Telescopes:

LARGE vs small

& design implications

Towards the European Coordination of the CMB programme
Villa Finaly, Florence

Date: 2017-09-07

Author : Jon E. Gudmundsson
Affiliation : Stockholm University

These slides are largely based on work by a number of Simons Observatory members, including, but not limited to:

Mark Devlin, **Simon Dicker**, **Patricio Gallardo**, Nicholas Galitzki, Richard Hill, Akito Kusaka, Adrian Lee, **Fred Matsuda**, **Philip Mauskopf**, Jeff McMahon, **Michael Niemack**, Adrian Lee, Lyman Page, Sara Simon, Suzanne Staggs, Grant Teply

Also, see **Adrian Lee's** talk later today

Relevant talks from previous meetings

- GRASP Simulations and Beam Testing (Sandri et al.) — CERN, May 2016
- Optical Testing (B. Maffei) — CERN, May 2016
- COrE + telescope (K. Young et al.) — CERN, May 2016
- Planck HFI systematic effects, strategy for COrE (G. Patanchon) — CERN, May 2016
- Polarised beam window functions & QuickPol (E. Hivon) — CERN, May 2016
- Simons Observatory Optics Studies: Crossed Dragone Telescopes (M. Niemack) — CMB-S4 Meeting Stanford, Feb 2017
- Three Mirror Anastigmat (TMA) Style Optics Design (F. Matsuda) – CMB-S4 Meeting Stanford, Feb 2017
- Modified Crossed-Dragone Optics (R. Hills) – CMB-S4 Meeting Stanford, Feb 2017
- The Simons Observatory (M. Devlin) — CMB-S4 Meeting Stanford, Feb 2017
- Optics and Beam Forming: A Review (D. McGarthy) — Florence, Sep 2017

Stockholm University

Science goals [CMB-S4 / Simons Observatory]

- Measure gravitational lensing of CMB polarization
- Constrain the amplitude of primordial tensor perturbations

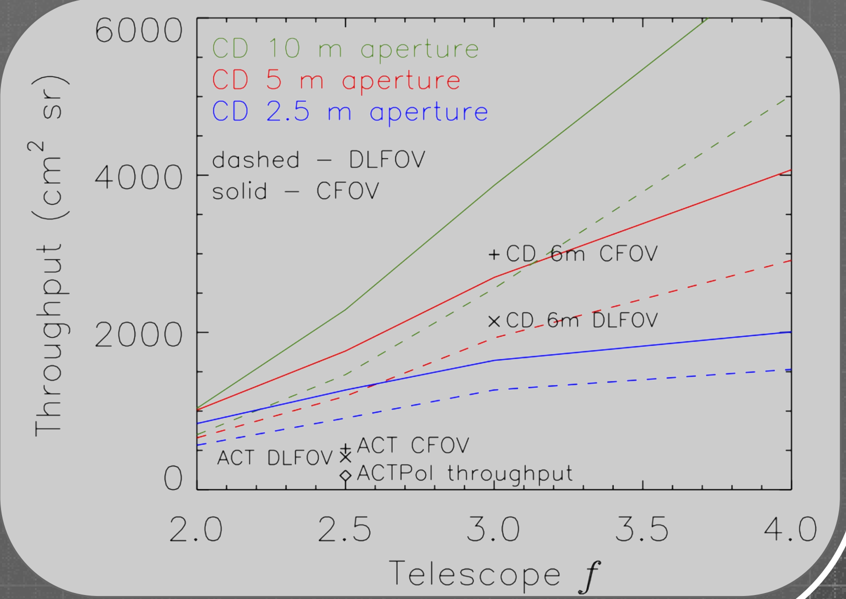
We get closer to these goals by putting a few 100,000 detectors on the sky

What kind of telescopes do we build to field 100,000 detectors?

Stockholm University

Back of the envelope

- A hundred thousand 5.5mm pixels require approximately 3.0m^2 of focal plane area
  - 100 GHz TES bolometers will likely not be smaller than about 5-6mm^2
- Largest CMB focal plane area in operation is ~0.15 m^2 (SPT3G)
  - Tenfold increase in throughput
  - This also means 10x increase in sub-Kelvin thermal mass
    - Estimate 200 kg at 100 mK



M.D. Niemack Applied Optics (2016)

