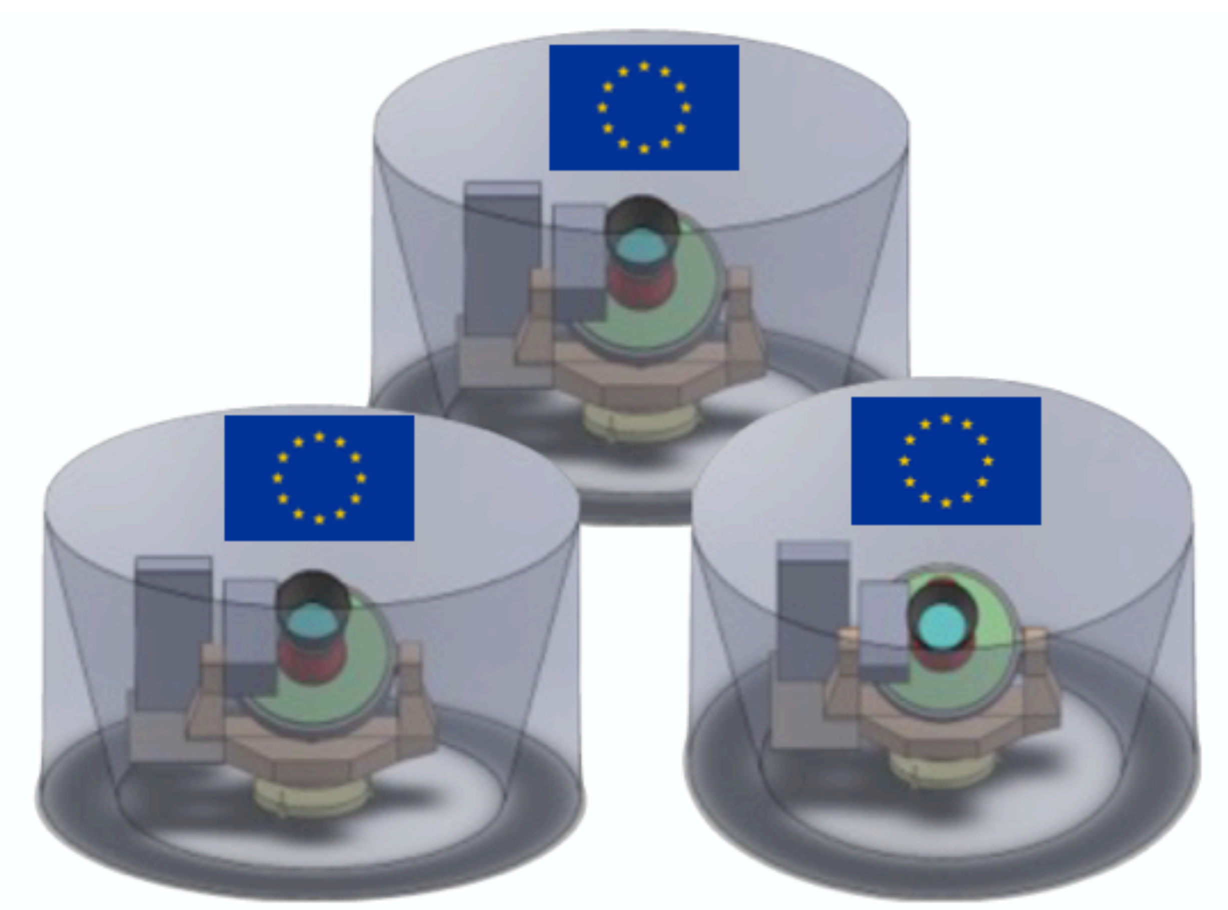
The SO:Europe Telescope Array
A small aperture facility in Chile



SIMONS OBSERVATORY

Michael Brown

The University of Manchester

What is the SO:Europe Telescope Array?

- A **proposal developed by a European (so far, mostly UK) consortium** for a major CMB instrument at the SO site in Chile.
- The proposal is subject to **agreement with the SO collaboration** (who we anticipate working closely with).
- Institutes involved in discussions to date:

UK:
University of Cardiff
University of Cambridge
Imperial College London
University of Manchester
University of Oxford
University of Sussex

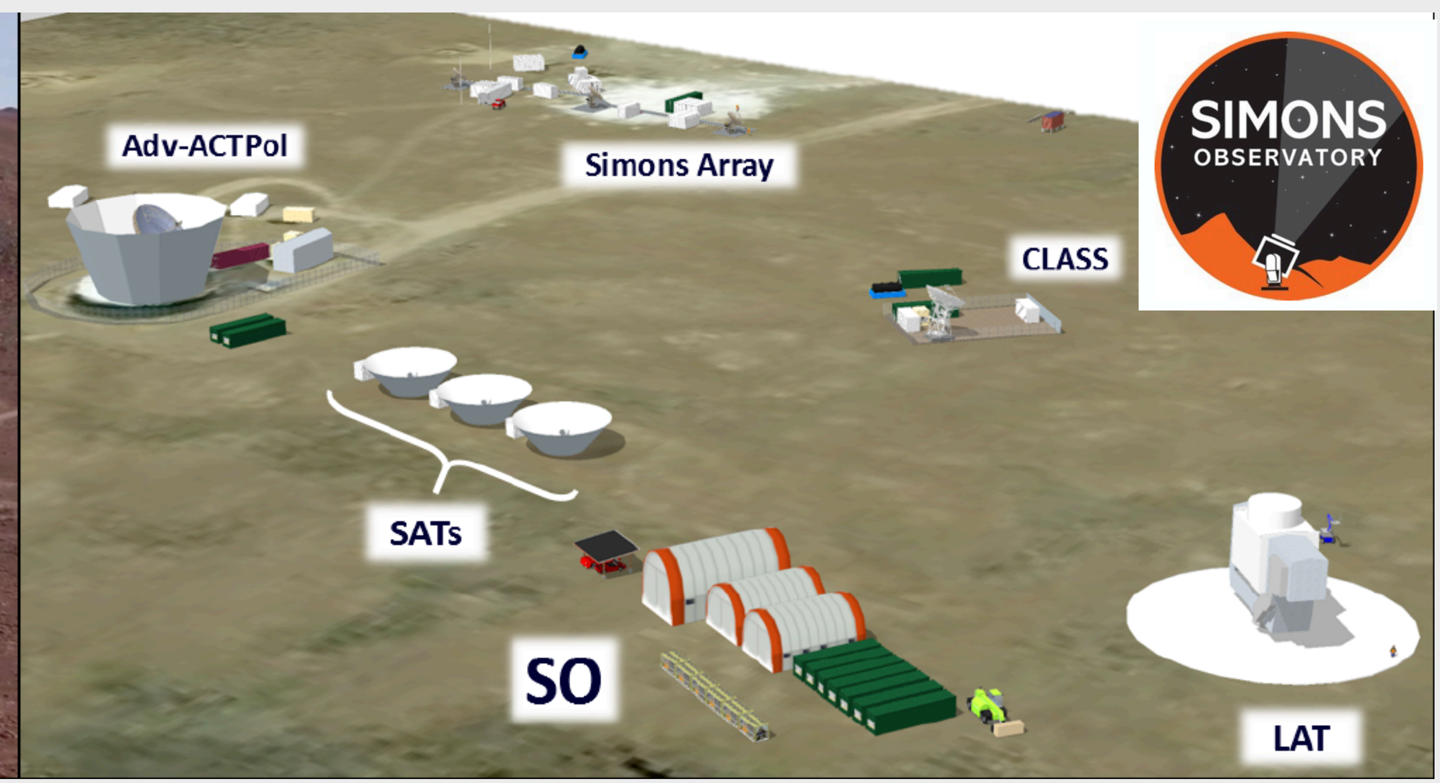
France:
APC

Italy:
SISSA

…and informed by initial discussions with SO.

Why Chile / Simons Observatory?

- Existing, well established CMB presence in Chile (POLARBEAR/Simons Array, ACT, CLASS).
- Simons Observatory (SO) is a funded project and under construction - can benefit from the momentum, experimental know-how and infrastructure/site facilities that SO offers.
- Strong network of European collaborators already exists within SO (including several European scientists in leadership roles).



The Simons Observatory collaboration

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers**

United States
- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Japan
- KEK
- IPMU
- Tohoku
- Tokyo

Canada
- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- University of British Columbia

Chile
- Pontificia Universidad Catolica
- University of Chile

Europe
- Stockholm University - Sweden
- APC – France
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa
- Kwazulu-Natal, SA

Australia
- Melbourne

Israel
- Tel Aviv

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- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

Already a large European presence in SO - can build on this.

