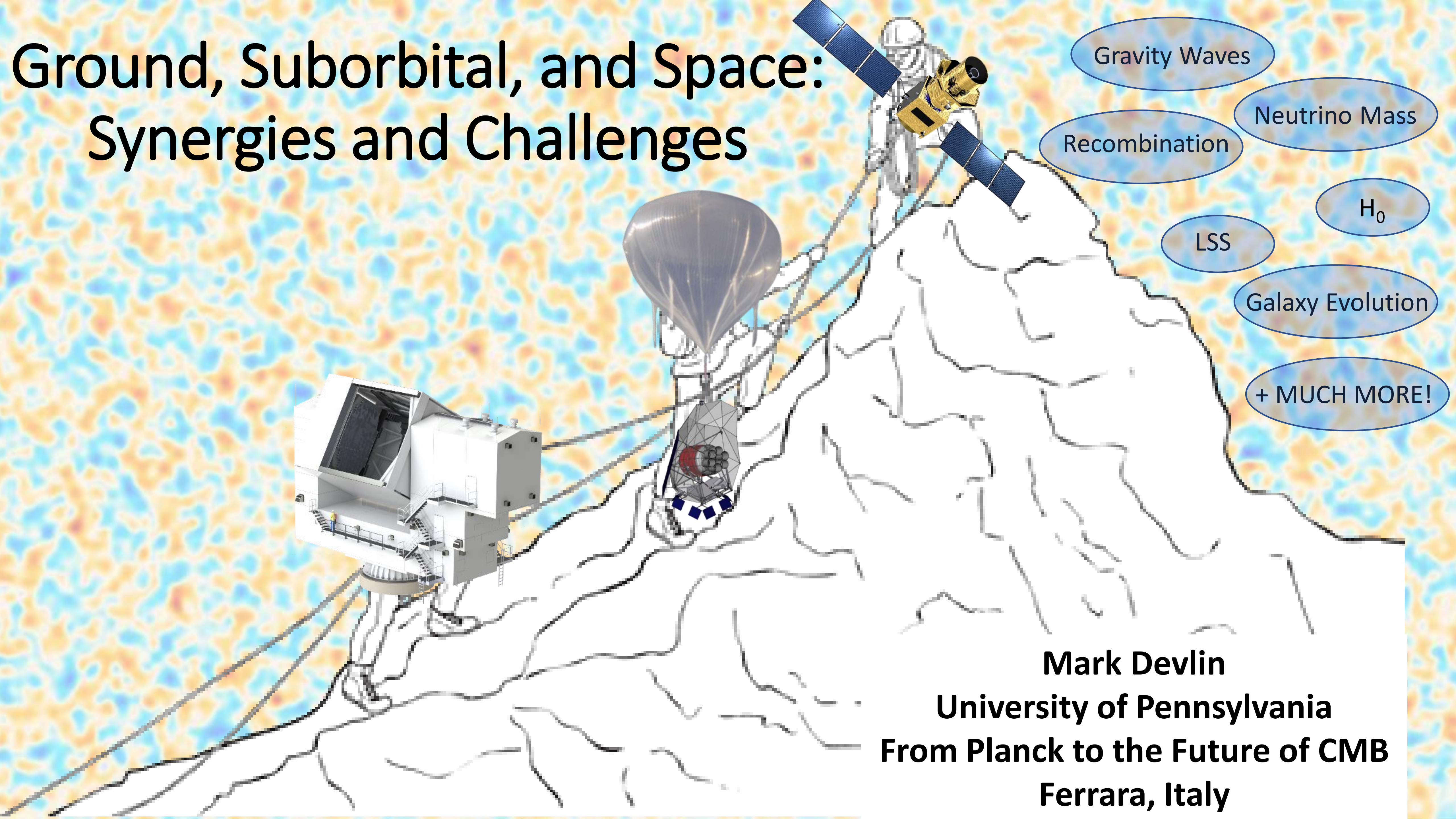
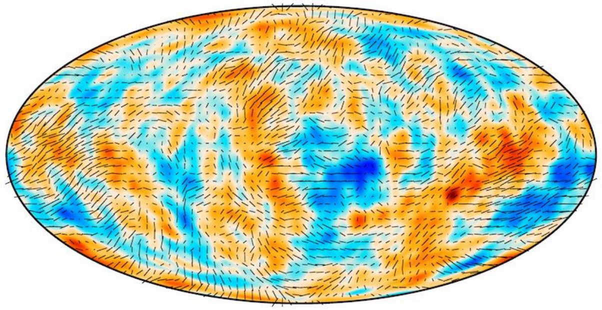
Ground, Suborbital, and Space: Synergies and Challenges

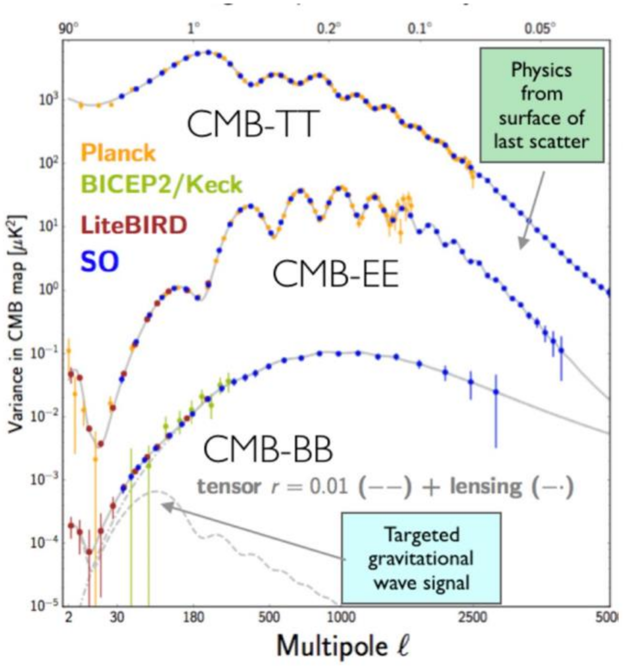


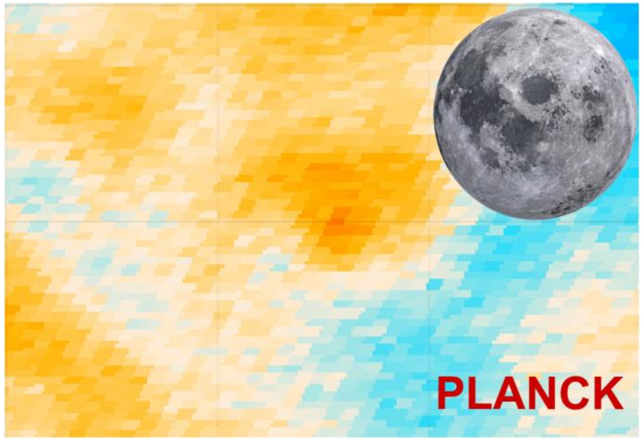
Mark Devlin
University of Pennsylvania

From Planck to the Future of CMB
Ferrara, Italy

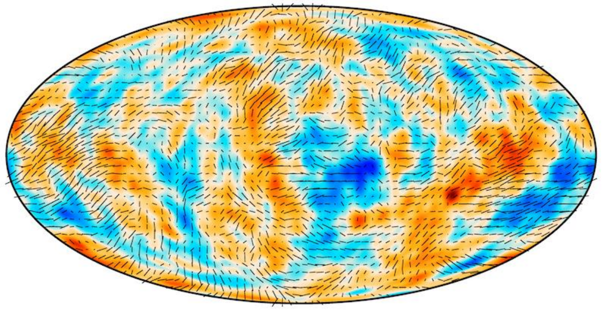
More Realistically….

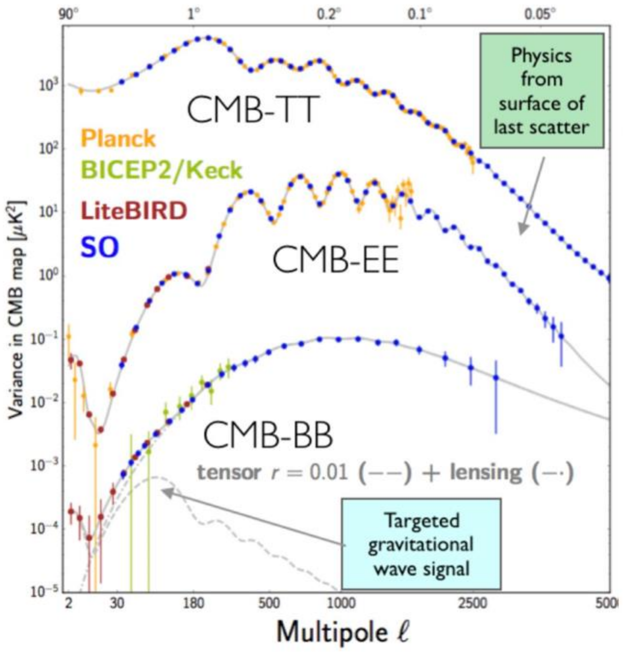


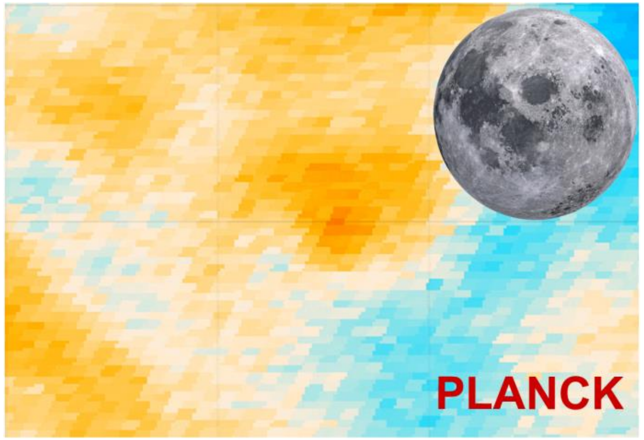




EVEN More Realistically….



