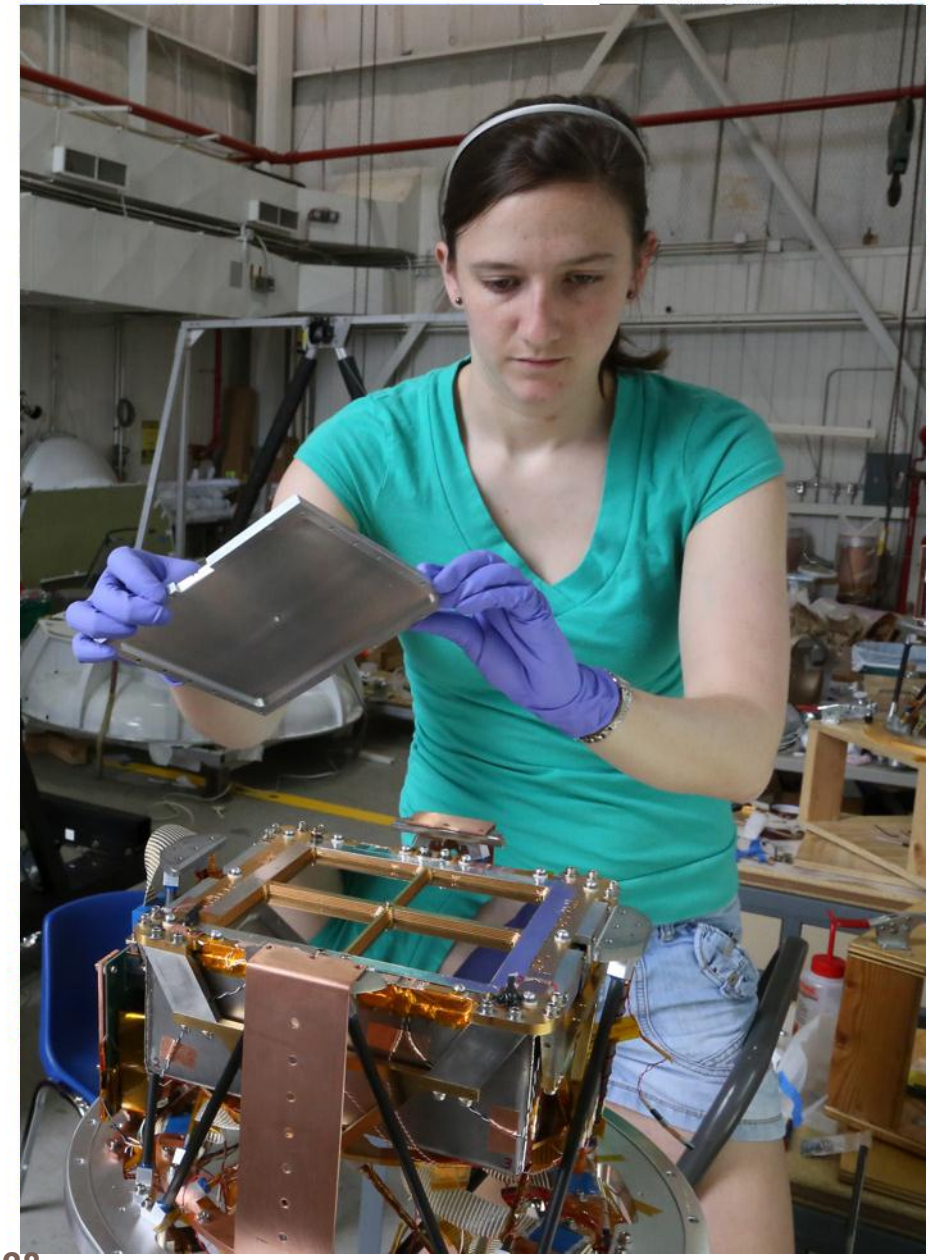


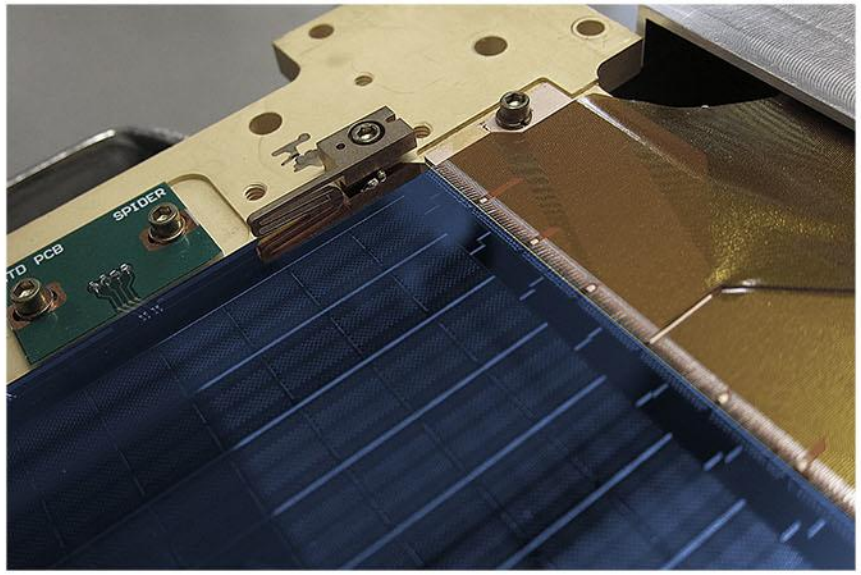


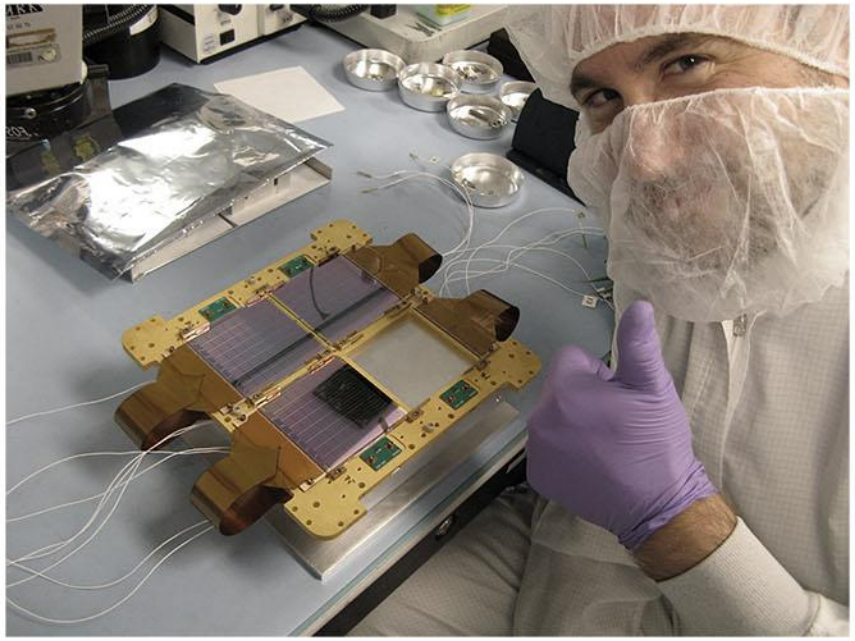
Focal Plane Assembly

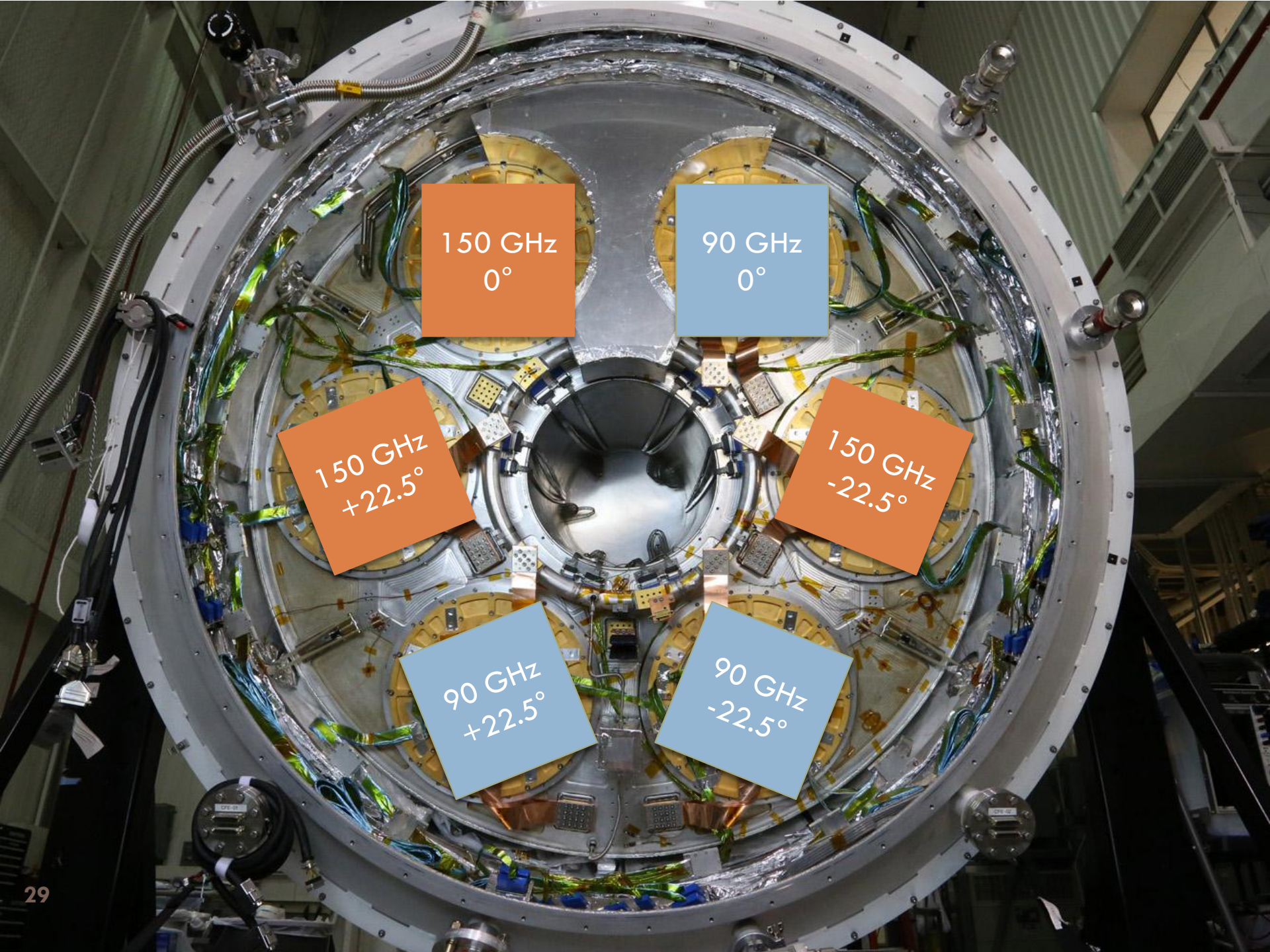


Magnetic shielding factor ~10^8 (requirement ~10^7)



