SAT Features, Tradeoffs, and Risks

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External Review of Analysis of Alternatives

November 4-5, 2022

CMB-S4

Outline

- Introduction
  - Particular low-ell challenges and risks
- Baseline SAT design, overview and motivation
- Risks of Alternative SAT instrument models
  - Site specific shielding (Ground, Solar (RF and heating), lunar, ...)
  - Site specific sky noise mitigation (fast scanning, half-wave plates…)
  - Impact of half-wave plates
    - Angular resolution considerations (beam size variation across band)
    - Systematic and Technical risks
  - "Aggressive" design risks (spillover, edge taper -> sidelobes and beam systematics)
  - Site specific RF shielding issues, potential impact, risks
- Design Choices And Optimizations
  - Site specific design issues (snow storm clean up, weather protection…)
  - Tube Configurations
- Summary

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Introduction: particular low-ell risks

Science Requirement driving SATs:

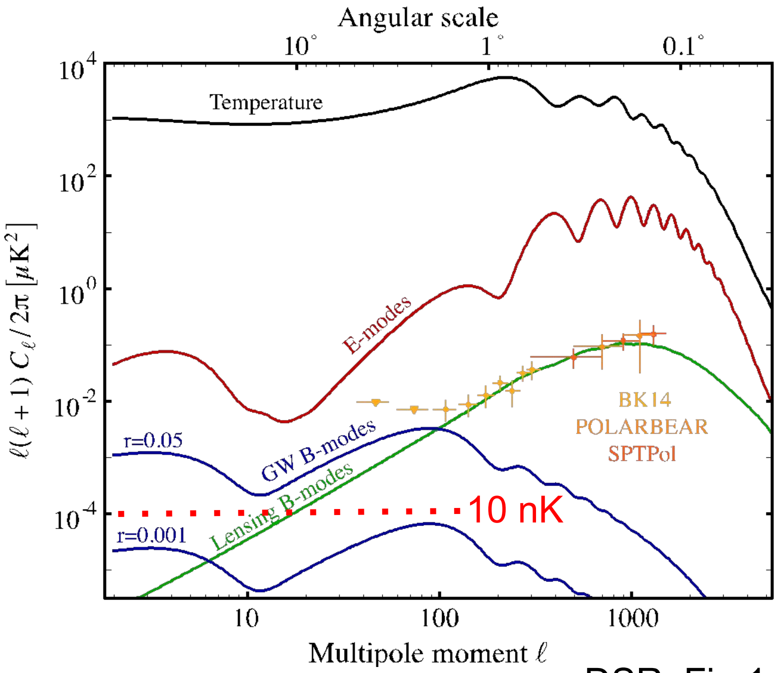
- *r* < 0.001 at 95%, or detect *r* = 0.003 at high confidence

This means < 10 nK (!) uncertainties at degree scales:

- raw sensitivity
- systematic control
- foreground separation

…all made harder at low-ell (i.e. degree scales) by 1/ell noise & red-spectrum astrophysical and environmental confusion signals

Couplings must be suppressed by up to 10^{20} in power



DSR, Fig 1

Extreme experimental challenge – paper studies alone cannot retire risks.

→ Our design approach: build on what's proven to work in deep *r* measurements for Stage 1, 2, 3…

Introduction: particular low-ell risks

Ab initio sensitivity calculations have greatly overestimated the performance of low-ell CMB experiments

- See many examples cited in CMB-S4 Forecasting paper
- more low-ell experiments never got even that far…

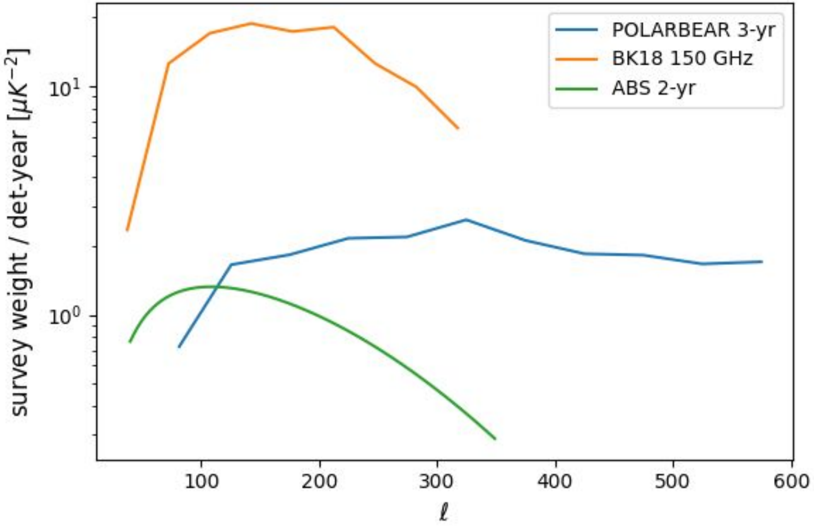
Complex environmental interactions mean large uncertainties in factors limiting achievable performance

- Strong dependence on site *and* measurement approach

(Final) Sensitivity and Systematics are **linked**

- Tradeoff is sometimes very steep to find “clean” data
- Necessary cuts, filtering, mitigations, and ultimate measurement floors can only be assessed through end-to-end analysis of deep B-mode spectra
- Final observing efficiency, sensitivity, & systematics must be assessed together, through fully analyzed, full-season deep maps

  (instantaneous sensitivity and checks not sufficient)



Survey Weight per detector-year at 150 GHz
C. Bischoff, CMB-S4 Science Council Logbook, 8 April 2022

Introduction: particular low-ell risks

In SAT design, we've found it useful to define

- Engineering risk – lab demonstration can retire to reasonable level
- Science risk – requires field demonstration and direct comparative testing in making deep B-mode maps to gain reasonable assurance we can meet measurement and science requirements.

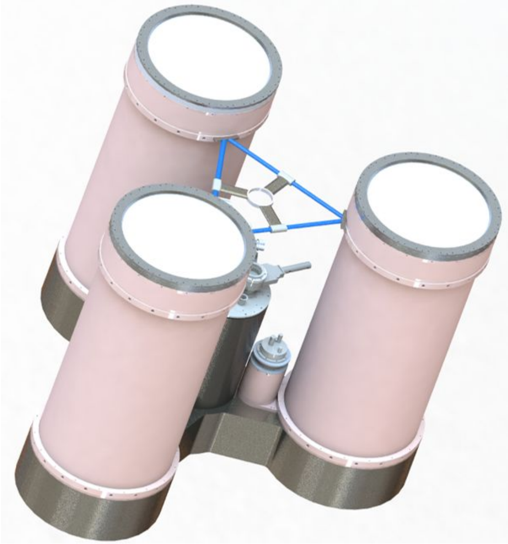
from DSR p. 115

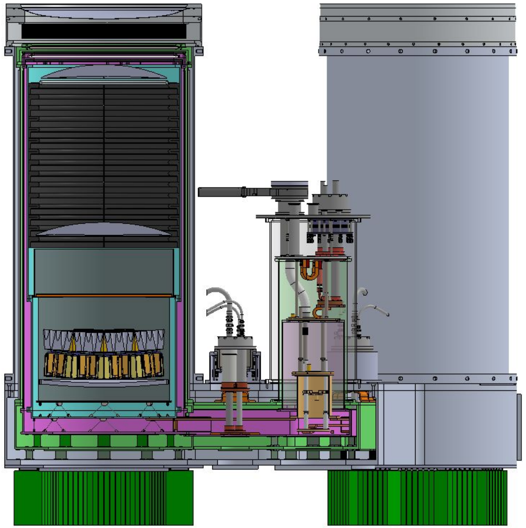
In making design choices we have distinguished between *engineering issues*, those that can be fully developed and demonstrated in the lab to retire risk, and *science issues*, those whose impact on successfully meeting the measurement and science requirements must be judged with comparison to direct experience of making deep B-mode maps. For example, cryostat design is primarily an engineering issue because we are confident our design choices can be fully validated in the lab. Examples of science issues include beam and sidelobe optical performance, polarization modulation approach, ground pickup and shielding, and other systematic effects, and for design choices that impact these issues we have endeavored to stay close to and to build upon proven experience.

Modularity of SATs makes possible direct comparative testing of new technologies in fielded prototypes (BICEP/Keck and other Stage 3 examples abound)

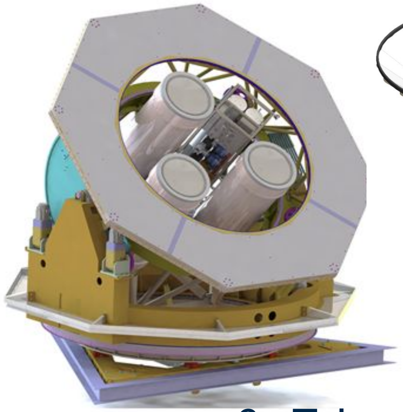
Baseline SAT design overview

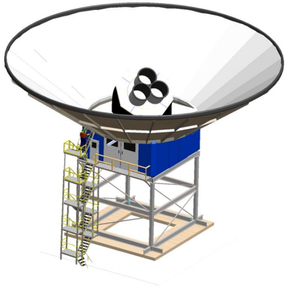
Cryostat System, Optics Tubes, Integration & Test



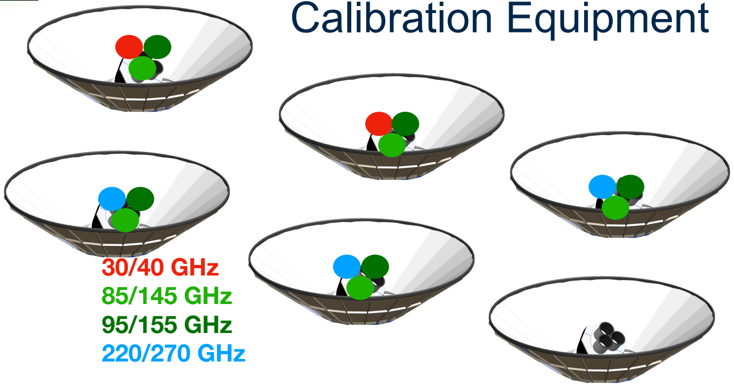


Integration and Test (including modules, readout, DAQ) before shipping to site





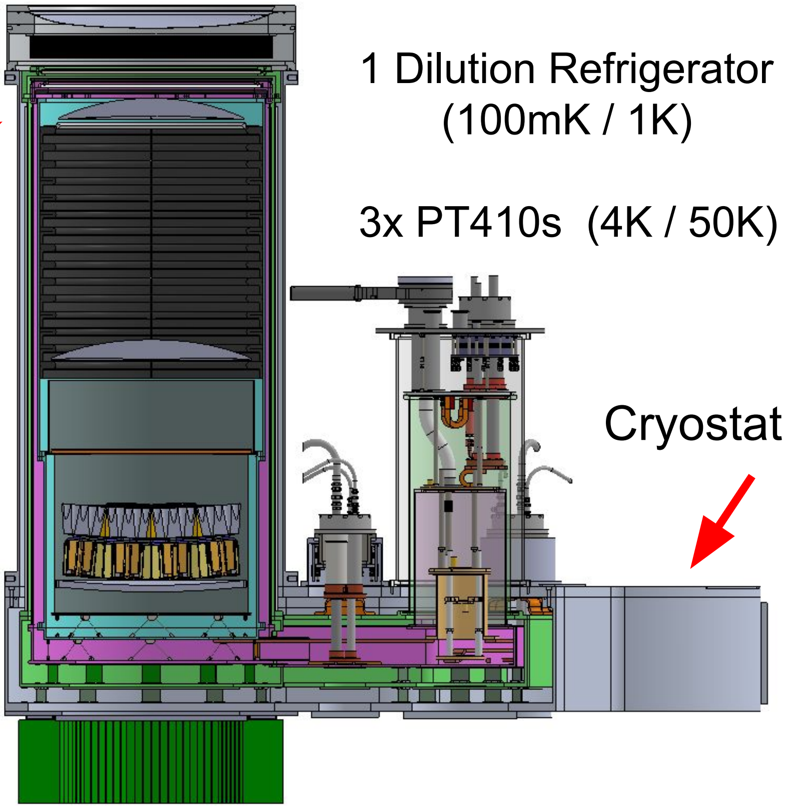
6x Telescope Mount, Ground Shield, Calibration Equipment



Baseline SAT Cryostat design

- SAT cryostat draws on design heritage from BICEP3, BICEP Array, and Simons Observatory Small Aperture Telescope Receivers
- Baseline cryostat power: 27 kW
- Risks are mainly engineering, to be retired by prototype lab test plan.