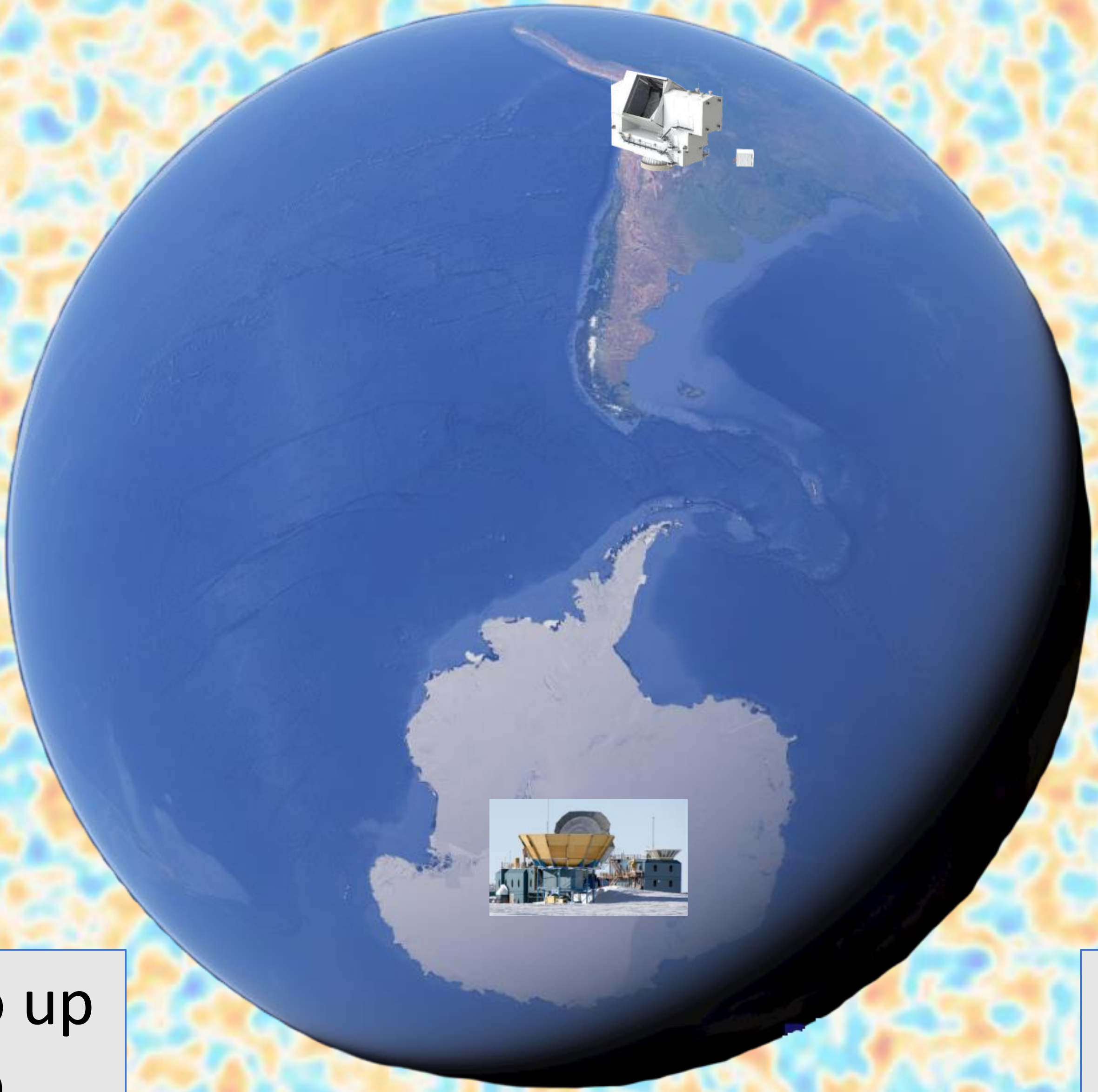




Some Definitions!

Ground: Things that stay put.

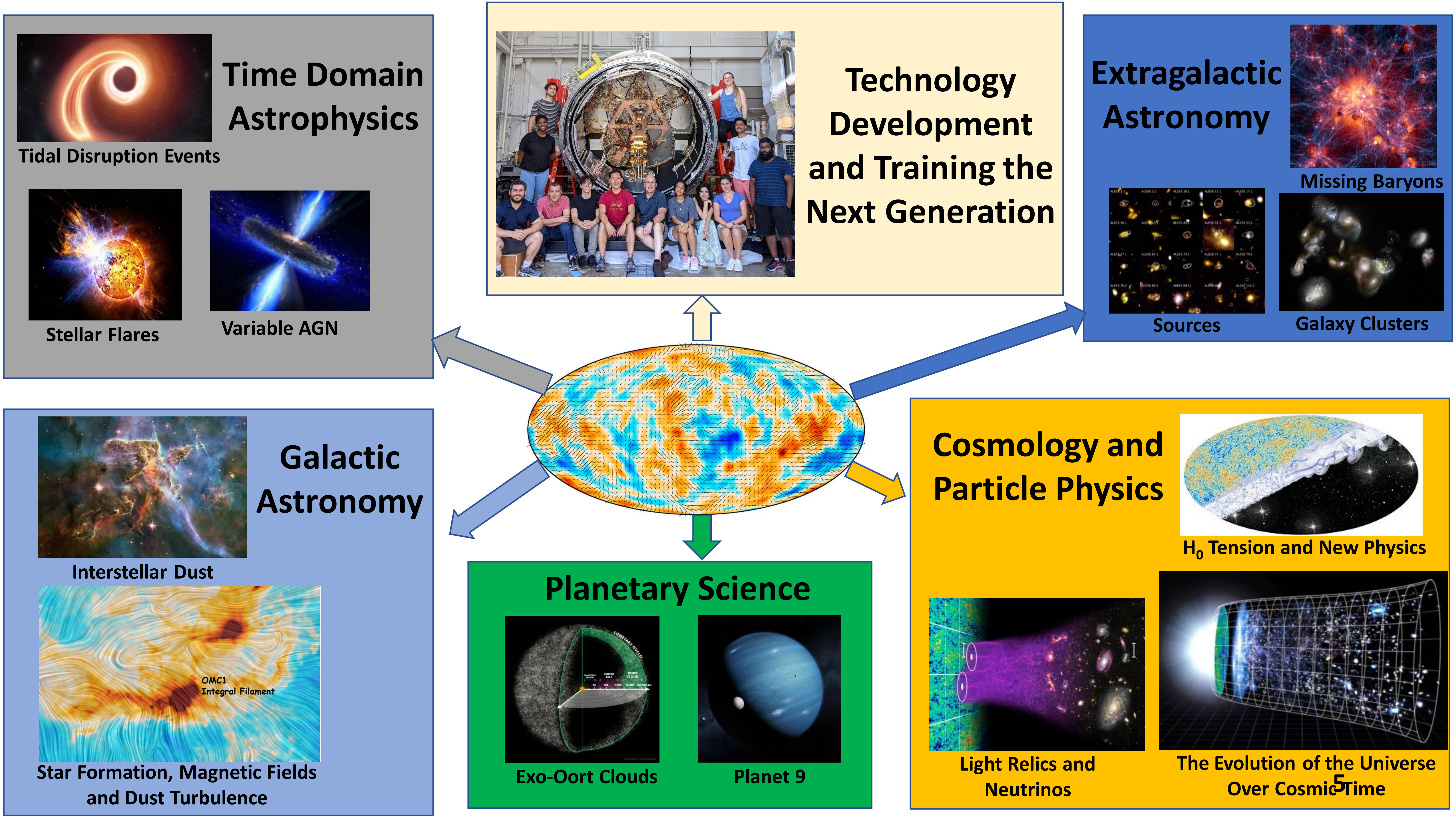
But Also: Drones and Calibrators



Synergy is not restricted to CMB bands!

Space: Things that go up and don’t come down.

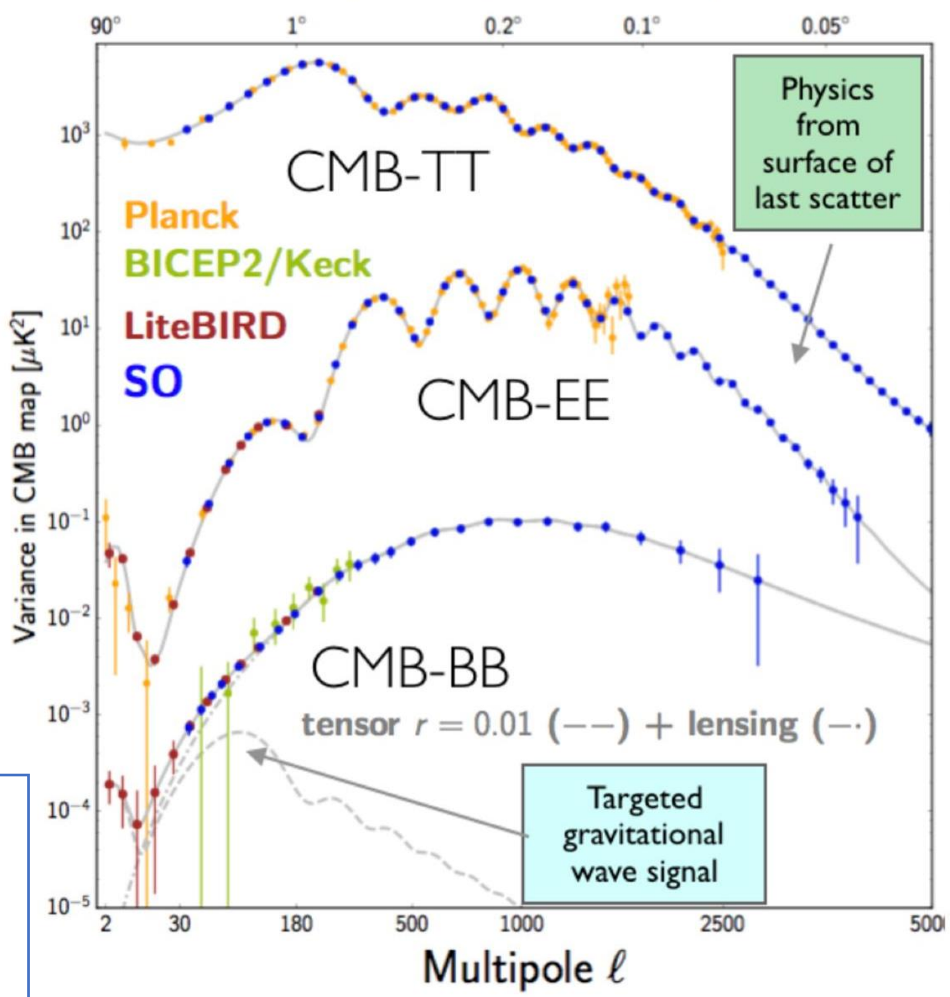
Suborbital: Things that go up and down.



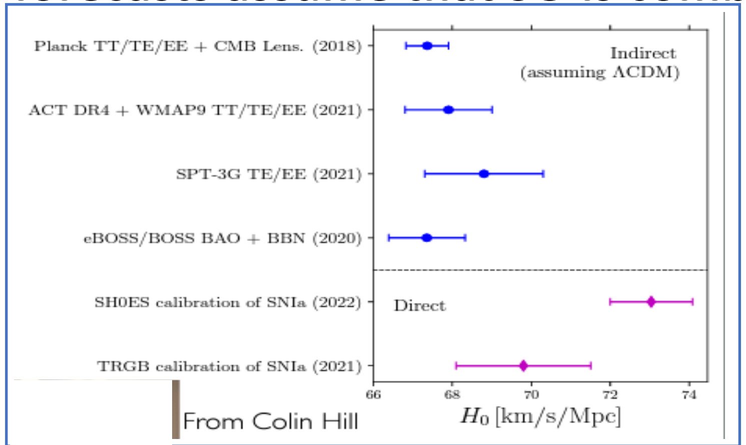
Time Domain Astrophysics
Tidal Disruption Events
Stellar Flares
Variable AGN
Technology Development and Training the Next Generation
Extragalactic Astronomy
Missing Baryons
Sources
Galaxy Clusters
Galactic Astronomy
Interstellar Dust
OMC1
Integral Filament
Star Formation, Magnetic Fields and Dust Turbulence
Planetary Science
Exo-Oort Clouds
Planet 9
Cosmology and Particle Physics
H_0 Tension and New Physics
Light Relics and Neutrinos
The Evolution of the Universe Over Cosmic Time

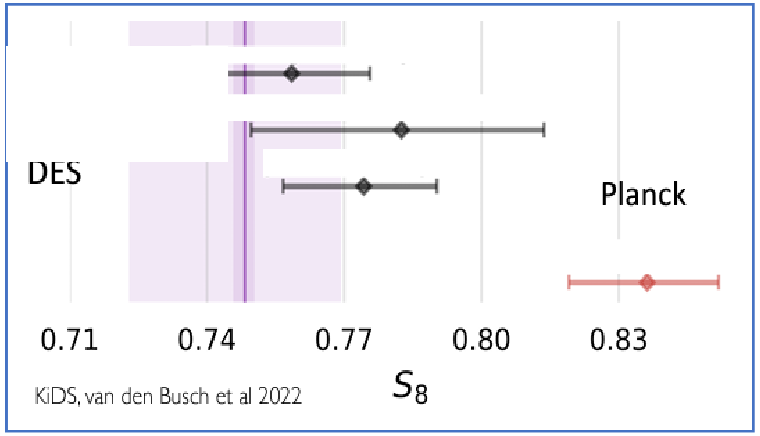
High Resolution Millimeter-Wave Maps Rely on Space and Ground-Based Telescopes to Achieve Their Full Potential

