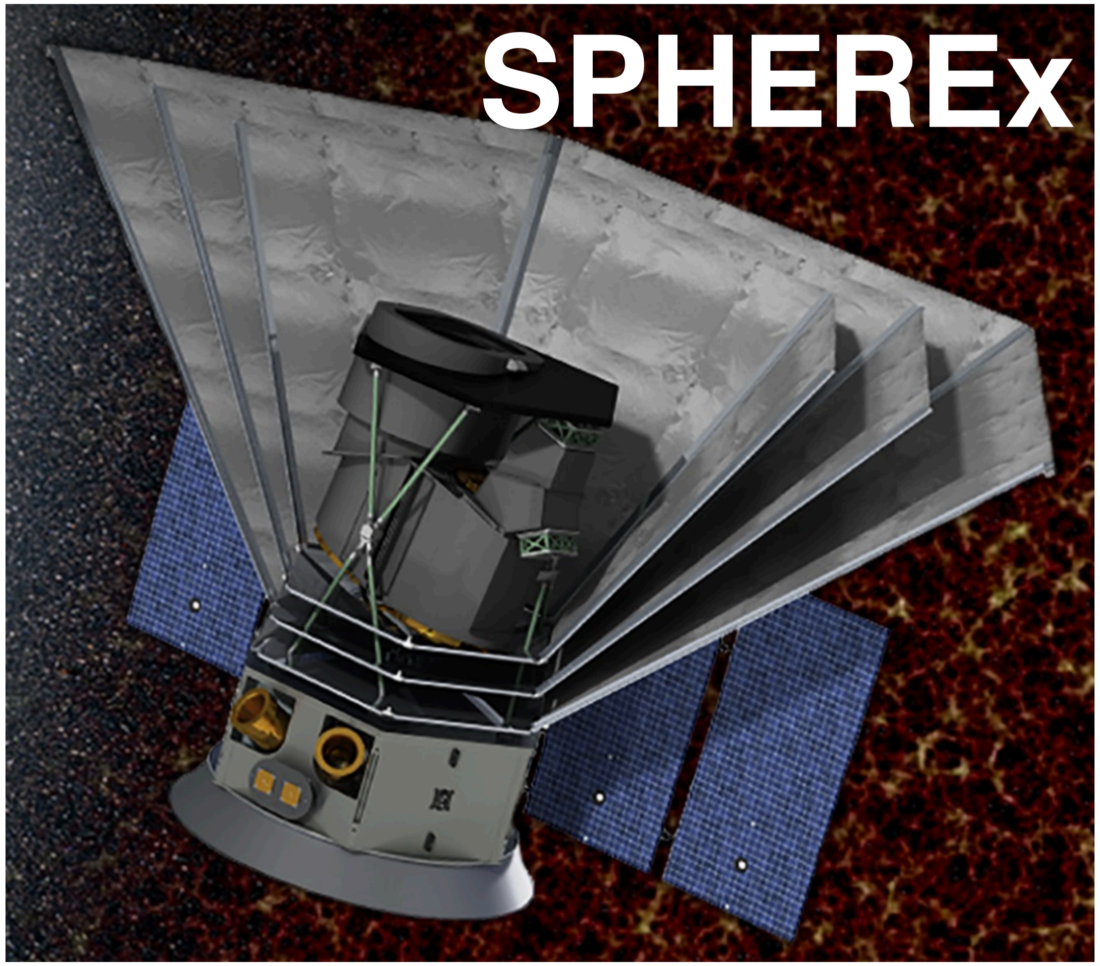


and

SIMONS OBSERVATORY

22°57'31" SOUTH, 67°47'15"WEST ELEVATION: 17,027.6'

PARQUE ASTRONÓMICO ATACAMA, CHILE

Synergies (Only a Subset!)

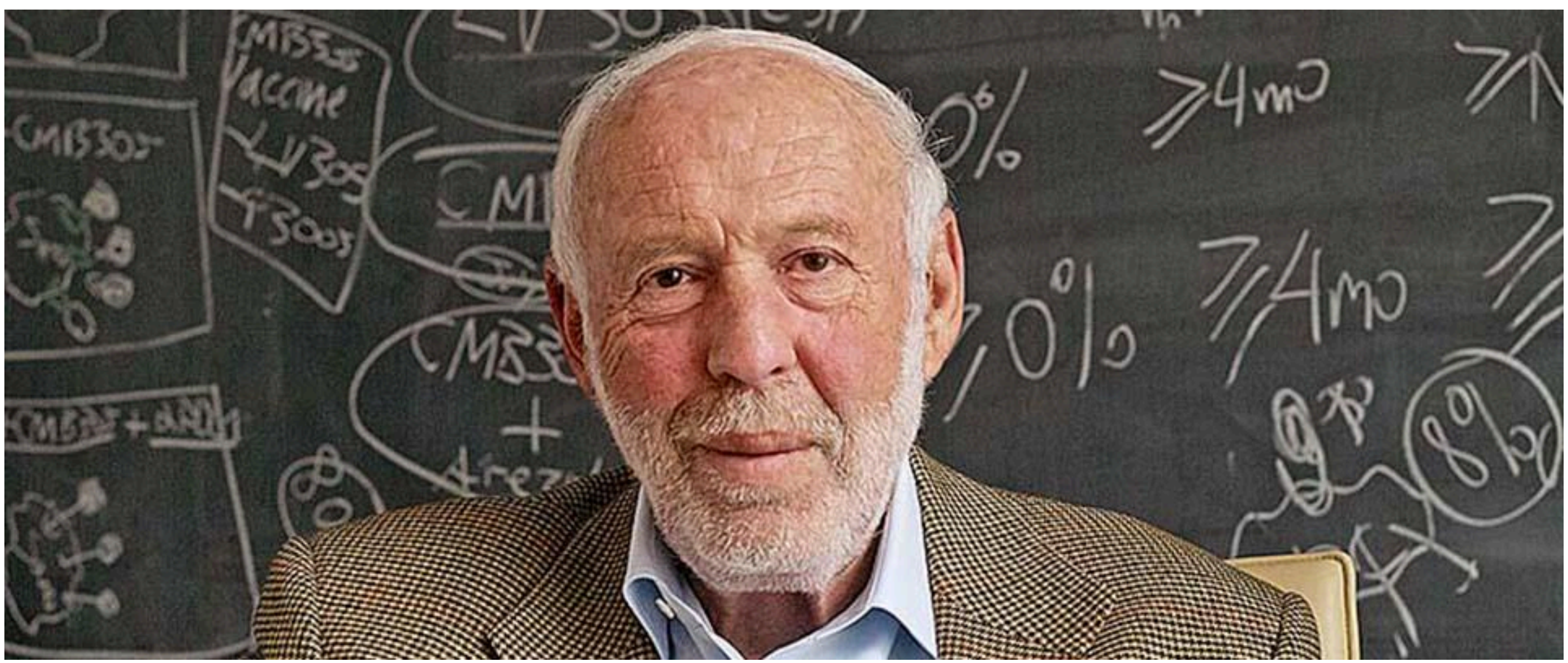
Colin Hill (Columbia/CCA)