- Melbourne

Israel

- Tel Aviv

SO people in Europe

THE SIMONS OBSERVATORY: SCIENCE GOALS AND FORECASTS

The Simons Observatory Collaboration[1]: Peter Ade[2], James Aguirre[3], Zeeshan Ahmed[4,5], Simone Aiola[6], Aamir Ali[7], David Alonso[2,8], Marcelo A. Alvarez[7,9], Kam Arnold[10], Peter Ashton[7,11], Jason Austermann[12], Humna Awan[13], Carlo Baccigalupi[14,15], Taylor Baildon[16], Darcy Barron[7,17], Nick Battaglia[18,19], Richard Battye[20], Eric Baxter[3], Andrew Bazarko[6], James A. Beall[12], Rachel Bean[18], Dominic Beck[21], Shawn Beckman[7], Benjamin Beringue[22], Federico Bianchini[23], Steven Boada[13], David Boettger[24], J. Richard Bond[25], Julian Borrill[9,7], Michael L. Brown[20], Sarah Marie Bruno[6], Sean Bryan[26], Erminia Calabrese[2], Victoria Calafut[18], Paolo Calisse[10,24], Julien Carron[27], Anthony Challinor[28,22,29], Grace Chesmore[16], Yuji Chinone[7,30], Jens Chluba[20], Hsiao-Mei Sherry Cho[4], Steve Choi[6], Gabriele Coppi[3], Nicholas F. Cothard[31], Kevin Coughlin[16], Devin Crichton[32], Kevin D. Crowley[10], Kevin T. Crowley[6], Ari Cukierman[7], Mitch D'Ewart[4], Rolando Dünner[24], Tijmen de Haan[11,7], Mark Devlin[3], Simon Dicker[3], Joy Didier[33], Matt Dobbs[34], Bradley Dober[12], Cody Duell[35], Shannon Duff[12], Adri Duivenvoorden[36], Jo Dunkley[6,37], John Dusatko[4], Josquin Errard[21], Giulio Fabbian[38], Stephen Feeney[19], Simone Ferraro[39], Pedro Fluxà[24], Katherine Freese[16,36], Josef Frisch[4], Andrei Frolov[40], George Fuller[10], Brittany Fuzia[41], Nicholas Galitzki[10], Patricio A. Gallardo[35], Jose Tomas Galvez Ghersi[40], Jiansong Gao[12], Eric Gawiser[13], Martina Gerbino[36], Vera Gluscevic[42,6,43], Neil Goeckner-Wald[7], Joseph Golec[16], Sam Gordon[44], Megan Gralla[45], Daniel Green[10], Arpi Grigorian[12], John Groh[7], Chris Groppi[44], Yilun Guan[46], Jon E. Gudmundsson[36], Dongwon Han[47], Peter Hargrave[2], Masaya Hasegawa[48], Matthew Hasselfield[49,50], Makoto Hattori[51], Victor Haynes[20], Masashi Hazumi[48,30], Yizhou He[52], Erin Healy[6], Shawn Henderson[53,5], Carlos Hervias-Caimapo[20], Charles A. Hill[7,11], J. Colin Hill[19,42], Gene Hilton[12], Matt Hilton[32], Adam D. Hincks[54,25], Gary Hinshaw[55], Renée Hložek[56,57], Shirley Ho[11], Shuay-Pwu Patty Ho[6], Logan Howe[10], Zhiqi Huang[58], Johannes Hubmayr[12], Kevin Huffenberger[41], John P. Hughes[13], Anna Ijjas[6], Margaret Ikape[56,57], Kent Irwin[4,53,5], Andrew H. Jaffe[59], Bhuvnesh Jain[3], Oliver Jeong[7], Daisuke Kaneko[30], Ethan Karpel[53,5], Nobuhiko Katayama[30], Brian Keating[10], Sarah Kernasovski[53,5], Reijo Keskitalo[9,7], Theodore Kisner[9,7], Kenji Kiuchi[60], Jeff Klein[3], Kenda Knowles[32], Brian Koopman[35], Arthur Kosowsky[46], Nicoletta Krachmalnicoff[14], Stephen Kuenstner[53,5], Chao-Lin Kuo[4,53,5], Akito Kusaka[11,60], Jacob Lashner[33], Adrian Lee[7,11], Eunseong Lee[20], David Leon[10], Jason S.-Y. Leung[56,57,25], Antony Lewis[27], Yaqiong Li[6], Zack Li[37], Michele Limon[3], Eric Linder[11,7], Carlos Lopez-Caraballo[24], Thibaut Louis[61], Lindsay Lowry[10], Marius Lungu[6], Mathew Madhavacheril[37], Daisy Mak[59], Felipe Maldonado[41], Hamdi Mani[44], Ben Mates[12], Frederick Matsuda[30], Loïc Maurin[24], Phil Mauskopf[44], Andrew May[20], Nialh McCallum[20], Chris McKenney[12], Jeff McMahon[16], P. 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[1] Correspondence address: so_tac@simonsobserv
[2] School of Physics and Astronomy, Cardiff University, The Parad
[3] Department of Physics and Astronomy, University of Pennsylvania, 209 South
[4] SLAC National Accelerator Laboratory, Menlo Par
[5] Kavli Institute for Particle Astrophysics and Cosmology, M
[6] Joseph Henry Laboratories of Physics, Jadwin Hall, Princeton University, Princeton, NJ, USA 08544
[7] Department of Physics, University of California, Berkeley, CA, USA 94720
[8] University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

Simons Observatory science goals

1. Primordial perturbations (r, $P(k)$, f_{NL})

2. Relativistic species

3. Neutrino mass

4. Deviations from Λ (σ_8 z=1-3, H_0)

5. Galaxy evolution (feedback in massive halos)

6. Reionization (typical duration)

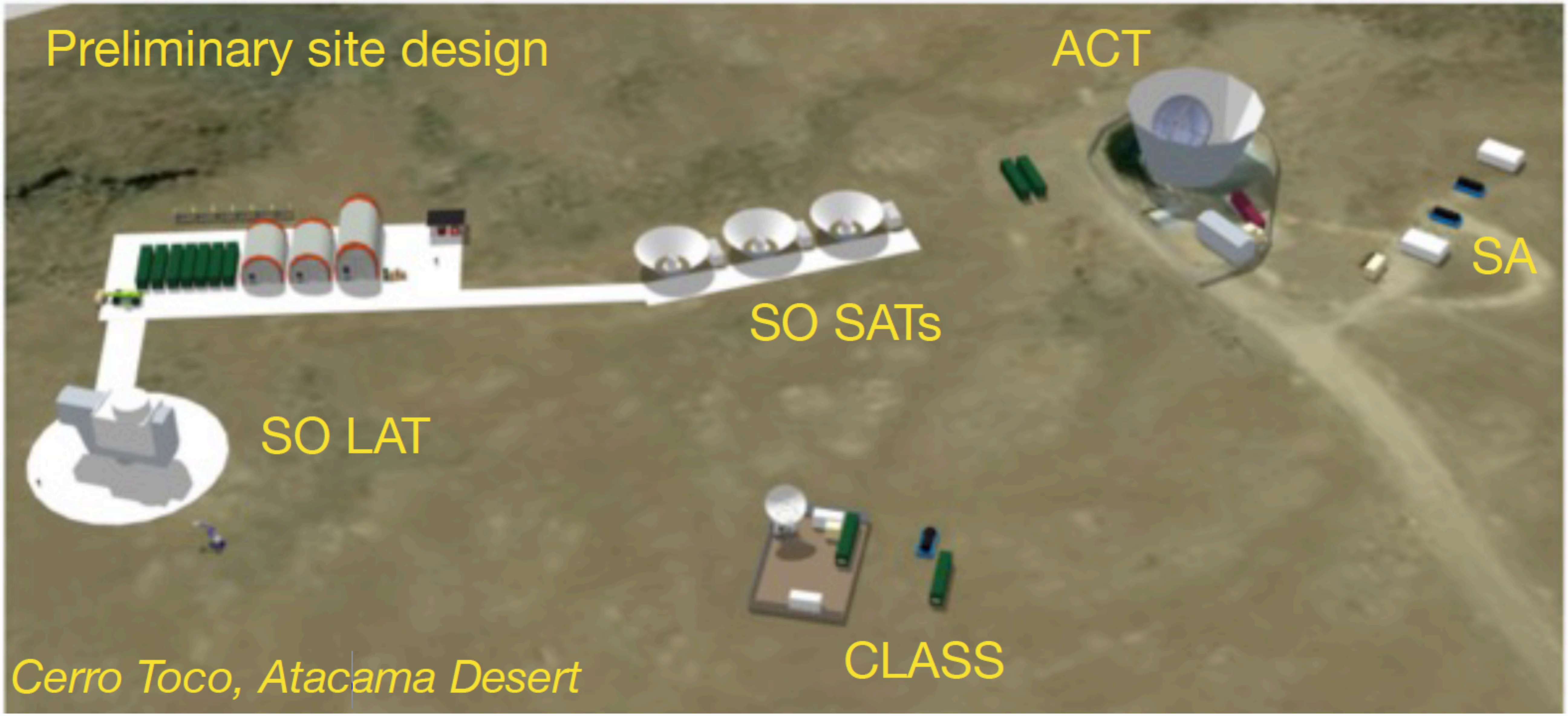
Legacy catalogs: clusters, radio galaxies, dusty star-forming galaxies