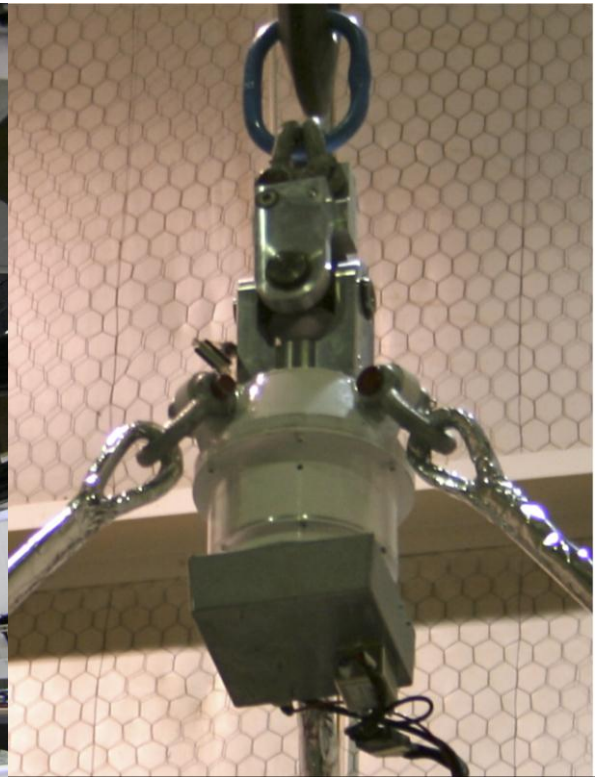

SPIDER
PCB




150 GHz
0°
90 GHz
0°
150 GHz
+22.5°
150 GHz
-22.5°
90 GHz
+22.5°
90 GHz
-22.5°

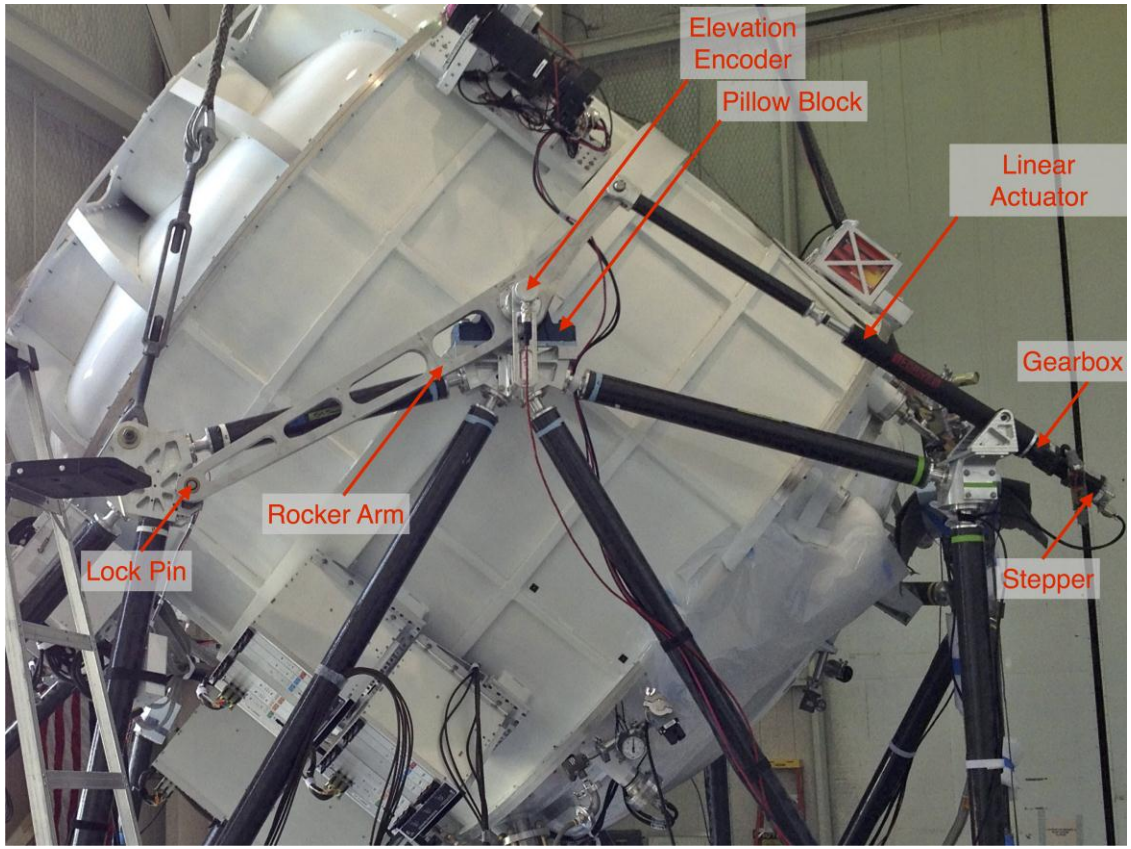
Pointing Control – Azimuth

- Reaction wheel – max a = 0.8°/sec^2, v = 6°/sec
- Pivot – prevent RW saturation



Pointing Control – Elevation

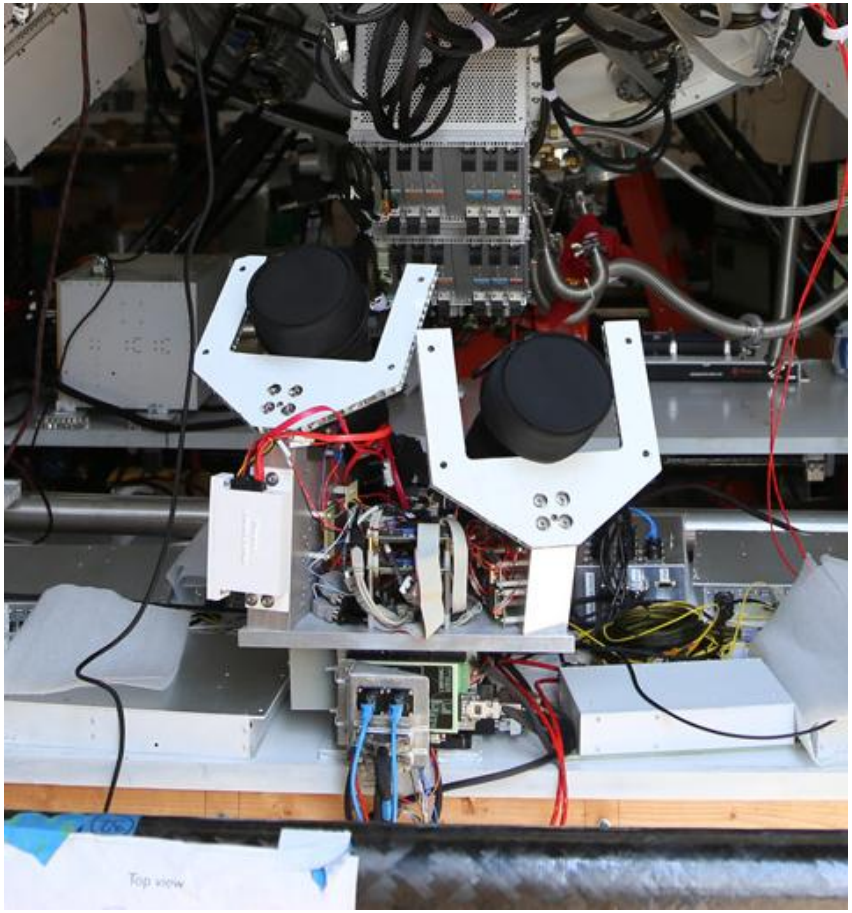
- Twin elevation drives – range 20° to 50°



JA Shariff

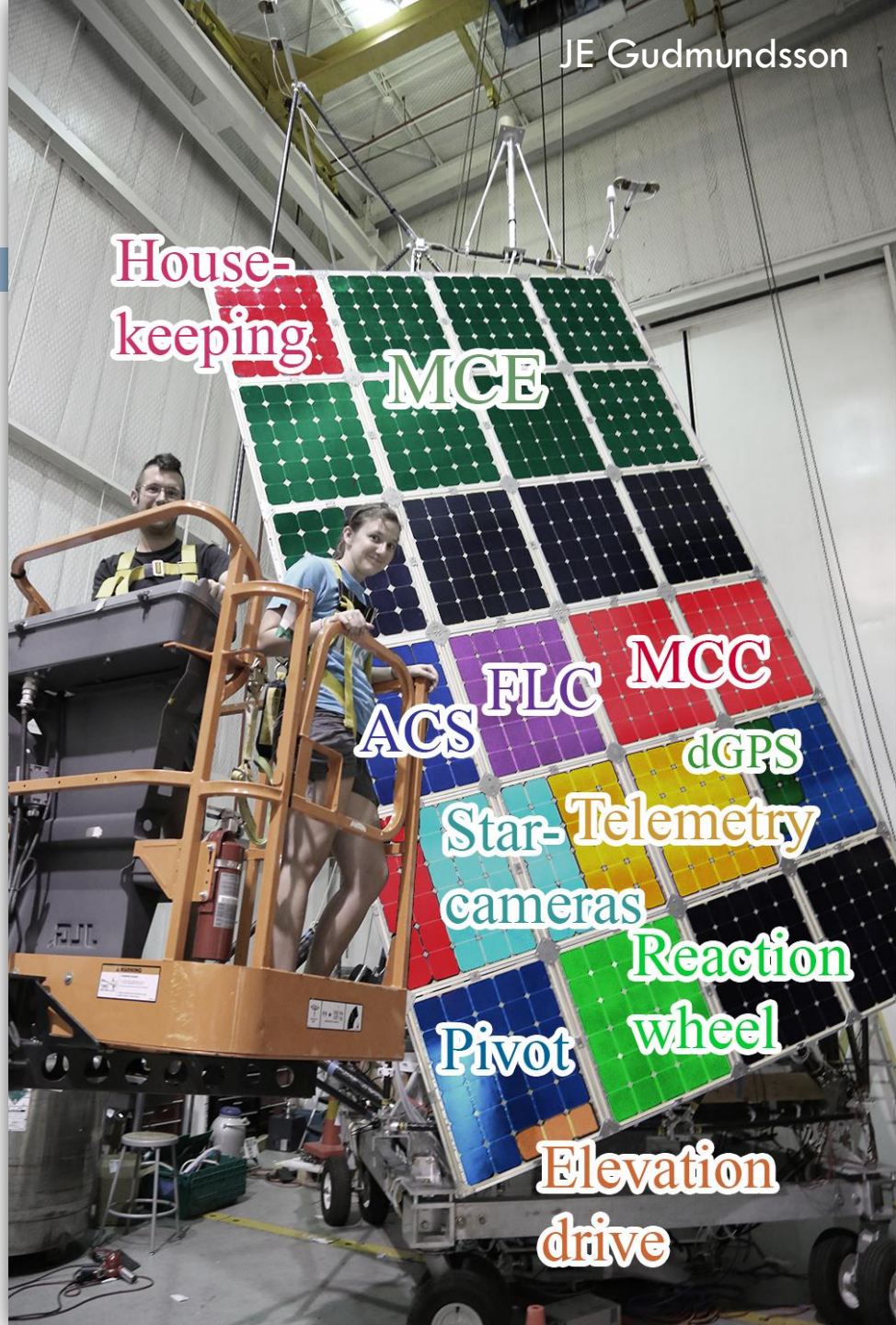
Pointing Sensors

- In-flight:
  - Differential GPS
  - Magnetometer
  - Pinhole sun sensors
  - 1' accuracy
- Post-flight
  - 3-axis gyros
  - Orthogonal star cameras on rotating table to track objects
  - Fixed boresight star camera
  - 6" accuracy



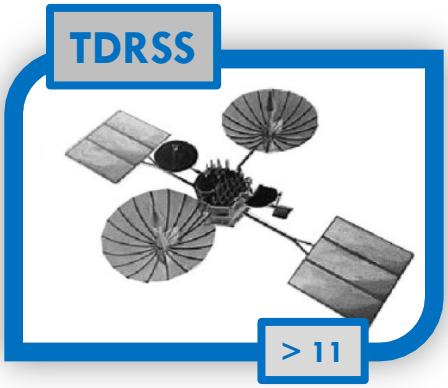
Power System

- Two independent power systems (two 4 x 3 arrays)
- Array Peak/Average 2200/1440 W, up to 21% efficiency
- Fully assembled and tested in Texas