SO Science Goals and Forecasts: 1808.07445

SPHEREx Workshop
Flatiron Institute
24 February 2020

Colin Hill
Columbia/CCA

The Simons Observatory is funded by generous grants from the **Simons Foundation** and the **Heising-Simons Foundation**



+ contributions from founding institutions

The Simons Observatory Collaboration

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
- Columbia University

Japan

- KEK
- IPMU
- Tohoku
- Tokyo
- Kyoto

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers** → **~300**

Canada

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

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

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

South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

Middle East

- Tel Aviv

The Simons Observatory Collaboration

- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
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- West Chester University
- Yale University

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South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

Middle East

- Tel Aviv

Simons Obs. Science Goals and Probes

Colin Hill
Columbia/CCA

primordial fluctuations

large scale B-modes
→ tensor-to-scalar ratio (BB)

damping tail
→ primordial power on small scales (TE, TT, EE)
→ primordial bispectrum (f_{NL} via TTT,TTE,… + lens/kSZ)

relativistic species

damping tail
→ N_{eff} (TE, TT, EE)

reionization

sources
→ duration of reionization (kSZ)
→ mean free path of photons (kSZ)

neutrino mass

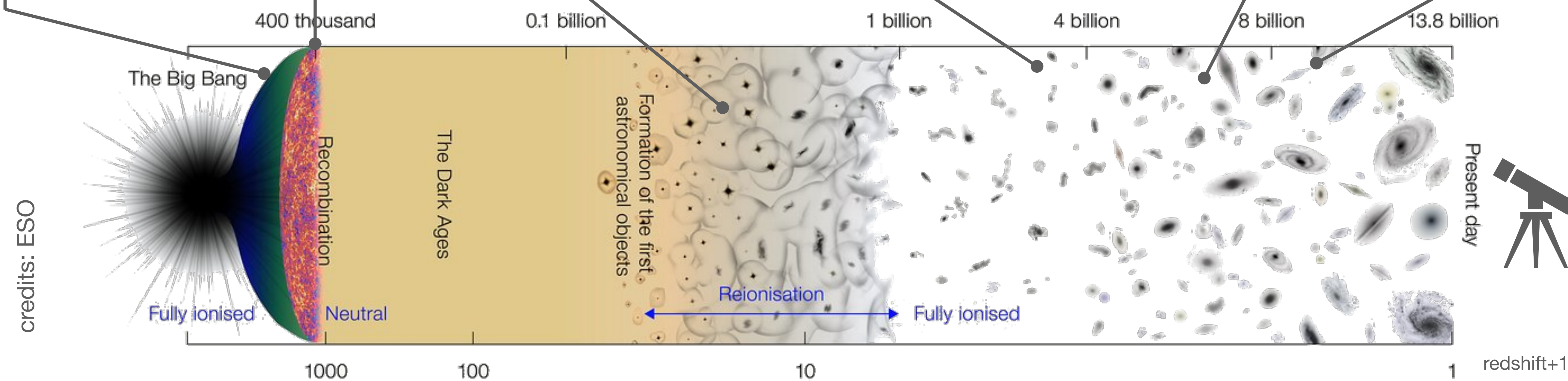
lensing potential (TT+EB), tSZ
→ Σm_ν

galaxy evolution

tSZ, kSZ
→ non-thermal pressure (tSZ+kSZ)
→ feedback efficiency (tSZ+kSZ)

dark energy

tSZ, lensing
→ σ_8 at z=2-3 (lensing, tSZ)
→ growth of structure (kSZ)



Additional science includes (but is not limited to):

- helium fraction, cosmic birefringence, primordial magnetic fields
- high-redshift clusters
- dark matter annihilation and interactions
- isocurvature
- calibration of multiplicative shear bias (e.g., for LSST)
- new sample of dusty star-forming galaxies
- transient sources
- cosmic infrared background