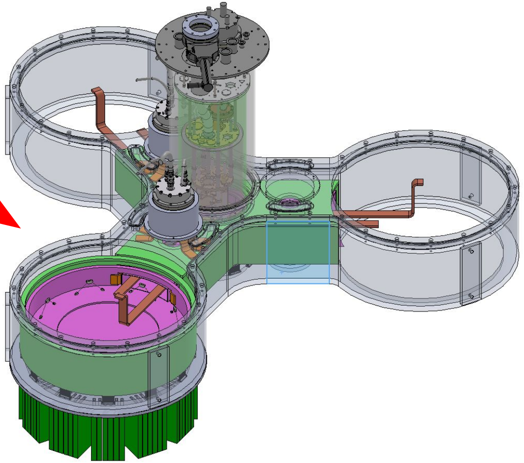
3x Receiver Tubes
(each with an optics tube and focal plane)



1 Dilution Refrigerator
(100mK / 1K)

3x PT410s (4K / 50K)

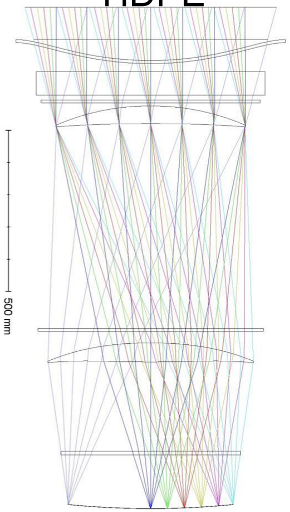
Cryostat Bus



Baseline SAT Optics Design

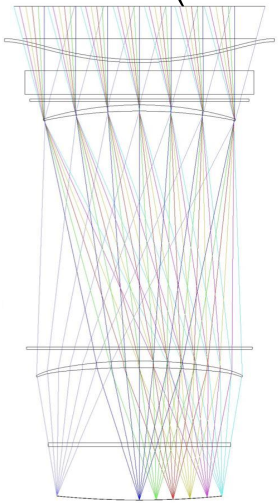
- Prioritizes control of science risks → clean, compact, extremely high throughput
  - Based on an evolution of the BICEP/Keck SAT designs
- Developments, improvements, and new risks vs. those designs:
  - **curved focal surface** (r = 2.4 m) dramatically improves performance of two-lens designs
  - **dichroic tubes** increase throughput but make systematics harder
  - **aperture coupling** specified to stay close to experience
  - **colder optics temperatures planned: 1K / 100mK**
  - **optimization of materials and AR** through comparative testing
- HDPE now baselined for all frequencies; alternatives to be evaluated

HDPE



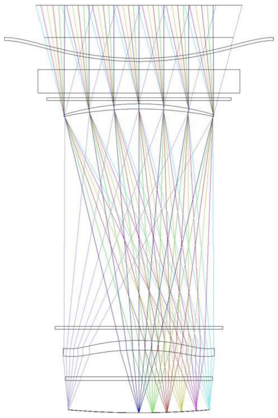
428 mm

Alumina / Si (columnar)

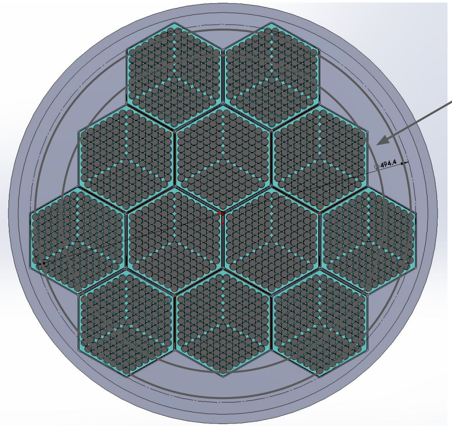


428 mm

Si (crystal)



336 mm



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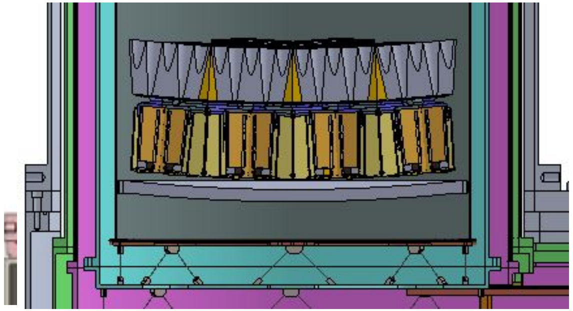


Risks of Alternative SAT Instrument Models

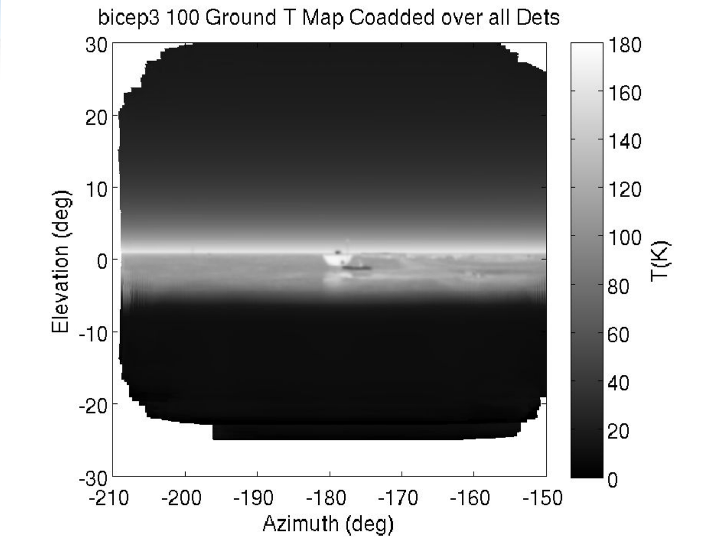
Ground Shields: Baseline

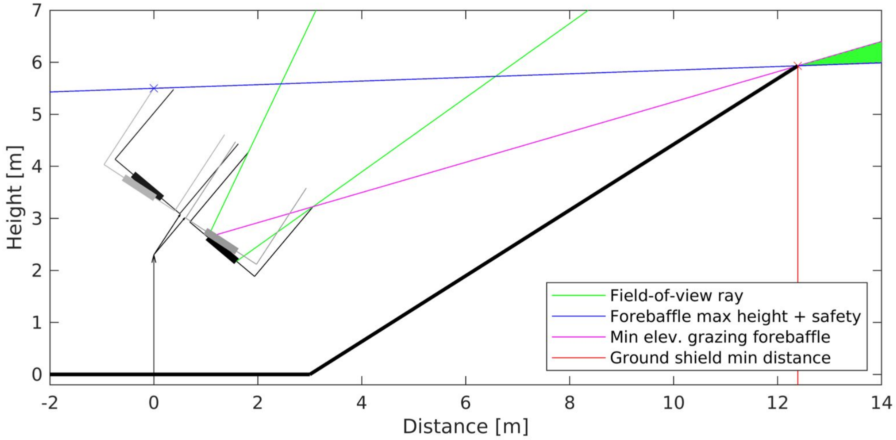
Key elements of proven approach to systematics control:

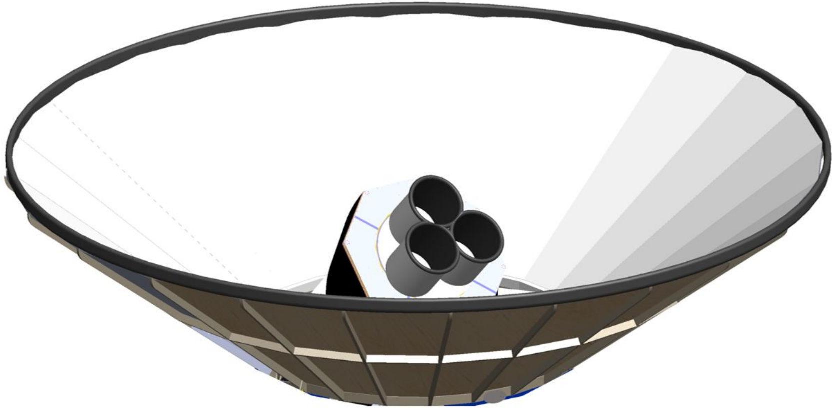
- Cylindrical warm forebaffles
- Reflective outer groundshield

Under double-diffraction criterion, at 50 degrees minimum elevation, geometry study found SAT 3-tube receiver can be shielded with:

- **Forebaffle**: 1.75 m tall, 0.8 m radius
- **Ground Shield**: 5.9 m tall, 12.4 m radius







Ground Shields: Chile risks

The closest mountain (Cerro Toco) peaks at elevation ~15 degrees, NE of site. Mountains that are further away peak at around elevation ~5 degrees. Approximately half of the azimuth range contains mountains that rise above the horizon.

→ Not possible to meet double-diffraction criterion for plausible-sized shield, so [Matsuda/Karkare Chile Alt. Shield Study]() defined a "relaxed double-diffration criterion"

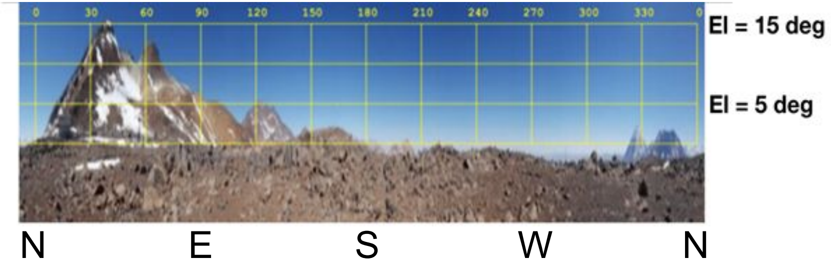
- **Forebaffle**: 1.75 m tall, 0.8 m radius (same)
- **Ground Shield**: 6.9 m tall, 15.6 m radius (~20% bigger)

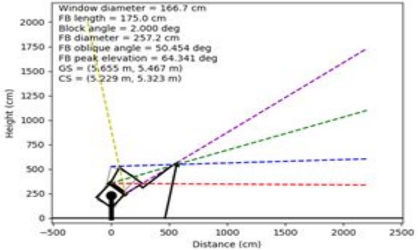
Ground/scan-synchronous signals are among the limiting factor for BICEP/Keck measurements

S4 performance needs to be better, not worse

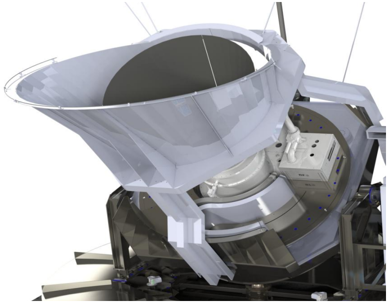
Diurnal variation and emissive terrain in Chile may be expected to drive worse ground temperature stability vs. Pole

Sun and Moon at Pole are always low; shielding is generally much better than in Chile. Science risk grows for angles < 90 deg





Example of 1 tube, 1.75 m forebaffle, 3 m tertiary

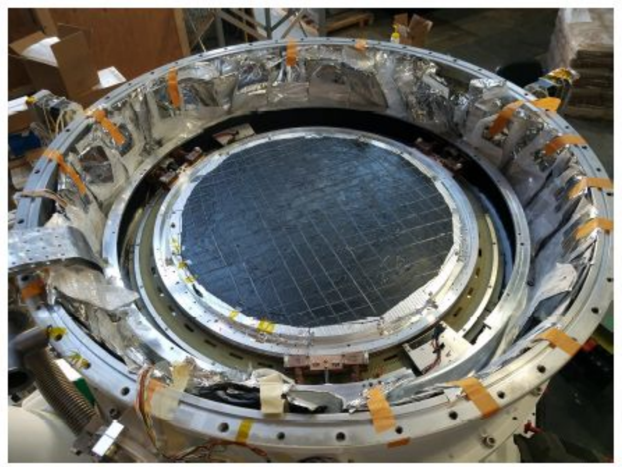


Example from Simons Observatory

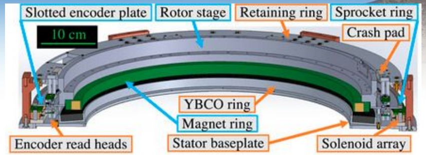
Site Specific Sky Noise mitigation

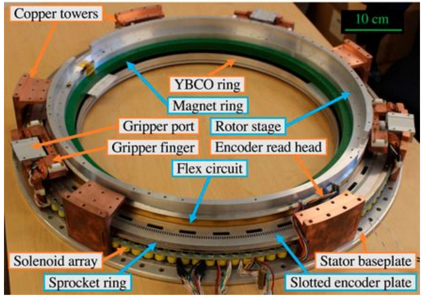
- At South Pole, atmospheric and environment stability allow simple fast-scan modulation for SATs to measure degree-scales
  - Alternative modulators have been tried at Pole in Stage 1-3 SATs, including half-wave plates, Faraday Rotators, continuous boresight rotation, but have proven unnecessary. Scan modulation is preferred as introducing less complication and fewer additional systematics
- In Chile, this stability is understood to be worse. There, low-ell B-mode measurements so far have relied on rapid polarization modulation schemes: switching radiometers, rapidly-spinning half-wave plates, or other modulators (e.g. CLASS).
  - So far, these do not give achieved performance in sensitivity that would allow CMB-S4 forecasts to scale from them.
- Polarized atmospheric noise is detected at both sights but relative levels are poorly understood. Polarization modulation does not mitigate this.
  - This is a particular unknown risk for Chile, given lack of achieved

Impact of Half-wave plates:
implementation



SO HWP rotation mechanism.





SA HWP rotation mechanism.

HWP rotating mechanism: high-Tc superconducting mag-lev bearing (no limit on aperture size).

Optical stack: three-layer sapphire stack, plus anti-reflection (AR) coating layers.