JE Gudmundsson

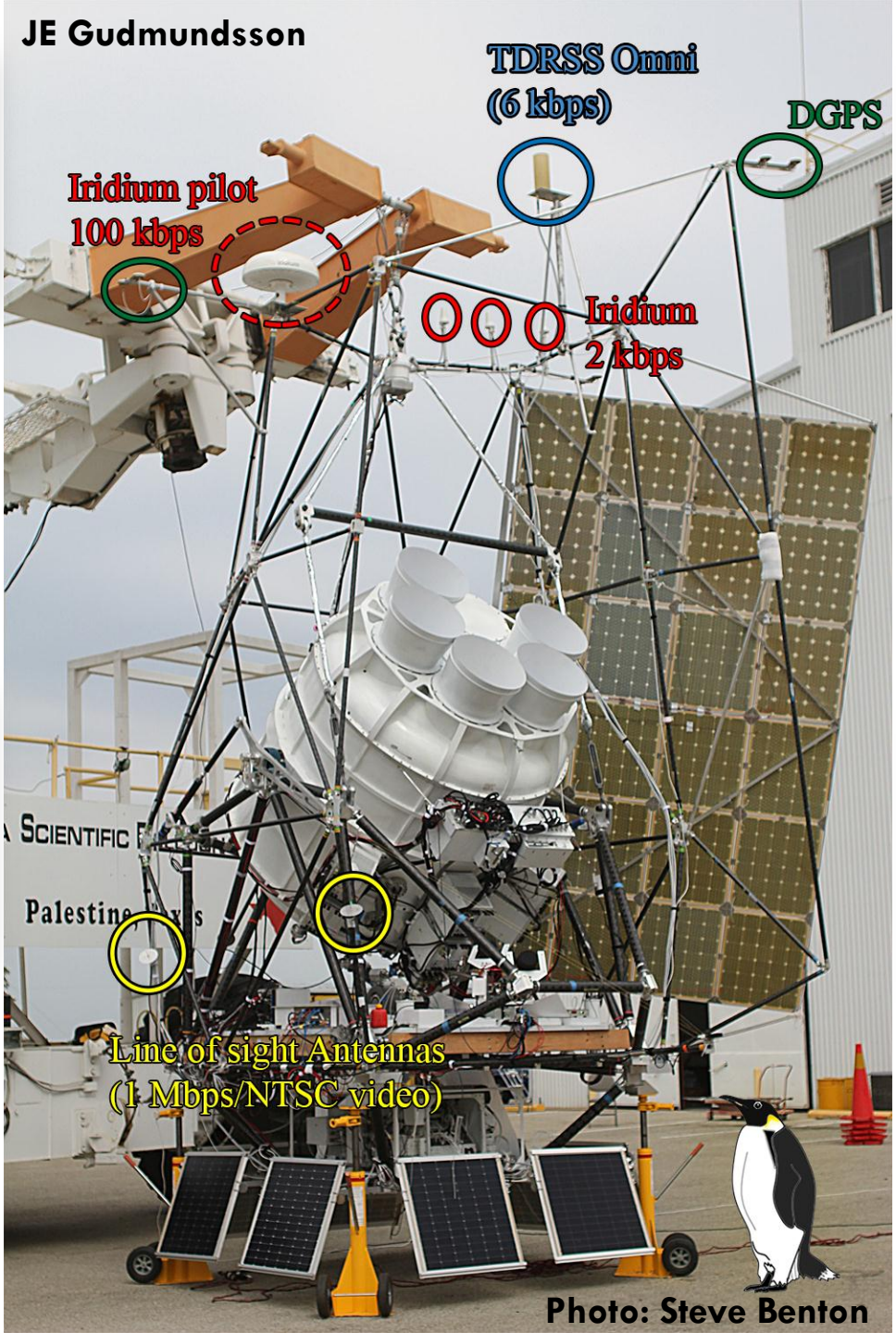
TDRSS



- Pentagon/NASA ops
- Cardioid beam shape
- RF Power = 5 W
- Pointing/HK/6-30 dets
- S-band: 2-4 GHz
- Geosynchronous

LOS

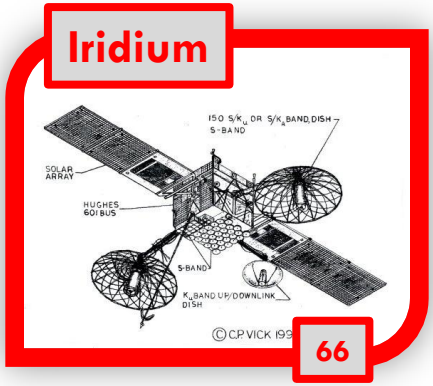
- Line of sight, 18-36 hours
- Omni directional
- RF Power ~ 15 W
- Pointing/HK/300 dets
- 1444/1515/1772 MHz
- Data/CSBF/Starcams



DGPS

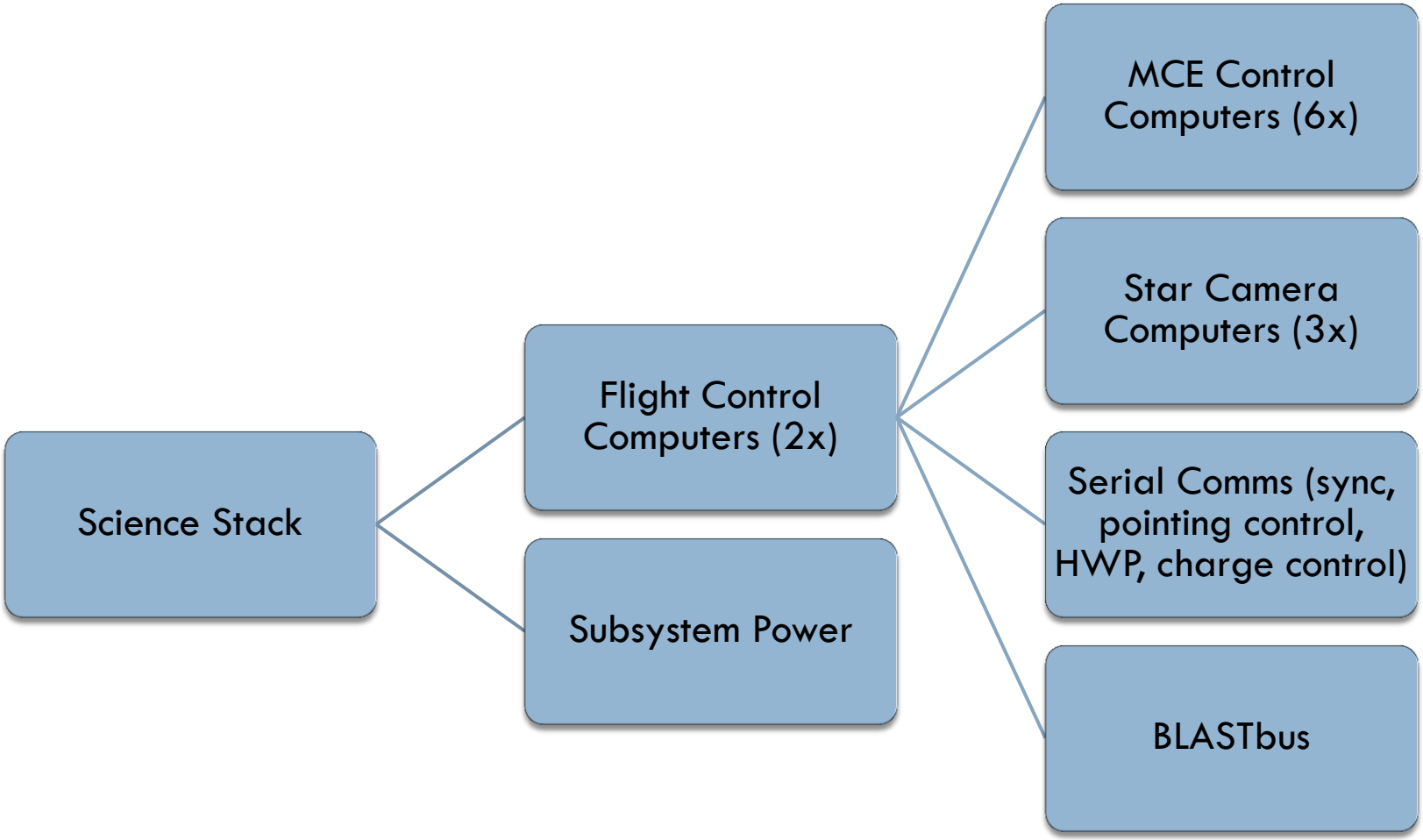
- Roughly 15 cm accuracy
- Semi-synchronous
- Location and 0.5 degree pointing attitude
- 1575 MHz

Iridium



- Commercial system
- Omni directional
- RF Power = 7 W
- Pointing/HK/one detector
- 1616-1627 MHz
- Low Earth polar orbit
- Pilot assigns static IP

Flight Electronics



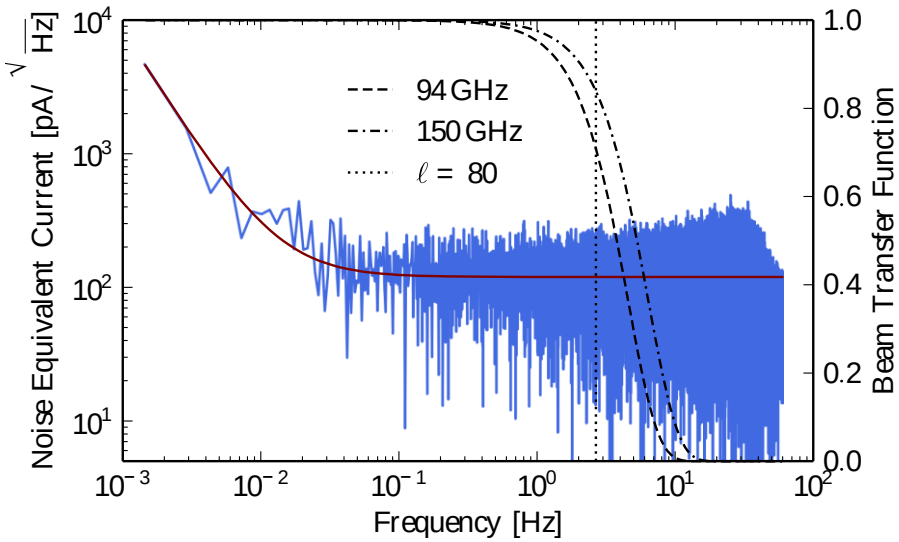
Talk Outline

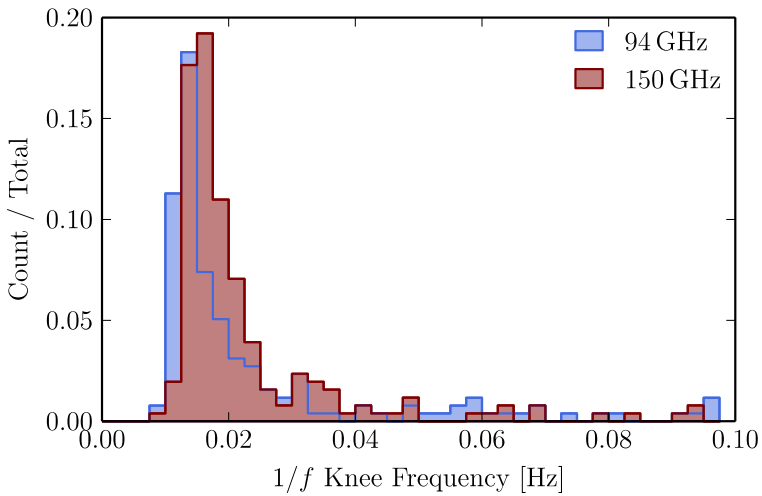
- Introduction
- Instrument description
- **Integration status**
- Science prospects