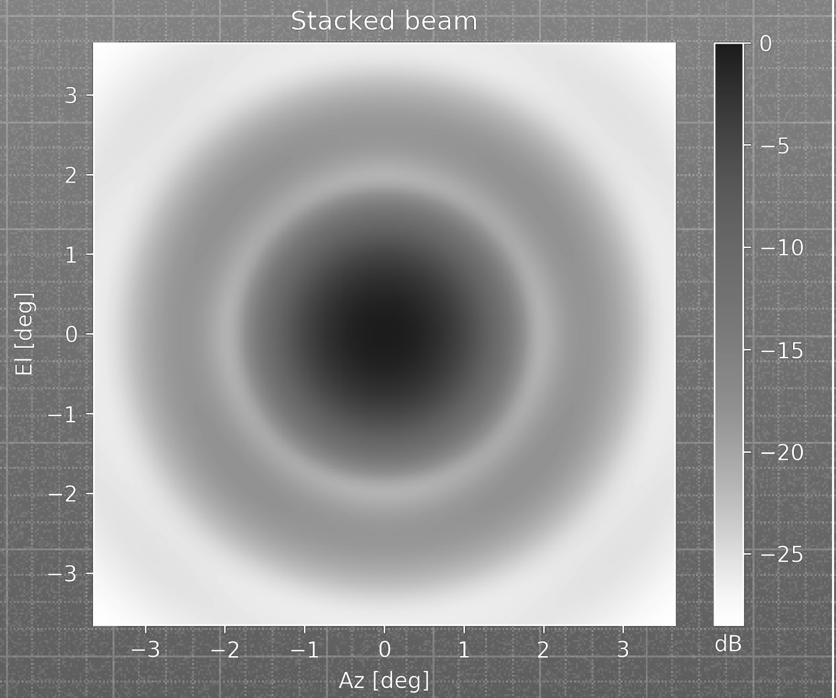
Stockholm University

Angular resolution and strehl ratios

Fundamental limit to resolution of optical system

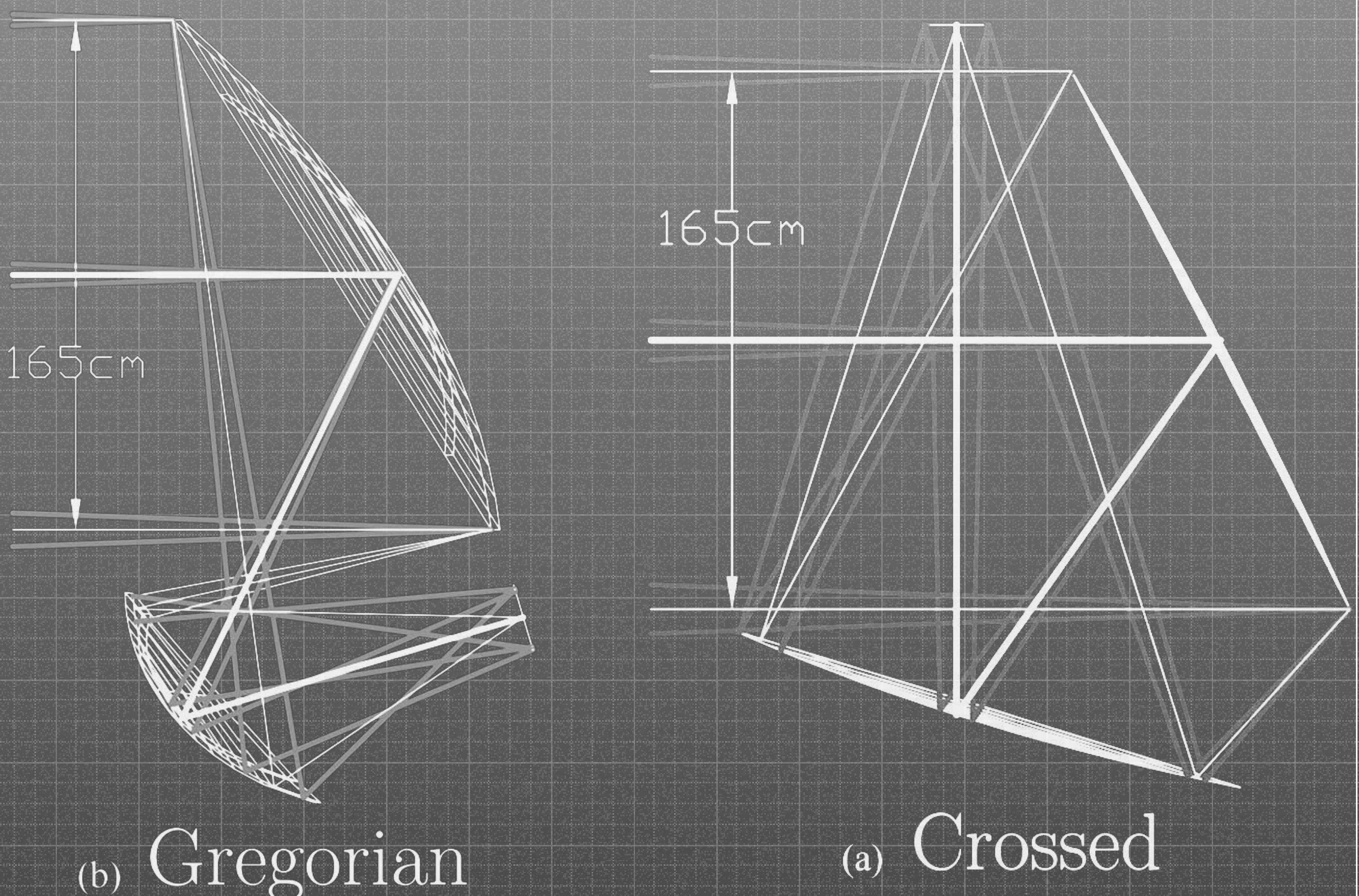
$$\theta = 1.22 (\lambda / D)$$

This is commonly referred to as the **Rayleigh criterion**



Strehl ratio quantifies the average wave-front error integrated over all rays the are incident on a particular location of the focal plane

$$S = |\exp(i\varphi)|^2$$



H. Tran et al. Applied Optics (2008)

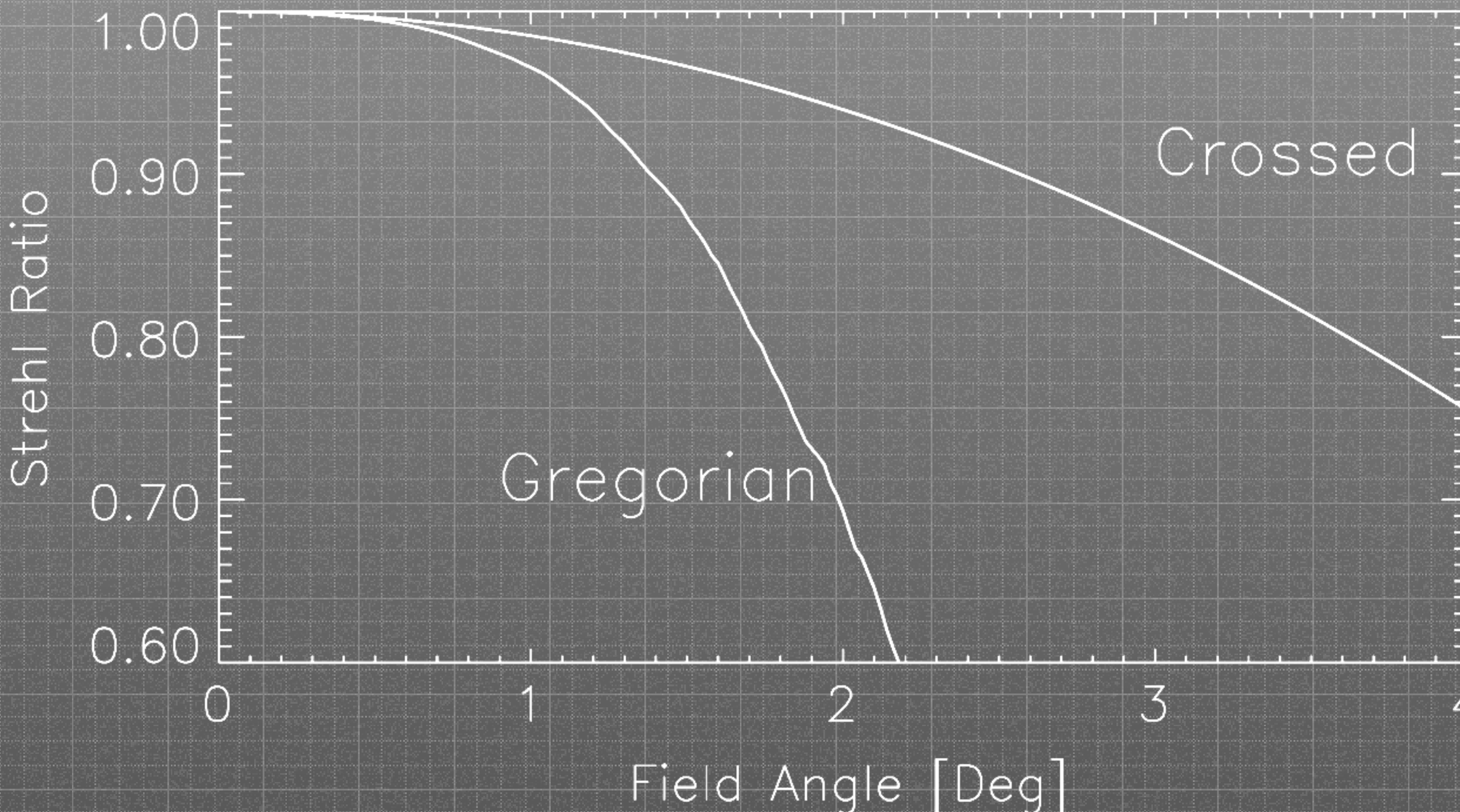
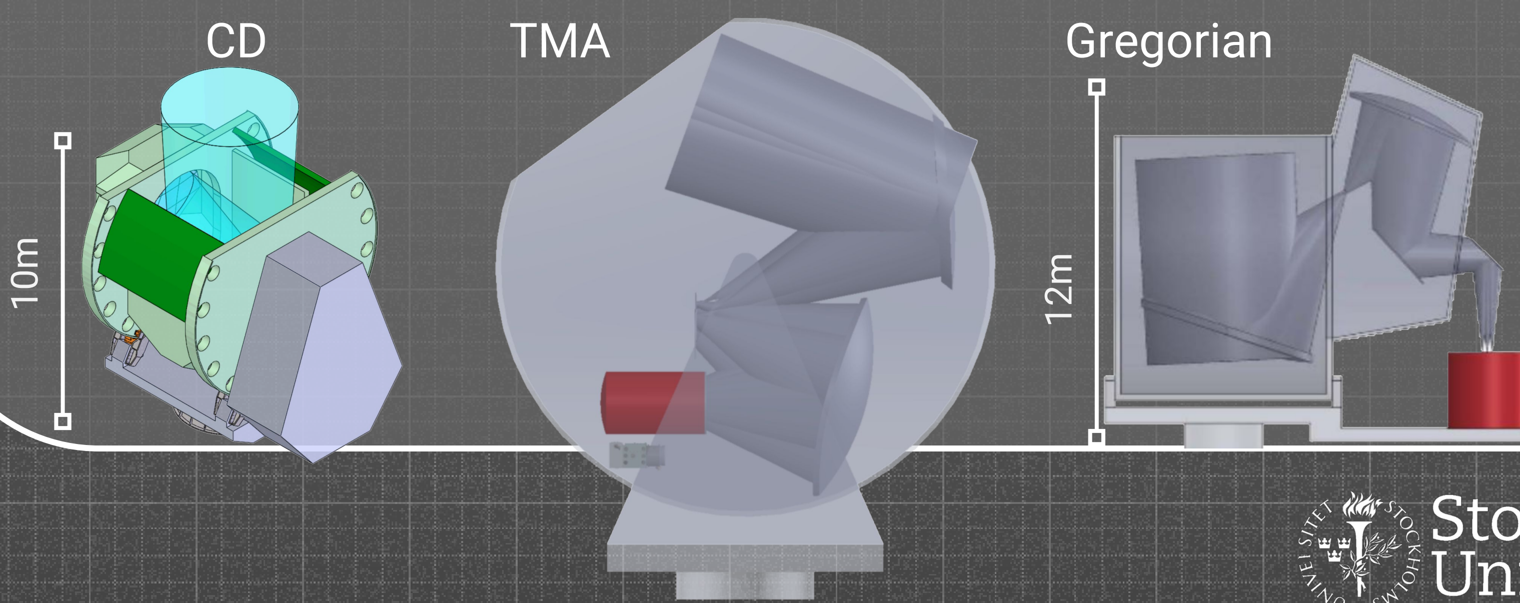


