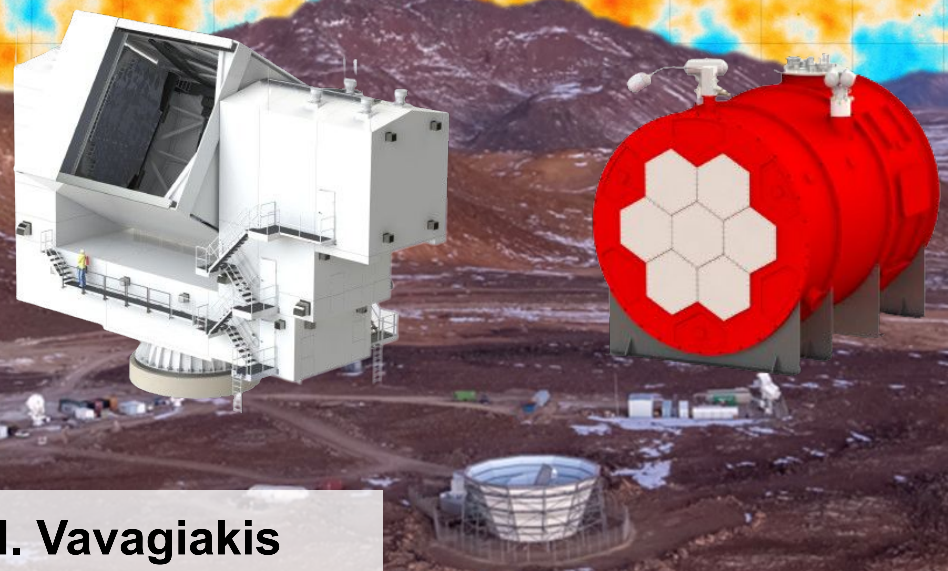
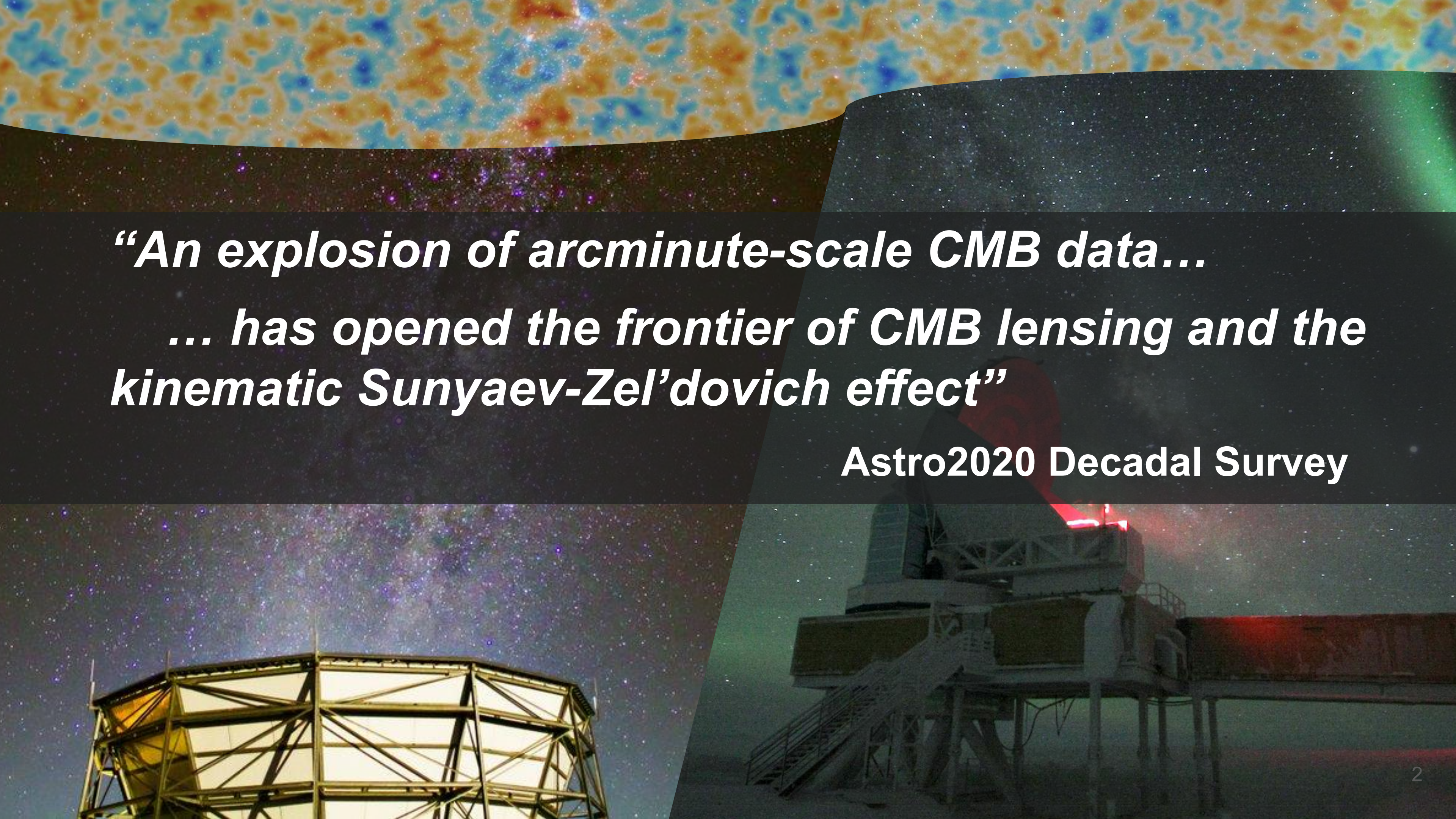
From ACT to Simons Observatory and CCAT:
Upcoming observations of the millimeter & submillimeter sky

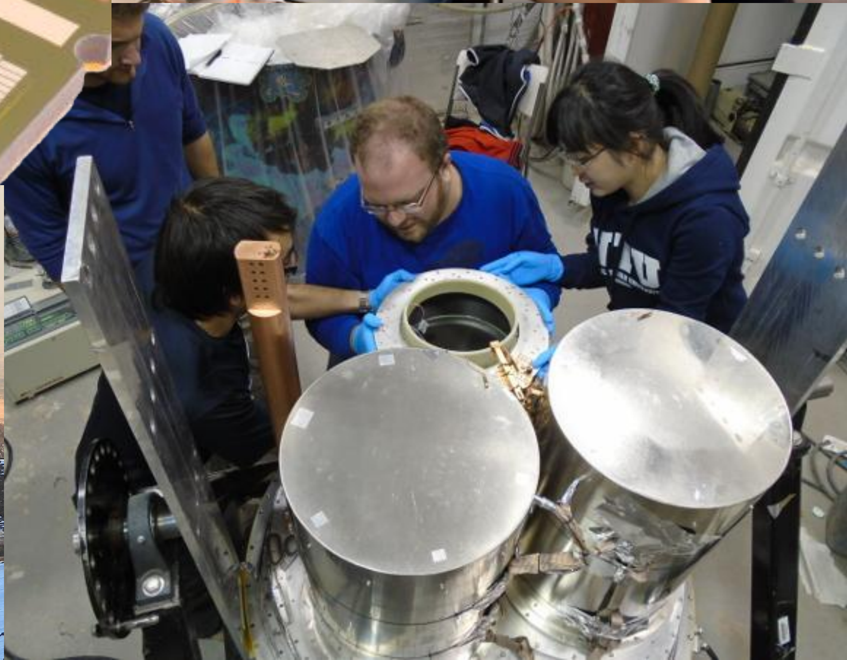


Eve M. Vavagiakis
Assistant Professor
Duke University

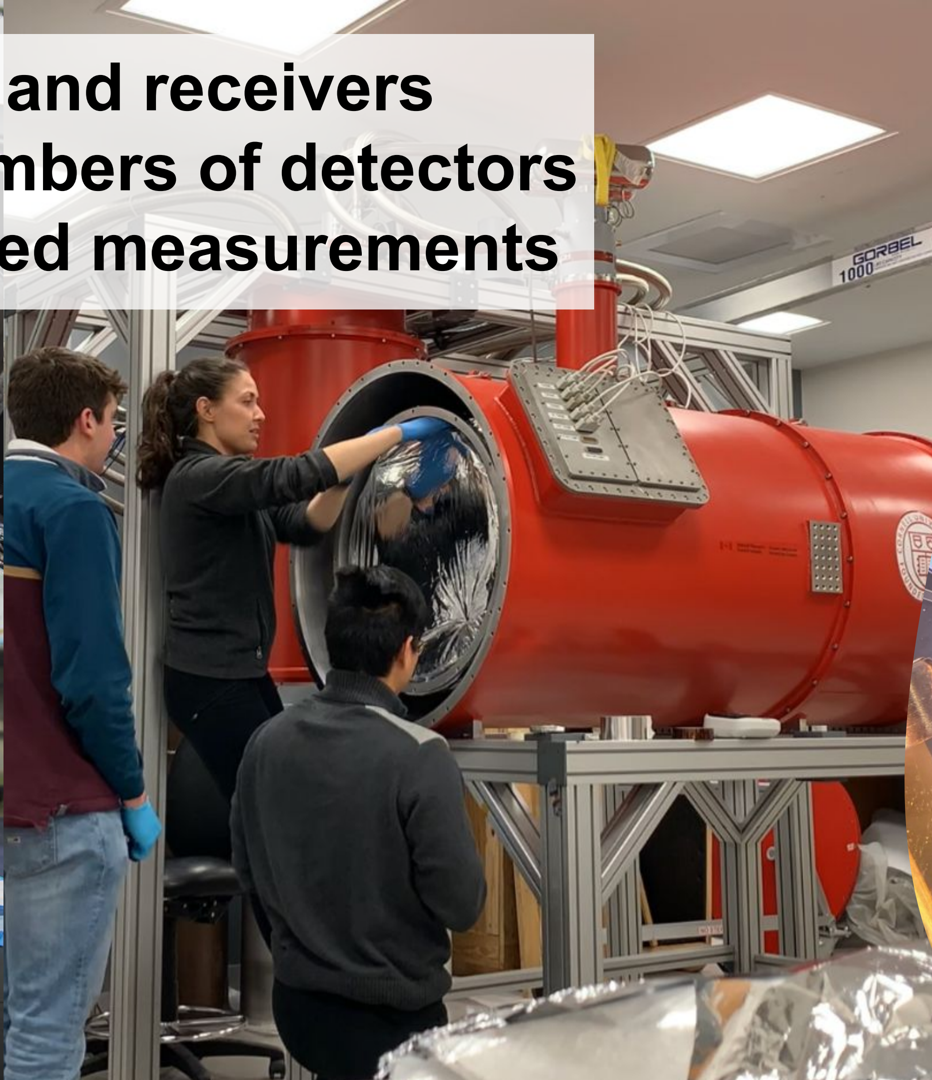
Duke Cosmology

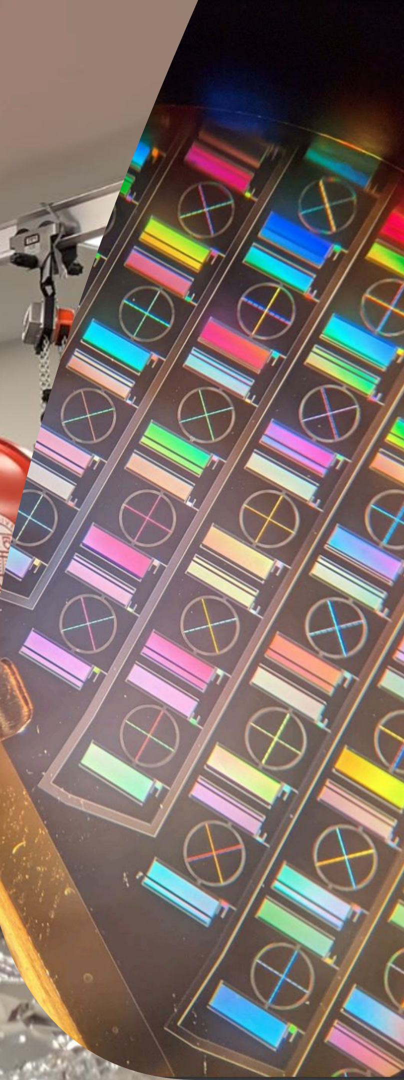

"An explosion of arcminute-scale CMB data…
… has opened the frontier of CMB lensing and the kinematic Sunyaev-Zel'dovich effect"
Astro2020 Decadal Survey

Technological advancements have rapidly developed our understanding of the universe

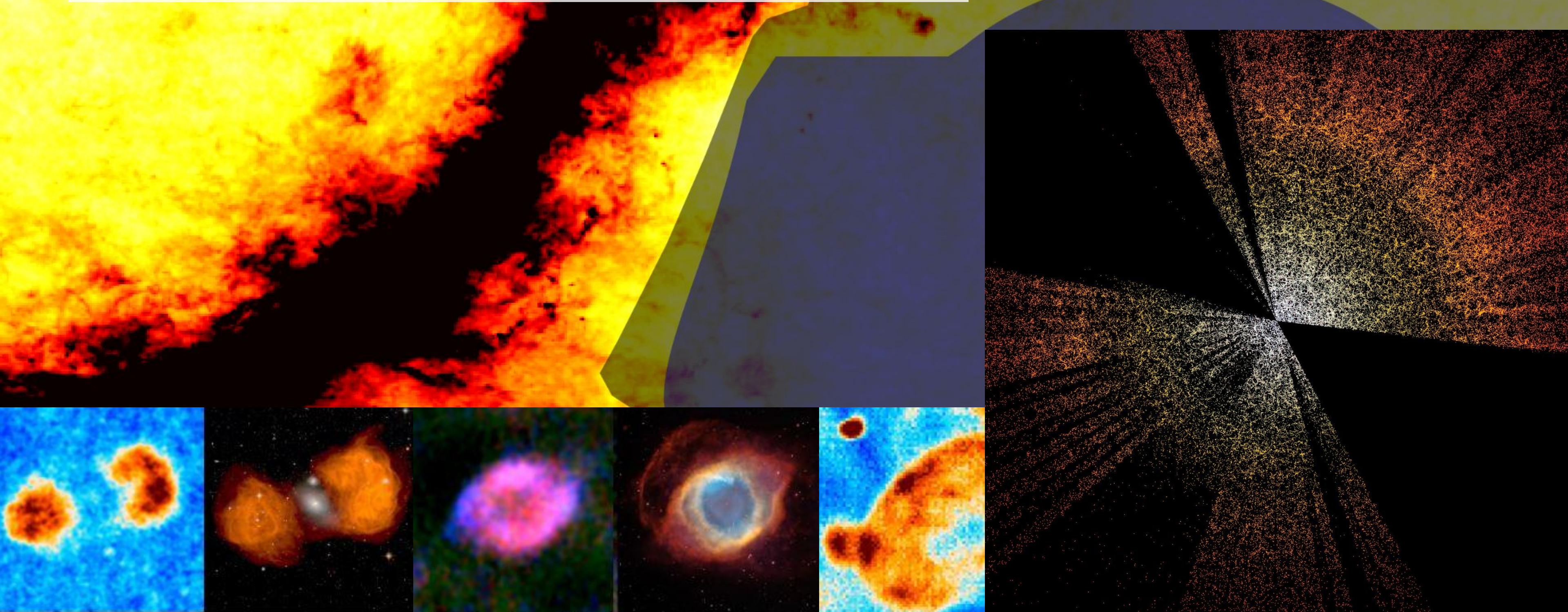


New telescopes and receivers deploy large numbers of detectors for unprecedented measurements





Upcoming surveys offer unparalleled opportunities for multifrequency cross-correlation



Today

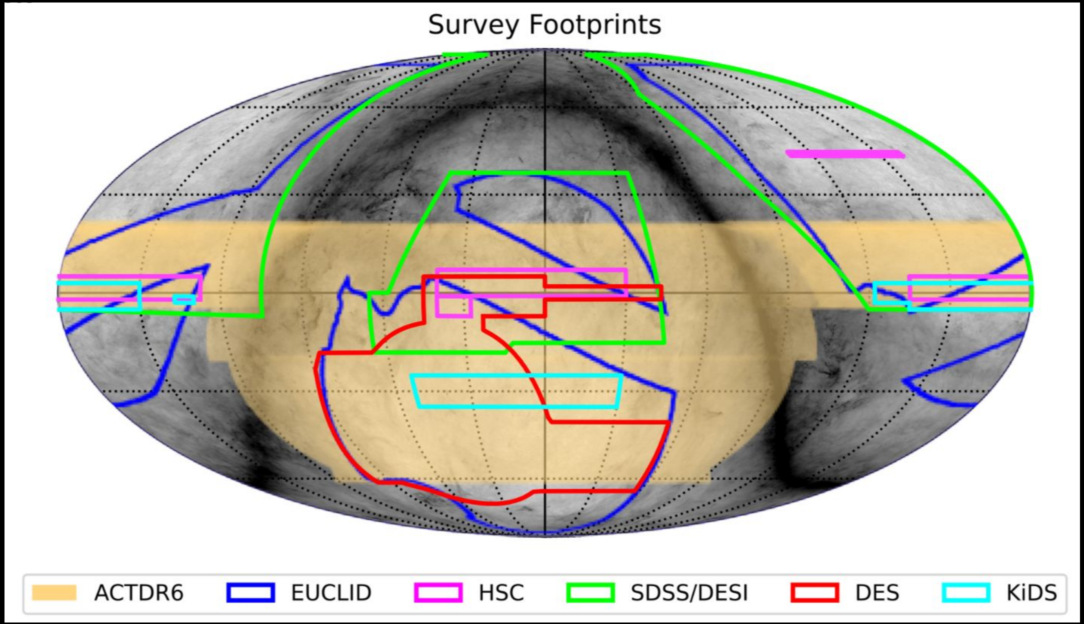
- The Sunyaev-Zel’dovich effects with ACT and future surveys
- Upcoming observations
  - The Simons Observatory
  - CCAT

Observing the CMB: Anisotropies

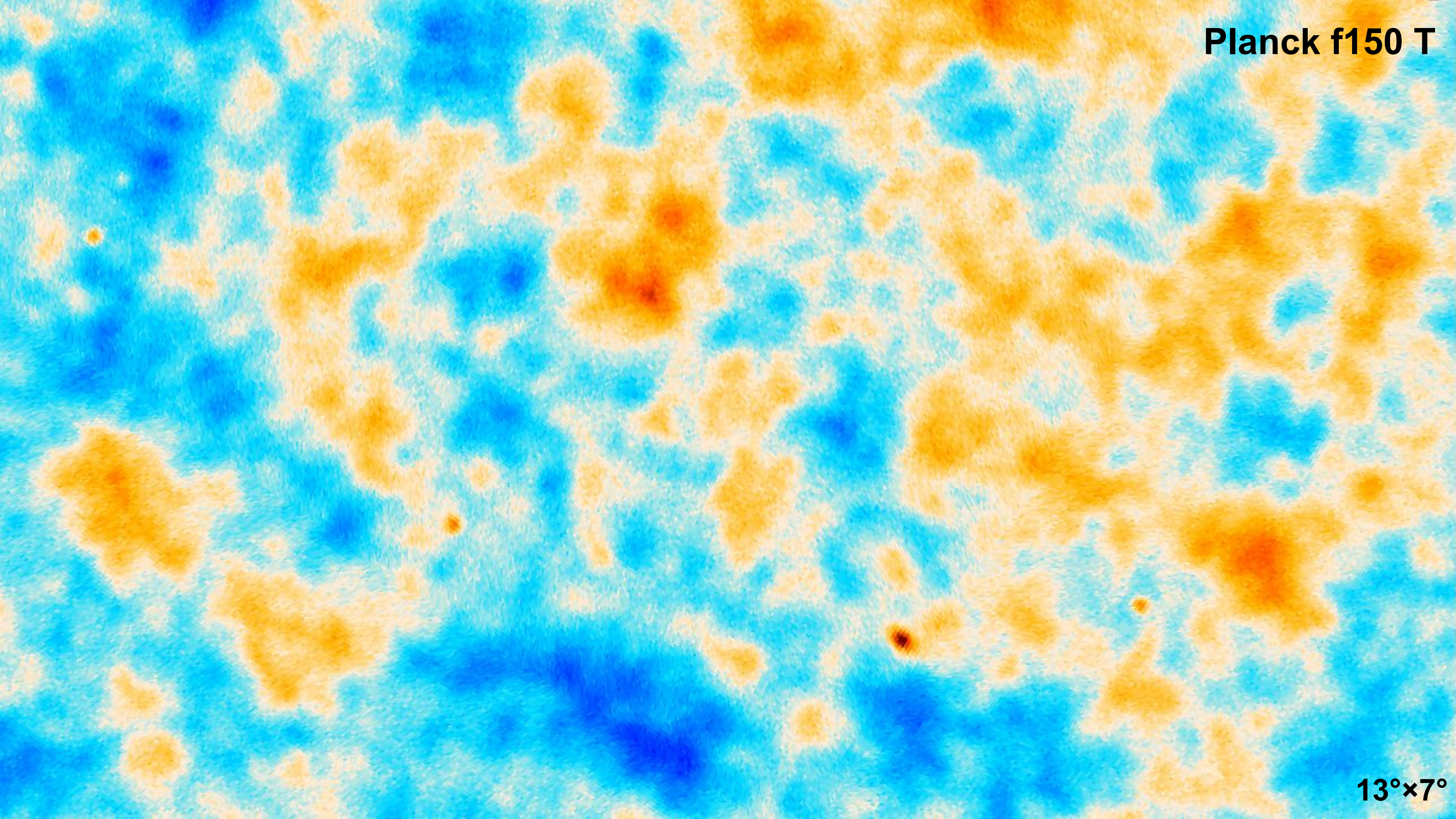
E. M. Vavagiakis, Illus: I. Lemesis, MIT Kids Press 2022

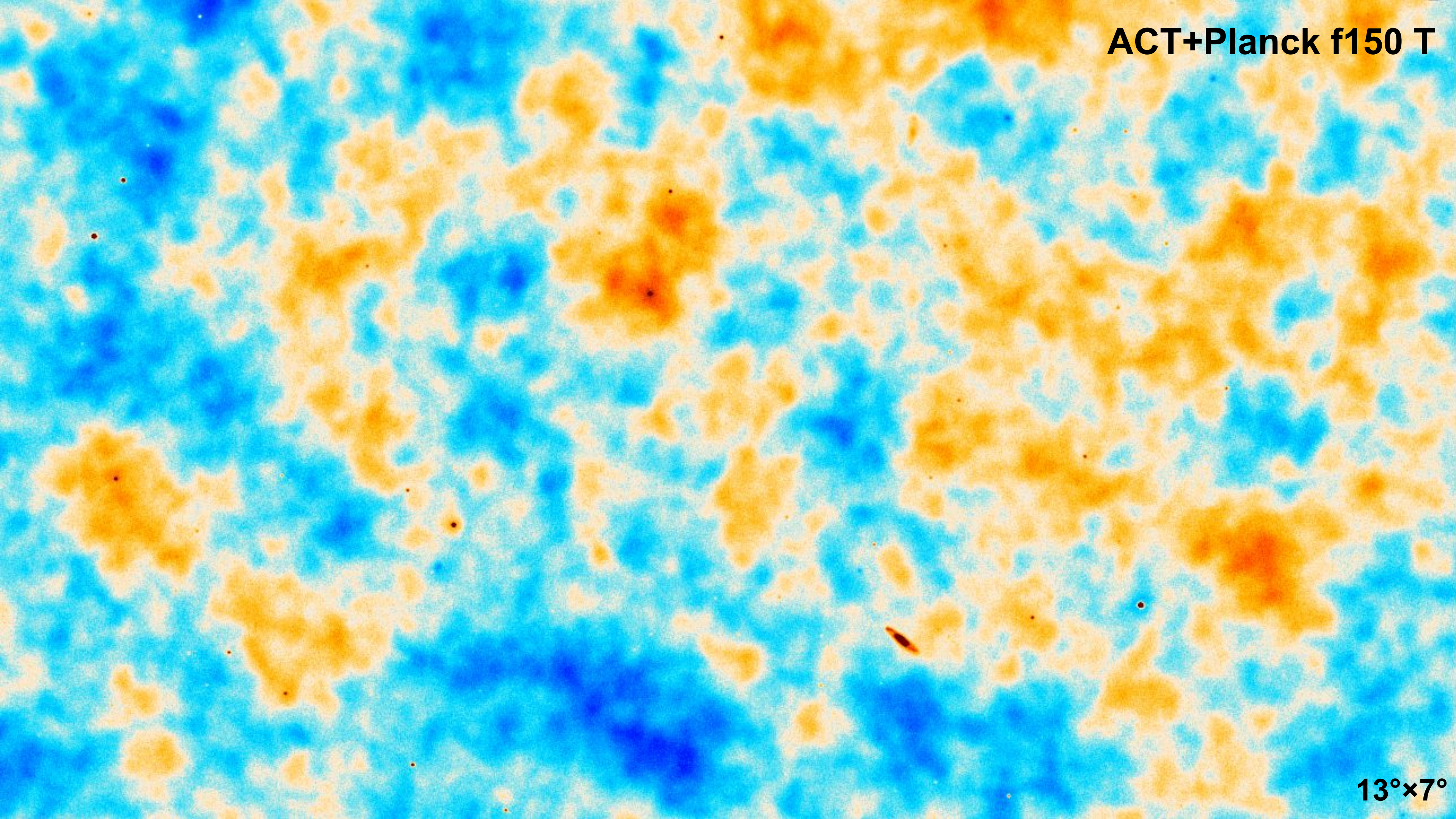
Cosmology with ACT: DR6

- 98, 150 and 220 GHz maps from 2017–2022 (AdvACT)
- 19,000 sq. deg., median combined depth 10 μK arcmin
- Data available on LAMBDA
- Interactive web atlas
- HiPS data sets in Aladin: https://alasky.cds.unistra.fr/ACT/DR4DR6/color_CMB/