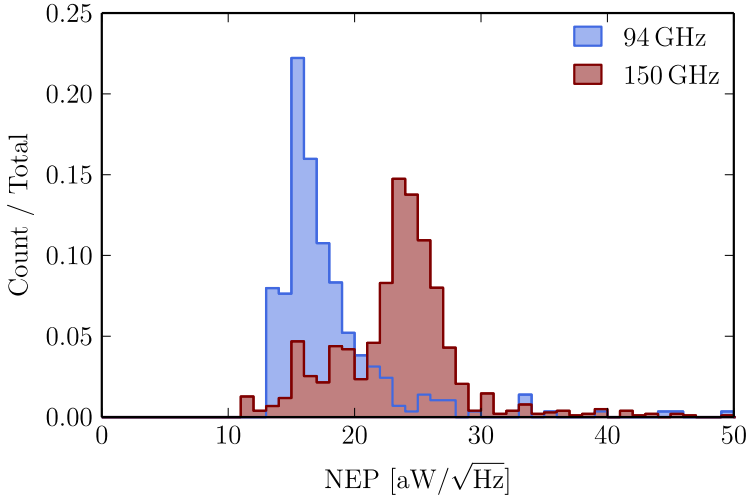
Current State

- Fully integrated system in August 2013
- Deployed for December 2013 flight, boomeranged due to shutdown
- Re-integrated in Princeton
  - Improvements for cryogenic performance
  - Dark run for work on detector characterization and automation
- Currently preparing an optical run for final optical calibrations

Detector Performance



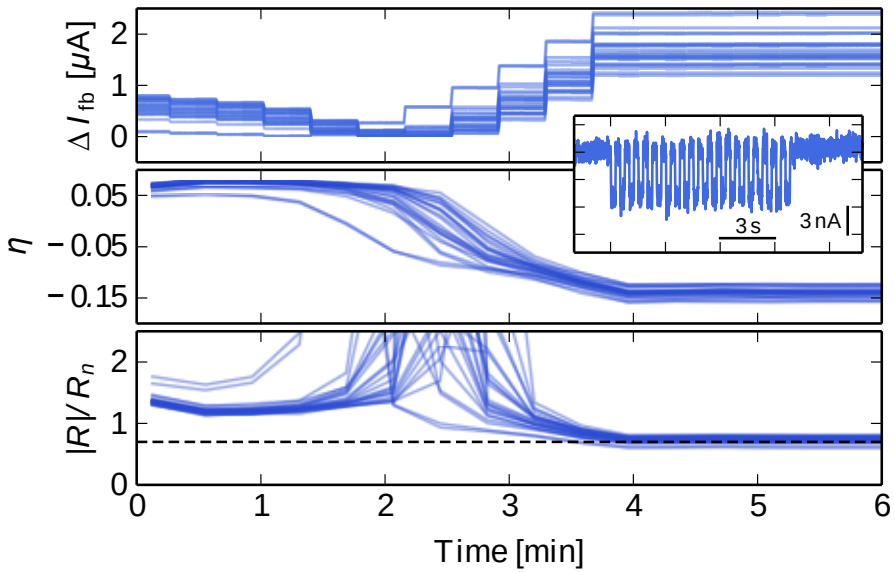




- Low noise, 1/f
- Typical scan speed 6 dps
- Science band 0.5-8 Hz

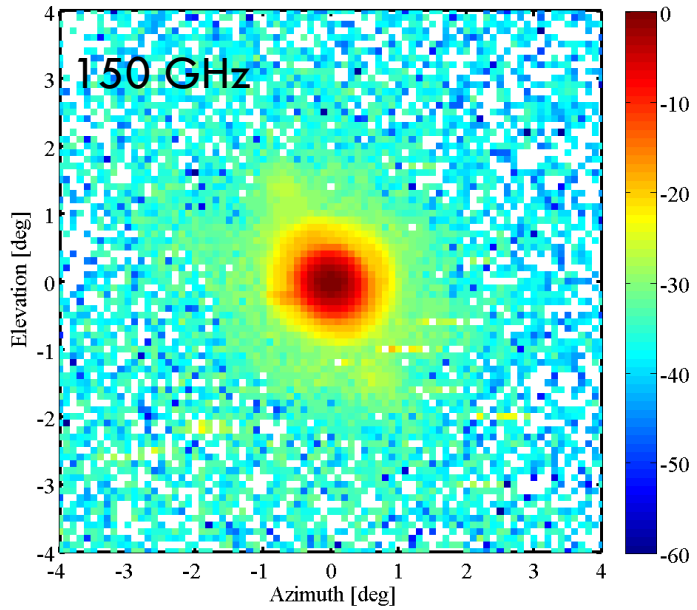
Detector Tuning and Monitoring

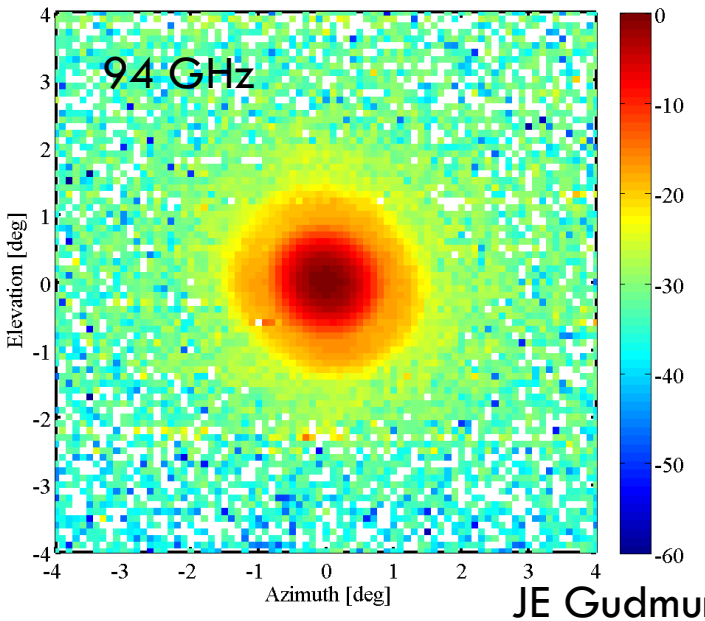
- Entirely automated
  - Send down minimal set of statistics during flight
  - Maximize observing efficiency
- SQUID Tuning
  - 5 min initial tuning, 1 min checkup
  - Detects and adjust for bias drift due to heating
- Detector stability
  - Detect and turn off poorly behaved channels
- Detector responsivity
  - Electrical bias steps as proxy for optical gains
  - Monitor and adjust bias automatically during flight



Beams

- Differential parameters consistent with expectations (~1% level)
- Ghosting and cross-talk at 1-2%, also as expected
- Plan to measure beams using Planck/WMAP data





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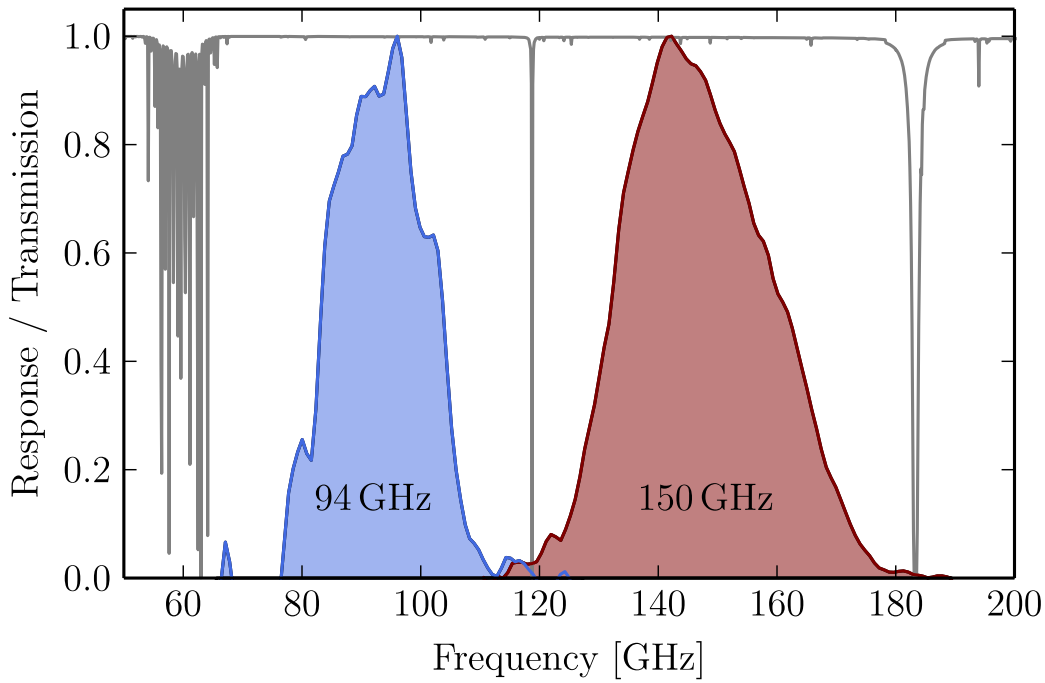
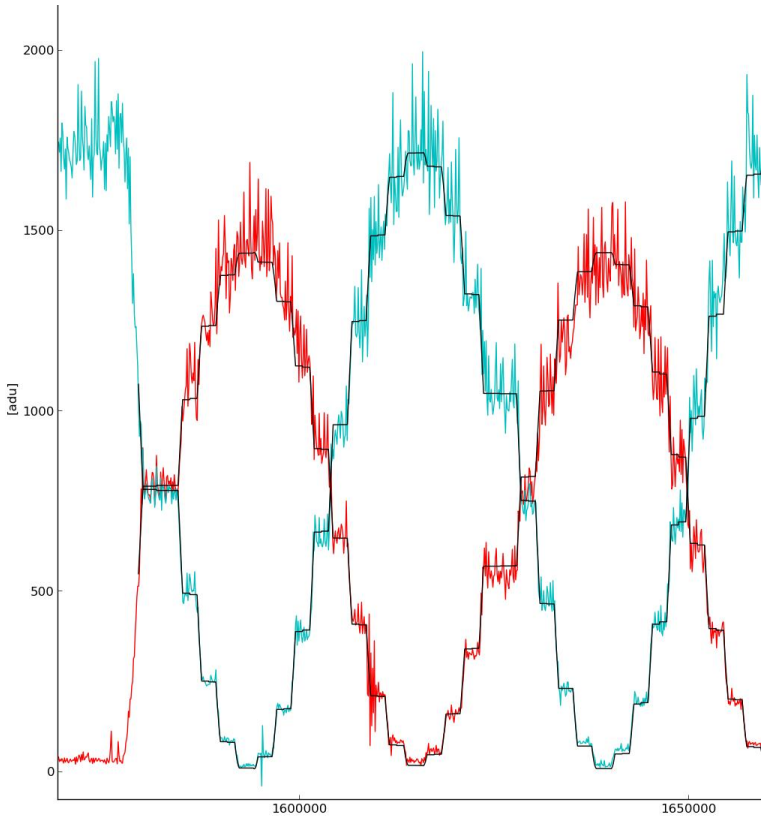
Spectral Response