Fig. 2. Strehl ratios across the focal plane, calculated at 150 GHz. Crossed shows a clear advantage in terms of DLFOV. A design is considered diffraction-limited if the Strehl ratio is above 0.8.

H. Tran et al. Applied Optics (2008)

The path to a queen size focal plane

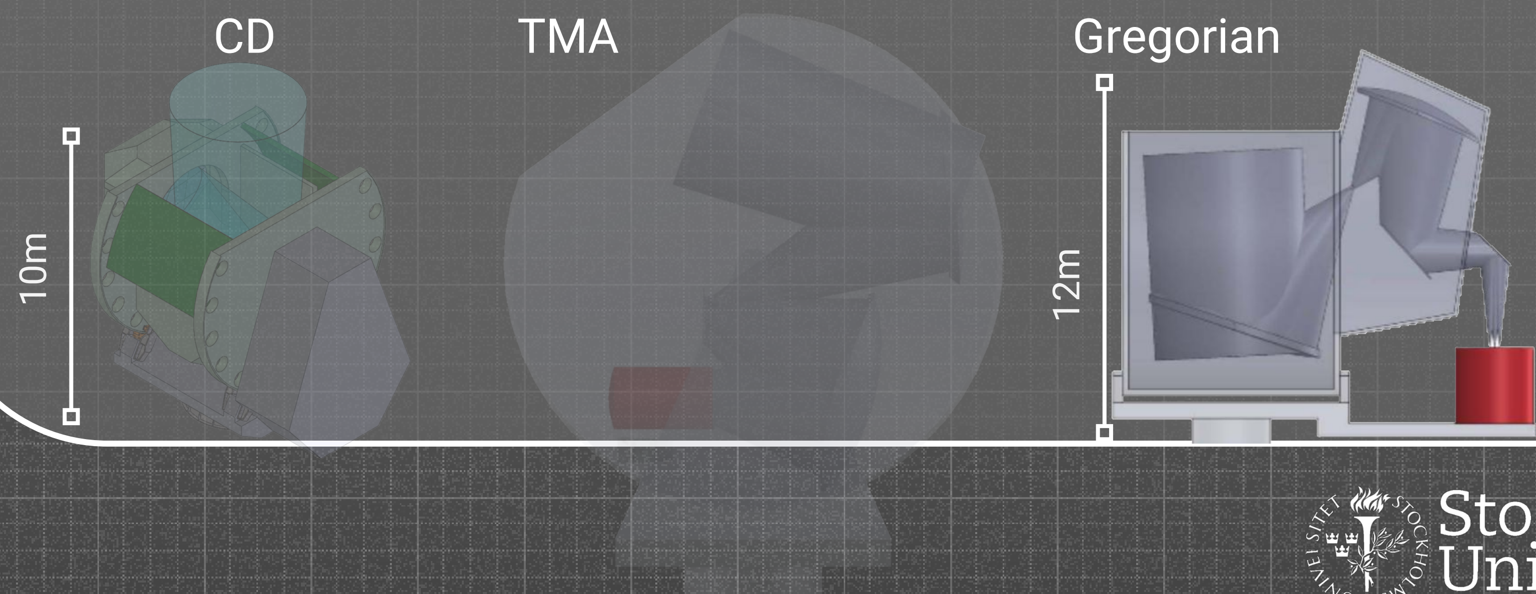
- SO studied three families of designs
  - Simon Dicker, Fred Matsuda, Phil Mauskopf, Michael Niemack, many others
  - Designs went through external review before downselect
- Crossed Dragone designs offer compact envelope, hence lowest mass and cost
  - See M.D. Niemack *Applied Optics* (2016), H. Tran et al. Applied Optics (2008)