		Current	SO-Nominal 2024-2029	CMB-S4 2030–	Uses Rubin DESI, or *Euclid*
Transient Detections	GRB reverse shocks		✗		✓
	Stellar flares	10s	✗		✓
Variable AGN	Light curves	$\sim$ 1000	✗		✓
Planet 9	Distance limit	400 AU	✗		✓
Galactic science	Molecular clouds	10s	✗		-
High-z clusters	$z > 2$ catalog	1	40	500	✓
Galaxy evolution	Feedback efficiency η	25%	3%		✓
Dark energy	$\sigma_8(z = 1 - 2)$	7%	2%	1%	✓
Reionization	Optical depth τ	0.01	0.007	0.003	-
Neutrino mass	Σm_ν (eV)	0.1	0.03	0.02	✓
Primordial perturbations	Tensor-to-scalar r	0.01	0.002	0.0005	✓
	Non-Gaussian $f_{\rm NL}^{\rm local}$	5	2	0.6	✓
New relic particles	$N_{\rm eff}$	0.2	0.06	0.03	-

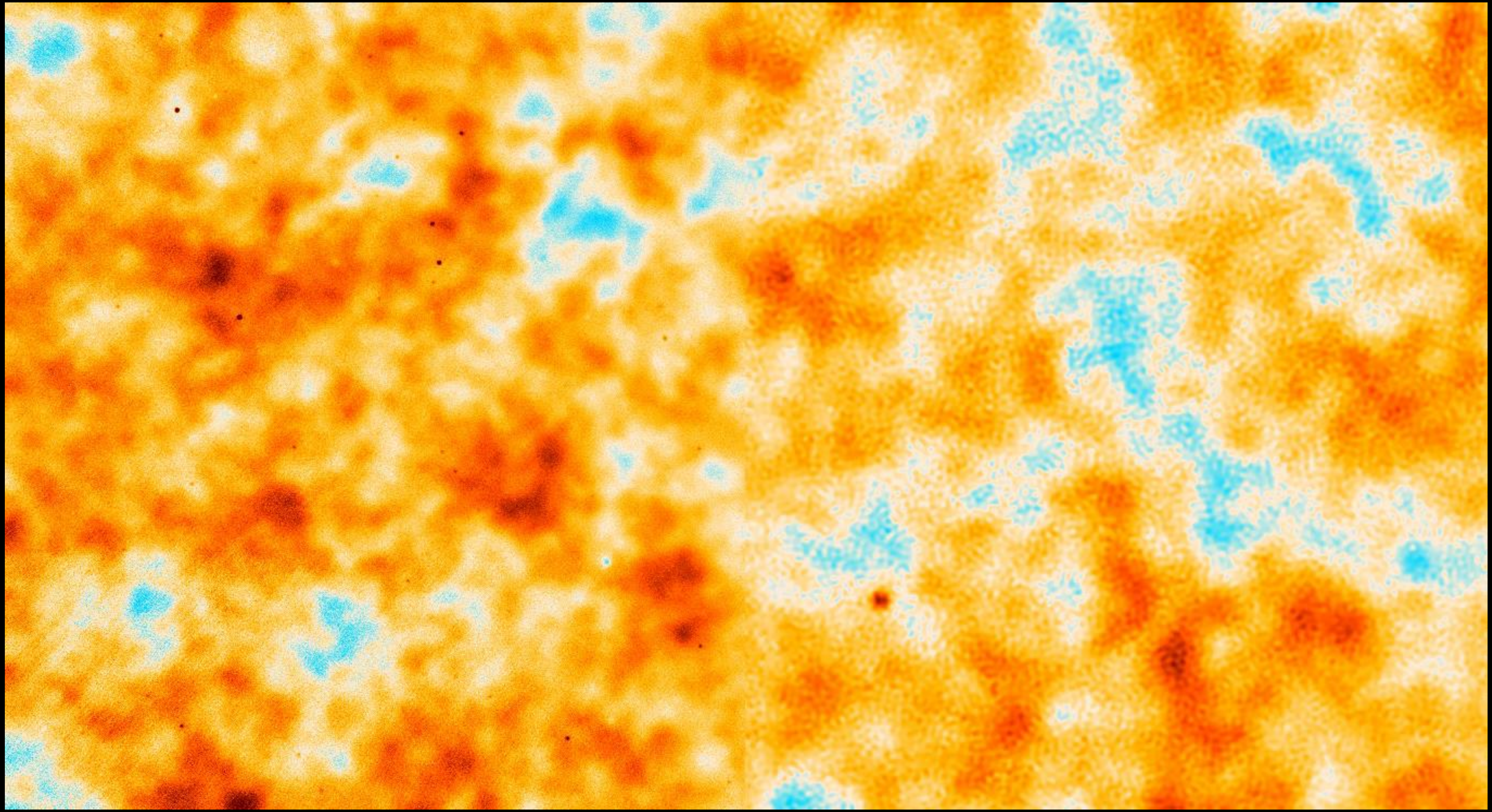


From the SO Forecast Paper: "All of our SO (cosmological) forecasts assume that SO is combined with *Planck* data.

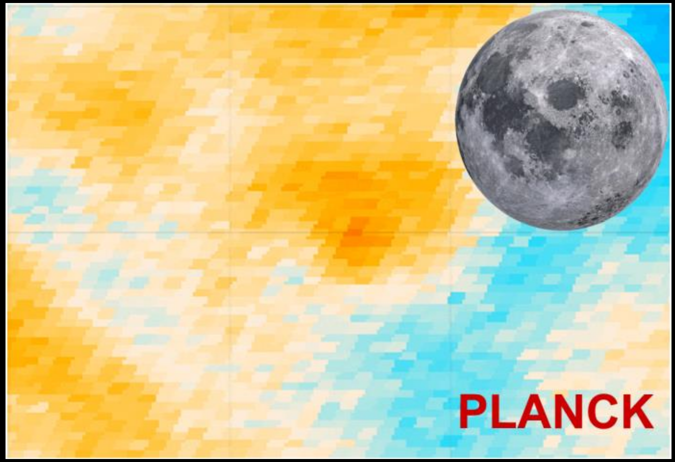




ACT+Planck Planck



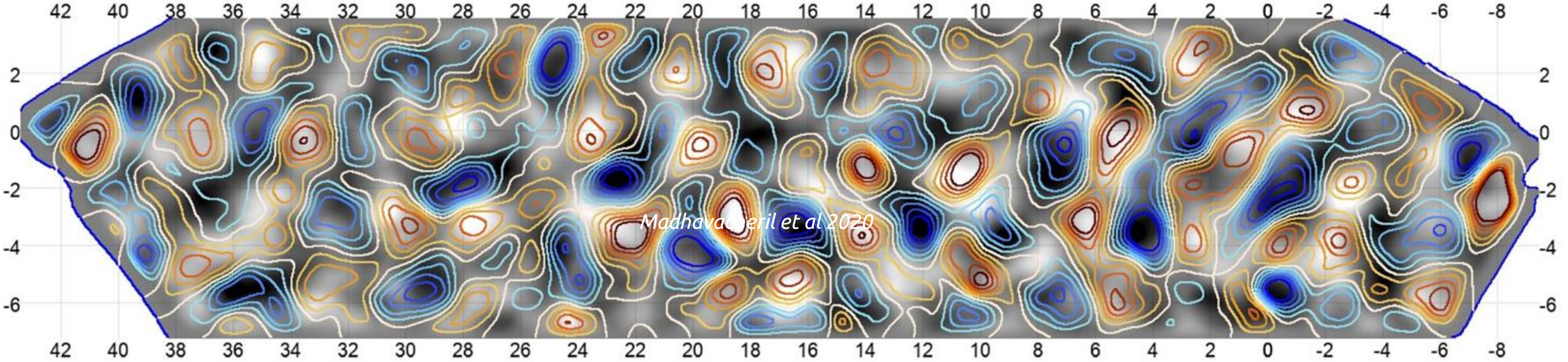
Combined ACT+Planck maps reveal the power of large and small scales in millimeter maps.



Video: Sigurd Naess

Mass and Gas Maps Over 2100 deg^2

Darwish et al 2020



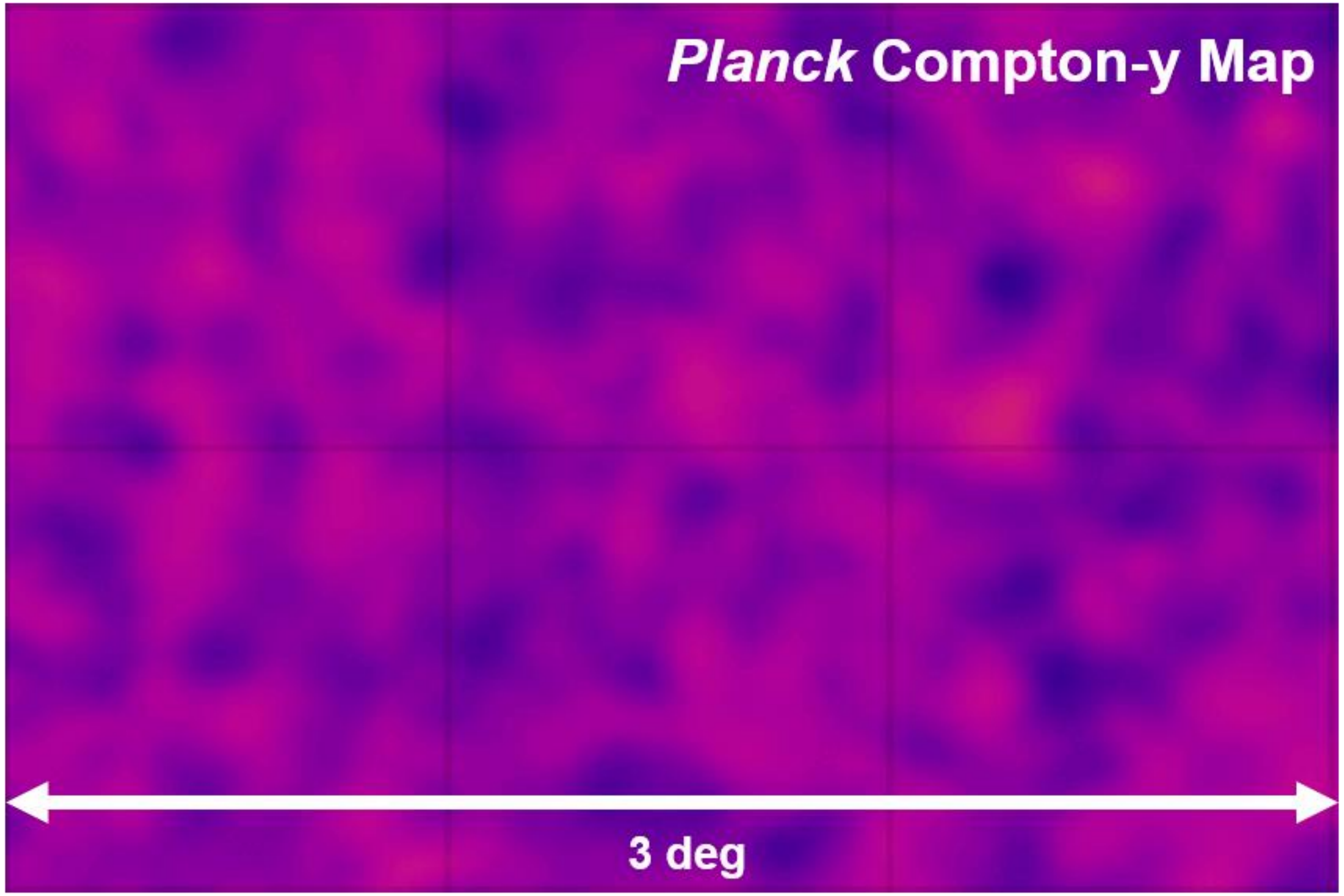
Signal-dominated **Gravitational lensing** maps. Contours are cosmic infrared background. The lensing potential and CIB are highly correlated.

