Pushing the Limits of Cosmology with Next-Generation Millimeter-Wave Telescopes

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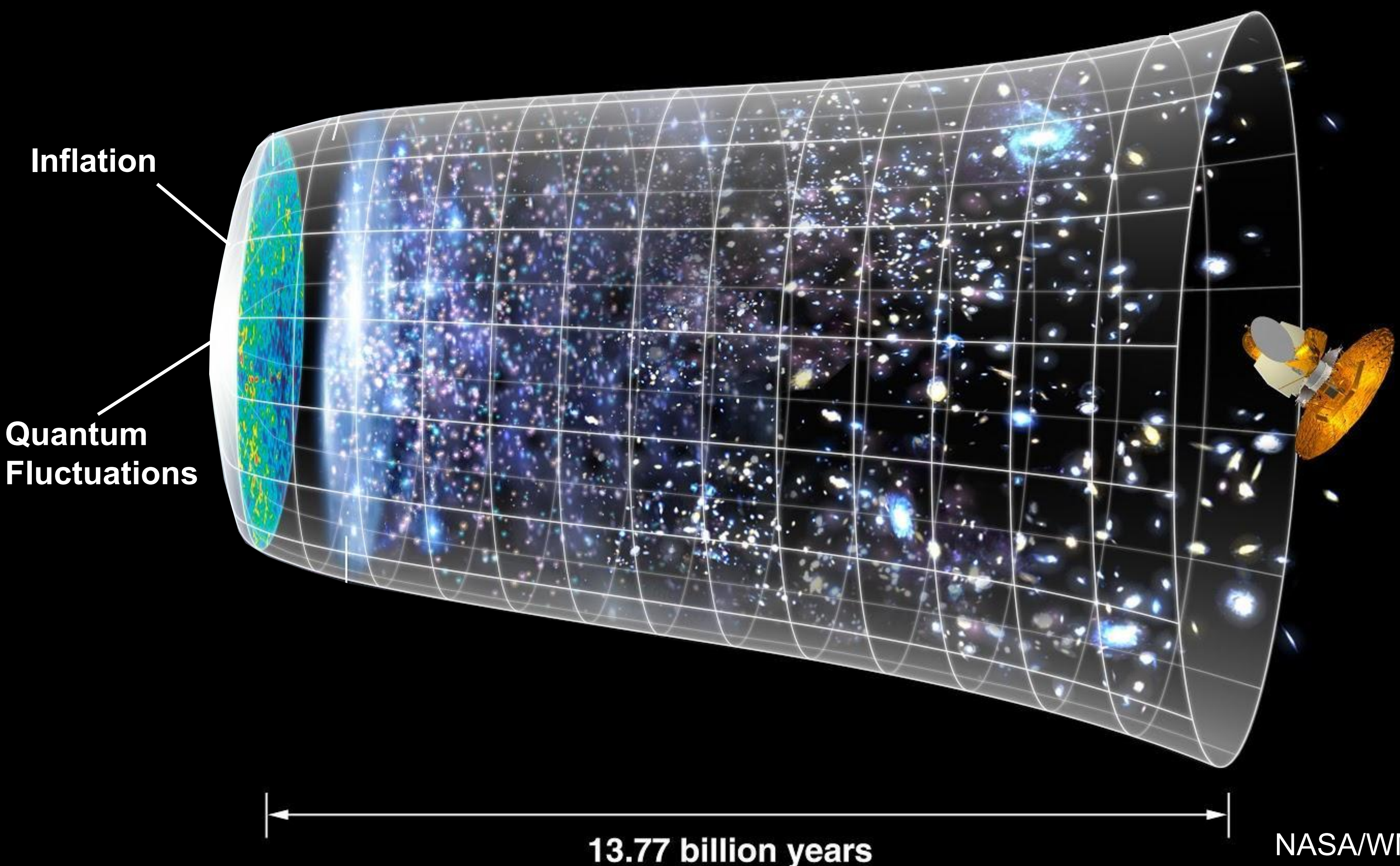
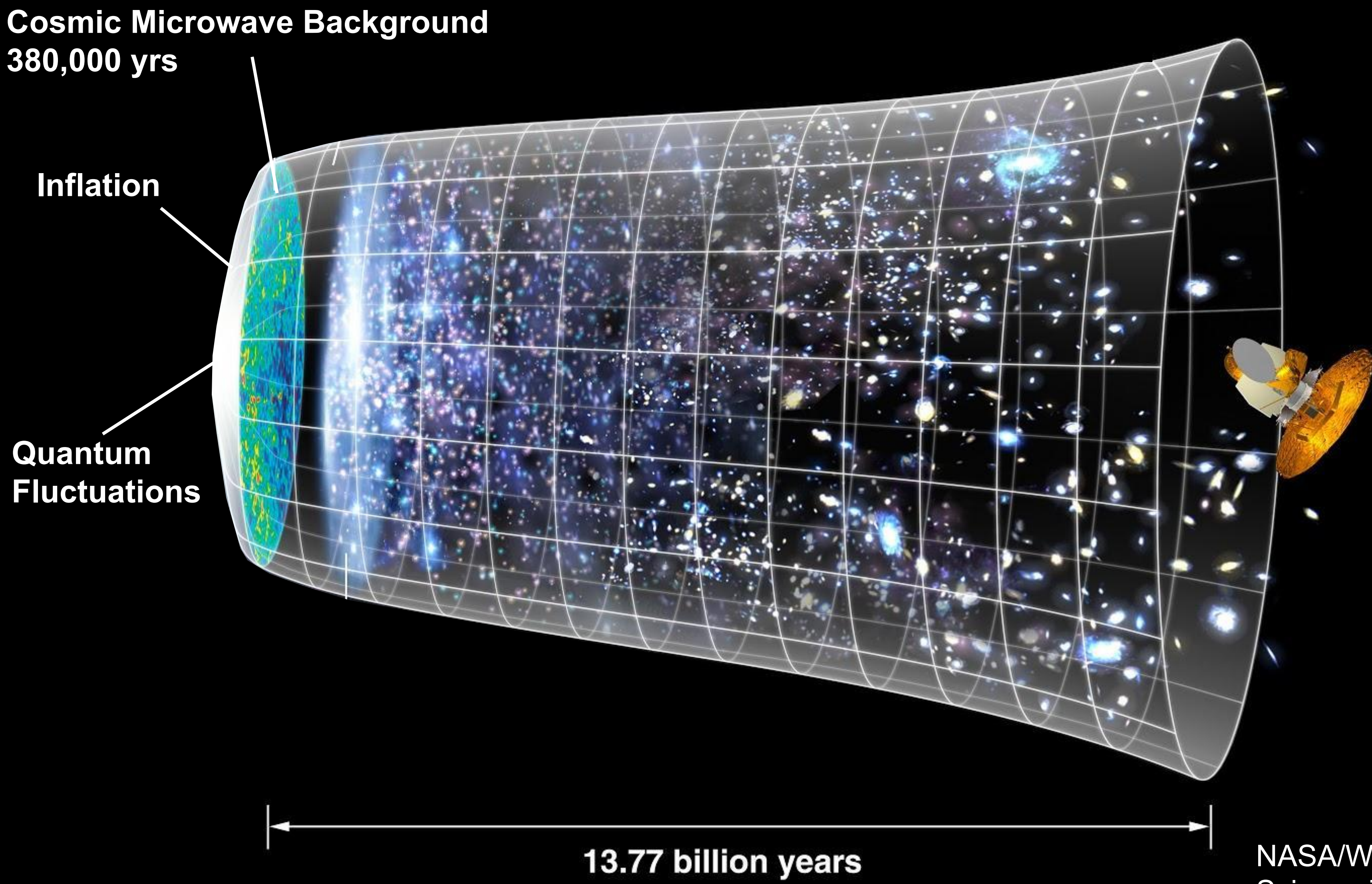
Lawrence Berkeley National Laboratory, 2022-02-24



NASA/WMAP
Science Team



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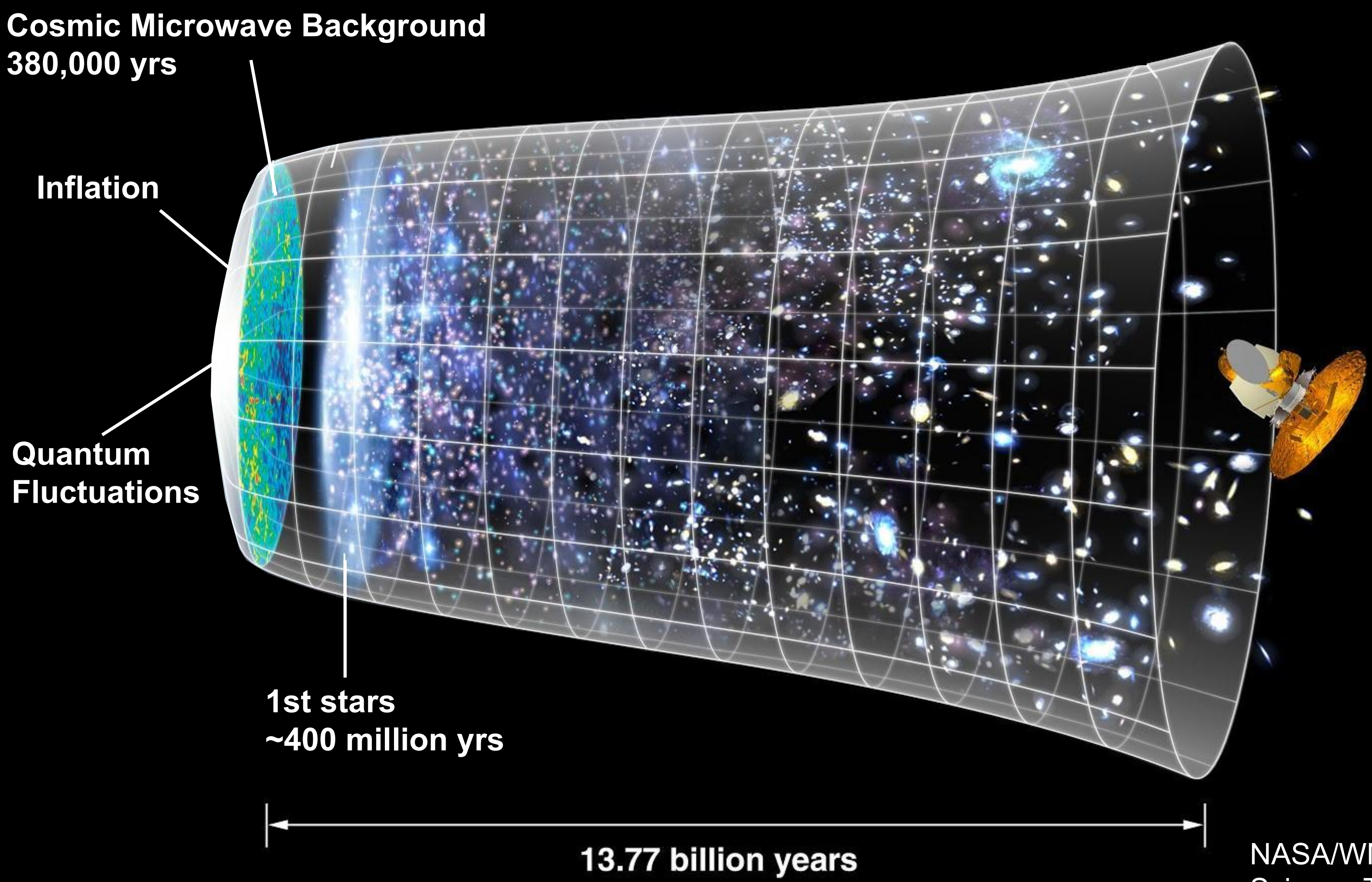

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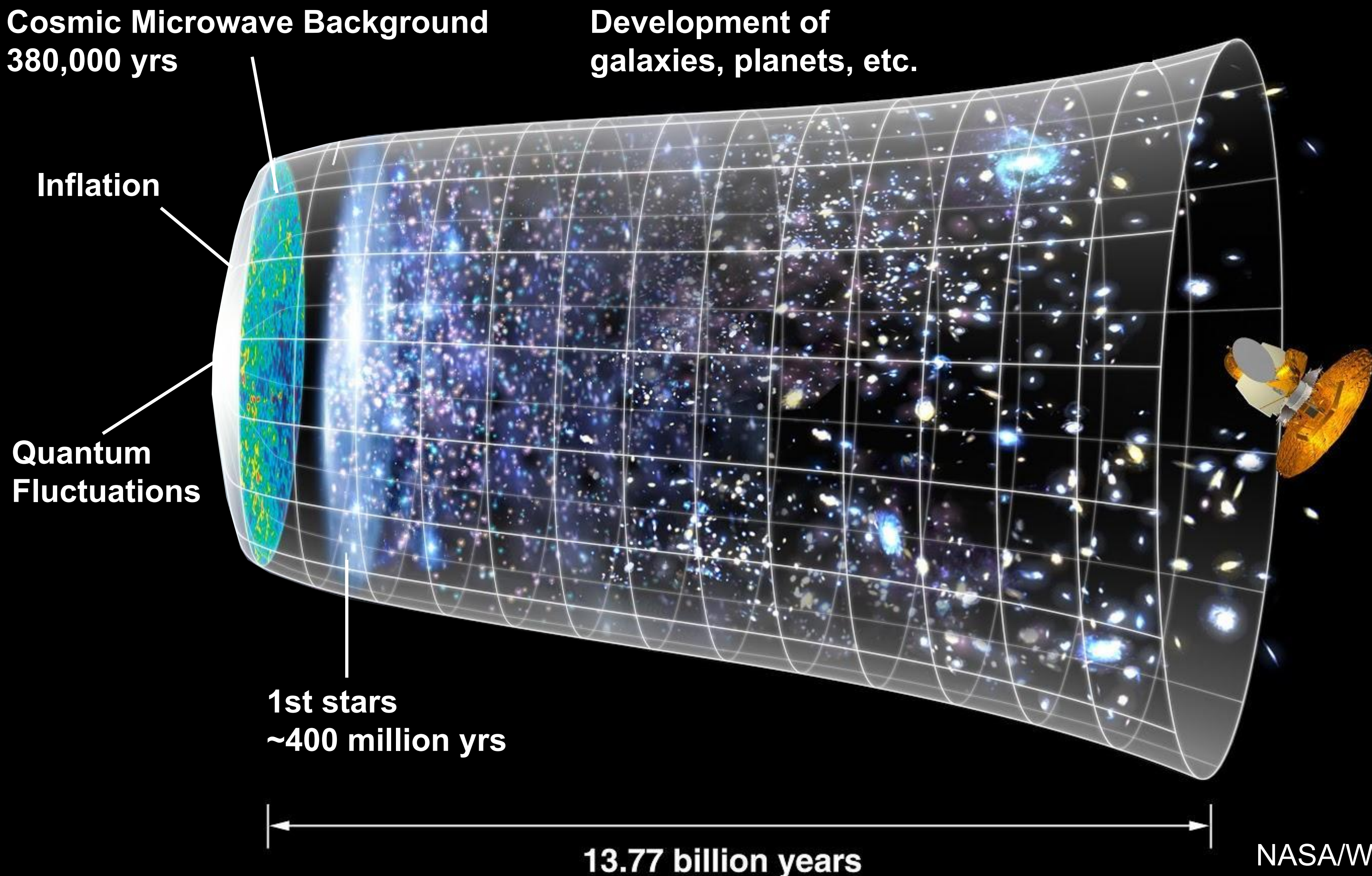

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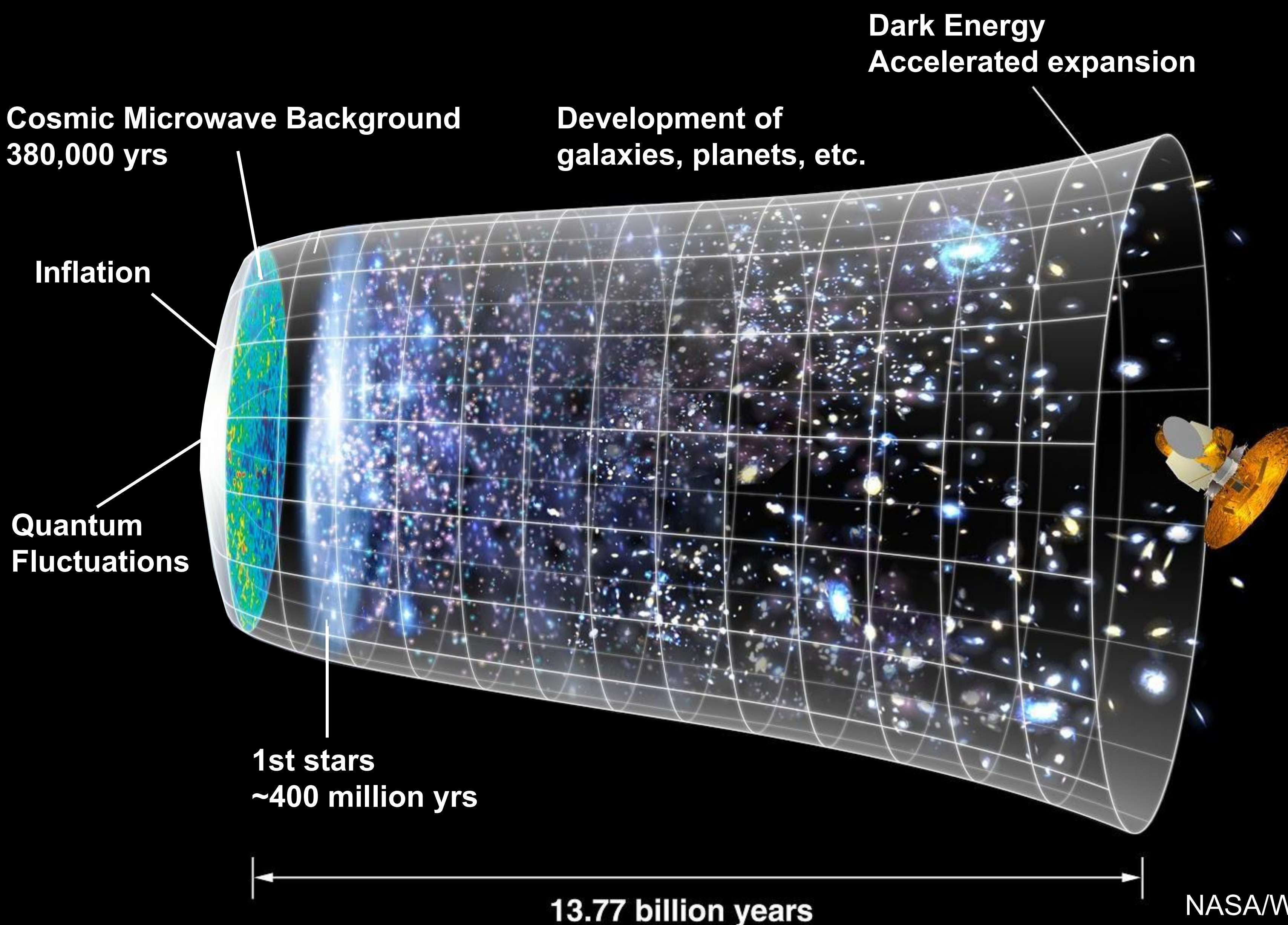

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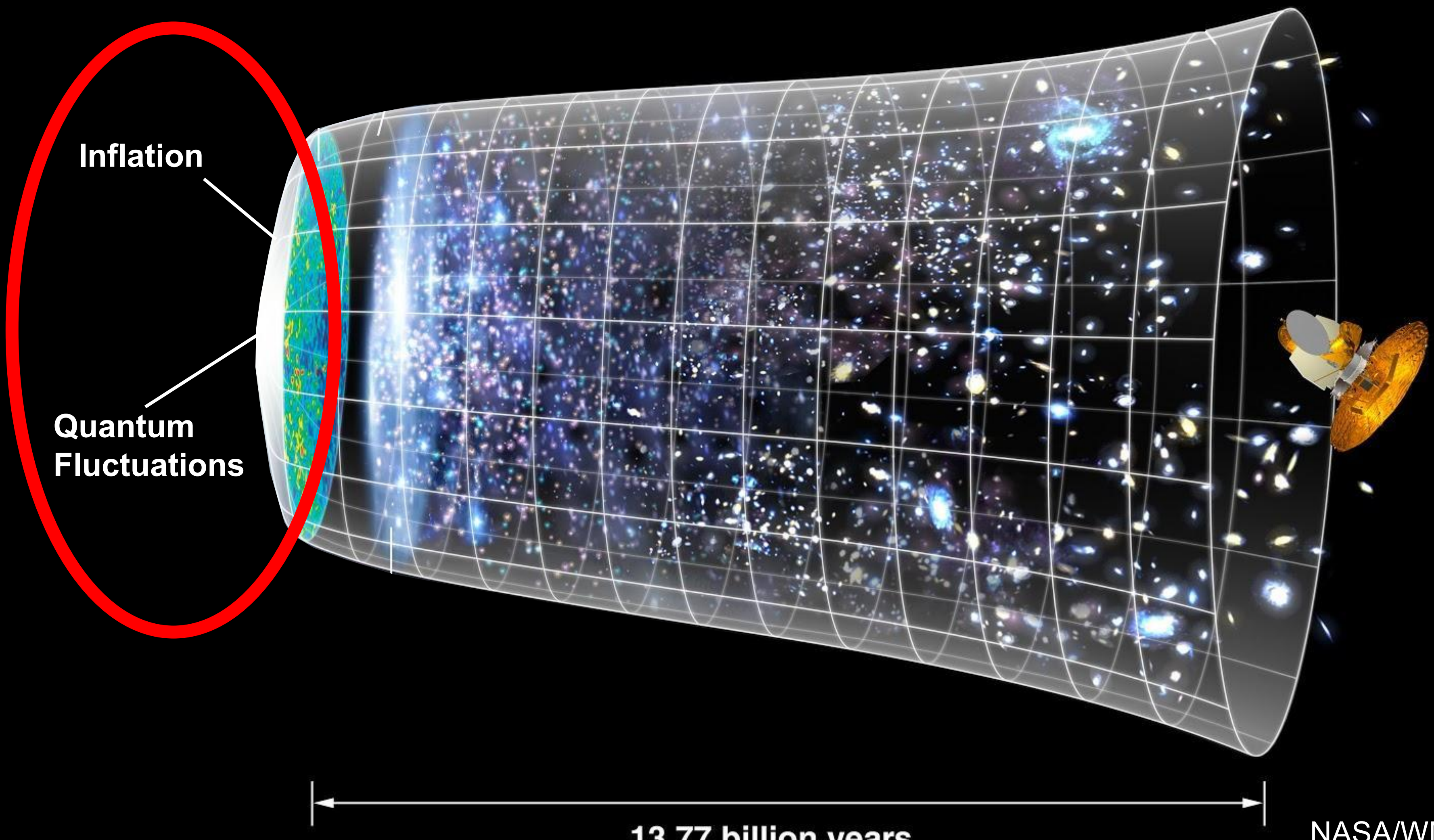

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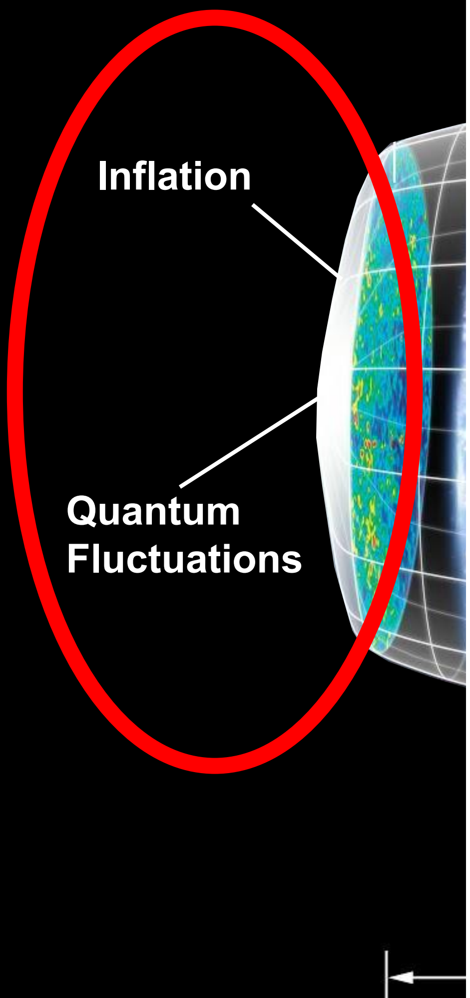
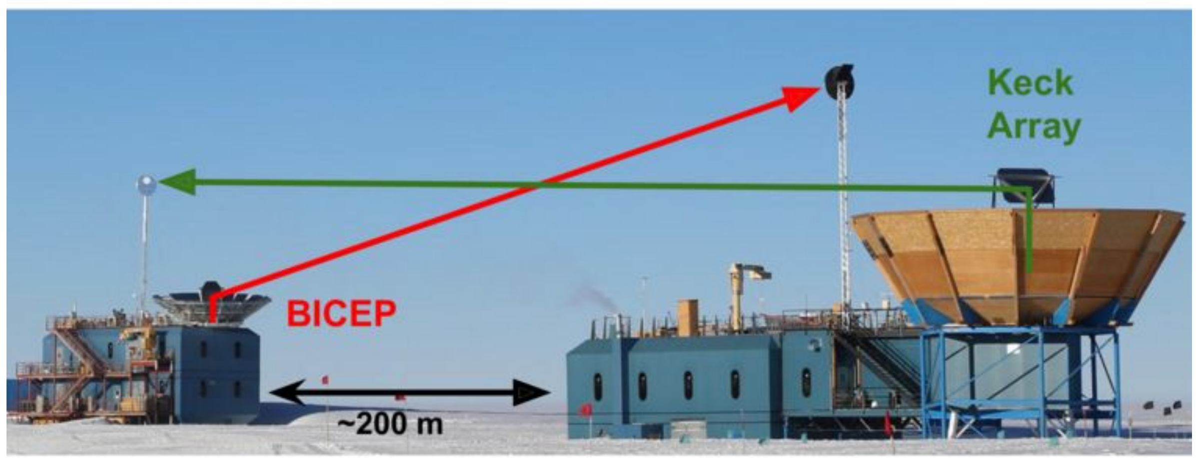
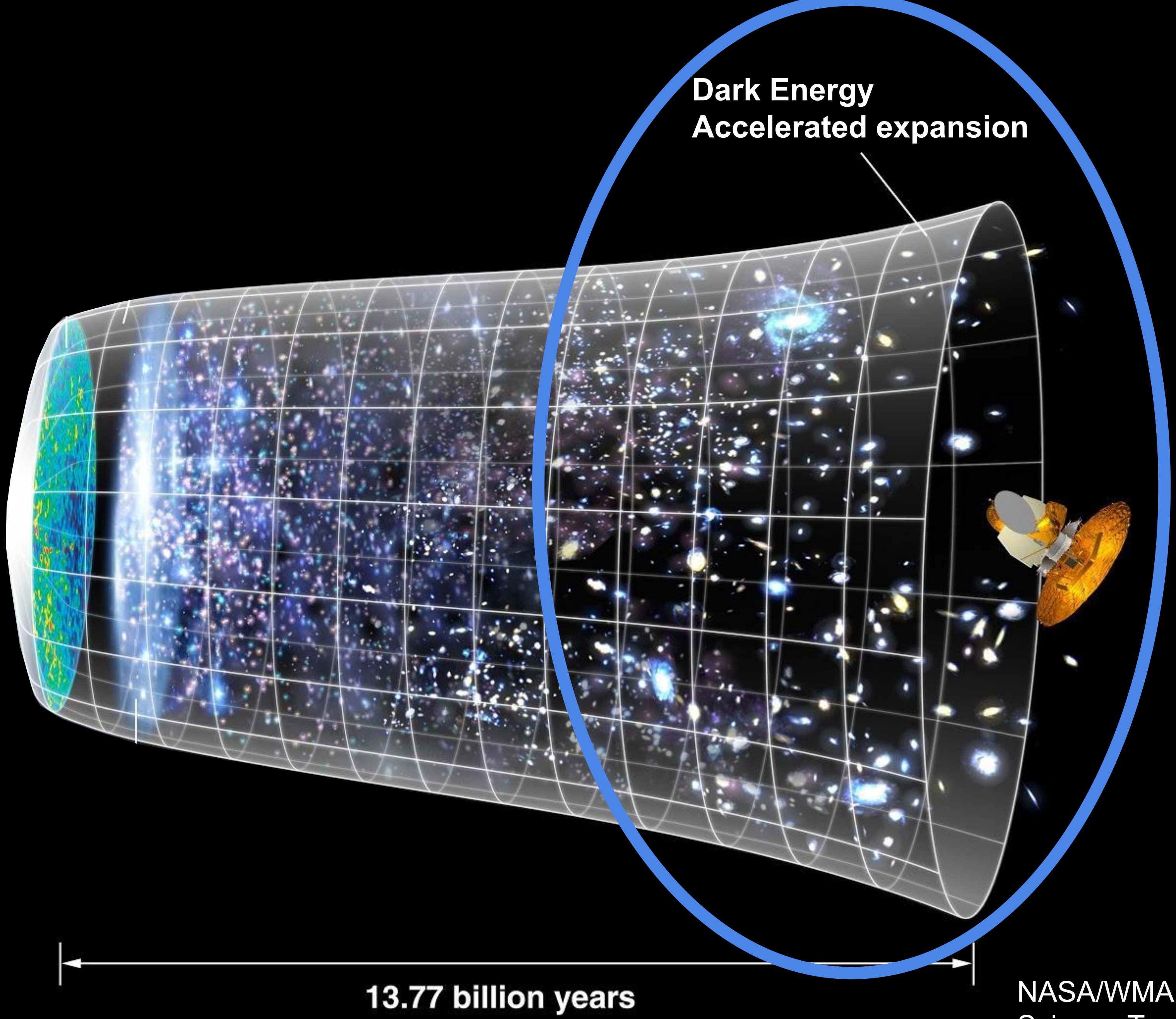


Challenge 1:
Test the physics of inflation.

How:
Measure B-mode polarization in the CMB using BICEP and CMB-S4.

Calibrate instrument and control systematics with extreme precision.