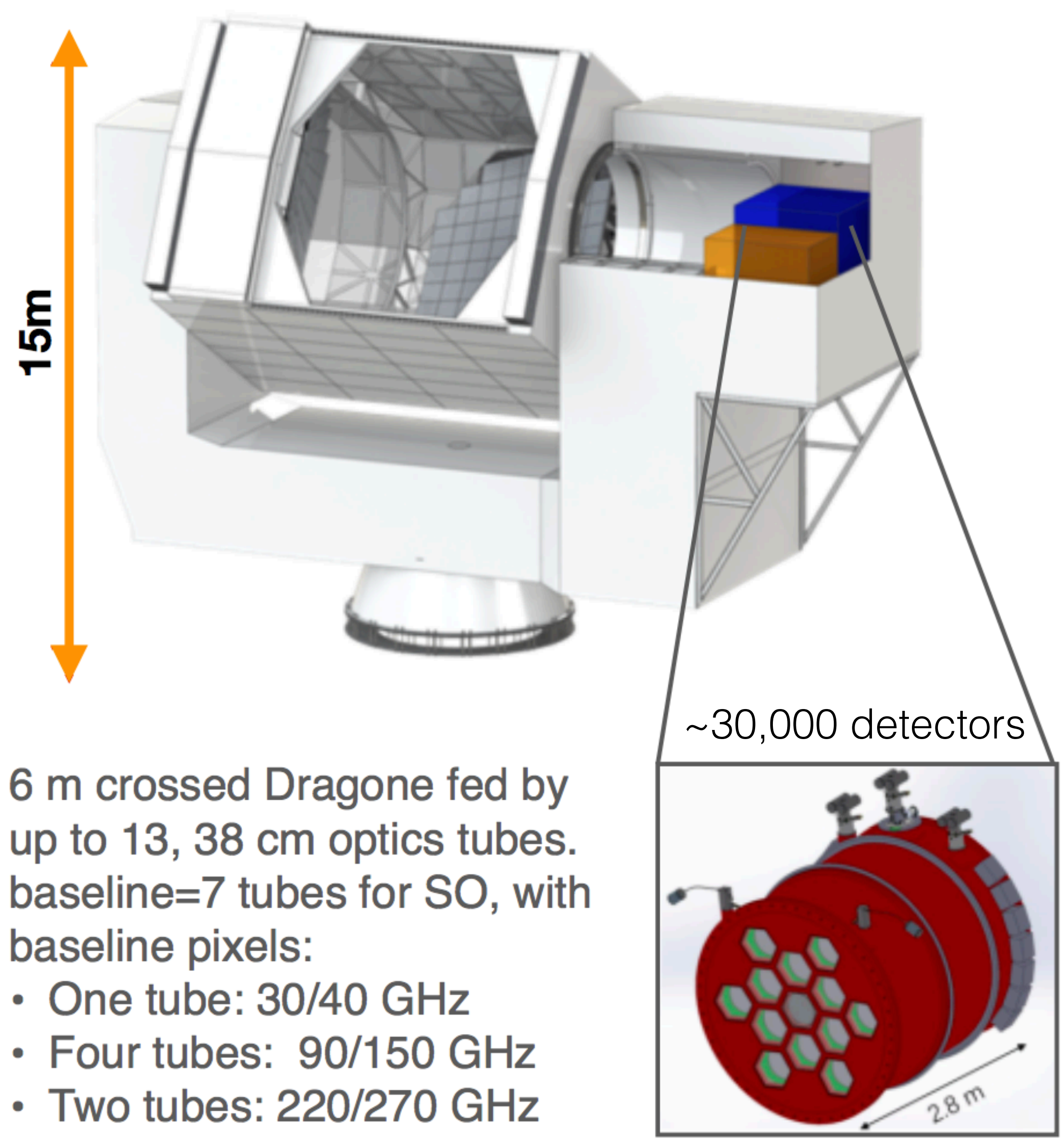
THE SIMONS OBSERVATORY: SCIENCE GOALS AND FORECASTS

arXiv:1808.07445
JCAP 02, 056 (2019)