Results:

- Lensing x **KiDS** cross correlation (*Robertson et al 2020*)
- **Template kSZ** and tSZ stacking (*Schaan et al 2020, Amodeo et al 2020*)
- **Pairwise kSZ** and tSZ stacking (*Calafut et al 2020, Vavagiakis et al 2020*)
- **Oriented signal from superclustering** in *Lokken et al 2021.*
- Also see cosmological parameters from **delensing** in *Han et al 2020 + more!*

New ACT + Planck y-maps of 30% of the Sky Available Soon!

PRELIMINARY



Analysis led by **Will Coulton**

(also see SPT results – Bleem et al., 2022)

Preview of arcminute-resolution wide area maps of tSZ / gas pressure / Compton-y from ACT using data up to 2021

Large-Area, High Resolution Compton y-maps can be combined with current and future surveys:

- Dark Energy Survey
- Rubin Observatory
- Euclid

Science:

- Provide constraints on structure evolution.
- Evolution of gas properties from galaxy to cluster+ scales over cosmic time.

What are the Areas for Potential Future Synergies?

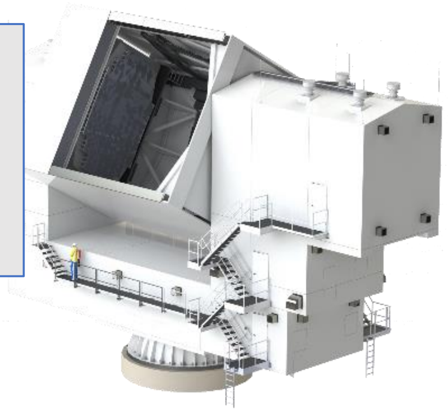
Time Domain:
- Tool for fast analysis.
- Alert system.
- Joint observations.

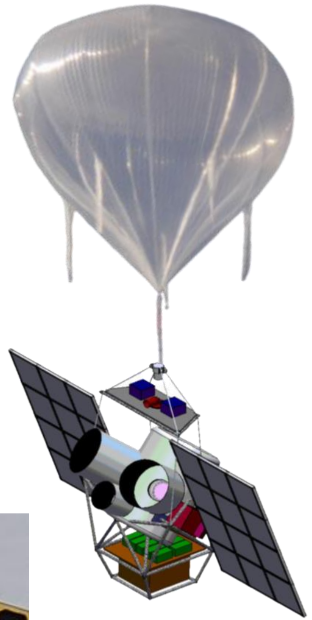
Data Pipelines: These are EXPENSIVE pieces of infrastructure. Can common pipeline tools be developed?

Extended Frequency Coverage: Does EVERY instrument need to rely only on itself for component separation?

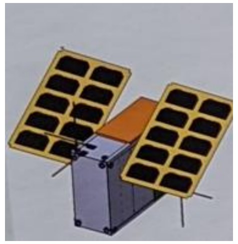
Systematics: Common standards and techniques for:
- Precision Beam Measurements
- Band Passes
- Polarization
- Noise

Linked Missions: Must every experiment stand on its own? Are "supporting" measurements "fundable"?





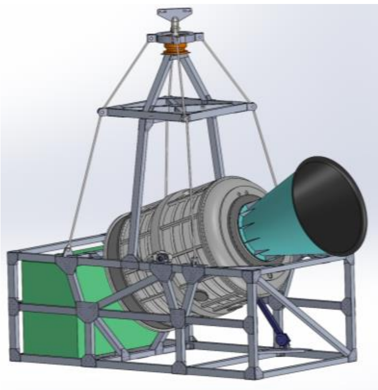
Extend Angular Dynamic Range: Full sky down to arcmin (or less) maps. Advanced planning could optimize the final maps and science.



Calibration:
- Deployed measurements.
- Precision Astronomical Calibrations.
- Polarization Angles.

Technology Development:
- Detectors
- Readout
- Optics

Suborbital BIG MISSION SCIENCE!



BIG MISSIONS:

- Stand alone significant goals
- TAU
- B-Modes
- Spectral Distortions

Paolo Says:

- **@150 GHz :** One day on a balloon is like >16 days at the best site on the ground.
- **@350 GHz:** One day is like >100 days at the best site on the ground.
- **Cost:** roughly 1/100 of a satellite mission.
- **Cost Efficiency:** Recover and refly.
- **Long Flights:** 40+ days.

Jia Liu says (paraphrased):

- "This is great. How come we don't fly 10 or more of these?"
- Great Question!

Let's Be Honest:

- Big Balloon Missions ARE expensive ~$20M through launch.
- They are risky and have not returned significant CMB results since Boomerang.

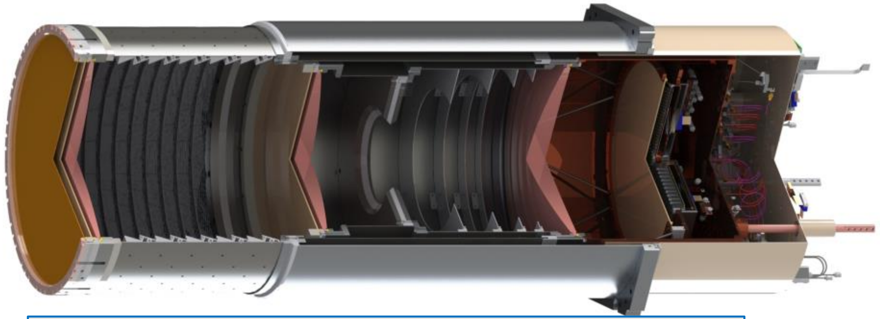
Why? It is not because it is not possible! But, a combination of:

- The review process rewards a promise of significant returns at unrealistically low costs.
- Pushed to the large and complex payloads.
- Funding not commensurate with the complexity of the task.

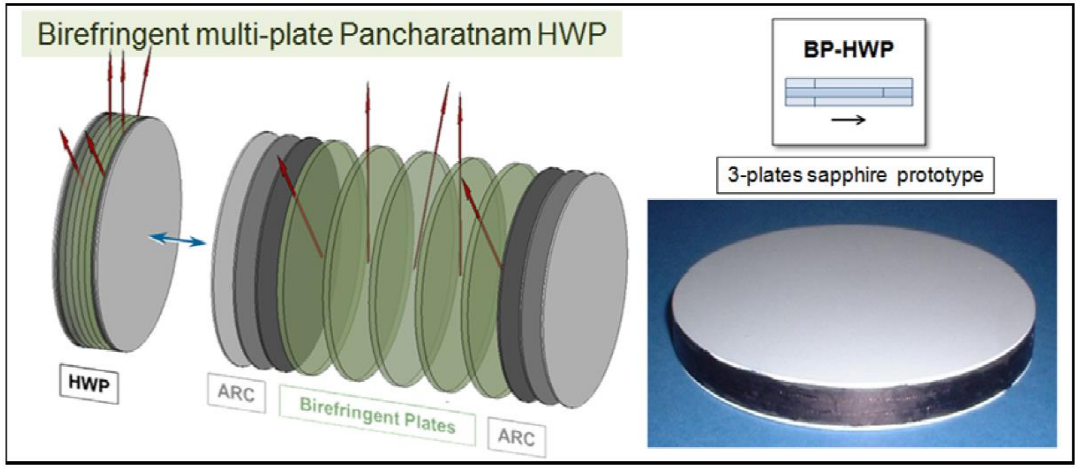
Don't Give up on Suborbital!

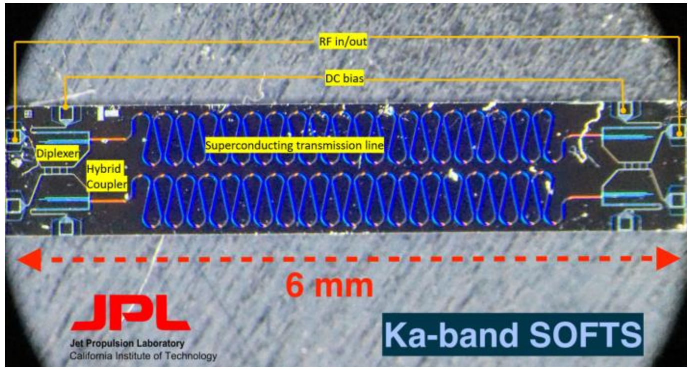
Technology Development – Just a Few Examples

Development has across all three platforms has benefited the entire field. A coordinated approach might yield a more efficient outcome, but the results have been very good so far!

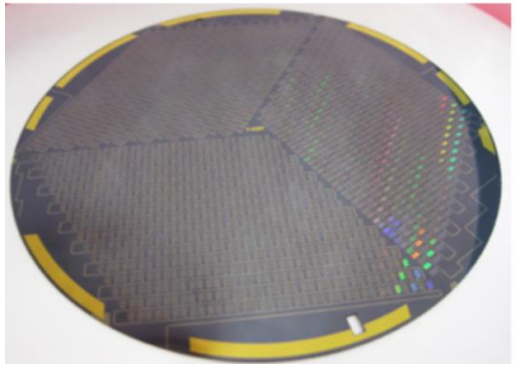


SO LAT Optics Tube:
- Detectors
- Multiplexed Cryogenic Readout
- Metamaterial Lenses
- Metamaterial Absorbing tiles.