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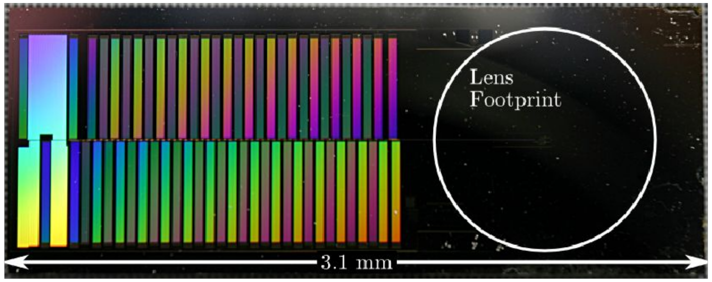
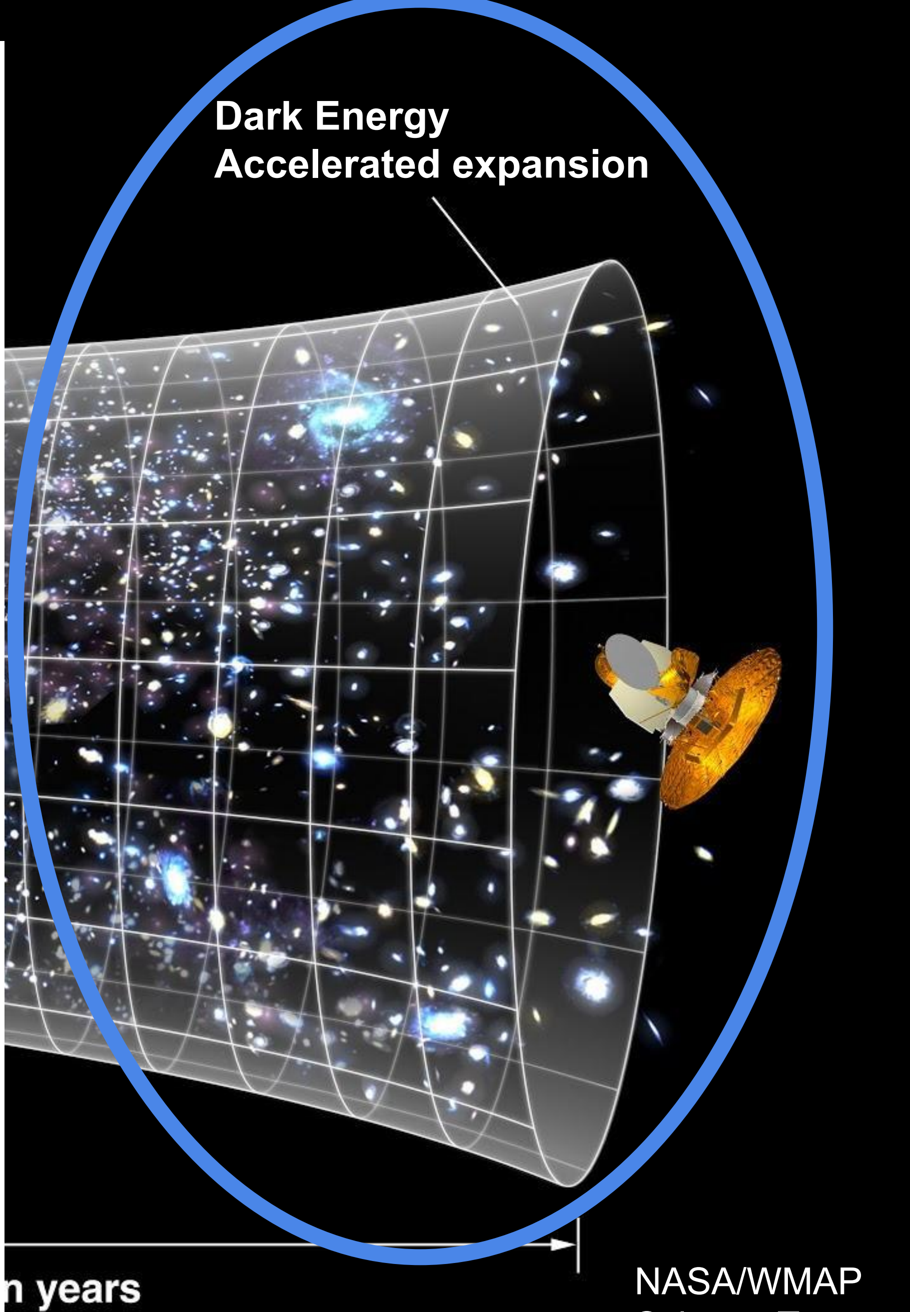
Science Team

Challenge 2:
Measure large-scale structure over larger volumes to test the physics of dark energy and neutrinos.

How:
Millimeter-wave line intensity mapping (LIM).

Demonstrate on-chip spectrometers with SuperSpec and SPT-SLIM.





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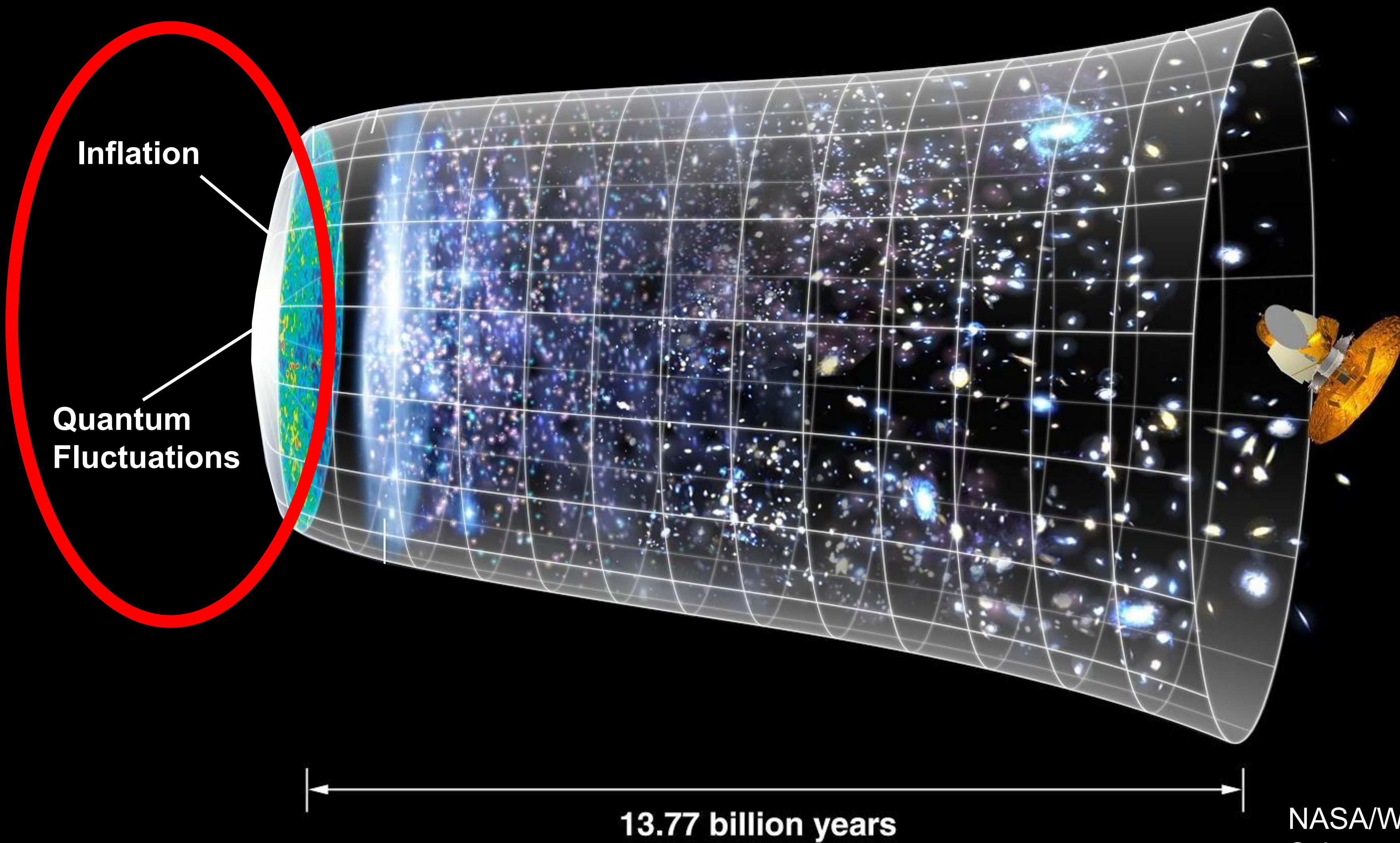
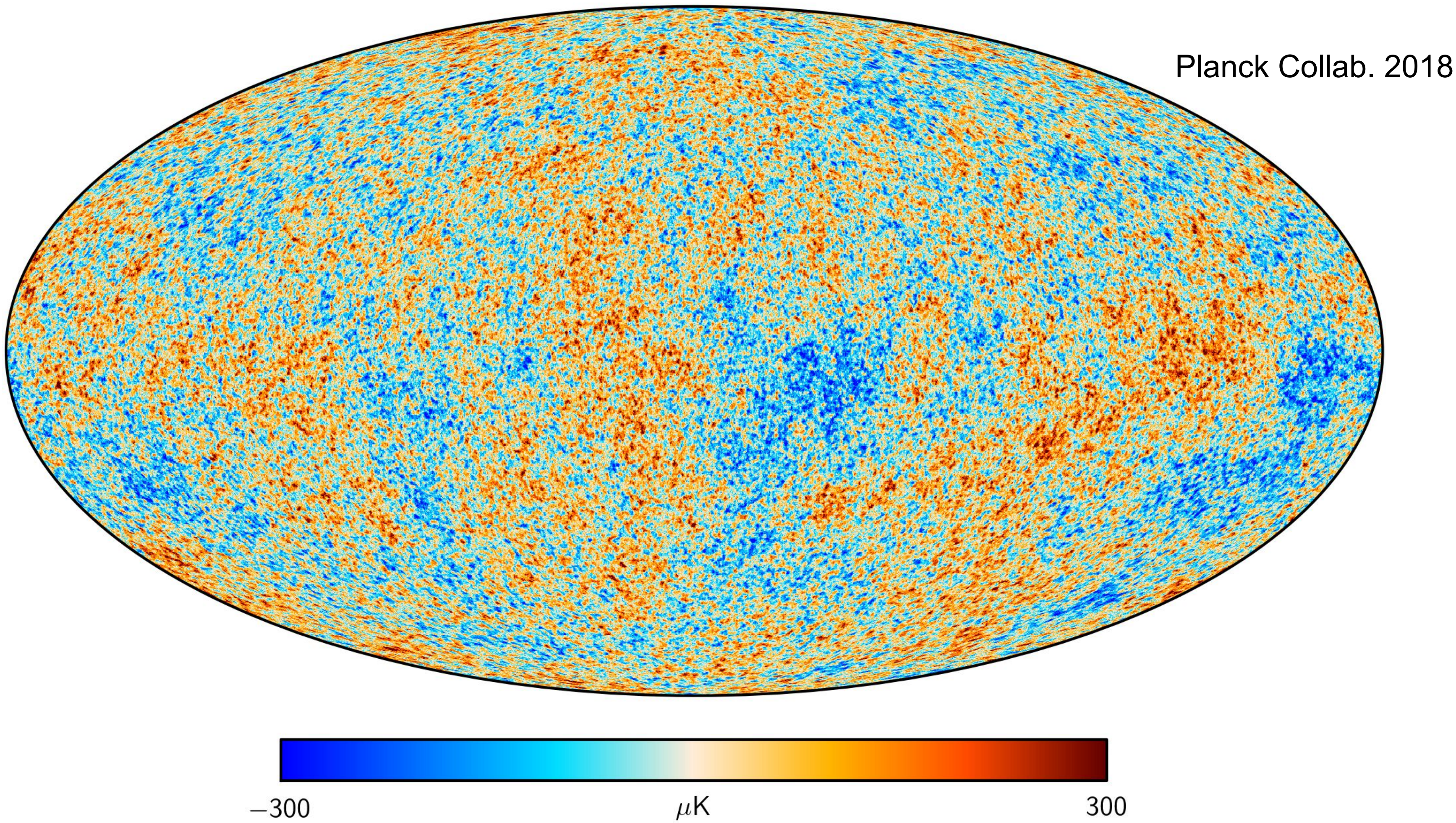
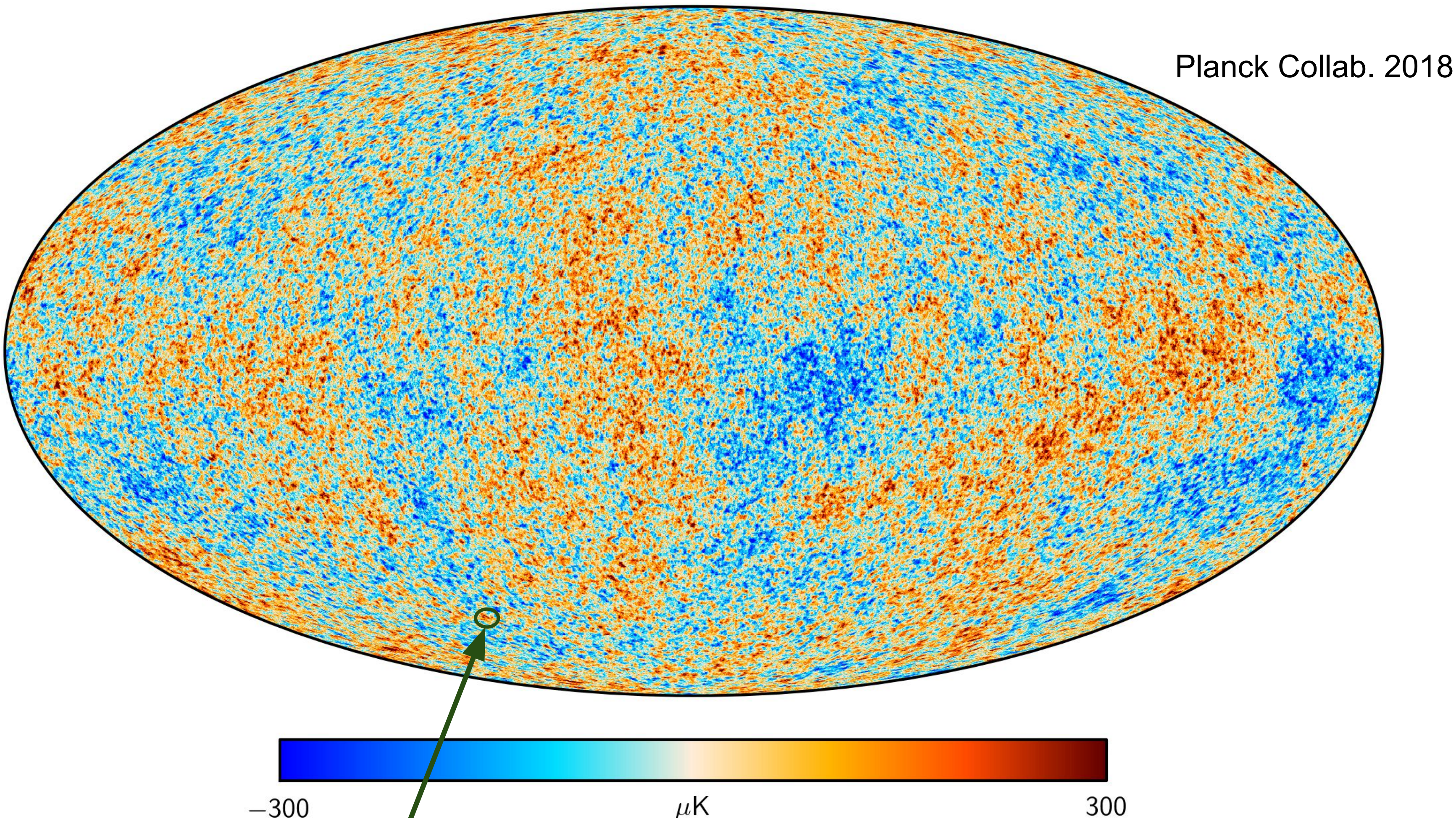


NASA/WMAP
Science Team

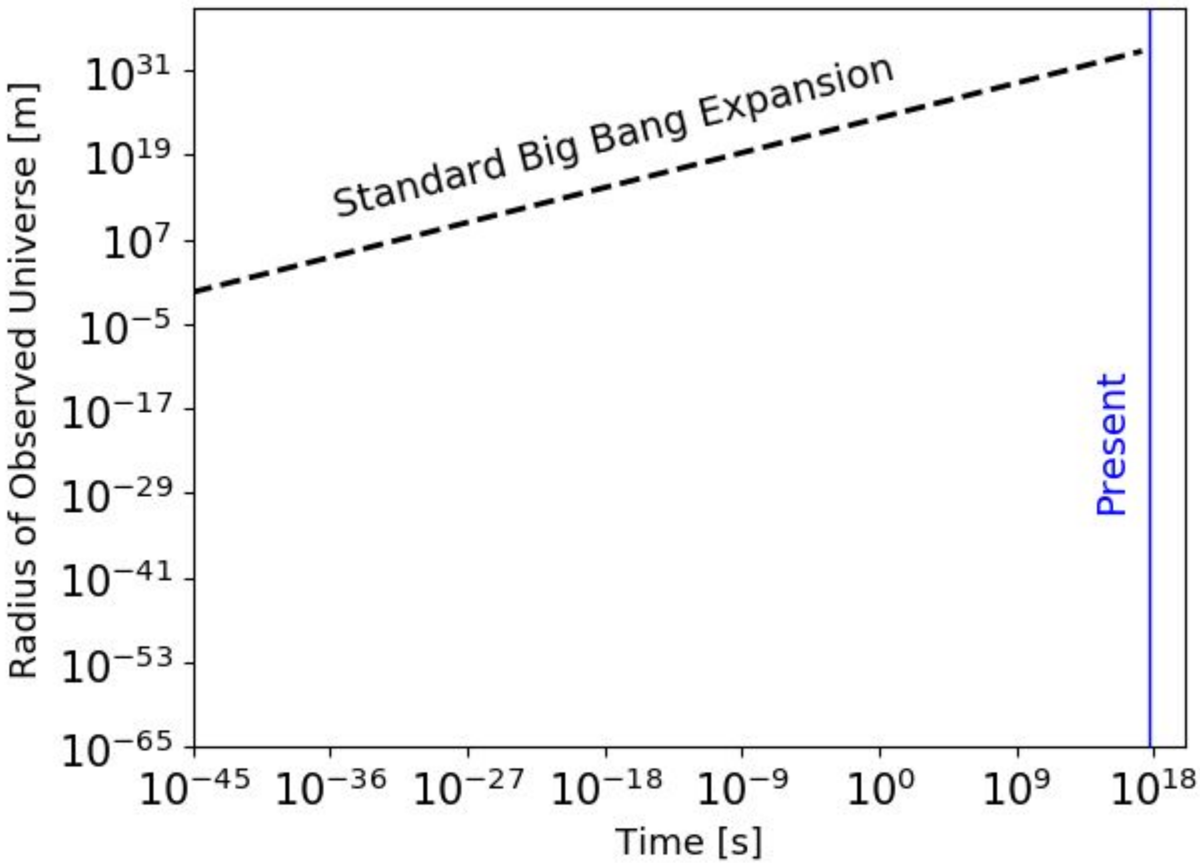

Planck Collab. 2018
−300
μK
300

The CMB temperature across the sky is remarkably uniform...

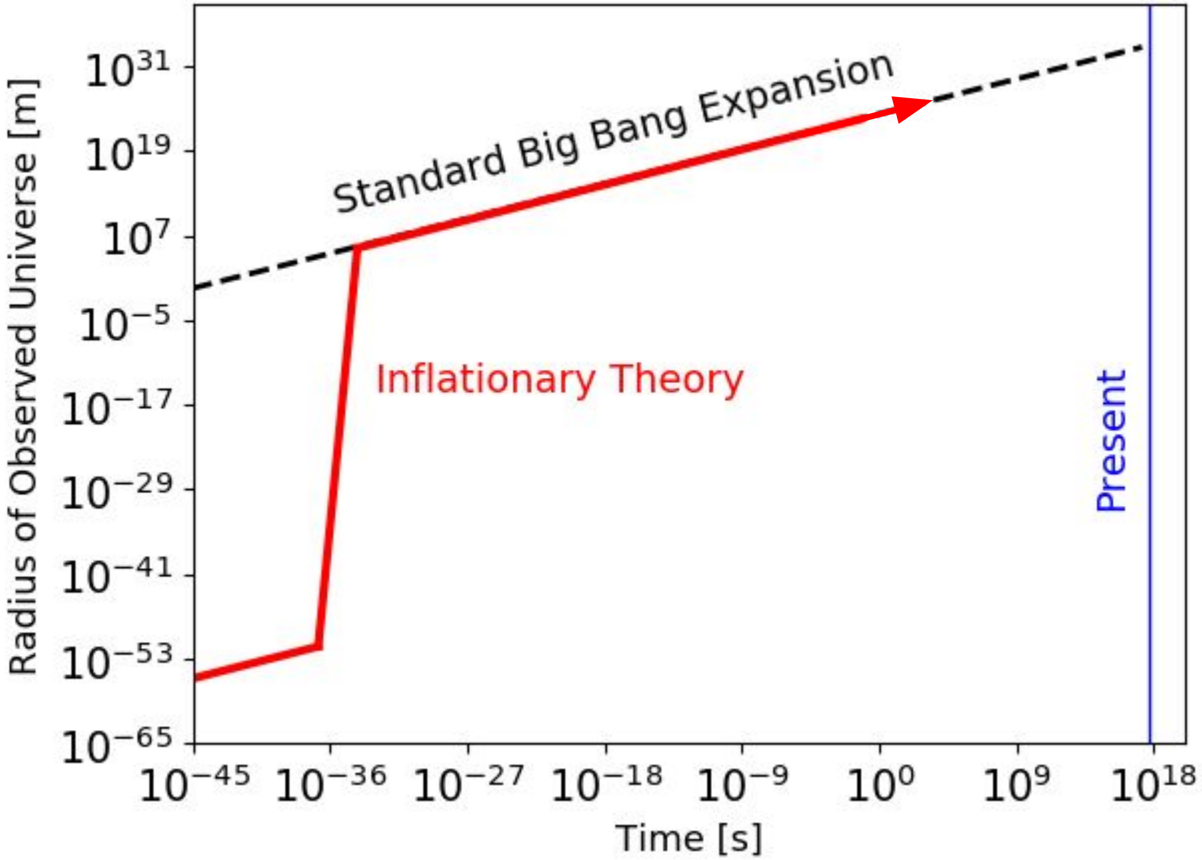


...but a causally-connected region when the CMB was emitted is only ~1°!

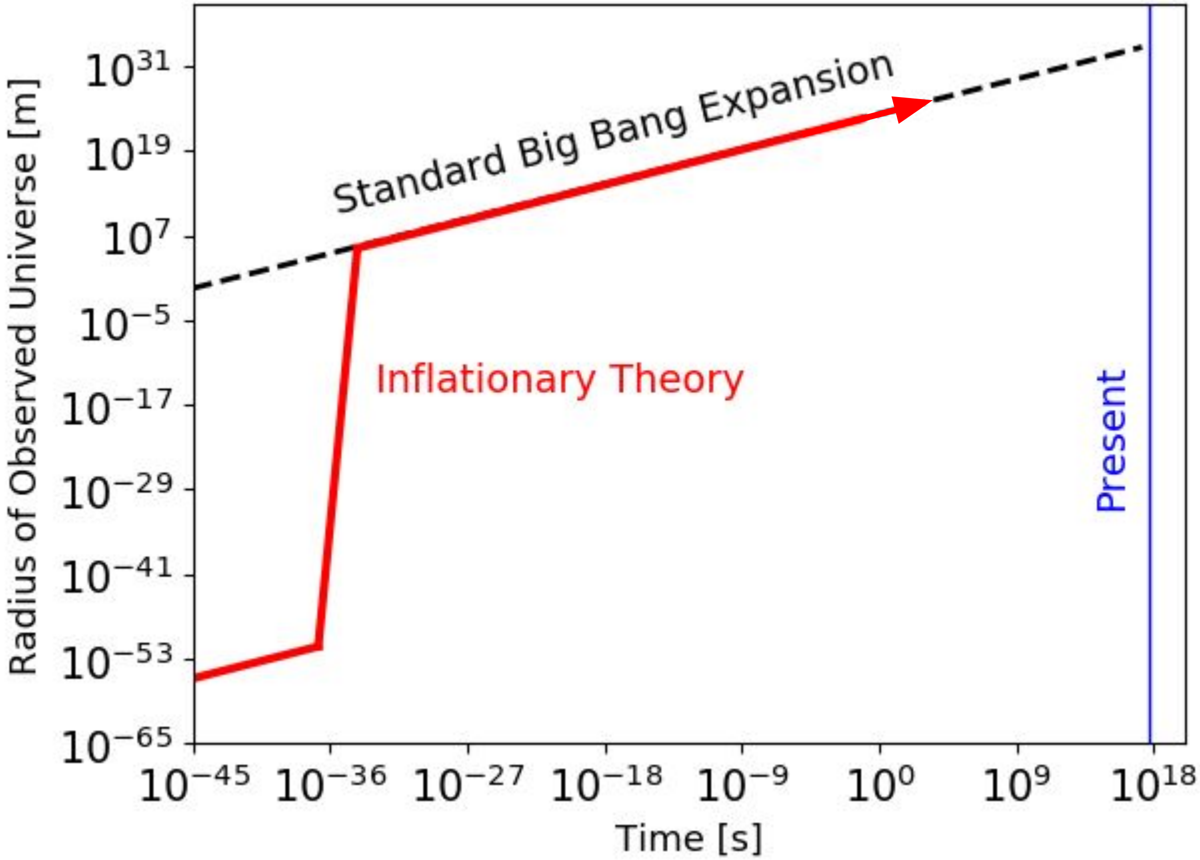
Expansion of the Universe

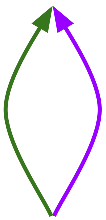


The Inflationary Paradigm

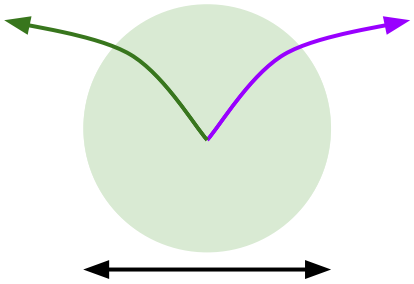


The Inflationary Paradigm



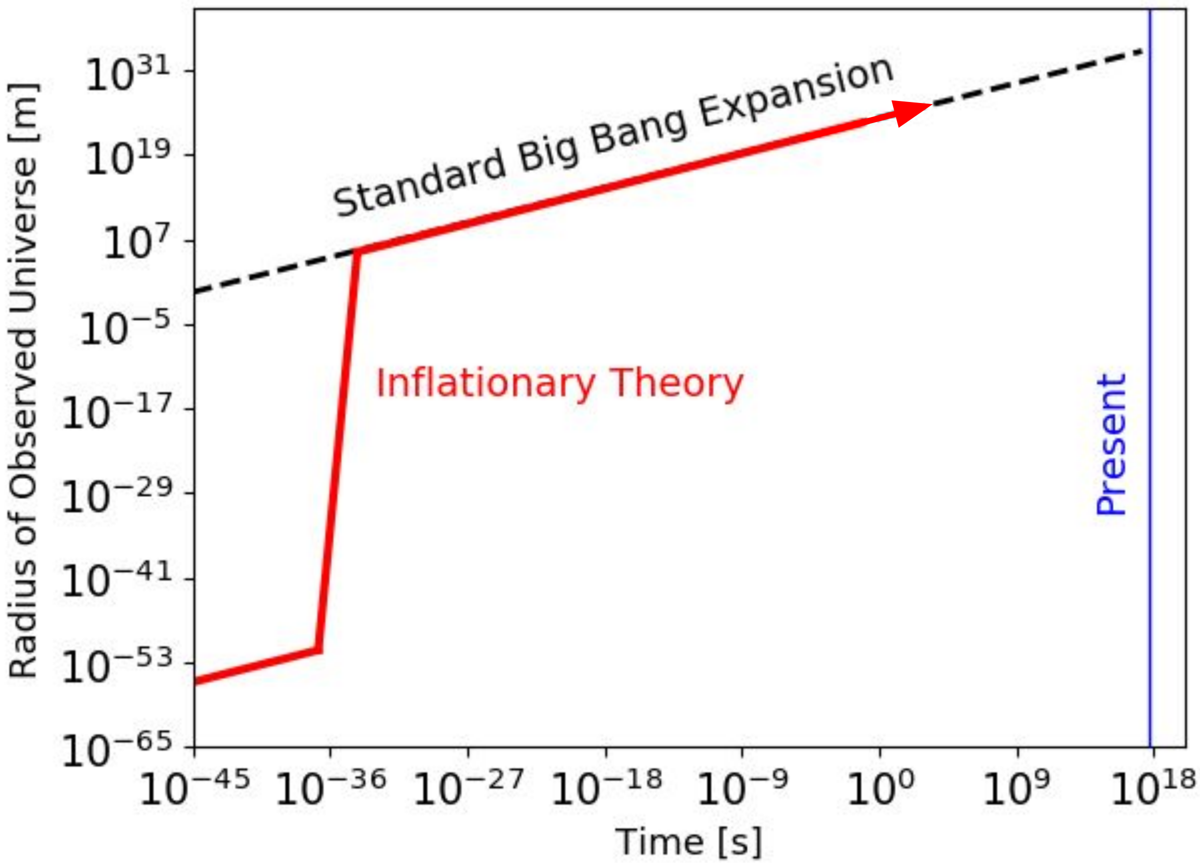


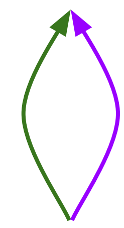
Particle/antiparticle pair



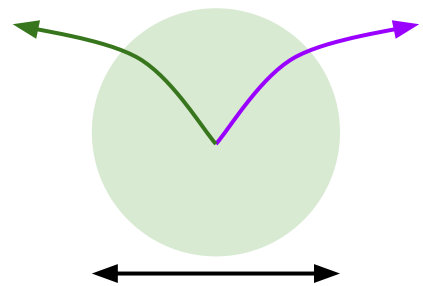
Particles moved out of causal contact

The Inflationary Paradigm





Particle/antiparticle pair

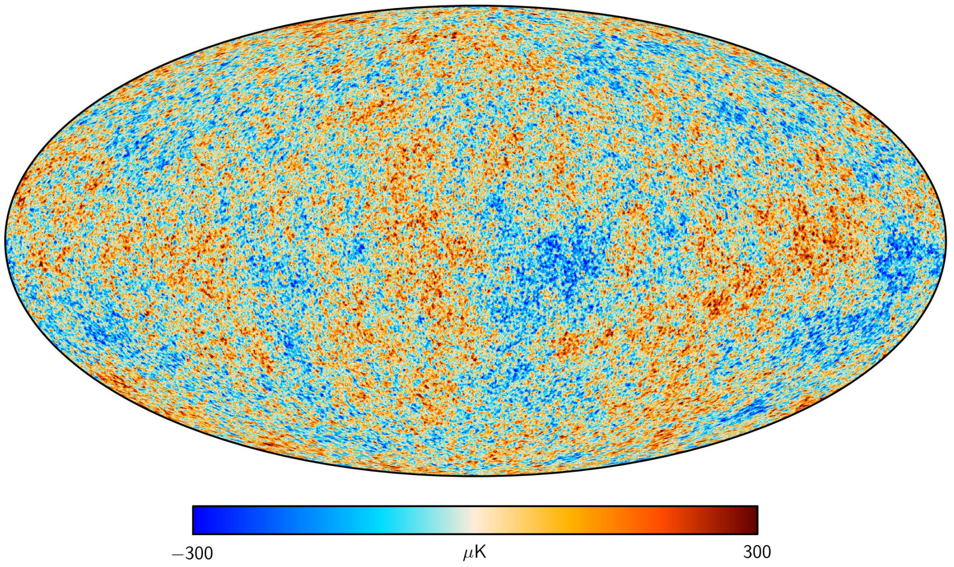


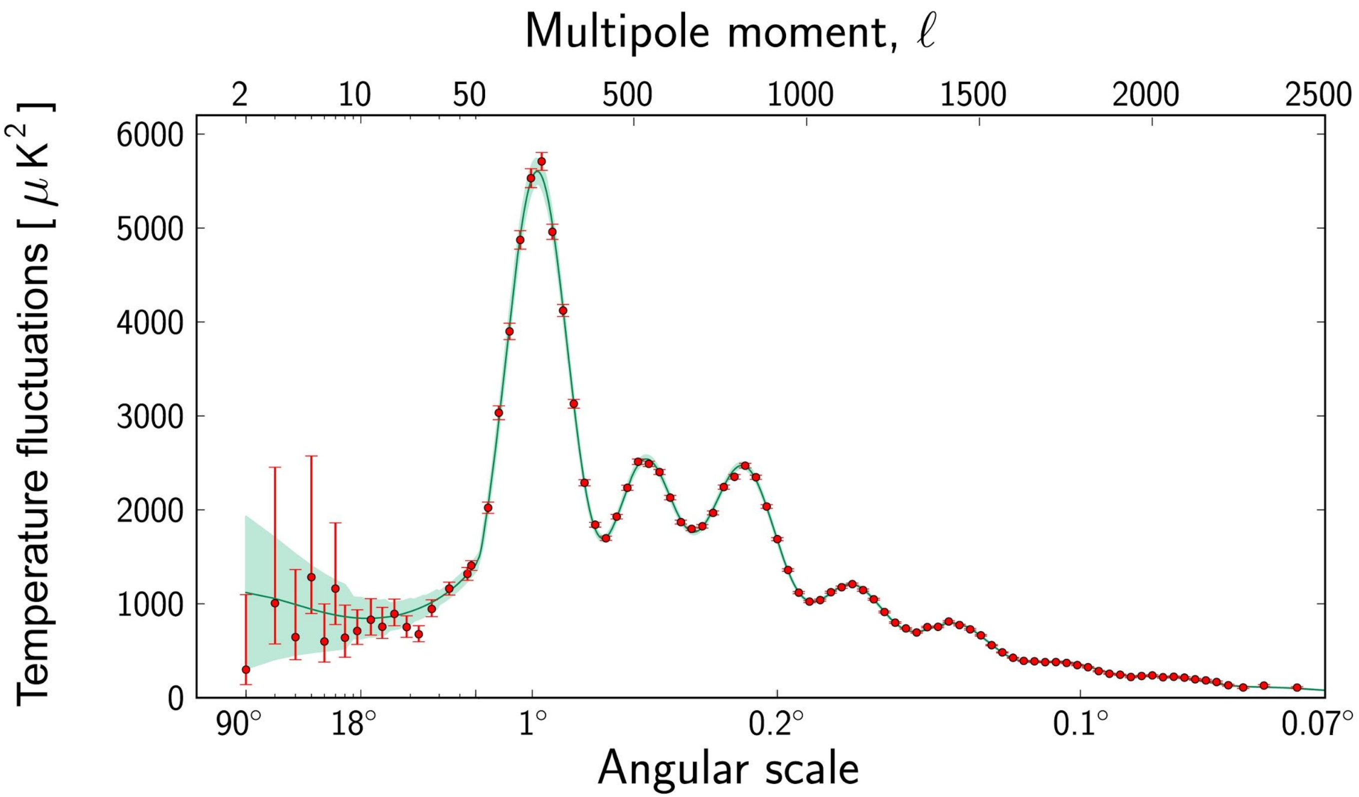
Particles moved out of causal contact

Inflation predicts a background of ***primordial gravitational waves*** *imprinting* ***B-mode polarization*** *in the CMB!*