- Spectral response well characterized
- 24% bandwidth
- 30-40% efficiency



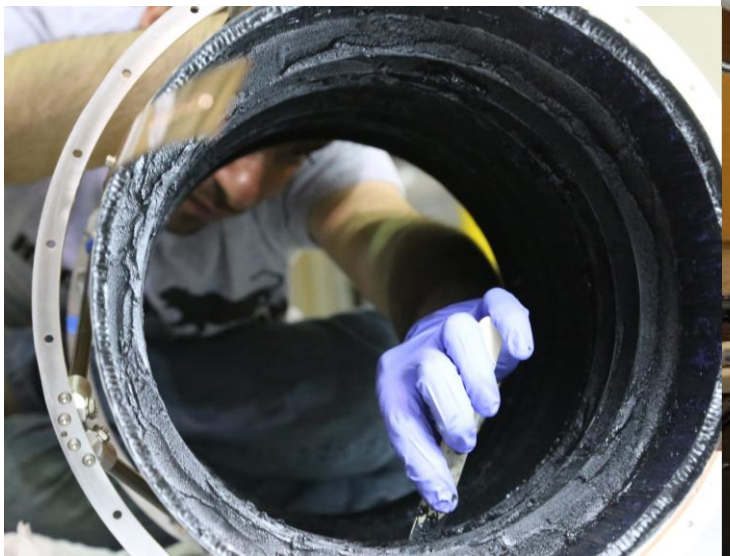
Polarization Sensitivity

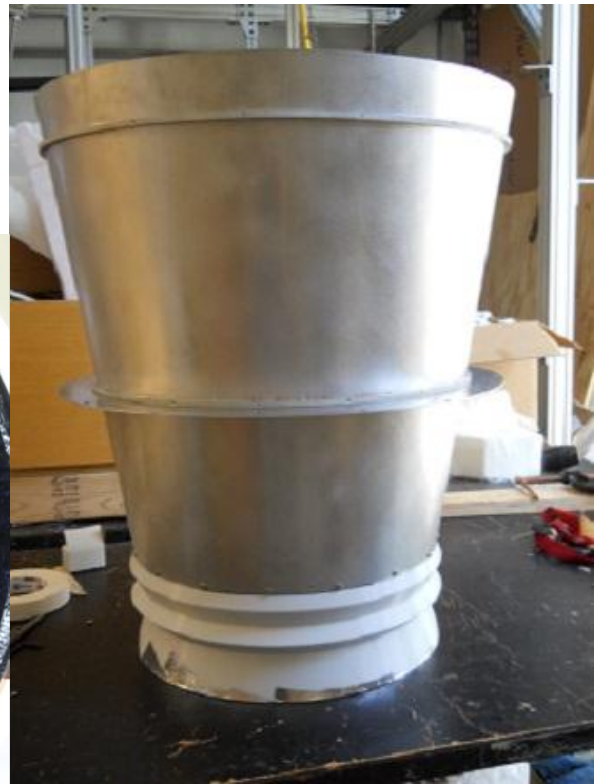
- Measured cross-polar leakage < 0.5%
- Final angle calibrations coming next month
  - Relative angles to each other and to HWP
  - Absolute angles to cryostat
  - Requirement ~1°



Sidelobes

- Excess loading observed with blackened window baffle
  - Reflective window baffles ensure wide-angle scattering does not reach the sky
  - Baffle rings along the 2K sleeve scatter away internal reflections
- Reduced loading measured in Texas





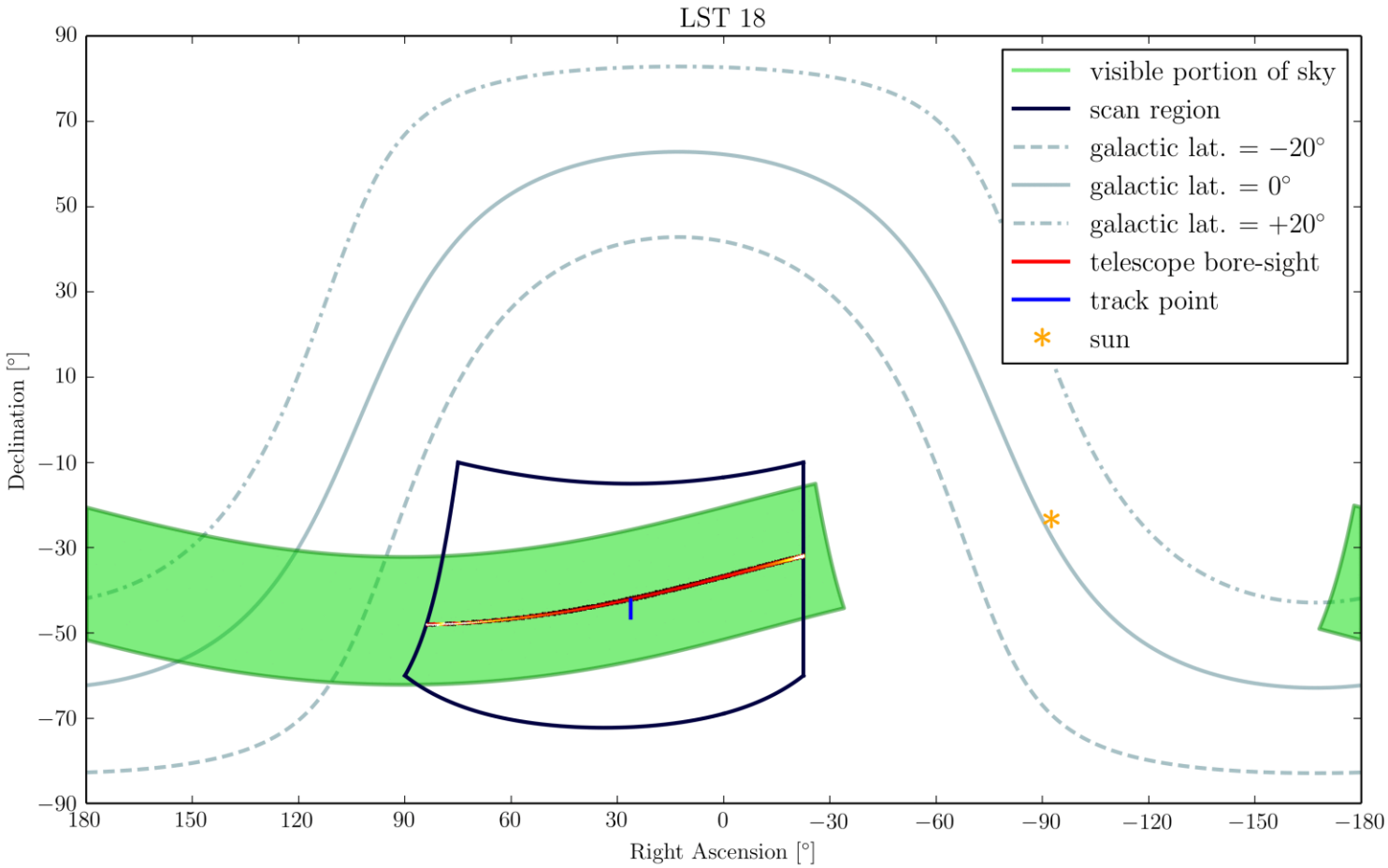
Final Integration, Redux

- Remaining optical testing next month
  - Polarization calibration
  - Archival spectra and optical efficiencies
  - Sidelobe studies
- Full system scan tests in Princeton high bay
  - Power and communications shake-down
  - Scan-synchronous noise
- Shipping again, August 2014 for December 2014 flight

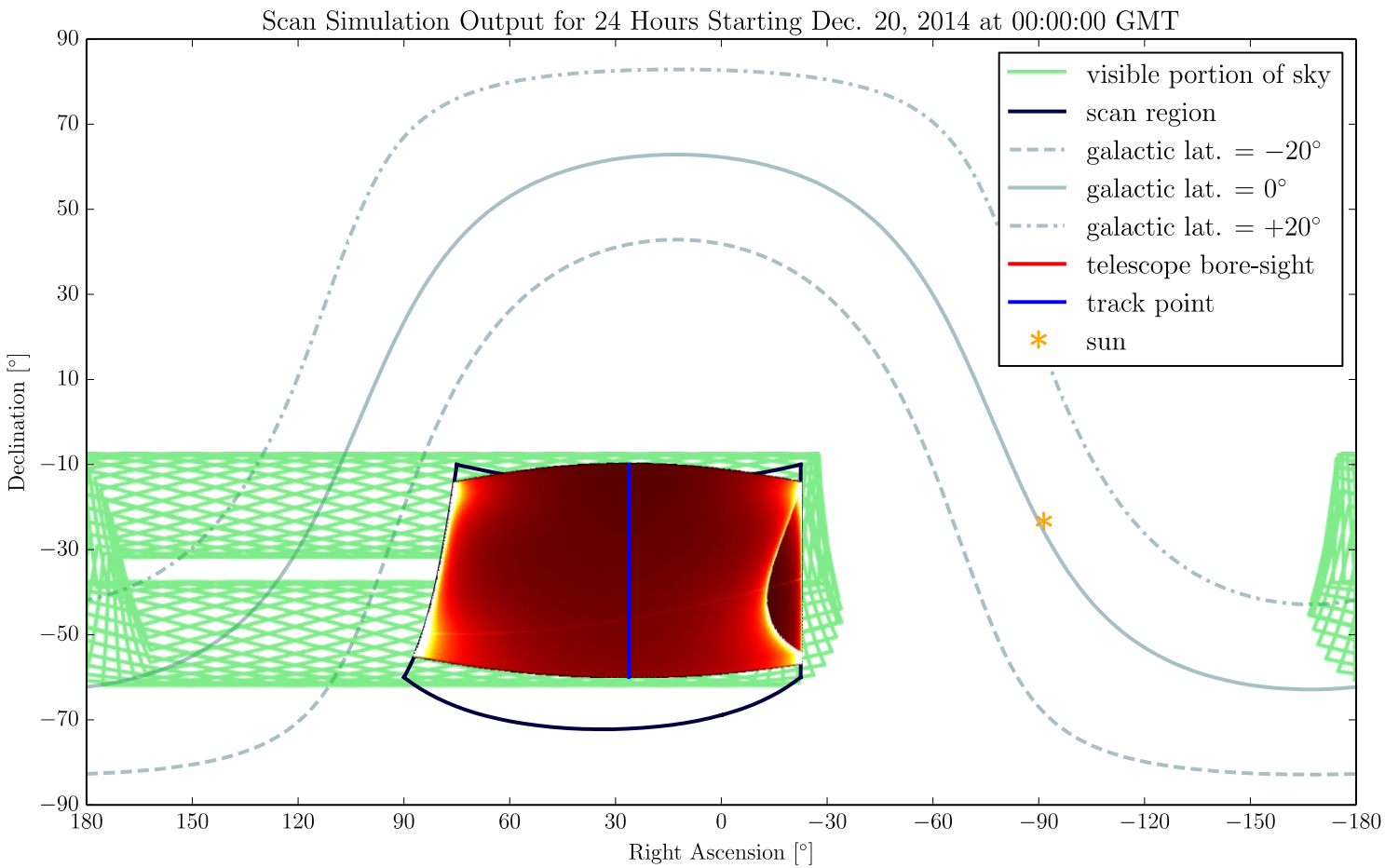
Talk Outline

- Introduction
- Instrument description
- Integration status
- **Science prospects**