Stockholm University

The path to a queen size focal plane

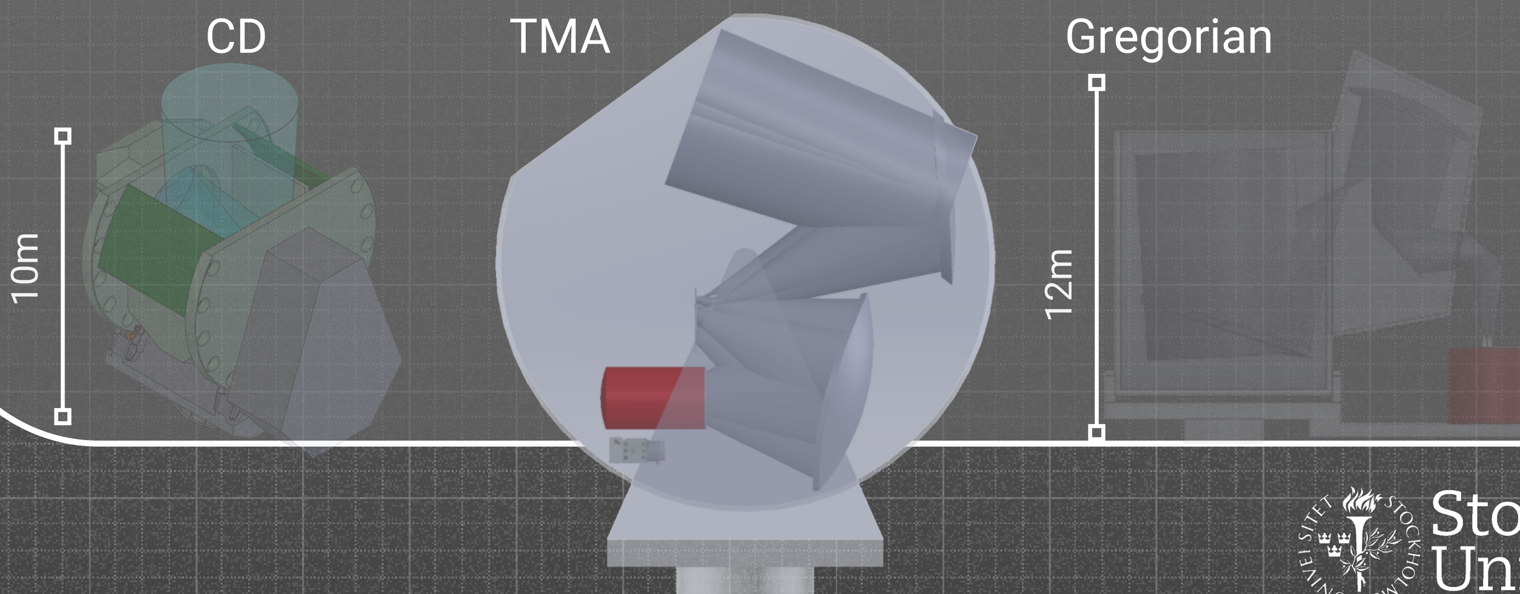
- Gregorian telescope – Phil Mauskopf
  - Has an accessible sky image between primary and secondary
  - Found to have significantly smaller FOV compared to CD design for same design volume
  - Telescope focal plane generally had larger curvature
  - Similar conclusions for Cassegrain designs that were studied



Stockholm University

The path to a queen size focal plane

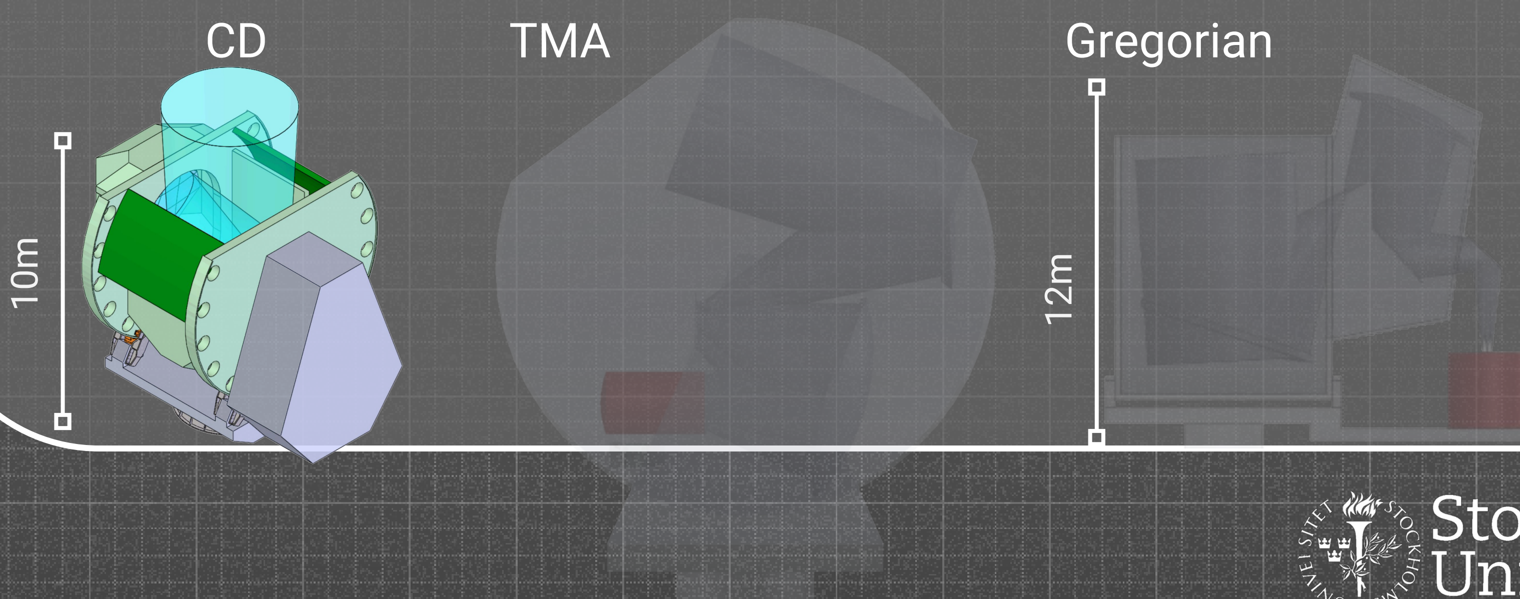
- Three mirror anastigmat (TMA) — Fred Matsuda
  - No reimaging optics required
  - Minimizes three main aberrations: spherical, coma, and astigmatism
  - Base design by Mike Lampton (LBNL)
    - Based off Cook's 1979 off-axis design
  - No heritage in CMB field
  - Large and difficult to build/deploy



Stockholm University

The path to a queen size focal plane

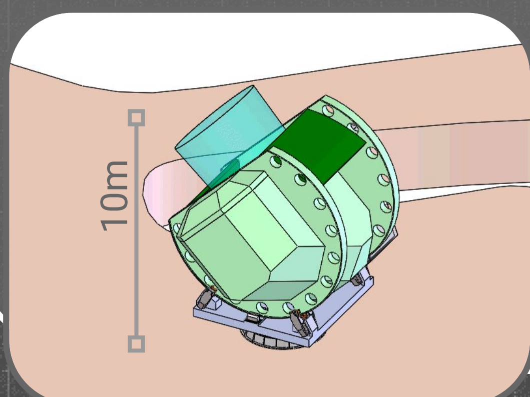
- Crossed Dragone [1/2] — Michael Niemack
  - Found to provide most compact (low cost) design for a fixed diffraction-limited FOV of all designs studied by SO
  - All image quality, cross-pol, instrumental polarization, calculations provided better performance than existing telescopes and other designs under consideration
  - Two mirror design found to offer greater sensitivity than three (or more) mirror designs