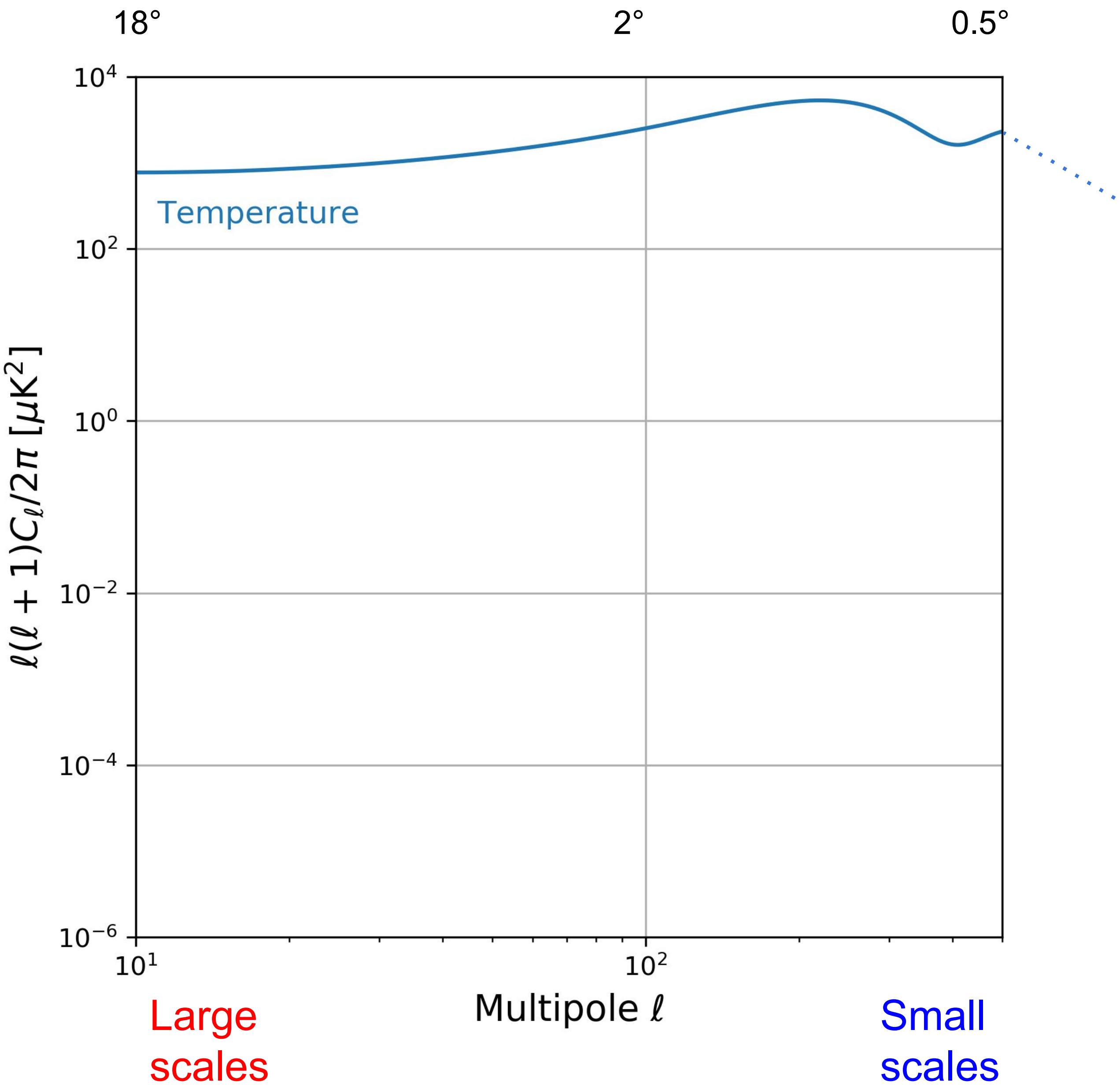
The **power spectrum** quantifies the fluctuations in a map as a function of angle or length.

Natural domain for comparing observation to theory.

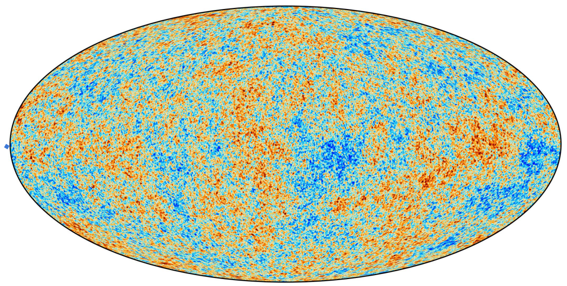


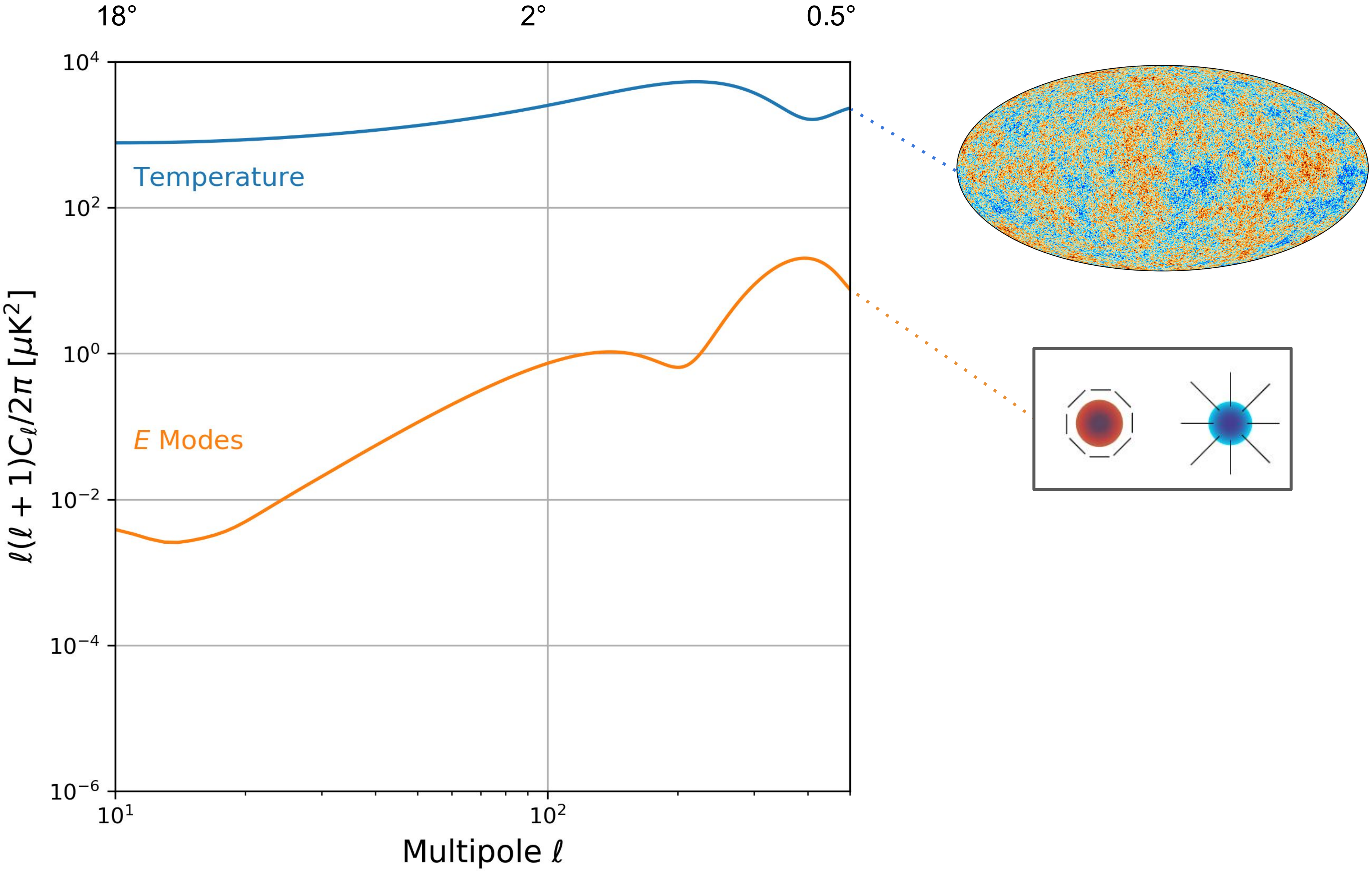


Planck, 1807.06205

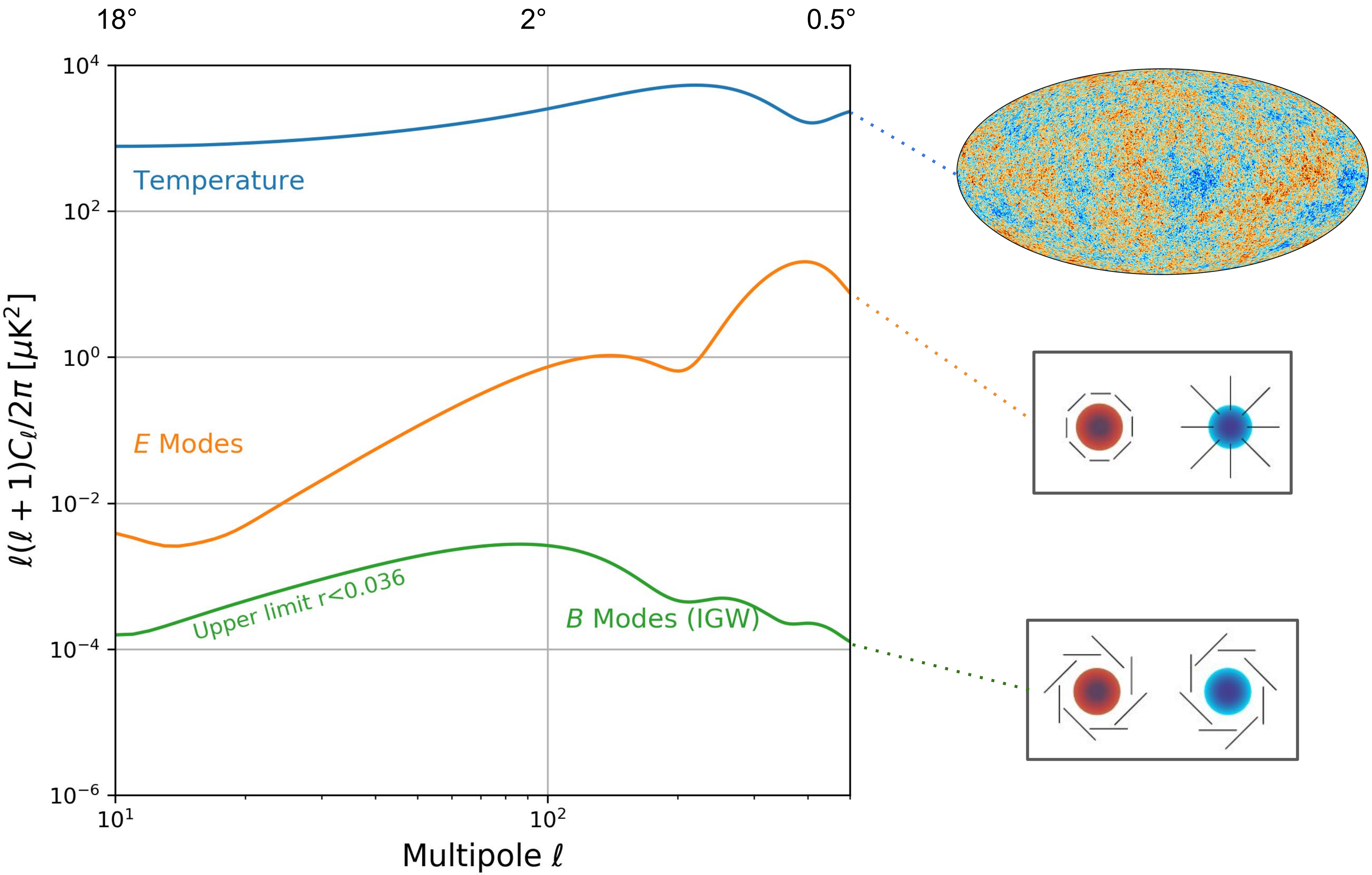


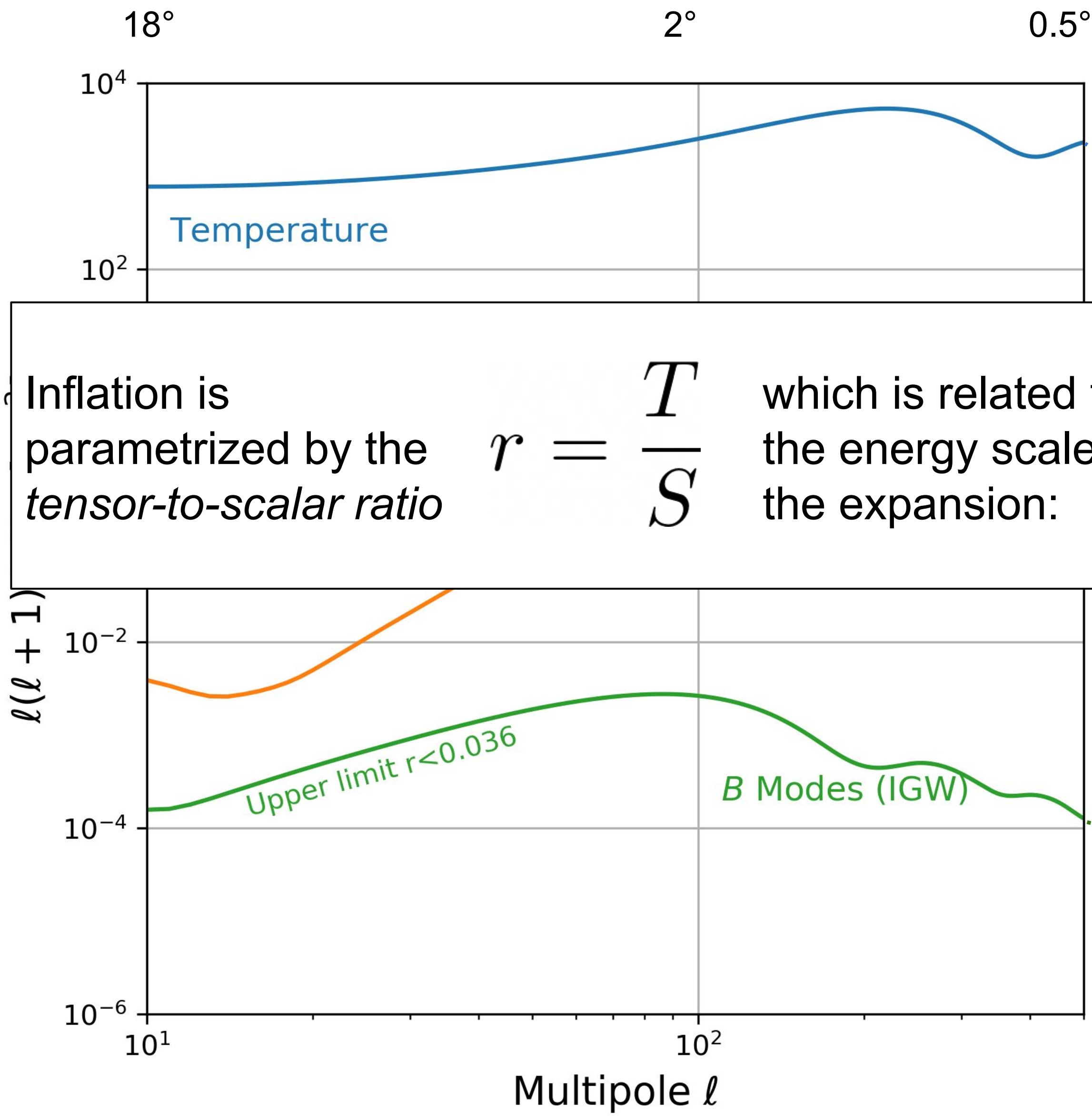
18°
2°
0.5°
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Temperature
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^1
10^2
Multipole ℓ
Large scales
Small scales

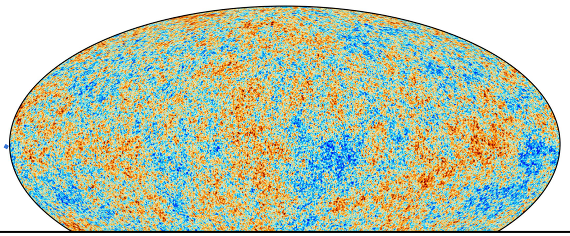




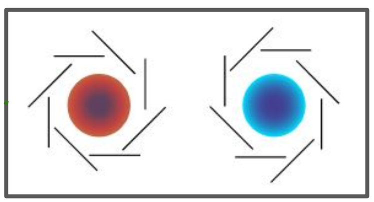
18°
2°
0.5°
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Temperature
E Modes
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^1
10^2
Multipole ℓ

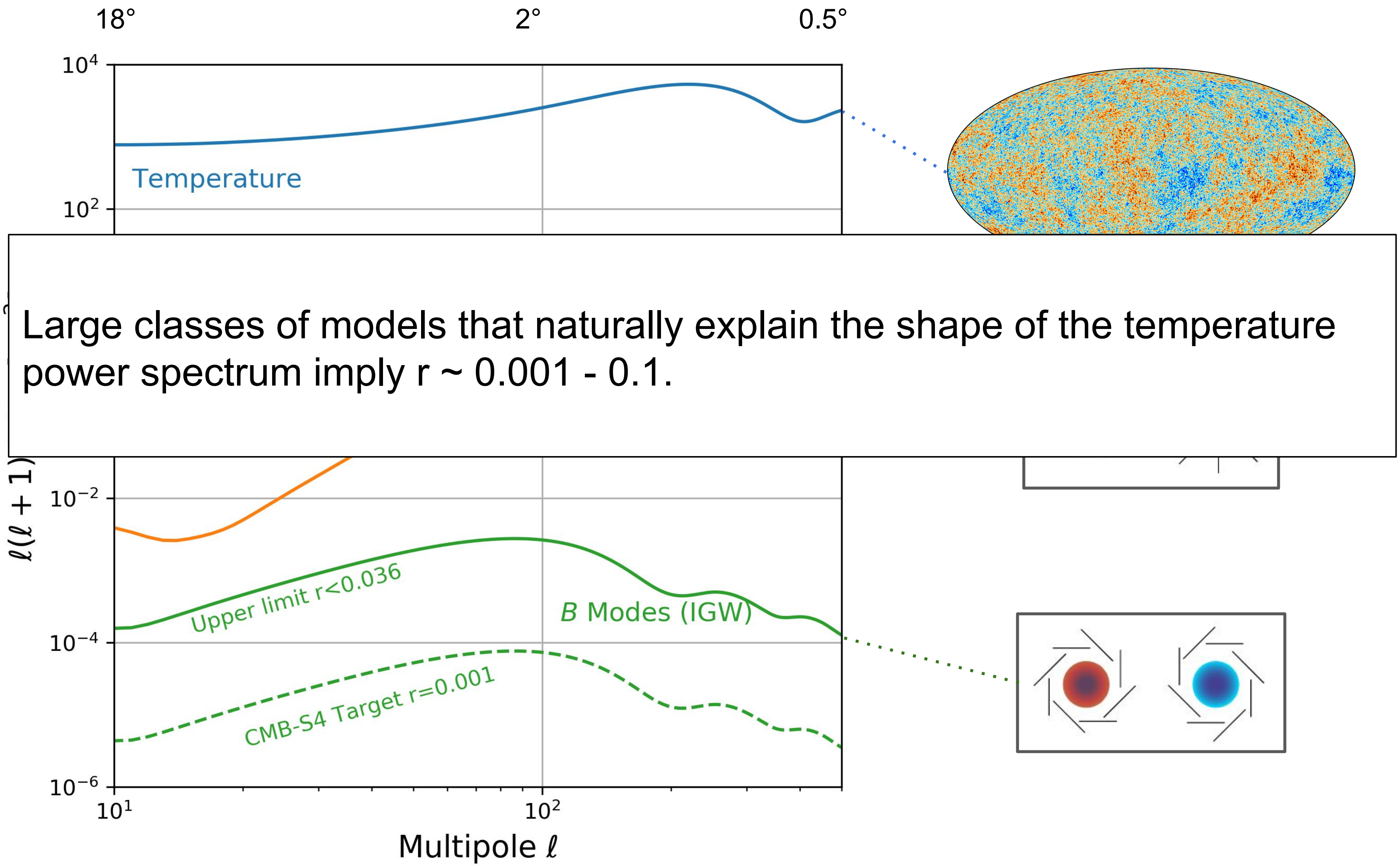

18°
2°
0.5°
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^1
10^2
Temperature
E Modes
Upper limit r<0.036
B Modes (IGW)
Multipole ℓ
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$



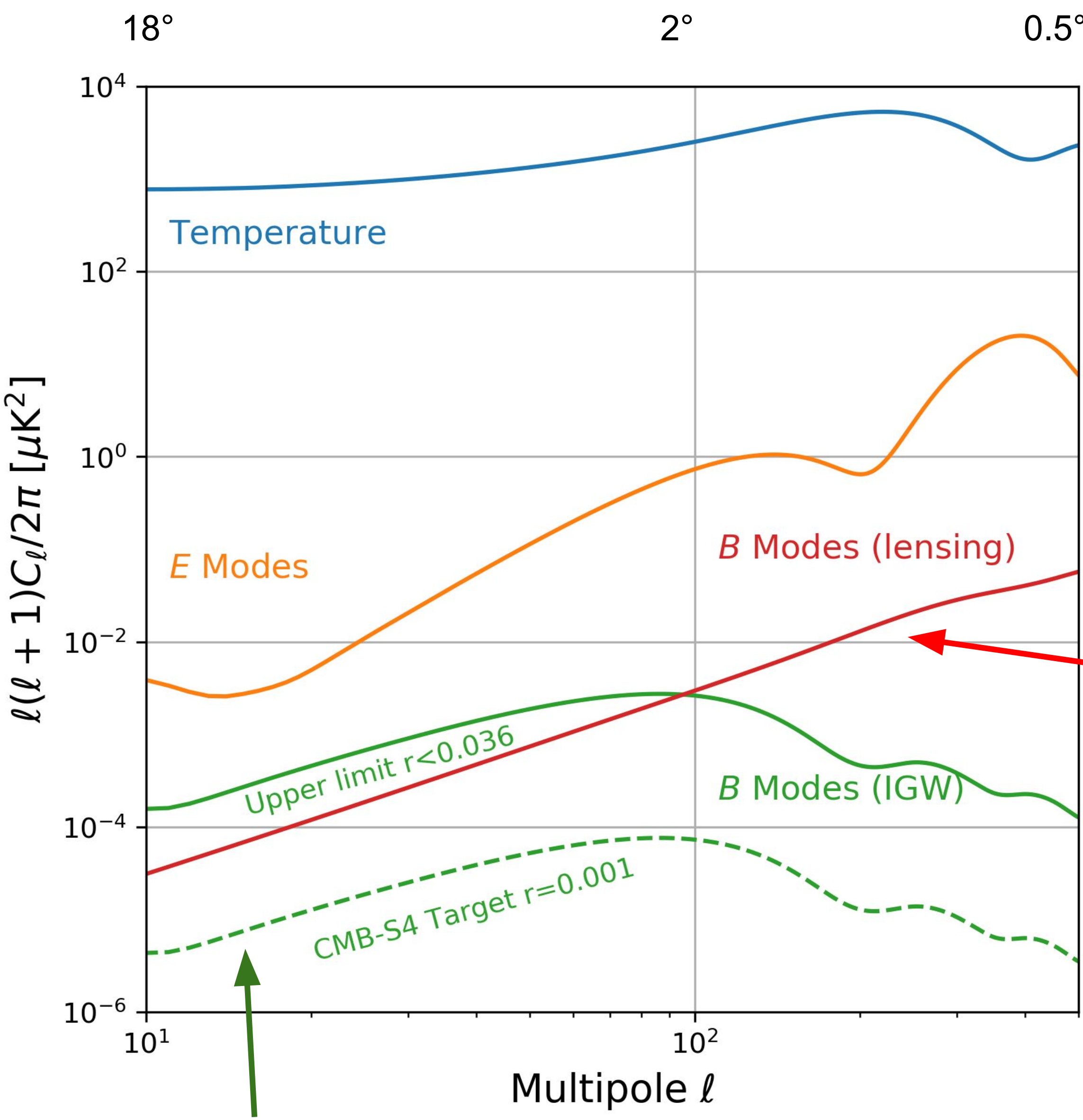


Inflation is parametrized by the *tensor-to-scalar ratio* $r = \frac{T}{S}$ which is related to the energy scale of the expansion: $V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\mathrm{GeV}$





Large classes of models that naturally explain the shape of the temperature power spectrum imply r ~ 0.001 - 0.1.



~nK-level signal!

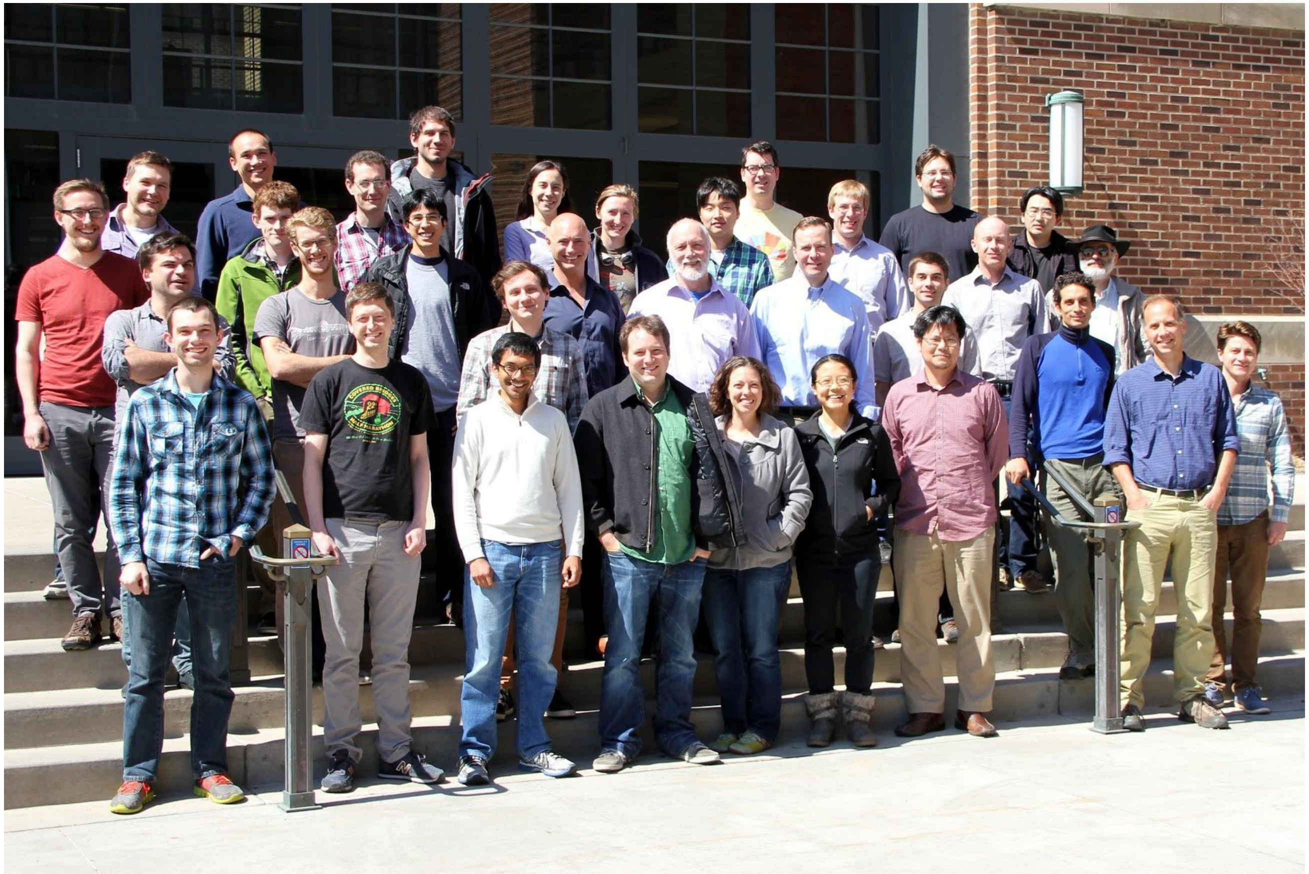
This is a hard measurement!