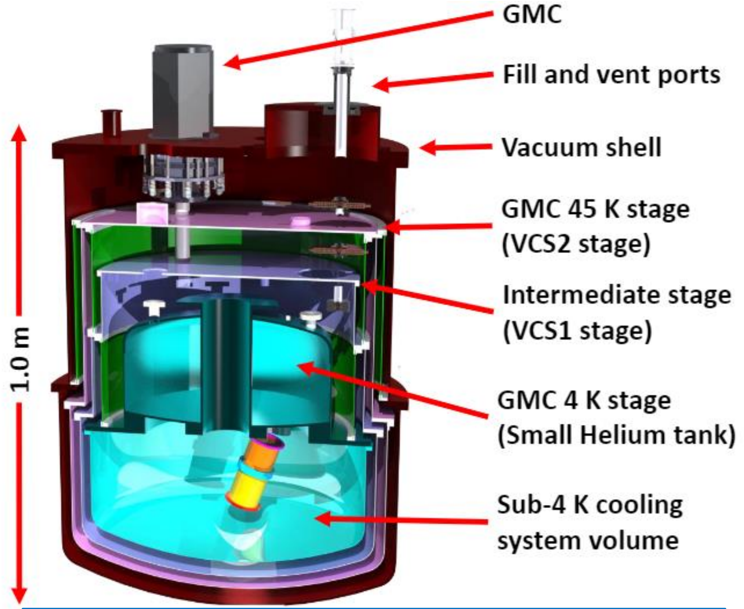




Superconducting On-chip
Fourier Transform Spectrometer



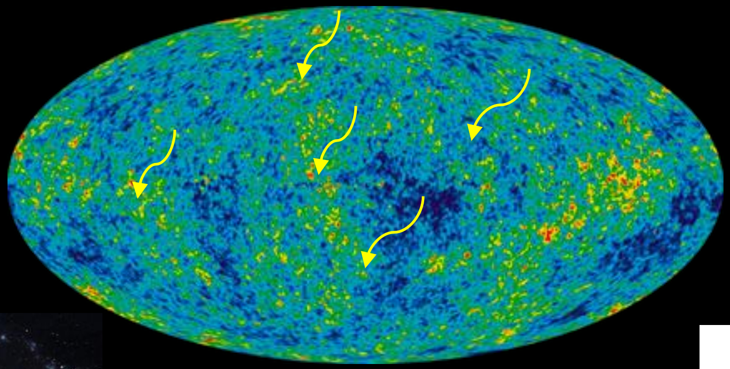
BLAST MKID Array
Developed and proven In-FLIGHT



Advanced Cryogenics for Balloons

Challenges: Systematics and Foregrounds

- **Primary Temperature Anisotropy - ~120 μK RMS**
- **Primordial B-Mode - 30-90 nK RMS**
- **Systematics and Foreground emission can easily dominate the B-Mode signal.**

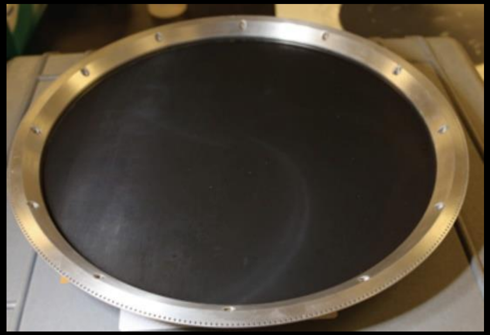


Galactic Dust

Ground and Sky Pickup!

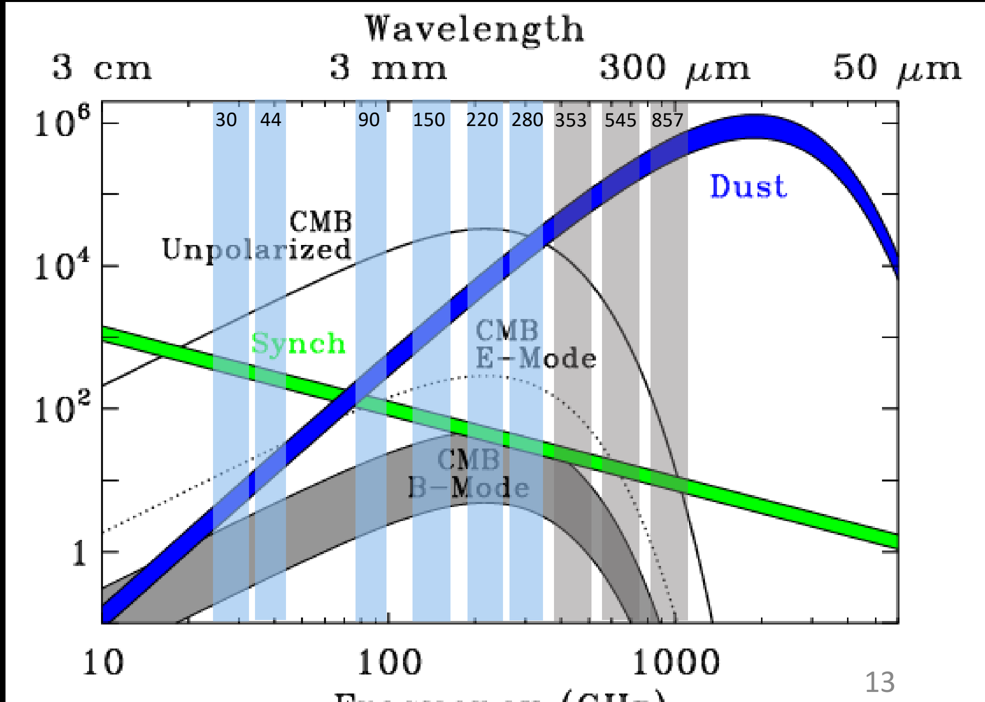
Careful optical design and baffling to minimize instrument and ground pickup.

Meet the Challenge!



Rotating Half Wave Plates to modulate the polarization signal.

Multiple Frequency Bands to Measure and Remove Foregrounds

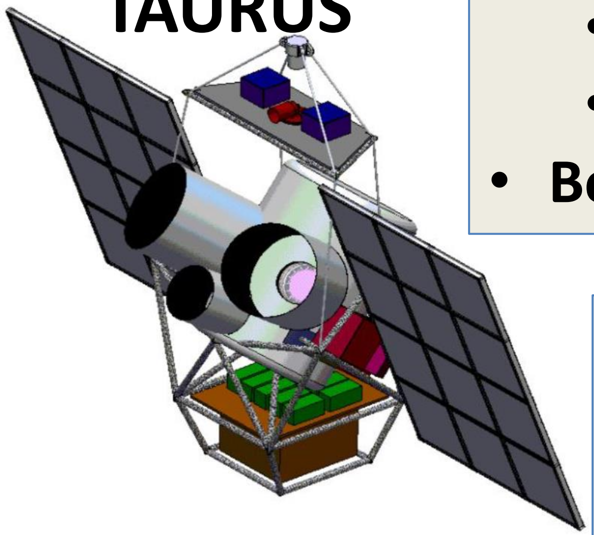


Adapted from Kogut 2016

Suborbital Directly Supporting Ground Observations

- **Space Mission (LiteBIRD):**
  - Many bands over a large spectral range
  - Robust against a universe with pernicious dust models.
- **Ground Observatories:**
  - Dither bands - more spectral resolution
  - Limited spectral coverage.
- **Both assert their plan is necessary/sufficient**

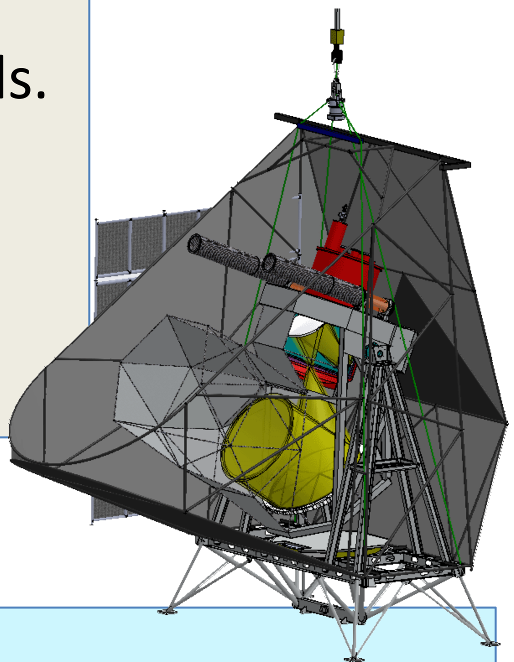
TAURUS



What would a sub-orbital mission DEDICATED to cleaning CMB fields look like?

Band Center (GHz)	Bandwidth (GHz)	Beam FWHM (arcmin)	Number of Detectors	Absorbed Power (pW)	Detector Sensitivity ($\mu K_{CMB}\sqrt{s}$)	Instrument Sensitivity ($\mu K_{CMB}\sqrt{s}$)
150	40	60	3024	0.9	76	1.5
220	55	40	3024	1.1	123	2.4
280	70	60	2016	1.4	220	5.4
350	85	50	2016	1.6	550	13.4