+ lots more great science: dark matter, BBN, modified gravity, birefringence…

Common suite of science topics with CMB-S4

Simons Observatory

One 6m Large Aperture Telescope
Three 0.5m Small Aperture Telescopes
Five-year survey planned 2021-26, six frequencies 30-280 GHz

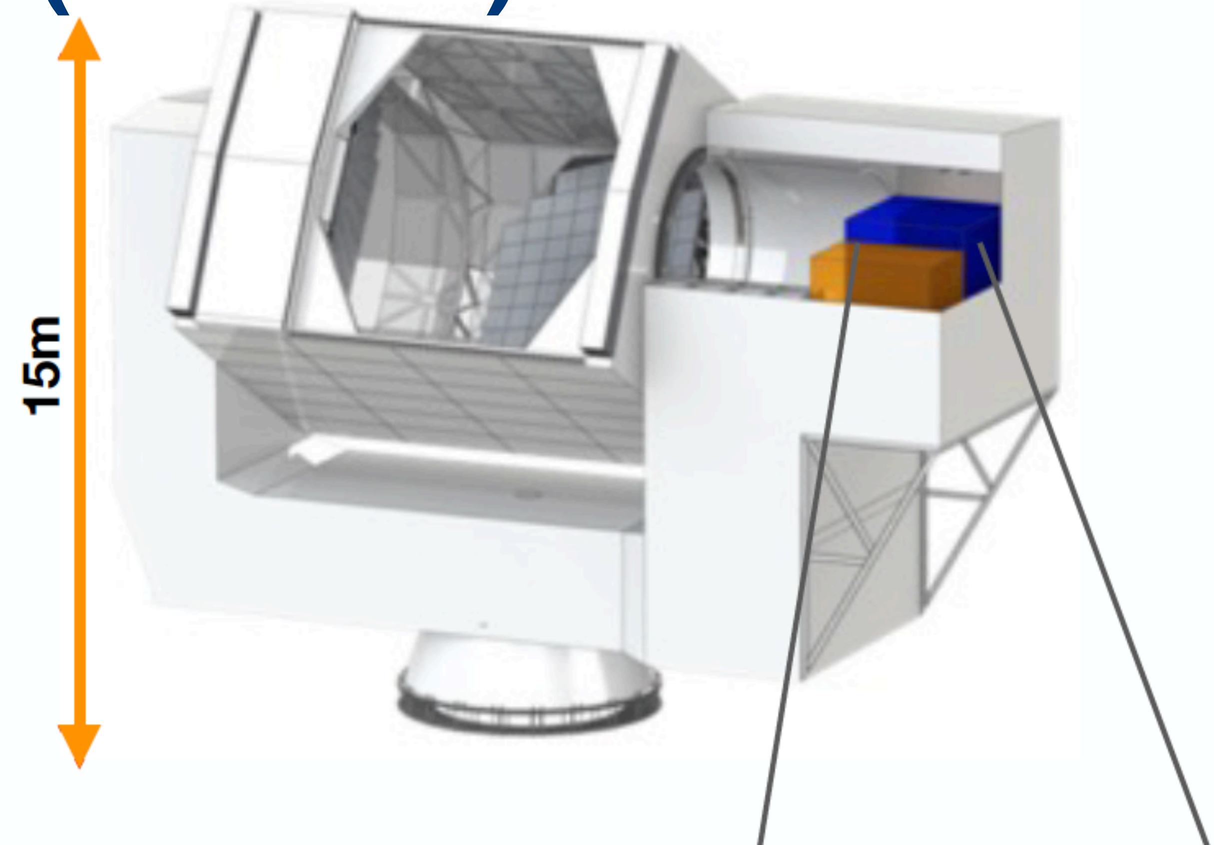


Large telescope: resolution needed for all science goals except tensor-to-scalar ratio
Small telescopes: lower noise at the few-degree-scale B-mode signal, for tensor-to-scalar ratio

The Simons Observatory instruments and technology

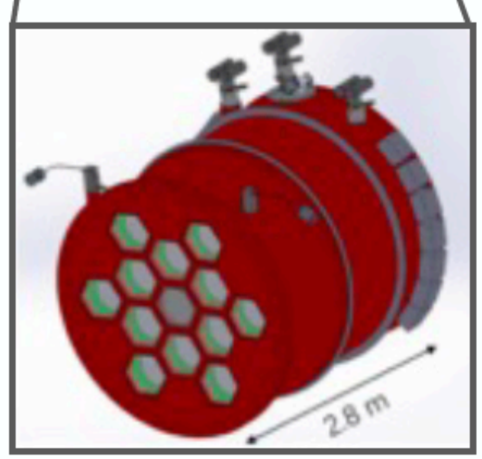
large aperture telescope (1 "LAT")

30,000 detectors



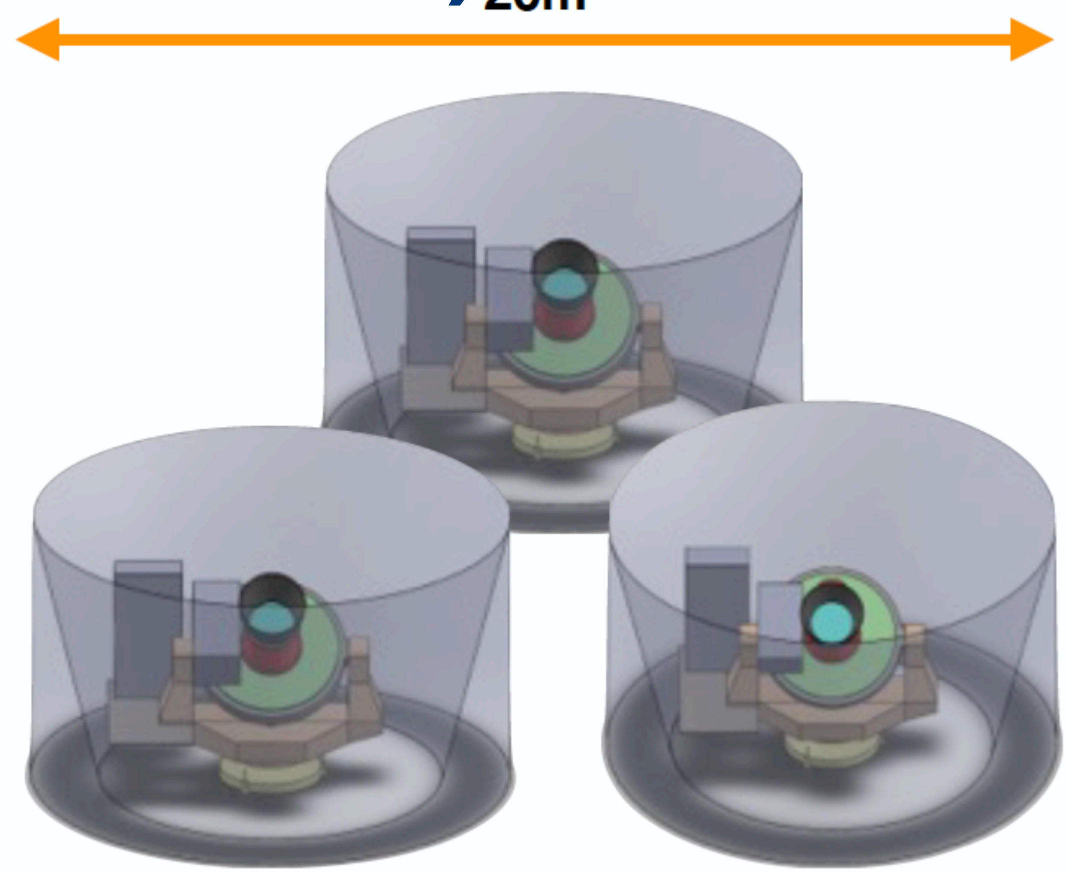
6 m crossed Dragone fed by up to 13, 38 cm optics tubes. baseline=7 tubes for SO, with baseline pixels:

- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz



small aperture telescopes (3 "SATs")

30,000 detectors



Three 42 cm diameter refractors, baseline dichroic pixels:
30/40 I 90/150 I 90/150 I 220/270 GHz