Scan Strategy

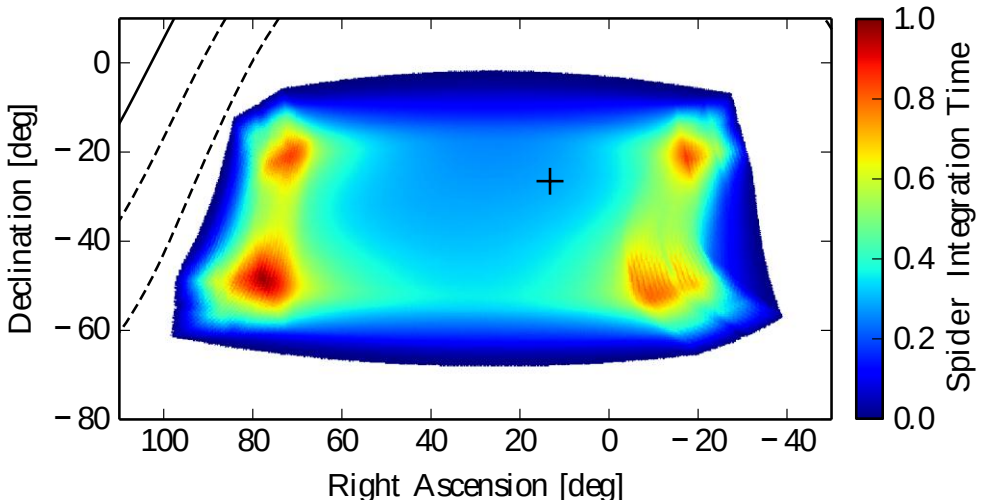


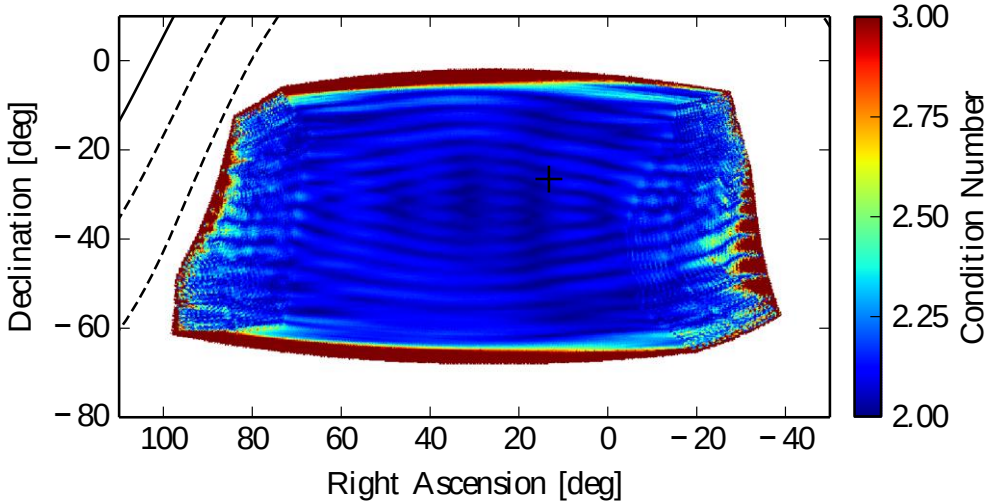
Scan Strategy



Coverage

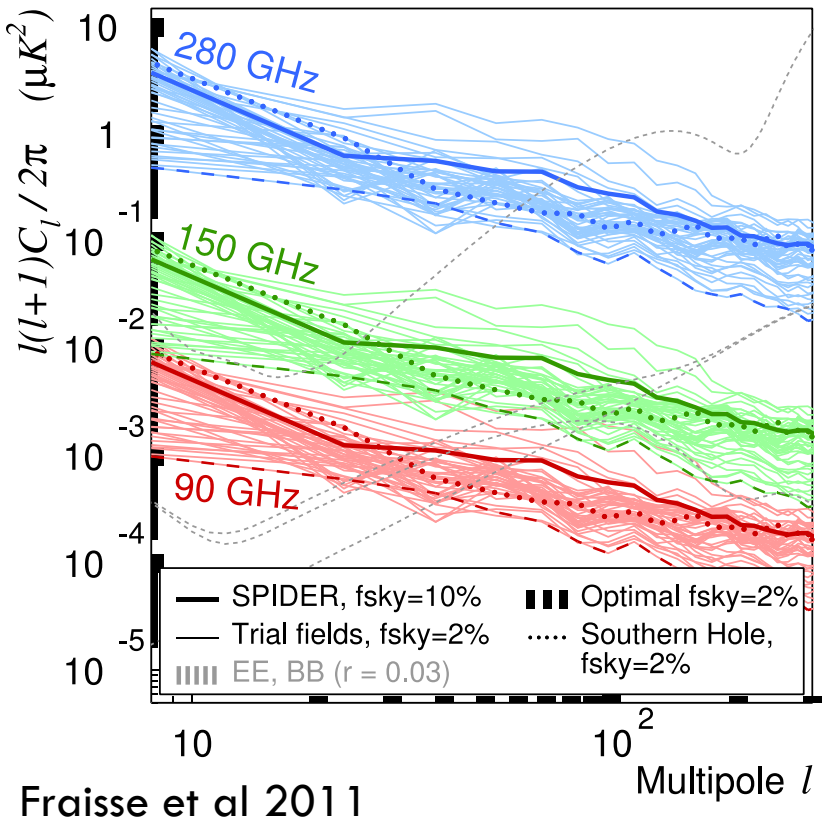
- Observe 15% of sky every day
  - Hits-weighted → 7.5%
- Step HWP by 22.5° twice daily + sky rotation
  - Reconstruct Q/U map per detector pair after one day
  - All HWP angle combinations observed after 8 days
  - Detector differencing, deprojection unnecessary