Sapphire diameter limited to 505 mm for current technology, which set HWP throughput limits

Metamaterial (conductive and/or dielectric) may allow expanded diameter, but *major* R&D expansion of scope would be needed to develop (and field-test?) this to similar maturity.

AR coating : conservative approach is to glue AR-coated Alumina on.

(Some of the Alumina-candidate technologies can direct AR coat onto Sapphire)

Impact of Half-wave plates:
systematics mitigation

- Atmospheric Fluctuations
  - Mitigated: (unpolarized) additive fluctuations.
  - Not mitigated: polarized or multiplicative fluctuations. (incl. non-linearity driven by atmospheric fluctuations. This exists in pair-diff as well.)
  - (https://doi.org/10.1063/1.4862058, https://doi.org/10.1117/12.2232280)
- Polarized Beam Systematics
  - Mitigated: diff. response of detectors and elements between HWP and detectors.
  - Not mitigated: 50 K filter and window (but a large scale common mode)
  - (https://doi.org/10.1063/1.4962023, https://doi.org/10.48550/arXiv.1808.07442)
- Polarized Sidelobe Systematics
  - Mitigated: pol. sidelobe due to aperture stop diffraction, pol. sidelobe due to differential illumination on warm baffle/shield.
  - Not mitigated: sidelobe polarization due to baffle/shield diffraction and scattering.
- Crosstalk-induced pol. leakage
  - Mitigated: Crosstalk between “X” and “Y” detectors becomes P → P leakage.

Impact of Half-wave plates:
additional systematics issues / risks

- HWP-specific systematics introduce new risks to evaluate:
    - Frequency dependence of beam mismatch, polarization angle, and polarization efficiency
        - additional complication and risk in calibration, systematics mitigation, and galactic foreground separation approaches
    - HWP non-uniformities → false 4f (polarization) signals, correlated 1/ell

- At BICEP/Keck levels of sensitivity, effects like ground pickup from sidelobes (polarized by diffraction/scattering) and polarized atmosphere have an impact on achieved performance
    - These are not easier in Chile, and the HWP does not mitigate them.

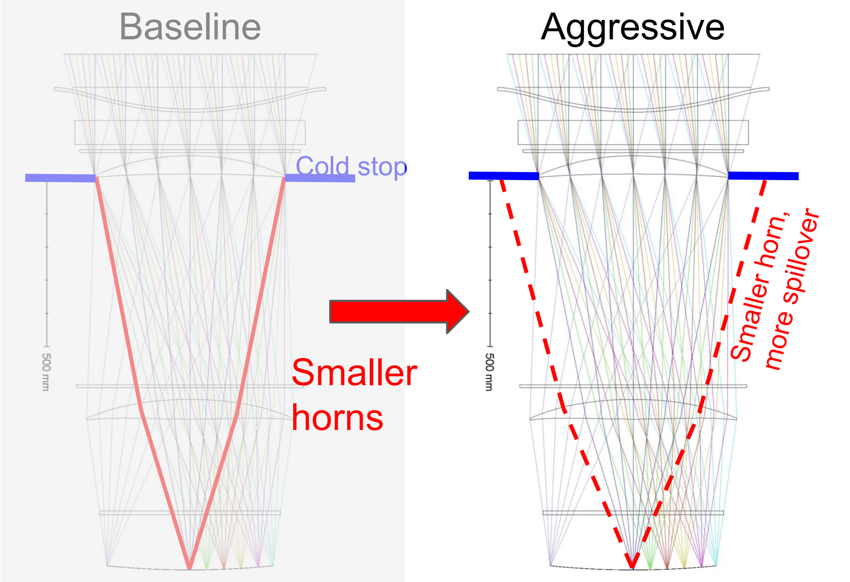
- Engineering risks of sapphire HWP implementation appear manageable, but substantial science risks of relying on a different measurement approach require field validation
    - Need comparative full-season, full efficiency, deep, cleaned maps and BB spectra

“Aggressive” optics design risks

(slide from John Ruhl’s talk)

"Aggressive" here => higher edge illumination and spillover at the cold stop, so increased beam systematic and sidelobe risks.   (Spillover ~ matched to SO)

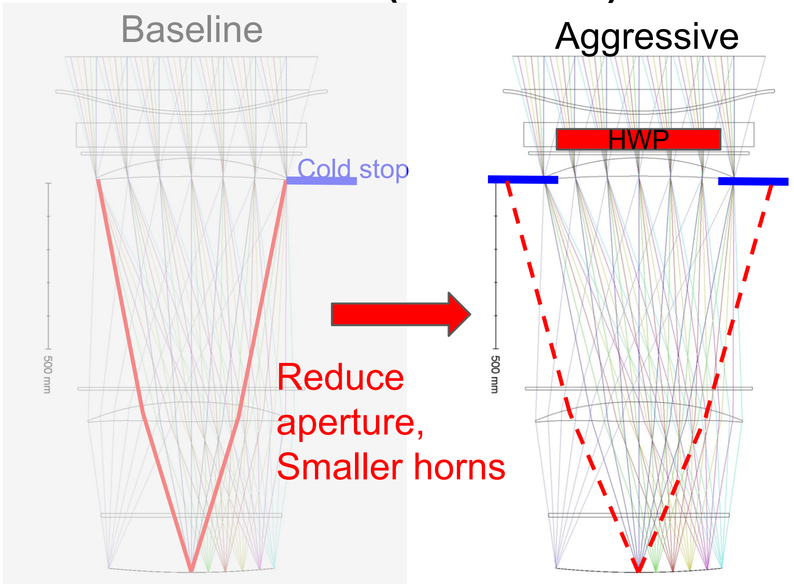
South Pole (no HWP)



Baseline Optics

Baseline Optics
with **more (smaller) horns**,
to match SO spillover

Chile (with HWP)



Baseline Optics

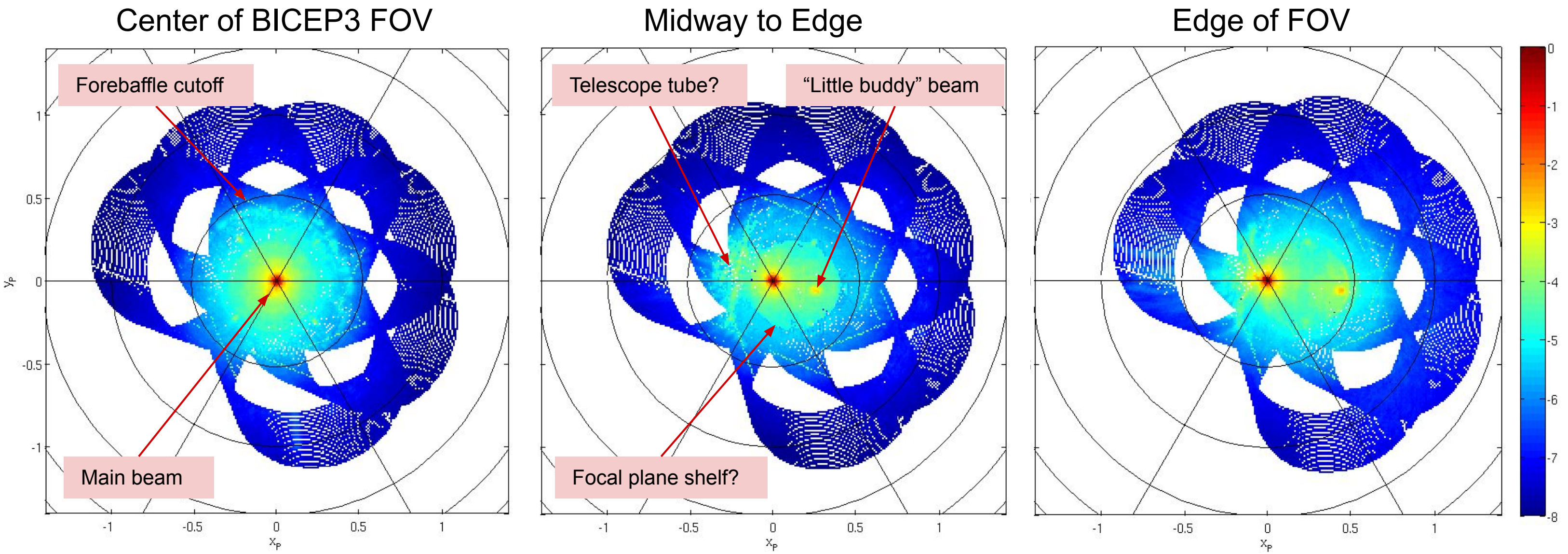
Smaller aperture,
(higher f/#)
with **more (smaller) horns**,
to match SO spillover

slide from “SAT Lessons Learned on Optics… (Bock/SATs 2019, CMBS4-Doc-850)

Sidelobes in Refracting Optics: Reflections and Edge Taper

We have been conservative on edge taper to control extended beams

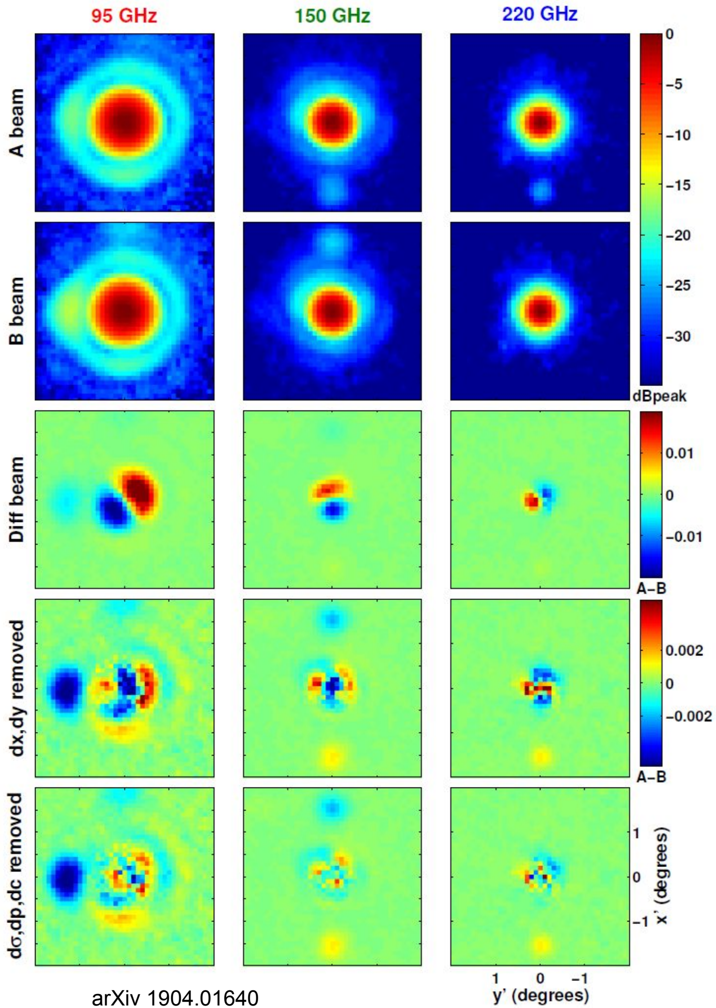
	units	BICEP1	B2-150	Keck-95	Keck-220	Keck-270	BICEP3	BA-30	BA-40	BA-95	BA-150	BA-220	BA-270
Edge taper at aperture (band&az-avg; center pix)	dB	-20	-12.8	-7.8	-12.3	-14.1	-11.4	-10.1	-12.7	-11.4	-11.1	-12.3	-15.4
fractional spill-over	%		13.3	19.2	13.2	12.5	16.2	18.6	16.2	16.4	16.3	15.4	14.2



Likely causes of degree-scale sidelobe patterns: reflections, scattering, and spillover

"Aggressive" optics design risks

- Understanding and controlling degree-scale beam mismatch are a major, ongoing focus of systematics control in real BK data
  - Primary focus of 5 PhD theses so far (Sheehy 2013, Wong 2014, Kernasovskiy 2014, Karkare 2017, St. Germaine 2021), covered in ~10 others, evolution described in BK-I, III, IV, V, X, XI, XIII, XV …
  - Result from 2021 BK-XV "r result" paper:
    - Residual bias on r of 0.0015 +/- 0.0011
    - Paths to demonstrating improvement on real data are being worked on. Hard.
- CMB-S4 needs to do better
- Aggressive illumination could make this worse
- Aggressive illumination, like HWPs, can be expected to increase frequency dependence, a serious complication



arXiv 1904.01640

Site Specific RFI impacts and risks

- CMB-S4 convenes an RFI working group to study the RFI environment relevant to CMB-S4 now, and that expected over the life of the project, for South Pole and Chilean sites.
  - considers ground-based and satellite transmitters, and regulatory constraints, assesses potential impacts on CMB-S4 observations
  - Read more at this confluence page and in these presentations.
- **Quick summary**: Both Chile and South Pole sites have regulatory protections against local transmitters, and regimes in place to allow enforcement, but monitoring/identification of problems is typically led by CMB projects
- While low-ell and high-ell experiments may have different requirements on allowable RFI, the sites themselves probably present comparable local RFI risk and management challenges.
- RFI from satellites is more complicated. Unclear what control we will have, but perhaps more hope at South Pole.