Colin Hill
Columbia/CCA

Simons Obs. Instruments & Technology

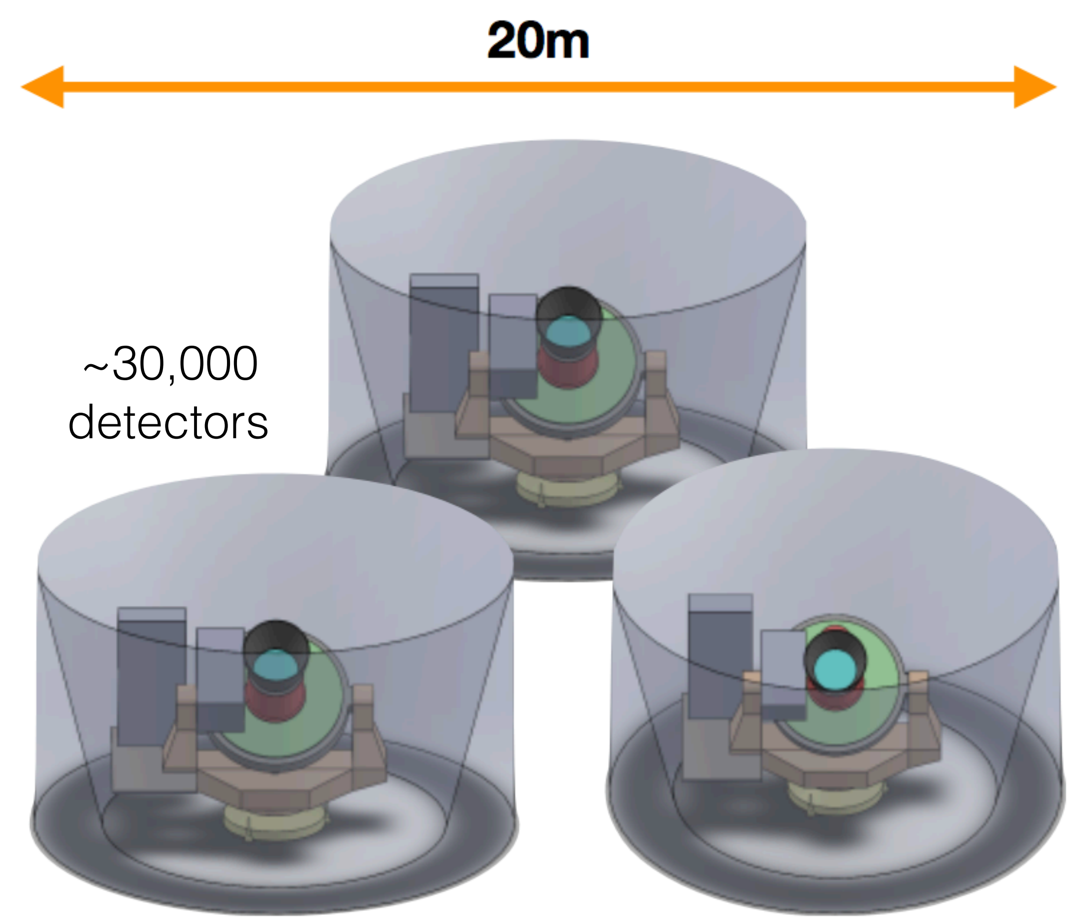
large aperture telescope



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



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

FIRST LIGHT IN 2021

>$80M of funding secured

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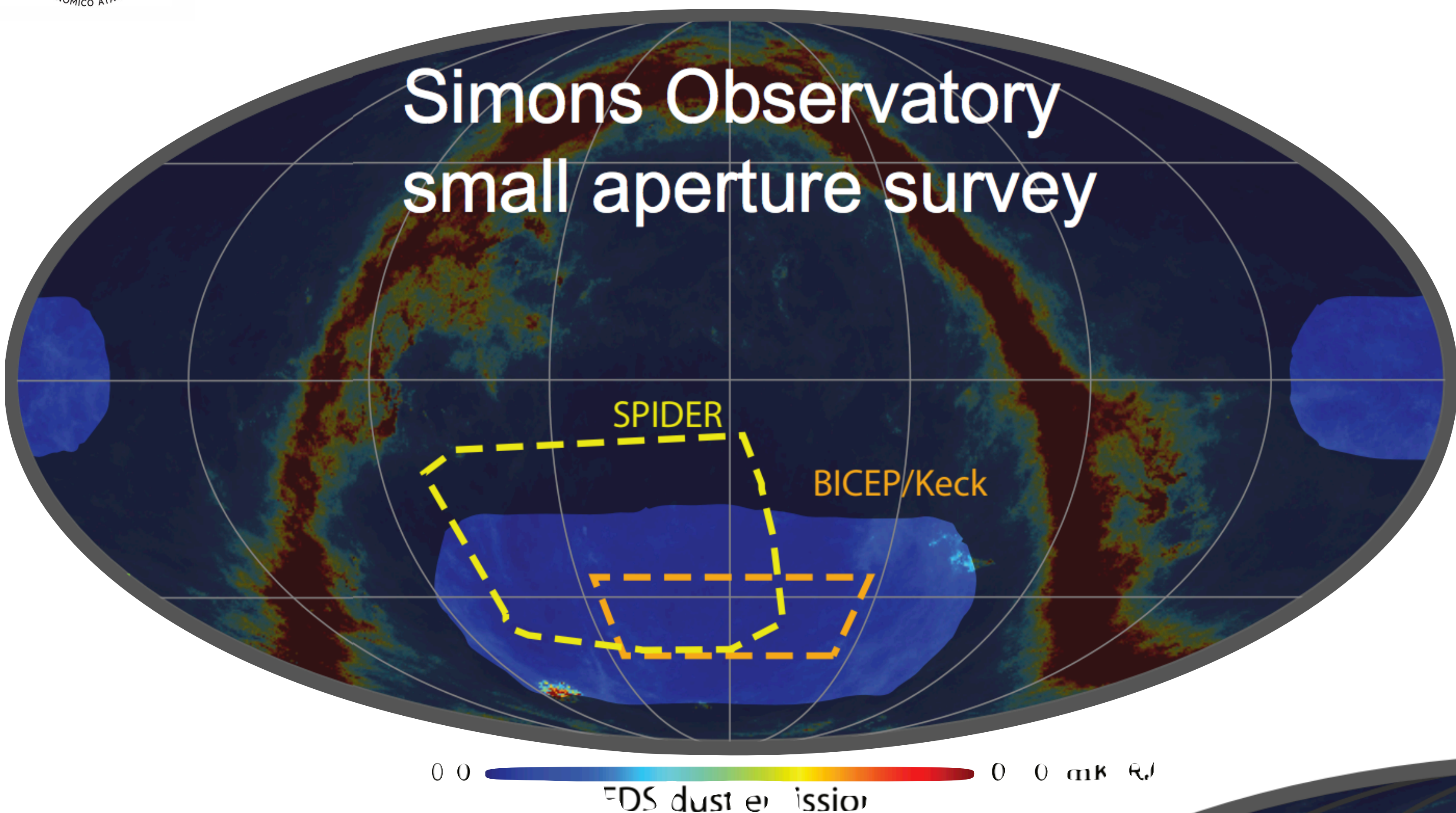
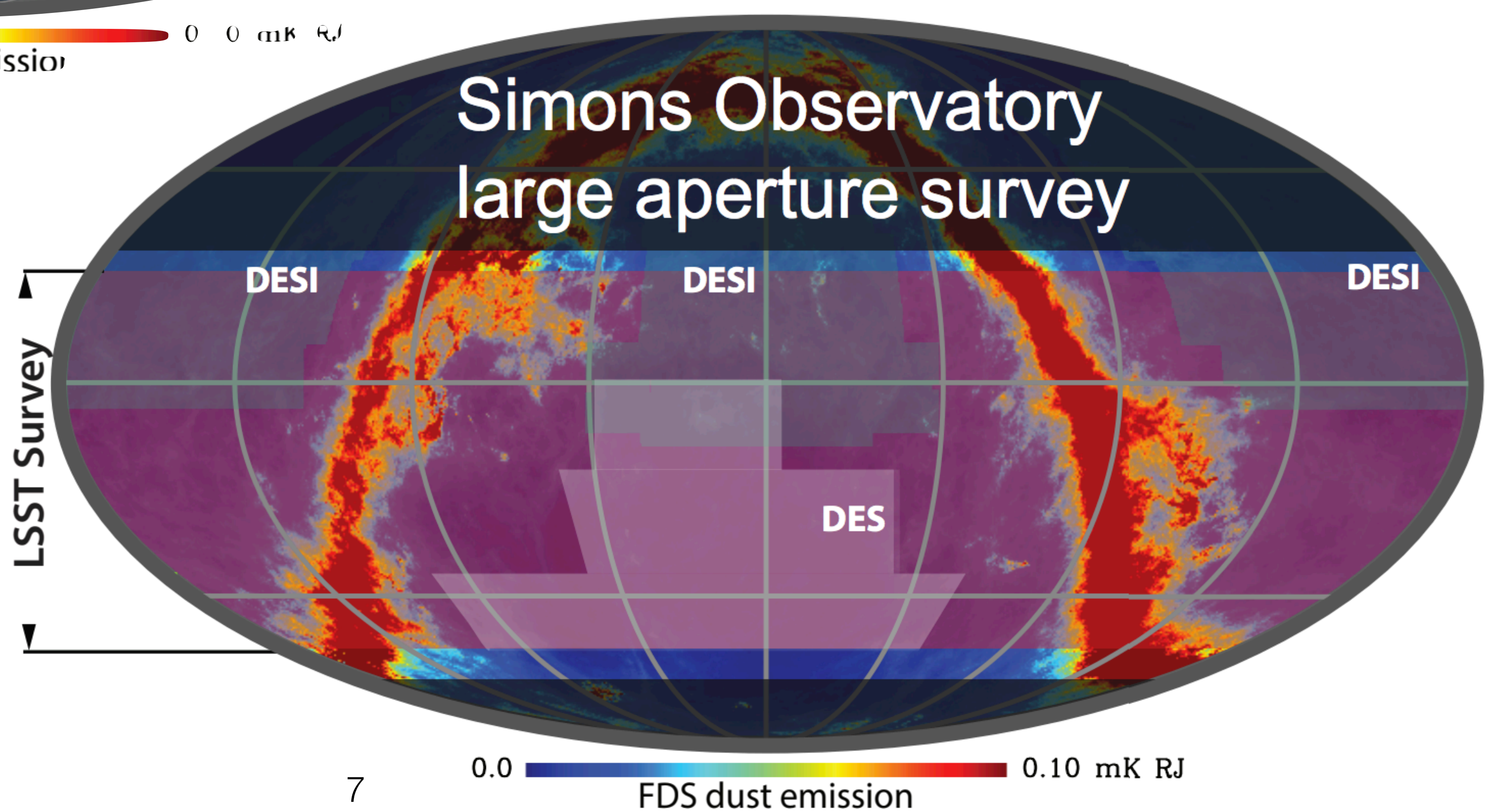
Anticipated Sky Coverage