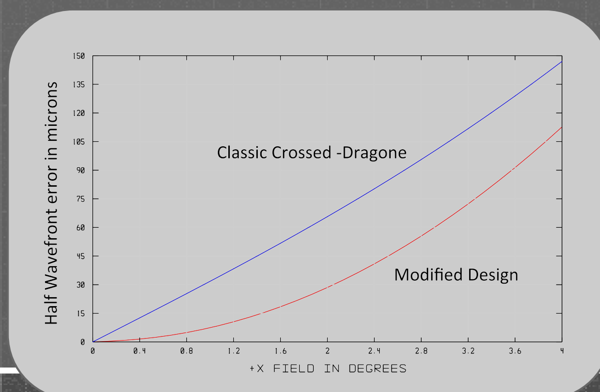
Stockholm University

The path to a queen size focal plane

- Crossed Dragone [2/2]
  - **Two** ~5–6 m reflectors on a Nasmyth mount
    - Looking into monolithic options
  - Instrument (telescope tube) rotator will be incorporated to facilitate instrument boresight rotation
  - Elevation range of 0-180 deg, enabling additional partial boresight rotation
  - Incorporates Coma-corrected surface (Ritchey-Crétien) for Crossed Dragone system based on Prof. Richard Hills’ (Cavendish Lab) suggestion
  - Recently decided to aim for f/2.6 (from f/3.0) with 5.5m aperture for a more compact telescope and improved mechanical performance

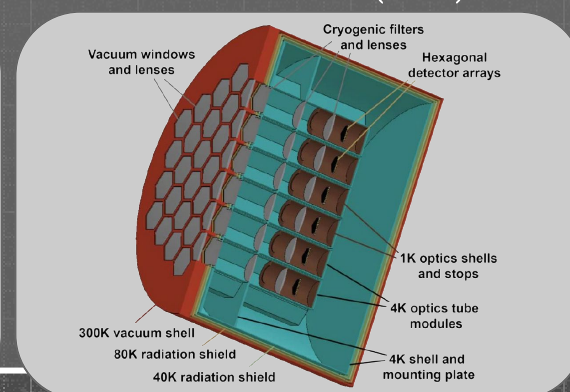


CCAT-p Nasmyth mount design
Credit: S. Parshley



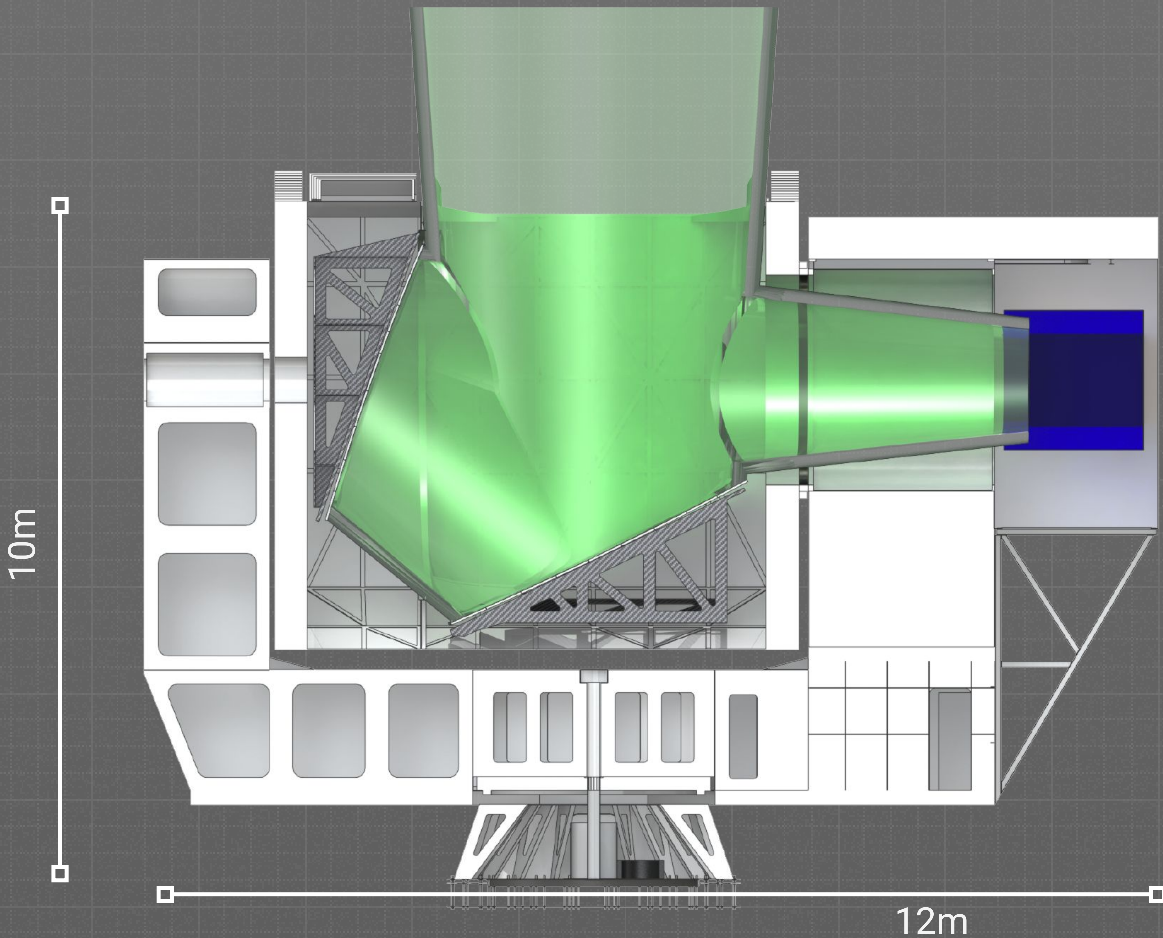
from Richard Hills

from Niemack (2016)



Stockholm University

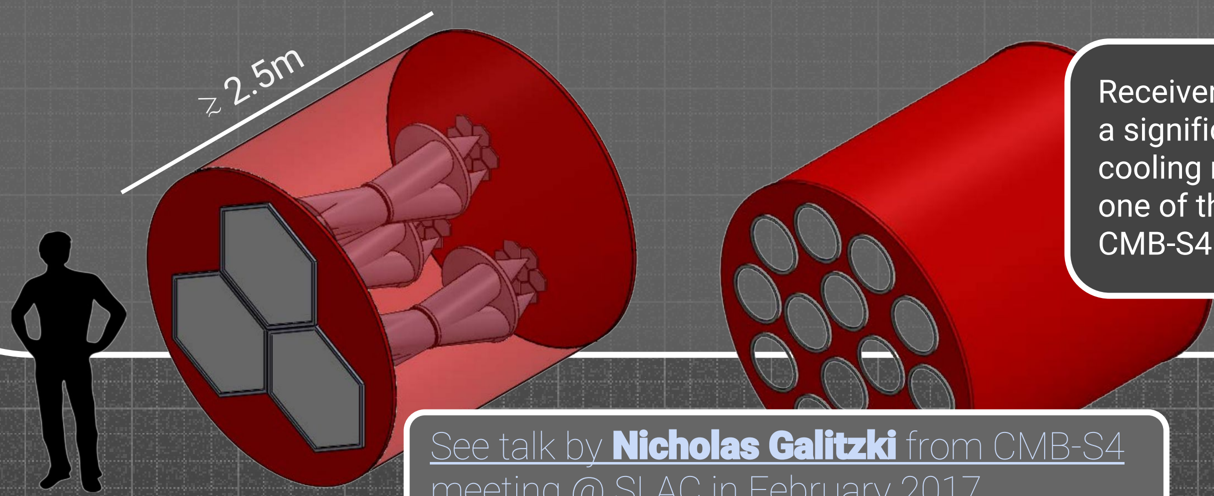
Preliminary design CCAT-p / SO



Stockholm University

Receiver architecture

- Single large cryogenic receiver found to couple most cost effectively & optically efficiently to reflector design
- Simons Observatory working on ~2.0m cryostat housing reimaging optics for large aperture
  - Can cryostat/receiver technology be shared for both small and large aperture solutions?
- Partially populated with up to 35k detectors
  - but with room for up to 80–100k detectors