SAT Design Choices and Optimizations

Site Specific Design Issues

- Mentioned were: snow storm clean up, weather protection…
- I don’t have much to say on how these impact AoA

  …perhaps these are engineering issues?

(1a) Reducing SAT cooling power consumption

From SAT Cryostat Loading Review (6 June 2022), DocDB-847, by Paul Williams and Joe Saba

Old estimates

99 W on 50 K stage

50 K	Tube (W)	Cryostat (W)
Readout	6.1	18.3
Support	5.1	15.4
Radiative	5.9	17.8
Optical	12.5	37.5
Tube SubTotal(s)	30	89
Support - Cryobus		5.0
Radiative - Cryobus		5.3
Cryobus SubTotal		10
Total		99

New Estimates

70 W on 50 K stage

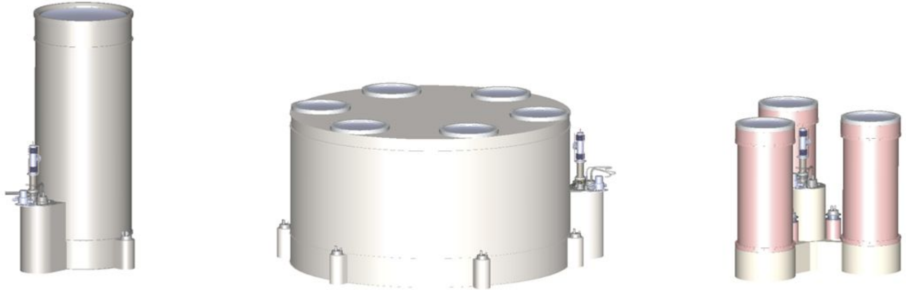
50 K	Tube (W)	Cryostat (W)
Readout	4.6	13.7
Support	2.3	6.8
Radiative	4.5	13.4
Optical	10.7	32.1
Tube SubTotal(s)	22	66
Support - Cryobus		2.3
Radiative - Cryobus		1.5
Cryobus SubTotal		4
Total		70

NB: These numbers come with caveats and risks, see their slides

Reducing SAT cooling power consumption

- SAT Cryostat Loading Review (6 June 2022), DocDB-847, by Paul Williams and Joe Saba
- New baseline of 2+1 PT410s have a cooling power of 2 x 40 W = 80 W at 40 K
  - Substantial risks in aggressive baseline thermal model
    - Impacts: schedule (more time prototyping), performance (less sensitive detectors), cost (more prototyping)
    - Mitigations include: prototyping, design optimization
- Doing *better* than the new baseline looks hard
  - Prior estimate of 25.1 → 18 kW PT cooling per SAT w/ VFDs seems optimistic
  - Prototyping is essential to retire baseline risk and tell if margin can be found
    - Would require improvement over state-of-art
    - Possibly up to 5 kW per SAT might be saved

Alternative SAT cryostat configurations:



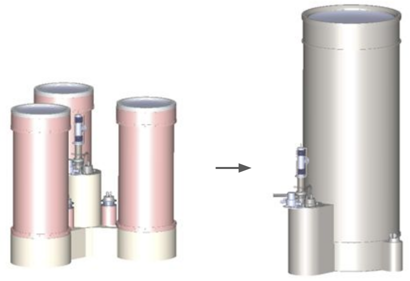
“BIG SAT” **6-Tube SAT** **Baseline SAT**

- Baseline SAT configuration resulted from work of Cryostat Configuration Task Force (2019-2020)
  - Report captured in DocDB-737
  - Wide variety of single-tube and multi-tube configurations considered,
  - Factors evaluated then included: cooling capacities, costs, power consumption, design, integration and operation risks, cryogenic and mechanical performance, optical shielding

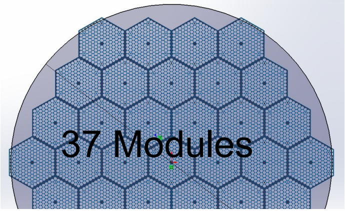
- For AoA, we revisited specific alternatives now with new focus on power consumption,
  - optics developments open new possibilities
  - Assume we will keep shielding and systematics risks at same levels

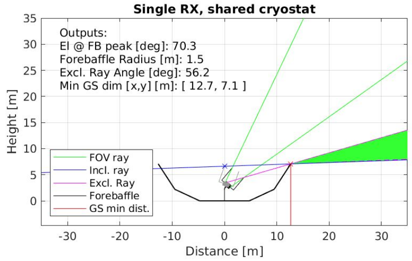
Alt-SAT cryostat configs explored: “Big SAT”

- Recent optics developments (thin plastic windows, curved FP) make larger diameter SATs seem more feasible:
  - Baseline SAT: 56cm aperture, 72cm window
- Tony Stark’s memo14 shows an example of a “Big SAT” that gives excellent optical performance through 300 GHz
  - ~scaled by x1.8, 100.8cm aperture, 129.6cm window
  - Joe’s analysis shows 37 modules in single FP (vs 36), with cooling power requirement nearly identical–no power savings
- Kirit’s shielding analysis shows shielding works
  - Requires larger forebaffle (1.75m → 3.15m)
- Sensitivity per detector will be roughly the same (slight gain from smaller beams, slight loss from thicker lenses)
- Drawbacks and Risks:
  - R&D required for optical elements this large
    - Risk in lenses, filters, vacuum windows
  - Breaks HWP compatibility
  - Single frequency-type per SAT mount



Baseline SAT **“BIG SAT”**





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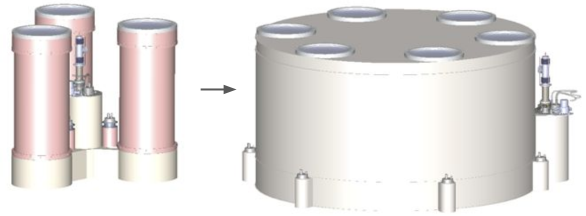
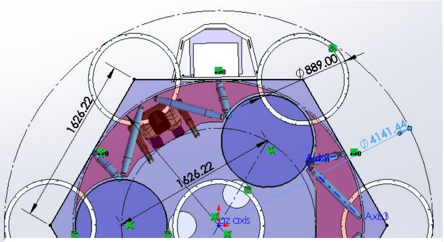
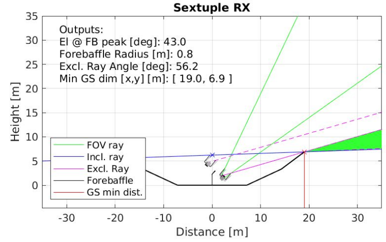
Alt-SAT cryostat configs explored: 6-tube SAT

- Electrical power priority → more tubes per SAT cryostat?
- Shielding requirement
  - Shared baffle gets impossibly large, c.f. original study
  - Individual baffles dictates maintaining baseline spacing
  - Kirit's analysis shows shielding grows as expected
    - outer groundshield 38m dia (vs 24m baseline)
- Joe's analysis shows cooling power requirement is again similar
  - Only potential benefit is from sharing DR for 6 tubes
  - Saves at most 5 kW per original 3-tube unit, but allows only 7mW cooling per 1K optics tube (serious risk!)
- Drawbacks and risks
  - Breaks assumption of re-use of BART tower and 2 existing BA mounts
  - Requires much larger mounts, towers, and I&C facilities
  - Atmospheric correlations will increase (fewer lines of sight)



Baseline SAT **6-tube SAT**





Summary
SAT Alternatives: Risks and Opportunities

- Baseline Design prieoritizes control of science performance risk + readiness
  - New features (curved focal plane, dichroic optics, 100mK, etc) offer reasonable path to risk retirement
- Alternatives will carry additional science risk (field demo) or engineering risk (lab R&D)
- Chile site and HWP alternatives considered, with additional significant science risks
  - Can place only lower bound on Chile SATs needed vs Pole, upper bound is harder (requires field demo)
  - Experience* has shown that full-season deep maps from site, with specific proposed technical approach, are needed to narrow such uncertainties to < 2x
    - Reduction/cleaning of deep, full-season maps needed to assess trade between systematics and 1/ell
- Pole alternatives to baseline can be considered, with different timelines to retiring risks
  - More aggressive optics illumination
    - This also probably requires prototype field demonstration to reasonably retire science risk
  - Reducing SAT power consumption is most straightforward “engineering risk” path to more SATs at Pole
    - On paper, a path cryo cooling *might* gain back up to ~5kW per SAT cryostat
    - Point-of-use solar installation on each SAT tower could offset another ~5kW per SAT cryostat

* “Experience over hope.” - Jim Yeck

Backup Slides

Sensitivity evaluation of alternatives & Necessary prototyping efforts

- The **white noise** and **survey coverage** factors can be easily analyzed
  - Can be calculated for Optics Alternatives 1, 2, and 3 to immediately place a lower bound on the number of SATs in Chile needed to equal the baseline (6 SATs / 18 tubes) at Pole, for each of those alternatives.
- Chile vs. Pole differences in ground pickup and atmospheric noise lead to additional uncertainty in **achievable sensitivity per tube, particularly at large scales (1/ell)**.
  - Current gap between Pole vs Chile end-to-end achieved performance leaves room for this additional factor to be potentially very large.
- Experience* has shown that full-season deep maps from site, with specific proposed technical approach, are needed to narrow such uncertainties to < 2x
  - Reduction/cleaning of deep, full-season maps needed to assess trade between systematics and 1/ell
- A deployment of an S4 prototype SAT in Chile for 1-2 seasons operation, prior to finalizing required number and design of Chile SATs would seem prudent
  - Achieved performance with e.g. option 3 and option 1 vs Pole SAT baseline could be judged
  - SO SATs may offer information on one point design, but need full-season, full efficiency, deep, cleaned maps
  - Requirement differences for design, including shielding and calibrations, could also be validated

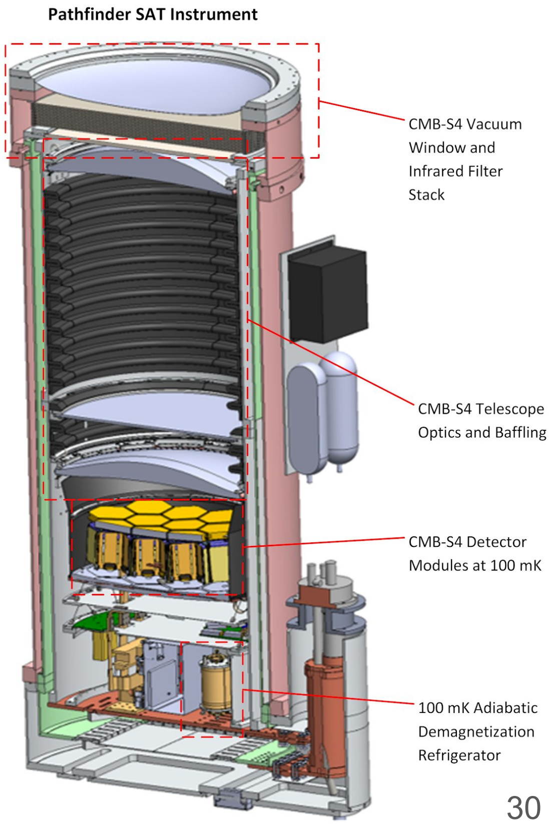
* “Experience over hope.” - Jim Yeck

CMB-S4

pSAT: Risk retirement and design optimization for CMB-S4

pSAT = single tube, 100mK MF-2 prototype testbed in spare BA cryostat aims to offer CMB-S4 :

- "Direct correlation of laboratory component-level performance measurements with deployed system performance"
- Risk retirement on in-field sensitivity and systematics resulting from new S4 design features; comparative testing vs. previous choices:
    - Dichroic optics (sensitivity, optics performance)
    - Curved focal plane and other S4 baseline optics refinements
    - Horns (crosstalk, beam systematics)
    - Subsystem performance of prototype modules, readout, potentially DAQ, cal
- Updated estimates for end-to-end map depth per detector
- Potential for design optimization studies
    - Optics Tube throughput (horn density, aperture)
    - External Shielding geometry – informs # tubes possible for given footprint
- "Experience gained in integrating, deploying, and calibrating CMB-S4 hardware during the pSAT effort will help inform CMB-S4's commissioning, calibration, and operations planning, well in advance of construction of the CMB-S4 production hardware."



"Science Risks" for low-ell BB to worry about:

- Shielding from time-variable scan-fixed pickup from ground, sun, …
  - Ground subtraction limits BK filtering and low-ell information recovery
  - Chile environment is dramatically different in terrain and diurnal stability
  - SPLAT shielding may not include absorbing forebaffle or outer groundshield
- Boresight rotation
  - 360-deg boresight rotation tests/mitigates effects @ 90- and 180-deg (table 2 arXiv:1502.00608)
  - SO and SPLAT may have more limited rotation (45-deg Q→U)
- Correlated polarized 1/ell from atmosphere
  - Measurable effect on current BK 1/ell in higher bands (~partially factored into forecasting)
  - Not well understood how scales between sites or angular scales
  - Impact of concentrating lines of sight with many more detectors needs to be understood
- Correlated polarized 1/ell from instrument
  - Control of common-mode polarized pickup from mirrors, baffles (everything outside window)
- Unknown unknowns
  - for any unproven approach to this challenging measurement, we can expect new problems to emerge.