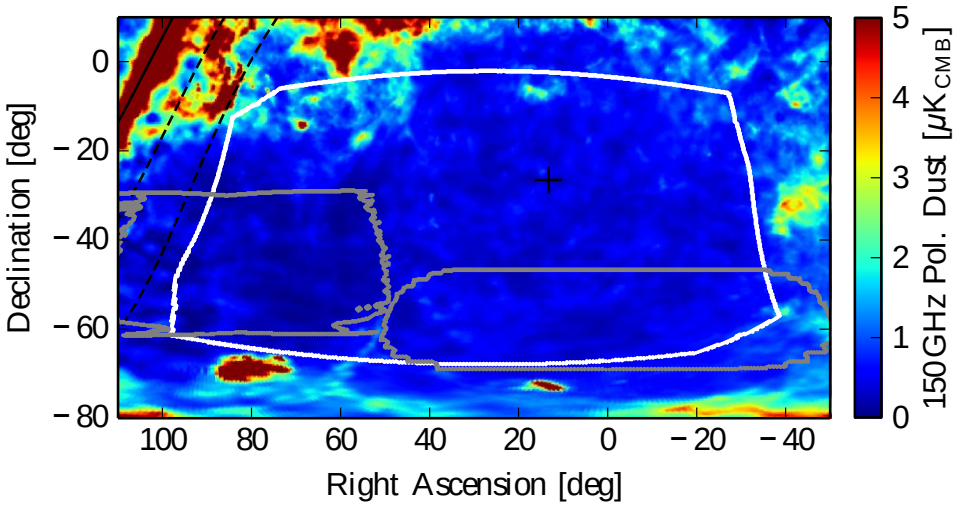


Foregrounds

- Power spectra of 2° sub-fields in SPIDER region

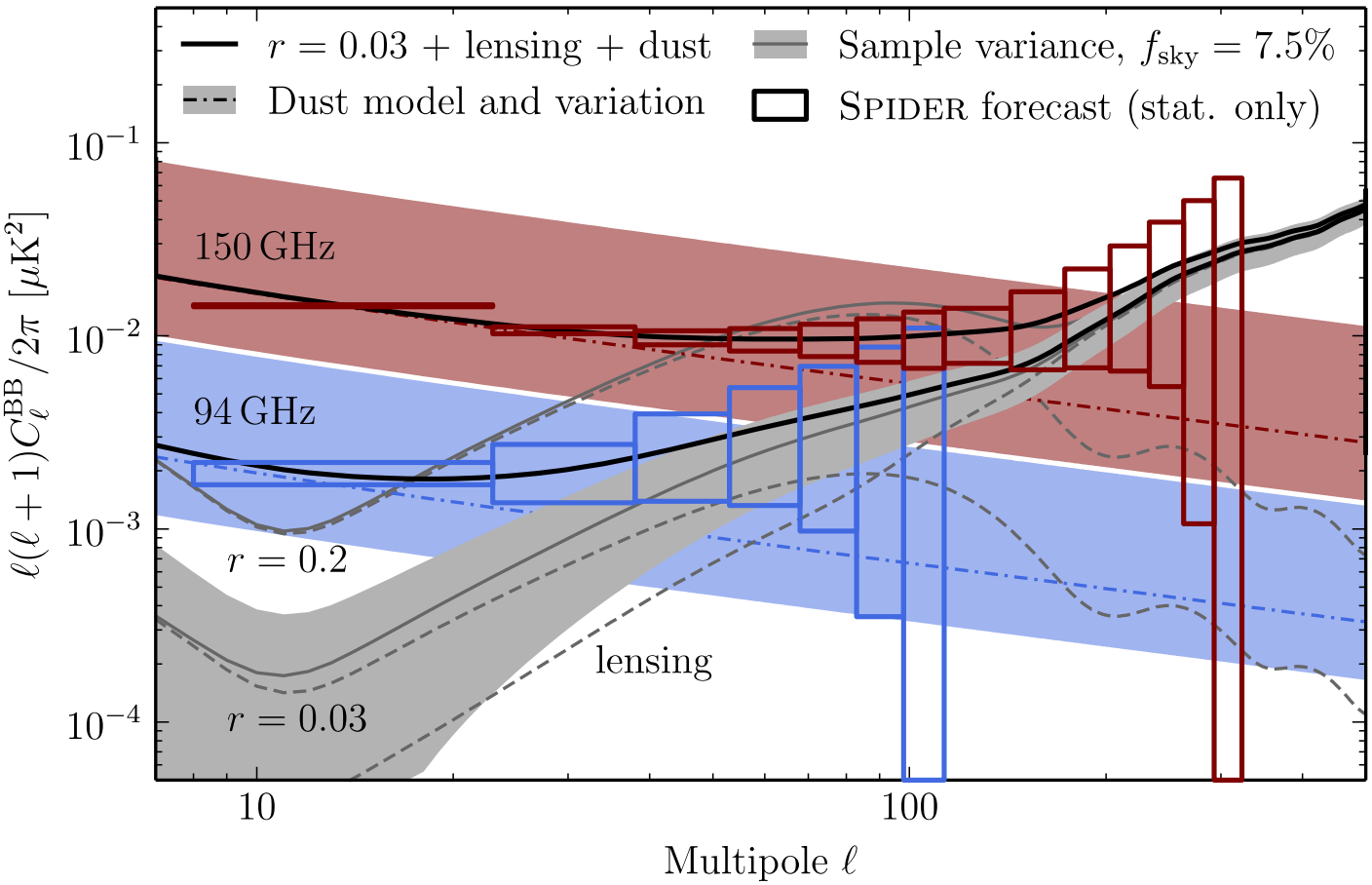


Fraisse et al 2011

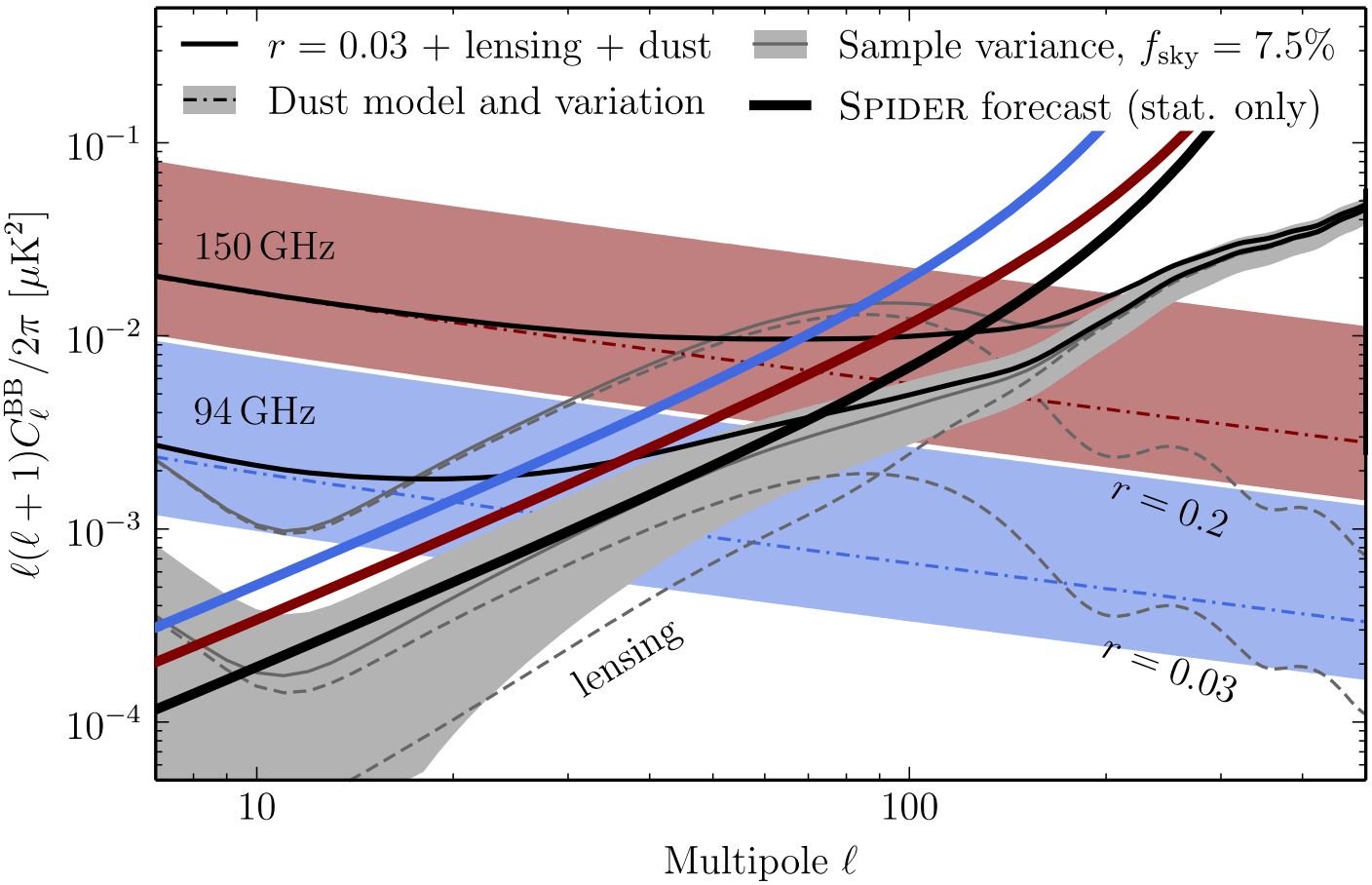


- Cleanest Southern regions will be observed by SPIDER
- "Southern Hole" is typical of other regions
- Significant dust contamination likely (Flauger et al)

Expected Sensitivity

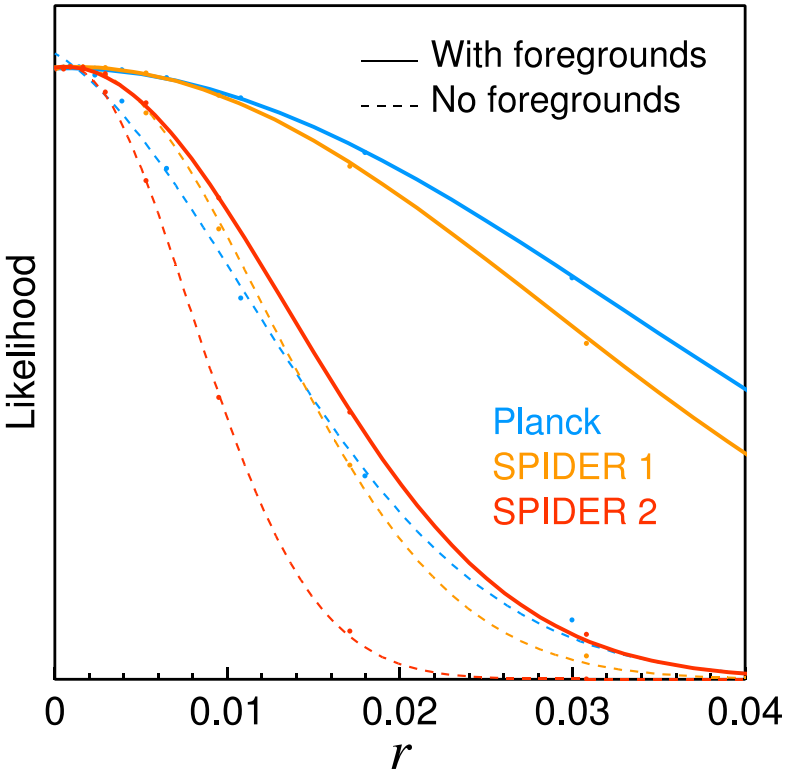


Expected Sensitivity



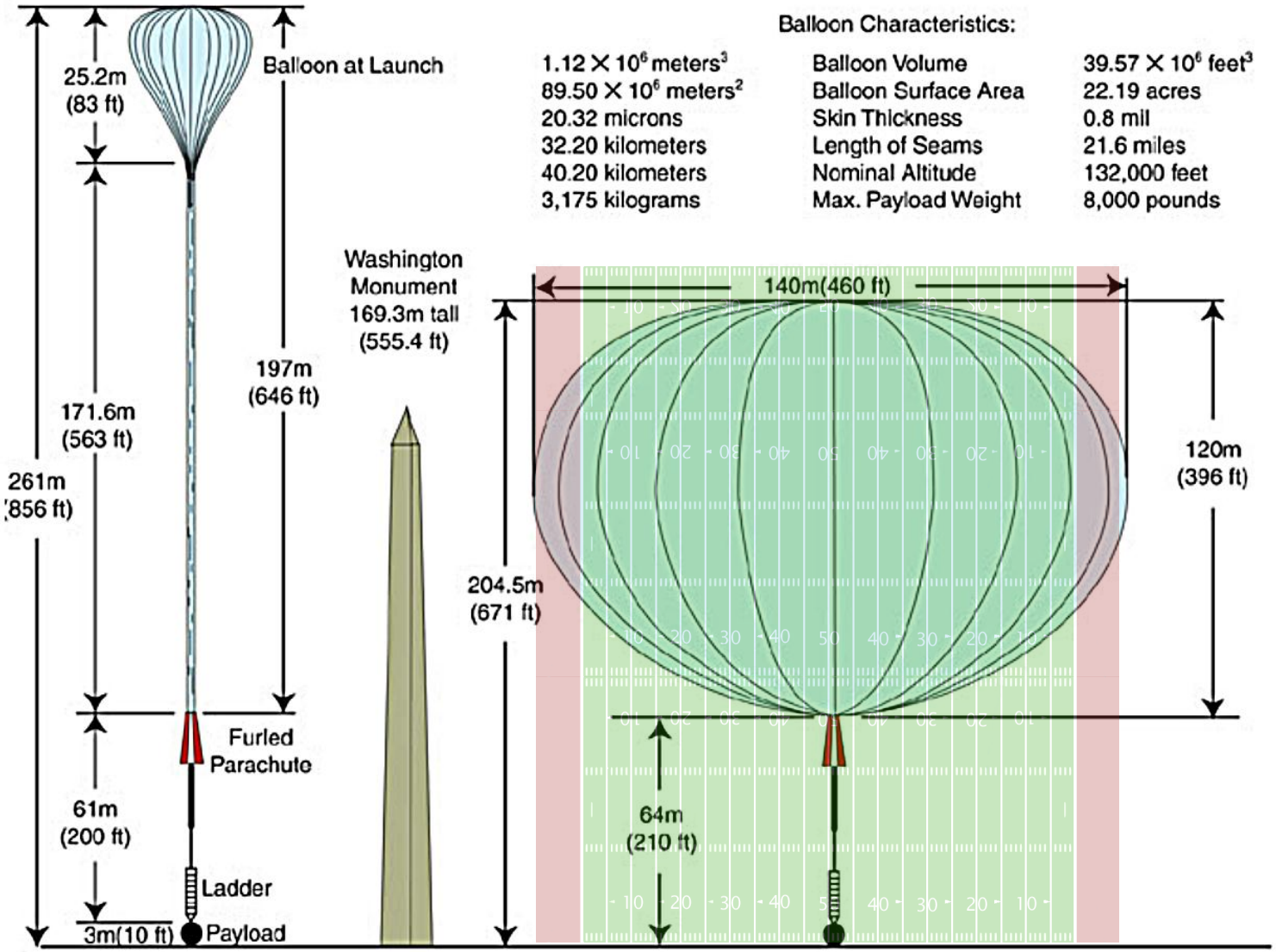
B-mode Detection Requirements

- Angular spectrum
  - Many uncorrelated bins out to large scales
- Statistical Isotropy
  - Large sky area, select sub-regions
- Frequency spectrum
  - If r is large, can distinguish r from foregrounds with one flight (two frequencies)
  - If r is small, need more frequencies for separation
    - Flight 2 will have 200+ GHz band
    - Planck release imminent



Fraisse et al 2011

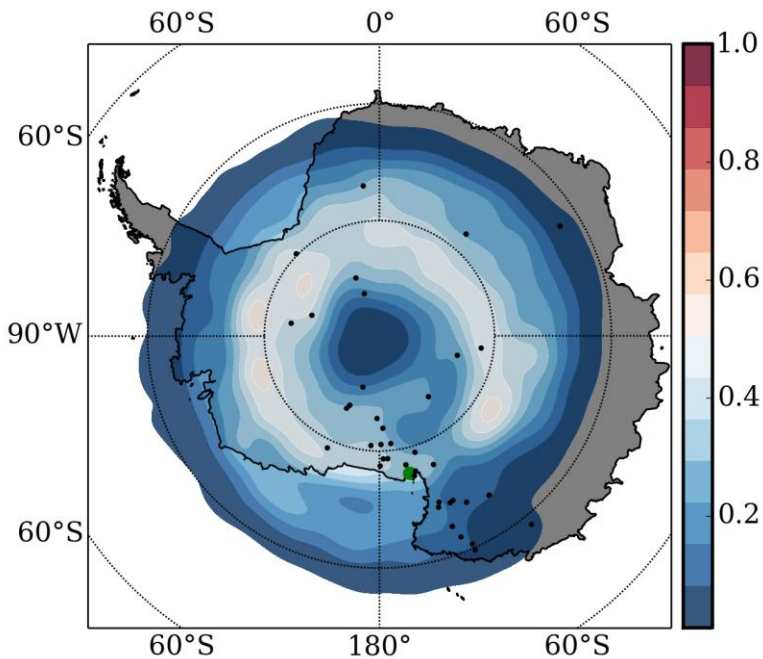
Thank you!

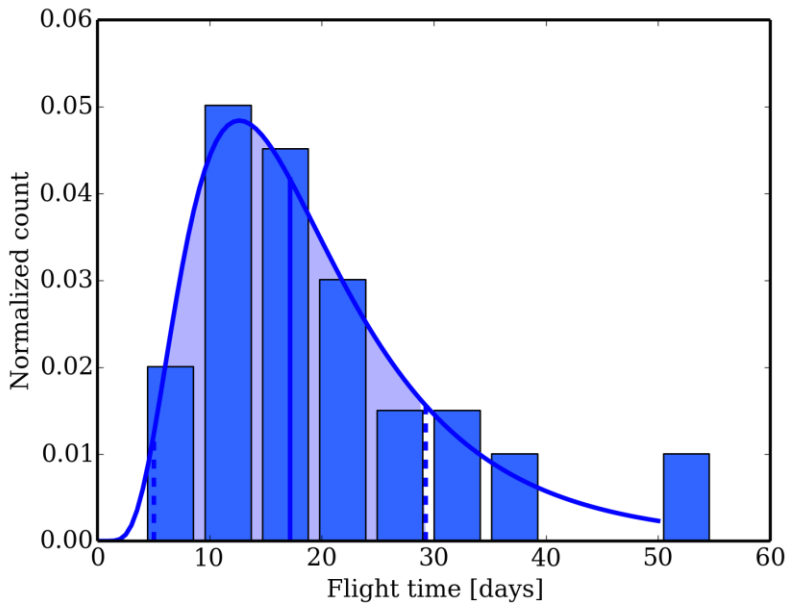

Balloon Characteristics:
1.12 X 10^6 meters^3 Balloon Volume 39.57 X 10^6 feet^3
89.50 X 10^6 meters^2 Balloon Surface Area 22.19 acres
20.32 microns Skin Thickness 0.8 mil
32.20 kilometers Length of Seams 21.6 miles
40.20 kilometers Nominal Altitude 132,000 feet
3,175 kilograms Max. Payload Weight 8,000 pounds
Balloon at Launch
25.2m (83 ft)
171.6m (563 ft)
261m (856 ft)
197m (646 ft)
Furled Parachute
61m (200 ft)
Ladder
3m(10 ft)
Payload
Washington Monument 169.3m tall (555.4 ft)
140m(460 ft)
204.5m (671 ft)
120m (396 ft)
64m (210 ft)

CSBF

Why Antarctica?