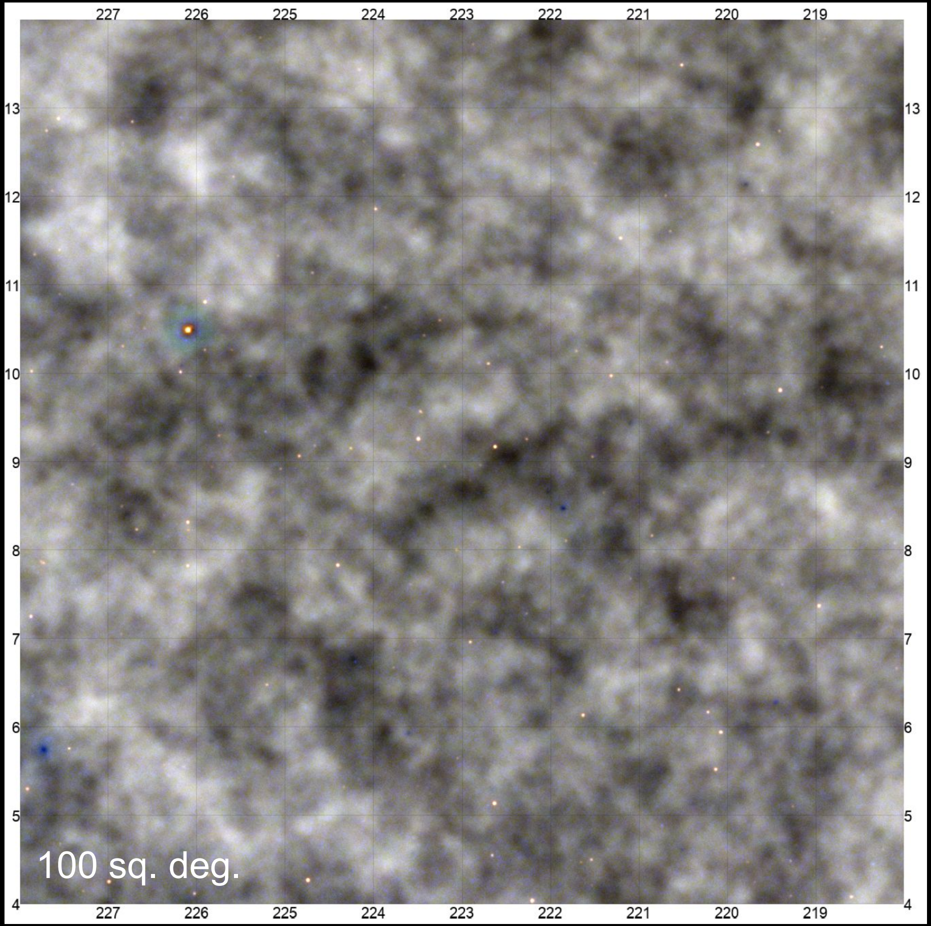


arXiv:2503.14451


Planck f150 T
13°×7°


ACT+Planck f150 T
13°×7°

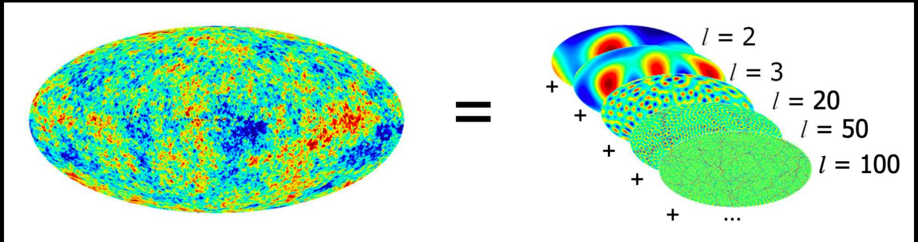
Cosmology with ACT: DR6



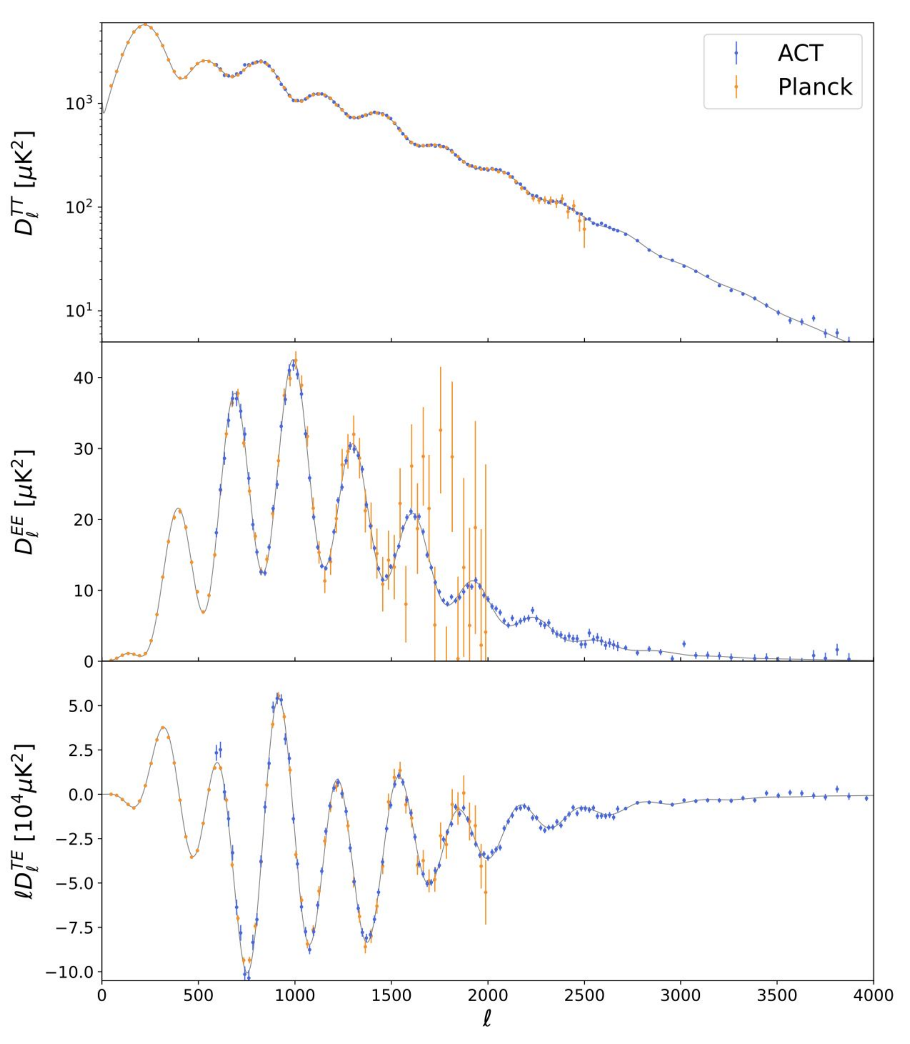
arXiv:2503.14451

Cosmology with ACT

- Excellent agreement of ΛCDM to now more precise data
- Extended measurement to smaller scales

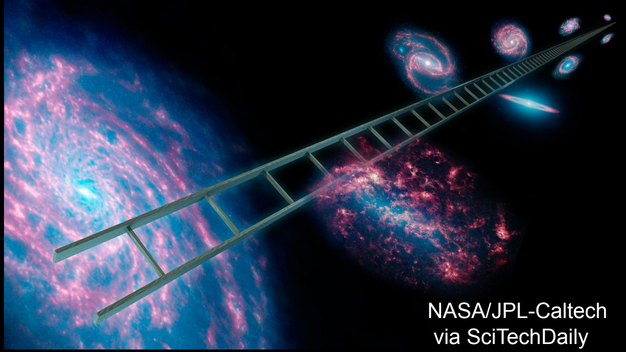


arXiv:2503.14452

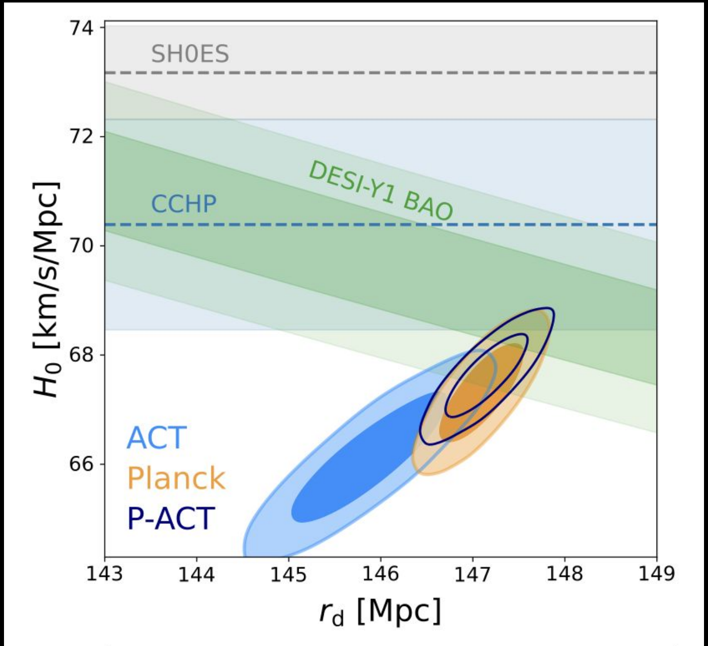


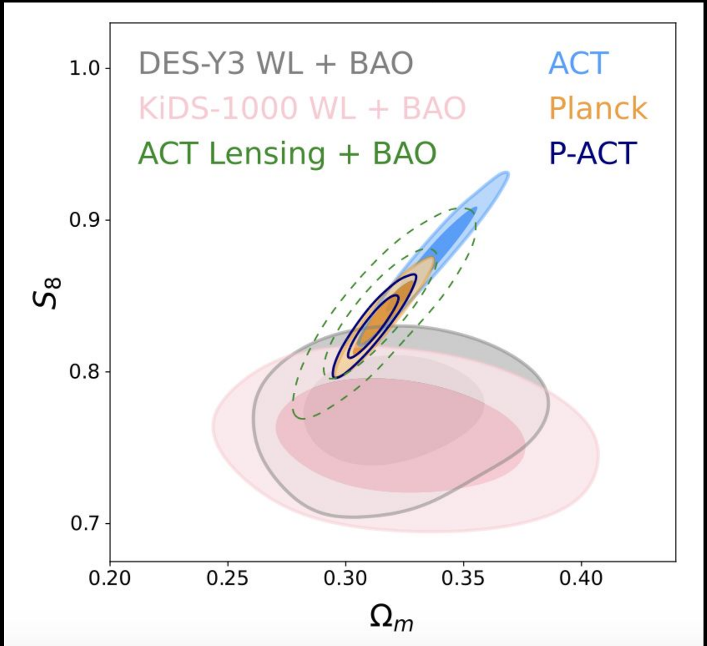
Cosmology with ACT: Tensions

- Rule out high H_0 constant >4σ
- H_0 x sound horizon consistent with DESI
- H_0 consistent with SPT-3G results (arXiv:2212.05642)
- Higher S_8 than cosmic shear



NASA/JPL-Caltech via SciTechDaily

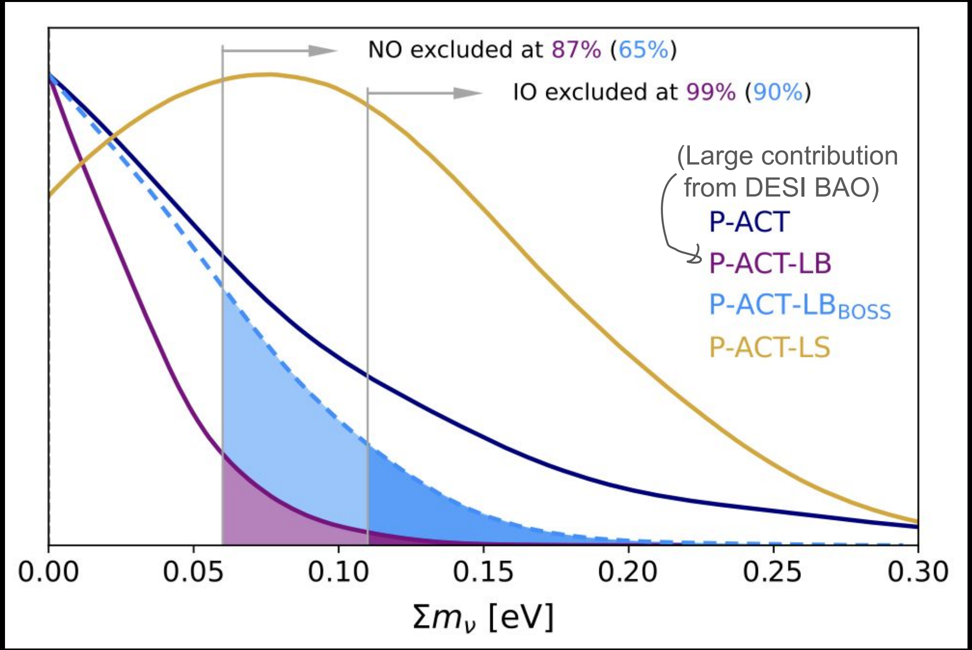


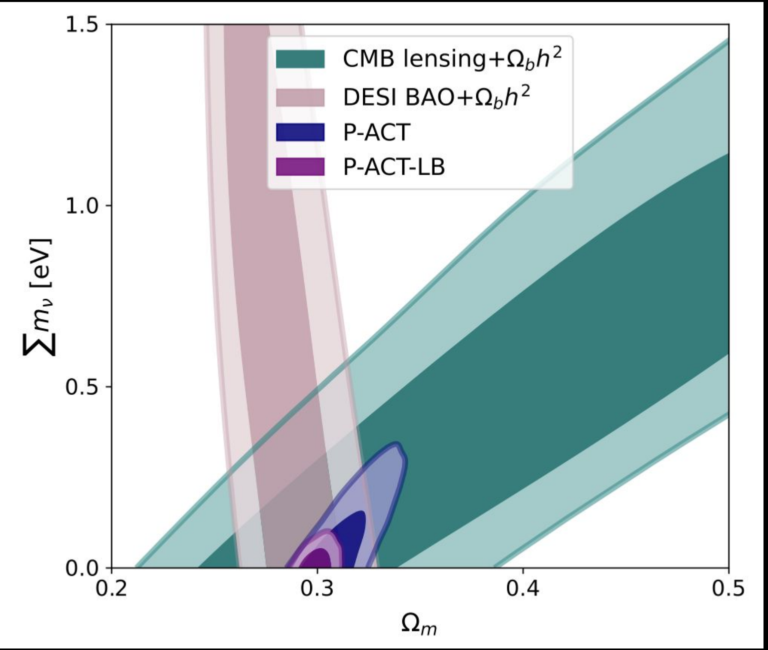


arXiv:2503.14452

Cosmology with ACT: Extended models

- Consistent neutrino properties with Standard Model
  - No evidence for new relativistic species
- Consistent with standard BBN
- Cosmological constant; no EDE

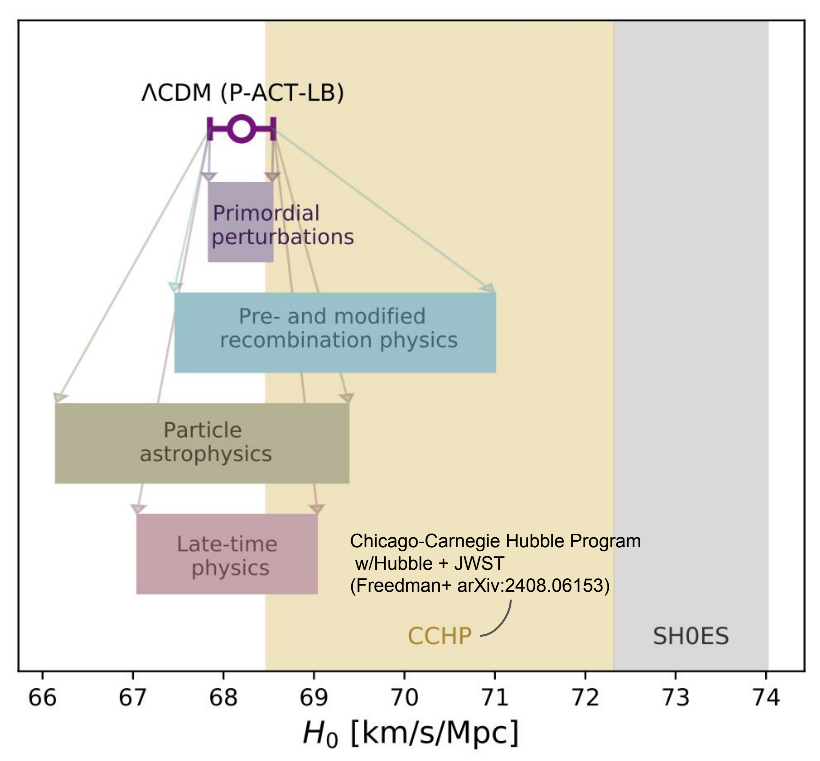


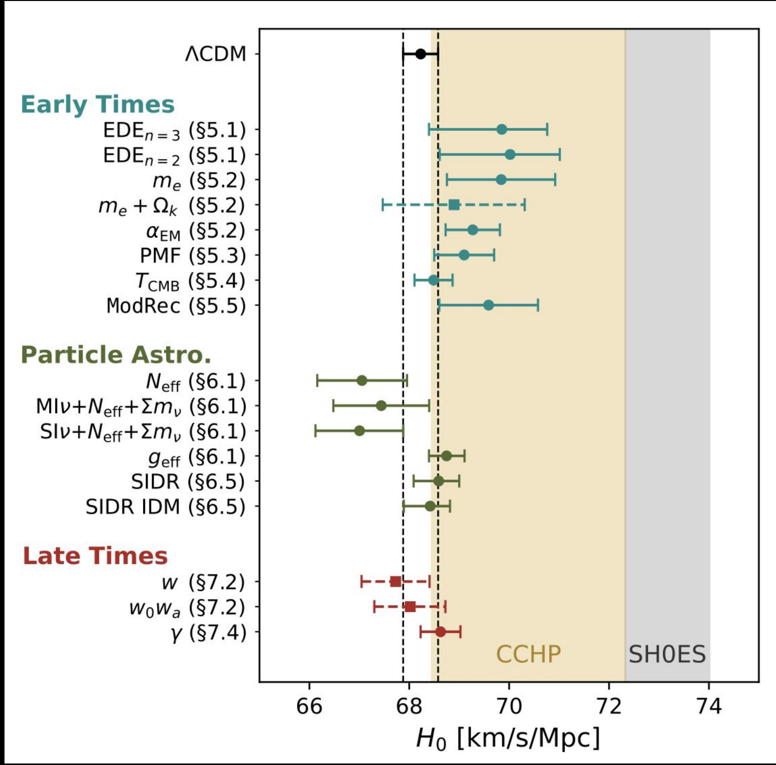


arXiv:2503.14454

Cosmology with ACT: Extended models

- Cosmological constant; no EDE (or other models)

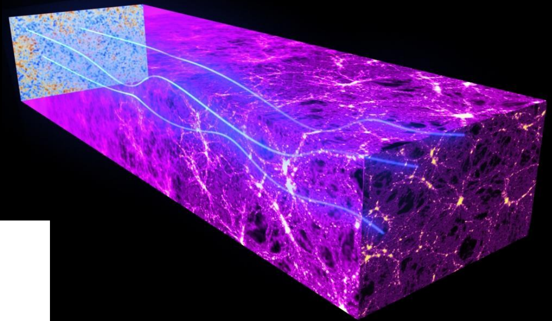


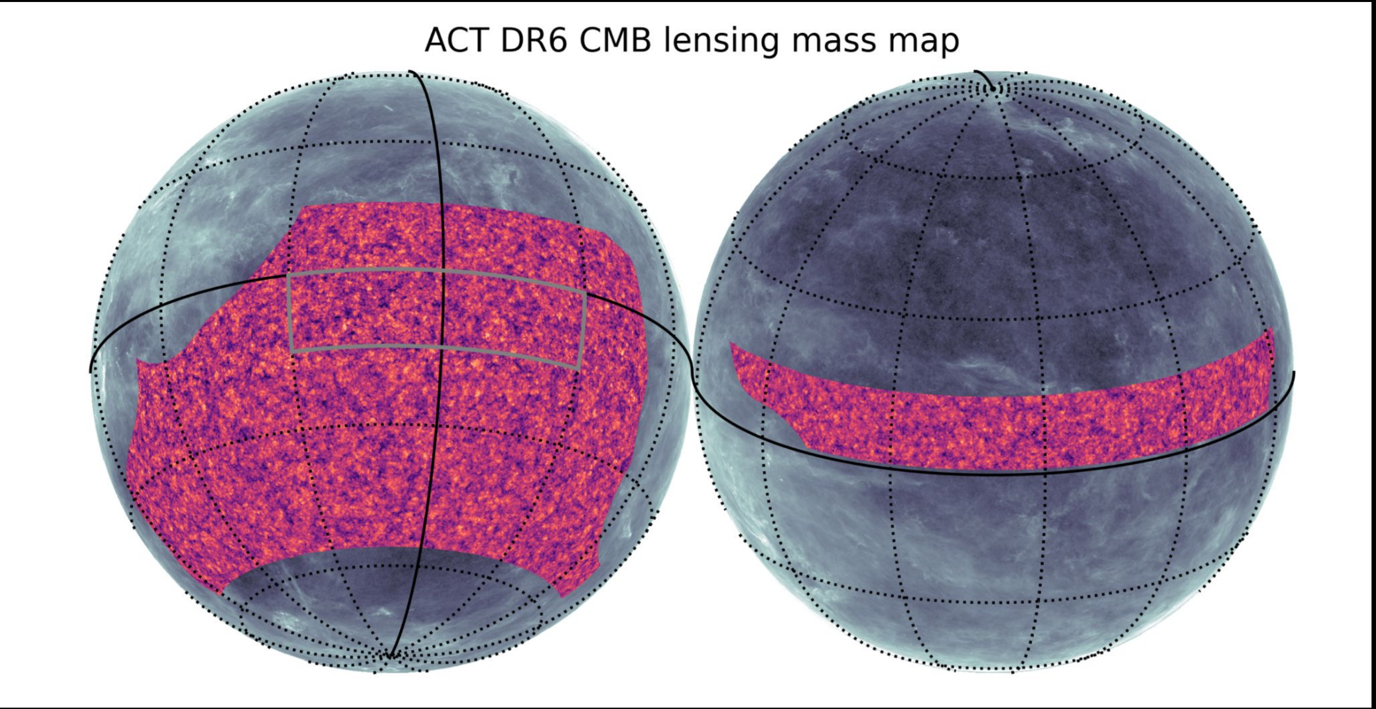


arXiv:2503.14454

Cosmology with ACT: Secondary anisotropies

- Cosmological constraints from DR6 consistent with ΛCDM
  - H_0, σ_8, neutrino mass, spatially flat, GR