SAT implementation in Chile risks, existing database (1)

Atacama B-mode Search (SAT: 25 cm aperture, cryogenic mirrors; warm HWP)

- CMB power spectrum results
- HWP beam systematics mitigation
- HWP atmospheric fluctuation mitigation

POLARBEAR (MAT: 2m aperture, warm mirrors; warm HWP)

- CMB power spectrum results 1, results 2
- HWP atmospheric fluctuation mitigation

QUIET (MAT: 1.4m aperture, warm mirrors; phaseswitch modulation)

- CMB power spectrum results 1 (40 GHz), results 2 (90 GHz)

Simons Observatory SATs (first light 2023~2024)

- 42 cm aperture, equipped with cryogenic HWP

Slides below are directly drawn from April-July SAT AoA presentations.

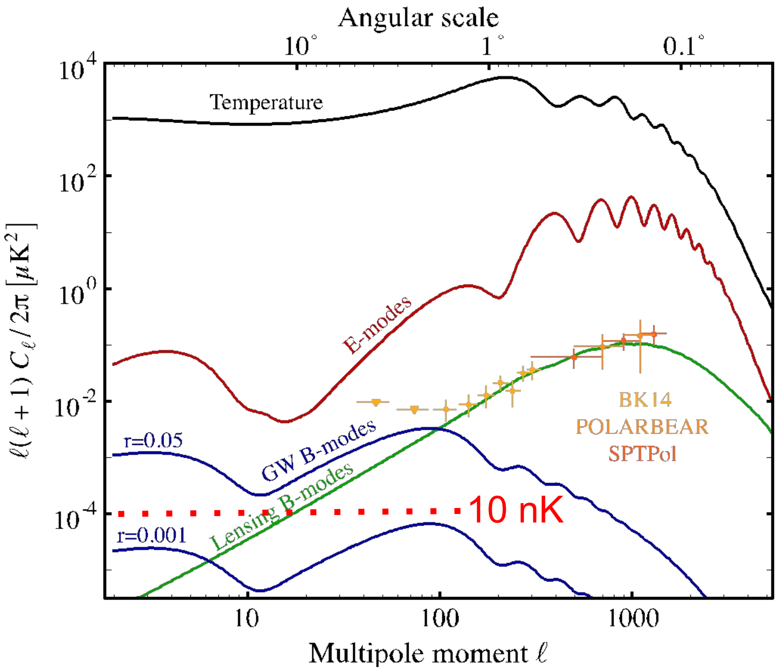
Introduction

SAT/low-ell Design Drivers (slides from 2018-2020 & DSR)

- Science Requirement driving SATs:
  - *r* < 0.001 at 95%, or detect *r* = 0.003 at high confidence (DSR ch. 2)
- this means < 10 nK (!!) uncertainties at degree scales:
  - raw sensitivity
  - systematic control
  - foreground separation

…all made harder at degree scales by

1/ell noise & red-spectrum confusion signals



DSR, Fig 1

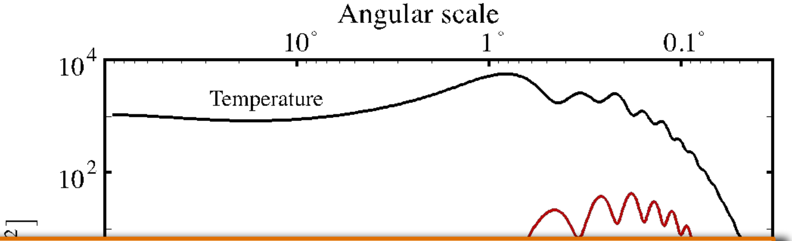
Extreme experimental challenge – paper studies alone cannot retire risks.

→ Our design approach is to build on what's been proven to work in deep *r* measurements for Stage 1, 2, 3…

Introduction

SAT/low-ell Design Drivers (slides from 2018-2020 & DSR)

- Science Requirement driving SATs:



from DSR p. 115

In making design choices we have distinguished between *engineering issues*, those that can be fully developed and demonstrated in the lab to retire risk, and *science issues*, those whose impact on successfully meeting the measurement and science requirements must be judged with comparison to direct experience of making deep B-mode maps. For example, cryostat design is primarily an engineering issue because we are confident our design choices can be fully validated in the lab. Examples of science issues include beam and sidelobe optical performance, polarization modulation approach, ground pickup and shielding, and other systematic effects, and for design choices that impact these issues we have endeavored to stay close to and to build upon proven experience.

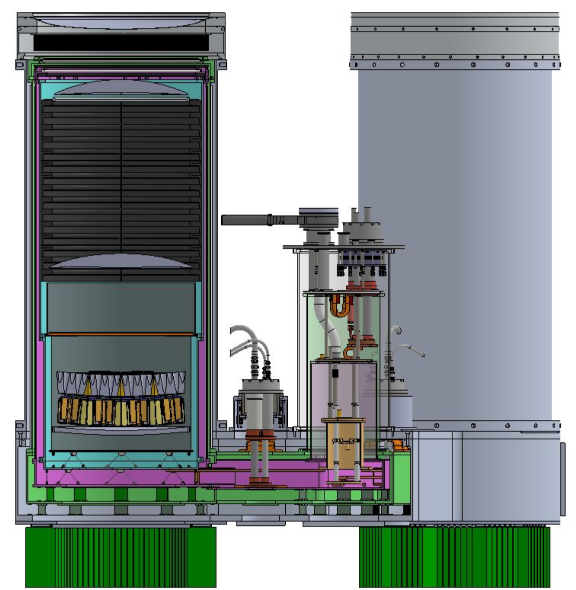
1/ell noise & red-spectrum confusion signals

Extreme experimental challenge – paper studies alone cannot retire risks.

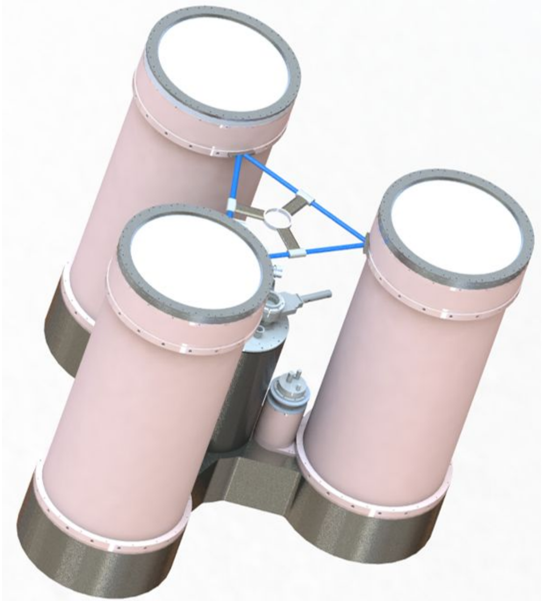
→ Our design approach is to build on what's been proven to work in deep *r* measurements for Stage 1, 2, 3…

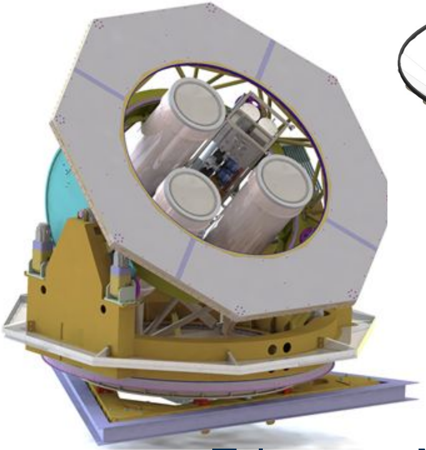
DSR, Fig 1

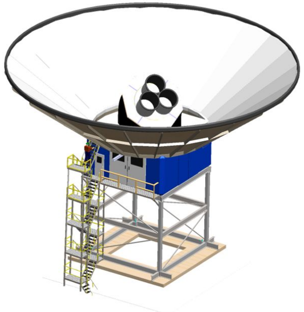
Baseline SATs



Cryostat System, Optics Tubes, Integration & Test

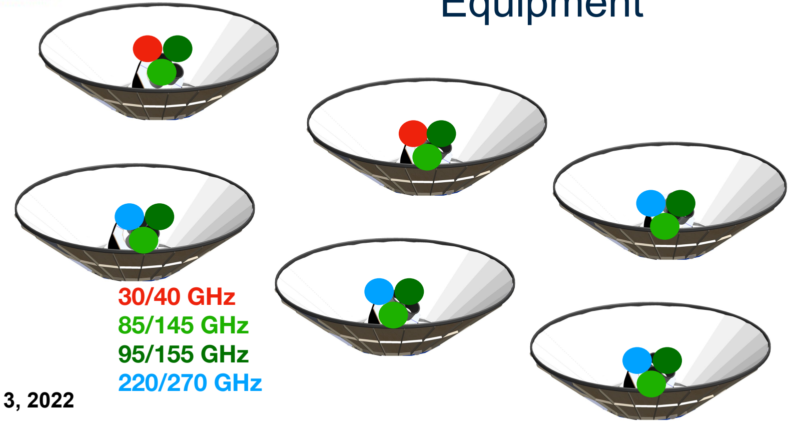






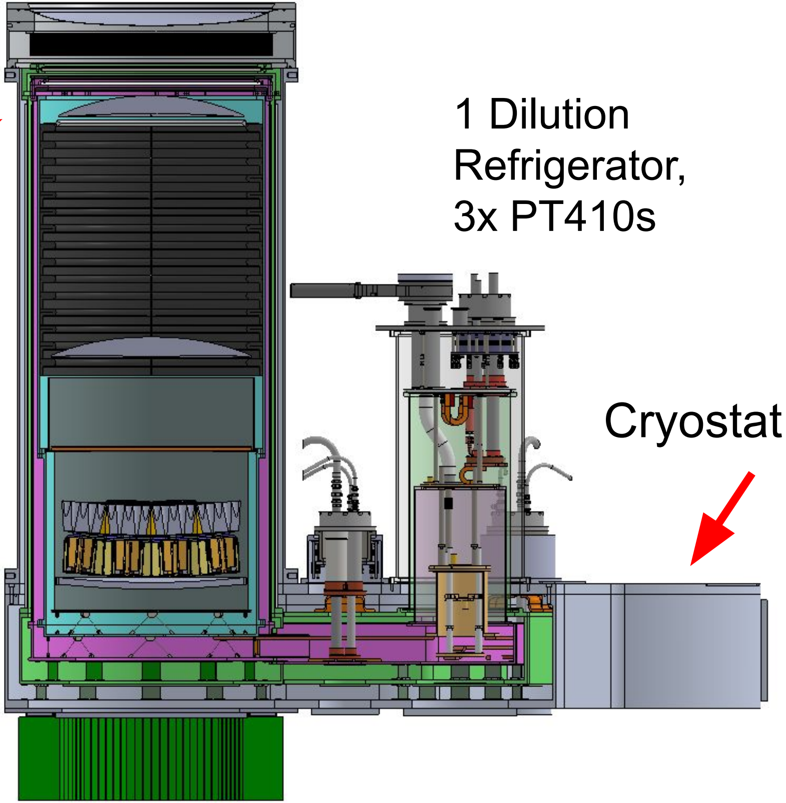
Telescope Mount, Ground Shield, Calibration Equipment

Integration and Test (including modules, readout, DAQ) before shipping to site



Baseline SAT Cryostat design

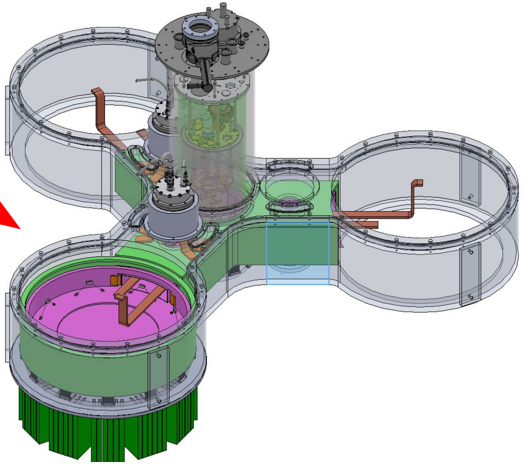
3x Receiver Tubes
(each with an optics tube and focal plane)



1 Dilution Refrigerator,
3x PT410s

Cryostat Bus

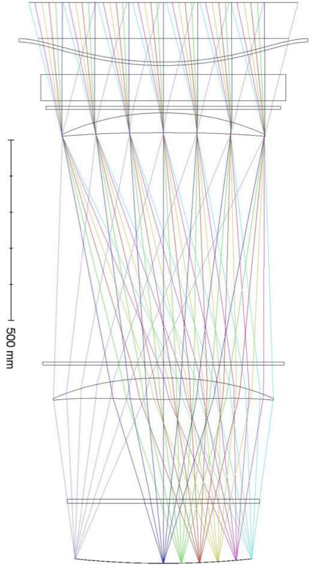
- SAT design draws directly on design heritage from BICEP3, BICEP Array, and Simons Observatory Small Aperture Telescope Receivers
- Design is maturing this year, driven by prototype test schedule
- Baseline cryostat power: 27 kW