effective f_{sky} ~ 10%

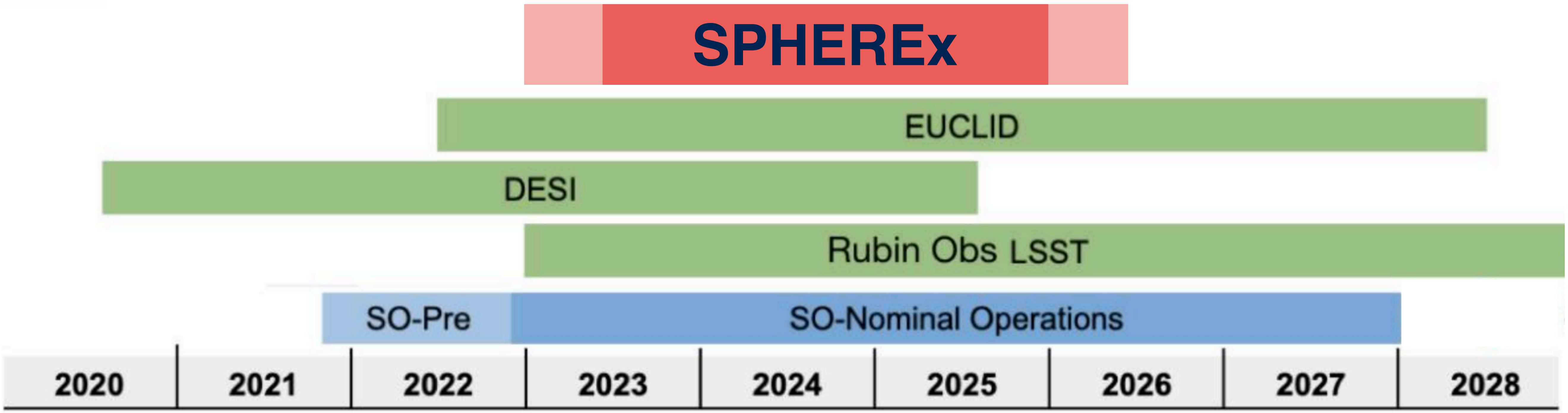
optimized to search for primordial gravitational waves