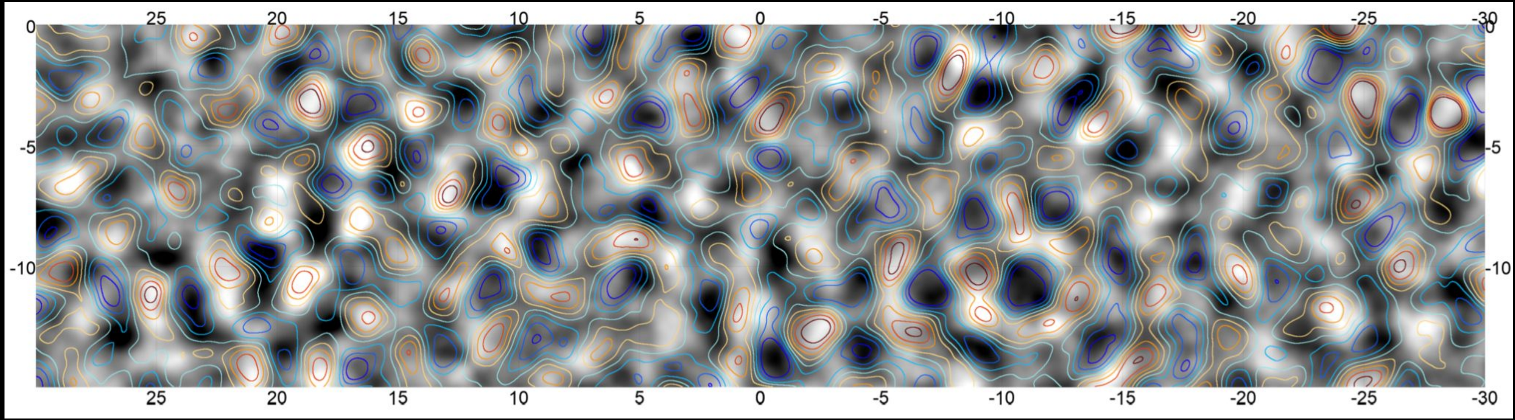
9400 deg^2 (nearly ¼ sky) lensing mass map

Dark-matter dominated mass distribution: Peaks and voids

arXiv:2304.05203

Cosmology with ACT: Gravitational lensing

- 900 deg^2 region of map showing correspondence between Planck CIB and mass map
  - Dusty star-forming galaxies live where the matter is

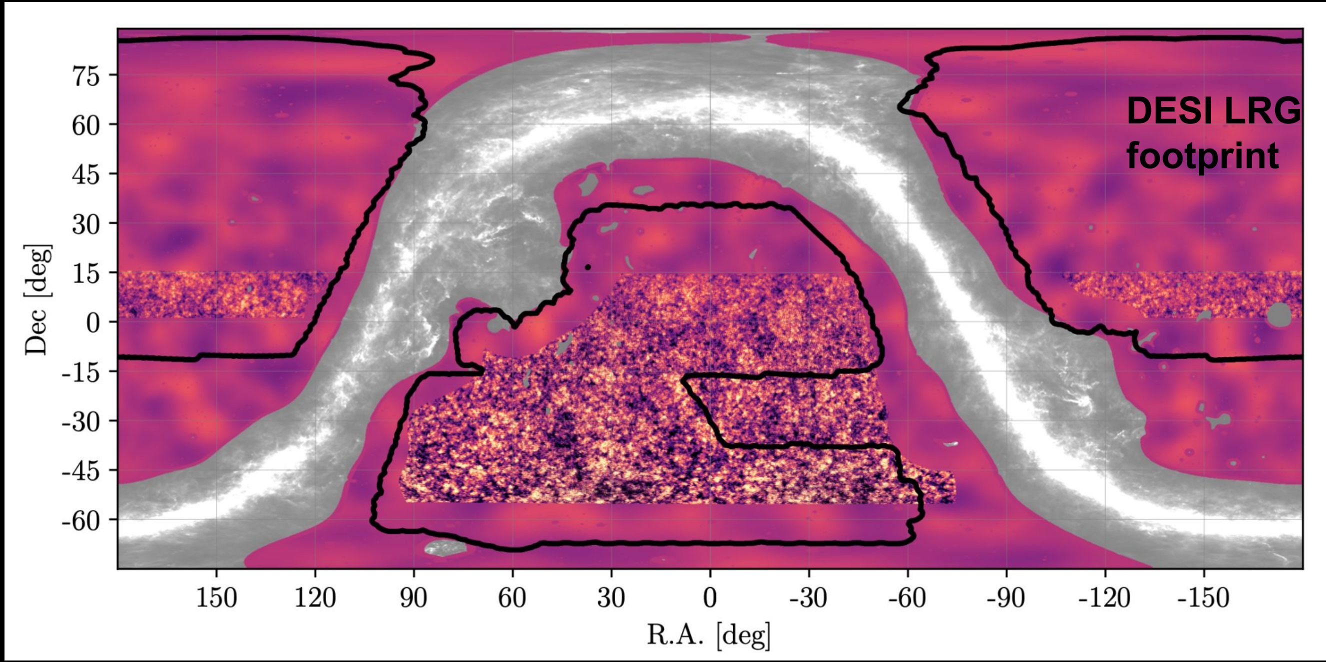


Mass distribution:
Peaks and voids

arXiv:2304.05203

Cosmology with ACT: Gravitational lensing

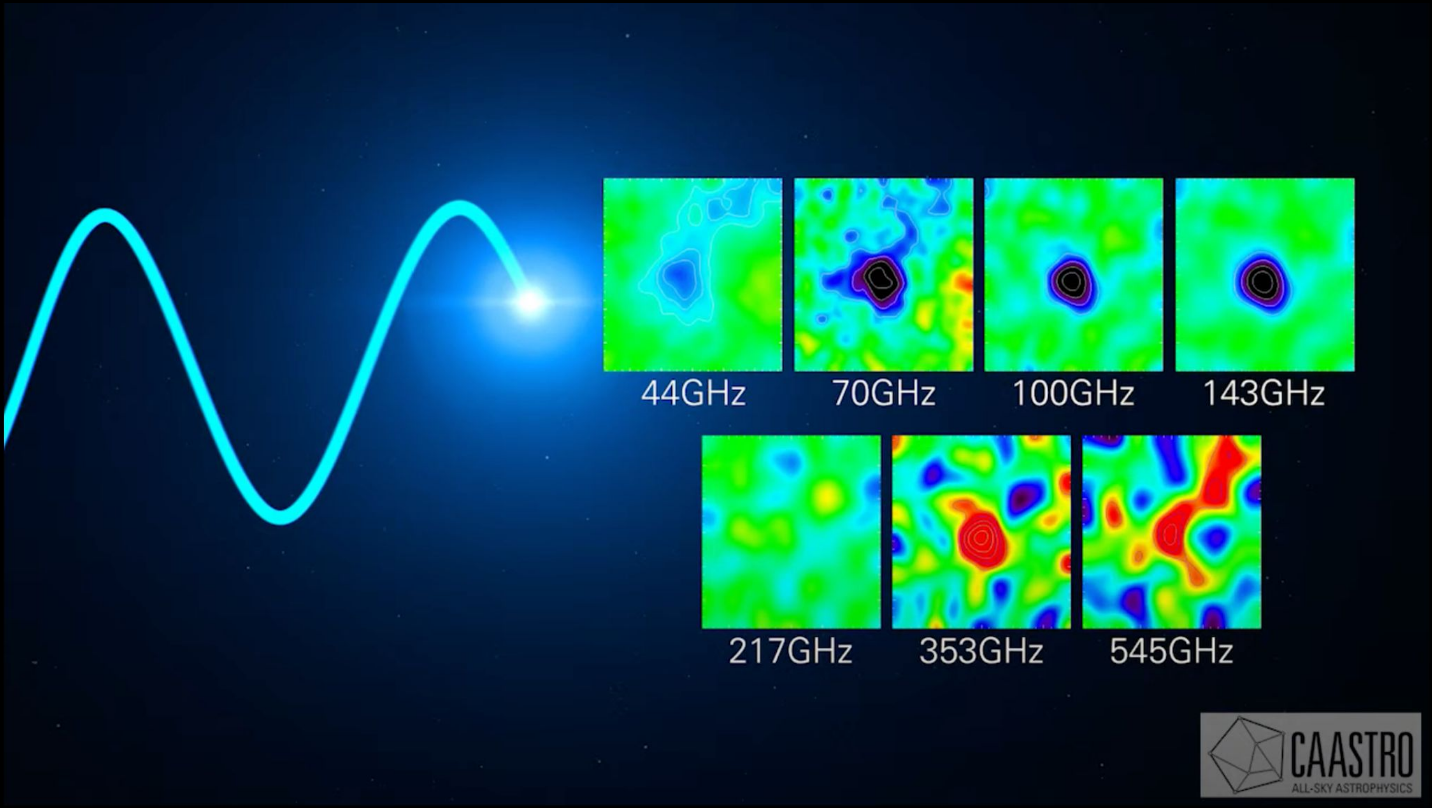
- High S/N (38σ) cross-correlation of lensing map with DESI LRGs
- Probe of structure formation consistent with early-universe results
- See also: tests of gravity with SDSS BOSS CMASS + LOWZ



arXiv:2407.04606

The Sunyaev-Zel'dovich (SZ) effect

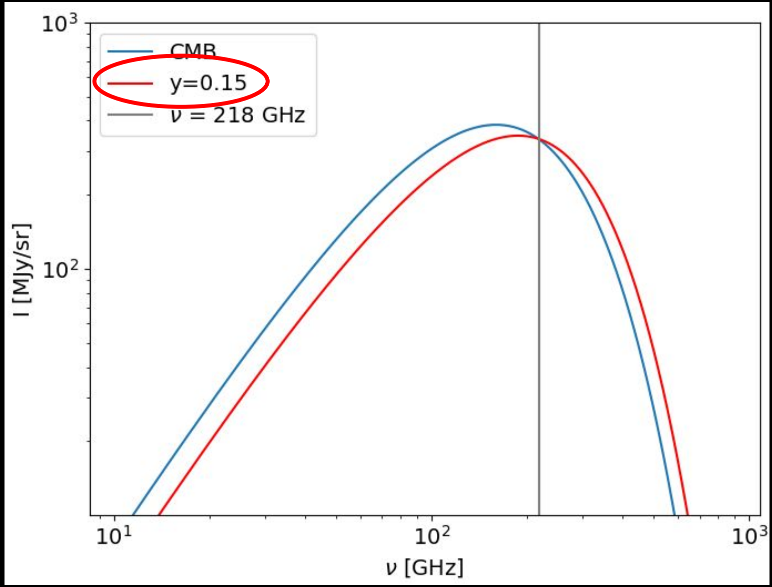
The Sunyaev-Zel'dovich (SZ) effect

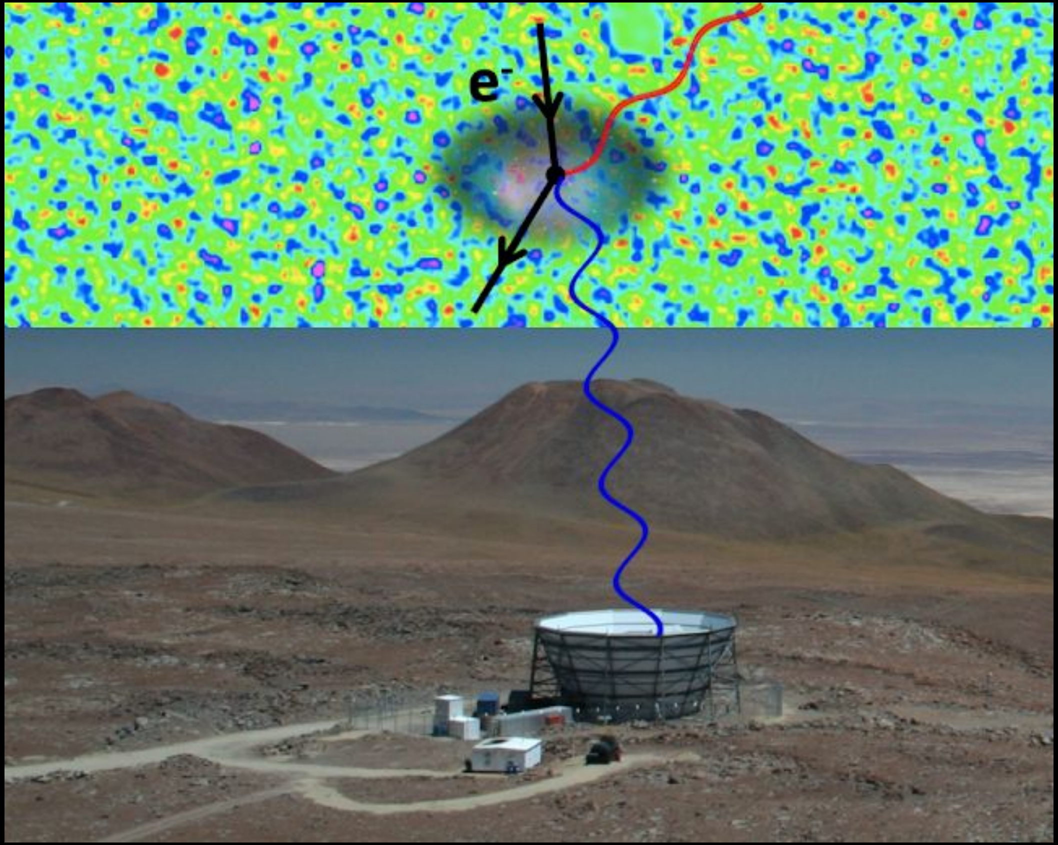


The thermal Sunyaev-Zel'dovich (tSZ) effect

$$y = \frac{\sigma_{\mathrm{T}}}{m_e c^2} \int_{\mathrm{LOS}} n_e k T_e \mathrm{d}l$$

Compton-y:
(Number of scatterings)(energy gain/scattering)

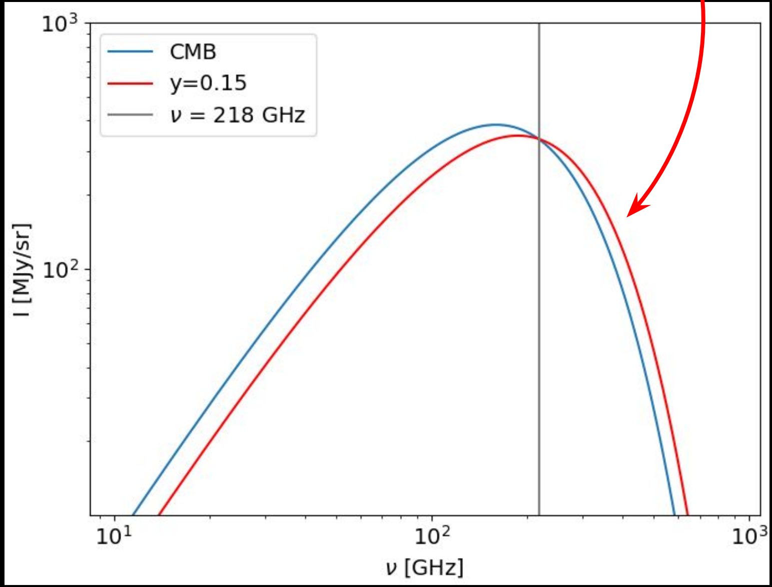


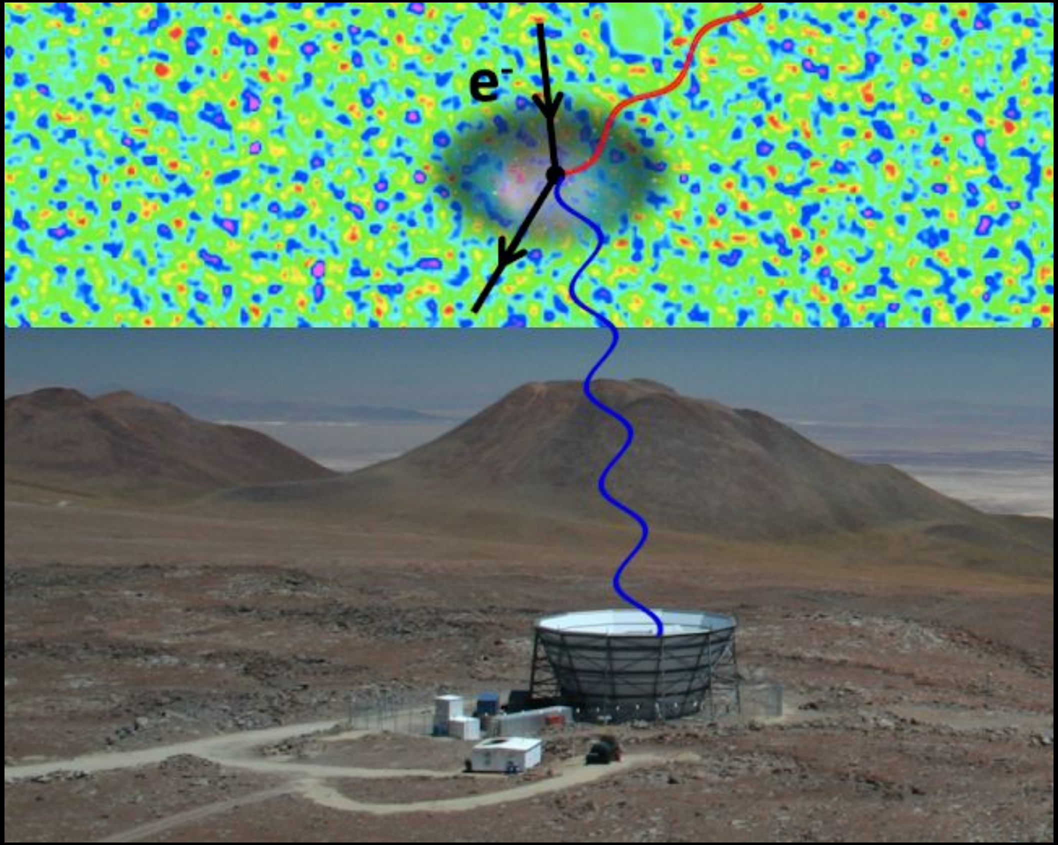


The thermal Sunyaev-Zel'dovich (tSZ) effect

$$y = \frac{\sigma_T}{m_e c^2} \int_{\rm LOS} n_e k T_e {\rm d}l \qquad \frac{\Delta T(\nu)}{T_{\rm CMB}} \propto y$$

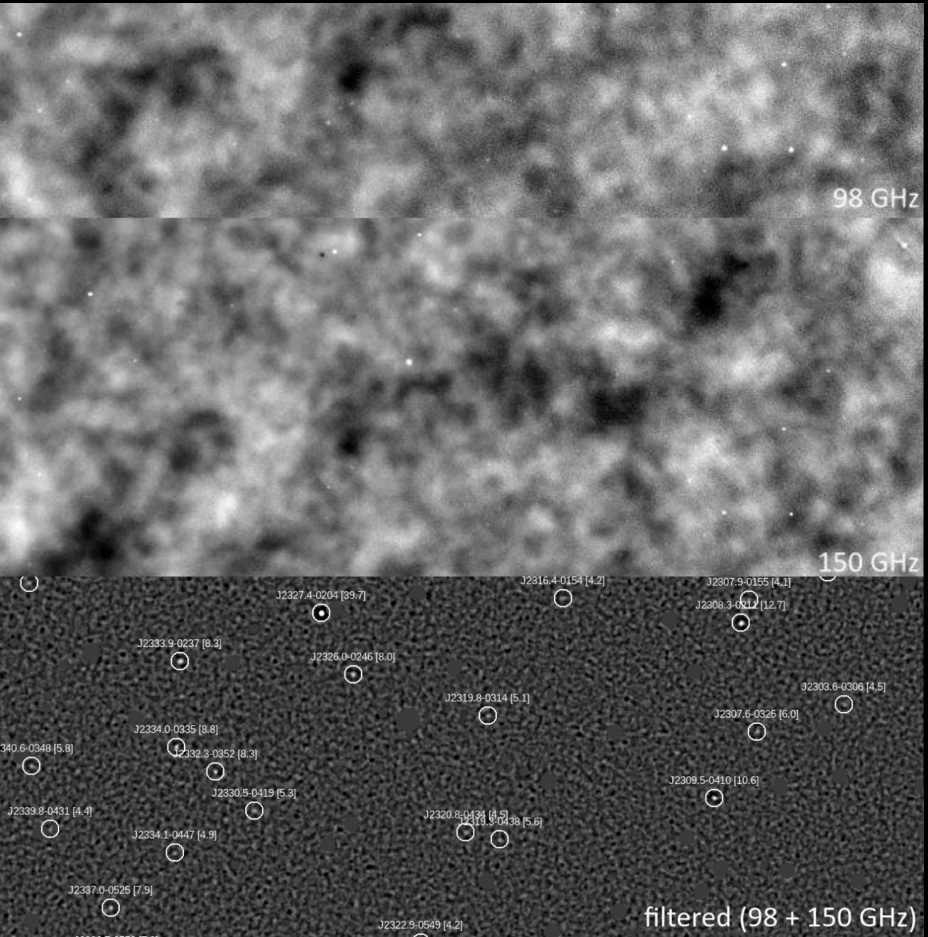
Observed temperature
is proportional to Compton-y

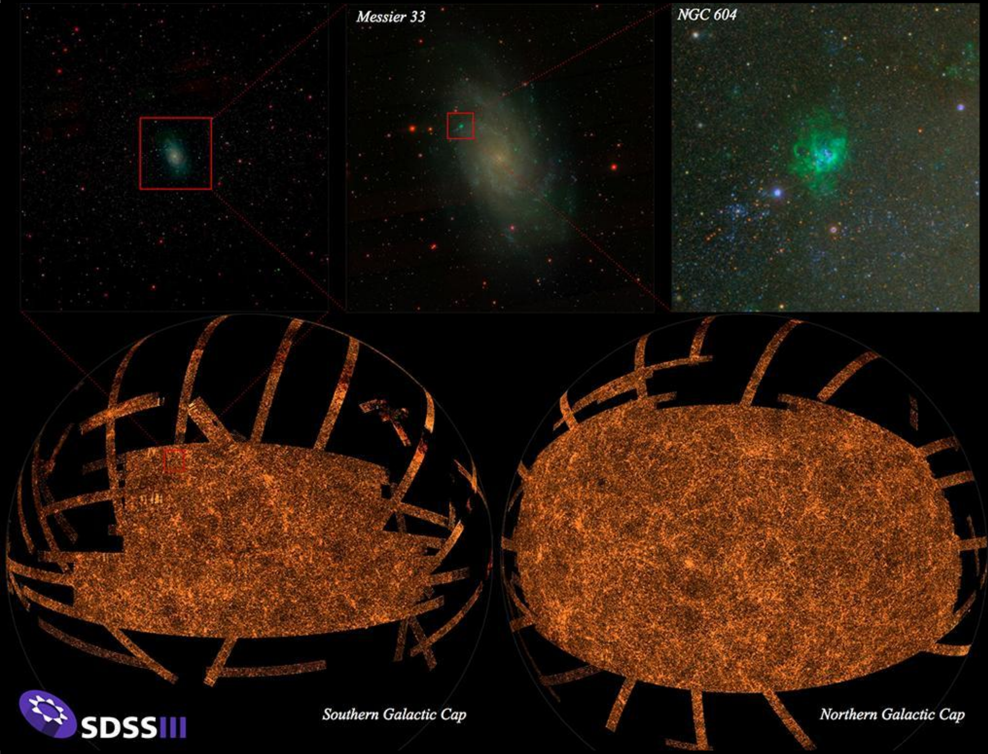




Identify clusters in CMB maps using SZ effect

Use external catalog to locate clusters and measure SZ effect

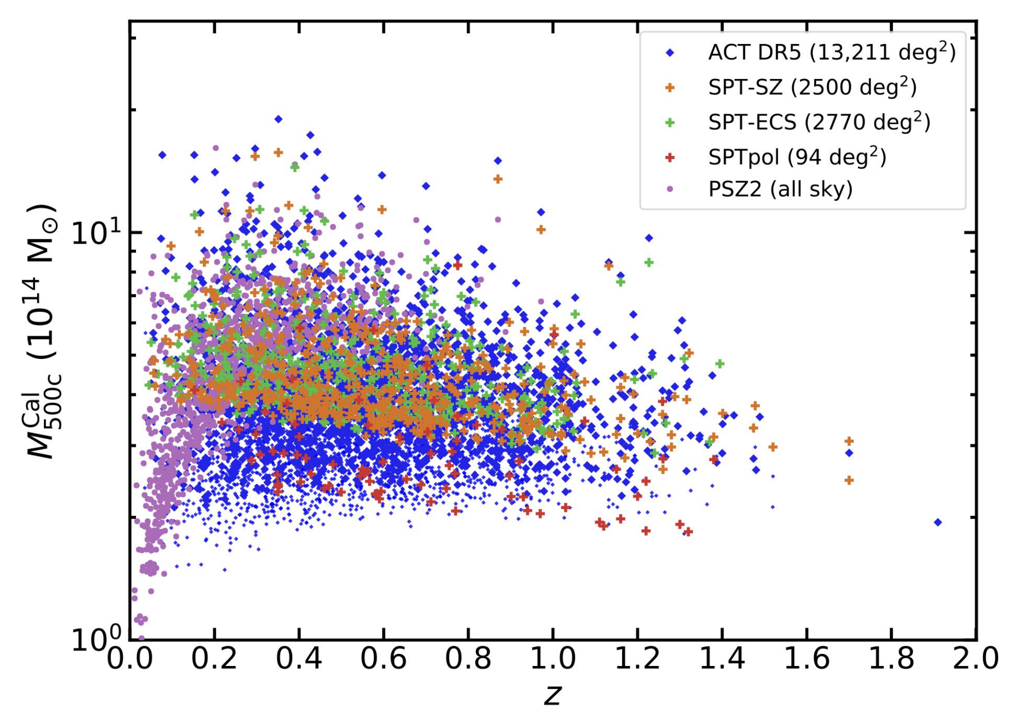




Science with the SZ effects: Cluster catalogs

Identify clusters in CMB maps using SZ effect

- ACT cluster catalog will get an expansion with DR6 soon: stay tuned!