Baseline SAT Optics Design

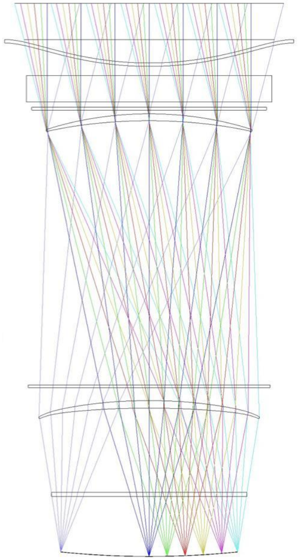
- Baseline **controls science risks** → clean, compact, extremely high throughput
  - builds on **only** proven approach for deep *r* measurements
- Recent developments:
  - **slightly curved focal surface** (r = 2.4 m) dramatically improves performance of two-lens designs
  - **MF optics / pixel layout study** defined baseline coupling for MF1/MF2
  - **initial material measurements** have bounded loss / birefringence in HDPE
- HDPE now baselined for all frequencies; alternatives to be evaluated

HDPE



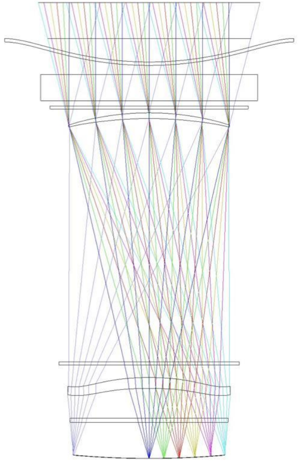
428 mm

Alumina / Si (columnar)

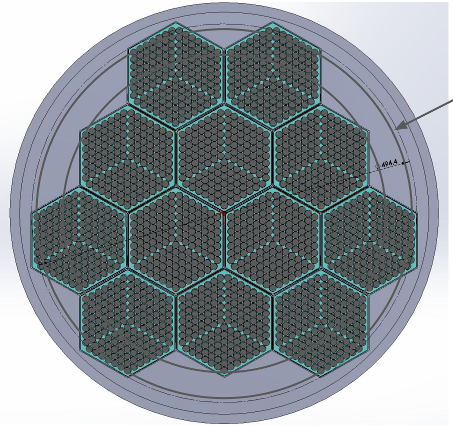


428 mm

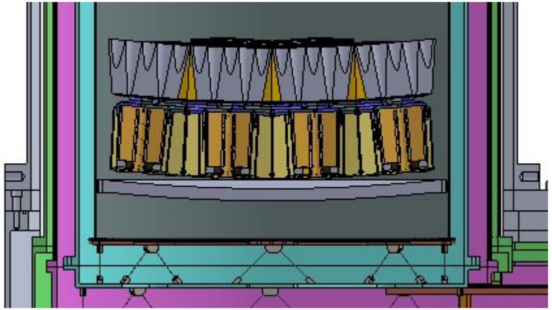
Si (crystal)



336 mm



490 mm



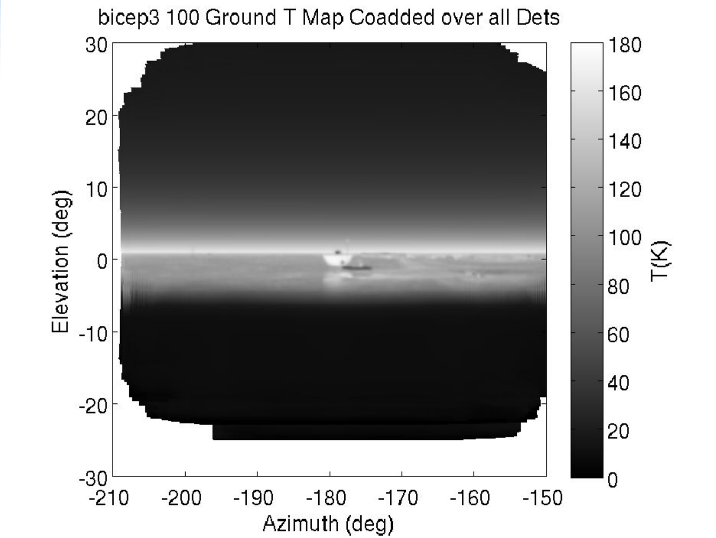
Baseline SAT Ground Shields

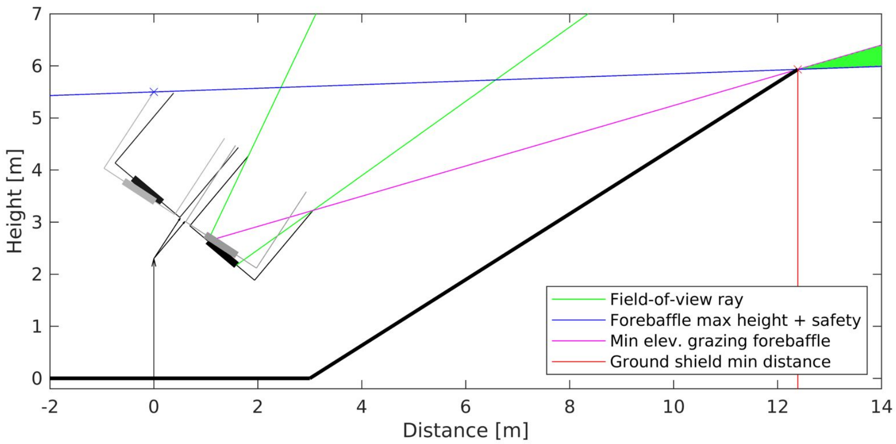
Key elements of proven approach to systematics control:

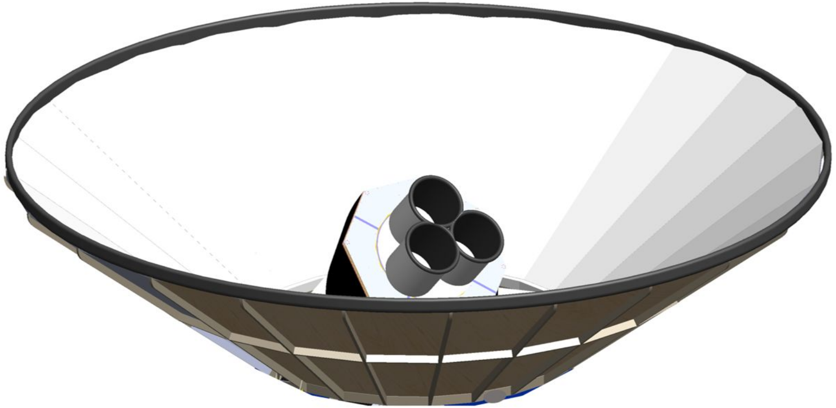
- Cylindrical warm forebaffles
- Reflective outer groundshield

Under double-diffraction criterion, at 50 degrees minimum elevation, geometry study found SAT 3-tube receiver can be shielded with:

- **Forebaffle**: 1.75 m tall, 0.8 m radius
- **Ground Shield**: 5.9 m tall, 12.4 m radius



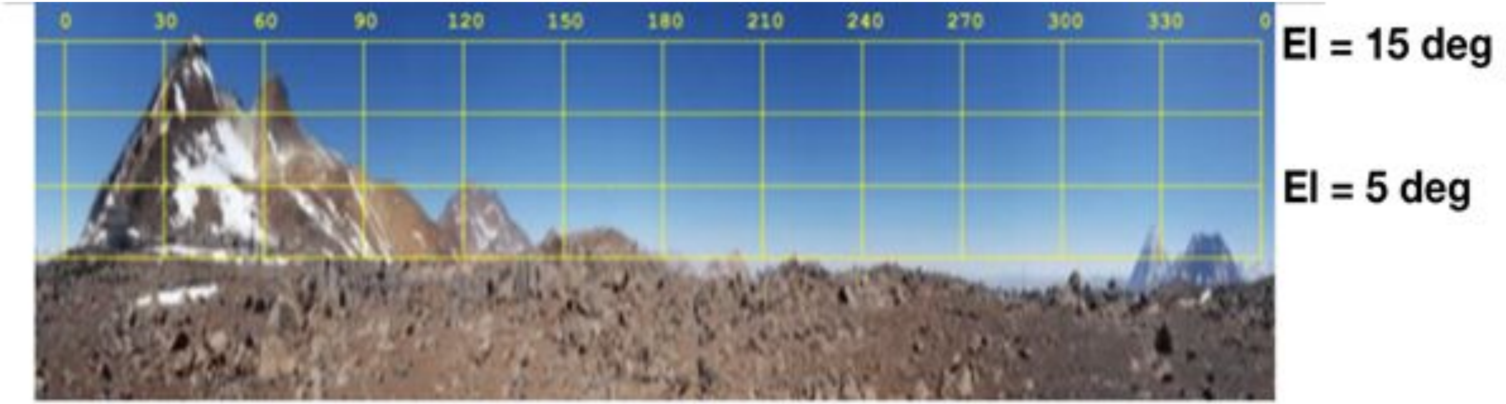




SAT Alternatives: Risks and Opportunities

- Baseline Design prioritizes control of science performance risk + readiness
- Alternatives will carry additional science risk (field demo) or engineering risk (lab R&D)
- Chile SATs, 2 alternative optical configurations considered
  - each carry different additional science risks
  - Can place lower bound on number SATs needed vs Pole, upper bound is harder (requires field demo)
- Pole alternatives to baseline can be considered, with different timelines to retiring risks
  - Reducing SAT power consumption is most straightforward “engineering risk” alternative
    - On paper, a path to ~18kW per SAT cryostat
  - Big-SAT idea: use much larger aperture to increase detector count per kW
    - Trying to keep shielding and systematics risks the same
  - Pushing to higher pixel count per SAT by using:
    - more aggressive optics illumination (e.g. Ruhl’s slide w/ Chile #3 level, gaining ~50% per tube)
    - alternate detector (planar antenna) or readout (RF mux for HF) technologies
    - relaxed shielding requirements

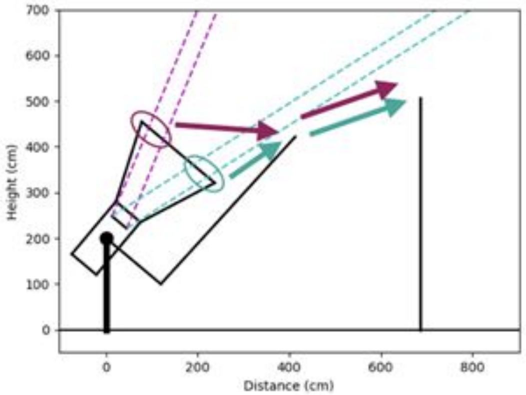
Distribution of Terrain at Chilean Site



The closest mountain (Cerro Toco) peaks at around elevation ~15 degrees from horizon, NE of site. Mountains that are further away peak at around elevation ~5 degrees from horizon. Approximately half of the azimuth range contains mountains that rise above the horizon.

Relaxed Double-Diffraction Criteria

From the Simons Observatory (SO) shielding study, we have adopted a “relaxed” version of the double-diffraction criteria due to that fact that extremely large ground shields are required to satisfy the full double-diffraction criteria. The relax double-diffraction criteria only has one difference. The relaxed criteria allows the diffraction off the top of the forebaffle to be able to “see” the top portion of Cerro Toco, but not the horizon or further off mountains. The diffraction off the top of the forebaffle is much smaller and sub-dominant compared to the diffraction off the bottom of the forebaffle which will be blocked in the relax criteria. Also sidelobes due to forebaffle scattering may also “see” the top portion of Cerro Toco.