effective f_{sky} ~ 40%+

maximal overlap w/ VRO-LSST and SPHEREx, large overlap w/ DESI

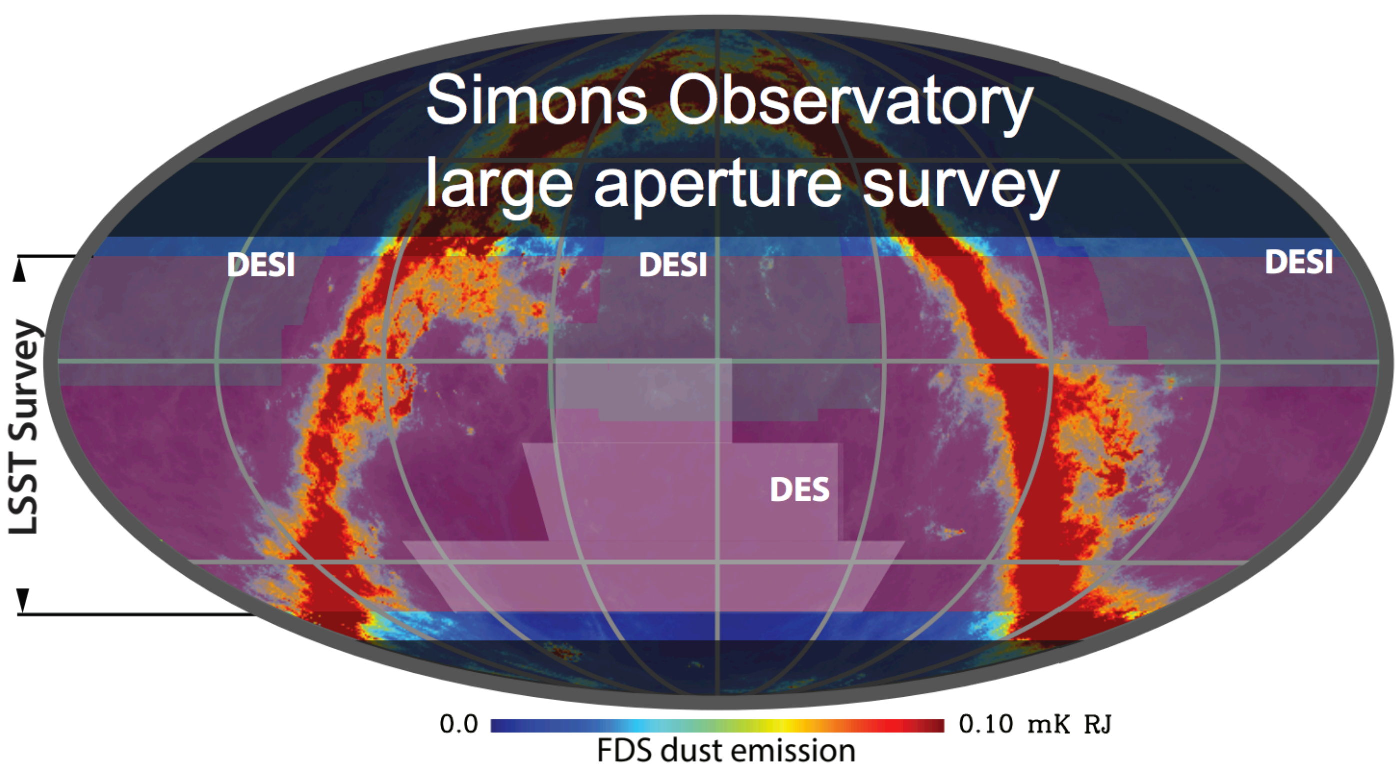
Timeline: Synergy with SPHEREx (and Others)



Joint science from:

SO: CMB lensing, tSZ, kSZ

SPHEREx: galaxies, quasars, clusters



- **Neutrino mass**
- **Structure growth: sigma8**
- **Non-Gaussianity: fnl**
- **Cluster mass calibration**
- **Shear bias calibration**
- **Constraints on baryonic feedback**

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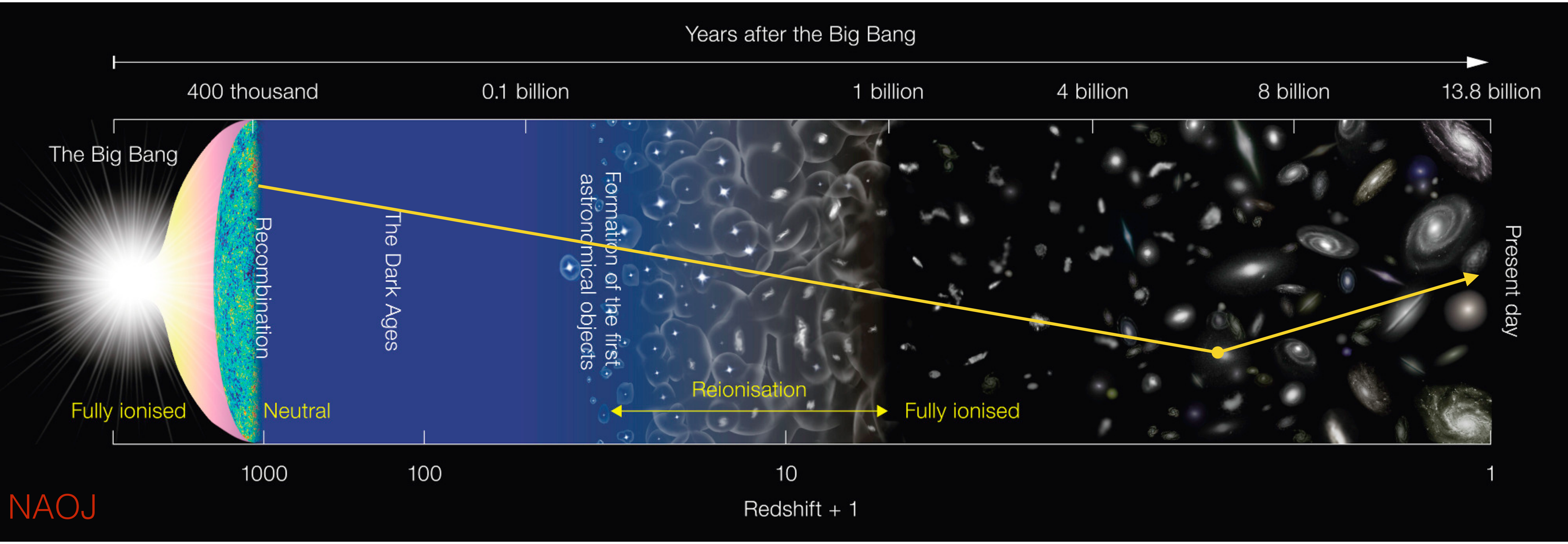