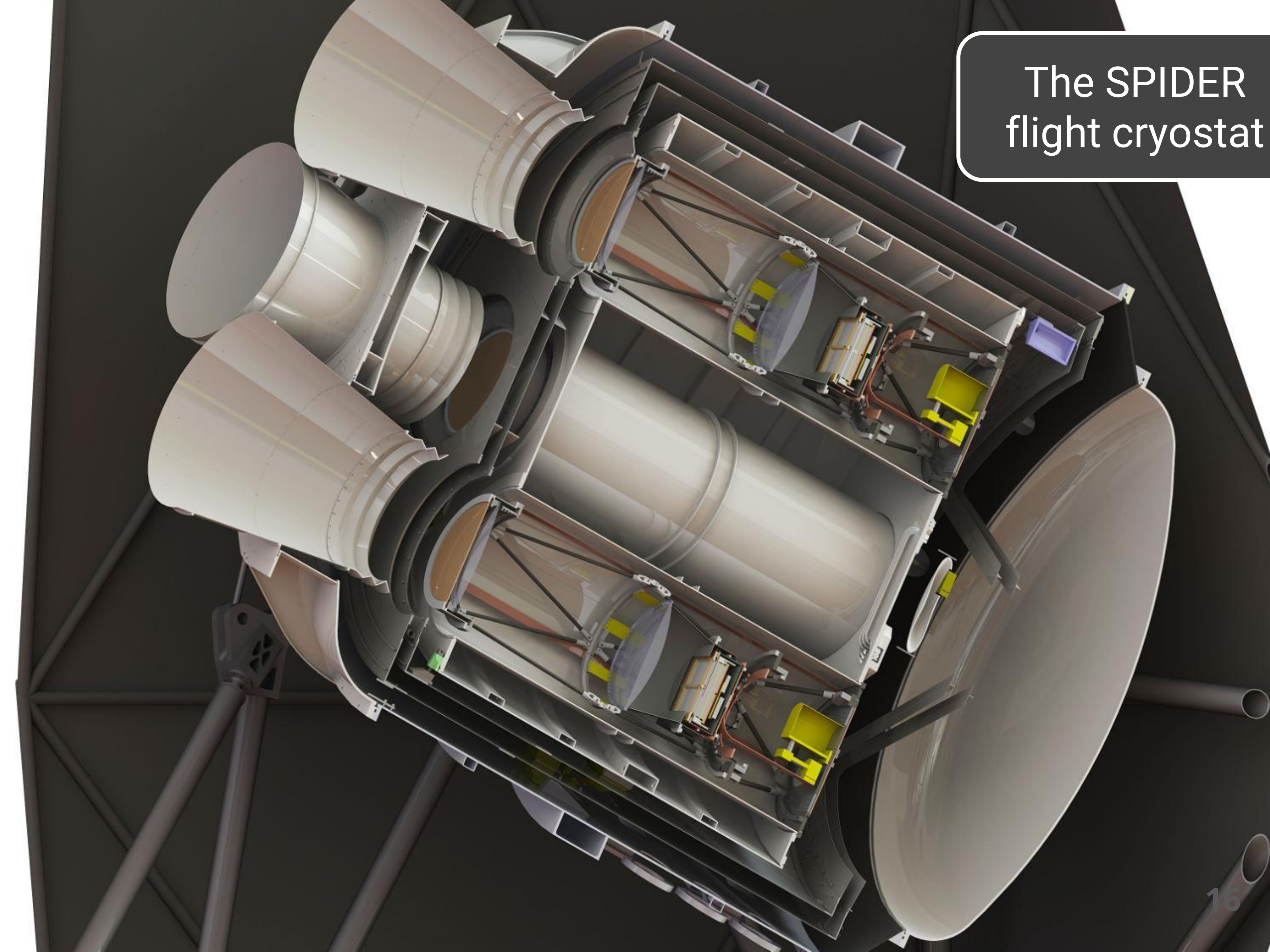


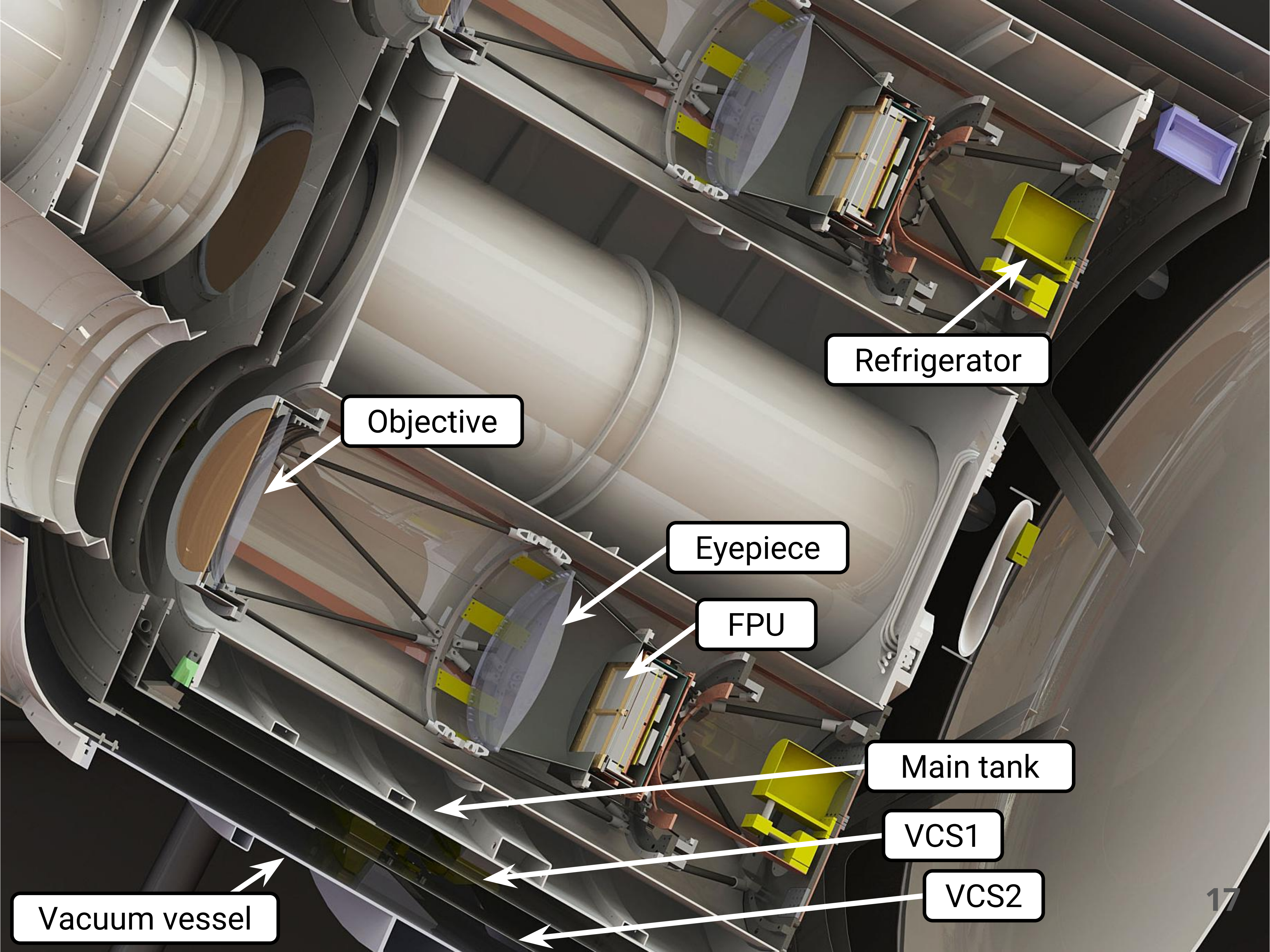
Receiver cryogenic effort include a significant push in sub-Kelvin cooling requirements — arguably one of the biggest challenges of CMB-S4 / Simons Observatory