Shielding geometry (Study by Fred and Kirit)

Option 1

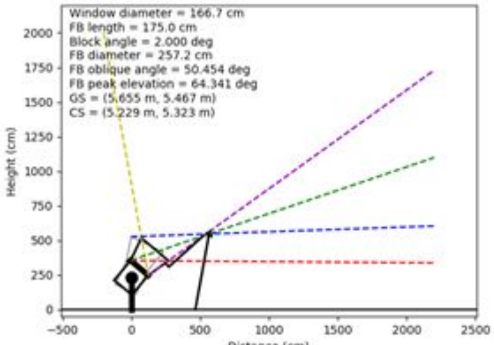
- Forebaffle: 1.75 m (same)
- Ground shield: R=15.6 m, H = 6.9 m

Option 2

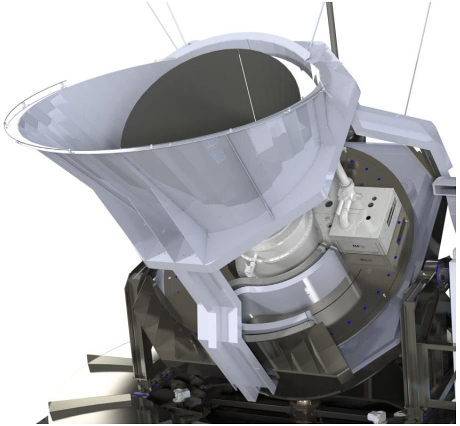
- Forebaffle: 1.75 m (same)
- Tertiary: 2 m (added)
- Ground shield: R=12.1 m, H = 6.6 m

Both w/ Relaxed double-diffraction criteria

Study by F. Matsuda and K. Karkare, DocDB XXX

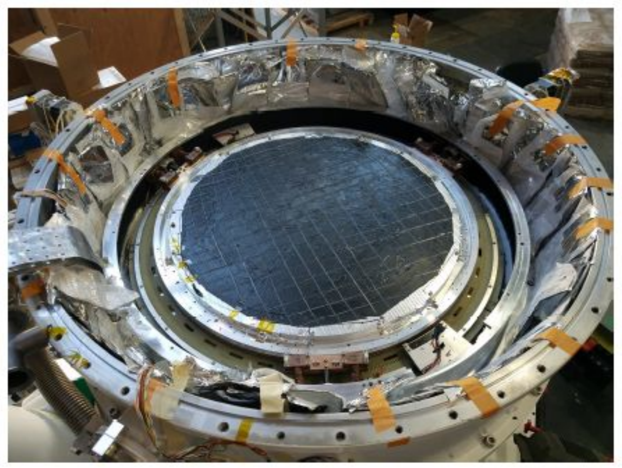


Example of 1 tube, 1.75 m forebaffle, 3 m tertiary

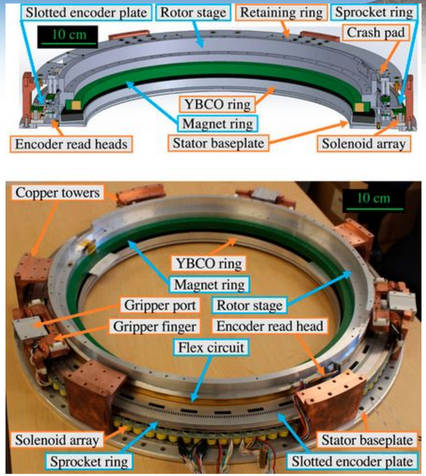


Example from Simons Observatory

Half-wave plate



SO HWP rotation mechanism.



SA HWP rotation mechanism.

HWP rotating mechanism: high-Tc superconducting mag-lev bearing. Virtually no limit on the aperture size.

Optical stack: three-layer sapphire stack with AR coating layers.
  Sapphire diameter limited to 505 mm for current technology.
    Metamaterial possible to expand diameter, R&D needed.
  AR coating : conservative: glue AR-coated Alumina on.
    Some technology can direct AR coat on Sapphire.

Half-wave plate - systematics mitigation

- Atmospheric Fluctuations
  - Mitigated: additive fluctuations.
  - Not mitigated: multiplicative fluctuations. (incl. non-linearity driven by atmospheric fluctuations. This exists in pair-diff as well.)
  - (https://doi.org/10.1063/1.4862058, https://doi.org/10.1117/12.2232280)
- Polarized Beam Systematics
  - Mitigated: diff. response of detectors and elements between HWP and detectors.
  - Not mitigated: 40 K filter and window (but a large scale common mode)
  - (https://doi.org/10.1063/1.4962023, https://doi.org/10.48550/arXiv.1808.07442)
- Polarized Sidelobe Systematics
  - Mitigated: pol. sidelobe due to aperture stop diffraction, pol. sidelobe due to differential illumination on warm baffle/shield.
  - Not mitigated: sidelobe polarization due to baffle/shield diffraction and scattering.
- Crosstalk-induced pol. leakage
  - Mitigated: Crosstalk between “X” and “Y” detectors becomes P → P leakage.

SAT implementation in Chile risks, existing database (1)

Atacama B-mode Search (SAT: 25 cm aperture, cryogenic mirrors; warm HWP)

- CMB power spectrum results
- HWP beam systematics mitigation
- HWP atmospheric fluctuation mitigation

POLARBEAR (MAT: 2m aperture, warm mirrors; warm HWP)

- CMB power spectrum results 1, results 2
- HWP atmospheric fluctuation mitigation

QUIET (MAT: 1.4m aperture, warm mirrors; phaseswitch modulation)

- CMB power spectrum results 1 (40 GHz), results 2 (90 GHz)

Simons Observatory SATs (first light 2023~2024)

- 42 cm aperture, equipped with cryogenic HWP

SAT implementation in Chile risks, existing database (2)

But there remains large uncertainty in the actual factors limiting achievable performance.

Site-dependent differences include dramatically different out-of-field pickup and atmospheric noise.

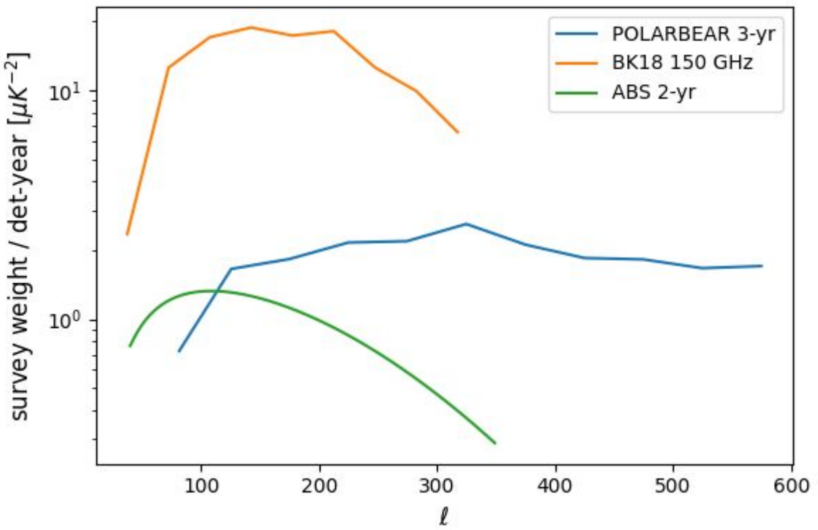
HWP modulation can mitigate polarized 1/ell from

1. Unpolarized atmosphere in main beam
2. Sidelobes in zero-diffraction directions

These are also relevant for Pole SATs, but *are not what currently limits* their polarized 1/ell performance.

Compared to these, polarized atmosphere and ground pickup from single and double-diffraction directions are suspected to be greater limiting factors for Pole SAT.

- Diffracted pickup expected to be worse in Chile and is not (obviously) mitigated by the HWP
- HWP-specific systematics introduce new risks to evaluate:
  - freq. dependence of bandpass, pol angle, efficiency
  - HWP non-uniformities → false 4f, 1/ell
- Without deep-map empirical characterization, hard to model/predict the impact on shielding requirements and ultimately achievable 1/ell performance



Survey Weight per detector-year at 150 GHz
C. Bischoff, CMB-S4 Science Council Logbook, 8 April 2022

CMB-S4

SAT alternatives

Dedicated past 2 SAT WG calls to collecting ideas and analyses. These are linked. We focused on:

(1) Reducing SAT power consumption (most straightforward "engineering risk" alternative)

- (1a) Can we reduce cooling loads to reduce pulse-tube power consumption?
- (1b) Can we reduce average power consumption with point-of-use solar?

(2) Alt-SAT ideas: alternative cryostat configurations to increase detector count per kW

- (2a) Big-SAT
- (2b) 6-tube SAT

(3) Pushing to higher pixel count per SAT by using:

- more aggressive optics illumination (e.g. Ruhl's slide w/ Chile #3 level, gaining ~50% per tube)
- alternate detector (planar antenna) or readout (RF mux for HF) technologies
- relaxed shielding requirements

(1a) Reducing SAT cooling power consumption

From SAT Cryostat Loading Review (6 June 2022), DocDB-847, by Paul Williams and Joe Saba

Old estimates

99 W on 50 K stage

50 K	Tube (W)	Cryostat (W)
Readout	6.1	18.3
Support	5.1	15.4
Radiative	5.9	17.8
Optical	12.5	37.5
Tube SubTotal(s)	30	89
Support - Cryobus		5.0
Radiative - Cryobus		5.3
Cryobus SubTotal		10
Total		99

New Estimates

70 W on 50 K stage

50 K	Tube (W)	Cryostat (W)
Readout	4.6	13.7
Support	2.3	6.8
Radiative	4.5	13.4
Optical	10.7	32.1
Tube SubTotal(s)	22	66
Support - Cryobus		2.3
Radiative - Cryobus		1.5
Cryobus SubTotal		4
Total		70

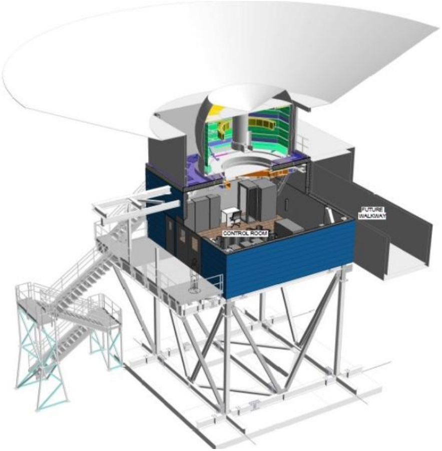
NB: These numbers come with caveats and risks, see their slides

(1a) Reducing SAT cooling power consumption

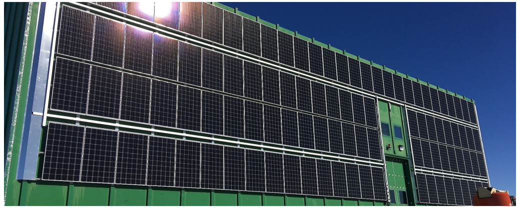
- New baseline of 2 PT410s have a cooling power of 2 x 40 W = 80 W at 40 K
  - Substantial risks in aggressive baseline thermal model
    - Impacts: schedule (more time prototyping), performance (less sensitive detectors), cost (more prototyping)
    - Mitigations include: prototyping, design optimization
- Doing *better* than the baseline looks hard
  - Prior estimate of 25.1 → 18 kW PT cooling per SAT w/ VFDs seems optimistic
  - Prototyping will tell if margin can be found
    - Would require improvement over state-of-art
    - Possibly up to 5 kW per SAT might be saved

(1) Reducing SAT SS power with point-of-use solar

- BART tower (a current NSF project) includes design provision for installation of solar arrays on exterior vertical surfaces
    - Estimate 132m^2 total area x 25% illumination x 300W/m^2 = 10kW summer average
- Supplementing station power plant with large solar farm seems a great idea, but
- “Point-of-use” solar, installed by project at telescope towers to reduce average draw, may be easier to baseline now
    - Supplementing station power plant with large solar farm seems a great idea, but may be more complicated
    - Point-of-use avoids siting, grid, maintenance questions
- Annual avg. up to 5 kW per SAT could be saved



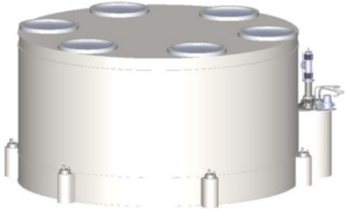
BART tower (planned)



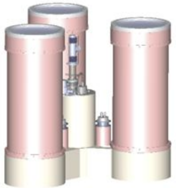
Casey Station (2019)

(2) Alt-SAT cryostat configs:

“BIG SAT”



6-Tube SAT



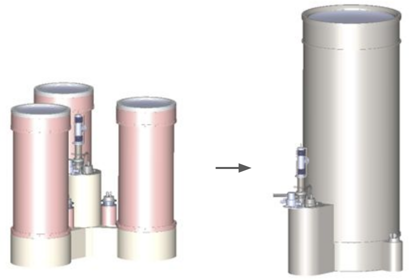
Baseline SAT

- Baseline SAT configuration resulted from work of Cryostat Configuration Task Force (2019-2020)
  - Report captured in DocDB-737
  - Wide variety of single-tube and multi-tube configurations considered,
  - Factors evaluated then included: cooling capacities, costs, power consumption, design, integration and operation risks, cryogenic and mechanical performance, optical shielding

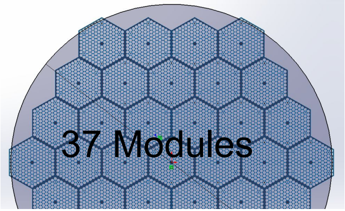
- Revisiting specific alternatives now with new focus on power consumption, optics developments
  - Assume we will keep shielding and systematics risks at same levels

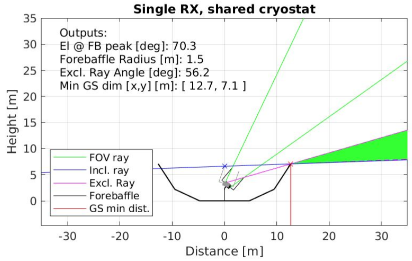
(2a) Alt-SAT cryostat configs: “Big SAT”

- Recent optics developments (thin plastic windows, curved FP) make larger diameter SATs seem more feasible:
  - Baseline SAT: 56cm aperture, 72cm window
- Tony Stark’s memo14 shows an example of a “Big SAT” that gives excellent optical performance through 300 GHz
  - ~scaled by x1.8, 100.8cm aperture, 129.6cm window
  - Joe’s analysis shows 37 modules in single FP (vs 36), with cooling power requirement nearly identical–no power savings
- Kirit’s shielding analysis shows shielding works
  - Requires larger forebaffle (1.75m → 3.15m)
- Sensitivity per detector will be roughly the same (slight gain from smaller beams, slight loss from thicker lenses)
- Drawbacks and Risks:
  - R&D required for optical elements this large
    - Risk in lenses, filters, vacuum windows
  - Breaks HWP compatibility
  - Single frequency-type per SAT mount