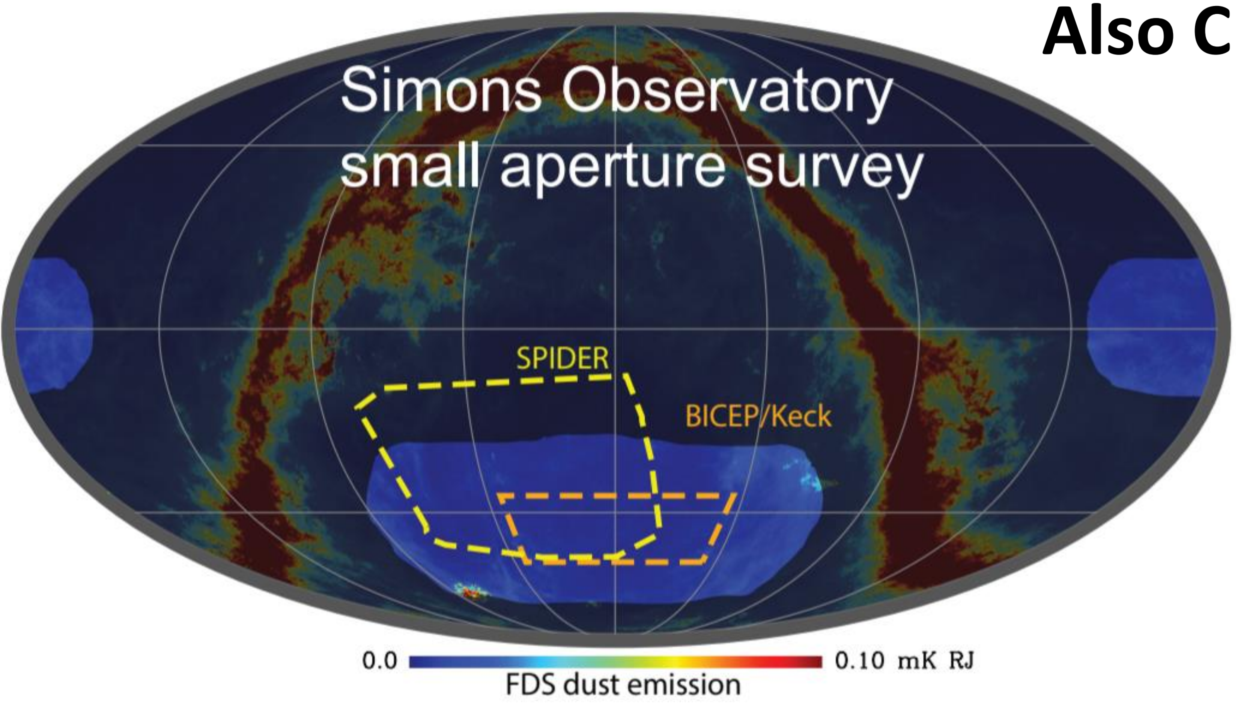
BFORE

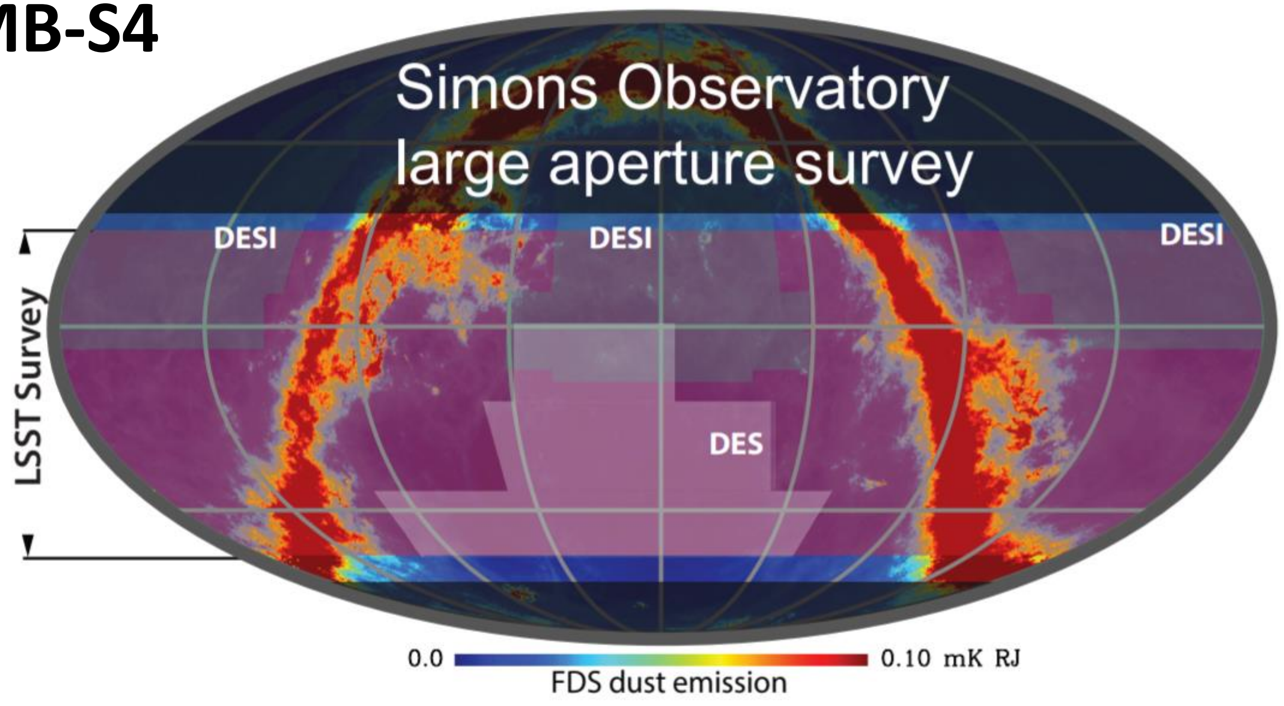


Detectors: 10,560
4,800 TES detectors at 150, and 217 GHz
5,760 TES detectors at 280 and 353 GHz
Telescope:
1.35 meter primary –> 2.6 to 6.1 arcmin
Flight:
28+ day flight, Launch from New Zealand
20,000 deg^2 overlapping ACT, BICEP/KECK, CLASS, PolarBear and SPT

Legacy Millimeter-Wave Surveys of the Sky

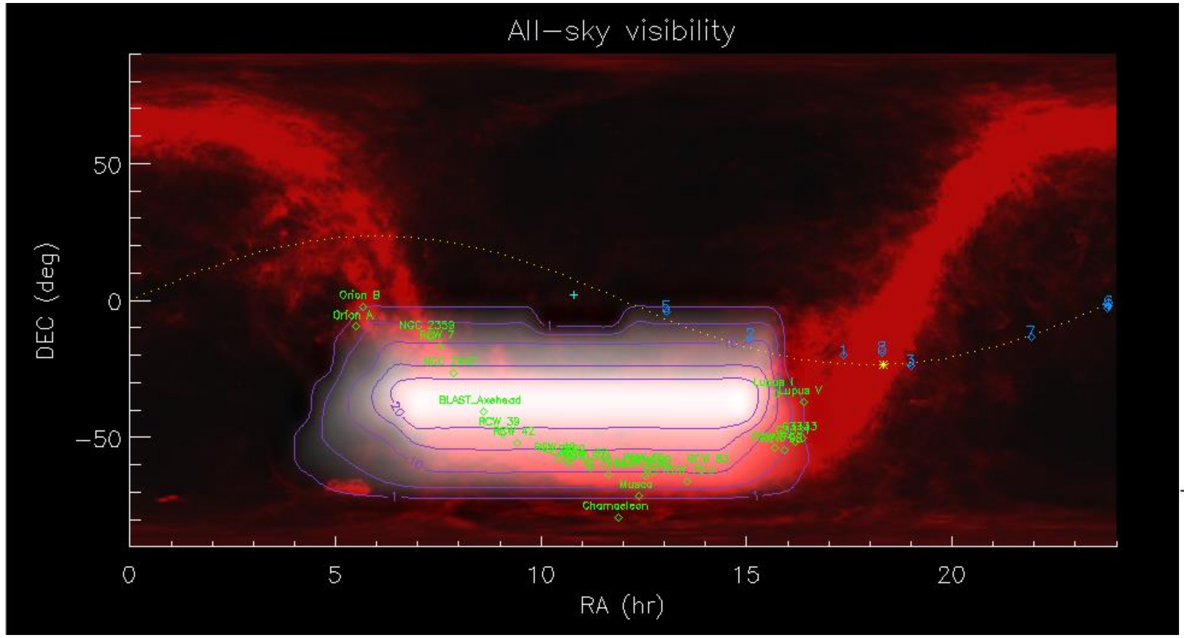
Also CMB-S4

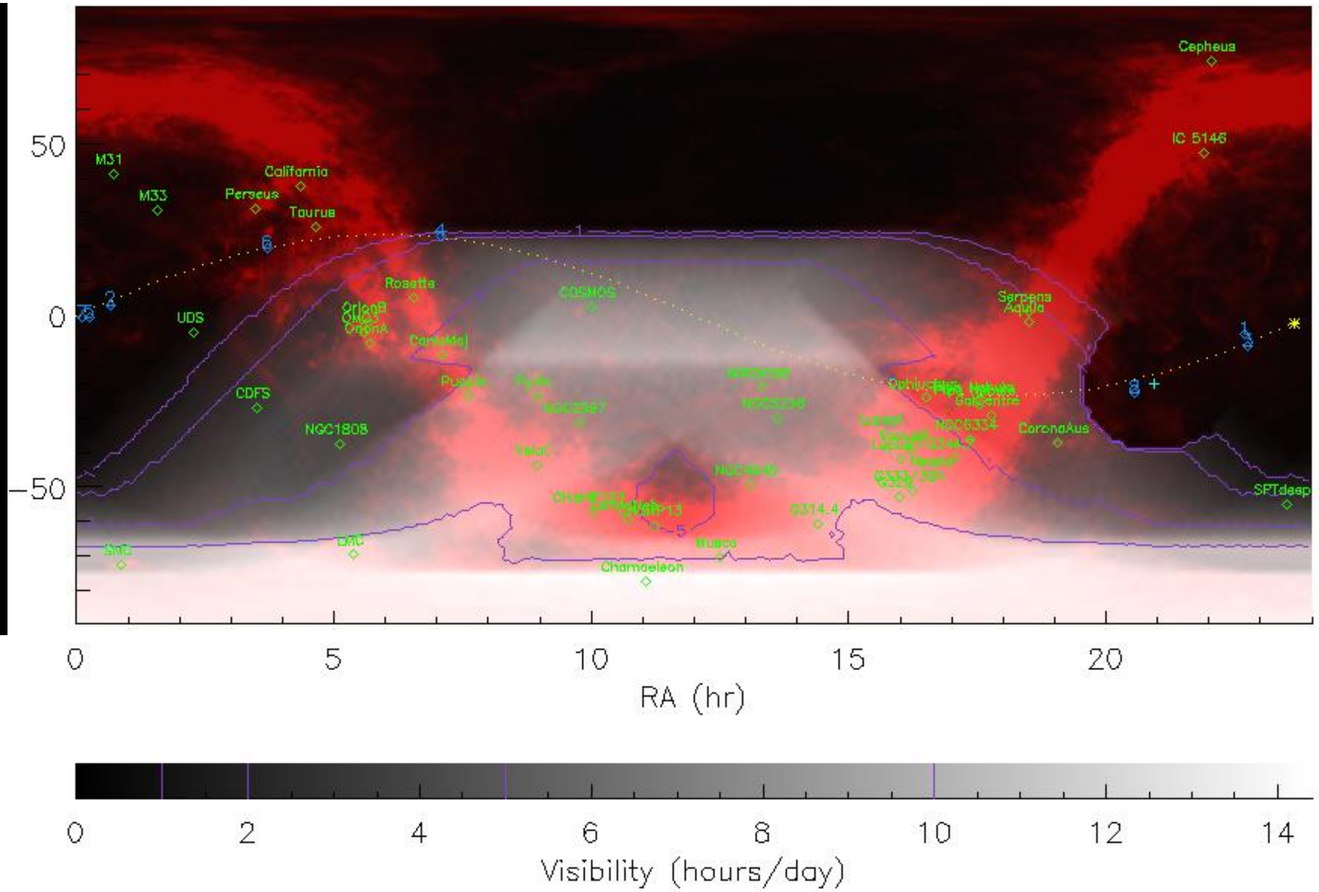




``Within the uncertainties of our analysis, we can conclude that there is no region in the sky where the foreground emission demonstrates to contaminate the CMB B modes at levels lower than a signal with tensor to scalar ratio r ~ 0.05.'' N. Krachmalnicoff et al. A&A 588, A65 (2016)

What Kind of Sub-Orbital Flight is Best?



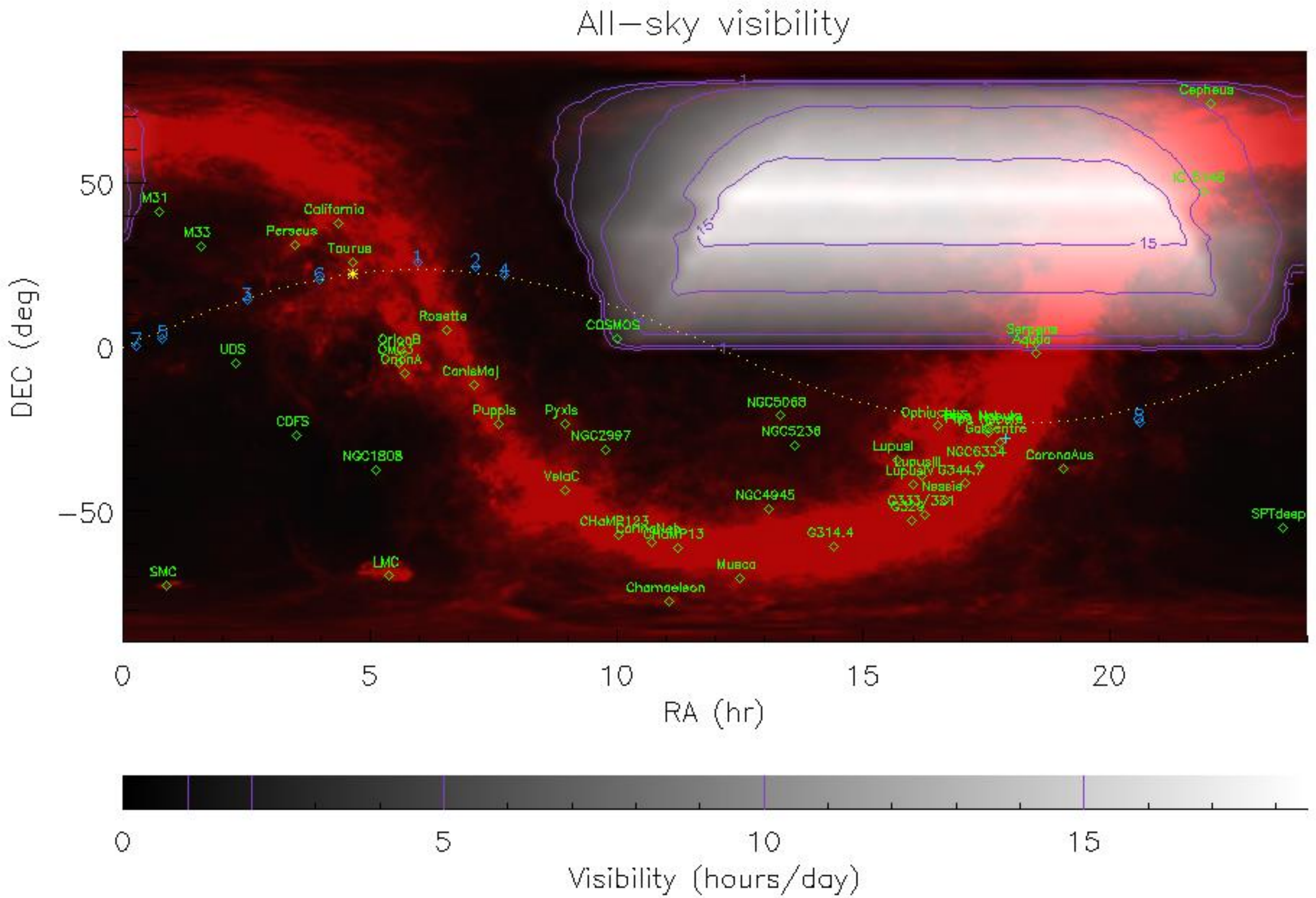


LDB Flight from Antarctica

- December 21st Launch
- ~40 day flights
- Almost no overlap with South Pole Fields.