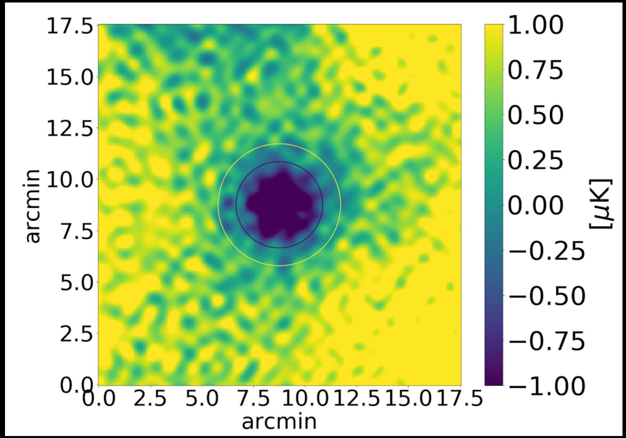
arXiv:2009.11043

Science with the SZ effects: Galaxy formation

Use external catalog to locate clusters and measure SZ effect

- Unique probe of high-z galaxy clusters
- Halo thermodynamics: feedback, non-thermal pressure
- Trace baryon content
- tSZ + kSZ: cosmology and astrophysics

$N = 23,504,\ L > 11.6 \times 10^{10} L_{\odot}$



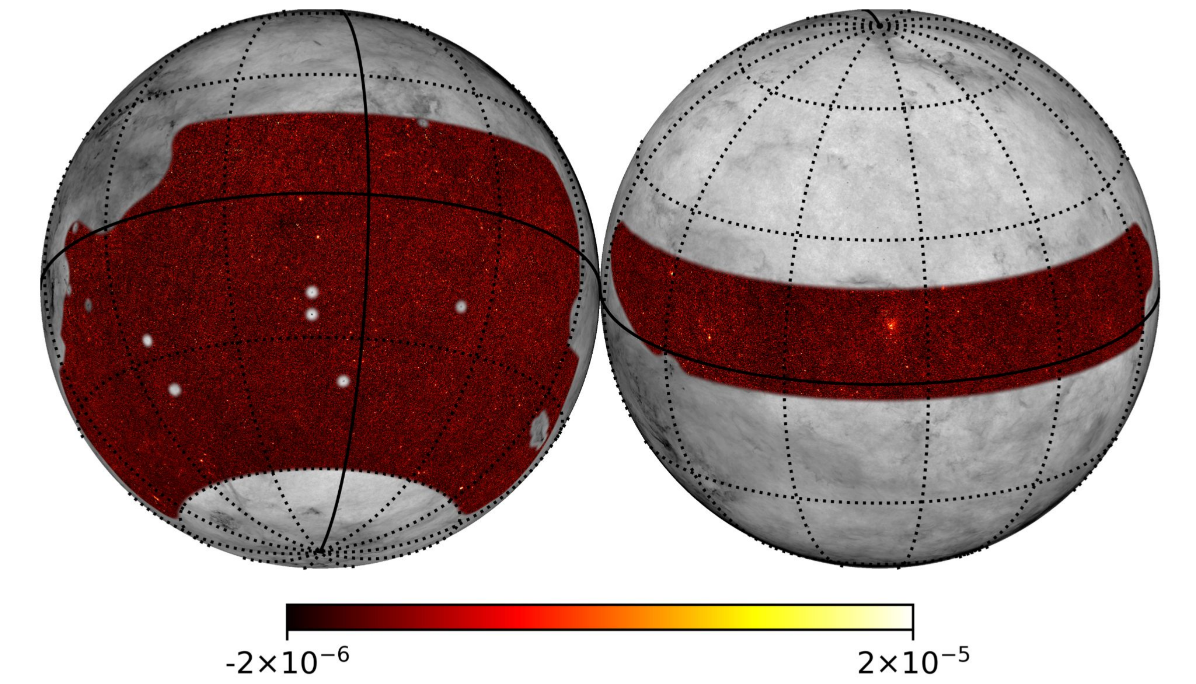
E. M. Vavagiakis, P. Gallardo, V. Calafut, S. Amodeo et al. PRD 2021 (arXiv:2101.08373)

The thermal Sunyaev-Zel'dovich (tSZ) effect

Coulton, Madhavacheril, Duivenvoorden, Hill et al. PRD 2024 (arXiv:2307.01258)

$$y = \frac{\sigma_{\rm T}}{m_e c^2} \int_{\rm LOS} n_e k T_e {\rm d}l \qquad \frac{\Delta {\rm T}(\nu)}{{\rm T}_{\rm CMB}} \propto y$$

- Probe distributions of baryons
- Optical depth



(a) ACT & *Planck* NILC Compton-y map.

Compton-y mapped over ~⅓ sky

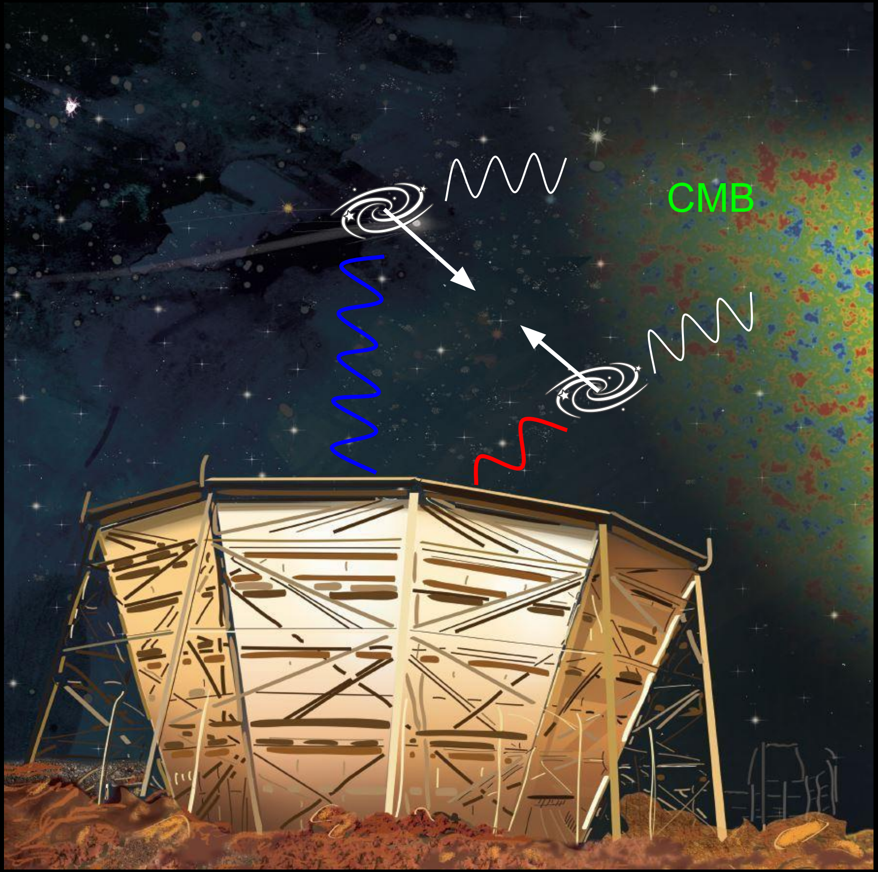
The kinetic Sunyaev-Zel'dovich (kSZ) effect

- Doppler shift of CMB photons due to bulk motion of gas

$$\frac{\Delta \mathrm{T}\left(\hat{\mathbf{r}}\right)}{\mathrm{T}_{\mathrm{CMB}}} = -\underbrace{\int \mathrm{d}l\, \sigma_{\mathrm{T}}\, n_e}\frac{\mathbf{v}\cdot\hat{\mathbf{r}}}{c}$$

$$\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}} = -\tau_{gal}\left(\frac{v_{e,r}}{c}\right)$$

Optical depth of galaxy cluster gas



E. M. Vavagiakis, Illus: I. Lemesis, MIT Kids Press 2022

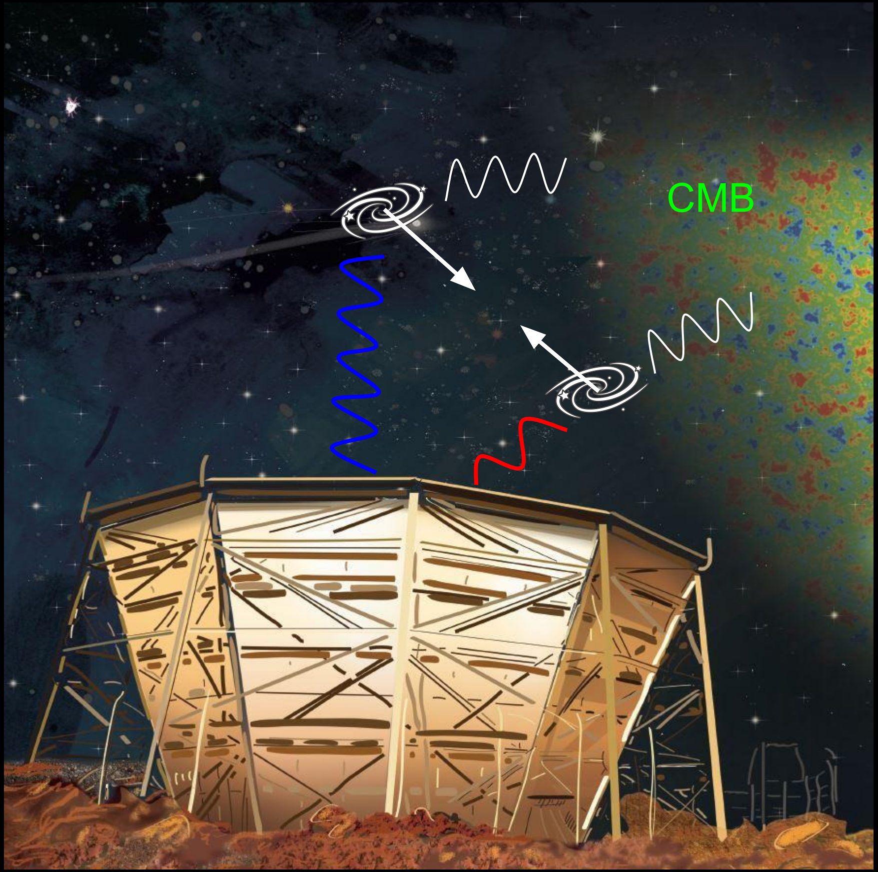
The kinetic Sunyaev-Zel'dovich (kSZ) effect

- Doppler shift of CMB photons due to bulk motion of gas

$$\frac{\Delta \mathrm{T}(\hat{\mathbf{r}})}{\mathrm{T}_{\mathrm{CMB}}} = -\int \mathrm{d}l\, \sigma_{\mathrm{T}}\, n_e \underbrace{\frac{\mathbf{v}\cdot\hat{\mathbf{r}}}{c}}$$

$$\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}} = -\tau_{gal}\left(\frac{v_{e,r}}{c}\right)$$

Velocity of gas along line of sight



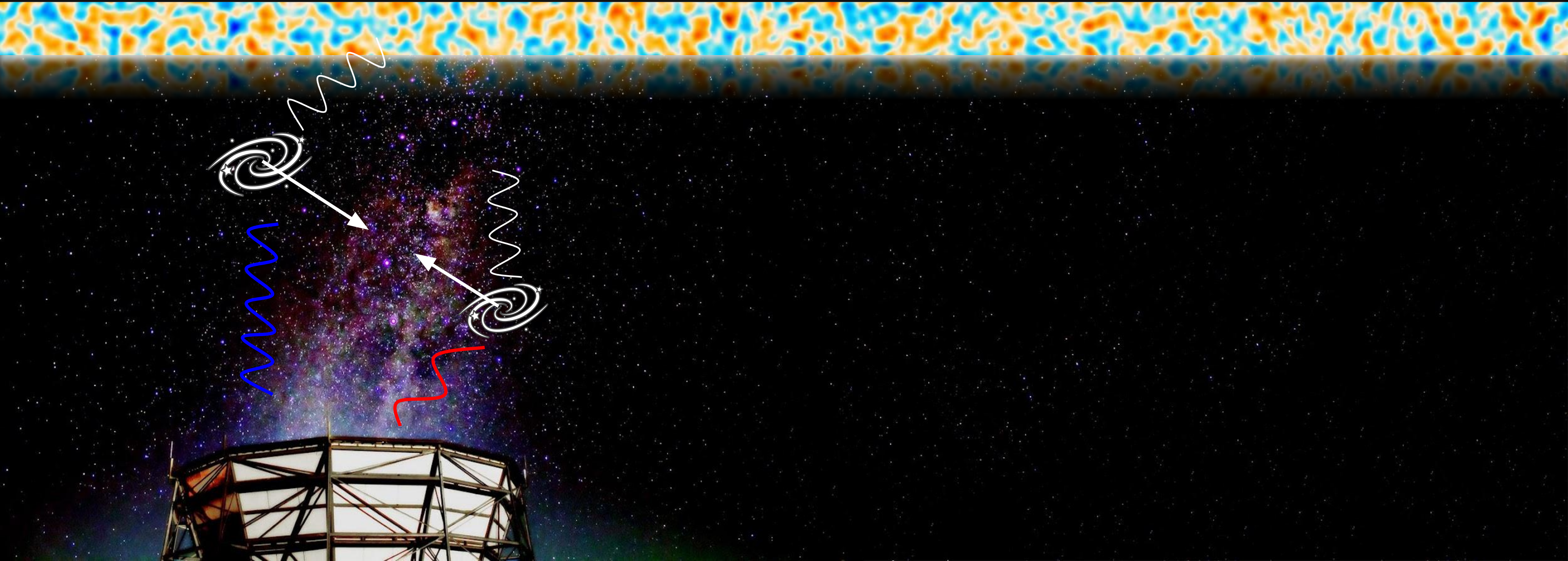
E. M. Vavagiakis, Illus: I. Lemesis, MIT Kids Press 2022

The pairwise kSZ effect

$$\frac{\Delta \mathrm{T}}{\mathrm{T_{CMB}}} = -\tau_{gal}\left(\frac{v_{e,r}}{c}\right) \longrightarrow \Delta \mathrm{T} \propto -\mathbf{p_i} \cdot \mathbf{r_i}$$

Measured kSZ signal

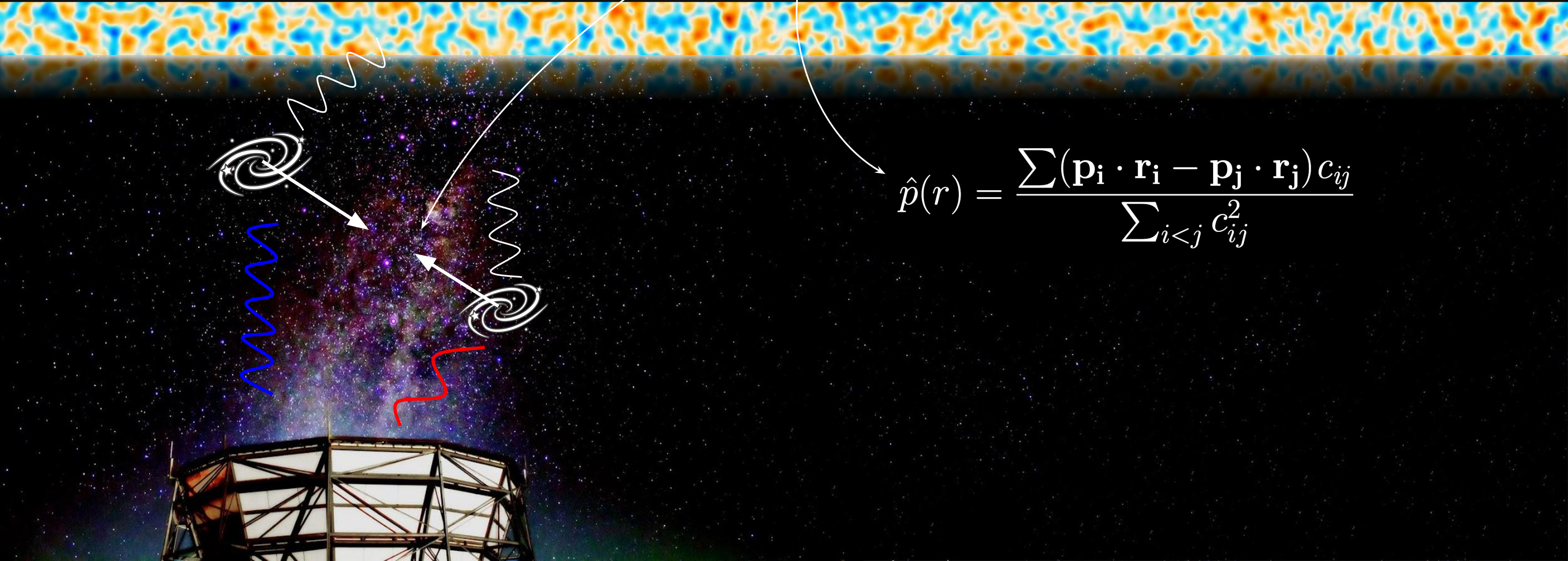
Line-of-sight gas momentum



The pairwise kSZ effect

$$\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}} = -\tau_{gal}\left(\frac{v_{e,r}}{c}\right) \longrightarrow \Delta \mathrm{T} \propto -\mathbf{p_i} \cdot \mathbf{r_i}$$

Mean pairwise momentum

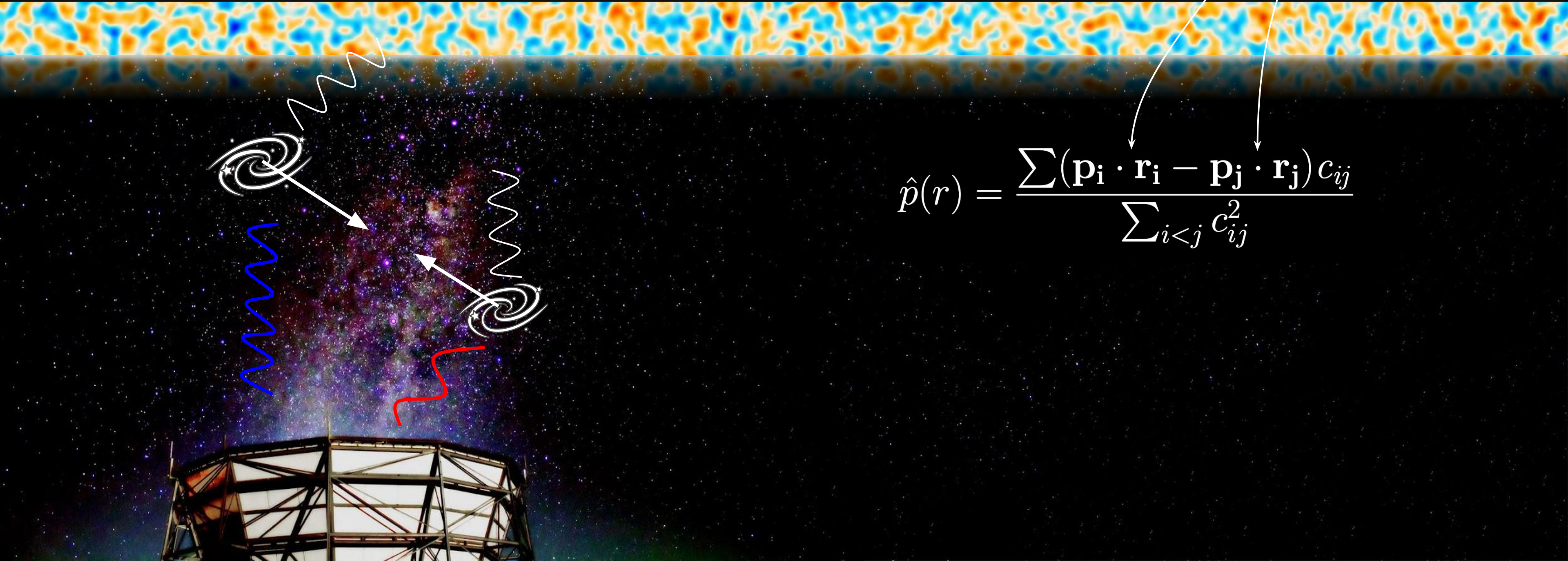


$$\hat{p}(r) = \frac{\sum(\mathbf{p_i} \cdot \mathbf{r_i} - \mathbf{p_j} \cdot \mathbf{r_j})c_{ij}}{\sum_{i<j} c_{ij}^2}$$

The pairwise kSZ effect

$$\frac{\Delta \mathrm{T}}{\mathrm{T_{CMB}}} = -\tau_{gal}\left(\frac{v_{e,r}}{c}\right) \longrightarrow \Delta \mathrm{T} \propto -\mathbf{p_i} \cdot \mathbf{r_i}$$