Extremely faint signal
- **Maximize sensitivity**

Astrophysical foregrounds
- **Measure with several frequencies** to remove the Galaxy
- **Remove lensing B modes**

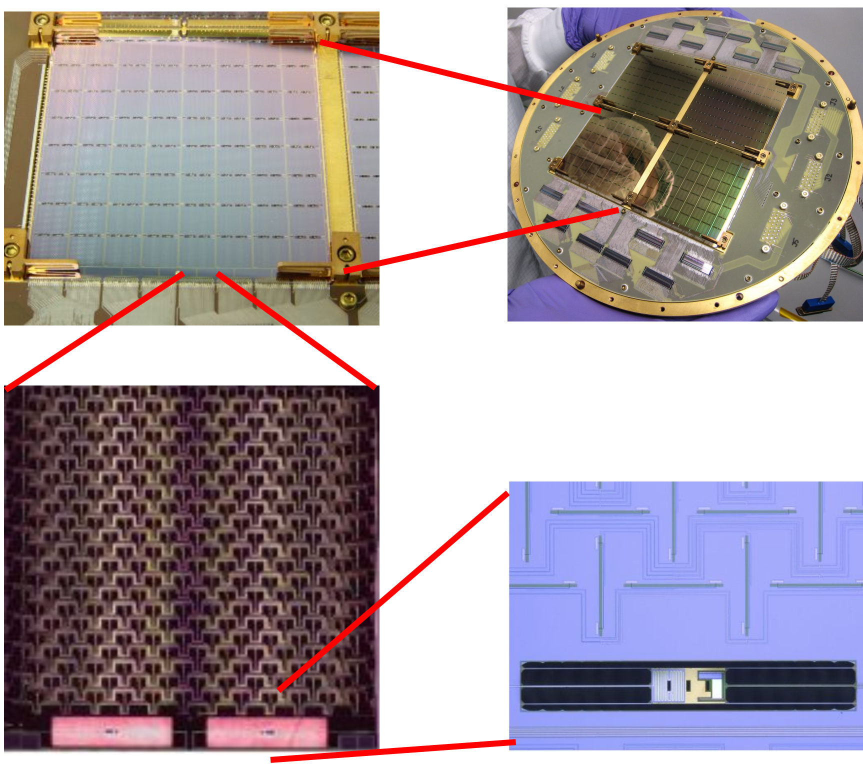
Instrumental systematics
- **Calibrate telescopes with extreme precision**
- **Mitigate systematics in analysis**

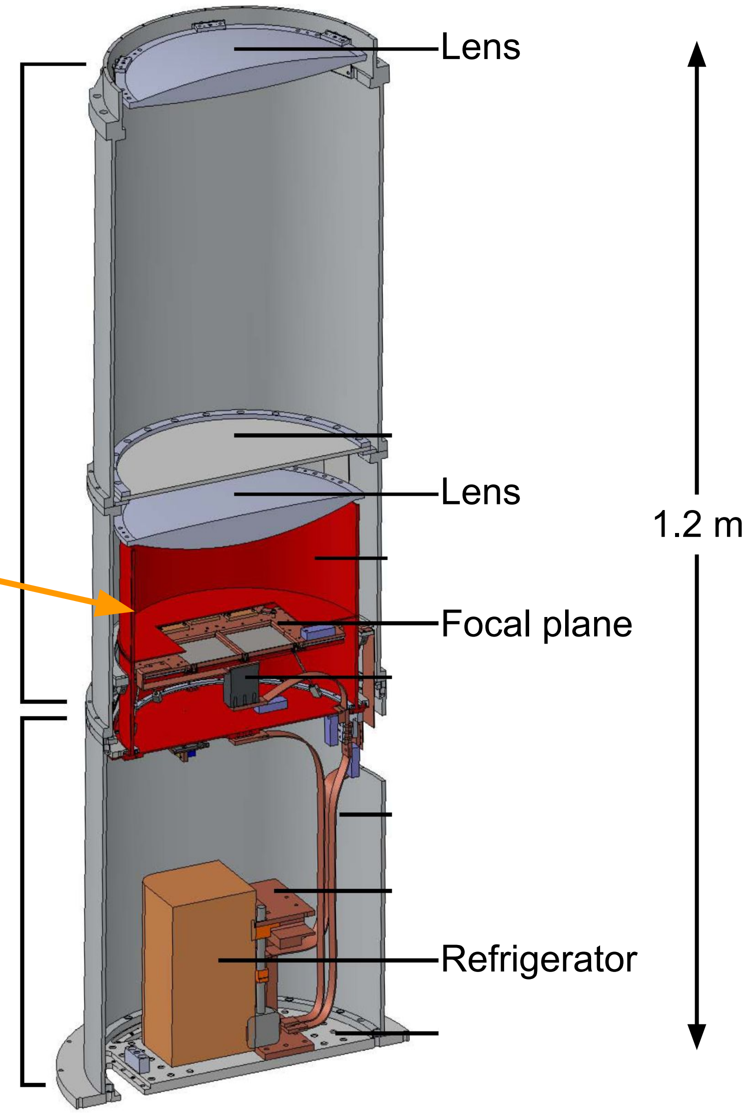
The BICEP/Keck Array Collaboration



The BICEP/Keck Telescopes

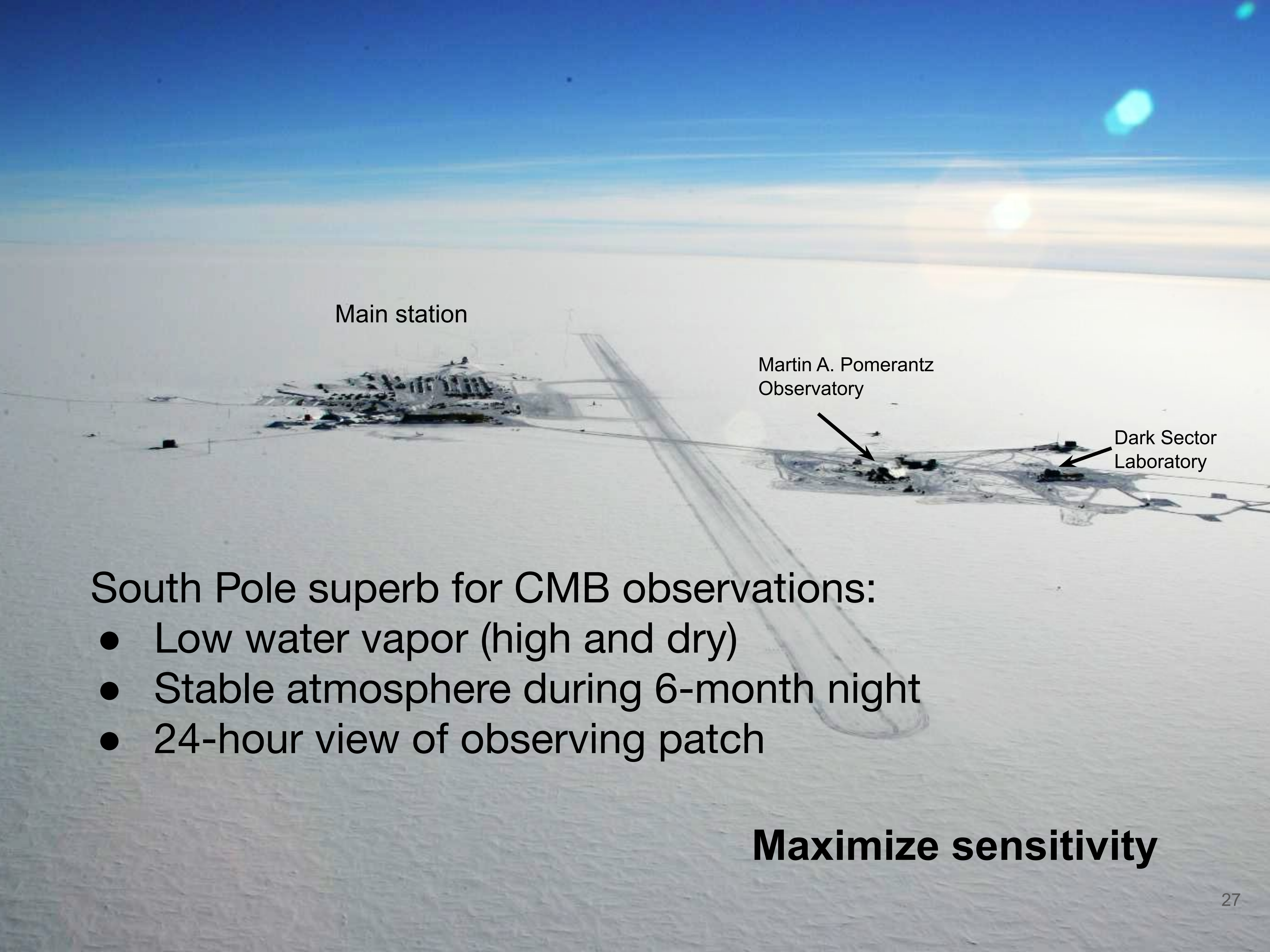
Simple, on-axis refractors optimized for degree-scale polarization measurements





Transition edge sensor bolometers held at ~250 mK, coupled to planar antenna arrays

Maximize sensitivity



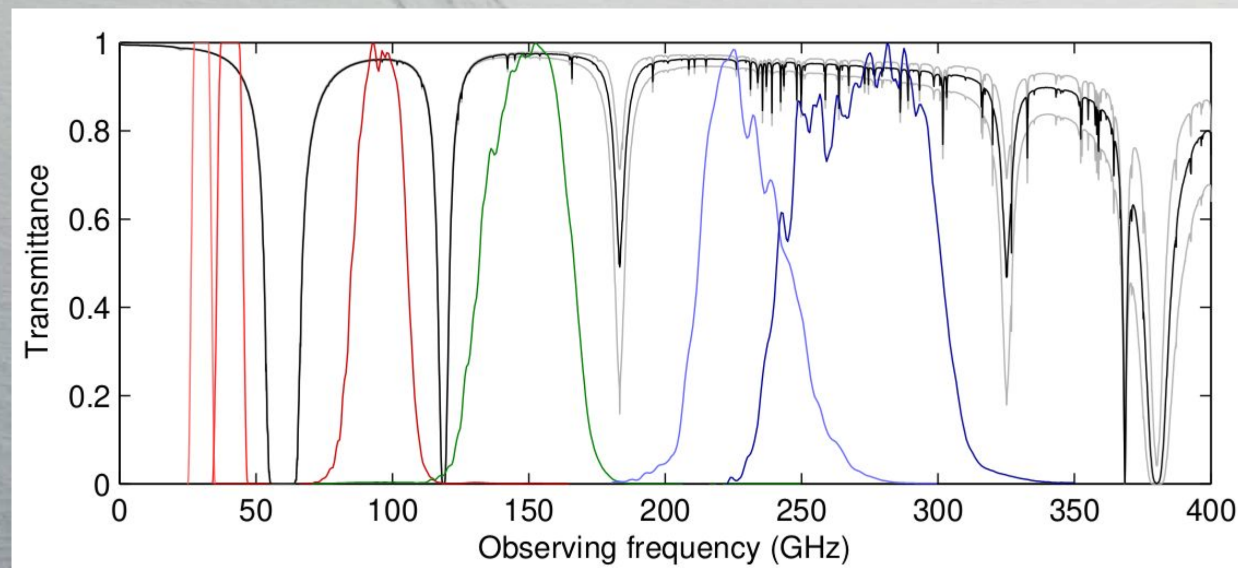
South Pole superb for CMB observations:

- Low water vapor (high and dry)
- Stable atmosphere during 6-month night
- 24-hour view of observing patch

Maximize sensitivity

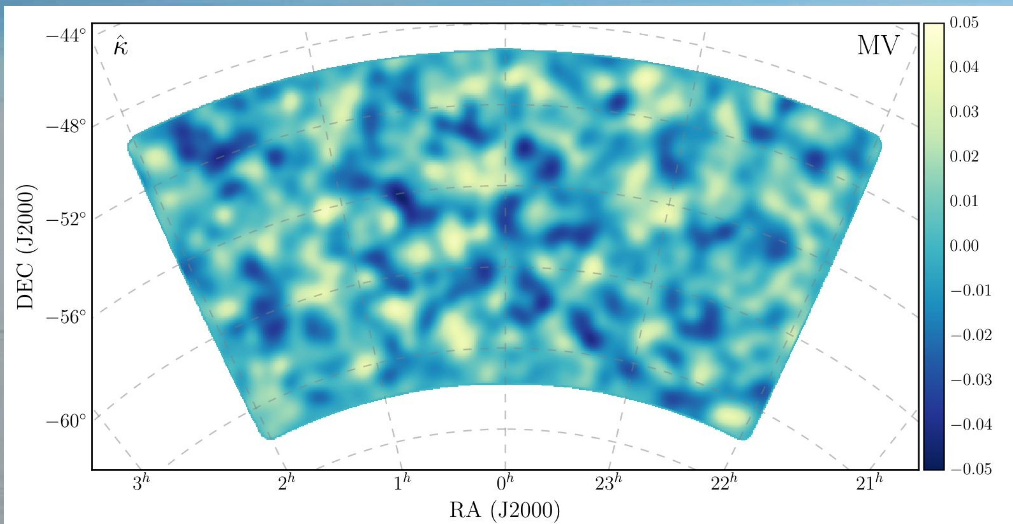
Measure with several frequencies to remove Galactic dust and synchrotron

Keck Array, 2011-2019



Remove lensing B modes

SPT-3G can reconstruct B modes induced by gravitational lensing

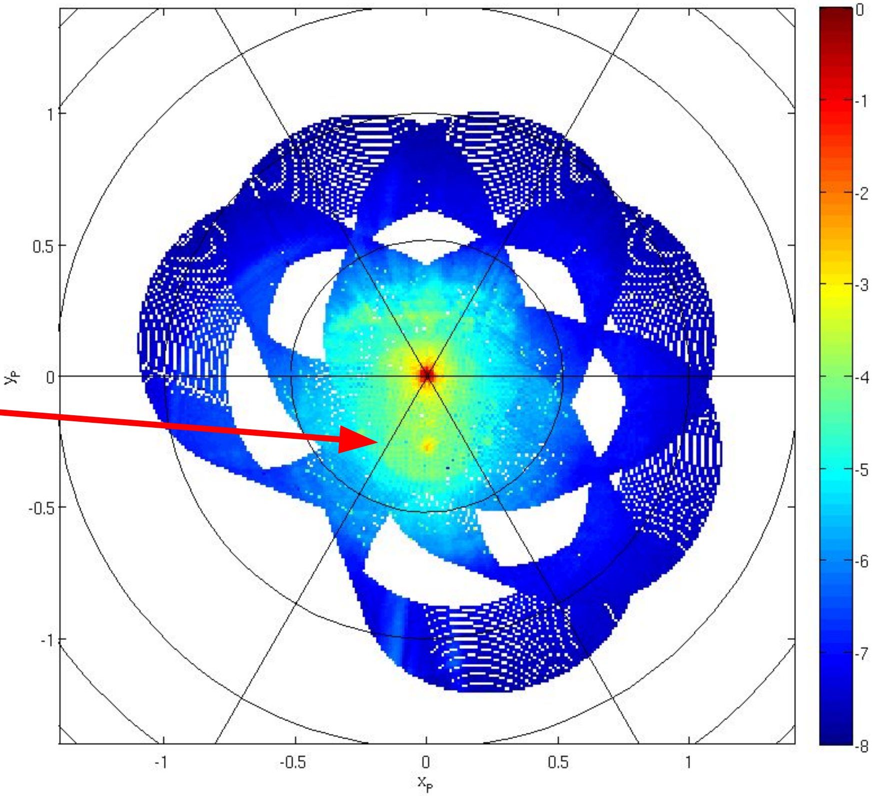


SPT lensing convergence
Wu+ 2019

Calibrate Telescopes with Extreme Precision

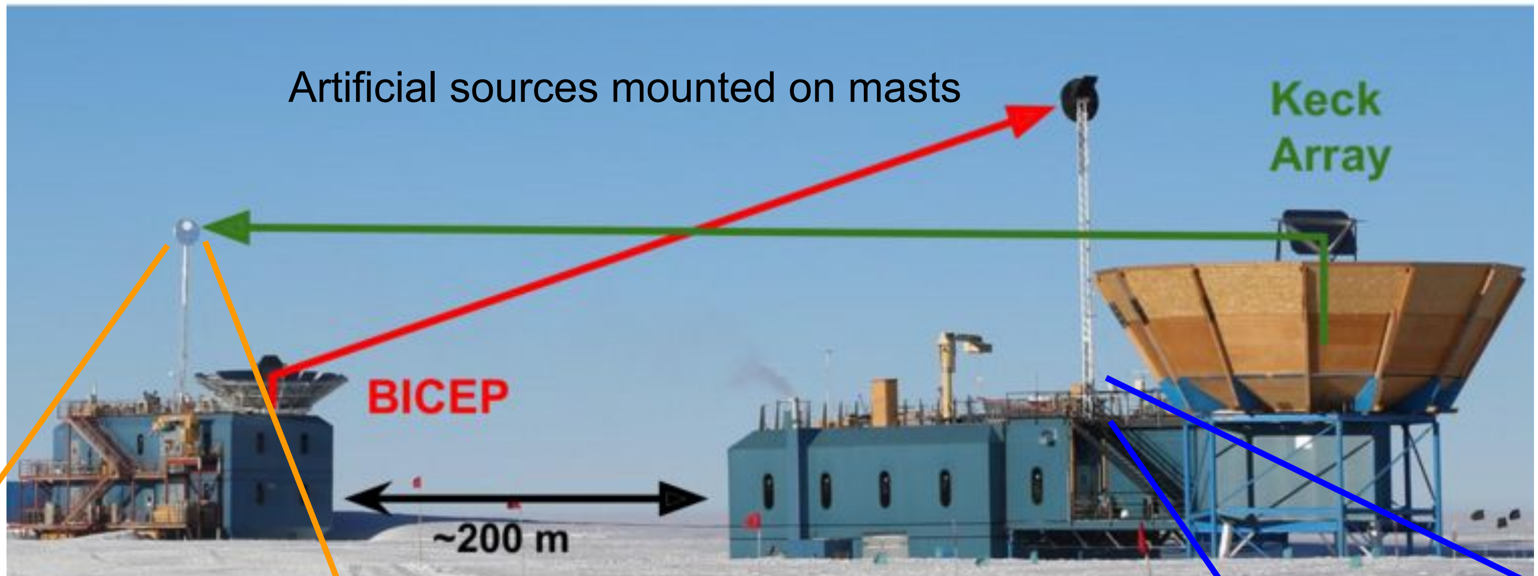
Nonidealities in the instrument can induce false, systematic B-mode polarization that biases the *r* measurement:

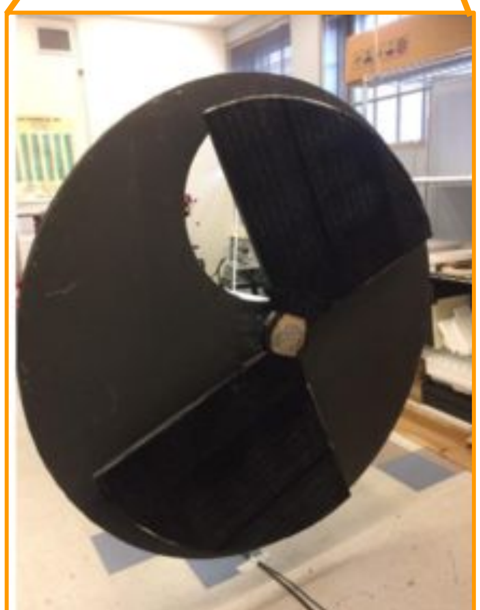
- Mismatched main beams
- Bandpass variations
- Sidelobes coupling to the ground
- Reflections in optics
- Gain variations
- Crosstalk
- Detector transfer functions
- Radio interference

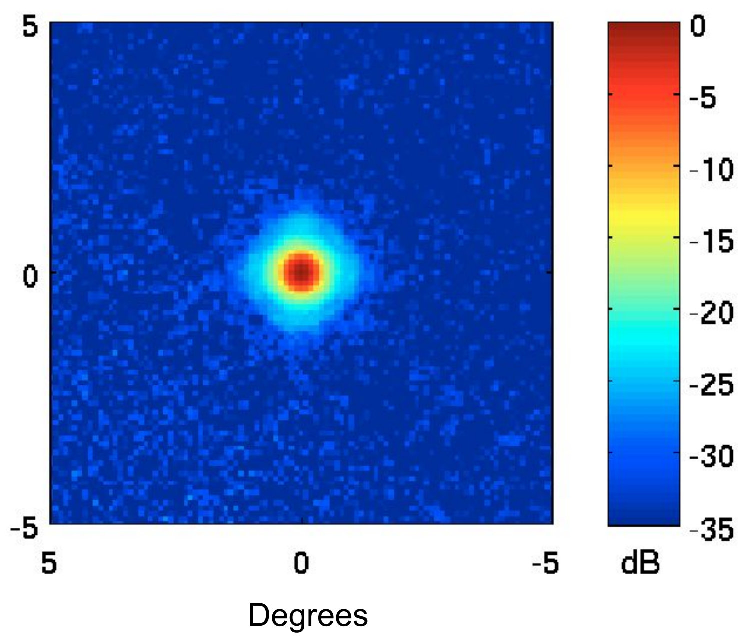


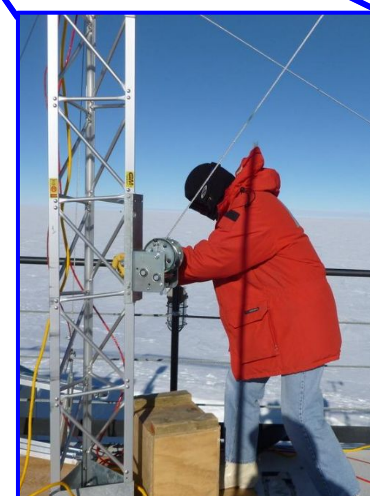
Dedicated calibration campaigns needed to quantify these effects.

Beam Shape (Point Spread Function) Measurement

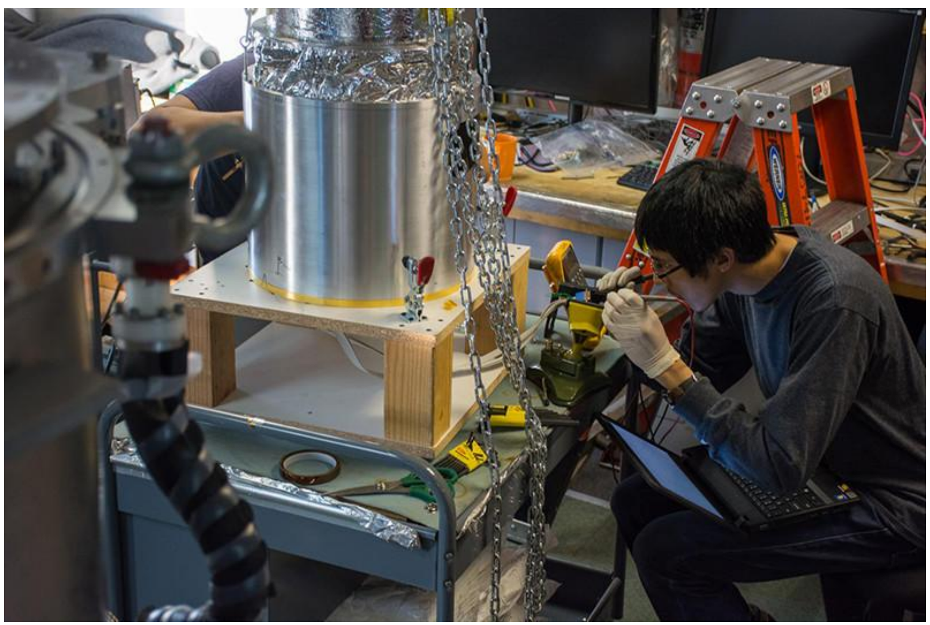








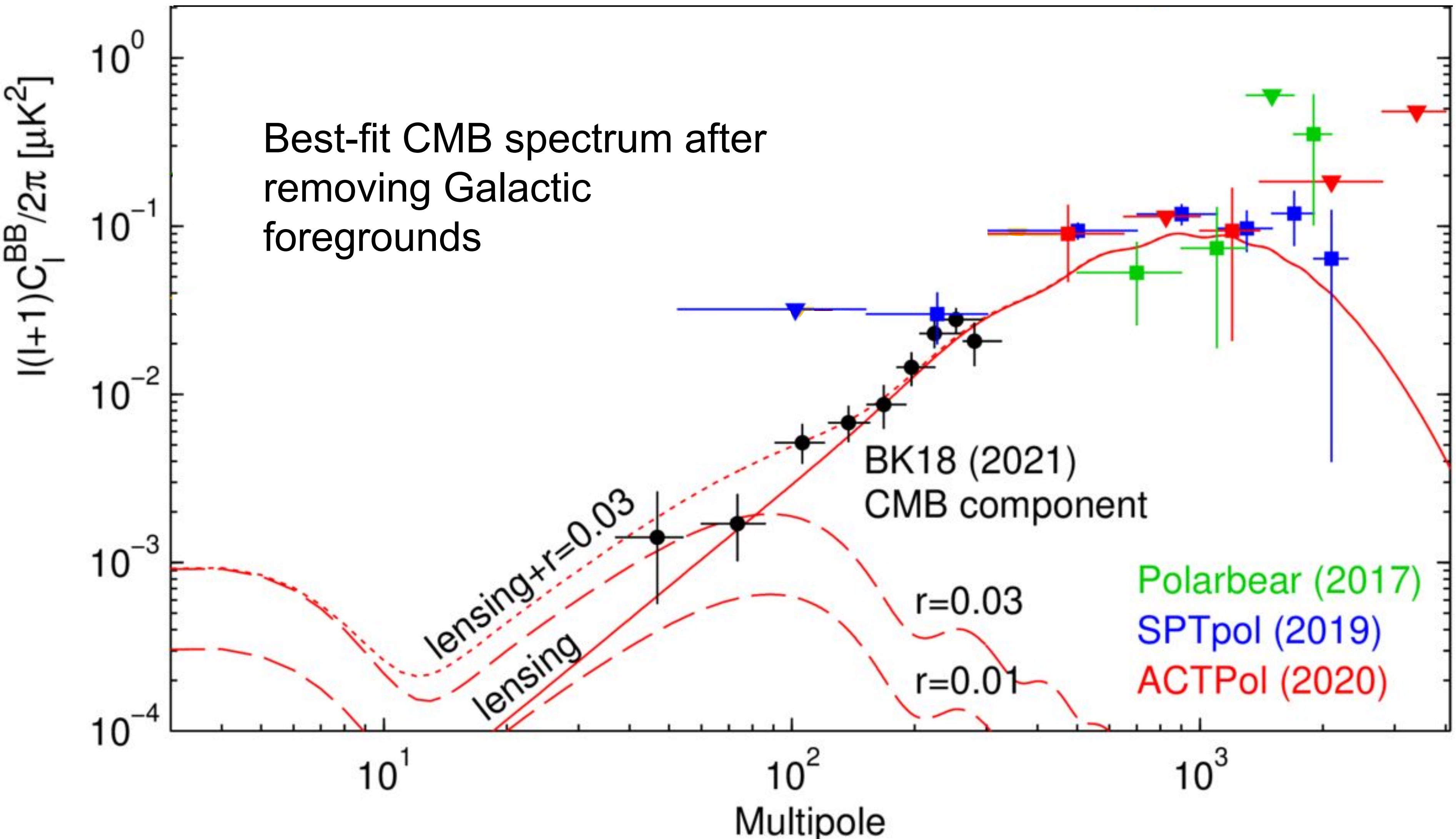
Karkare+, SPIE 2016
+ Tyler St. Germaine,
Clara Verges