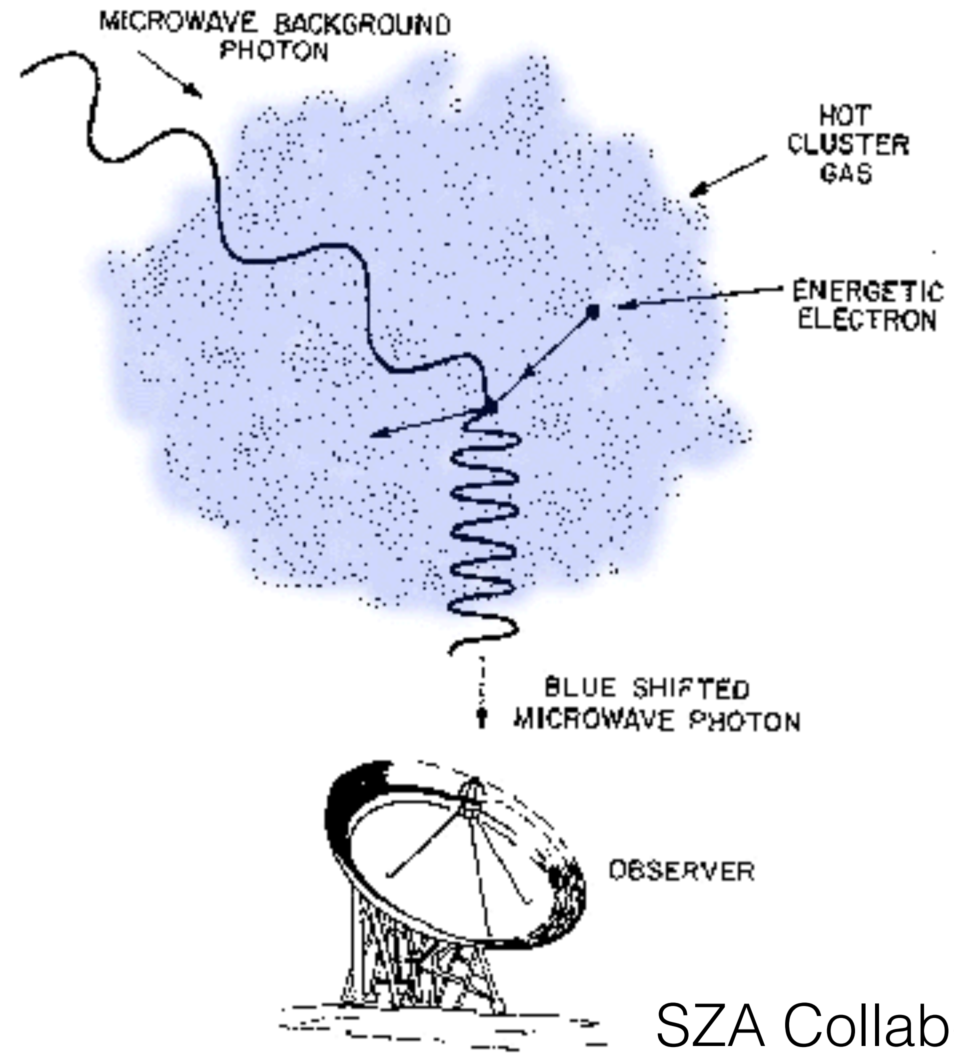
Focus for remainder of this talk: thermal and kinematic Sunyaev-Zel'dovich (SZ) effects

Thermal SZ Effect

Colin Hill
Columbia/CCA

→ Integrated Electron Pressure

Thermal SZ Effect:
Change in temperature of CMB photons due to inverse Compton scattering off hot electrons, most of which are in the intracluster medium (ICM) of galaxy clusters



SZA Collaboration

Compton-y

$$\frac{\Delta T_{\rm tSZ}}{T_{\rm CMB}} = g_\nu \frac{\sigma_T}{m_e c^2} \int P_e(\chi) d\chi$$