See talk by **Nicholas Galitzki** from CMB-S4 meeting @ SLAC in February 2017

Stockholm University

The SPIDER flight cryostat

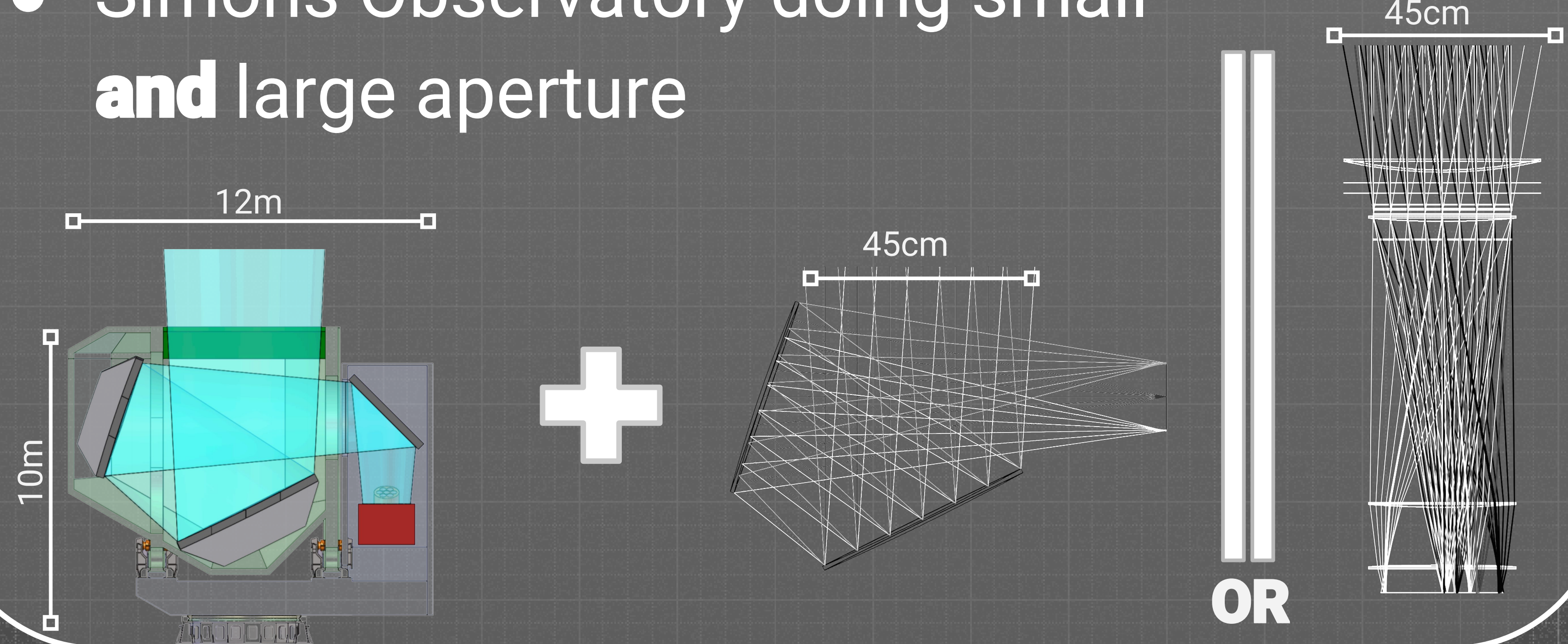



Refrigerator
Objective
Eyepiece
FPU
Main tank
VCS1
VCS2
Vacuum vessel

Telescope packing is a challenge!

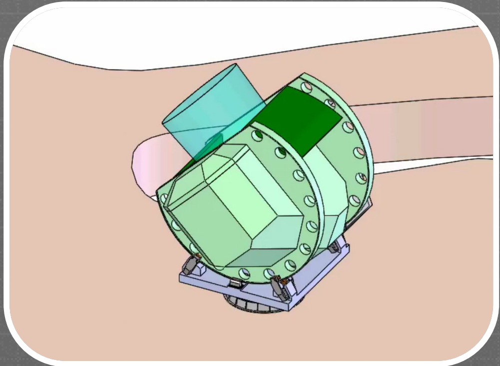
High resolution = large telescopes

- Can large telescopes do $\ell < 100$?
  - Still unclear, but see SPTPol's [Henning et al. (2017)]
- Simons Observatory doing small **and** large aperture



Large aperture telescope

- A challenge to pick the correct aperture size for large telescope
  - SO decided on ~6.0m primary aperture
    - Around 1.5 arcmin FWHM at 150 GHz
    - Sweet spot in science/cost parameter space
  - Deploying 3–5 frequency bands



- Sharing technology with CCAT-p
  - Sub-millimeter observations at 5600m
  - Galactic ecology: clusters, gas flow, SZ, etc.
  - Plan to start building this year
  - See **Frank Bertoldi**’s talk from yesterday

CCAT-p

FOV drivers

- Larger field of view (FOV) means more FPU area (throughput) and therefore the ability to use more detectors, but you also get
  - Larger curvature optics
    - More aberrations (systematics)
  - Higher index of refraction lenses
    - Can lead to optical ghosting
  - Detectors on edge of FOV forced to view not-so-clean sky patches
    - Effectively reducing sensitivity

Possible Systematics

- ...need to strike a balance between detector volume and systematics

Small aperture telescopes

Reflecting

Pros

- Fewer lossy elements (lenses)
- Optics need not be frequency optimized (unlike refractors)
- Larger FPU area relative to refracting telescopes
- Outsourced machining possible

Cons

- Spurious sidelobes
  - Sometimes direct path from aperture to focal plane
- Magnetic shielding challenges
- Higher sidelobe power
- Thought to require larger cryogenic volume for 1-4 K optics