STAR TREK


photo: Keith Vanderlinde

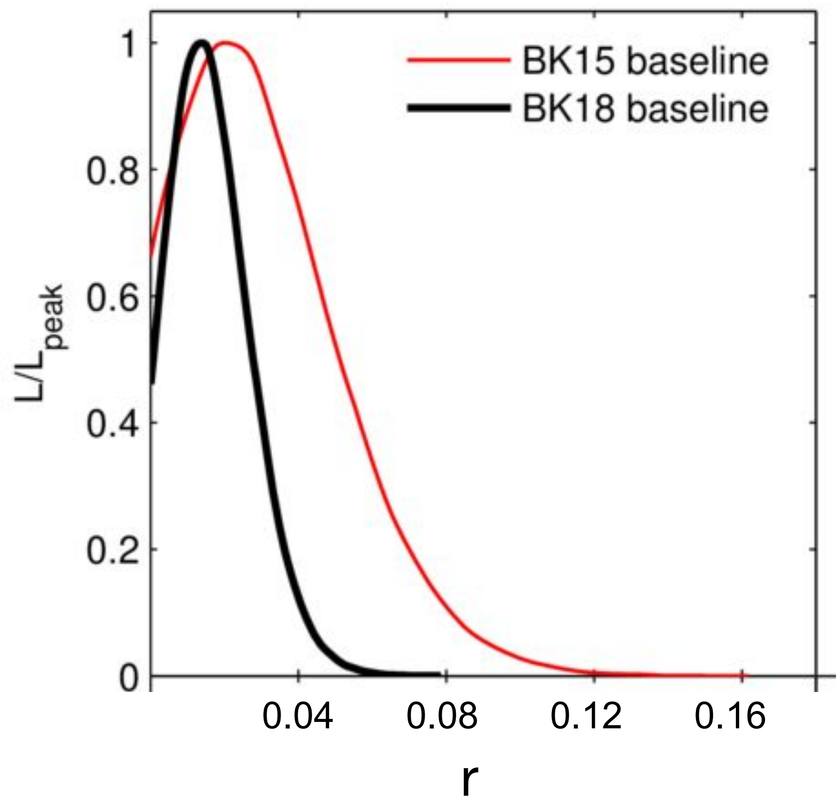
BK18 Foreground-Cleaned B-Mode Spectrum



BICEP Collaboration,
Phys. Rev. Lett. 2021

BK18 *r* constraint

BICEP Collaboration,
Phys. Rev. Lett. 2021

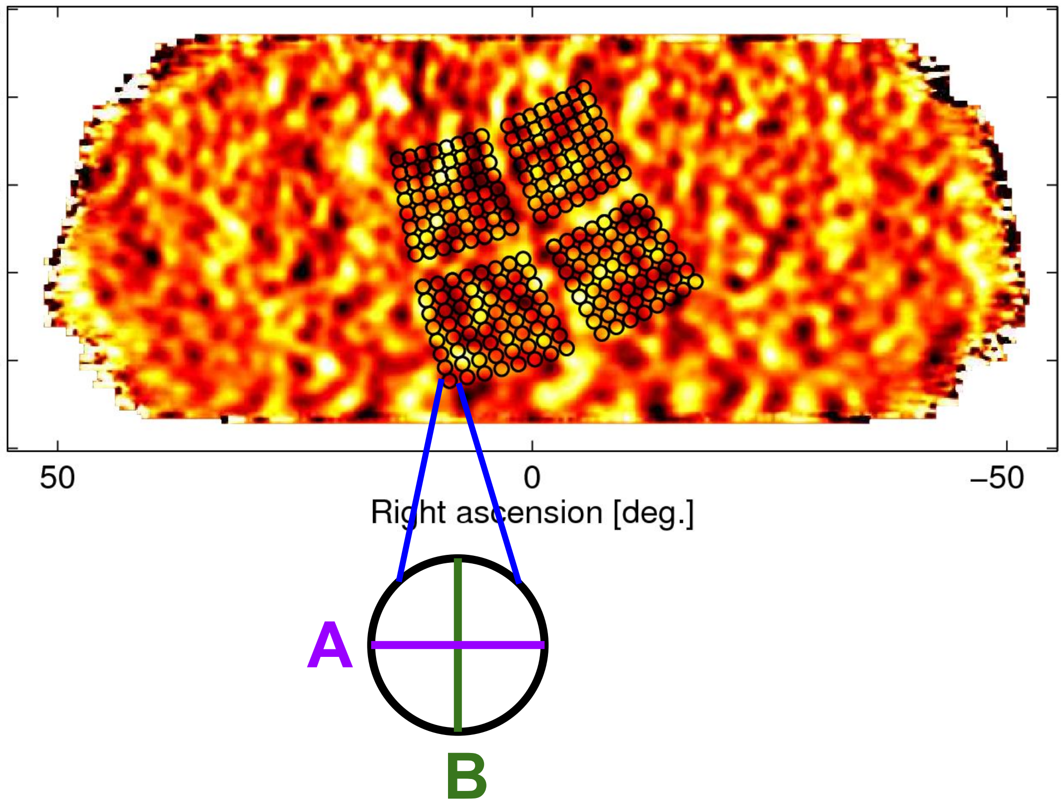


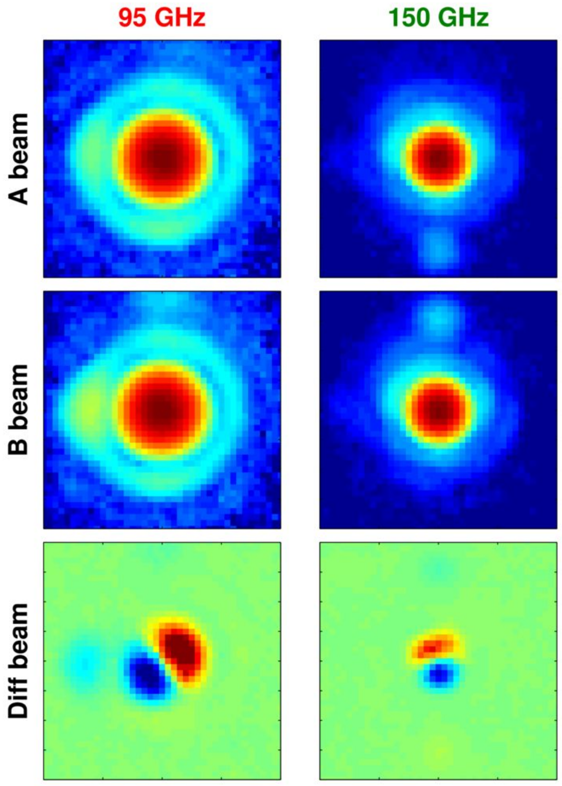
Marginalized *r* likelihood: **r < 0.036 (95%)**

Statistical uncertainty: **σ(r) = 0.009**

Beam Systematics Analysis

BICEP Collaboration
ApJ 2019 (Karkare lead)





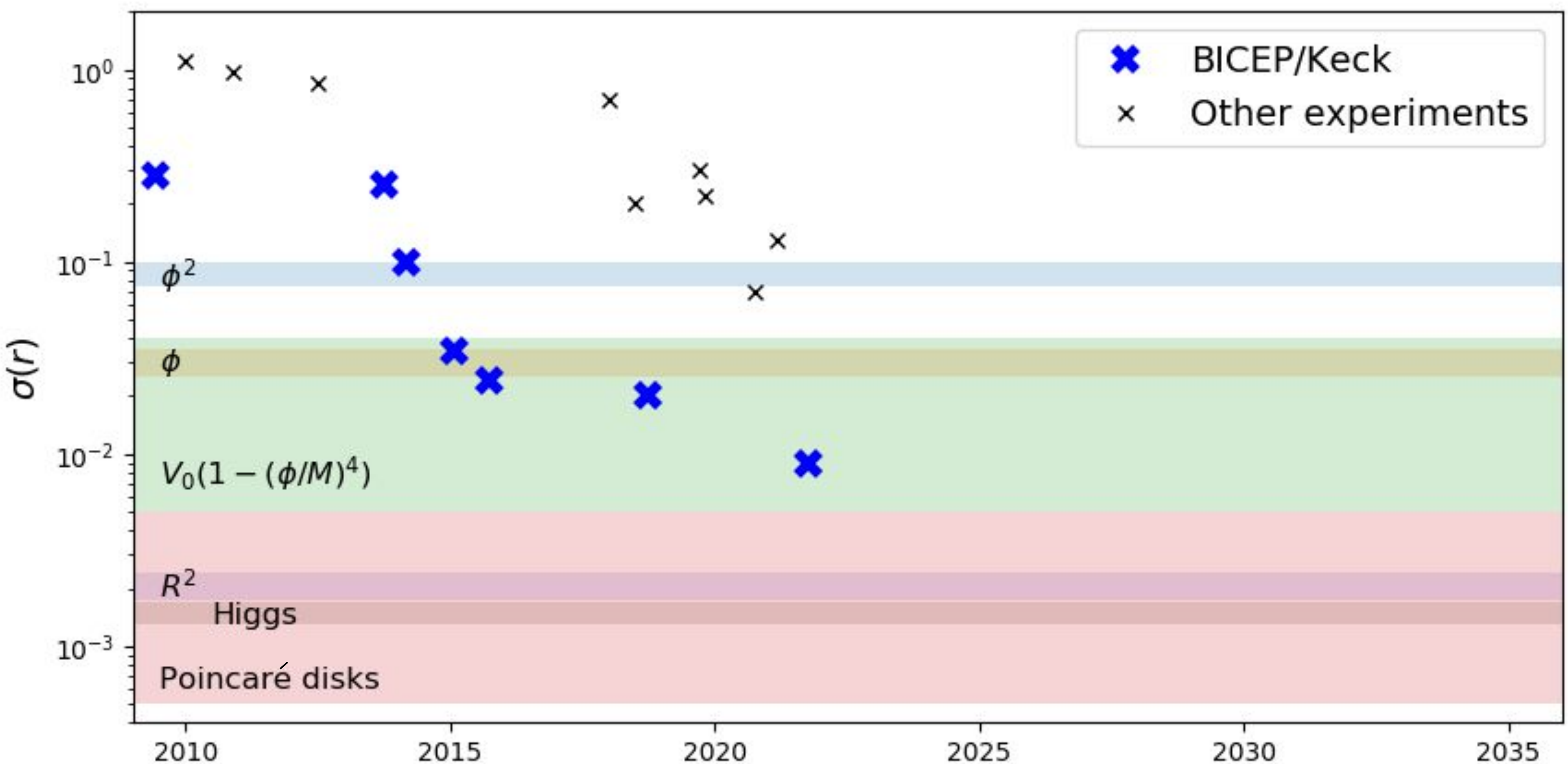
Beam shape differences leak the CMB temperature into polarization!

Use beam maps to identify beam differences and calculate/remove the systematic contribution to *r*.

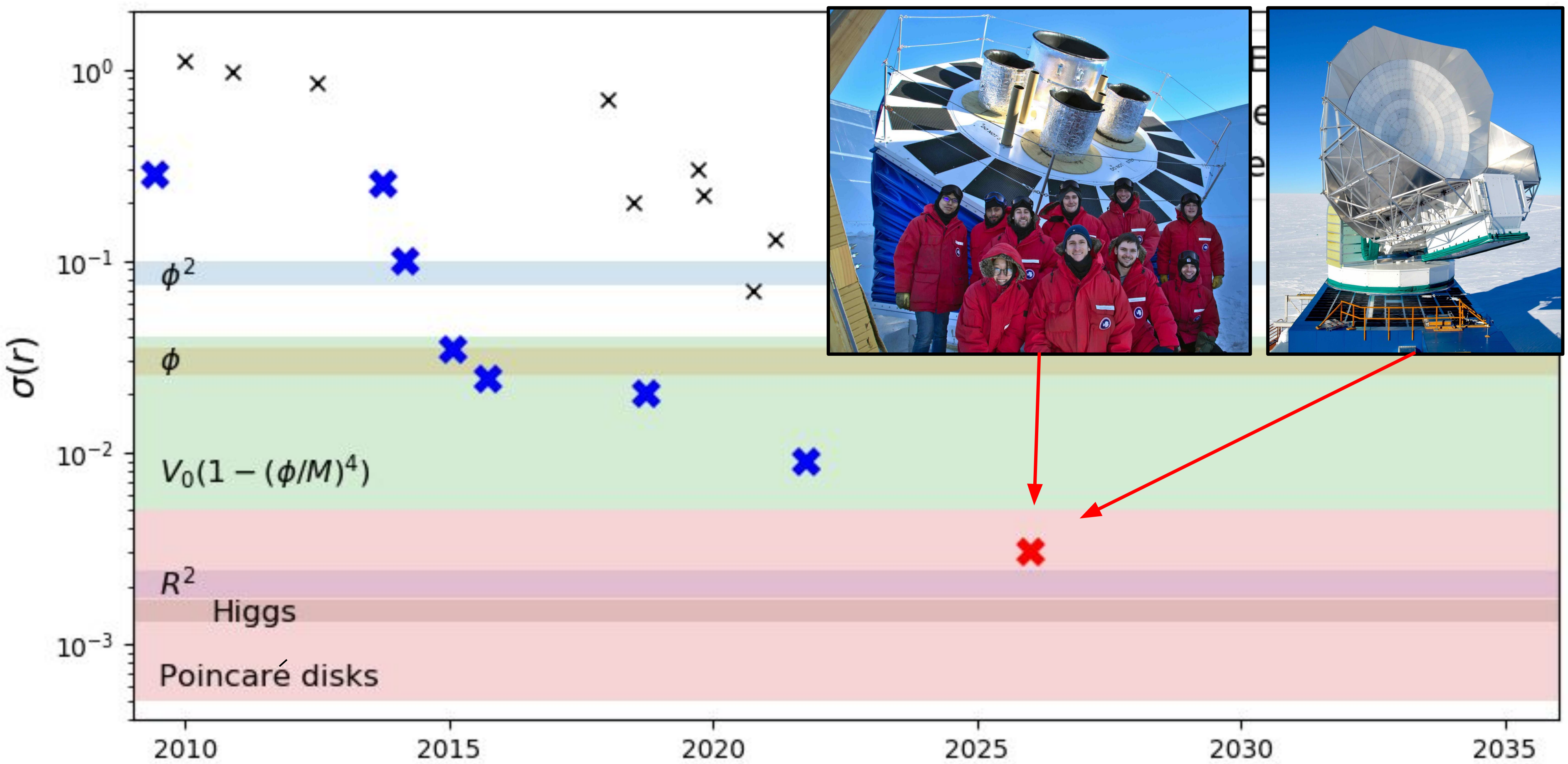
Bias from beam systematics in BK18 is
Δr = 0.0015 ± 0.0011

…which is much smaller than the statistical uncertainty of
σ(r) = 0.009

The Inflationary Landscape is Shrinking



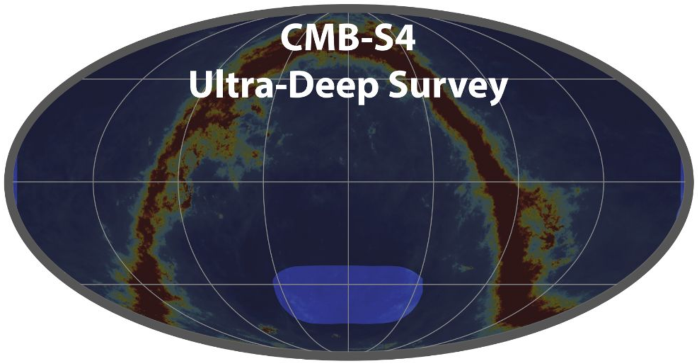
The Inflationary Landscape is Shrinking: BK+SPT



BICEP Array + SPT-3G delensing: anticipate σ(r) ~ 0.003.


CMB-S4
Next Generation CMB Experiment


SDSC East Entran



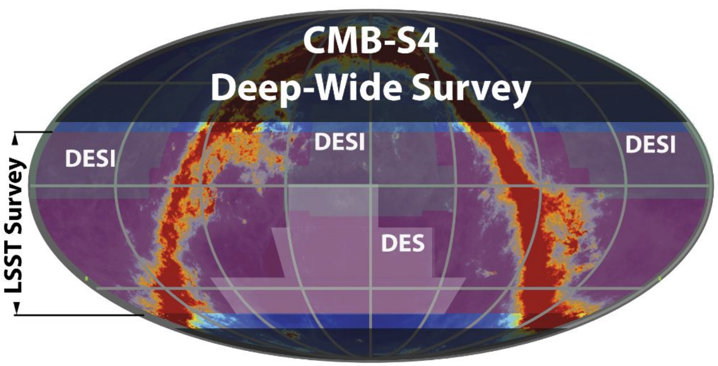
South Pole

“Ultimate” ground-based CMB experiment, ~2030-2036

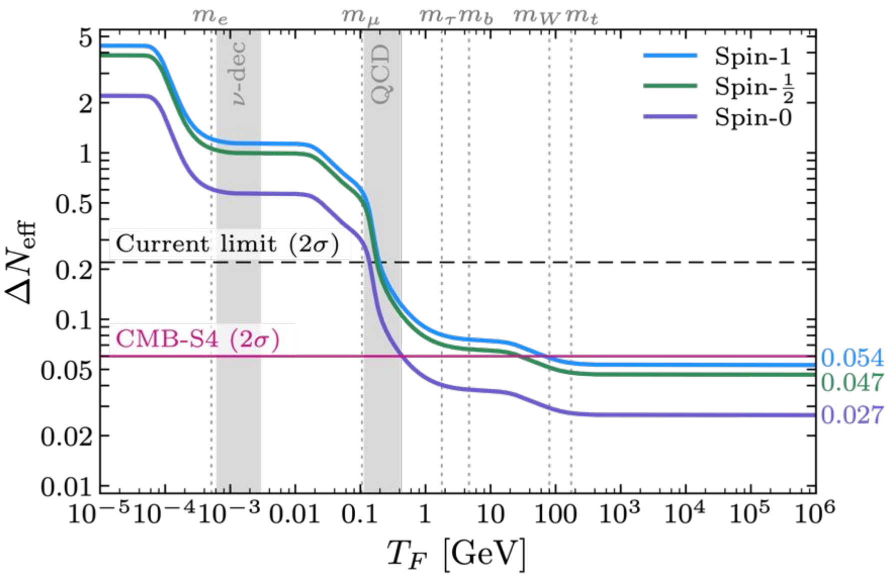
Surveys from two sites to address:

1. Primordial Gravitational Waves and Inflation
2. The Dark Universe
3. Mapping Matter in the Cosmos
4. The Time-Variable Millimeter-Wave Sky

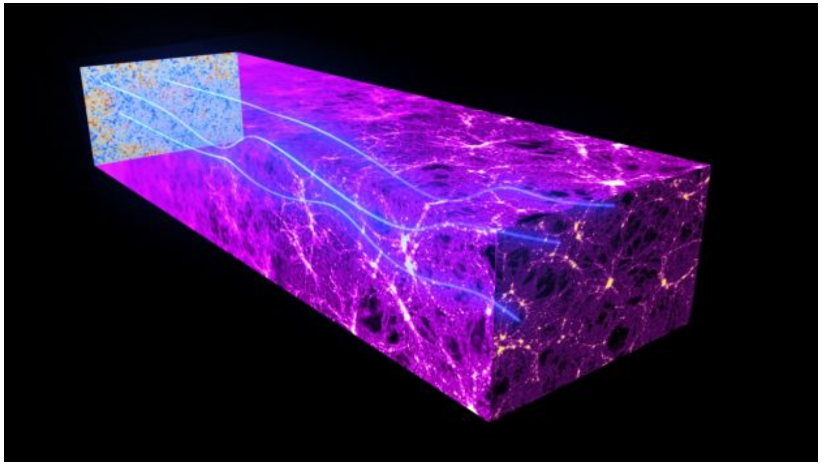
Cross critical thresholds in constraining *r* and light relic particles N_{eff}



Atacama Desert, Chile



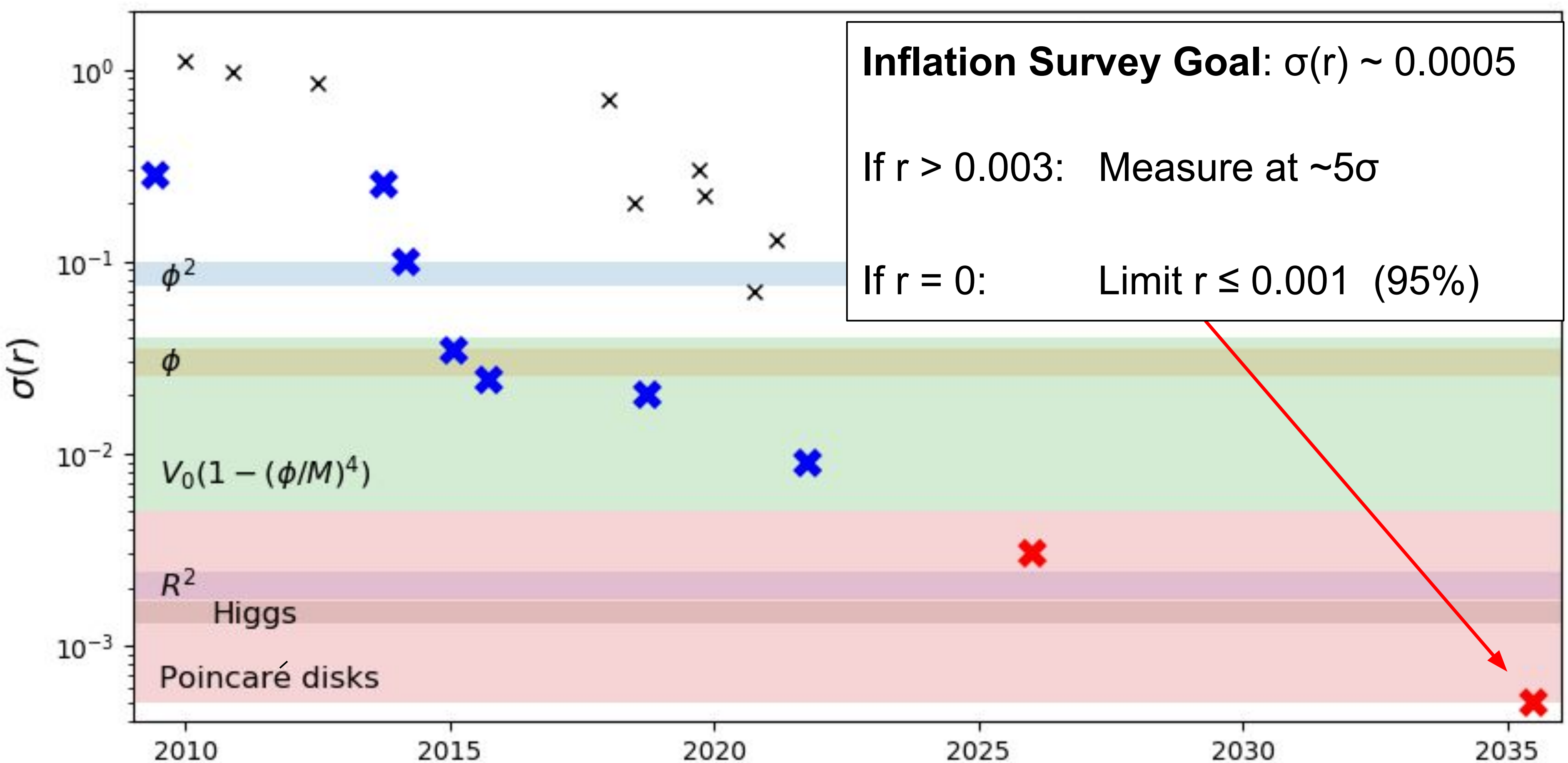
2. Thermal history of the Universe and light relic particles



3. Map *all* of the mass with lensing; find all massive clusters and characterize hot gas with SZ

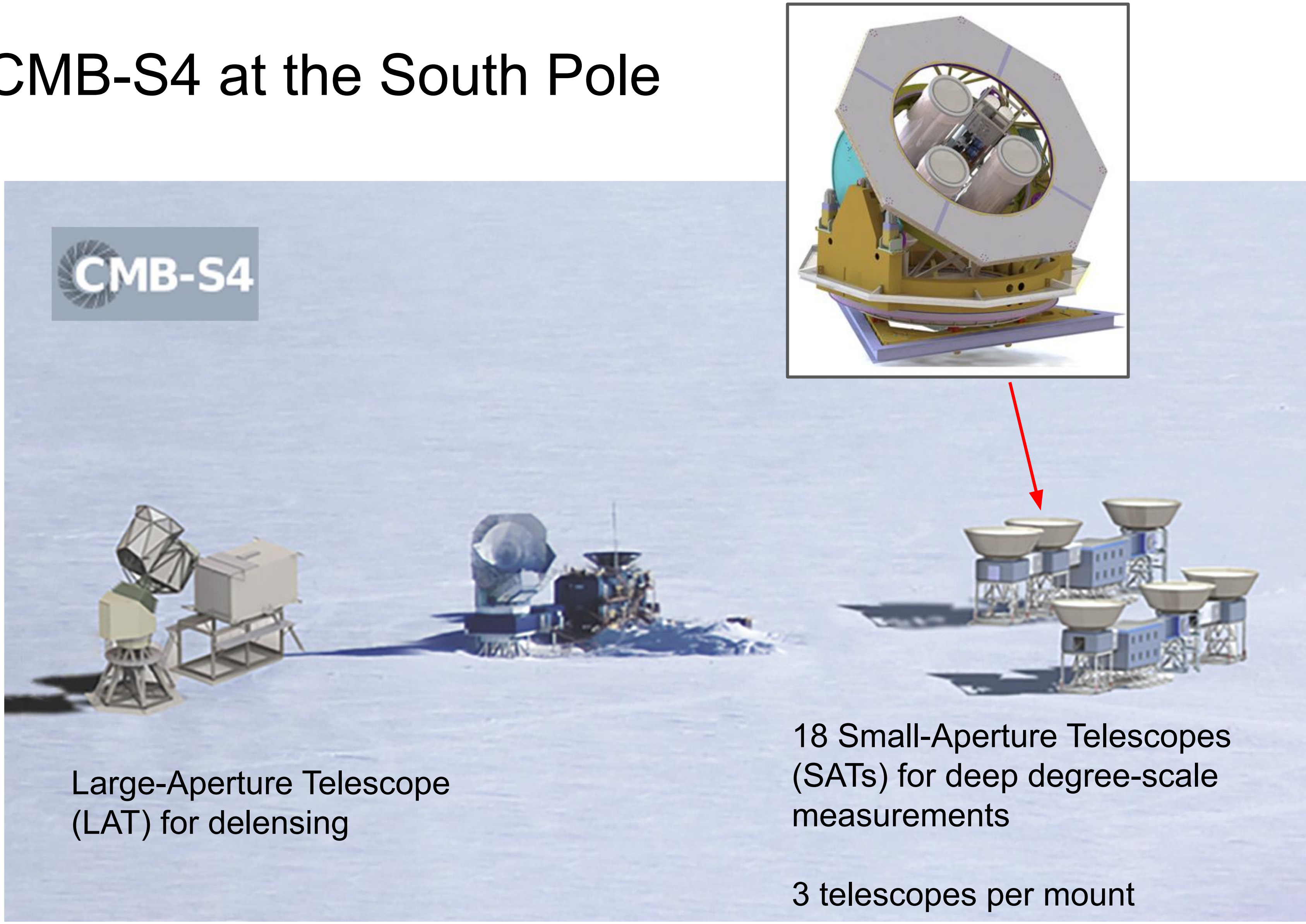
4. Produce transient alerts - learn about LIGO/IceCube events, GRBs, TDEs, AGNs, planets, comets, asteroids…

The Inflationary Landscape is Shrinking: CMB-S4



Models that naturally explain the deviation from scale invariance, with a characteristic scale equal to or larger than the Planck mass, predict $r > 10^{-3}$.

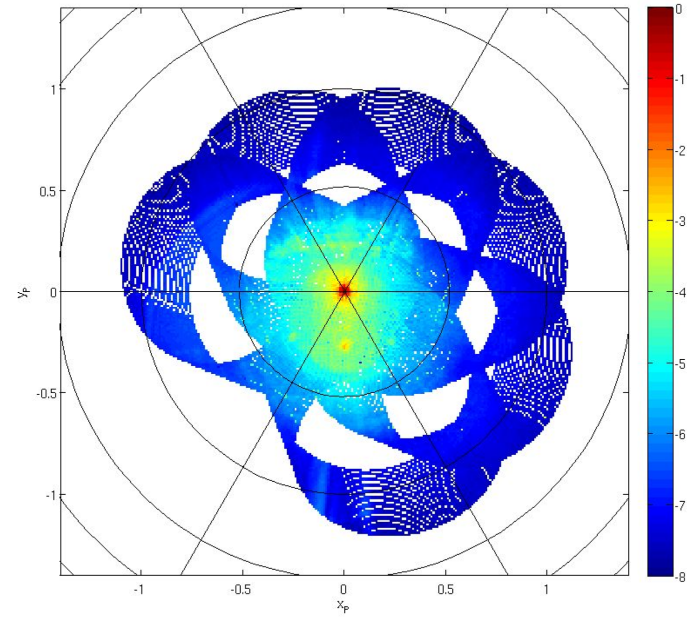
CMB-S4 at the South Pole

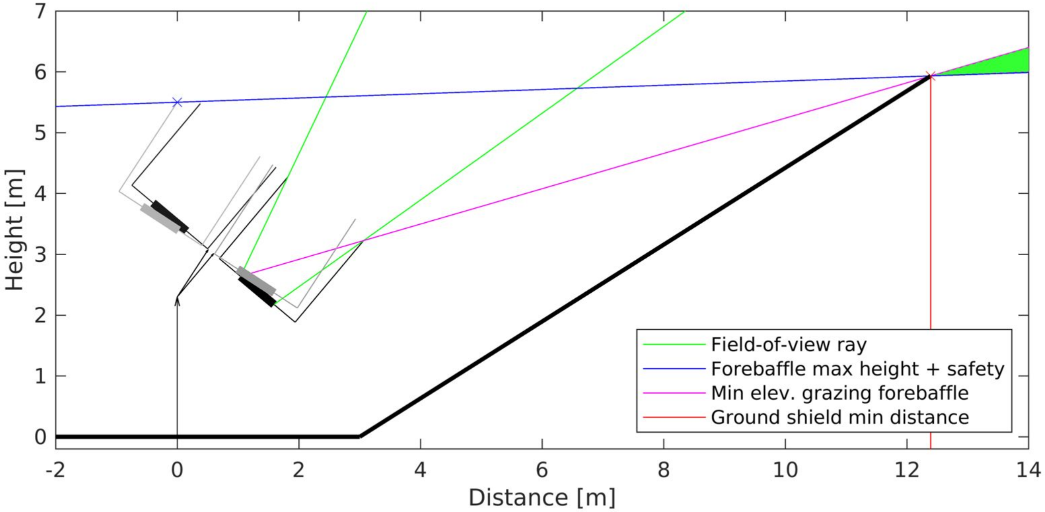


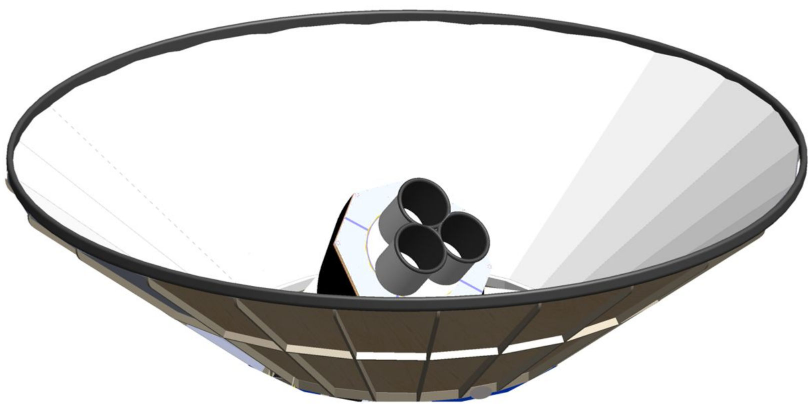
Minimize Systematics in Optical Design

We want to measure nK fluctuations on a 3 K background, from a 300 K environment!