- Steady circumpolar winds
  - 2 weeks / revolution
- Continuous solar power
- Clear dry atmosphere
- Long flight times





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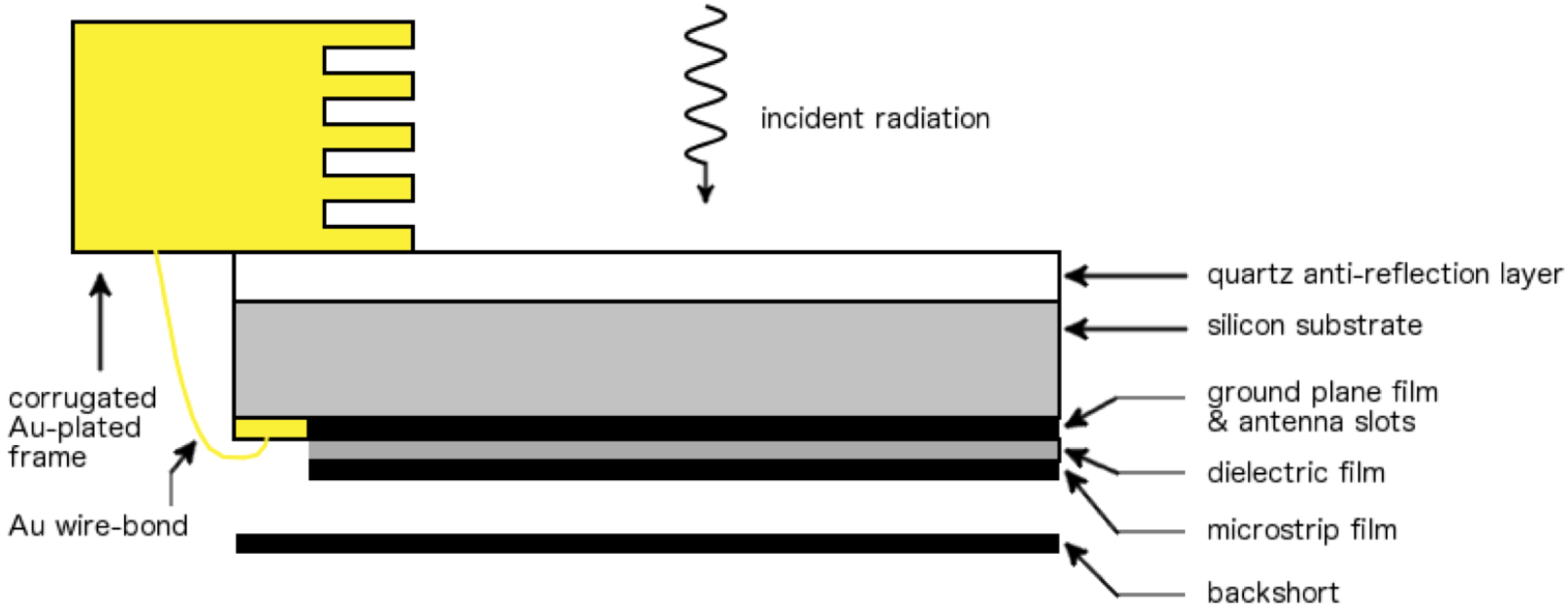
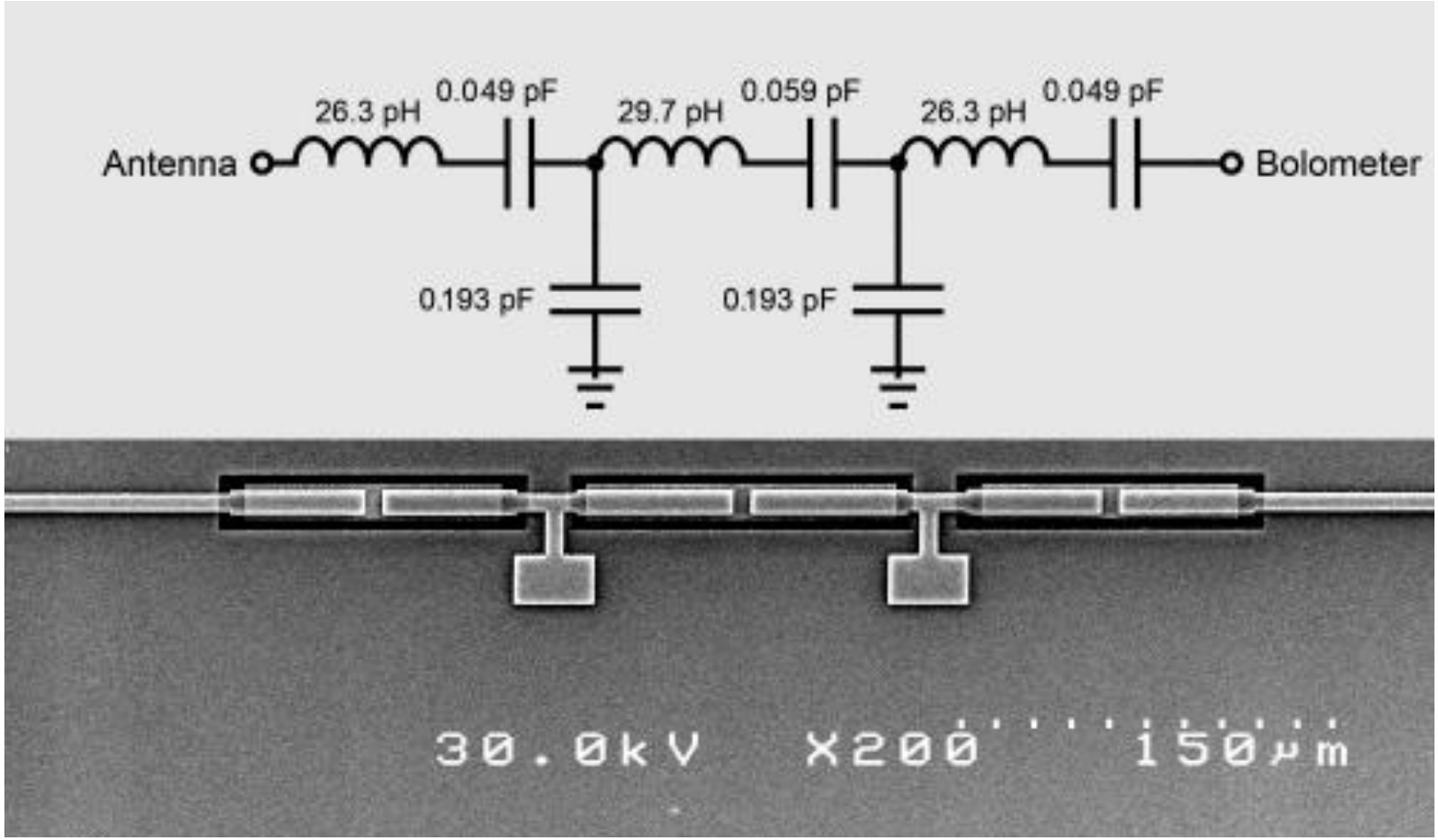
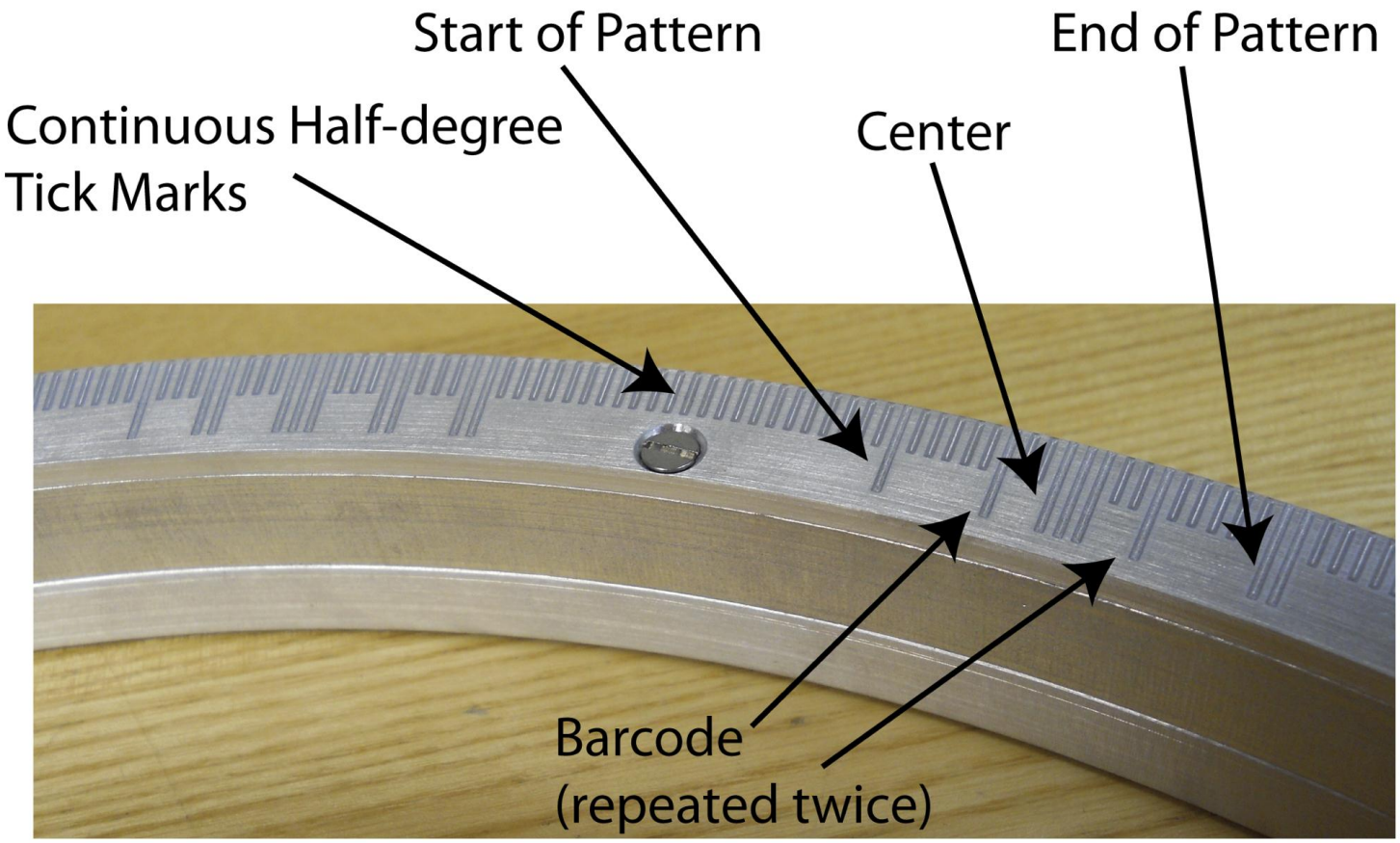
Detector Tile



Microstrip Filter



HWP Encoder Ring



SA Bryan