Same concept as CMB-S4: mixture of large and small aperture telescopes

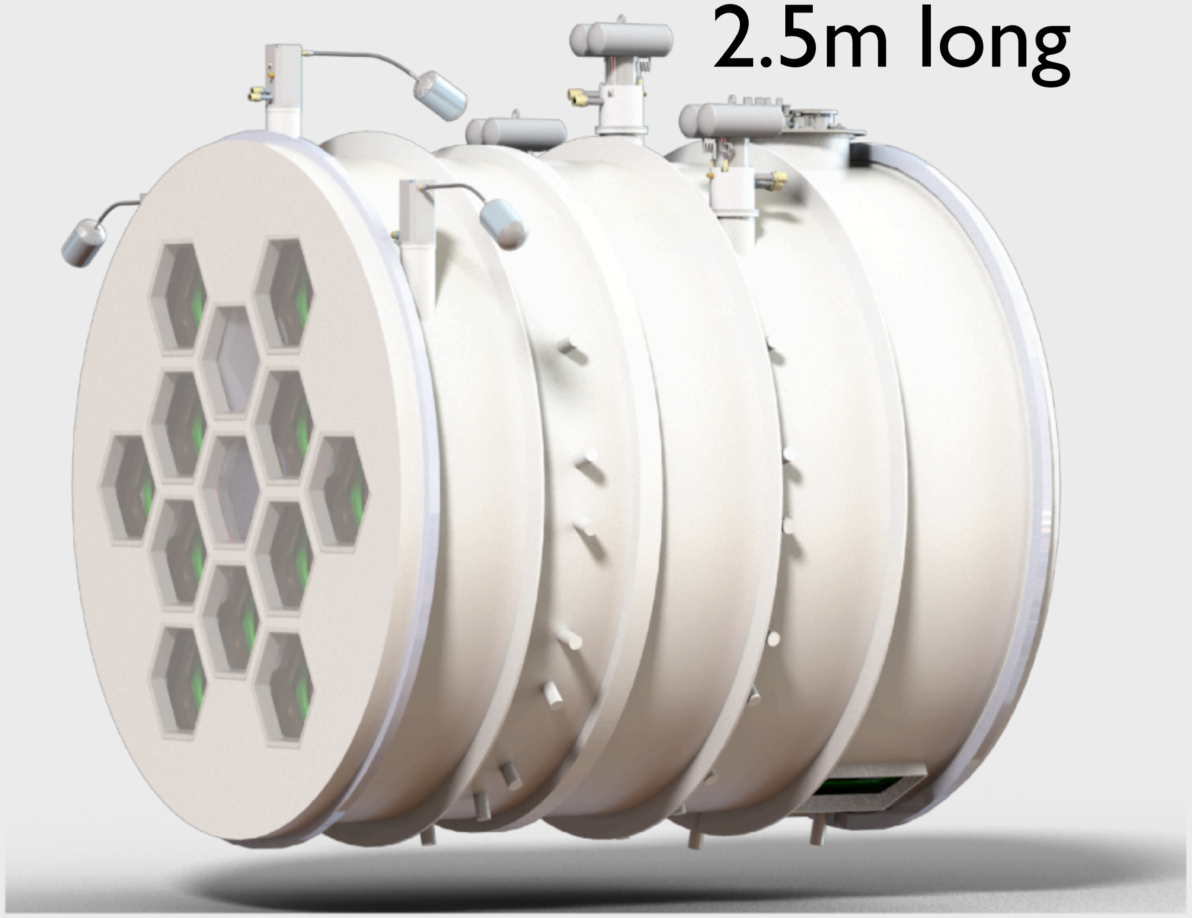
SIMONS OBSERVATORY
22°57'31" SOUTH, 67°47'15"WEST ELEVATION: 17,027.6' PARQUE ASTRONÓMICO ATACAMA, CHILE

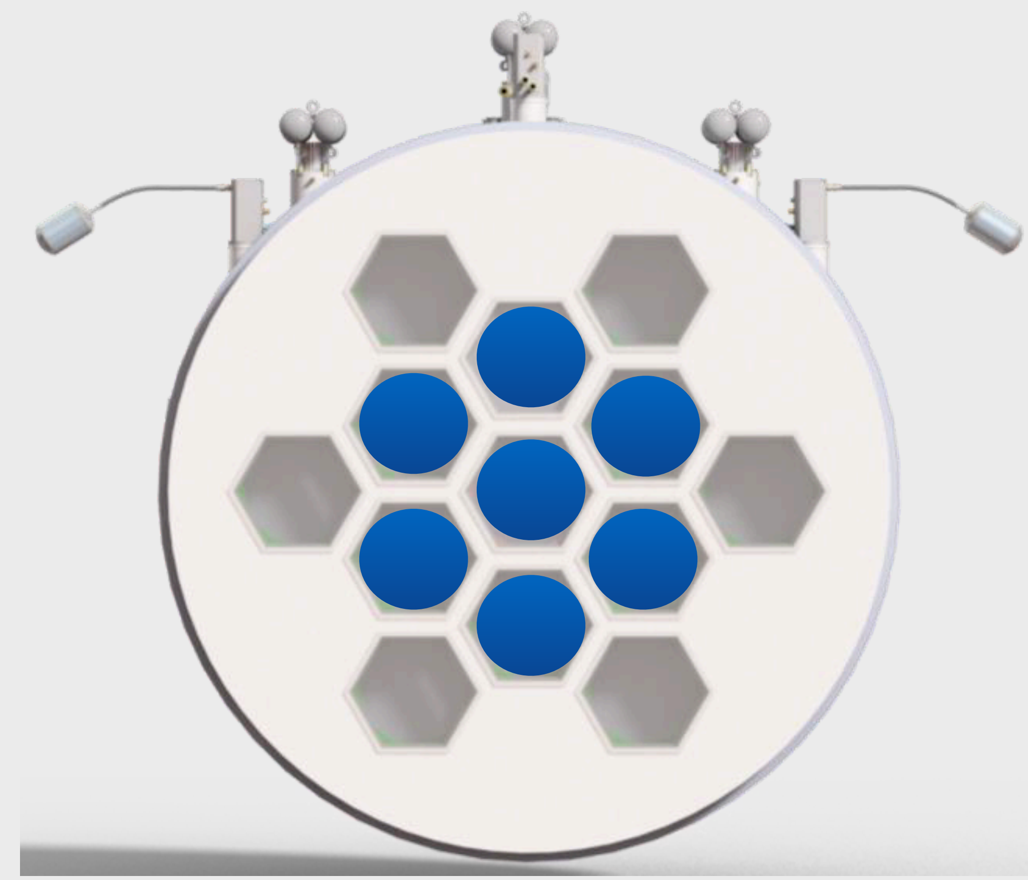
Why small apertures?

- Have assessed the potential science impact of two options for a major European instrumental contribution to SO.
- Forecasts & conclusions that follow are not those of SO - they are those of the **UK/European proposal team**.

Option 1: Adding 6 European optics tubes to LAT receiver:

2.5m long





2.4m diameter

~5,000 kg

30,000 detectors

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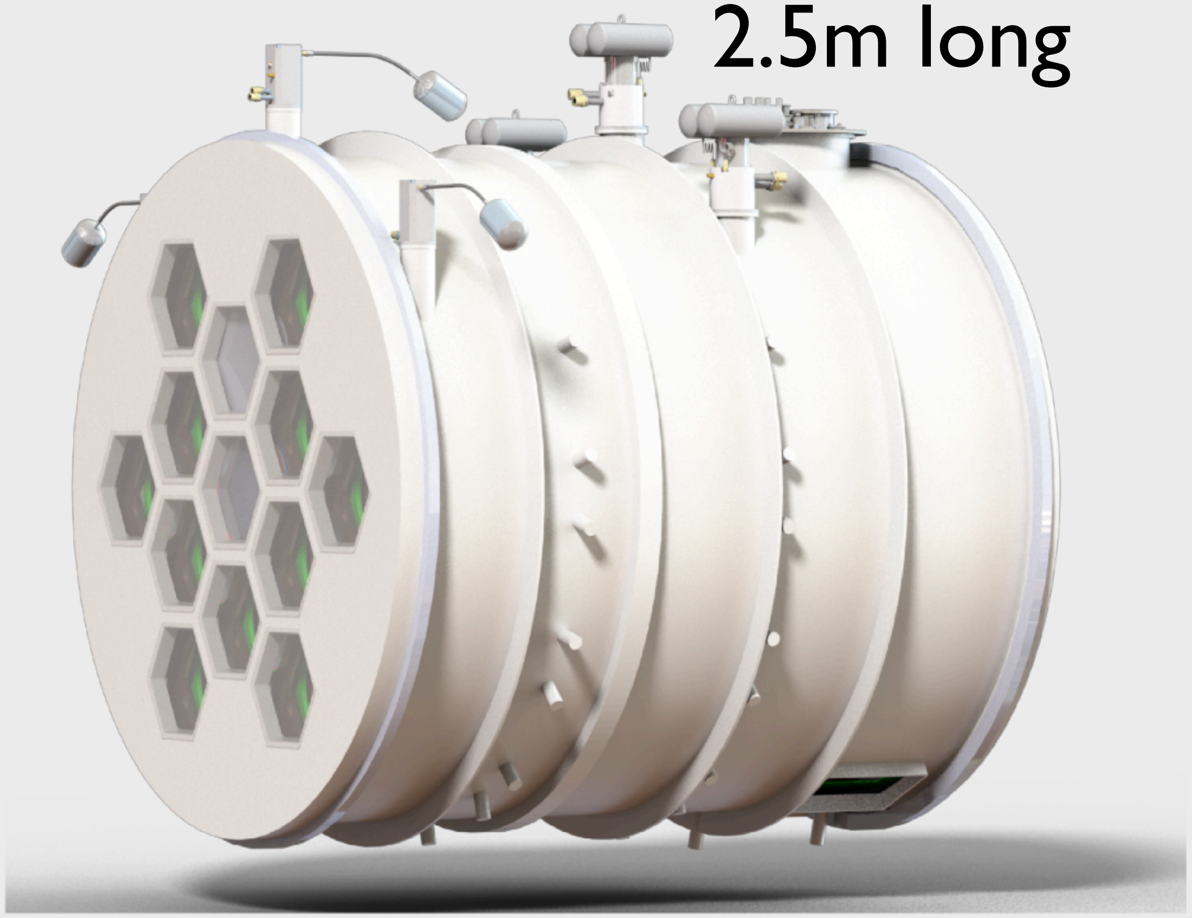
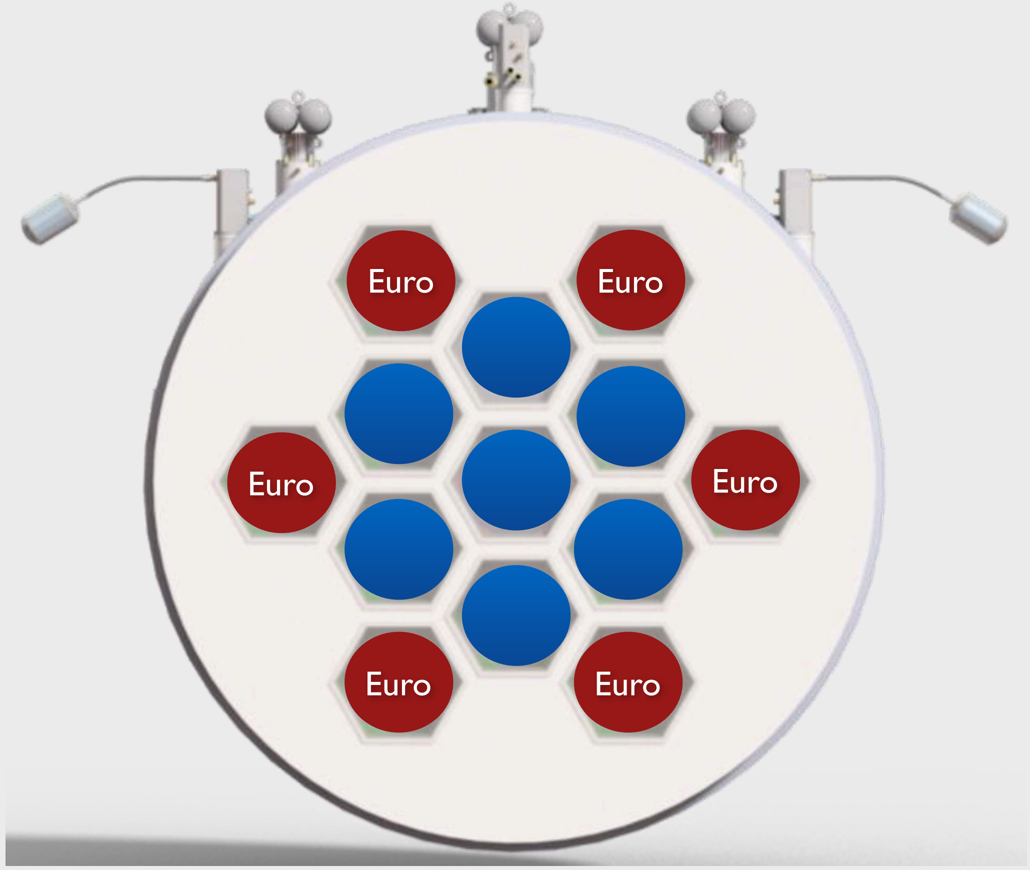




2.4m diameter

~5,000 kg

~60,000 detectors

Why small apertures?

Option 1: Adding 6 European optics tubes to LAT receiver:

- Focussed on high-ell science and de-lensing for "r".
- Forecasts for neutrino mass and N_{eff} after five year survey covering 40% of sky:

Baseline SO:	→	+ Euro tubes:
$\sigma(\Sigma m_\nu) = 74$ meV		$\sigma(\Sigma m_\nu) = 71$ meV
$\sigma(N_{eff}) = 0.055$		$\sigma(N_{eff}) = 0.050$

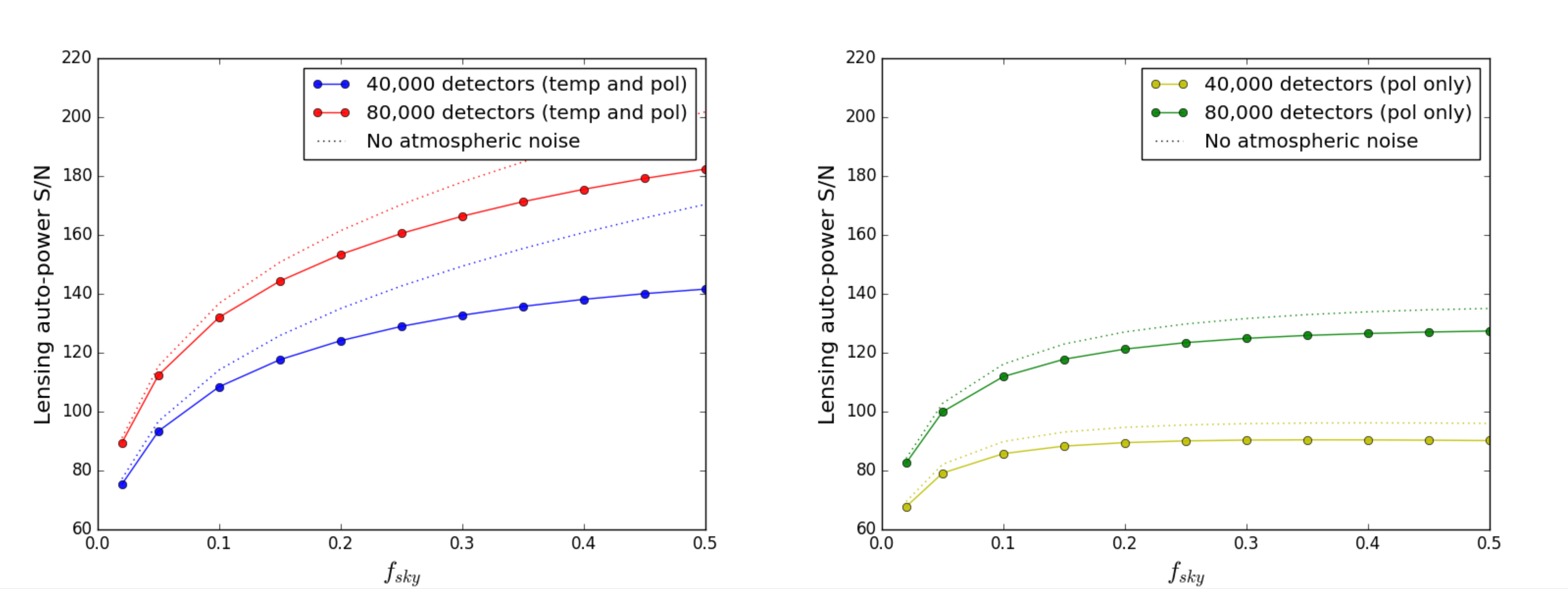
(E Calabrese)

- Even doubling the mapping speed of the LAT, difficult to make a large impact on headline science goals.
- Sample variance dominated at these noise levels so going deeper doesn't help much. (Also limited by external degeneracies, e.g. with optical depth, τ.)

Why small apertures?

Option 1: Adding 6 European optics tubes to LAT receiver:

- Improvement looks better in terms of S/N ratio of lensing potential reconstruction:



(D Han)

- Doesn't translate to better neutrino mass constraints, but useful for cross-correlations with LSS surveys.

Why small apertures?

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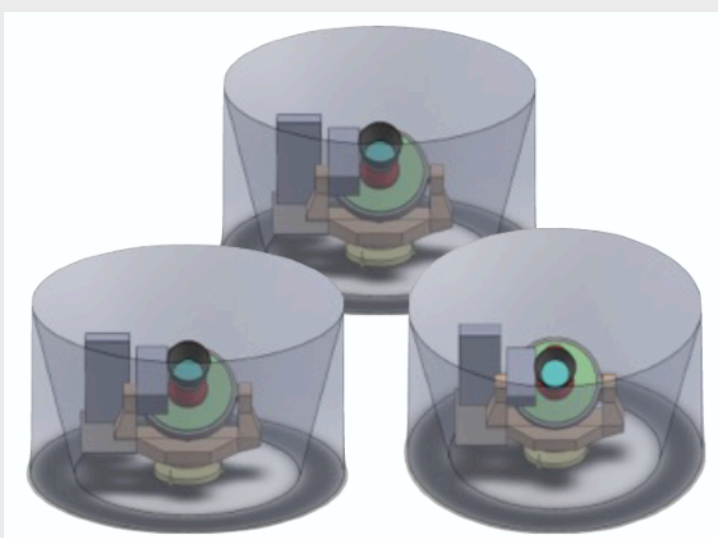
Option 2: Adding three European SATs:



30,000 detectors

60,000 detectors

Why small apertures?