Optimized SAT shield and baffling geometry, enabling selection of “three-tube” cryostat

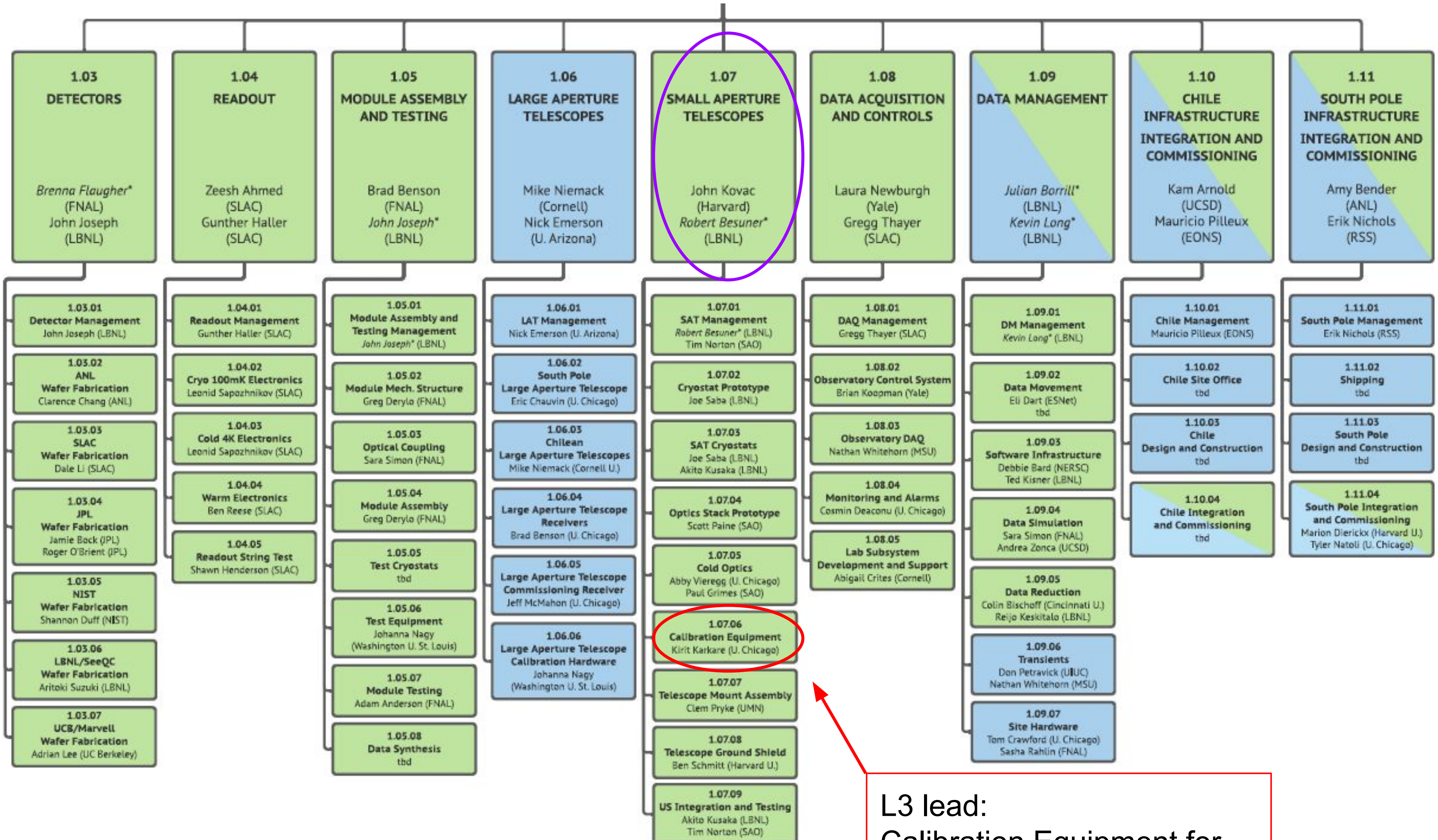






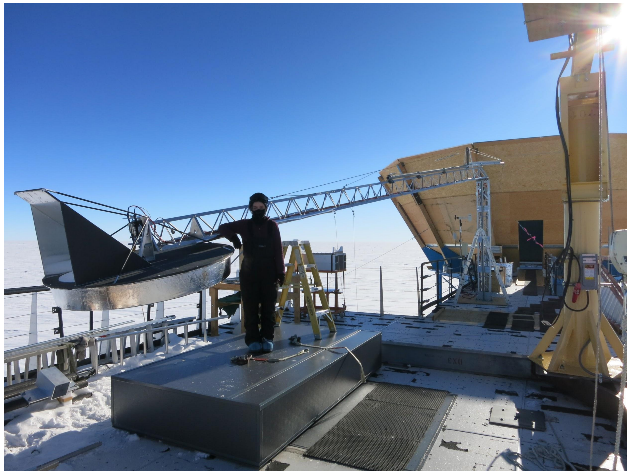
+ Fred Matsuda

CMB-S4 Org Chart

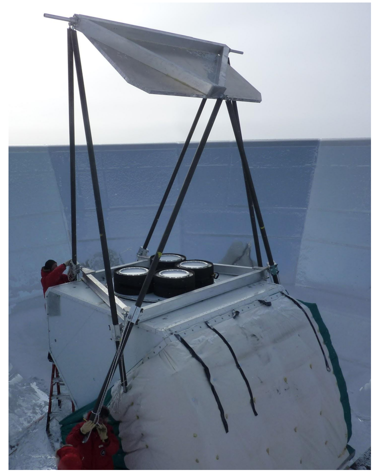


L3 lead:
Calibration Equipment for
Small-Aperture Telescopes
(DOE scope)

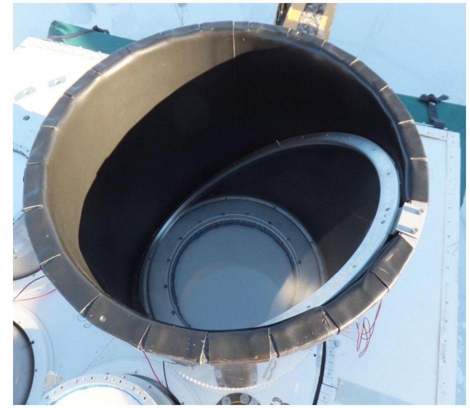
L3: Calibration for CMB-S4 Small Aperture Telescopes



Far-field chopper and mast

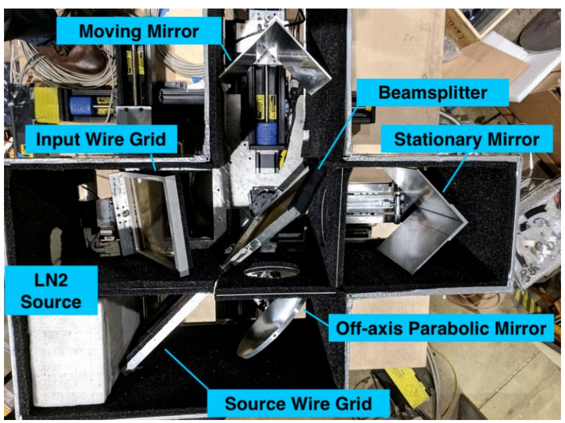


Redirecting mirror



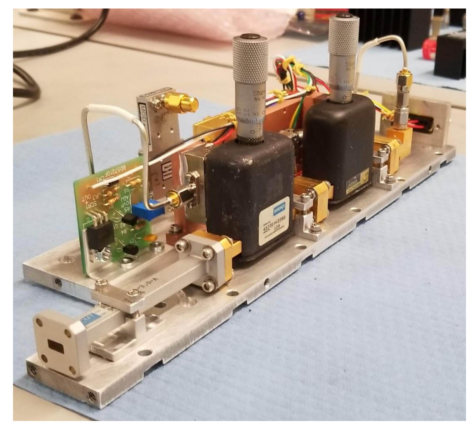
Polarization angle cal

x6



Fourier Transform spectrometer

Near-field beam mapper



Amplified sources….and much more!

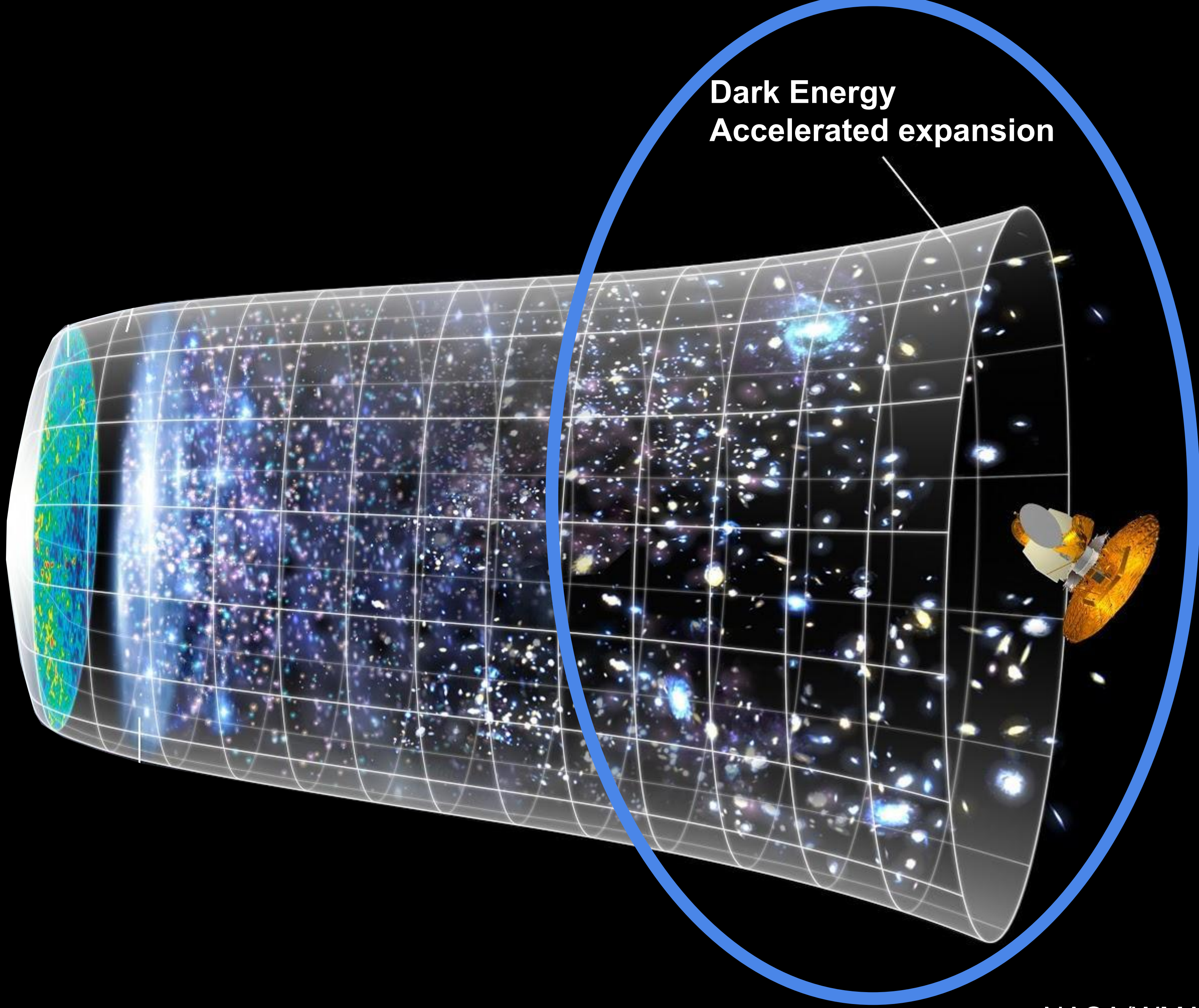
Defining calibration requirements needed for σ(r) ~ 0.0005.
Equipment design and production requires *large-scale effort!*

CMB-S4 SAT Calibration and Systematics Plan

- 2022: Define calibration requirements for $\sigma(r) \sim 0.0005$.
  Begin designing and prototyping equipment
- 2025: Lab-based equipment needed for SAT integration and commissioning
- 2028: Pole-based equipment needed for in situ calibration
- 2030: Survey begins. *L3 role naturally transitions to systematics analysis*

Immediate opportunities for systematics analysis development:

- Incorporate measured systematics into CMB-S4 simulations
- Use machine learning to analyze calibration data

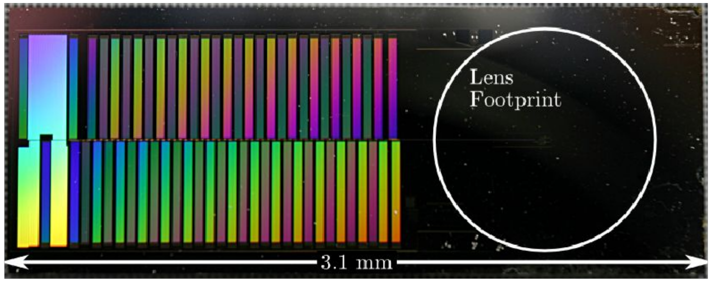


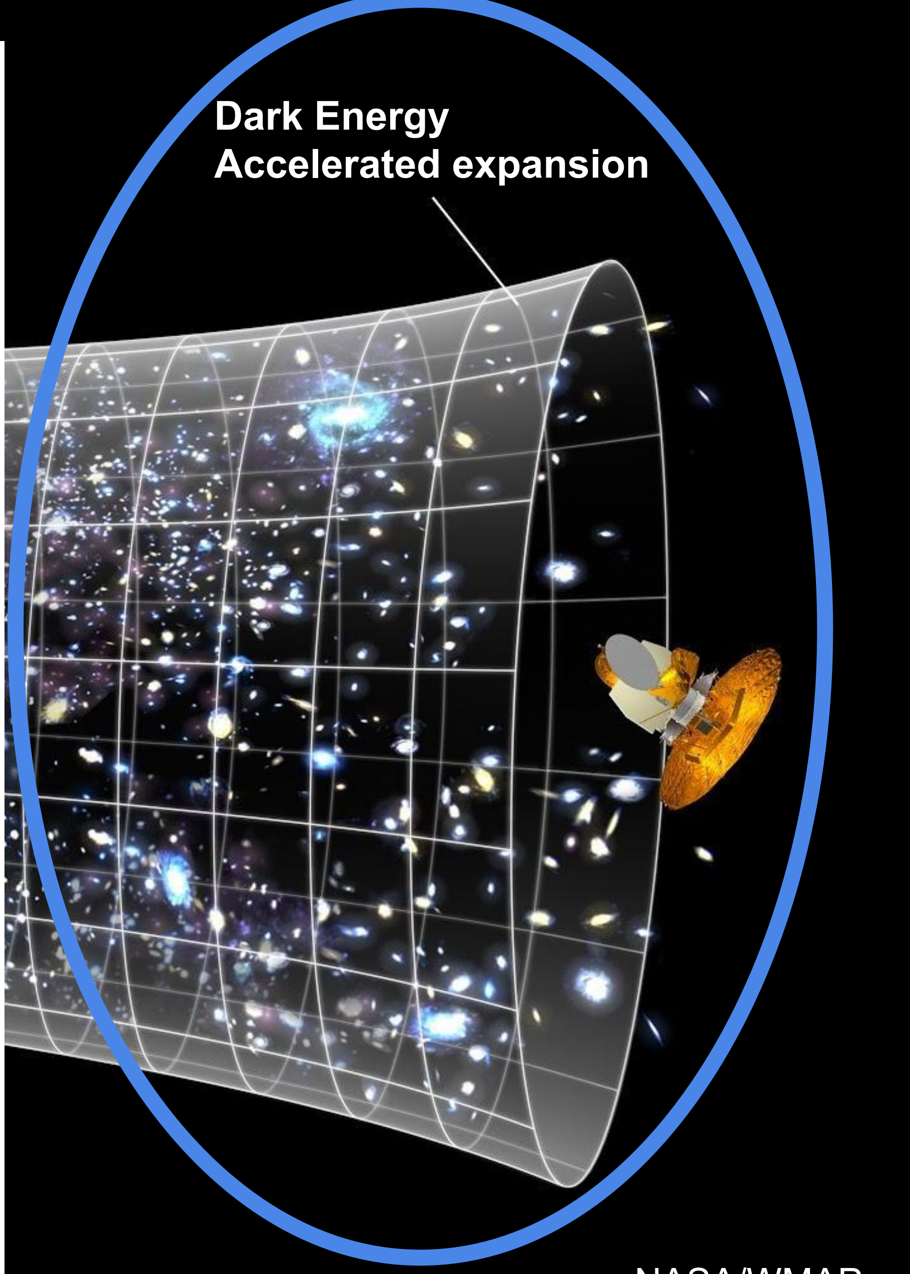
NASA/WMAP
Science Team

Challenge 2:
Measure large-scale structure over larger volumes to test the physics of dark energy and neutrinos.

How:
Millimeter-wave line intensity mapping (LIM).

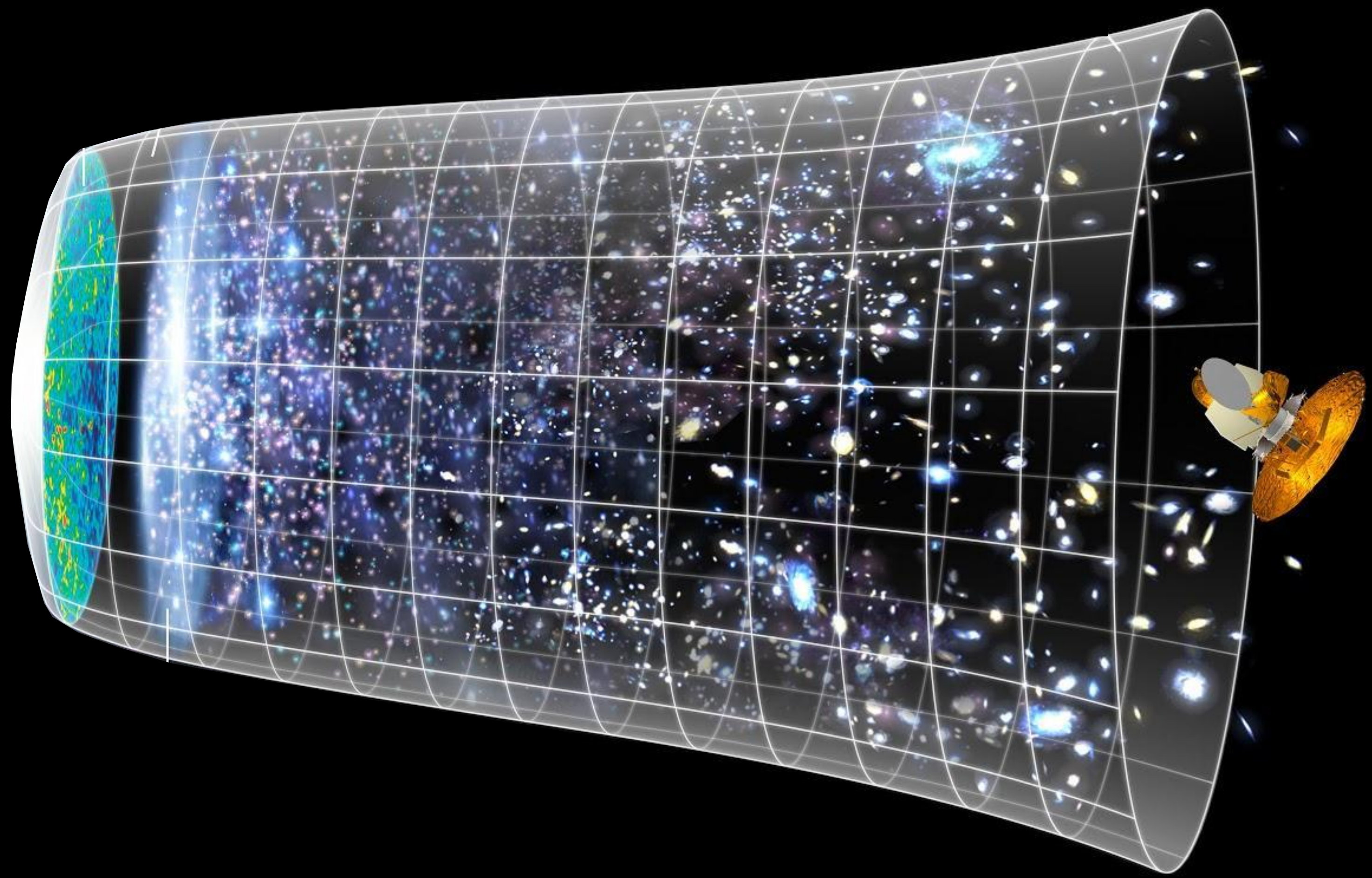
Demonstrate on-chip spectrometers with SuperSpec and SPT-SLIM.





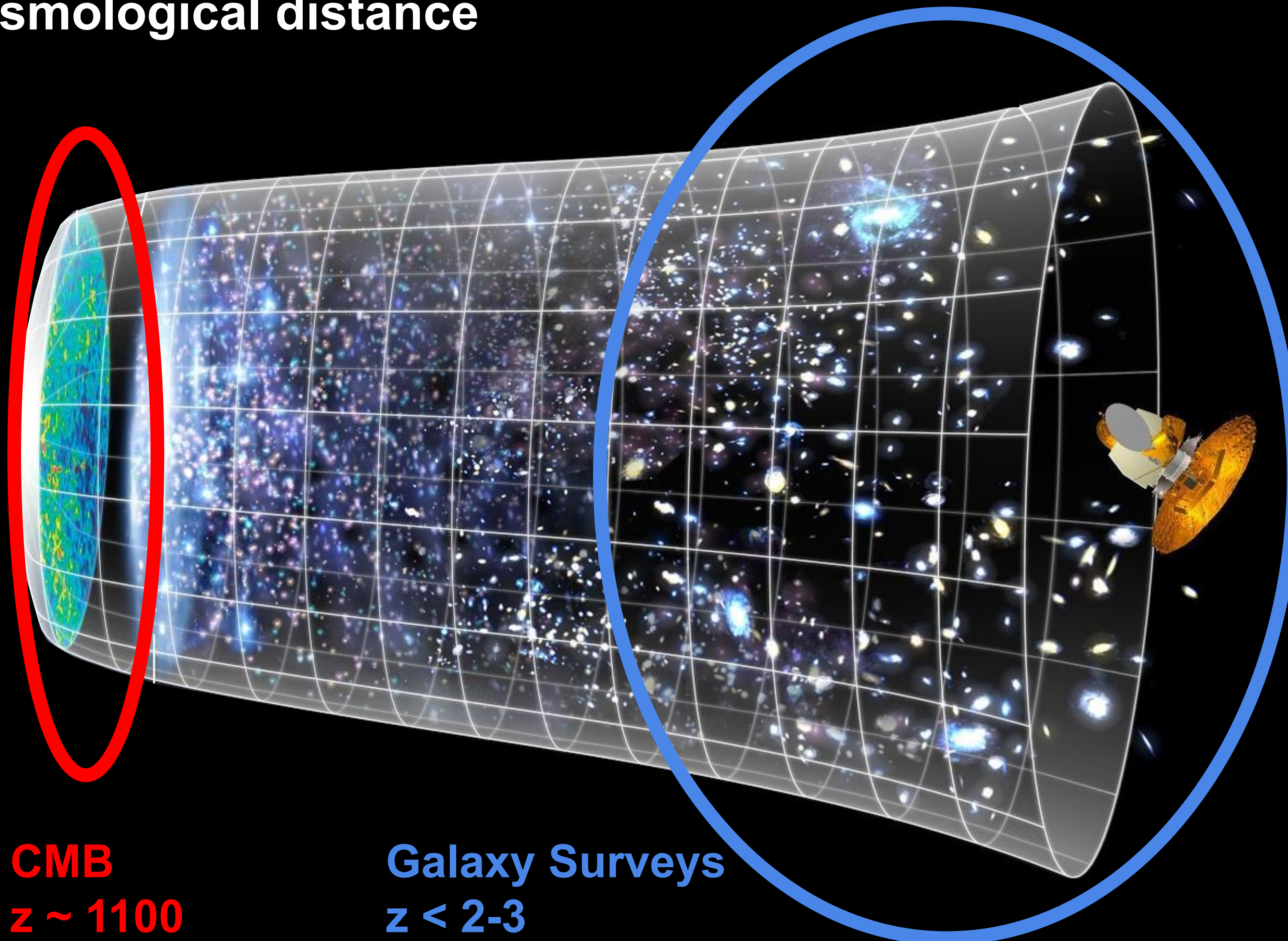
NASA/WMAP
Science Team

Redshift z: proxy for cosmological distance



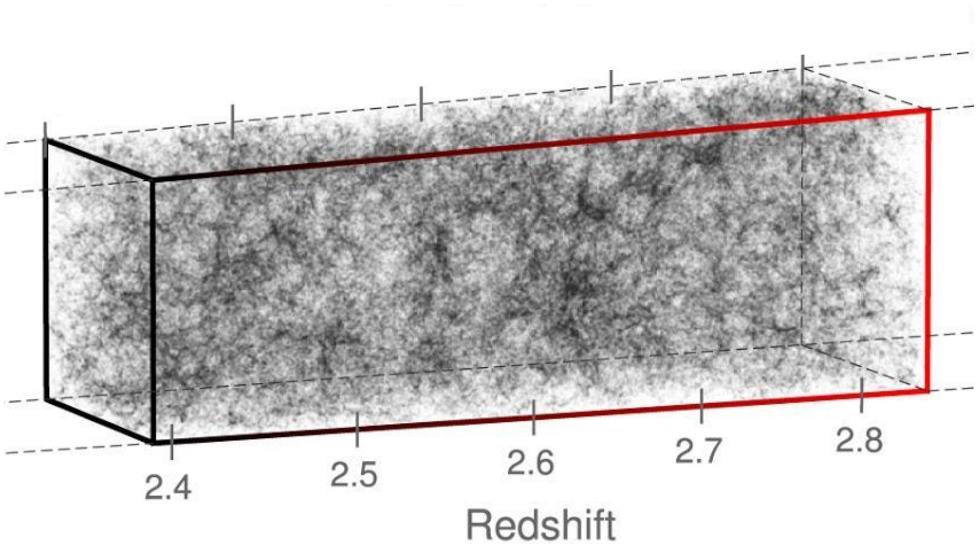
NASA/WMAP
Science Team

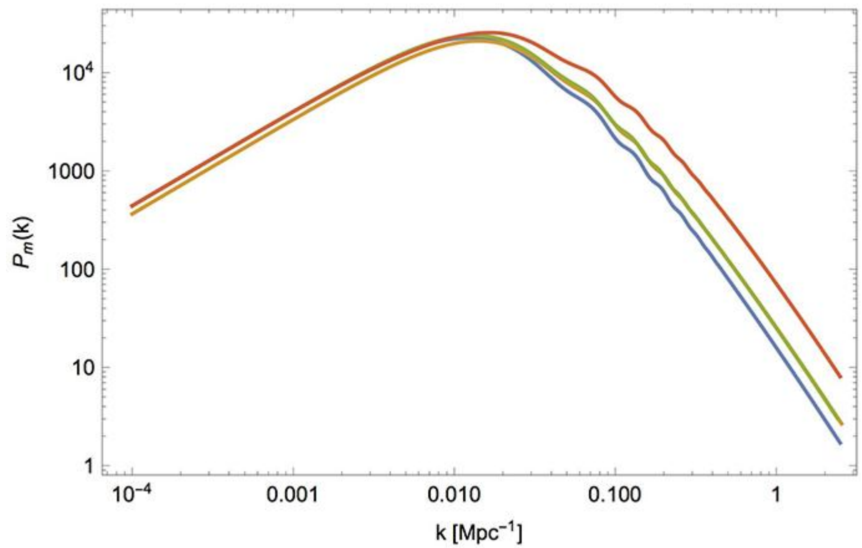
Redshift z: proxy for cosmological distance



NASA/WMAP
Science Team

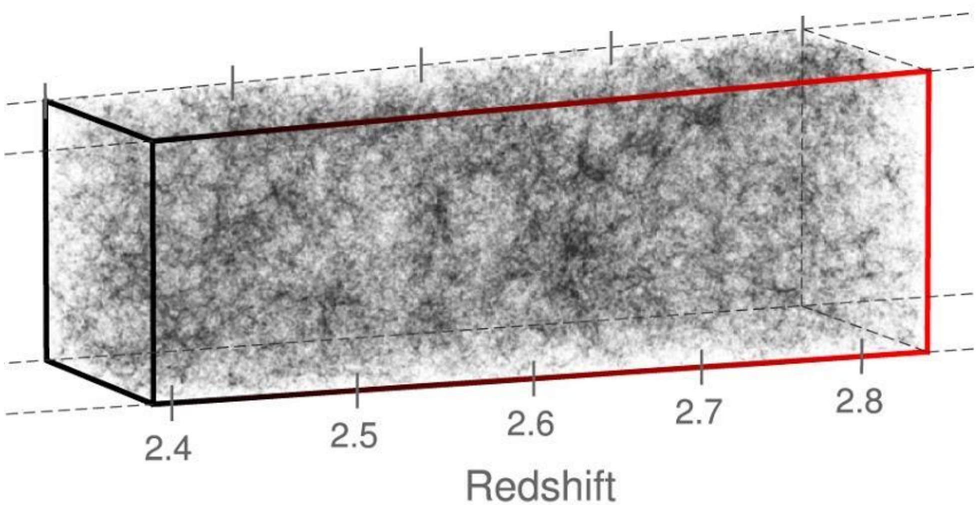
The Matter Power Spectrum

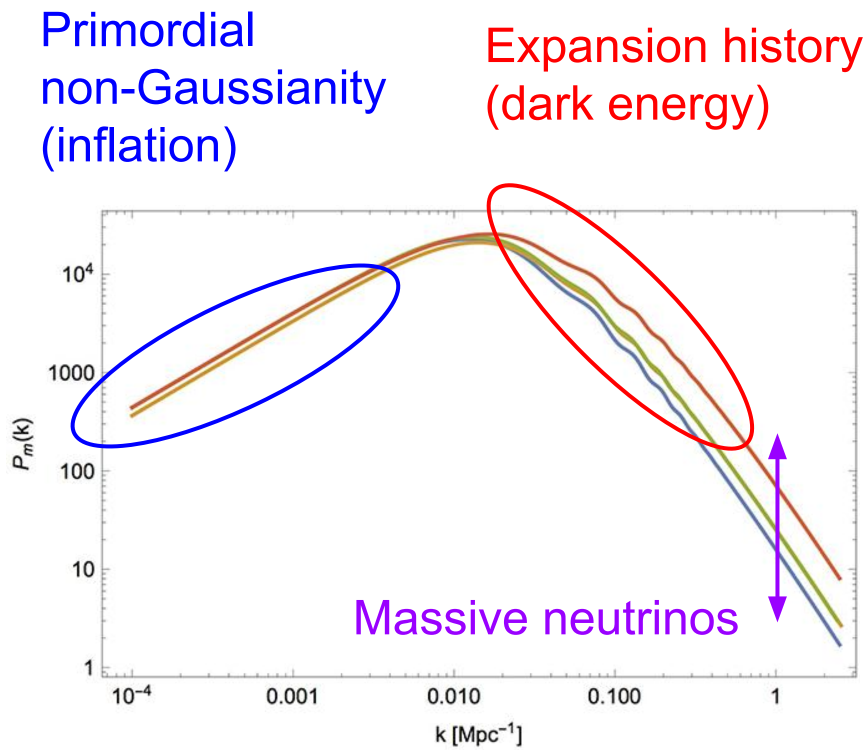




Li+ 2015

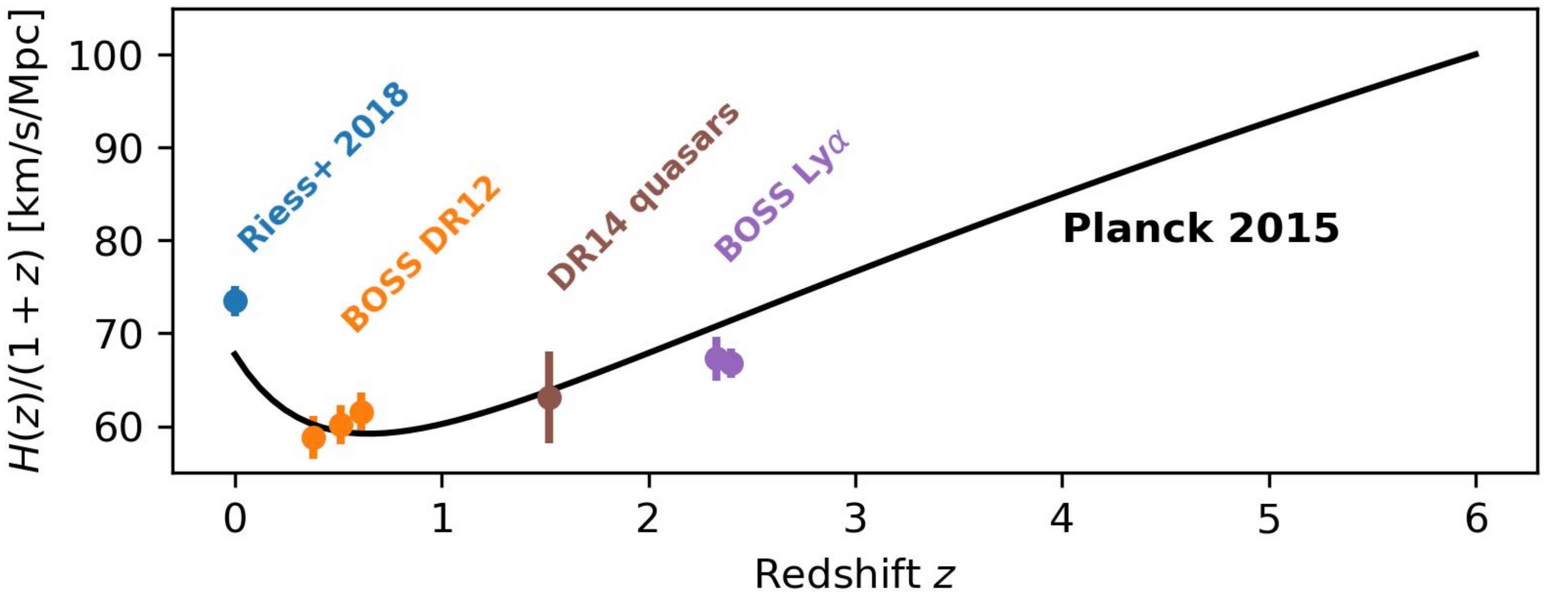
The Matter Power Spectrum





Li+ 2015

Why measure LSS at higher redshift?