Mean pairwise momentum can be estimated from the line-of-sight momenta

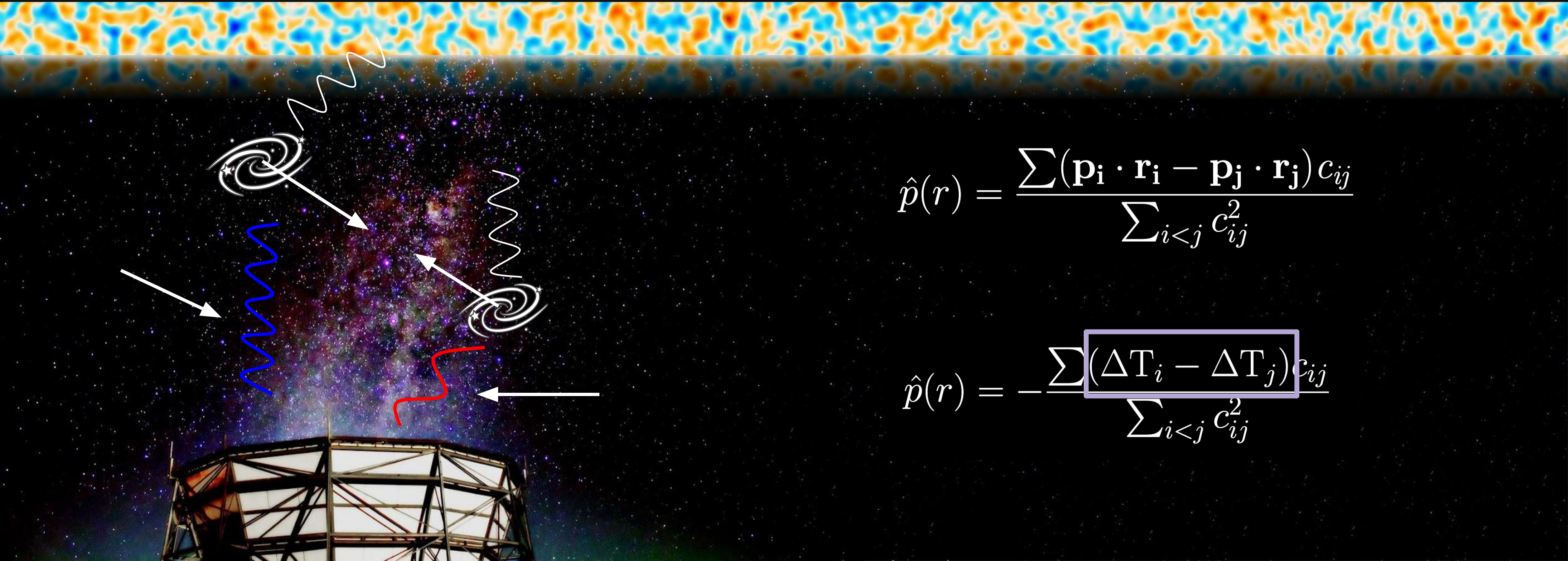


$$\hat{p}(r) = \frac{\sum(\mathbf{p_i} \cdot \mathbf{r_i} - \mathbf{p_j} \cdot \mathbf{r_j})\, c_{ij}}{\sum_{i<j} c_{ij}^2}$$

The pairwise kSZ effect

$$\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}} = -\tau_{gal}\left(\frac{v_{e,r}}{c}\right) \longrightarrow \Delta \mathrm{T} \propto -\mathbf{p_i} \cdot \mathbf{r_i}$$

Mean pairwise momentum can be estimated from the line-of-sight momenta through kSZ measurements

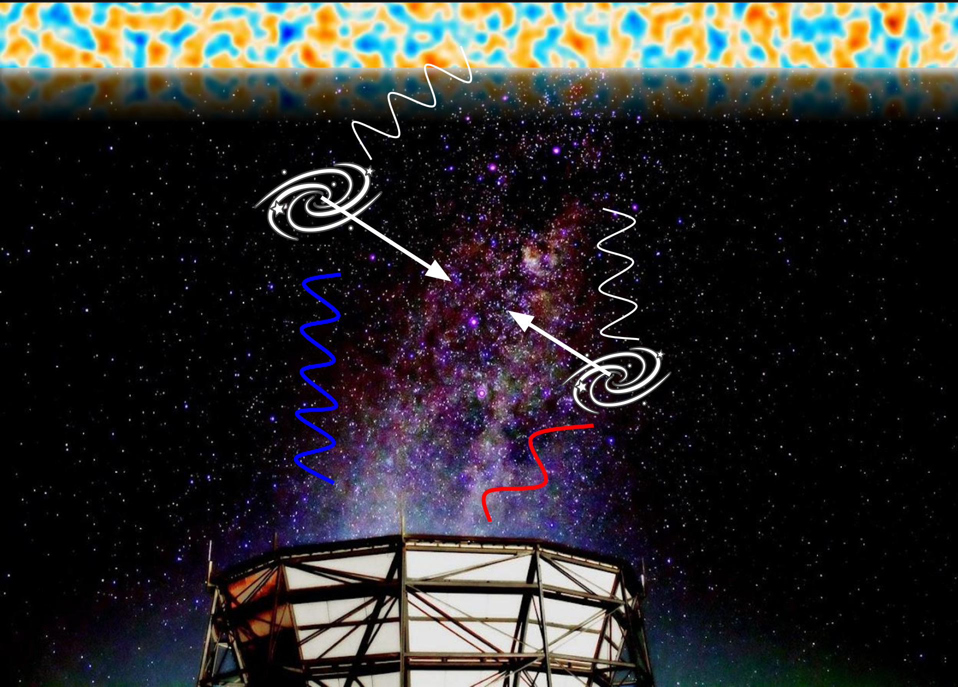


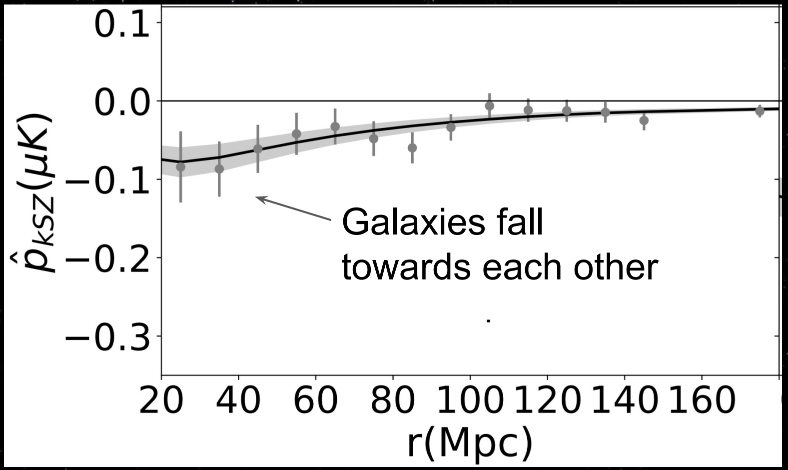
$$\hat{p}(r) = \frac{\sum(\mathbf{p_i} \cdot \mathbf{r_i} - \mathbf{p_j} \cdot \mathbf{r_j}) c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$\hat{p}(r) = -\frac{\sum(\Delta \mathrm{T}_i - \Delta \mathrm{T}_j) c_{ij}}{\sum_{i<j} c_{ij}^2}$$

The pairwise kSZ effect

$$\hat{p}(r) = -\frac{\sum(\Delta \mathrm{T}_i - \Delta \mathrm{T}_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$

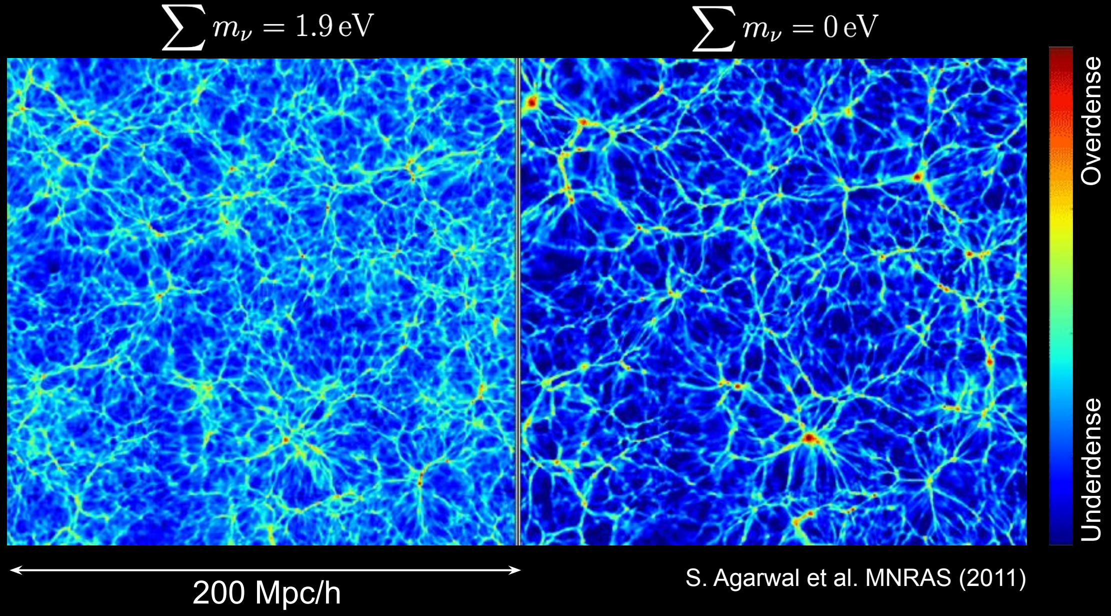




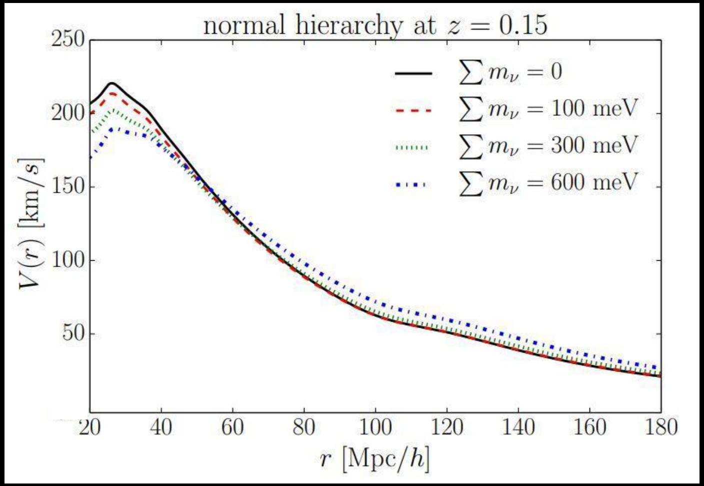
V. Calafut, P. Gallardo, E. M. Vavagiakis, et al.
PRD 2021 (arXiv:2101.08374)

Science with the SZ effects: Neutrino mass

- Massive neutrinos affected growth of structure
- Constrain neutrino mass sum
  - Input to cosmological models
  - Lab experiment interpretation



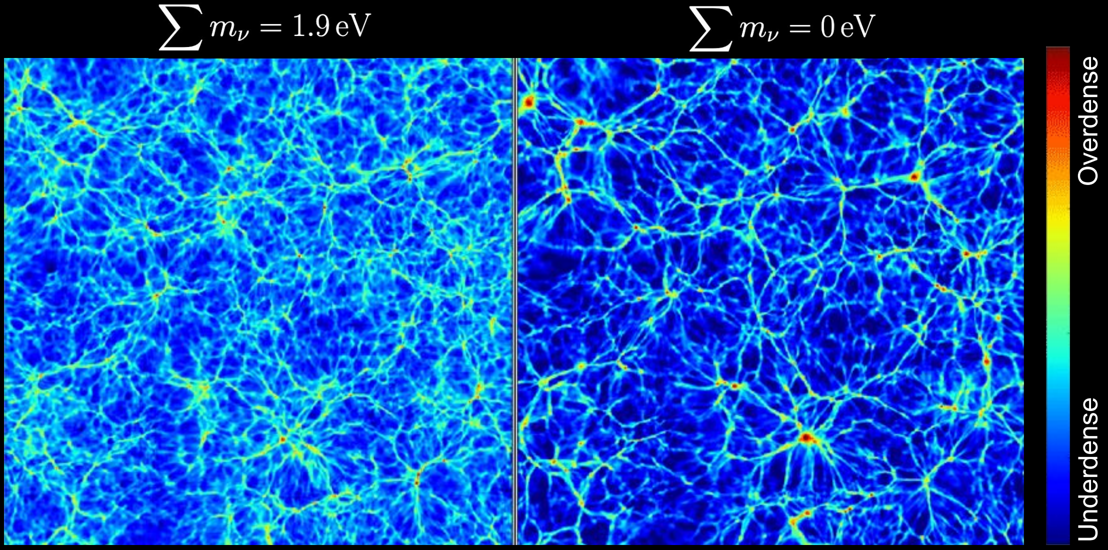
S. Agarwal et al. MNRAS (2011)



E. M. Mueller, F. de Bernardis, R. Bean, M. D. Niemack
PRD 2015 (arXiv:1412.0592)

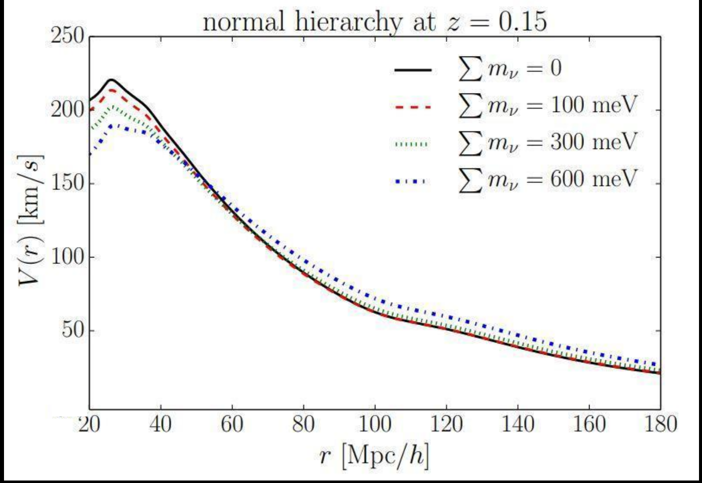
Science with the SZ effects: Neutrino mass

- Massive neutrinos affected growth of structure
- Nature of neutrino mass
  - Investigate matter-antimatter asymmetry



200 Mpc/h

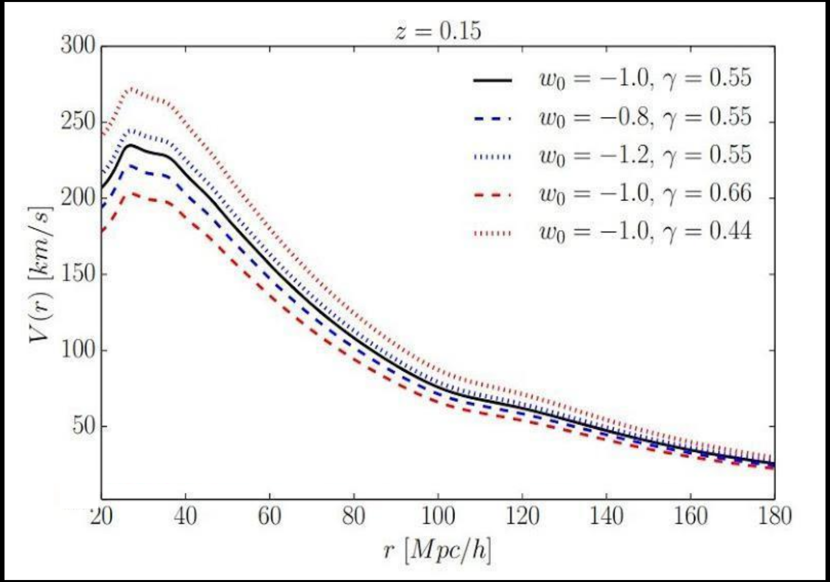
S. Agarwal et al. MNRAS (2011)



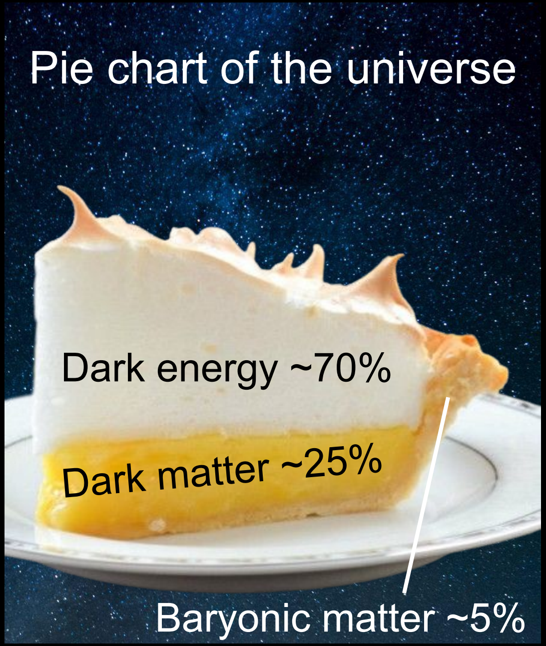
E. M. Mueller, F. de Bernardis, R. Bean, M. D. Niemack
PRD 2015 (arXiv:1412.0592)

Science with the SZ effects: Dark energy

- kSZ effect: probe of large scale structure sensitive to dark energy, gravity



E. M. Mueller, F. de Bernardis, R. Bean, M. D. Niemack
ApJ 2015, (arXiv:1408.6248)

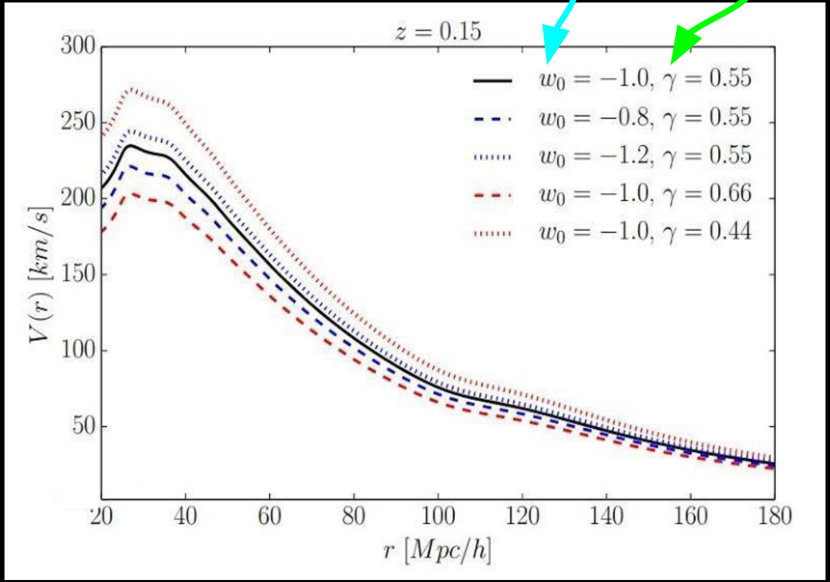


Science with the SZ effects: Dark energy

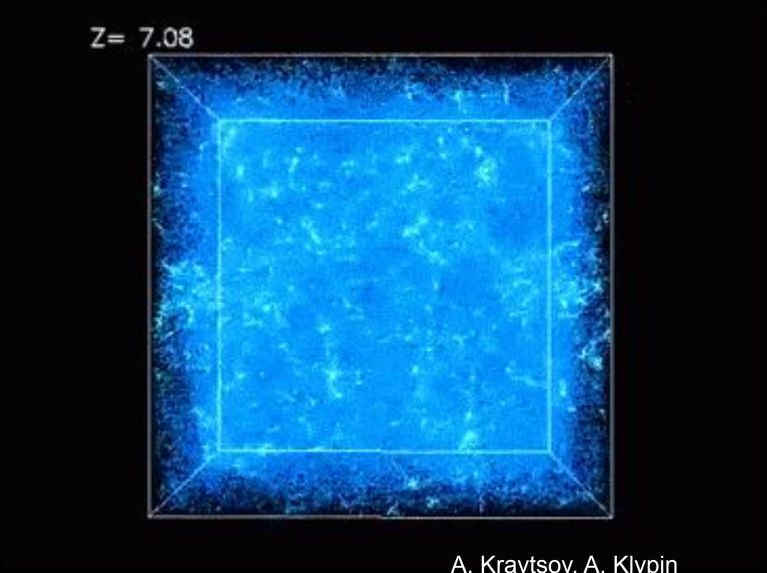
- kSZ effect: probe of large scale structure sensitive to dark energy, gravity

ΛCDM
Dark energy equation of state parameter

Growth index
General relativity



E. M. Mueller, F. de Bernardis, R. Bean, M. D. Niemack
ApJ 2015, (arXiv:1408.6248)

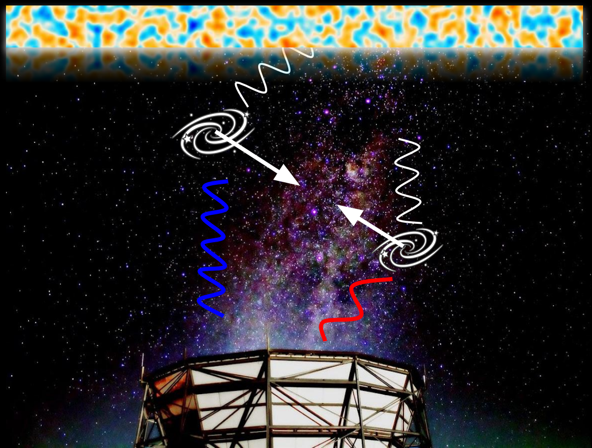


A. Kravtsov, A. Klypin
National Center for Supercomputer Applications

SZ measurements with ACT DR4-5 and SDSS DR15

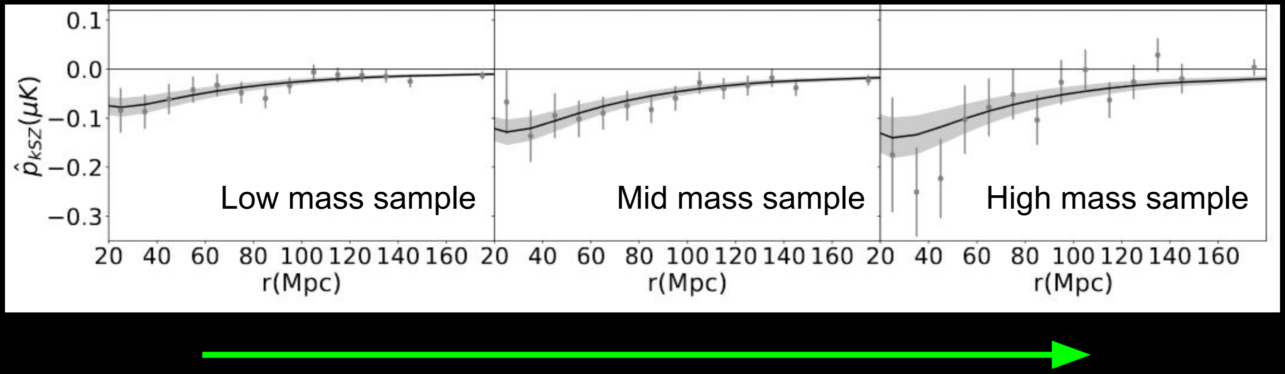
- **Highest significance detection of pairwise kSZ effect yet**: 5.4σ
- Optical depth fits trace baryon content

$$\hat{p}_{\rm th}(r,z) = -\frac{T_{\rm CMB}}{c}\bar{\tau}V(r,z)$$



High luminosity → more massive galaxies → higher signal

High luminosity → lower galaxy count → larger uncertainty



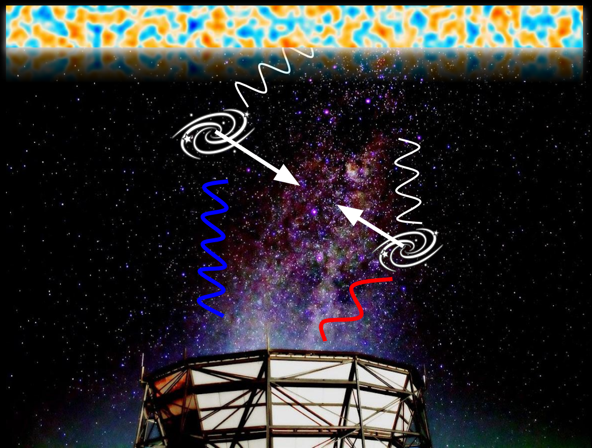
Average galaxy luminosity

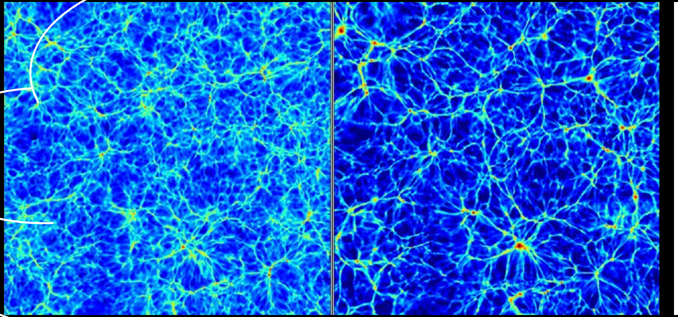
V. Calafut, P. Gallardo, E. M. Vavagiakis, et al., PRD 2021 (arXiv:2101.08374)