Option 2: Adding three European SATs:

- Focussed on search for primordial gravitational waves.
- Forecasts for "r" after five year survey covering 5% of sky:

Instrument Configuration	SO σ(r)	SO + SO-EBT σ(r)
No delensing:	4.8×10^{-3}	3.3×10^{-3}
50% delensing:	3.5×10^{-3}	2.1×10^{-3}
75% delensing:	2.8×10^{-3}	1.4×10^{-3}

Based on three forecasting pipelines:

- D Alonso
- J Errard
- C Hervias-Caimapo

- These results are for case where all Euro SATs are at 90/150 GHz (and existing SO SATs are spread across the $27 < \nu < 280$ GHz range).
- Also explored other options for Euro SAT frequencies but above was best-performing configuration.

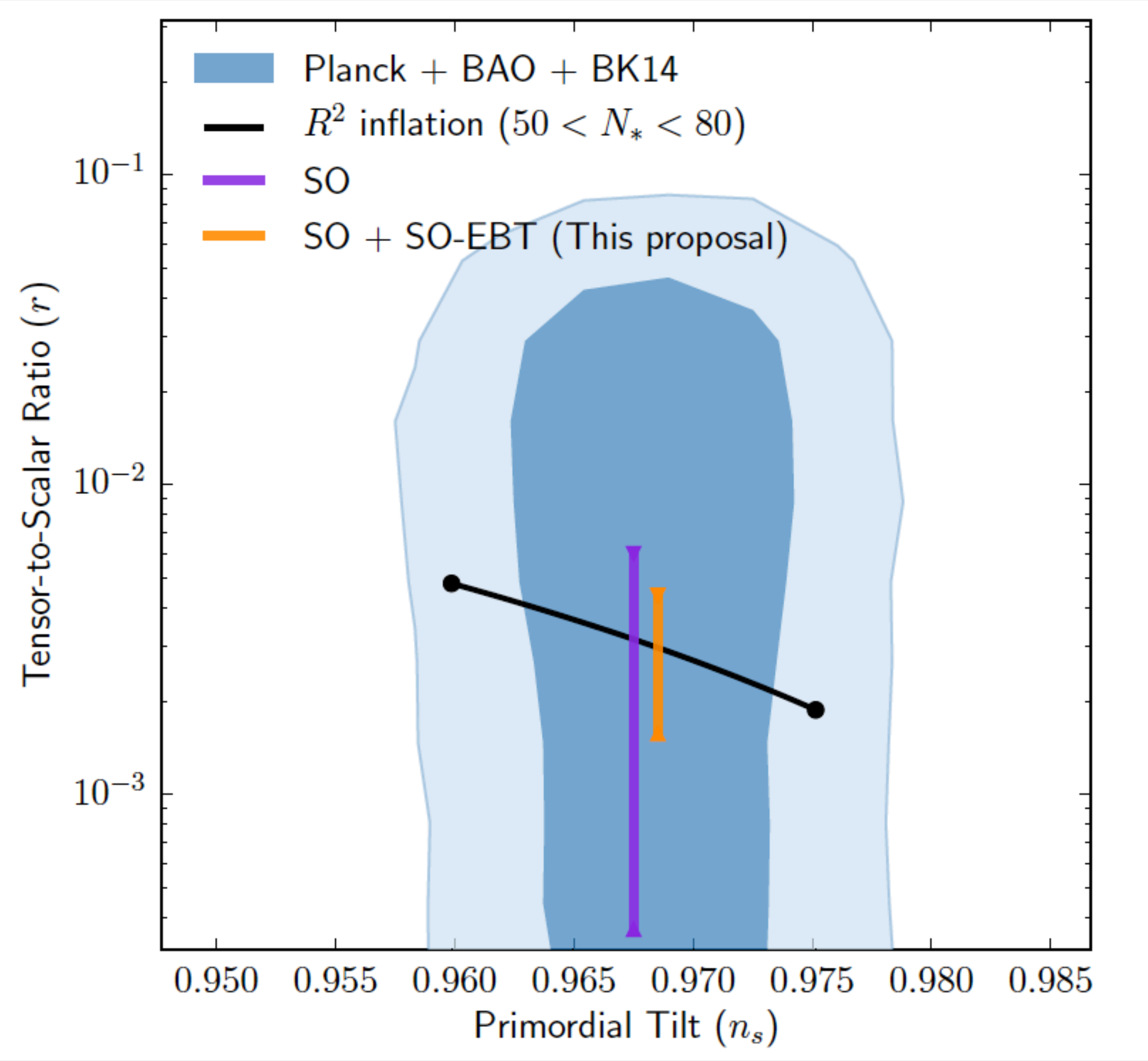
Why small apertures?

Option 2: Adding three European SATs:

- $1/N_*^2$ models (e.g. R^2 inflation) typically predict:

$$2 \times 10^{-3} < r < 5 \times 10^{-3}$$

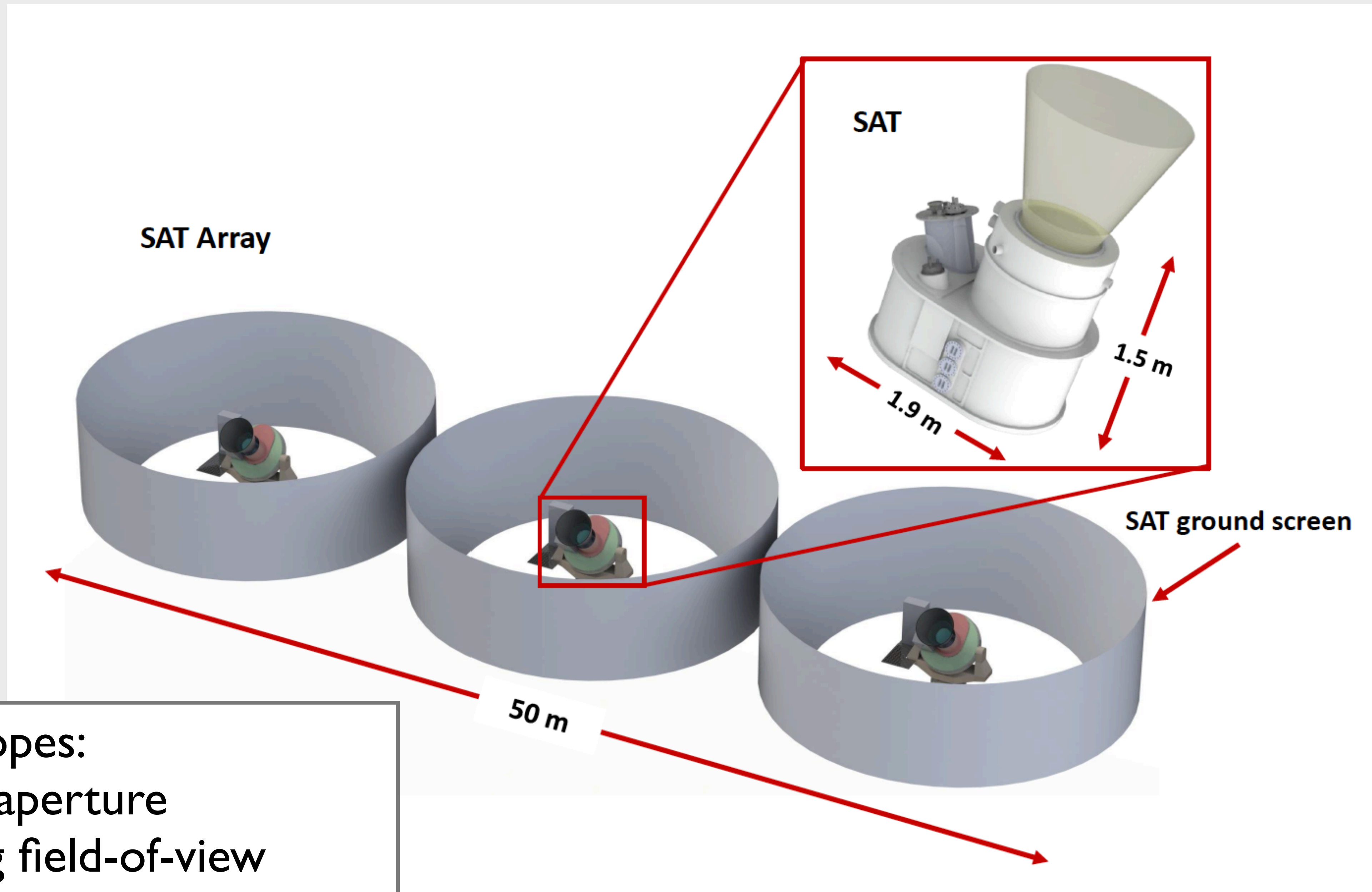
- Euro SATs can potentially bring this important class of models within reach of SO.