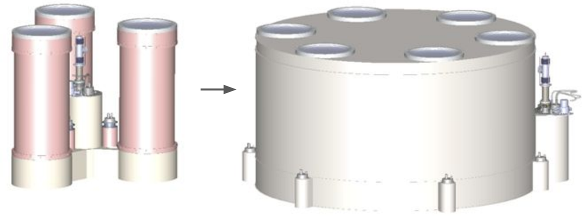
Baseline SAT **“BIG SAT”**



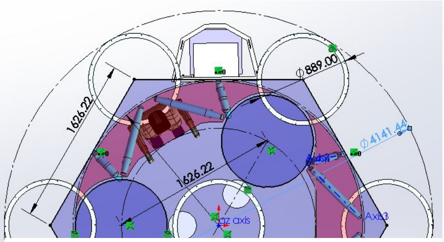


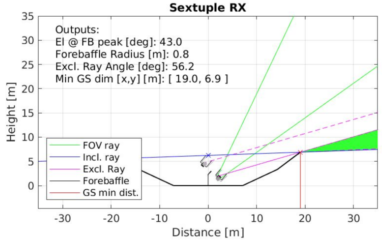
(2a) Alt-SAT cryostat configs: 6-tube SAT

- Electrical power priority → more tubes per SAT cryostat?
- Shielding requirement
  - Shared baffle gets impossibly large, c.f. original study
  - Individual baffles dictates maintaining baseline spacing
  - Kirit's analysis shows shielding grows as expected
    - outer groundshield 38m dia (vs 24m baseline)
- Joe's analysis shows cooling power requirement is again similar
  - Only potential benefit is from sharing DR for 6 tubes
  - Saves at most 5 kW per original 3-tube unit, but allows only 7mW cooling per 1K optics tube (serious risk!)
- Drawbacks and risks
  - Breaks assumption of re-use of BART tower and 2 existing BA mounts
  - Requires much larger mounts, towers, and I&C facilities
  - Atmospheric correlations will increase (fewer lines of sight)



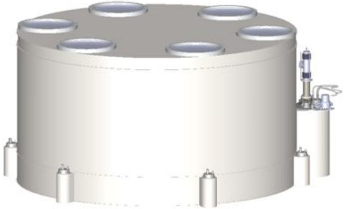
Baseline SAT **6-tube SAT**



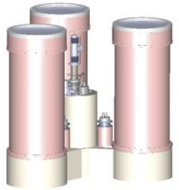


(2) Alt-SAT cryostat configs – comparisons

“BIG SAT”



6-Tube SAT



Baseline SAT

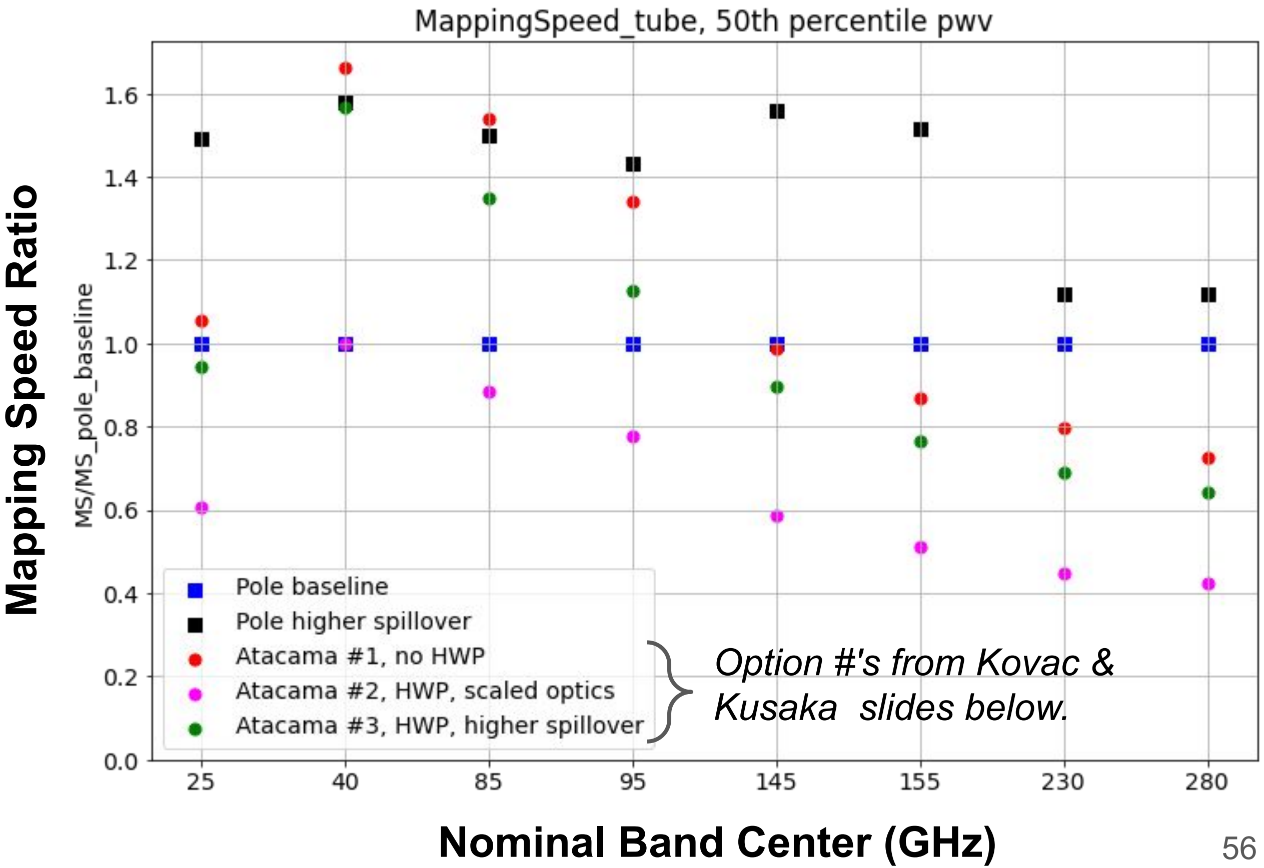
	“BIG SAT”	6-Tube SAT	Baseline SAT
Window Diameter (cm)	129.6 (1.8x)	72.0 (1x)	72.0 (1x)
Total Window Area (cm^2)	13,191 (1.1x)	24,429 (2.0x)	12,214 (1x)
Total Cryostat Surface Area (cm^2)	215,077 (0.9x)	597,204 (2.4x)	244,947 (1x)
Rough Cryostat Mass Estimate (kg)	1586 (0.6x)	4593 (1.8x)	2589 (1x)
Optical Throughput	1.1x	2.0x	1x

(3) Higher pixel count per SAT tube

John Ruhl's
SAT white noise sensitivities vs Pole baseline
(from May slides)

Black squares gain up to 50% mapping speed increase by increasing detector density
- no change in # of SAT modules
- increases spillover to the same as Chile HWP case

pSAT end-to-end field testing with prototype MF modules could offer a path to measuring achieved performance of this option, retiring current substantial science risk



SAT alternatives - conclusions

(1) Reducing baseline SAT power consumption

- 35 kW per SAT might be reduced by
  - Up to 5kW with further cooling optimization in prototype test, but baseline already is aggressive!
  - 5 kW (annual average) with assumption of point-of-use solar on SAT towers, like BART
- 25 kW x 4 = 100 kW, not much more than current 80 kW SAT use at Pole!

(2) Alternative SAT cryostat configurations

- Cryostat thermal loads are similar to baseline design. No large power savings (at most 5 kW per 3-tube unit)
- Big SAT and 6-tube SAT configurations each have substantial drawbacks vs baseline design

(3) Pushing to higher pixel count per SAT by using

- more aggressive optics illumination (e.g. Ruhl's slide w/ Chile #3 level, gaining ~50% per tube)
  - Requires field prototype testing to validate. Could be an opportunity the project holds open.
- alternate detector (planar antenna) or readout (RF mux for HF) technologies – did not evaluate
- Potential path to meet science requirements with only 4 SATs (rather than 6) at Pole, within 7-yr survey?

Sensitivity evaluation of alternatives & Necessary prototyping efforts

- The **white noise** and **survey coverage** factors can be easily analyzed
  - Can be calculated for Optics Alternatives 1, 2, and 3 to immediately place a lower bound on the number of SATs in Chile needed to equal the baseline (6 SATs / 18 tubes) at Pole, for each of those alternatives.
- Chile vs. Pole differences in ground pickup and atmospheric noise lead to additional uncertainty in **achievable sensitivity per tube, particularly at large scales (1/ell)**.
  - Current gap between Pole vs Chile end-to-end achieved performance leaves room for this additional factor to be potentially very large.
- Experience* has shown that full-season deep maps from site, with specific proposed technical approach, are needed to narrow such uncertainties to < 2x
  - Reduction/cleaning of deep, full-season maps needed to assess trade between systematics and 1/ell
- A deployment of an S4 prototype SAT in Chile for 1-2 seasons operation, prior to finalizing required number and design of Chile SATs would seem prudent
  - Achieved performance with e.g. option 3 and option 1 vs Pole SAT baseline could be judged
  - SO SATs may offer information on one point design, but need full-season, full efficiency, deep, cleaned maps
  - Requirement differences for design, including shielding and calibrations, could also be validated

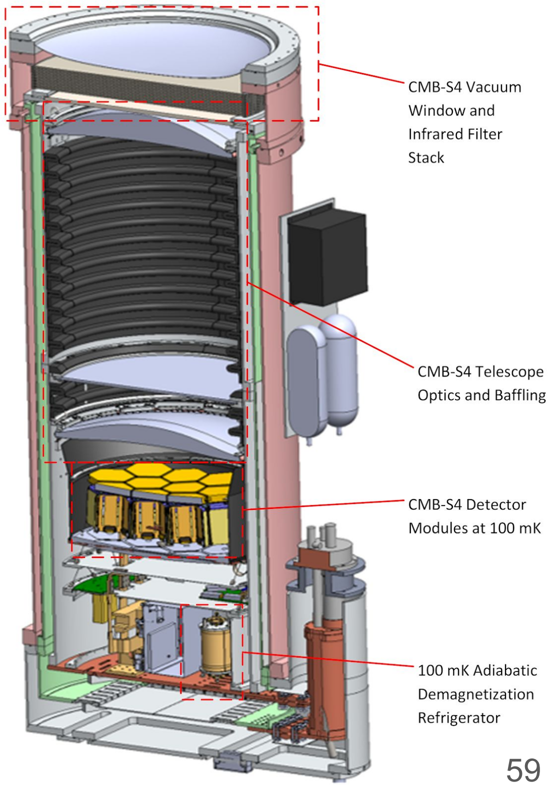
* “Experience over hope.” - Jim Yeck

pSAT: Risk retirement and design optimization for CMB-S4

pSAT = single tube, 100mK MF-2 prototype testbed in spare BA cryostat aims to offer CMB-S4 :

- "Direct correlation of laboratory component-level performance measurements with deployed system performance"
- Risk retirement on in-field sensitivity and systematics resulting from new S4 design features; comparative testing vs. previous choices:
  - Dichroic optics (sensitivity, optics performance)
  - Curved focal plane and other S4 baseline optics refinements
  - Horns (crosstalk, beam systematics)
  - Subsystem performance of prototype modules, readout, potentially DAQ, cal
- Updated estimates for end-to-end map depth per detector
- Potential for design optimization studies
  - Optics Tube throughput (horn density, aperture)
  - External Shielding geometry – informs # tubes possible for given footprint
- "Experience gained in integrating, deploying, and calibrating CMB-S4 hardware during the pSAT effort will help inform CMB-S4's commissioning, calibration, and operations planning, well in advance of construction of the CMB-S4 production hardware."

Pathfinder SAT Instrument



“Science Risks” for low-ell BB to worry about:

- Shielding from time-variable scan-fixed pickup from ground, sun, …
  - Ground subtraction limits BK filtering and low-ell information recovery
  - Chile environment is dramatically different in terrain and diurnal stability
  - SPLAT shielding may not include absorbing forebaffle or outer groundshield
- Boresight rotation
  - 360-deg boresight rotation tests/mitigates effects @ 90- and 180-deg (table 2 arXiv:1502.00608)
  - SO and SPLAT may have more limited rotation (45-deg Q→U)
- Correlated polarized 1/ell from atmosphere
  - Measurable effect on current BK 1/ell in higher bands (~partially factored into forecasting)
  - Not well understood how scales between sites or angular scales
  - Impact of concentrating lines of sight with many more detectors needs to be understood
- Correlated polarized 1/ell from instrument
  - Control of common-mode polarized pickup from mirrors, baffles (everything outside window)
- Unknown unknowns
  - for any unproven approach to this challenging measurement, we can expect new problems to emerge.