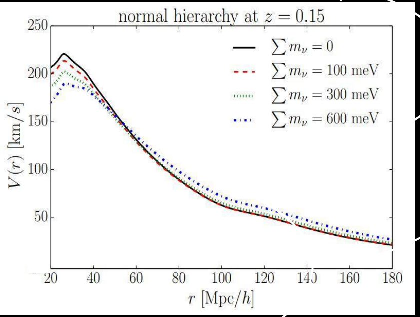
SZ measurements with ACT DR4-5 and SDSS DR15

- **Highest significance detection of pairwise kSZ effect yet**: 5.4σ
- Optical depth fits trace baryon content

$$\hat{p}_{\rm th}(r,z) = -\frac{T_{\rm CMB}}{c}\bar{\tau}V(r,z)$$





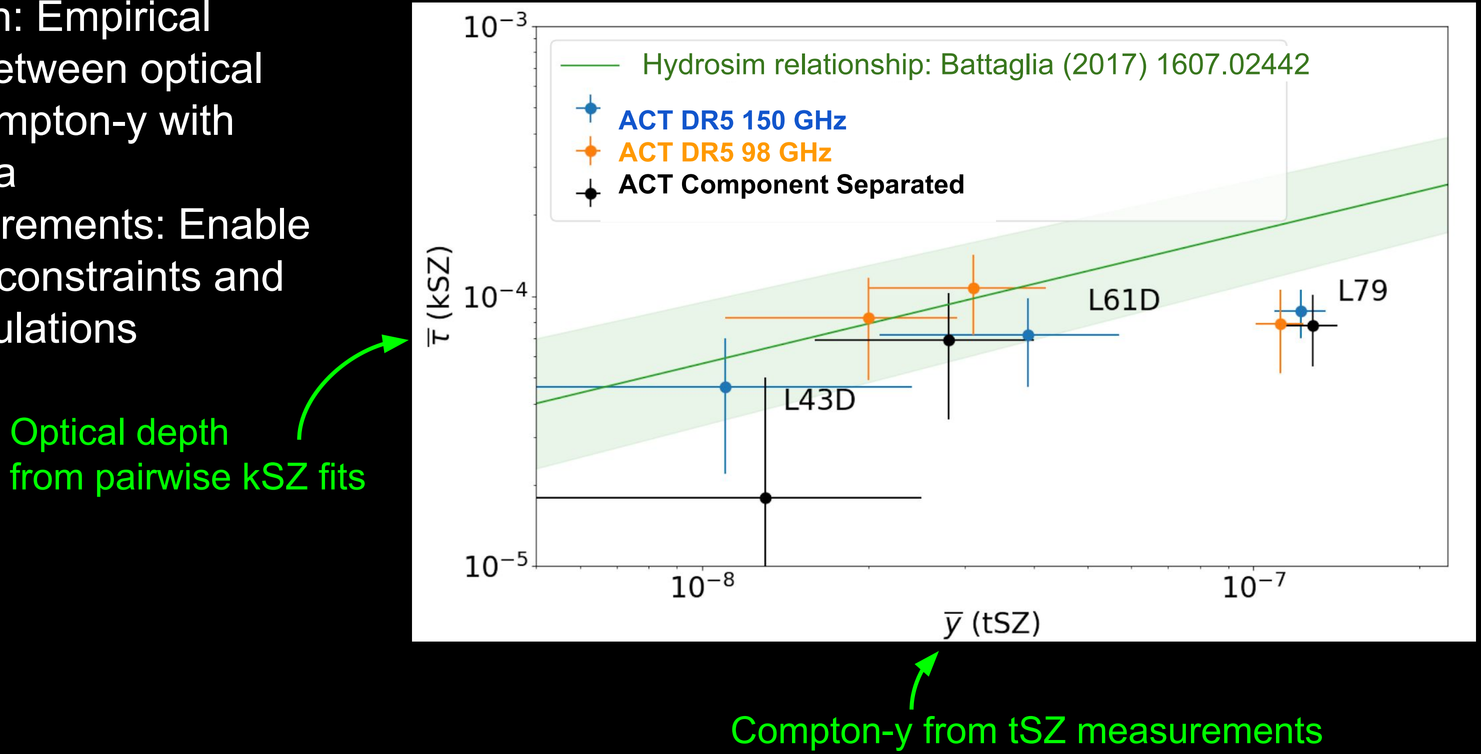


Need measurement of optical depth for cosmology with pairwise velocities

Can we use the tSZ effect?

Towards a new empirical relationship with the SZ effects

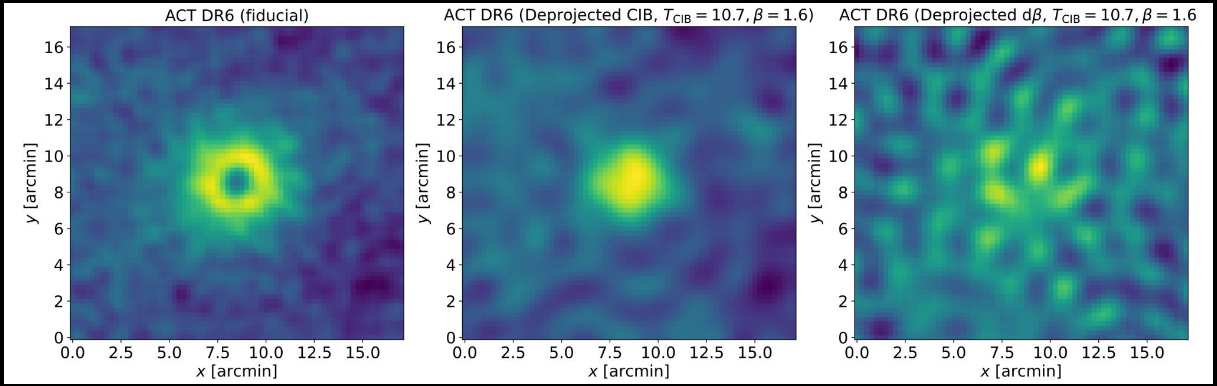
- New approach: Empirical relationship between optical depth and Compton-y with upcoming data
- Future measurements: Enable cosmological constraints and improved simulations

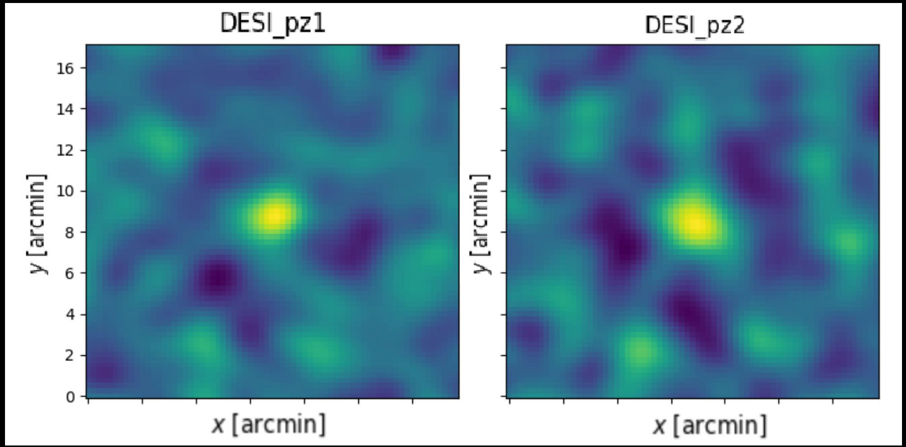


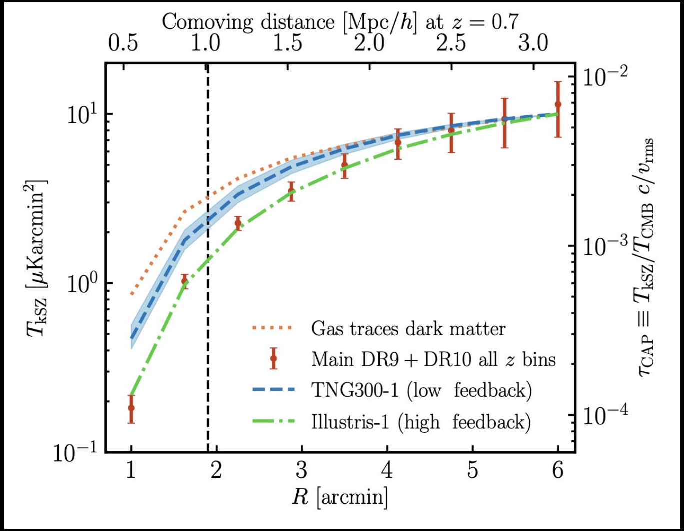
E. M. Vavagiakis, P. Gallardo, V. Calafut, S. Amodeo et al. PRD 2021 (arXiv:2101.08373)

ACTxDESI: Two recent examples

- Liu et al. 2025: arXiv:2502.08850: 19σ tSZ measurement, exploring dust emission
- Hadzhiyska et al. 2024: arXiv:2407.07152: 13σ stacked kSZ measurement, 40σ gas extended



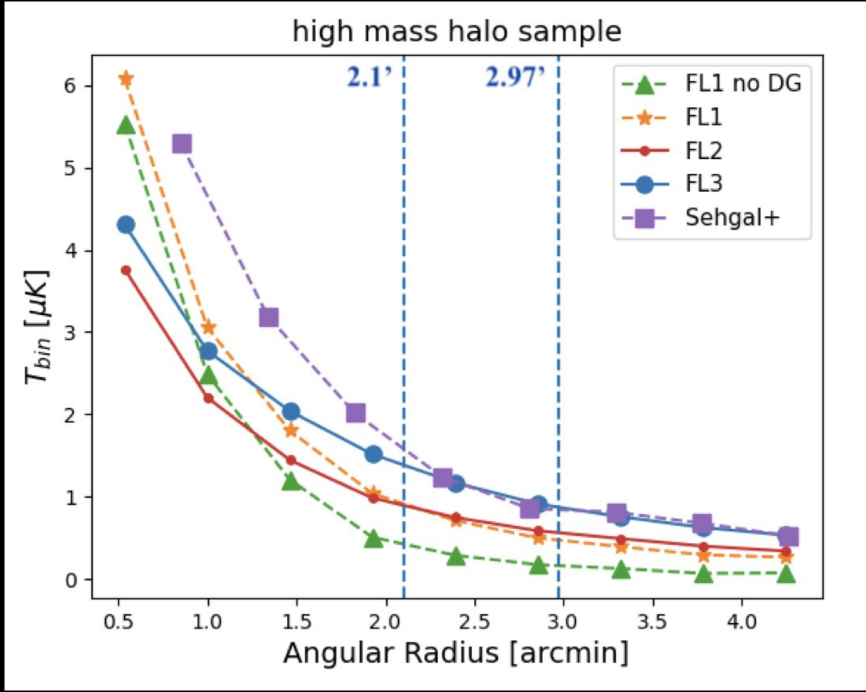




ACTxDESI: Forthcoming work

- Pairwise kSZ: ACT DR6 x DESI spectroscopic LRG, BGS, optical
- Stacked tSZ: Tau v. tau with the above. New simulation relationships

- Gong et al. 2024: removing bias from pairwise kSZ and stacked tSZ measurements: arXiv:2307.11894



Current and upcoming SZ work with…

Upcoming surveys!

Today

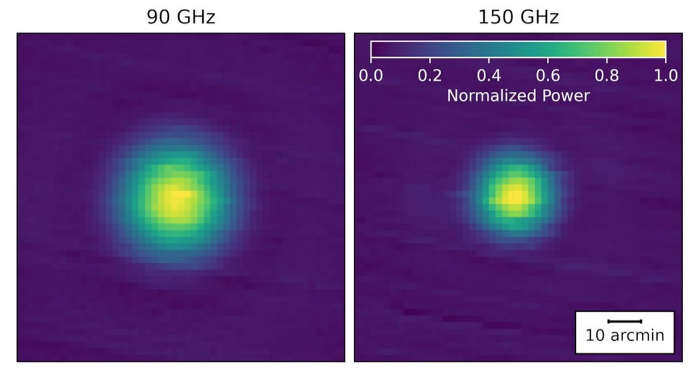
- The Sunyaev-Zel'dovich effects with ACT and future surveys
- Upcoming observations
  - The Simons Observatory
  - CCAT

The Simons Observatory

- Array of new telescopes
- Cerro Toco, Chile, 5190m
- First light achieved!!

The Simons Observatory

- 3x 0.5 meter Small Aperture Telescopes + SO UK/Japan
- ~30,000 detectors 27-280 GHz
- Constrain models of early universe inflation



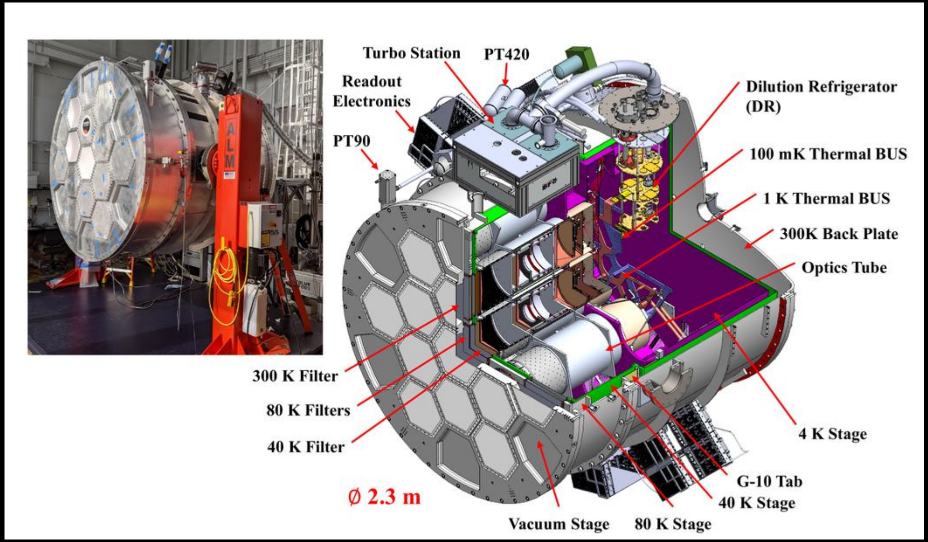
The Simons Observatory

- 6 m Large Aperture Telescope for arcmin resolution images
- ~30,000 detectors 27-280 GHz
- Largest cryogenic mm camera built to date

LATR team in Chile Jan 2023

The Simons Observatory

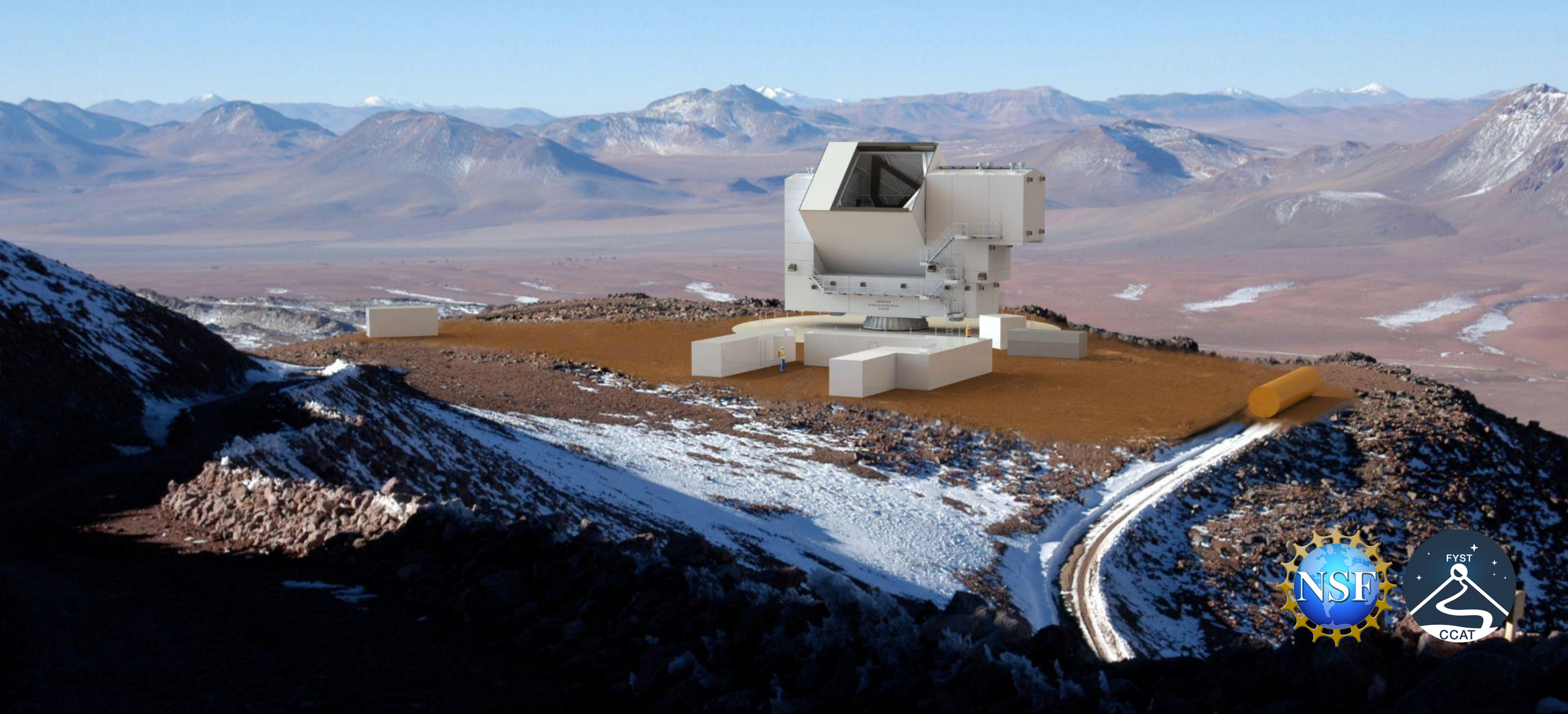
- Large aperture telescope surveys:
  - Thousands of SZ clusters
  - tSZ measurements to 300σ
  - kSZ measurements to 190σ
- Overlap with ~9,000 sq. deg. of DESI's survey
  - ~6x greater LRG density
  - ~10x increase in LRG tracers for pairwise kSZ
- First light just this month!



The Simons Observatory

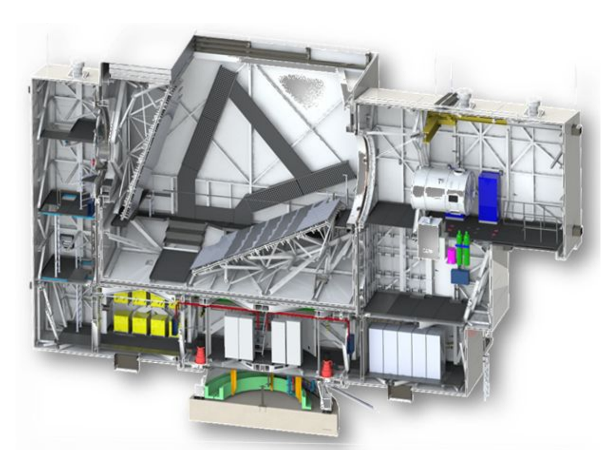
The Simons Observatory

CCAT: An exceptional site for the highest throughput sub-mm telescope ever built



The Fred Young Submillimeter Telescope & Site

- CCAT Collaboration: International consortium of universities led by Cornell
- Six-meter crossed-Dragone design
- Highest throughput sub-mm telescope ever built
- High surface accuracy (<10.7 μm HWFE)
- Large field of view (8 deg at 3 mm)
- Simons Observatory uses design for LAT
- Potential platform for CMB-S4

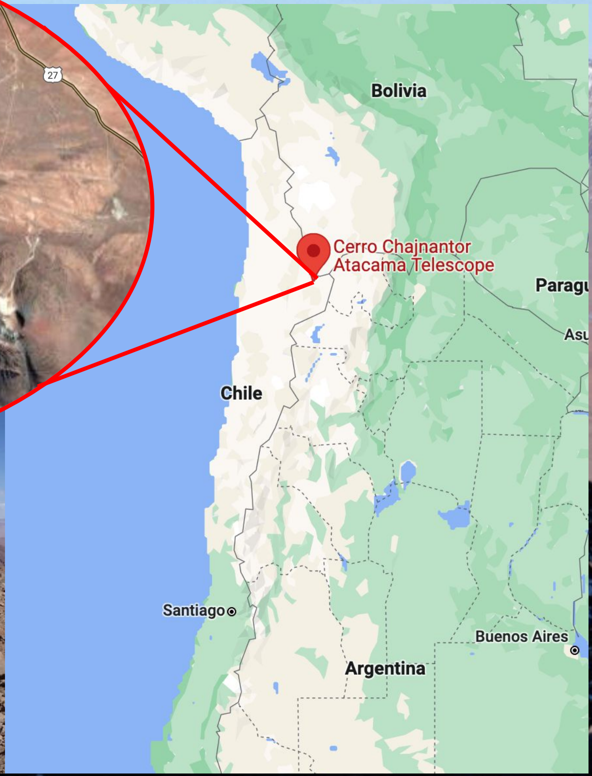


S. C. Parshey et al., Proc. SPIE 2018 (arXiv:1807.06678)

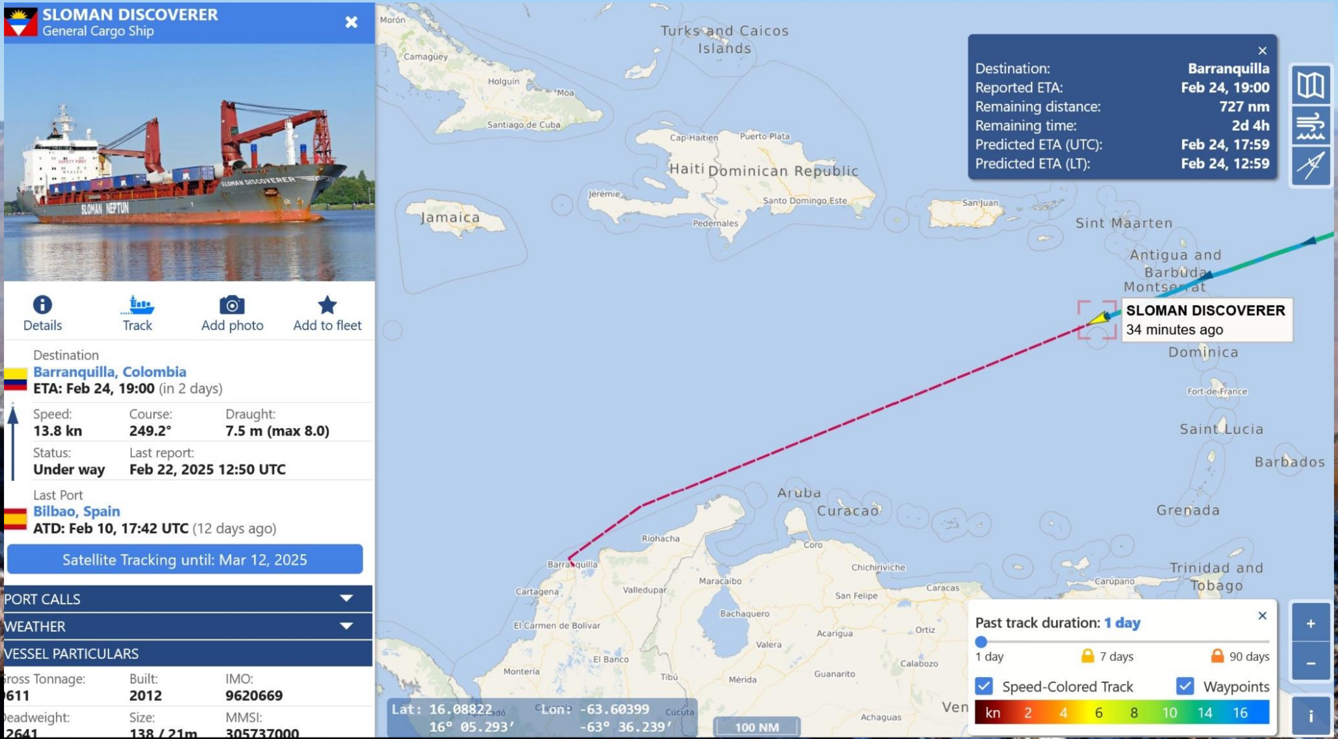
G. J. Stacey et al., Proc. SPIE 2018 (arXiv:1807.04354)