- Euro SATs providing 50% of SO sensitivity to primordial B-modes and potentially bringing important candidate inflation models within reach.

Instrument Concept

- Great deal of work already put into designing SO SATs. Will obviously want to use many aspects of that work…

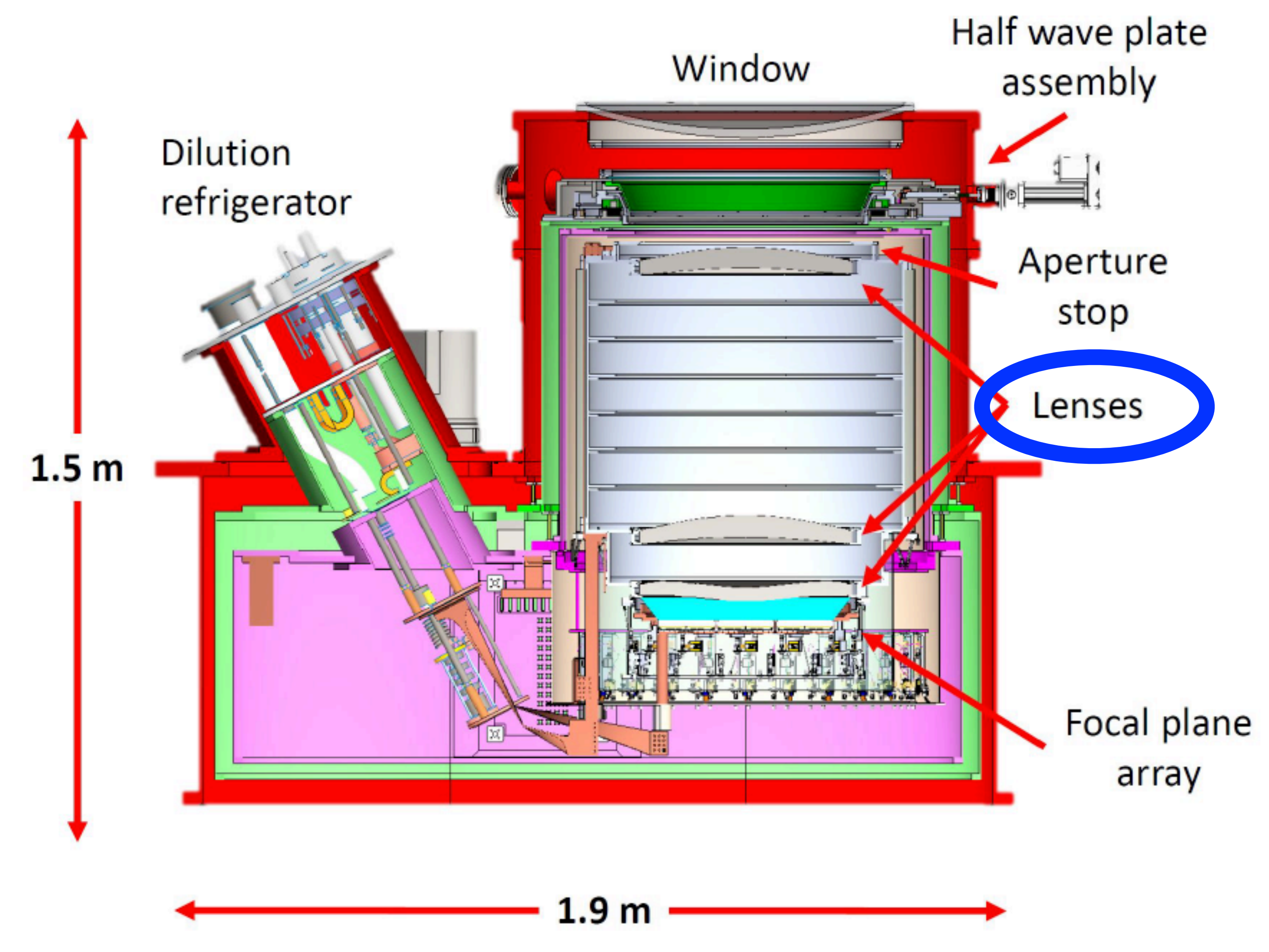


3 telescopes:
- 42cm aperture
- 35 deg field-of-view
- 2 x 90/150 GHz
- 1 x 220/270 GHz
- + 27/39 GHz optics tube

Instrument Concept

- …but also include key distinguishing features in SO:Europe Telescope Array (SO:ETA) design:

1. Meta-materials for optical components:

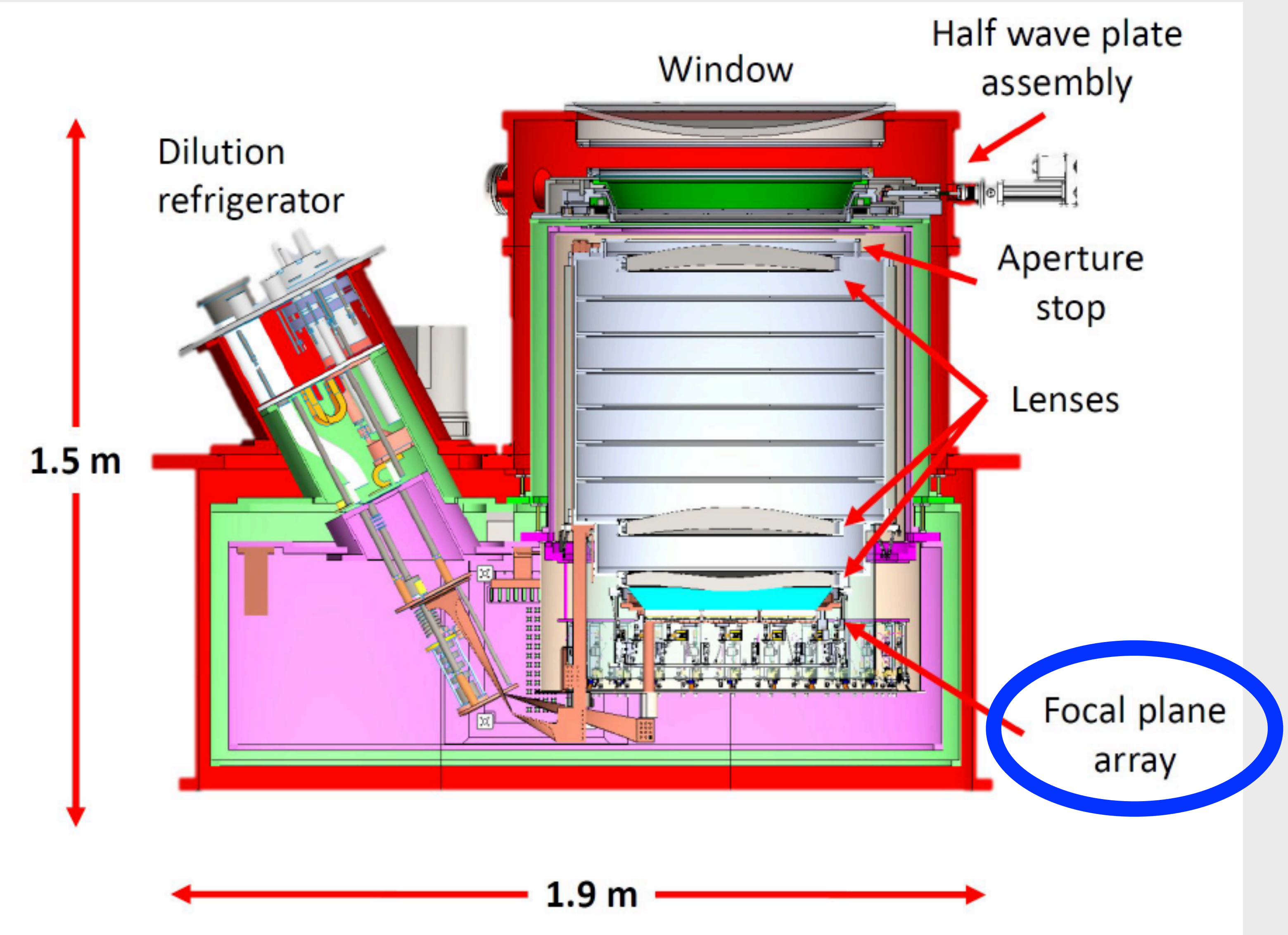


- Rather than traditional (curved) silicon lenses, will use **meta-material (MM) lenses**.
- MM lenses are fraction of mass of silicon lenses and are **flat** ⇛ **much easier to AR coat**.
- Likely to become **key enabling technology for CMB-S4**.
- Also use **metal-mesh filters** and **HWPs** - key technology developed in Europe.