ULDB Flight from New Zealand

- March 15th Launch
- ~40 day flight (100 with cryo development)
- No South Pole Fields. Cover Chilean Fields.



Kiruna Launch in June

Galactic Astronomy – Space/Suborbital/Ground Synergy

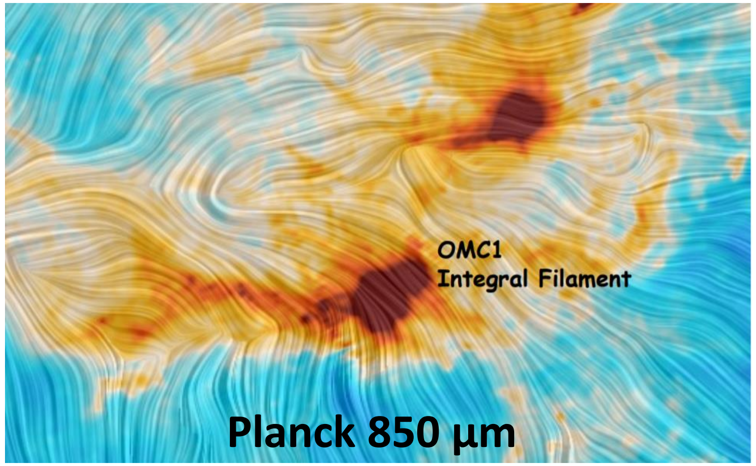
What Role Do Magnetic Fields Play in Star Formation?

The role of magnetic fields in the formation and evolution of molecular clouds is poorly understood.

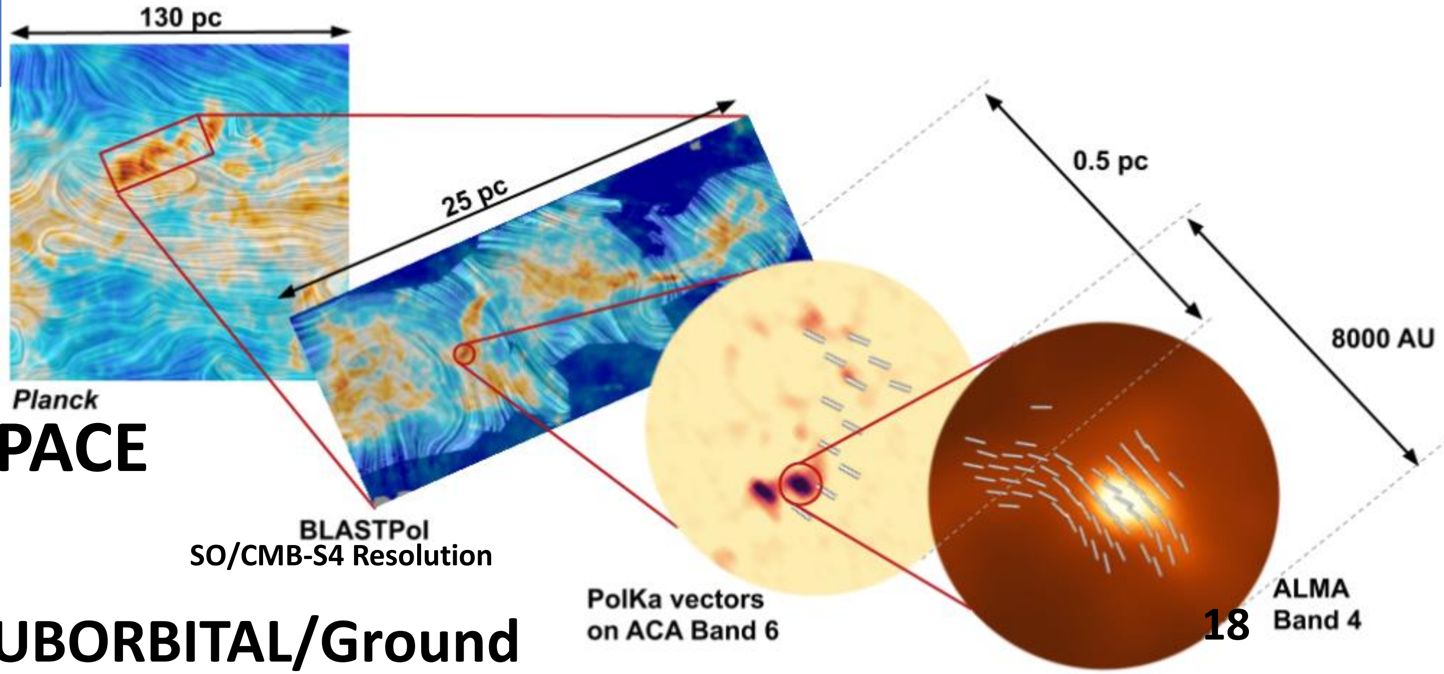
- SO and CMB S4 will measure magnetic fields at scales intermediate between *Planck* and ALMA
- 0.9′ angular resolution at 280 GHz corresponds to 0.03 pc at a distance of 100 pc
- **SO and CMB S4 will measure the magnetic field structure of well over a thousand molecular clouds with 1 pc resolution**

Multi-scale millimeter polarization maps:

- **Space/Planck**
  - Frequency Coverage
  - Large Scales
- **Sub-orbital**
  - Frequency Coverage
  - Medium Scales
- **Ground**
  - Medium to very small scales.



Polarization measurements can yield information about the density, bulk gas motions and turbulence.



SPACE

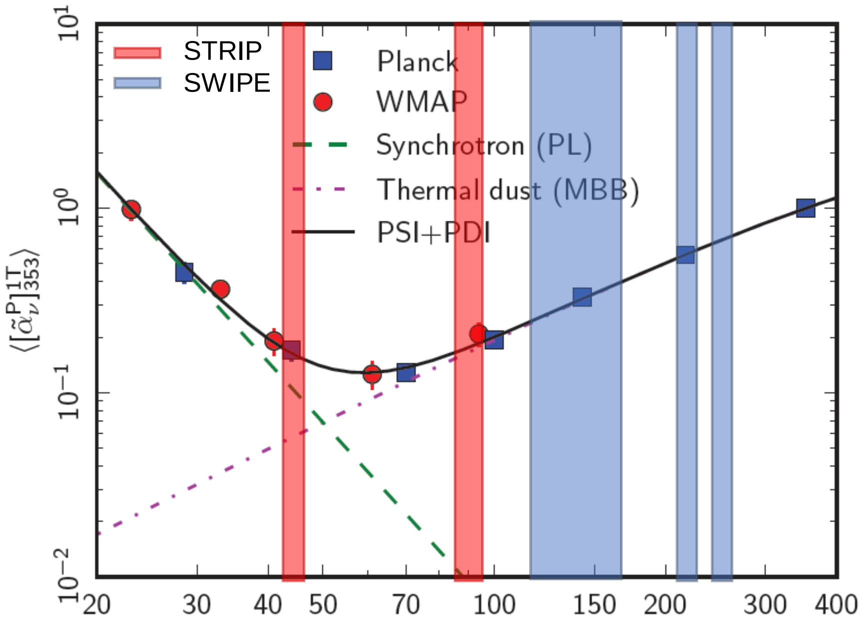
SUBORBITAL/Ground

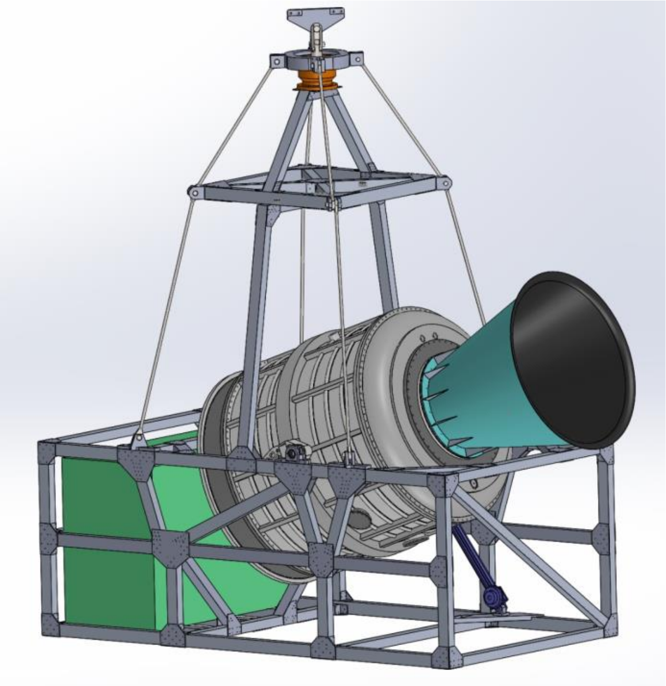
Synergy With Other Surveys Will Expand Our Science Reach

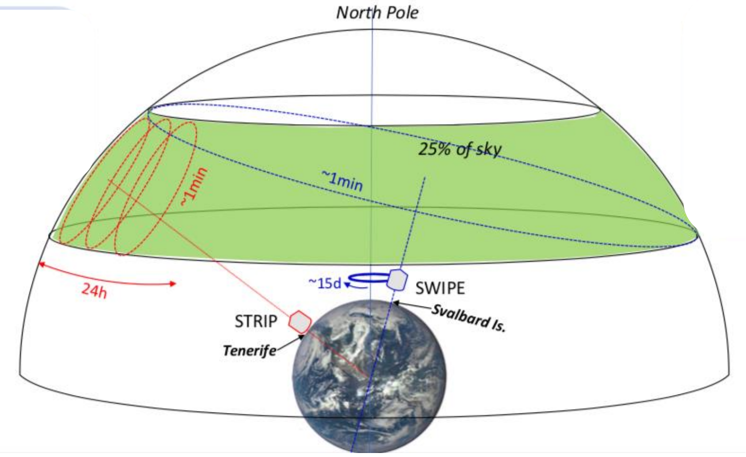
Advanced planning could open a new window into the time domain universe!