The Fred Young Submillimeter Telescope & Site

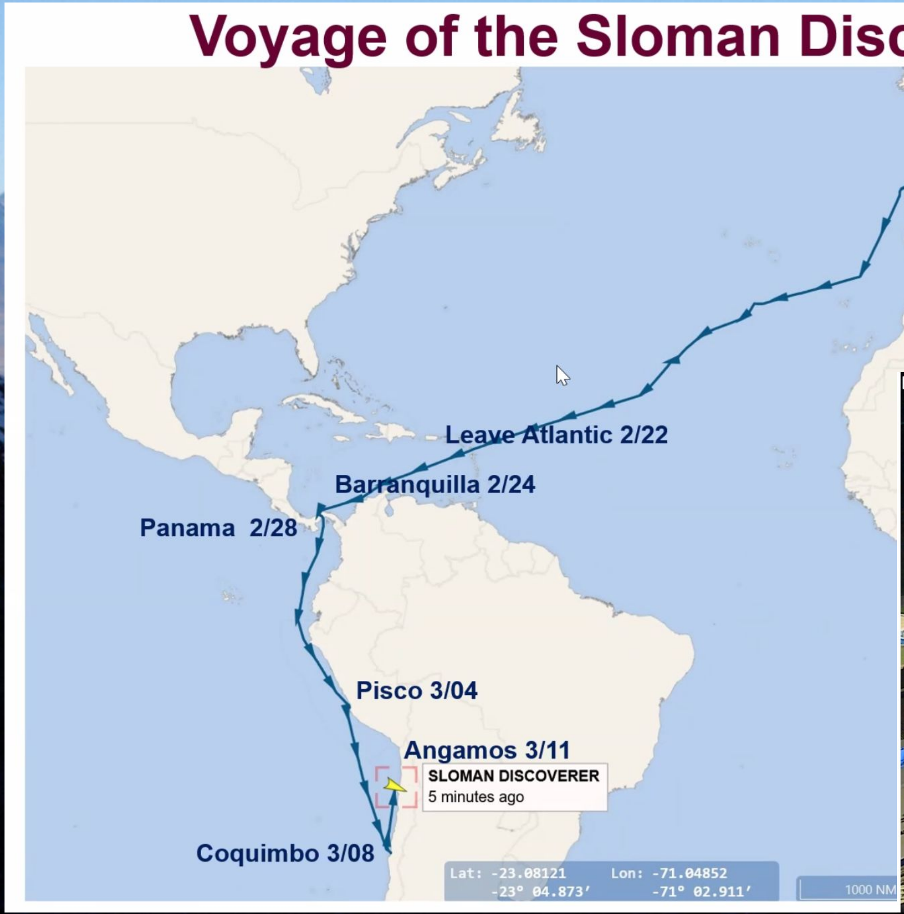
- Exceptional 5,610 m site for mm and sub-mm measurements
- Low precipitable water vapor
- Minimal atmospheric noise

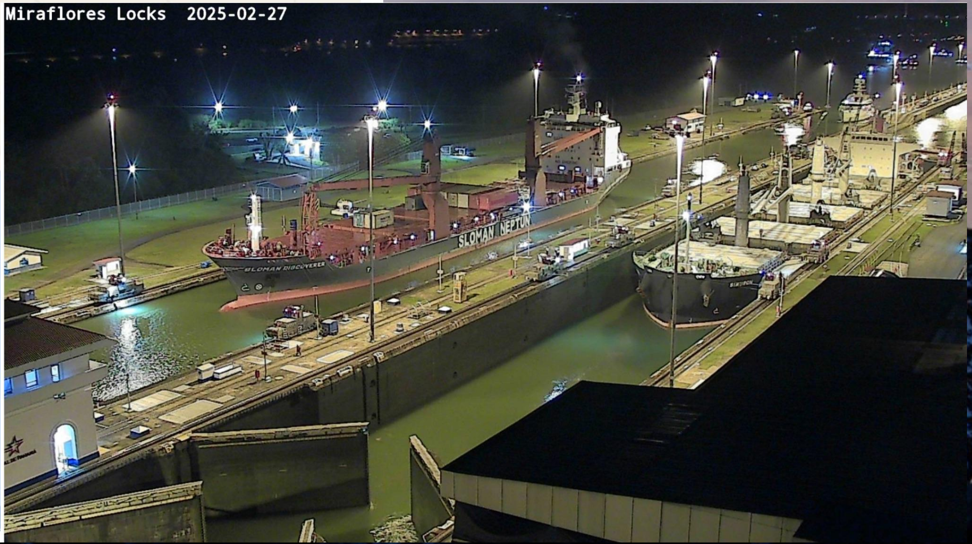


The Fred Young Submillimeter Telescope & Site

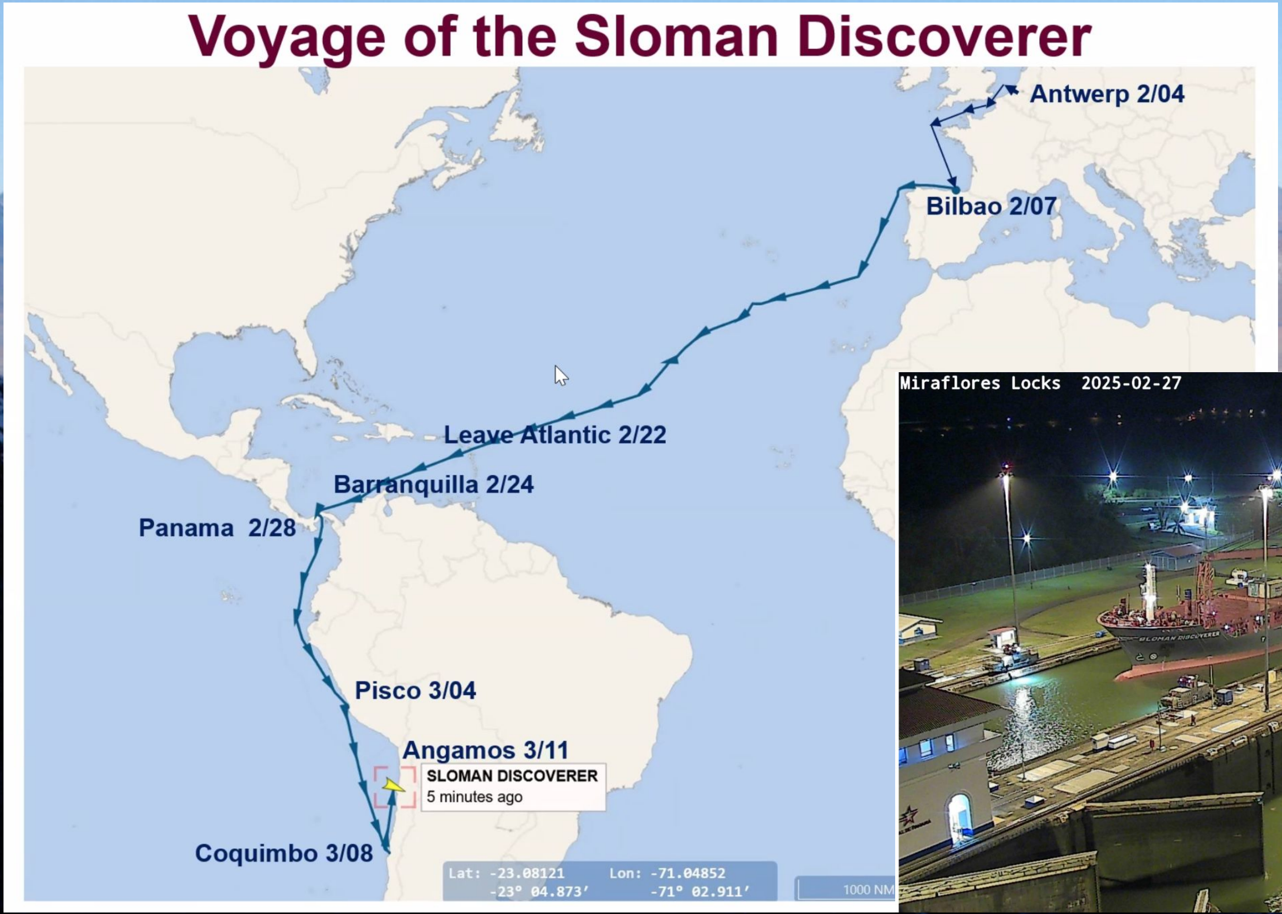


The Fred Young Submillimeter Telescope & Site

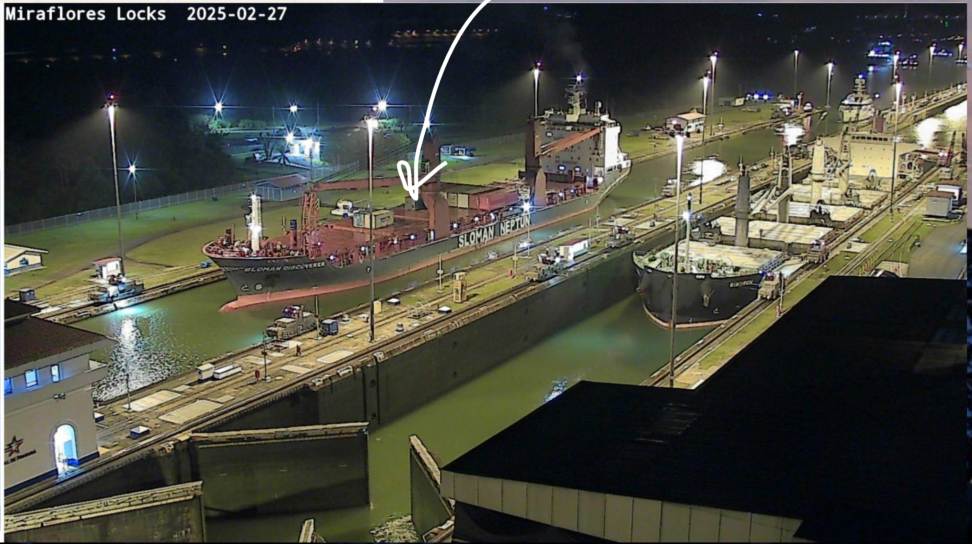




The Fred Young Submillimeter Telescope & Site

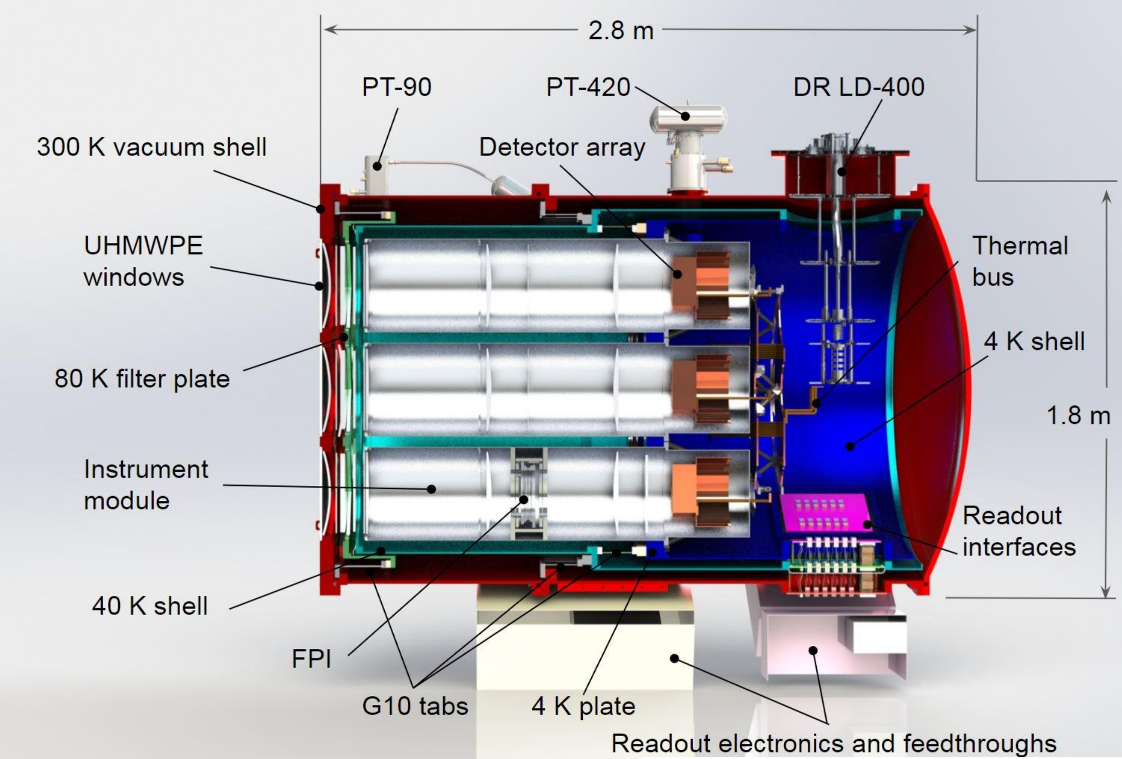


Unloading now!



Prime-Cam on FYST

- 1.8 meter diameter (~½ FoV)
- Up to 7 instrument modules: target specific science goals
- Largest scale deployment of kinetic inductance detectors yet (~100,000)



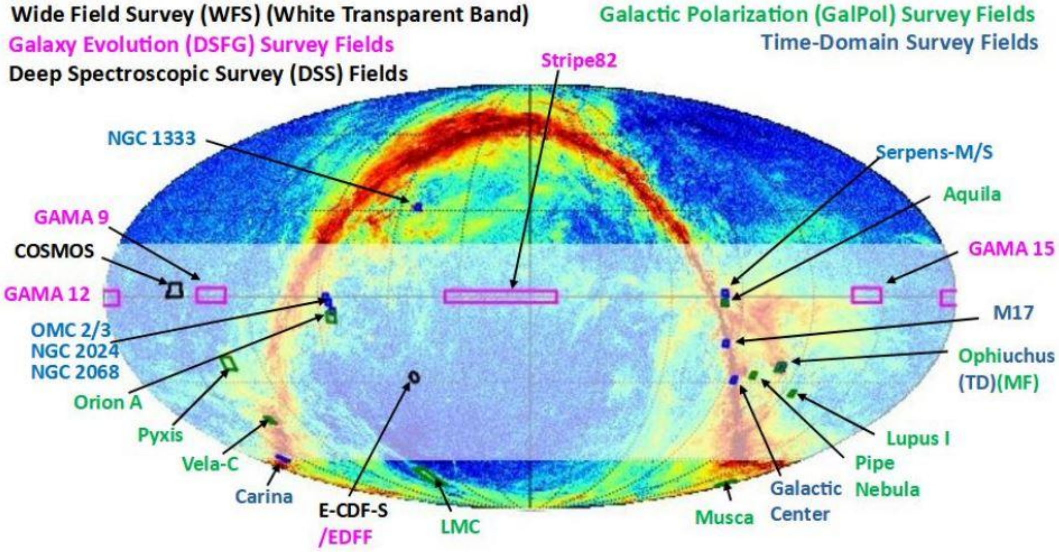
E. M. Vavagiakis et al. arXiv:1807.00058

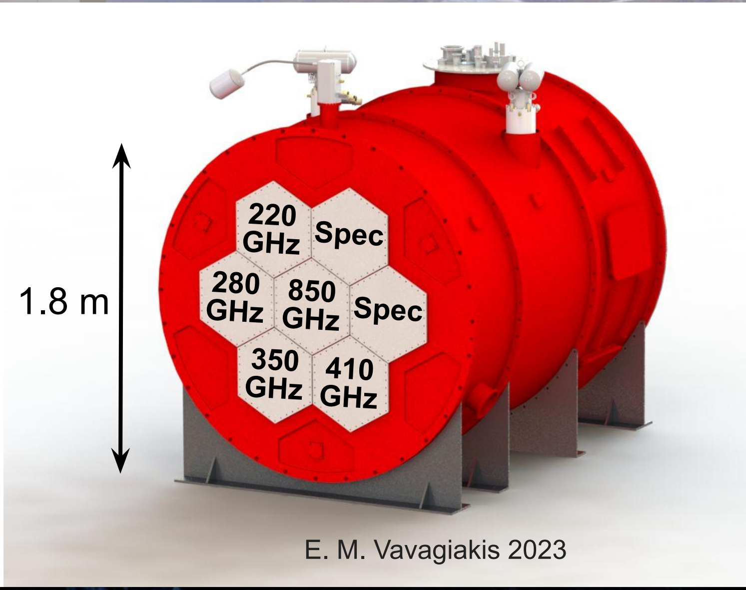
Huber et al. 2024:
Prime-Cam Optics & Status Update
arXiv:2407.20873


NSF
FYST
CCAT

Prime-Cam Science Goals: Surveys

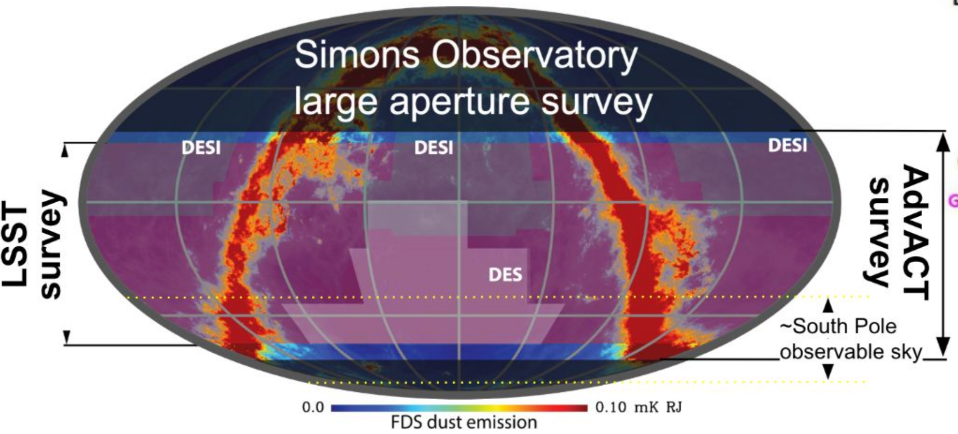
- Wide-field survey for CMB foregrounds, galaxy cluster evolution, Rayleigh scattering
  - Continuous wide-field mm/sub-mm survey is first of its kind
- Deep intensity mapping/reionization surveys, galaxy evolution surveys, Galactic polarization and time-domain science targets

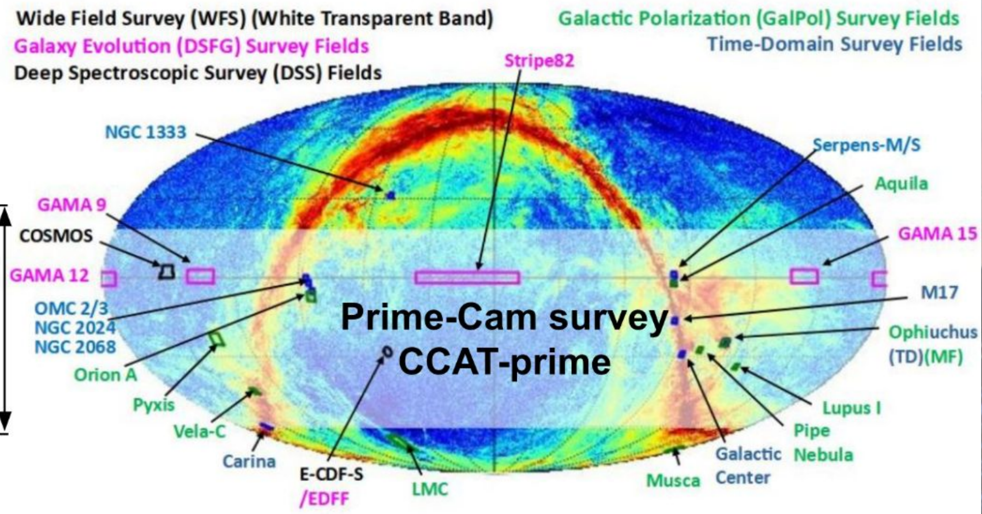




Prime-Cam Science Goals: Surveys

- Wide-field survey for CMB foregrounds, galaxy cluster evolution, Rayleigh scattering
  - Continuous wide-field mm/sub-mm survey is first of its kind
- Deep intensity mapping/reionization surveys, galaxy evolution surveys, Galactic polarization and time-domain science targets
- Rich opportunities for cross-correlations with other frequencies

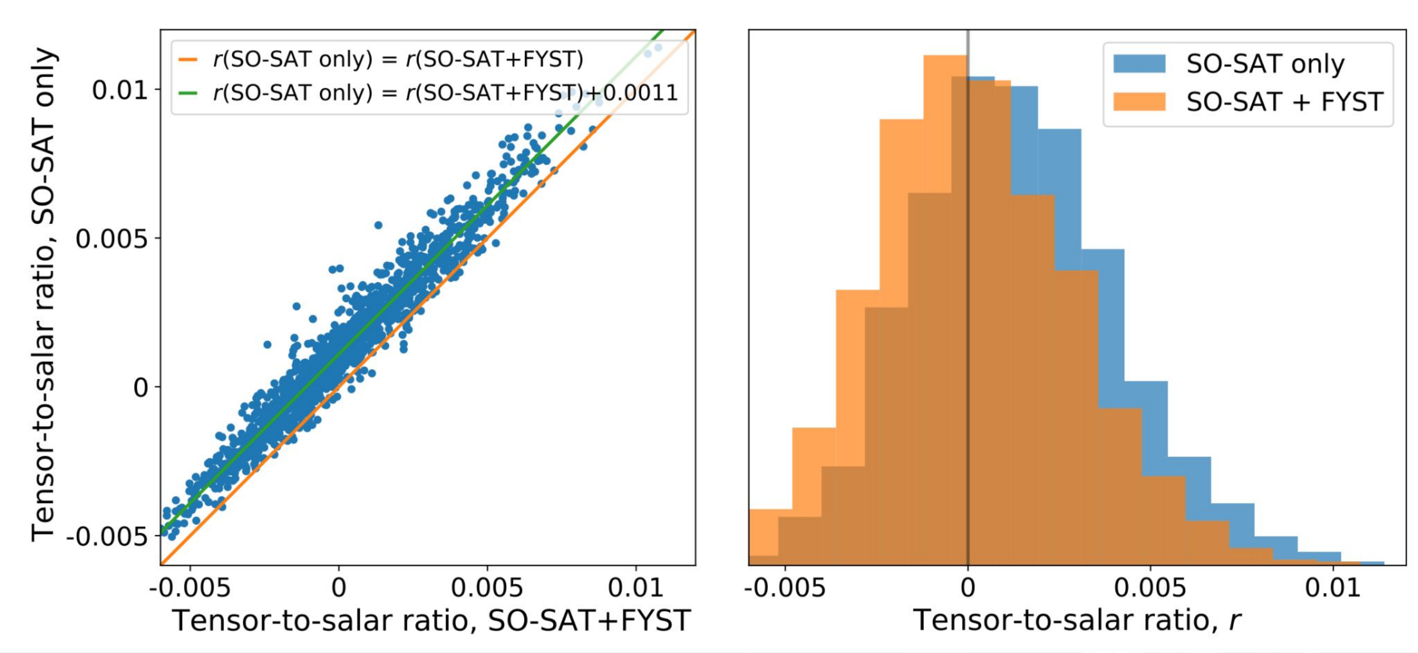




CCAT-prime Science Goals and Forecasts, ApJS 2023 (arXiv:2107.10364)