Instrument Concept

2. Kinetic Inductance Detectors for focal plane arrays:

(See talks by Catalano and Camus this morning.)



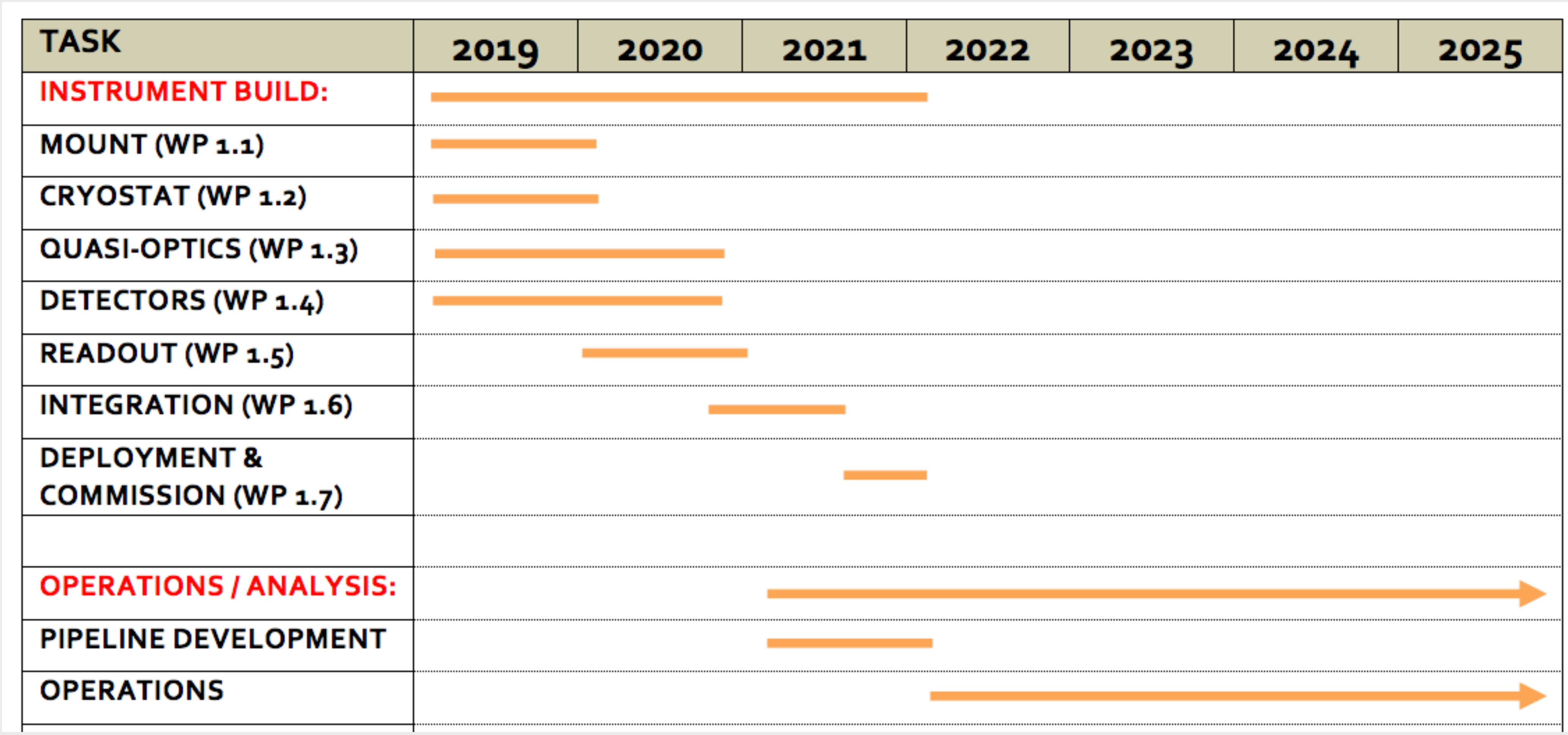
- Instead of the TES detectors **European SATs will use KID** focal plane arrays.
- Much **easier to fabricate** than TESs.
- Much **easier to readout** than TESs - do not require complex SQUID readout systems.
- Multiple **European** labs have world-leading **expertise is KIDs**.

- Likely to become **key enabling technology for CMB-S4**.

Proposed operations model

- Design, construction, deployment, commissioning and operations of the SO:ETA **led by the European team**.
- No separate arrangements required with **Chilean authorities** since we will be part of wider SO.
- SO:ETA pays a fee to SO in return for **site-related facilities** (e.g. foundations & concrete pads, power, internet, accommodation etc.).
- European team will also lead a separate **analysis pipeline** for the SO:ETA data processing, up to the production of frequency maps.
- **Higher-level science exploitation** (which requires combination with other SO SATs and LAT - and **publications** - will be done at the SO project-wide level.

Estimated schedule



- Procure **major components (e.g. mount, cryostats) from industry** - free up University labs to concentrate on bespoke items (detectors, optical components), integration & commissioning.
- **Re-purpose** much of **existing SO design work** to save time (and money!).
- Existing SO schedule has **first SO SAT** installed on site in **mid-2020**.
- A **2019 start** to SO:ETA project would put us **~one year behind**.

Estimated budget

Task 1 - Instrument Build & Commissioning:

WP 1.0 (Project Management)	3 FTE
WP 1.1 (Telescope Mounts)	2 FTE + €2.5M
WP 1.2 (Cryostats)	3.5 FTE + €1M
WP 1.3 (Quasi-Optics)	8.5 FTE + €0.1M
WP 1.4 (Detectors)	15.5 FTE + €0.3M
WP 1.5 (Readout)	3 FTE + €1M
WP 1.6 (Integration)	6 FTE
WP 1.7 (Deployment & commissioning)	2.5 FTE + €0.025M
WP 1.8 (Site access and operations)	€0.5M / year
Total	**€11M**

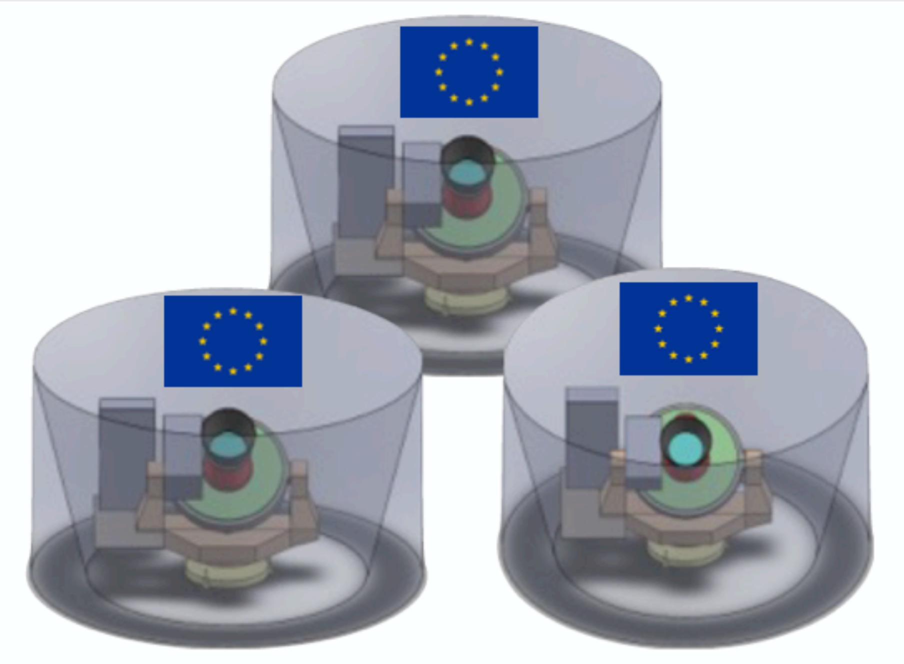
Task 2 - Operations and Analysis: (assuming 5-year survey)

WP 2.0 (Data analysis management)	3 FTE
WP 2.1 (Analysis computing support)	1 FTE + €0.5M
WP 2.2 (Observations)	10 FTE
WP 2.3 (Low-level processing)	6 FTE
WP 2.4 (Map-making)	8 FTE
WP 2.5 (Power spectra + likelihood)	7 FTE
WP 2.6 (Theoretical Interpretation)	2 FTE
Total	**€3.5M**

- Add 25% contingency ⇒ ~ €18M total.

Summary

- The SO:Europe Telescope Array will be a **distinctive, stand-alone facility** within the wider Simons Observatory.
- Major **enhancement of SO's science reach** in terms of primordial B-mode and inflation model constraints.
- Leverage leading role for Europe in SO (including **representation on SO Planning Committee / Executive Board**).
- Position Europe for becoming major player in **CMB-S4** (SO:ETA telescopes will be constructed as **"S4-ready" telescopes**).



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