Refracting

Pros

- Symmetric beams
- High Strehl across focal plane
- Easy to swap optics tubes
- Lower (f/#) relative to reflecting telescopes
- Shared development and technology with optics tubes for larger aperture telescopes

Cons

- AR coating challenges
  - Ghosting from flat surfaces
- Omnidirectional sidelobes
- Longer cryostats

Optical systematics

- Optical non-idealities often viewed in hindsight
  - Numerous ways to generate a spurious polarization signal
  - How can we state with confidence that our design is robust?
  - Do we reuse old designs that have stood the test of time?
    - Not unless we want to build a lot of telescopes...
  - Can we invent new systems that are better?
- Incredibly challenging to fully characterize/understand the shortcomings of an optical design pre-deployment. However, we can:
  - Try to learn from our mistakes
  - Identify high risk components through careful accounting
  - Budget in time to characterize the as-deployed instrument

Stockholm University

Optical systematics

- A few types of optical systematics
  - Beam ellipticity from asymmetrical stop/aperture illumination
  - Cross polarization and instrument T-P leakage
  - Diffraction on baffles on other edge elements
  - Stray reflections that directly illuminate focal plane
  - Scattering in imperfect optical components
  - **Internal reflections (ghost beams) from AR coating delamination**
  - Reflections due to surface roughness (Ruze envelope)
  - Spillover from detectors/feedhorns
  - Structural deformation from thermal effects
  - **Diffraction on panel gaps**
  - Ground, moon, sun, galaxy pickup
  - Window and lens distortion
  - Detector crosstalk (fake sidelobes)
  - and the list goes on...

Stockholm University

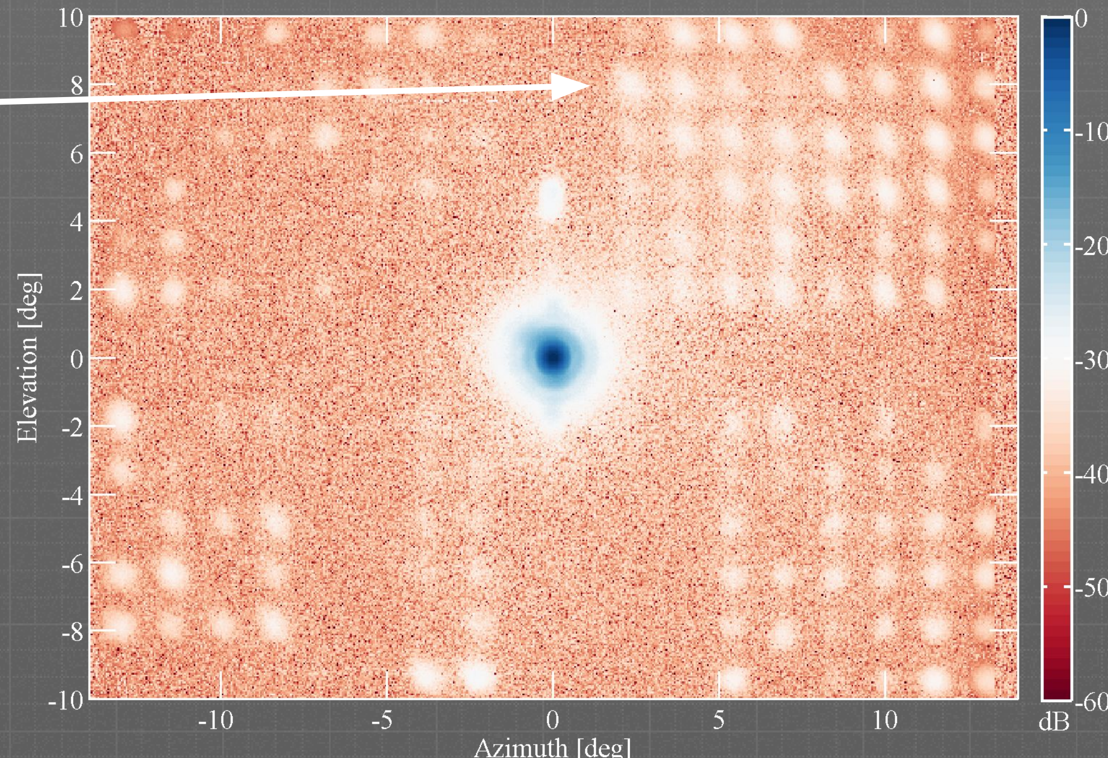
Optical ghosting (lens flare)

- Off-axis beam response caused by internal reflections
    - Often associated with non-idealities in anti-reflection coatings

Diffuse version of the main beam translated diagonally across focal plane

Seen here in SPIDER failed HWP AR coating (replaced before flight)

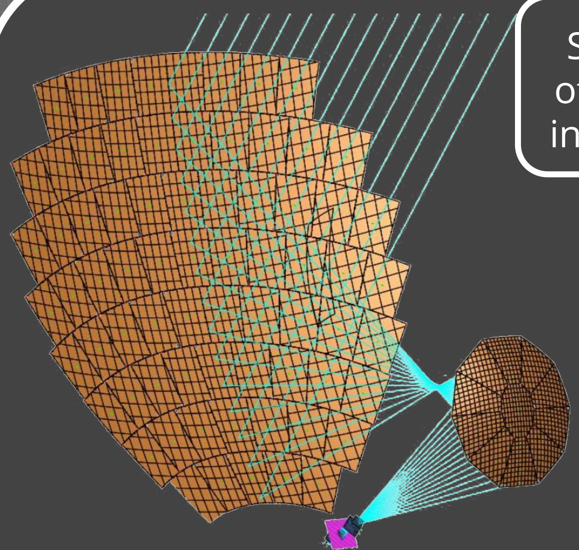
Number of potential failures can be large for complex optical systems



Stockholm University

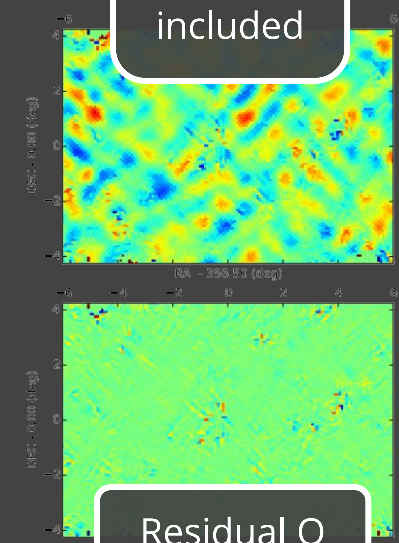
Panel gap diffraction

- Physical optics simulations show 2mm panel gaps create non-negligible T->P leakage in ACT



Simulations of these types of effects should be used to inform future reflector RFP's

Stokes Q w/ effect included



Residual Q

P. Fluxá et al (2016)

Stockholm University

Conclusions

- Crossed Dragone telescopes appear to offer the most compact way to field 100k detector focal planes
- Simons Observatory to deploy 5–6 m Crossed Dragone telescope feeding 35k detectors (with room for 100k)
- Also plans to deploy small aperture systems with approx. 45cm optics (reflector or refractor)
- We will face significant cryogenic challenges associated with making use of large focal plane area
- Full optical characterization is going to be very difficult

Stockholm University