MANY more modes available

Smaller nonlinearities, better correlated with initial conditions

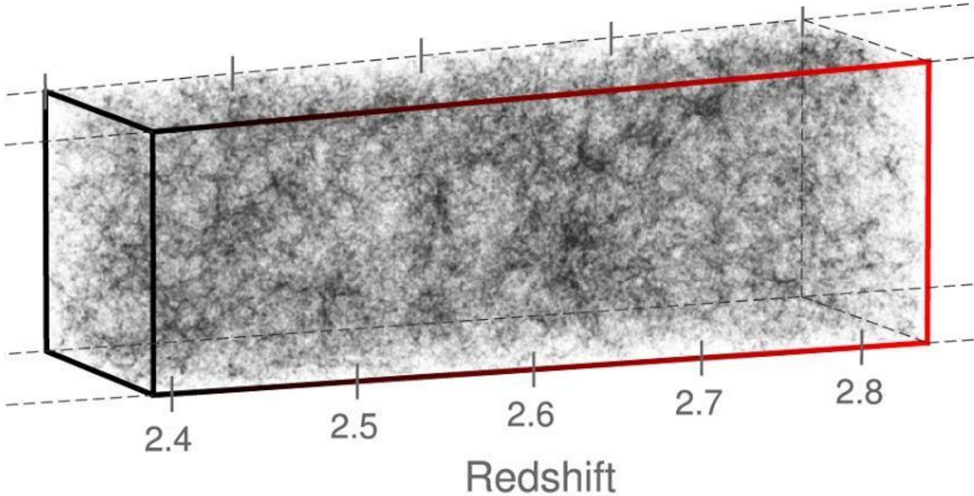
Wide redshift lever arm alleviates parameter degeneracies

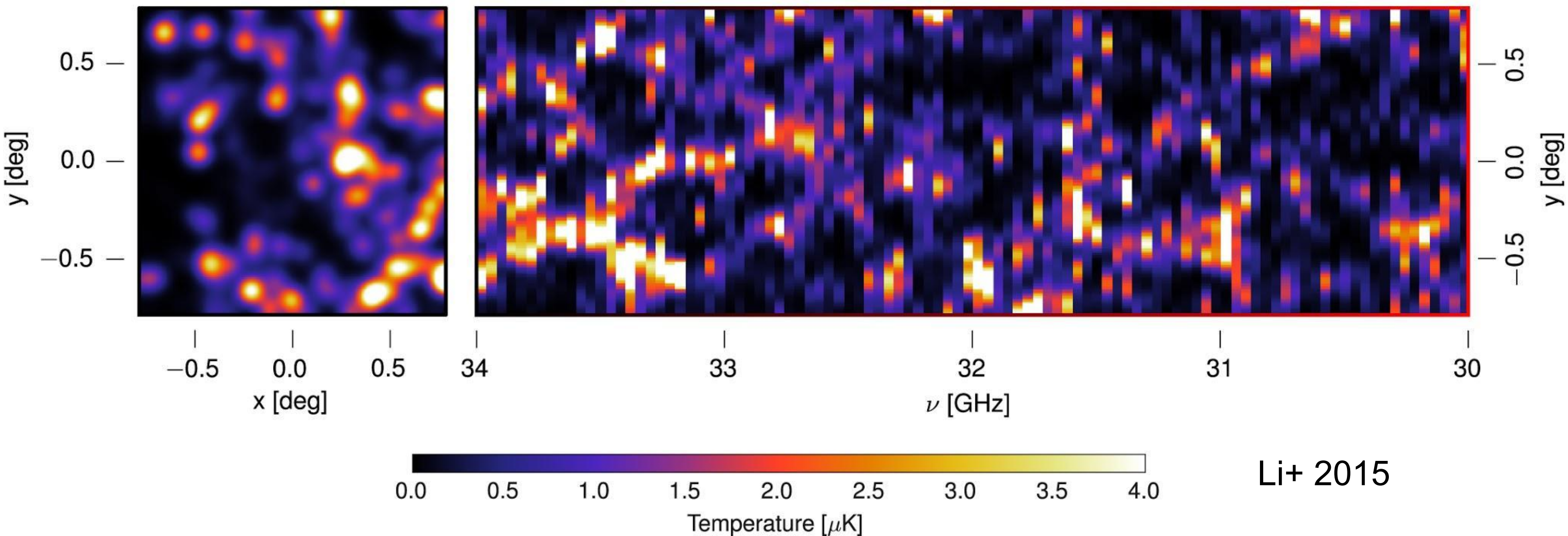
Karkare & Bird, PRD 2018:
mm-wave line intensity mappers could test DE beyond galaxy surveys

Line Intensity Mapping (LIM)

Low resolution: integrate over many emitters while retaining large-scale information.

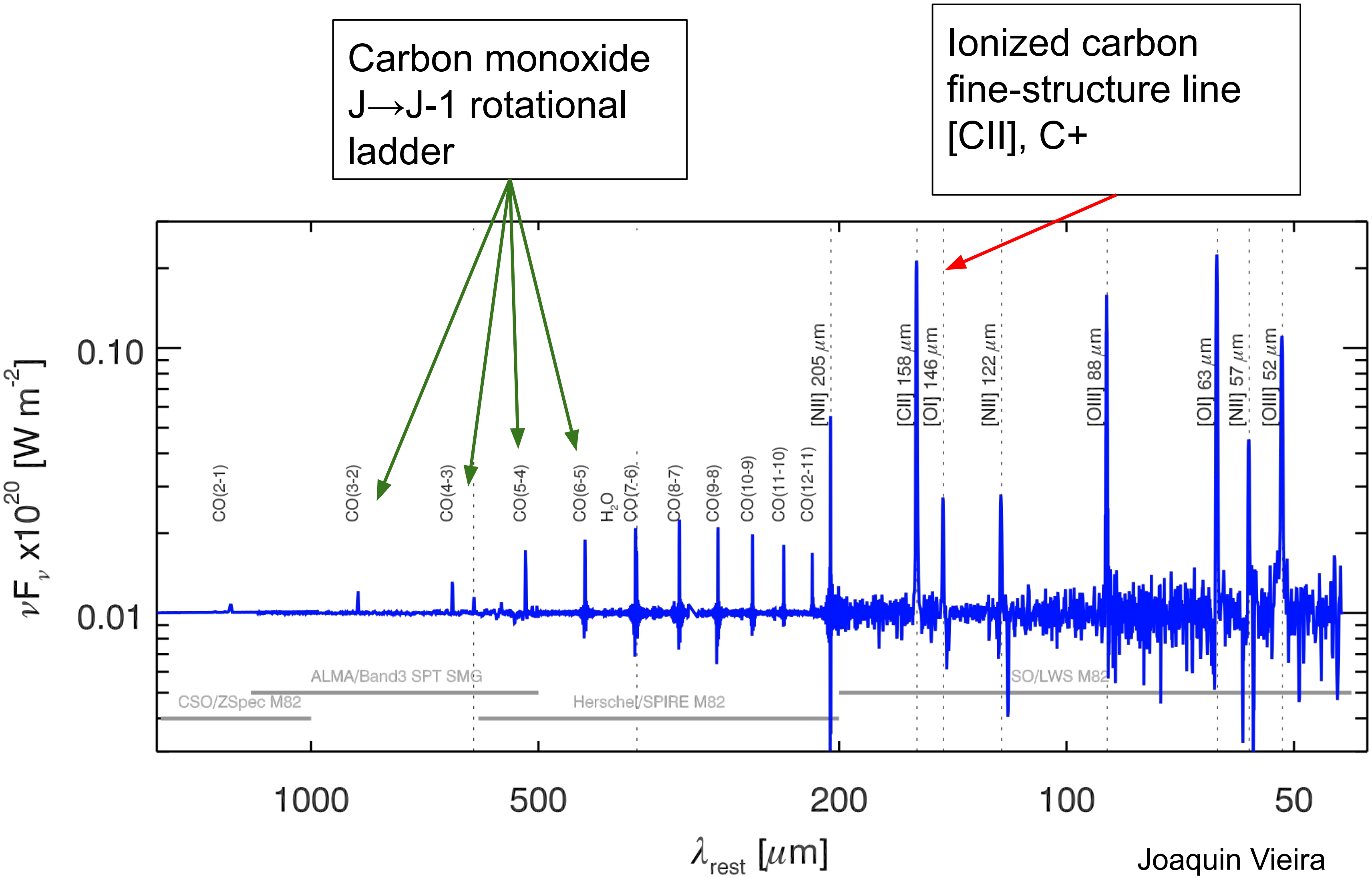
Observe an atomic/molecular line with a spectrometer. *The wavelength direction corresponds to redshift/distance.*





Li+ 2015

Pick a line to target: Far-IR lines in star-forming galaxies



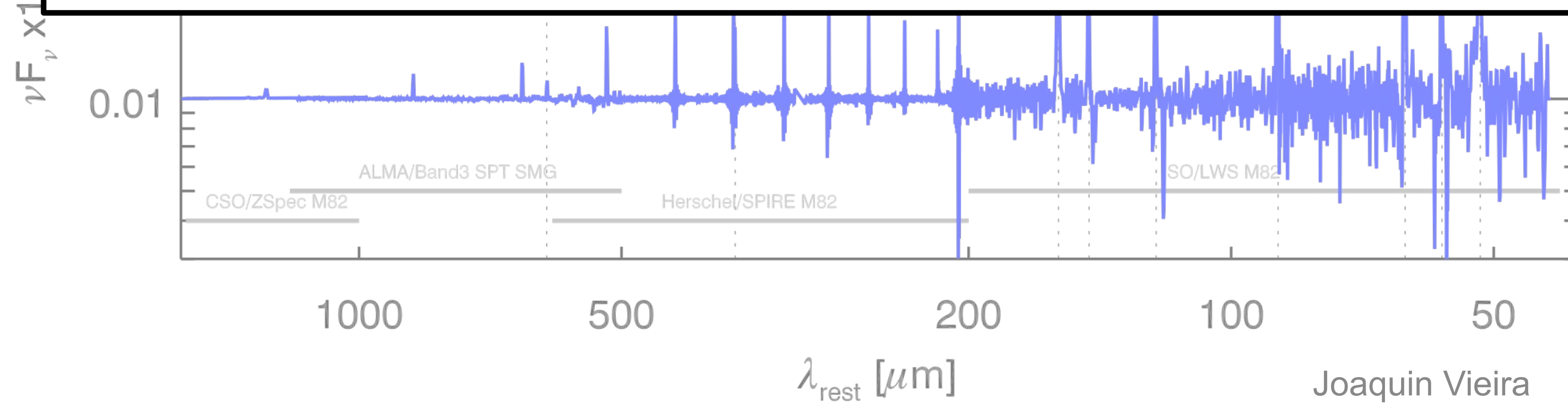
Joaquin Vieira

Pick a line to target: Far-IR lines in star-forming galaxies

LIM observations from 80-300 GHz would detect CO/[CII] from LSS at redshifts 0 < z < 10.

CMB instruments already make extremely sensitive mm-wave measurements of faint, diffuse fluctuations on large scales, over thousands of square degrees.

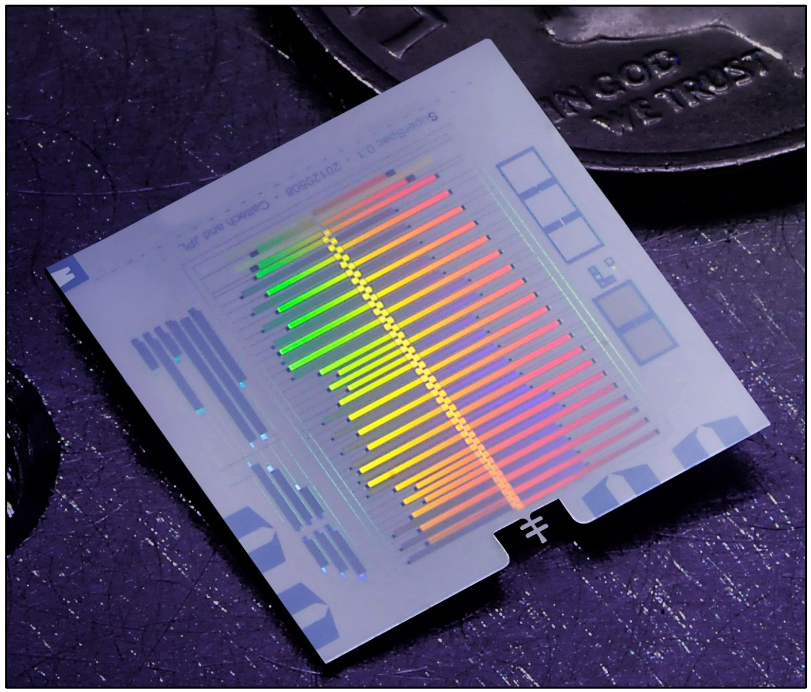
Just add spectroscopy!



Joaquin Vieira

SuperSpec (Superconducting Spectrometer)

Caltech/JPL
C. M. Bradford
H. G. LeDuc
S. Hailey-Dunsheath
R. M. J. Janssen
E. Kane
J. Redford
J. Zmuidzinas



University of Chicago
P. Barry (→ ANL)
K. S. Karkare
R. McGeehan
E. Shirokoff

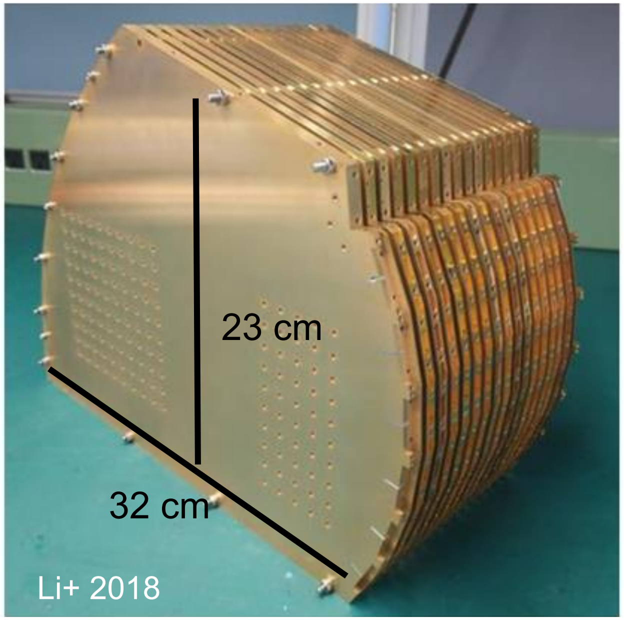
Arizona State University
S. Gordon
K. Massingill
P. Mauskopf

University of Colorado
J. Glenn (→ Goddard)
J. Wheeler (→ NIST)

Cardiff University
S. Doyle
C. Tucker

Dalhousie University
S. Chapman
C. Ross

The SuperSpec On-chip mm-wave Spectrometer

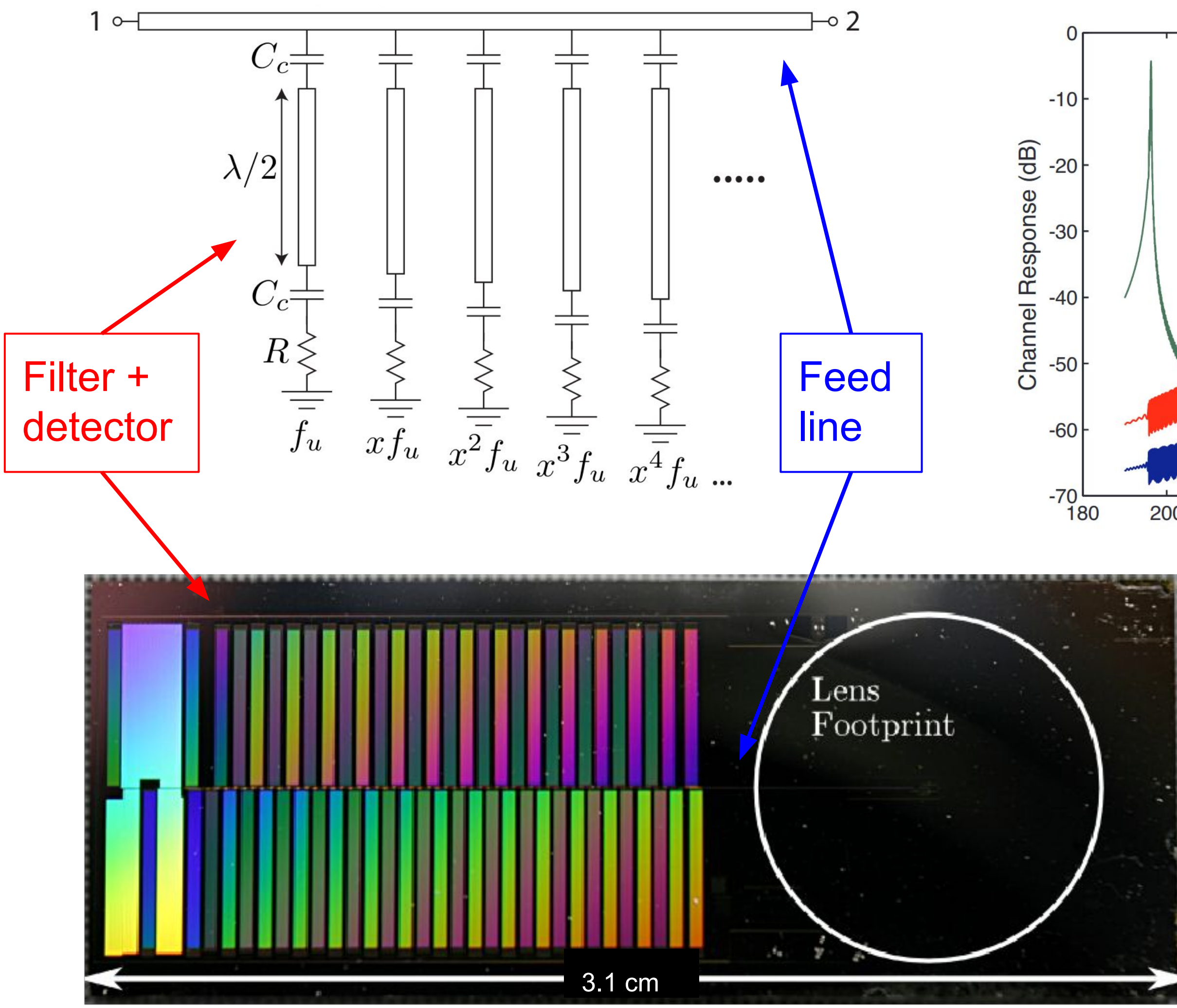


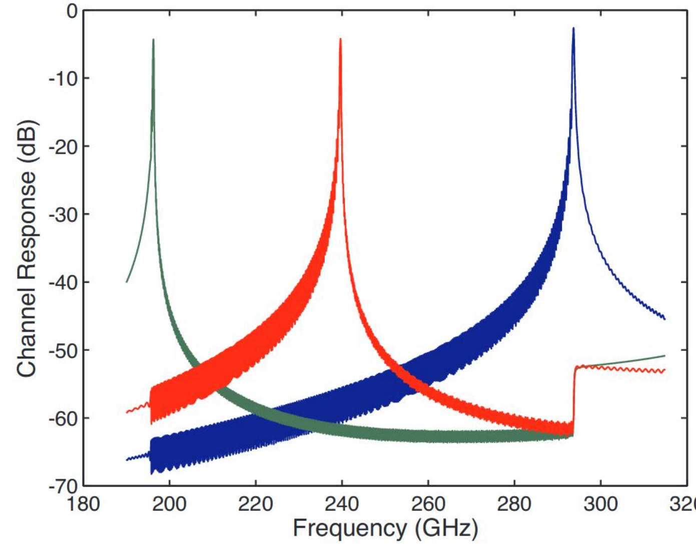
TIME grating: 32 x 23 x 1 cm
~ 736 cm^3

SuperSpec: 3.6 x 5.7 x 0.05 cm
~ 1 cm^3

A spectrometer that retains the wide bandwidth and high sensitivity of a grating, but in a much smaller package.

A Filter-Bank Spectrometer Printed on Silicon



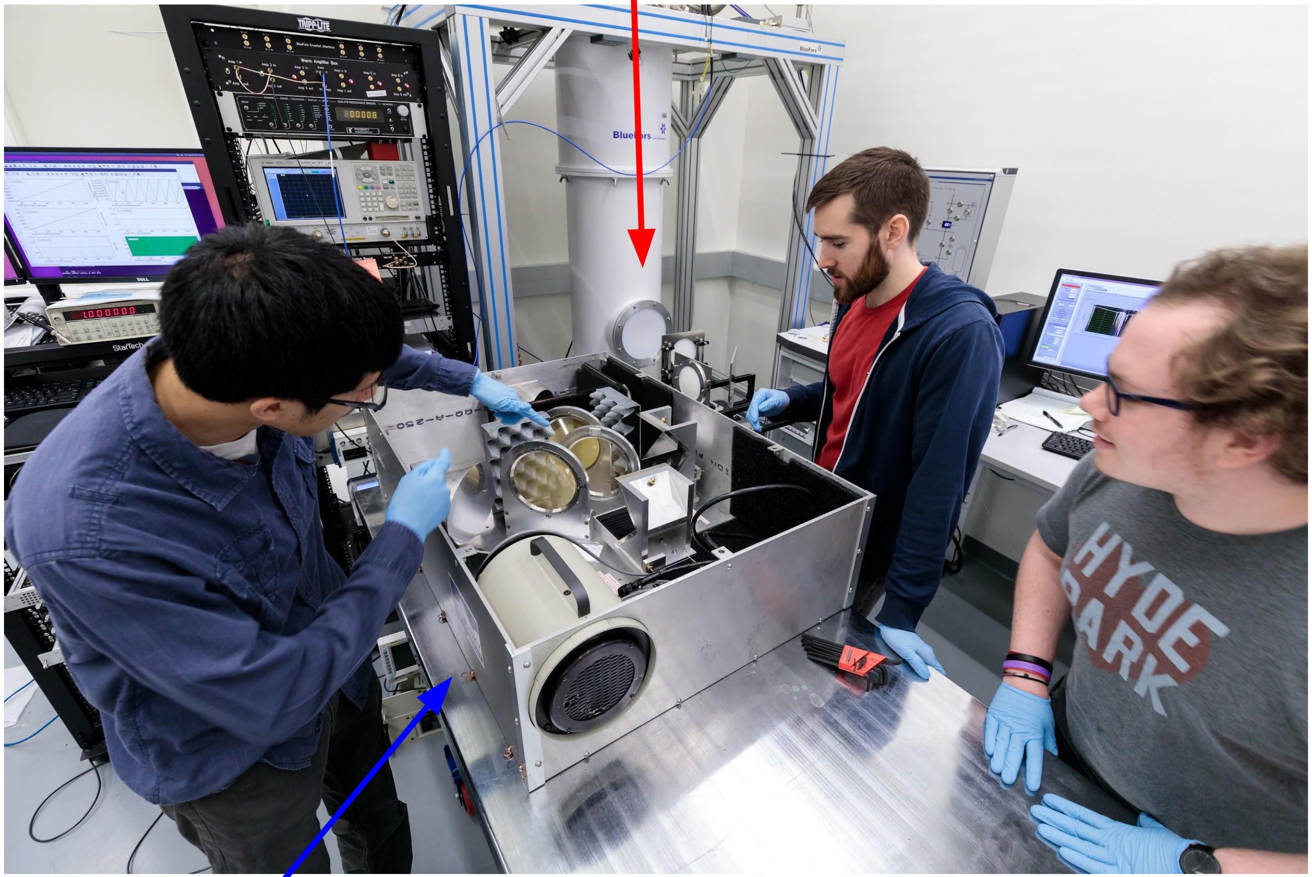


Kovacs & Zmuidzinas 2010

Karkare+
J. Low Temp. Phys. 2020

Lab-tested...

Cryostat with detector inside
(operates at 10-250 mK)

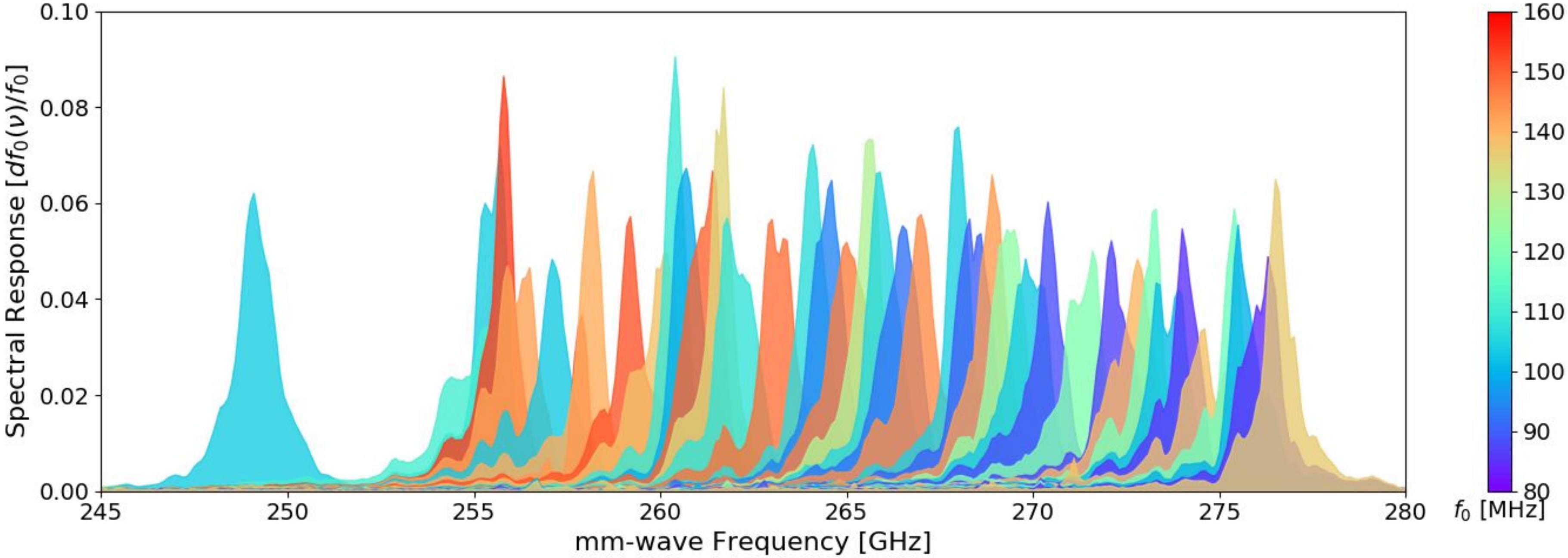


Fourier Transform Spectrometer
(measure spectral profiles)

\+ Ryan McGeehan,
Calder Sheagren

...and ready to deploy!

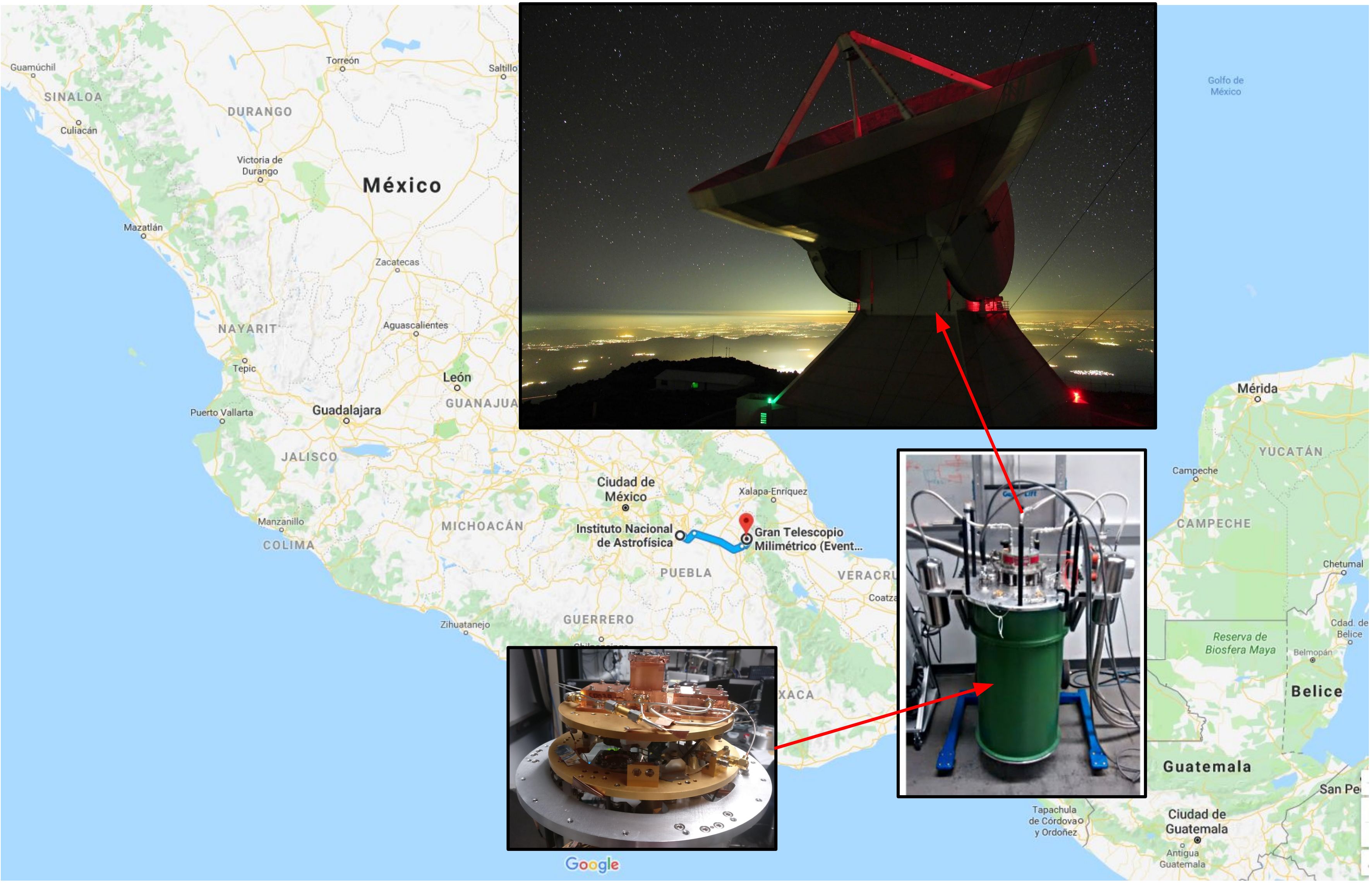
Karkare+
J. Low Temp. Phys. 2020



The filter bank works: each channel sees a different mm-wave frequency.