Prime-Cam Science Goals: Surveys

- Potential to aid search for primordial gravitational waves in significant manner
- Reduce bias on tensor-to-scalar ratio by factor of >6 while maintaining σ(r)
- 350, 410, and 850 GHz channels contribute ~equally to bias reduction



CCAT-prime Science Goals and Forecasts, ApJS 2023 (arXiv:2107.10364)

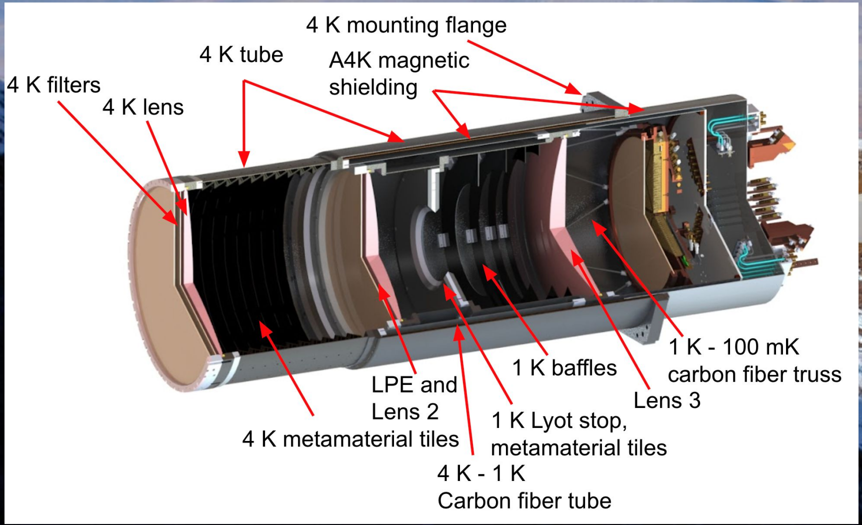
Mod-Cam: A single module cryogenic receiver

- Single optics module: 2026 first light on FYST, testbed for Prime-Cam
- Side-car DR design enables easy rear swapping of modules

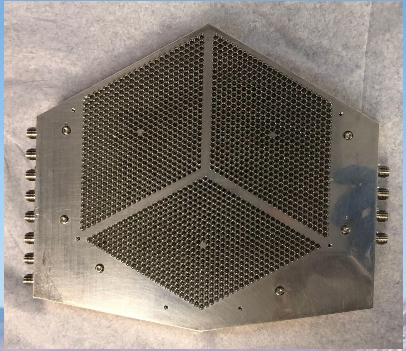
Vavagiakis, Duell et al., Proc. SPIE 2022, (arXiv:2208.05468)
Duell, Vavagiakis et al., Proc. SPIE 2020 (arXiv:2012.10411)

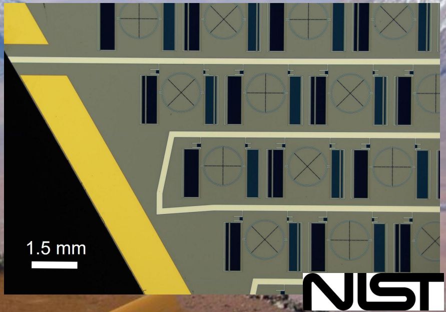
280 GHz Module and detector arrays

- Module tests ongoing
- >10,000 polarization-sensitive detectors
  - First arrays: in testing



E. M. Vavagiakis, C. Duell et al., Proc. SPIE 2022, (arXiv:2208.05468)

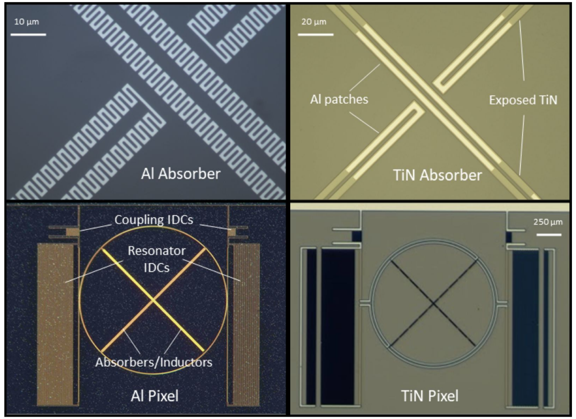


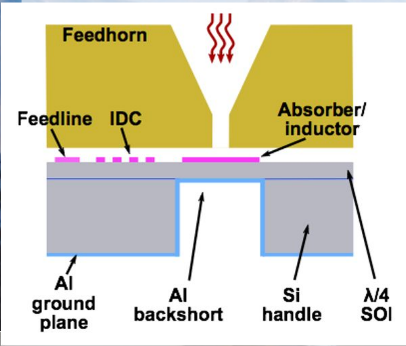


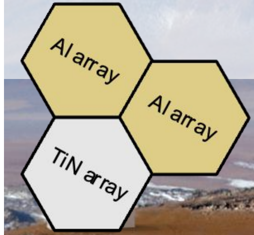
Choi et al., J. Low Temp. Phys 2022, (arXiv:2111.01055)
Duell, Vavagiakis et al., Proc. SPIE 2020 (arXiv:2012.10411)

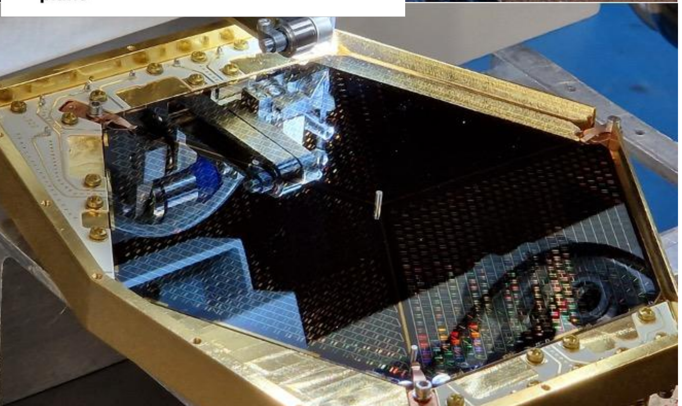
280 GHz detector arrays

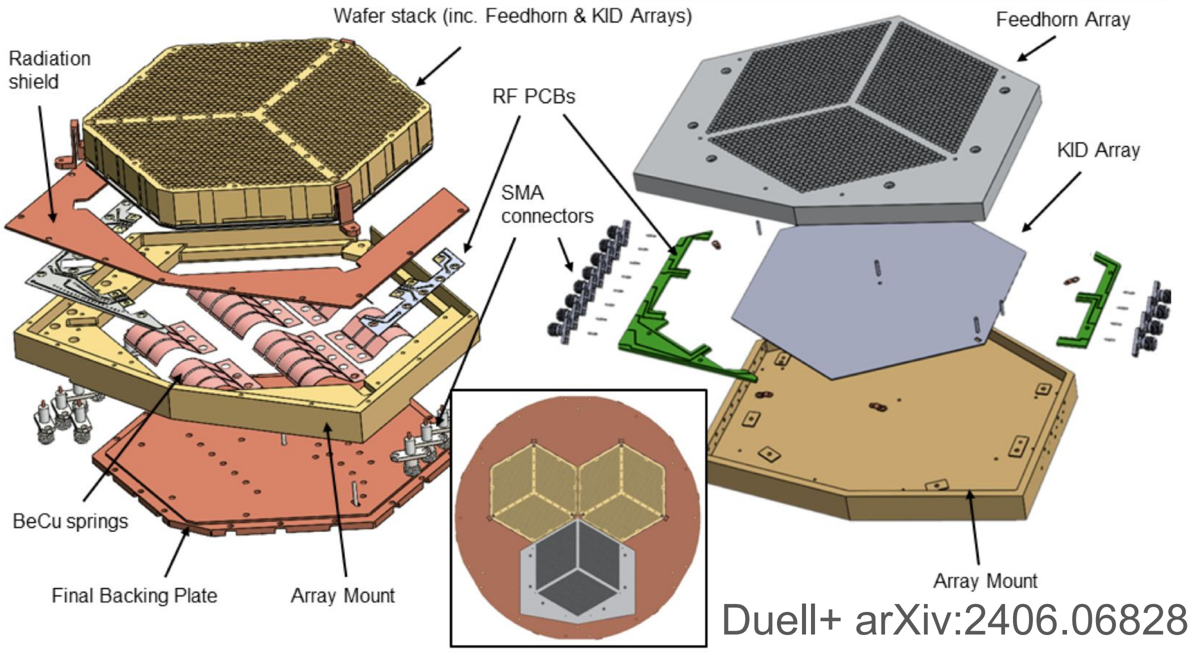
- One TiN, two Al MKID arrays: exciting technology comparisons
  - 3448 detectors (1724 pixels)/array
  - Feedhorn coupled
  - 24 polarization states across 280 GHz module focal plane







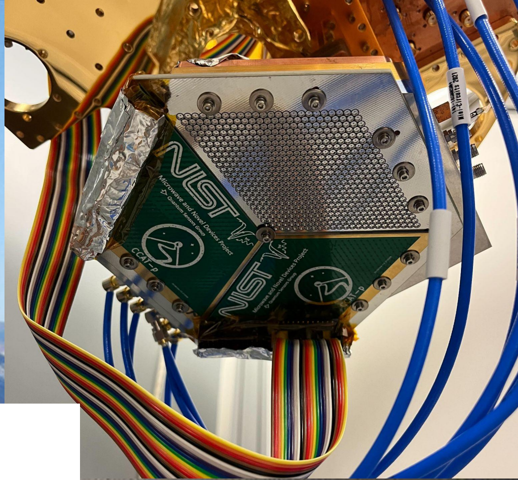


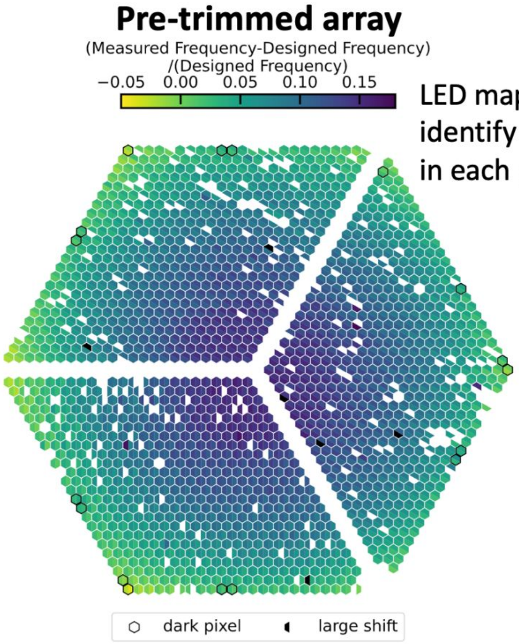


Duell+ arXiv:2406.06828

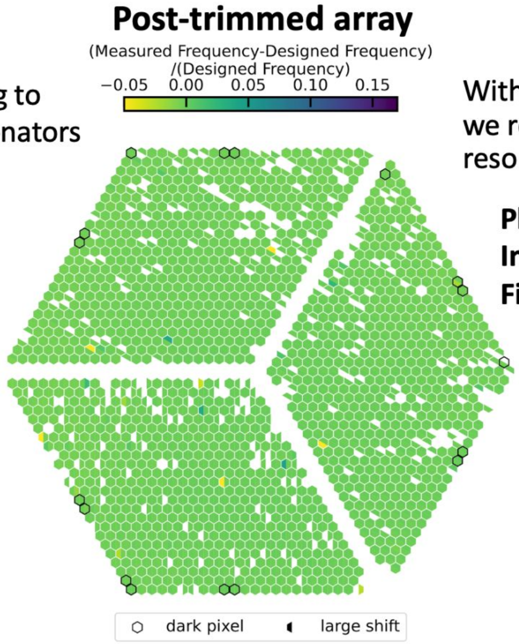
280 GHz detector arrays

- LED mapping to match resonator frequency to physical location on array
  - Reduce frequency collisions, maximize yield
- Capacitor trimming thereafter





LED mapping to identify resonators in each pixel



With capacitor trimming, we reduce colliding resonances

Physical yield: 97%
Initial resonator yield: 61%
Final resonator yield: 83%

Vaskuri+

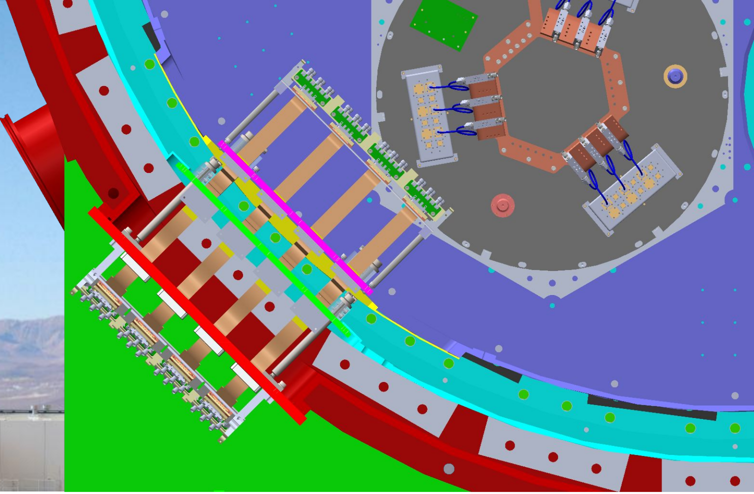
arXiv:2410.21396

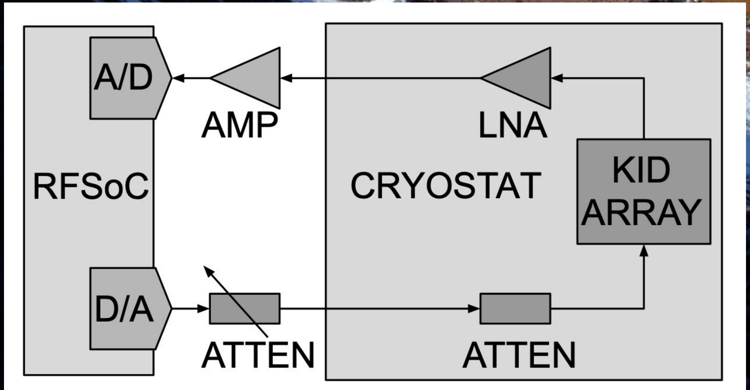
anna.vaskuri@nist.gov

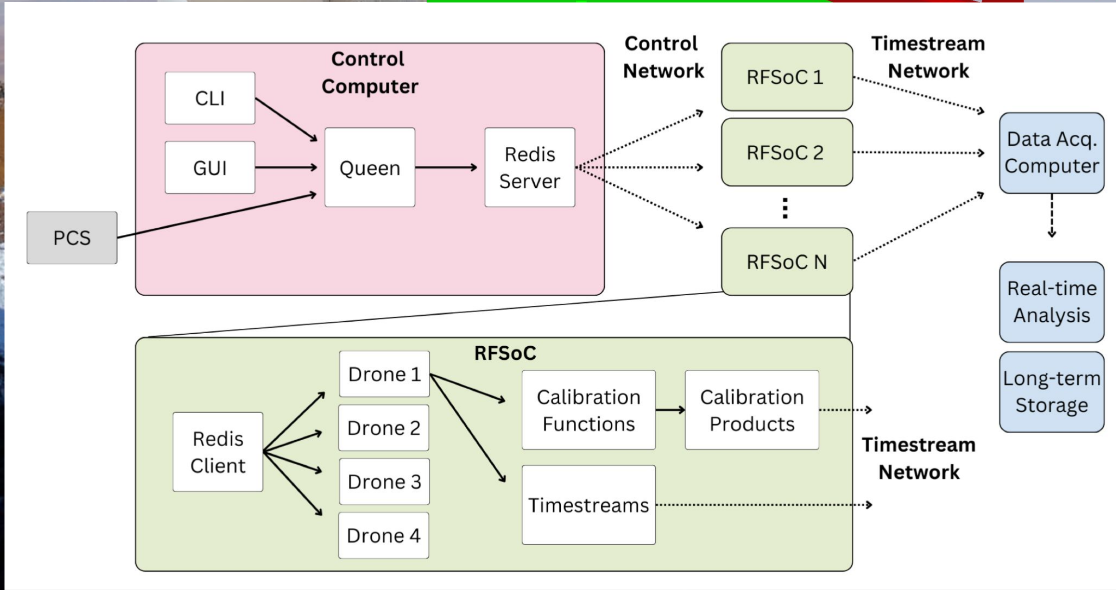
280 GHz readout

- Xilinx Radio Frequency System on a Chip (RFSoC)
    - Detector noise limited performance under expected optical loading conditions demonstrated
- Software in development: Simons Observatory heritage, updated for KIDs

Sinclair+ arXiv:2406.14892
Burgoyne+ arXiv:2406.01858



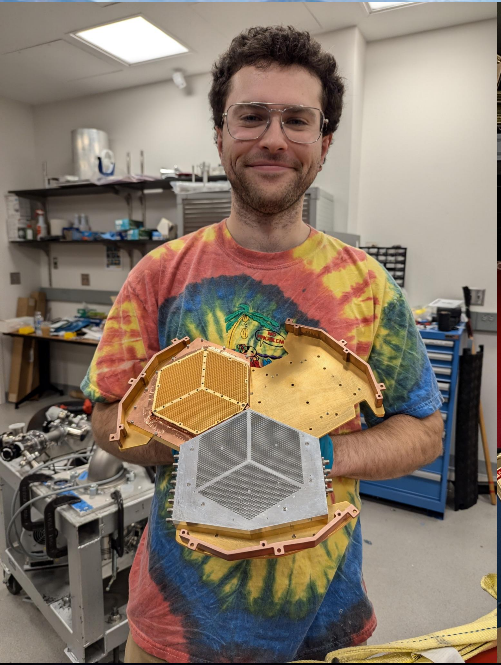


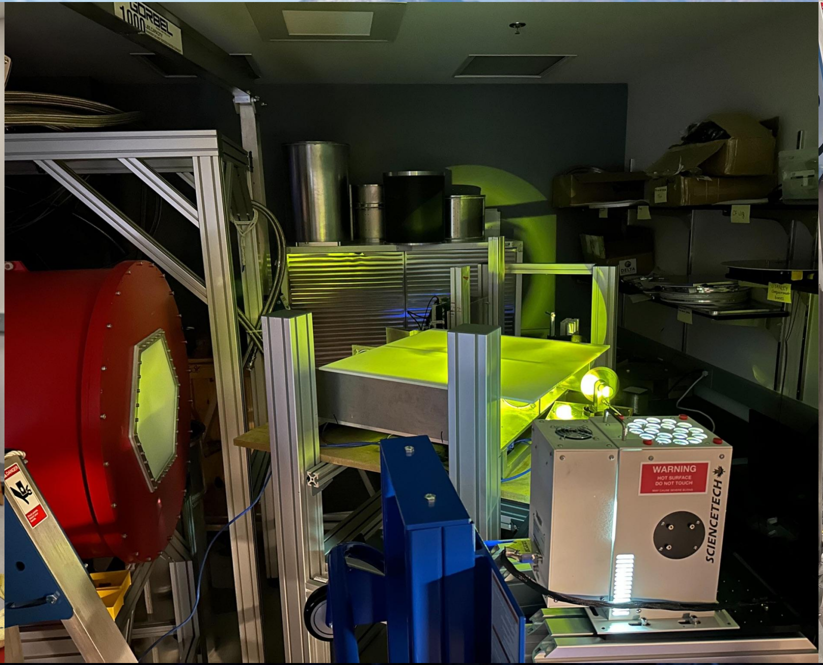


280 GHz Module testing status

280 GHz Module testing status

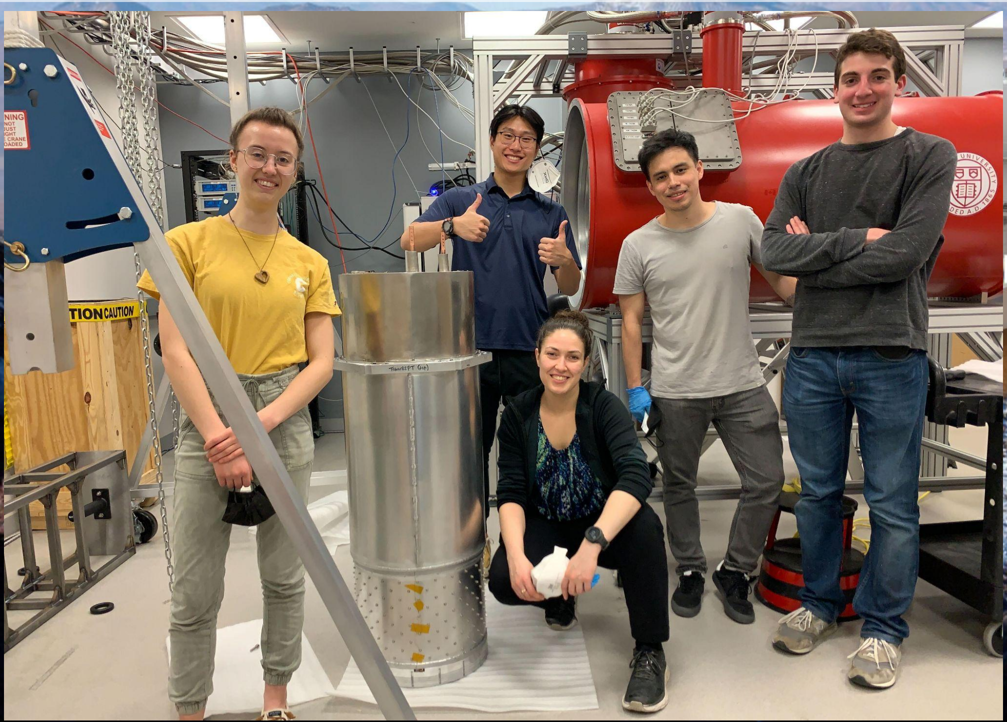
- Optical testing of first two arrays in Mod-Cam in progress
- “Pre-IRR” next week!





280 GHz Module: Early Science

- Wealth of early science: joint analysis with ACT DR6 for CMB foregrounds, galaxy clusters, dusty star forming galaxies, Galactic science, transients, atmosphere characterization



Summary

- Entering a new era of mm and sub-mm observations
  - Sensitivity, resolution, frequency coverage, data volume
- New ACT analyses in progress
  - Constraining the physics of our universe: Best H_0 measurement with ACT, improved further with SO
  - Probing astrophysics with DESI
- Simons Observatory, CCAT: first light now/soon
- New windows at 30-900 GHz, ready us for CMB-S4
- New analysis techniques preparing for systematics-driven era

Thank you!

Thanks to the ACT, SO and CCAT Collaborations

Contact:
eve.vavagiakis@duke.edu
EveVavagiakis.com
@EveVavagiakis.bsky.social