First REAL Example of Synergistic Planning? - LSPE

- The Large-Scale Polarization Explorer is an experiment to measure the polarization of the CMB and interstellar dust at large angular scales.
- Frequency coverage: 40 – 250 GHz (5 bands)
- 2 instruments: STRIP & SWIPE covering the same northern sky
- **STRIP** is a ground-based instrument working at 44 and 90 GHz
- **SWIPE** works at 140, 220, 240 GHz







Understanding the Instrument is Essential

"It's All About That B~~as~~s BEAM (sic)"
- Megan Trainor

Invited talk by Tomotake Matsumura (Kavli IPMU Tokyo) on "Scientific challenges expected from future space experiments"

Invited talk by Suzanne Staggs (Princeton University) on "Scientific challenges expected from future ground experiments"

Beam characterization for the Simons Observatory Small Aperture telescopes Credit: The Simons Observatory Collaboration Nadia Dachlythra

Invited talk by Jon Gudmundsson (Stockholm University) on "Knowing your **beams**"

Nicholas Galitzki (UCSD) "The Characterization and Calibration of the Simons Observatory Small Aperture Telescope: Status and future plans"

Clara Vergès (Harvard CfA) "**Beam** calibration campaign requirements to control temperature-to-polarisation leakage for CMB-Stage 4"

Kirit Karkare (Chicago University) "Calibration and Systematics for the CMB-S4 Inflation Survey Small Aperture Telescopes"

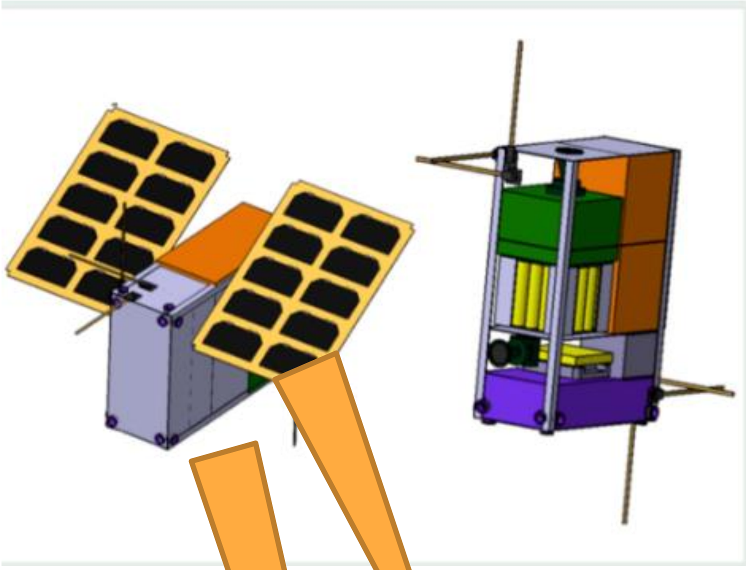
Clément Leloup (APC Paris) "Study of **beam** side-lobes systematics and calibration for the LiteBIRD mission"

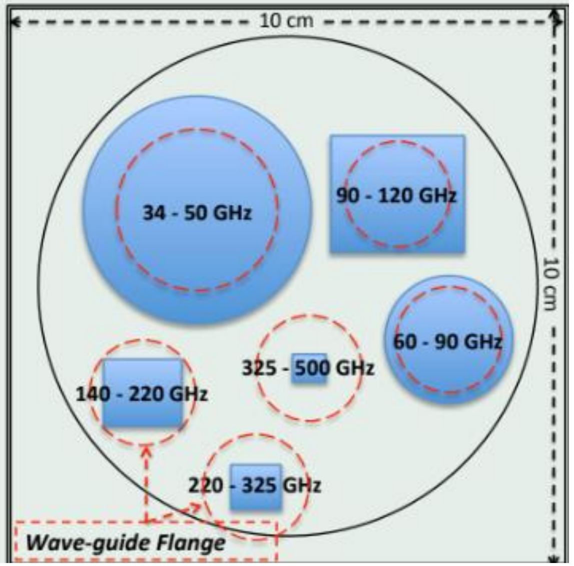
Emilie Storer (Princeton University) "Map-making and **Beams** for the Atacama Cosmology Telescope"

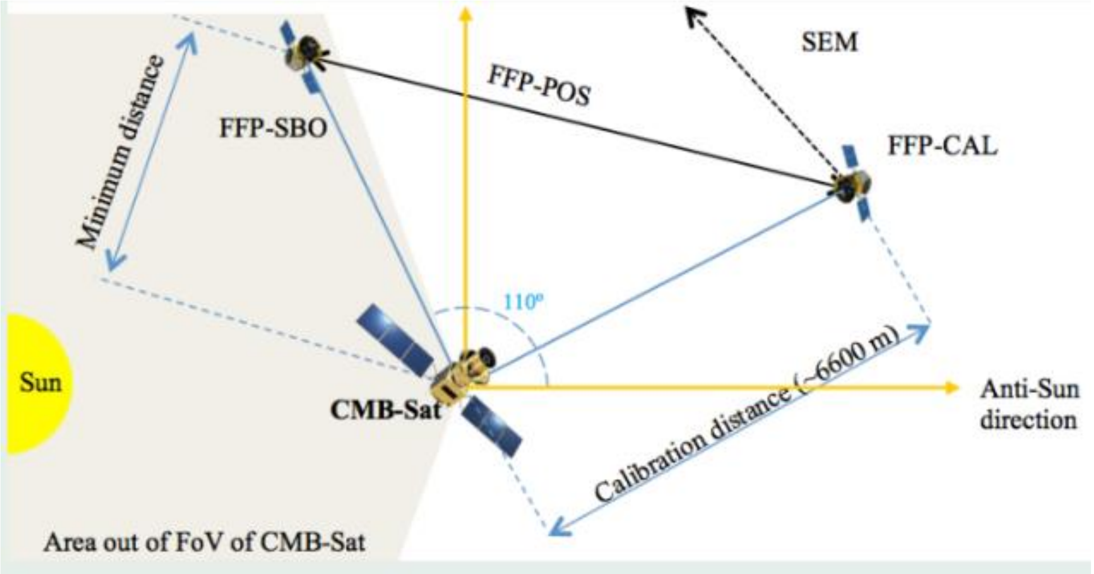
Gabriele Coppi (INFN Milan) "PROTOCALC: Design and Simulation of a Calibration Source for mm Telescopes"

Large Aperture Telescope (LAT)
High bay and Control Room
Small Aperture Telescopes (SAT)
Hover-Cal
Absolute angle
Polarized response
Shielding
Bandpass (FTS)
Beam, Sidelobes,
and Polarization

Small Satellites for Beam Characterization

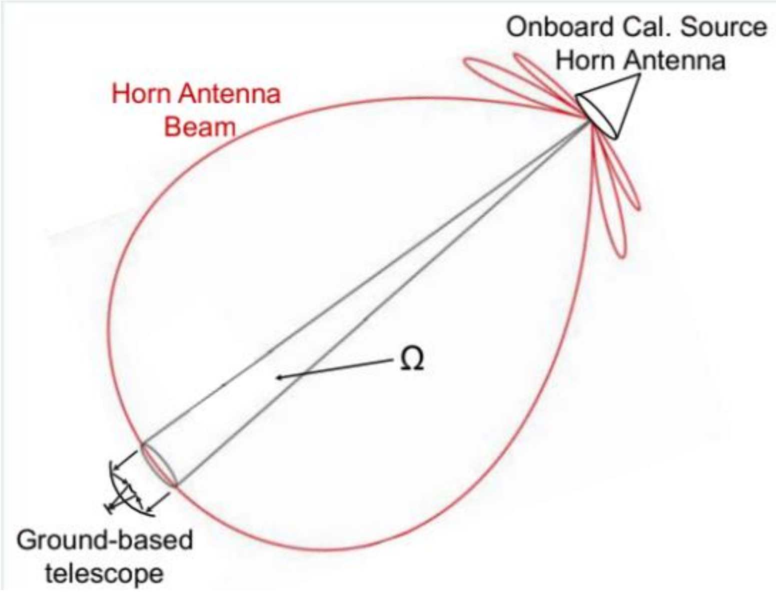






Satellite to Satellite
or
Satellite to Ground

No matter how well we trust current calibration methods, there is nothing like a well-characterized far-field source.



A staged approach

1) Pathfinder *ground-based* implementation: COSMO, on-going (PRIN, PNRA), see also ASPERA at low frequencies. COSMO will be used to validate the differential spectrometer measurement approach, well beyond FIRAS, using:

- A cryogenic Fourier Transform Spectrometer with ultra-high CMRR
- Tunable cryogenic reference blackbody for nulling
- Window temperature modulation method
- Fast KIDs detectors with fast atmospheric modulation to monitor and remove atmospheric fluctuations

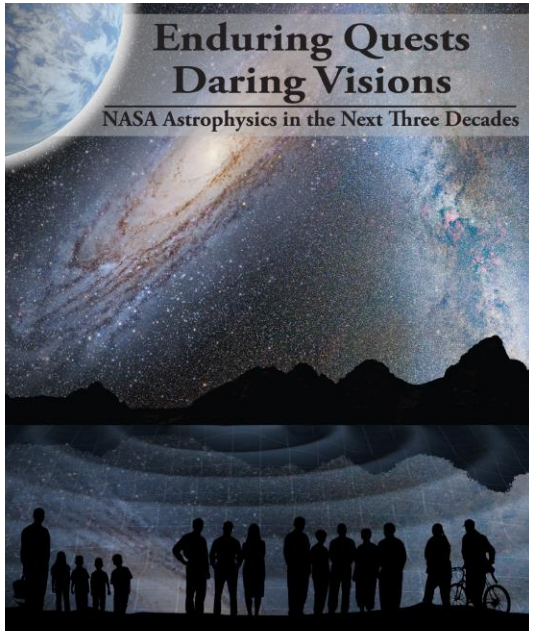
2) Same/similar hardware on a *stratospheric balloon* (in a LHe cryostat): COSMO-Balloon (ASI-Cosmos study), or BISOU (CNES study)

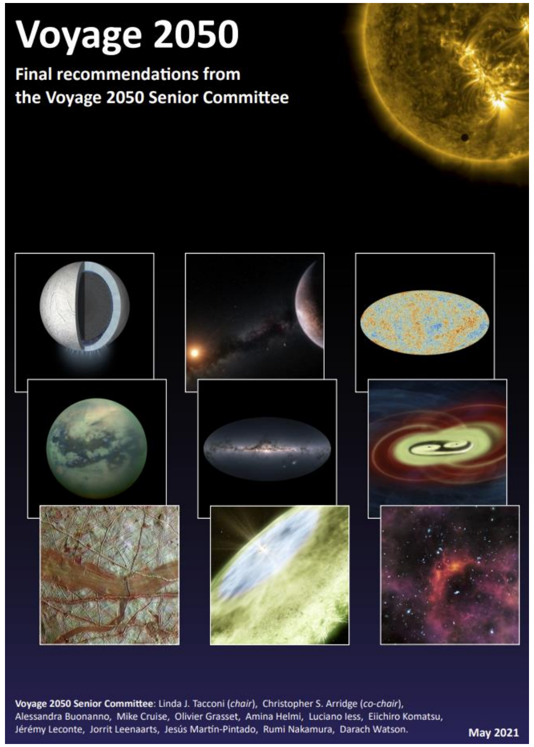
- To measure the largest y distortion, the astrophysical foregrounds, and demonstrate the efficiency of the separation methods

3) A dedicated *satellite mission*. (PIXIE, CORE, PRISTINE, FOSSIL, V2050 proposals)

- Note that the importance of this science has been officially recognized by
- NASA: 30 years study 2014: https://arxiv.org/abs/1401.3741
- ESA: Voyage 2050: https://www.cosmos.esa.int/documents/1866264/1866292/Voyage2050-Senior-Committee-report-public.pdf
- However, none of the proposals above has been approved, yet.

- The staged approach depicted here will certainly help the community to produce a convincing proposal, not only from the point of view of science, but also from the instrumental, methodological and programmatic points of view.





Conclusion

- Without any coordination we have benefited from combining maps/data from multiple instruments and telescopes.
- Advanced Planning of observations could greatly extend this benefit!
  - Sky Coverage
  - Scan strategy (cadence)
  - Alerts
- Coordinating future ground, suborbital, and satellite missions could lower cost and risk.
  - Technology
  - Frequency Coverage
  - Systematic Tests (beams, bands)
  - Pipelines