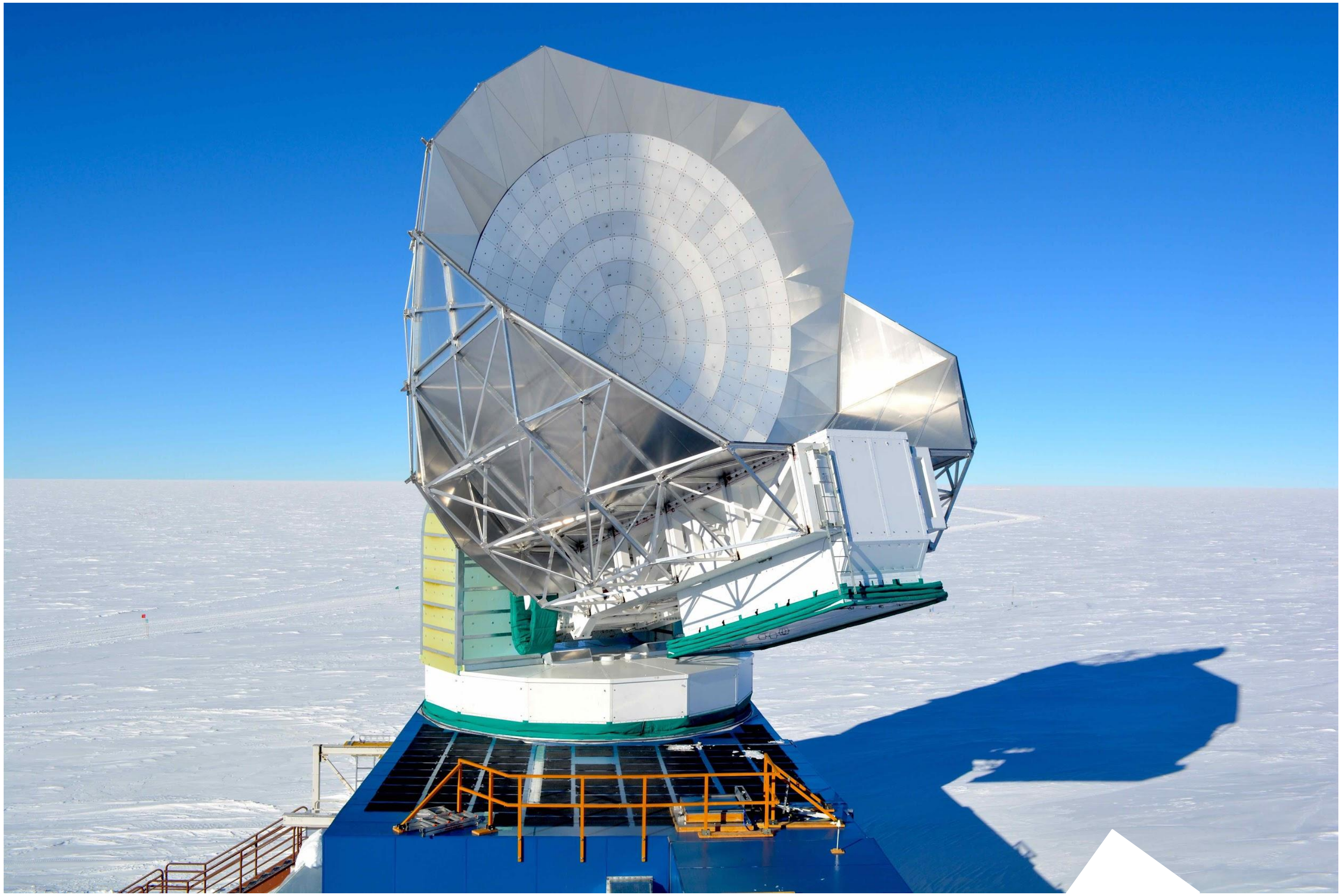
Noise levels are suitable for ground-based observations.

Imminent Demonstration on the 50-m Large Millimeter Telescope

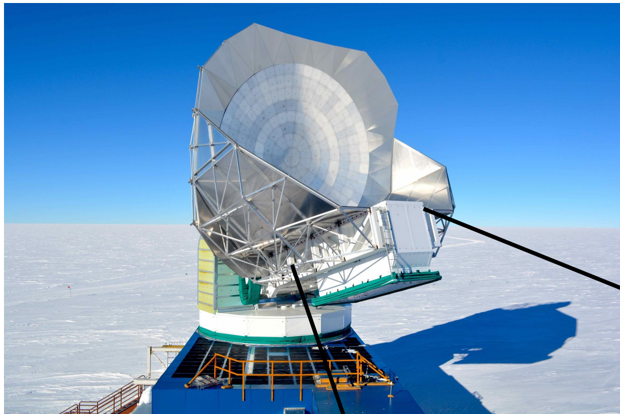


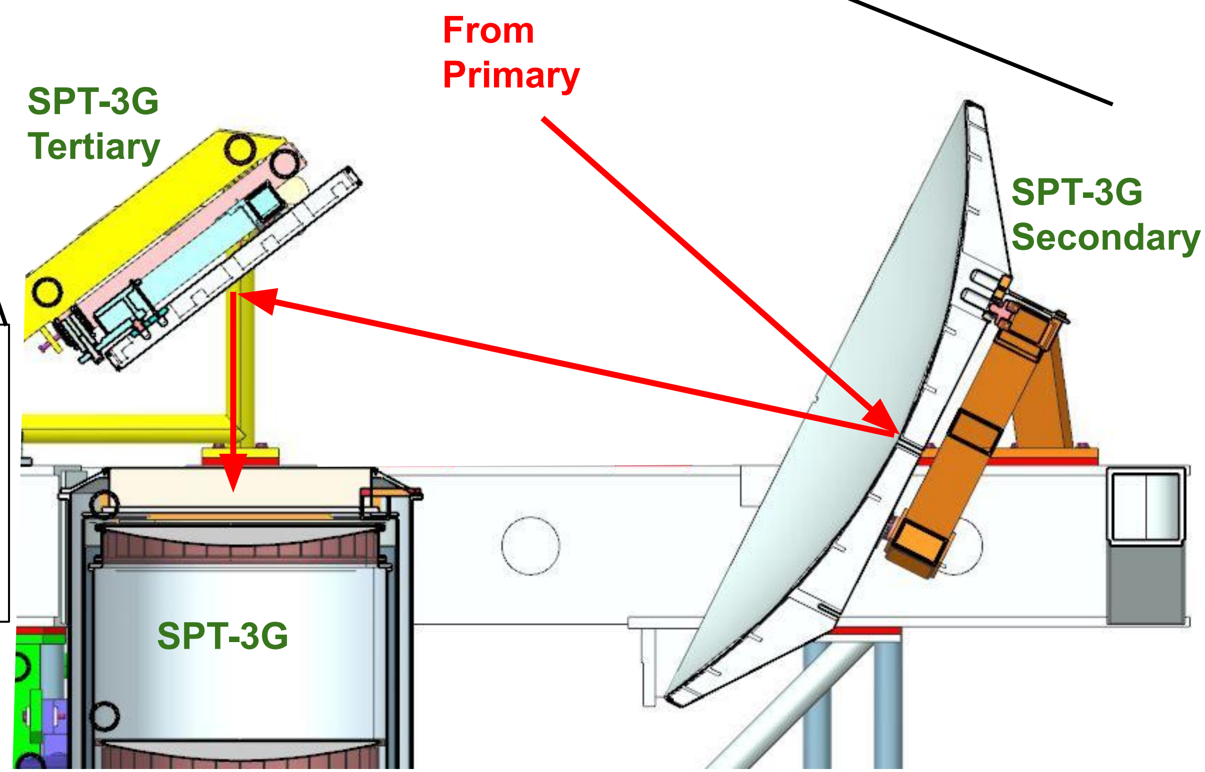

Sierra Negra
(15,000 ft)
Pico de Orizaba (18,400 ft),
3rd highest mountain in NA

The South Pole Telescope

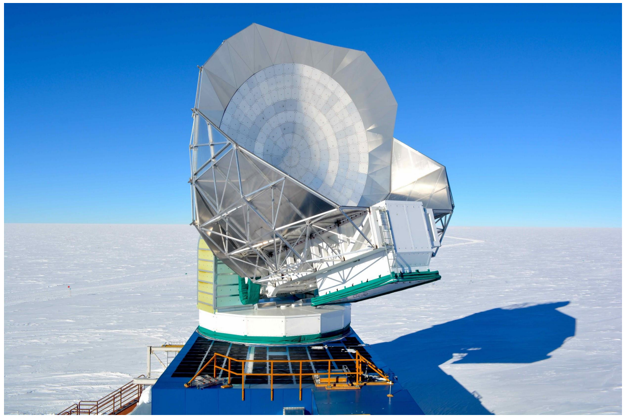


Inside the SPT Receiver Cabin





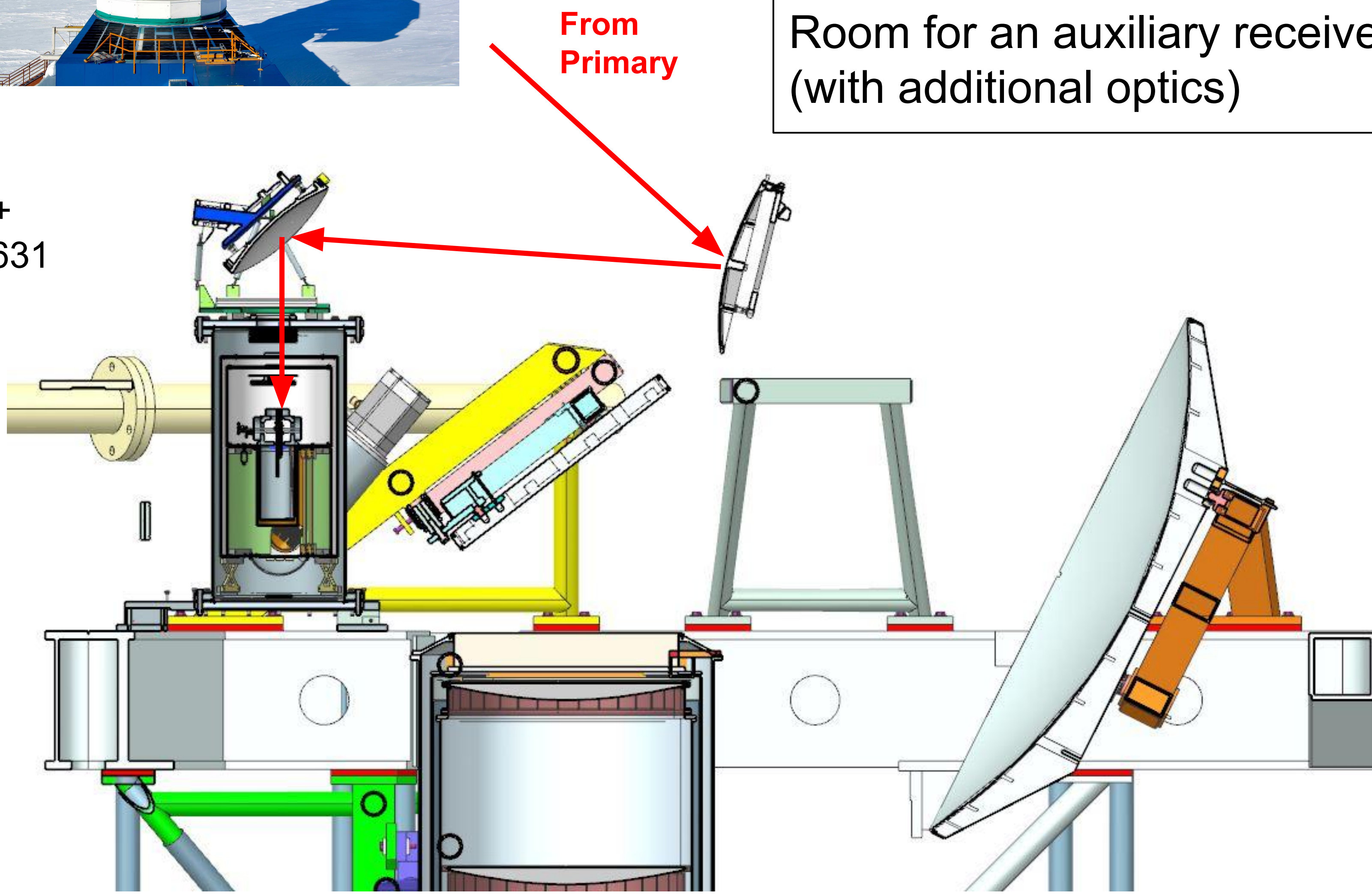
Primarily houses the SPT-3G receiver, which will observe until ~2025…



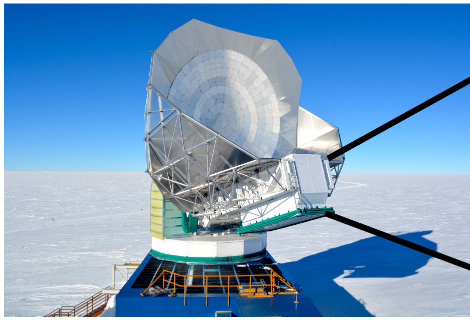
Inside the SPT Receiver Cabin

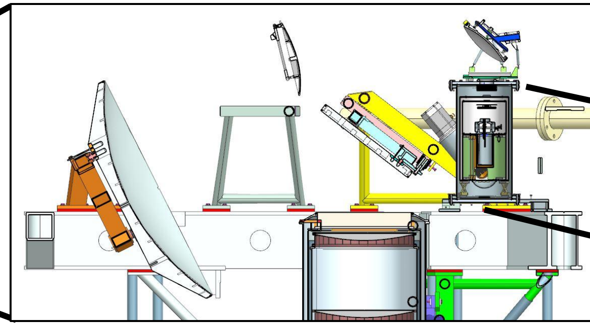
Room for an auxiliary receiver (with additional optics)

Karkare+ 2111.04631

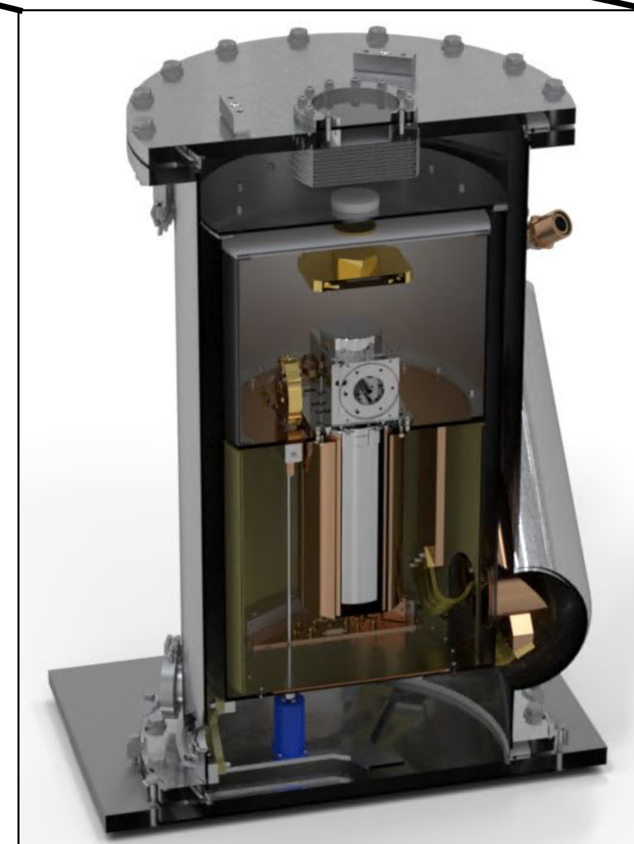


SPT-SLIM: SPT Summertime Line Intensity Mapper





Karkare+
2111.04631



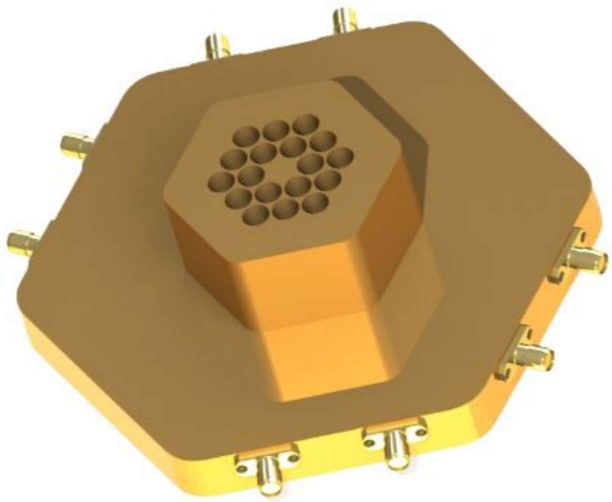
Funded in 2021:
Karkare co-PI of Fermilab LDRD

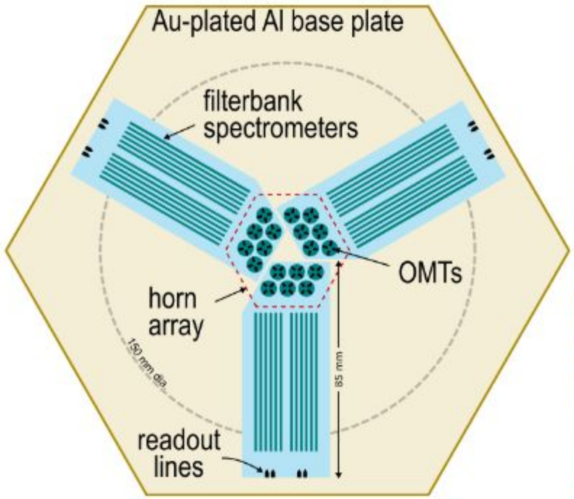
LIM Pathfinder using on-chip spectrometers

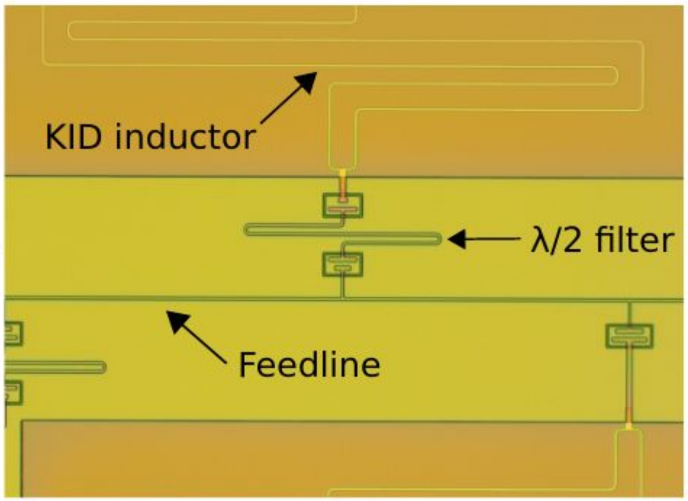
Observe in 2023/2024 Austral summer season

SPT-SLIM: SPT Summertime Line Intensity Mapper

Karkare+
2111.04631



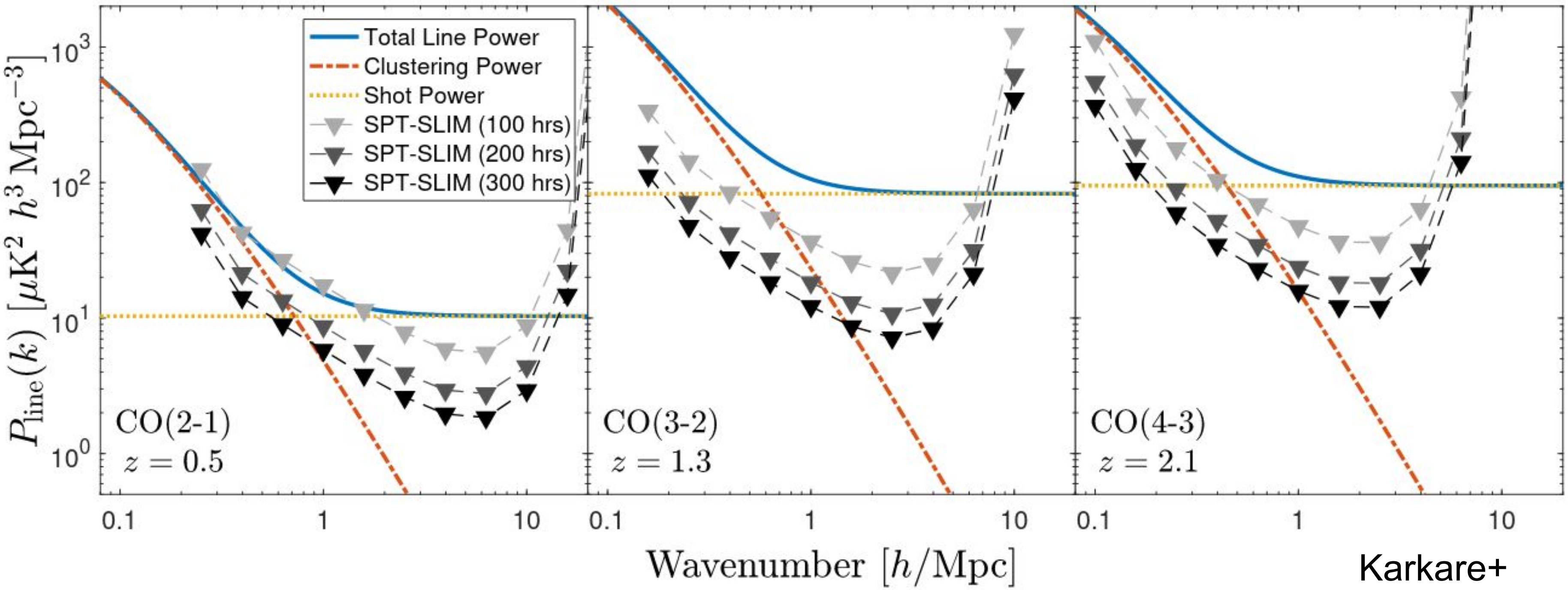




The first demonstration of LIM with on-chip spectrometers

18x dual-pol, 120-180 GHz, R=300

SPT-SLIM: SPT Summertime Line Intensity Mapper



Karkare+
2111.04631

SPT-SLIM will validate technology and observational techniques needed for LIM cosmology!

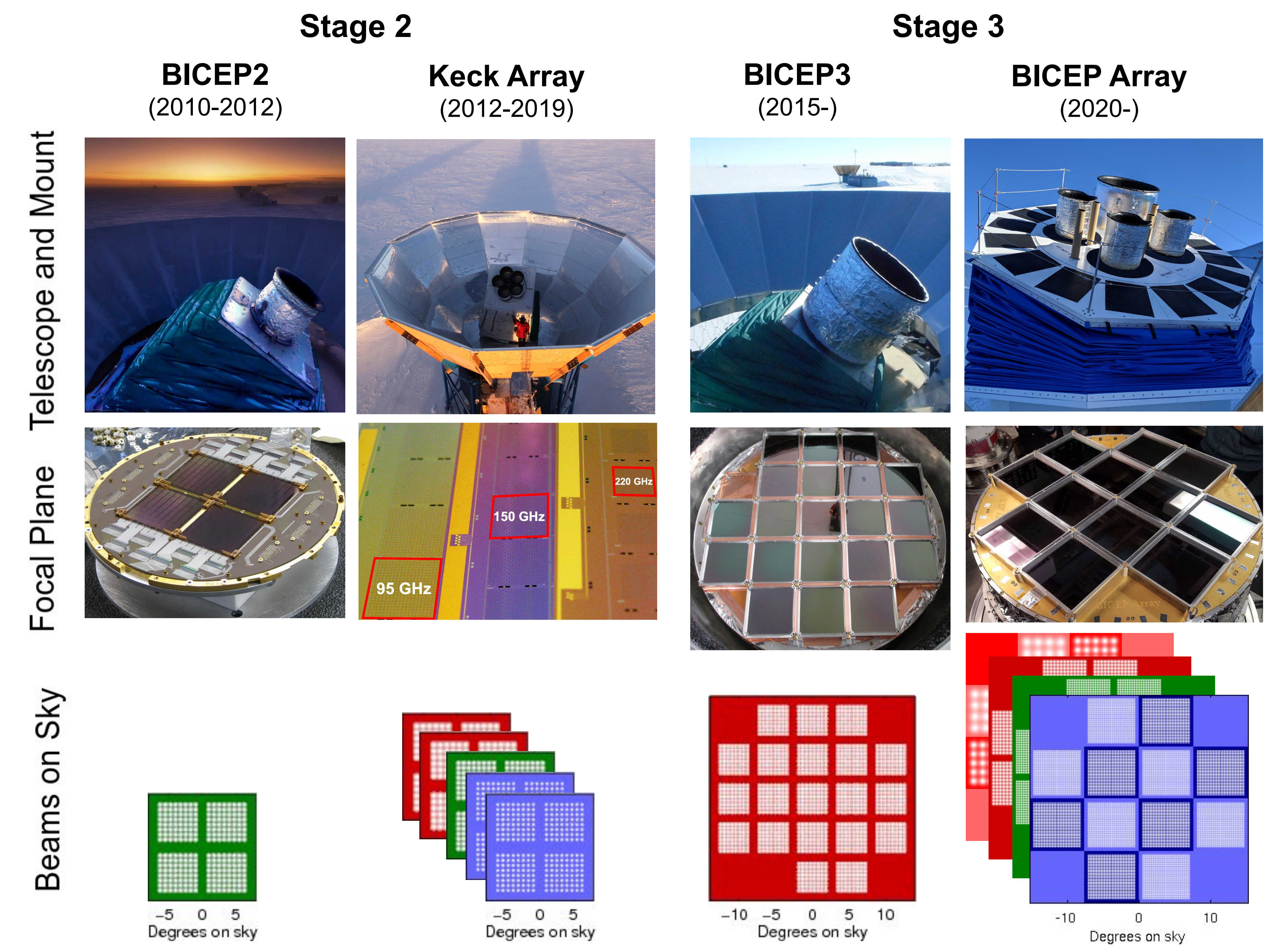
The next-generation SPT receiver (2026+) will deploy a LIM focal plane incorporating lessons learned from SPT-SLIM.

Future LIM Projections for Snowmass 2021

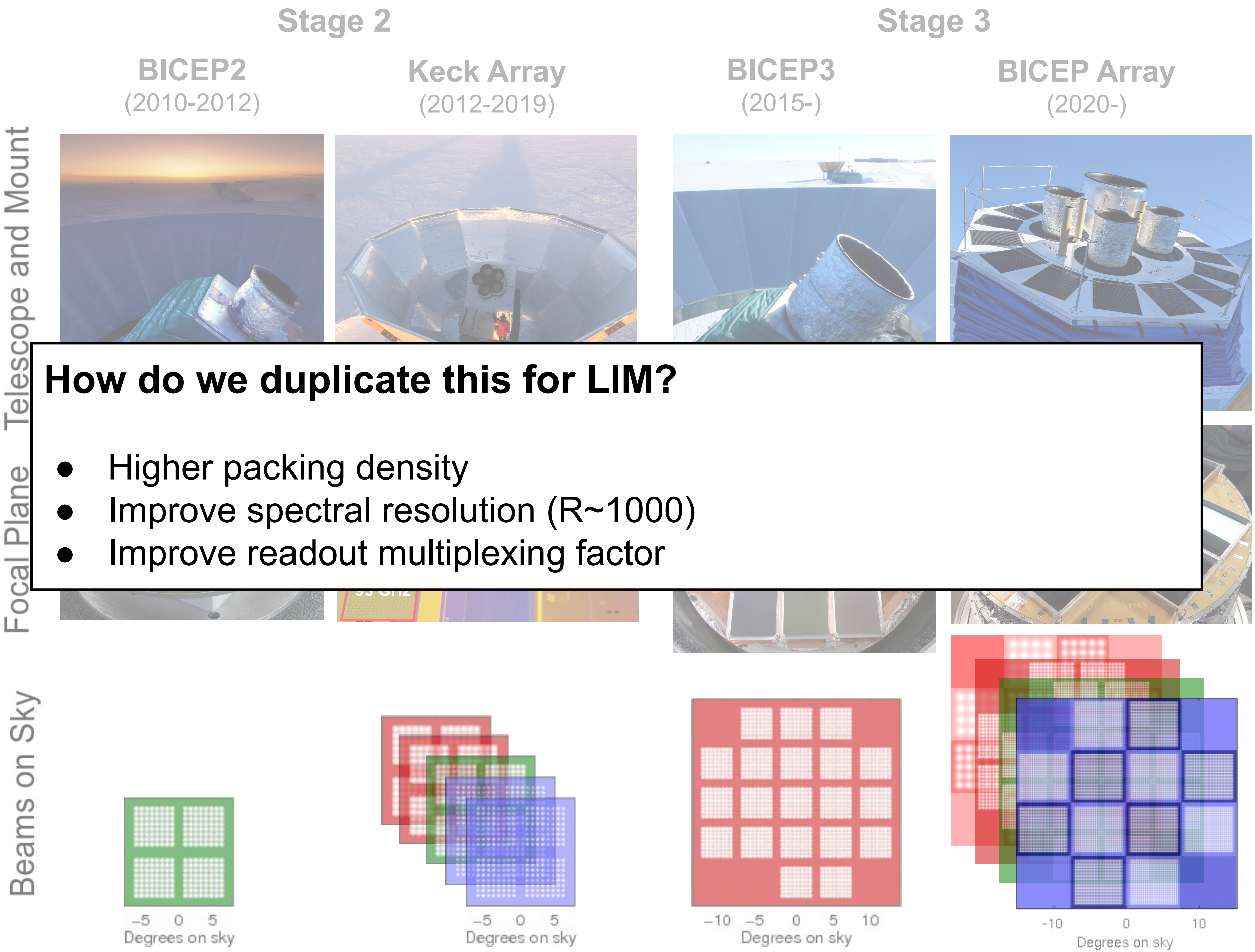
Spec-hrs	Example	Timescale [yr]	$\sigma(M_\nu)$ [eV]	$\sigma(w_0)$	$\sigma(f_{NL})$
10^5	TIME, SPT-SLIM	1-2			
10^6	TIME-EXT	4	0.047	0.03	13
10^7	SPT, 1 tube	6	0.028	0.013	4
10^8	SPT, 7 tubes	9	0.013	0.005	1.5
10^9	CMB-S4, 85 tubes	15	0.007	0.003	0.5

Forecast constraints on neutrinos, dark energy, primordial non-Gaussianity as a function of *spectrometer-hours* (sensitivity)

Adapted from Moradinezhad Dizgah+ 2021 (incl. Karkare), ApJ in press



Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
220 GHz
150 GHz
95 GHz
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
-10 0 10
Degrees on sky



How do we duplicate this for LIM?

- Higher packing density
- Improve spectral resolution (R~1000)
- Improve readout multiplexing factor

New mm-wave instruments and technologies are pushing our understanding of cosmology to the limit.

- BICEP constrains inflation to $\sigma(r) \sim 0.009$.
- CMB-S4 will limit $r < 0.001$, testing well-motivated inflation models.
- LIM is a promising high-redshift observable. First detections coming soon, but much more sensitivity is required for cosmology.

My plans:

- **CMB-S4 inflation survey calibration** - ensure that *r* constraints are statistics- and not systematics-limited.
- **Advance LIM with on-chip spectrometers** using SuperSpec, SPT-SLIM, and future instruments.

Thank you and stay tuned!