tSZ spectral function — electron pressure — line-of-sight integral

Thermal SZ Effect

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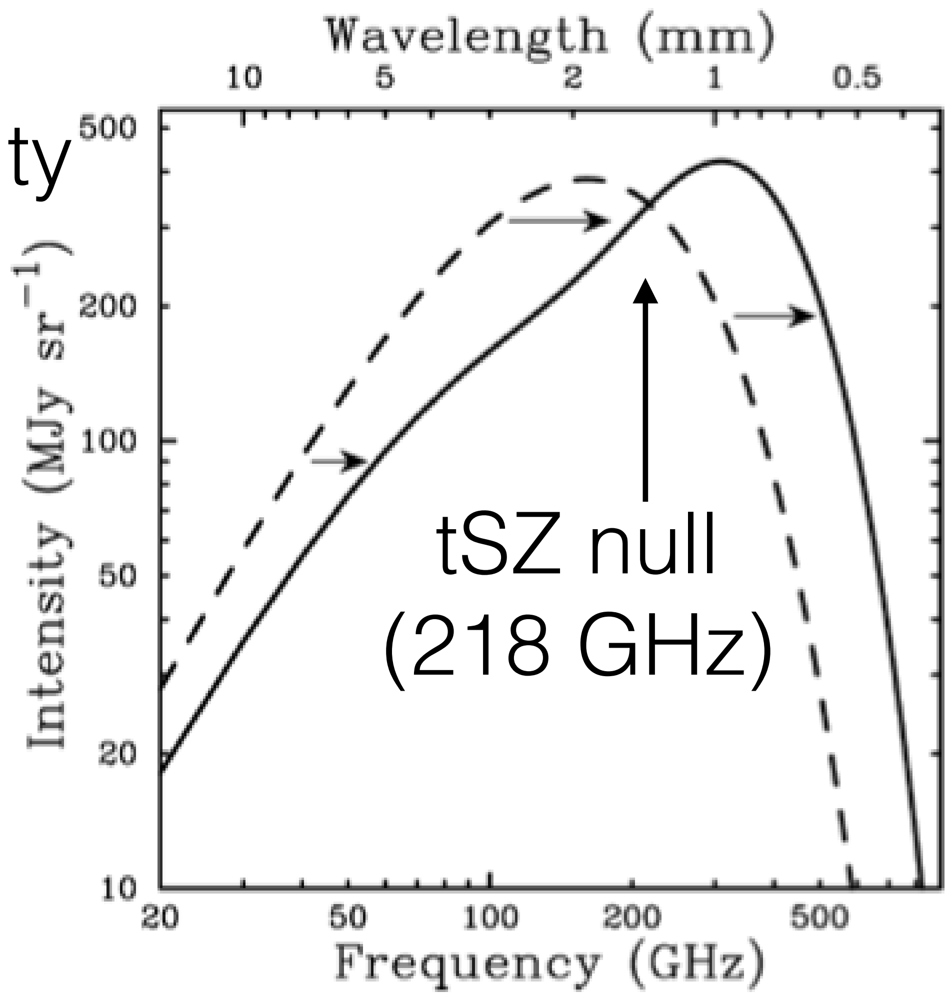
Columbia/CCA

→ Integrated Electron Pressure

Unique spectral signature

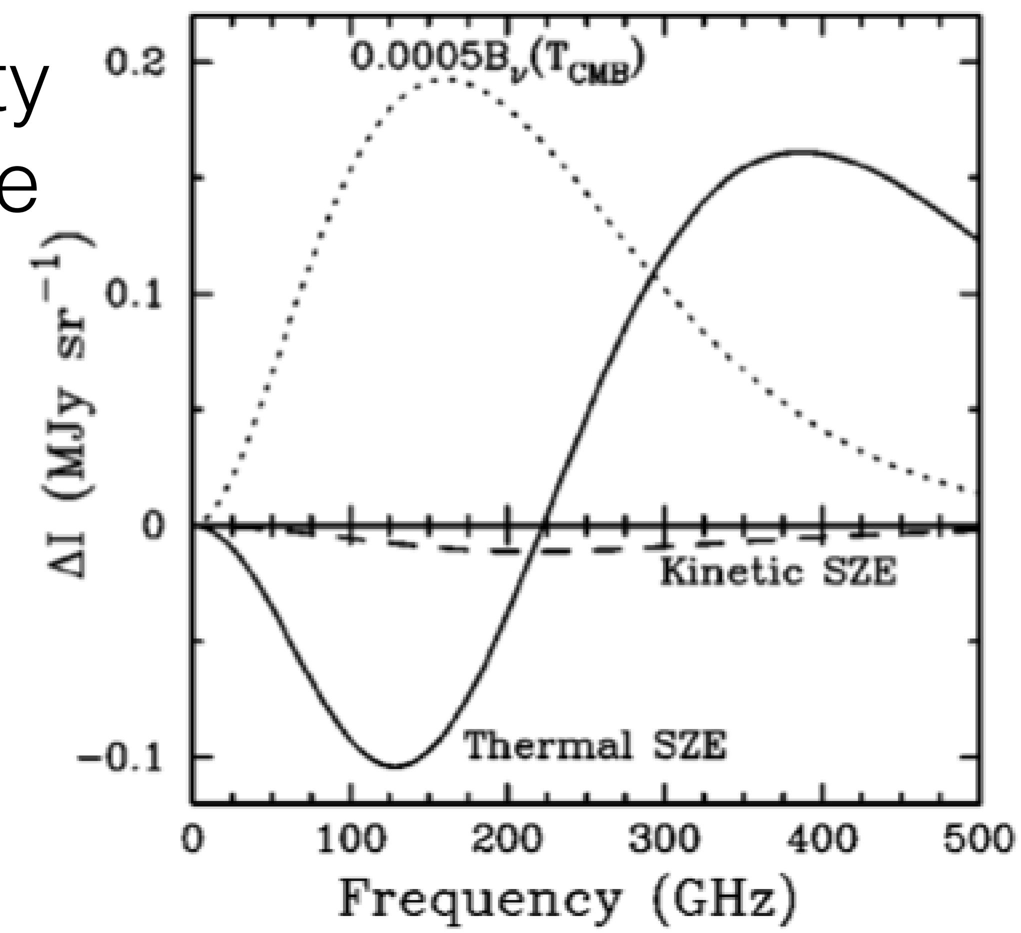
intensity



tSZ null
(218 GHz)

frequency

intensity change



frequency

Figures: Carlstrom+ (2002)

Kinematic SZ Effect

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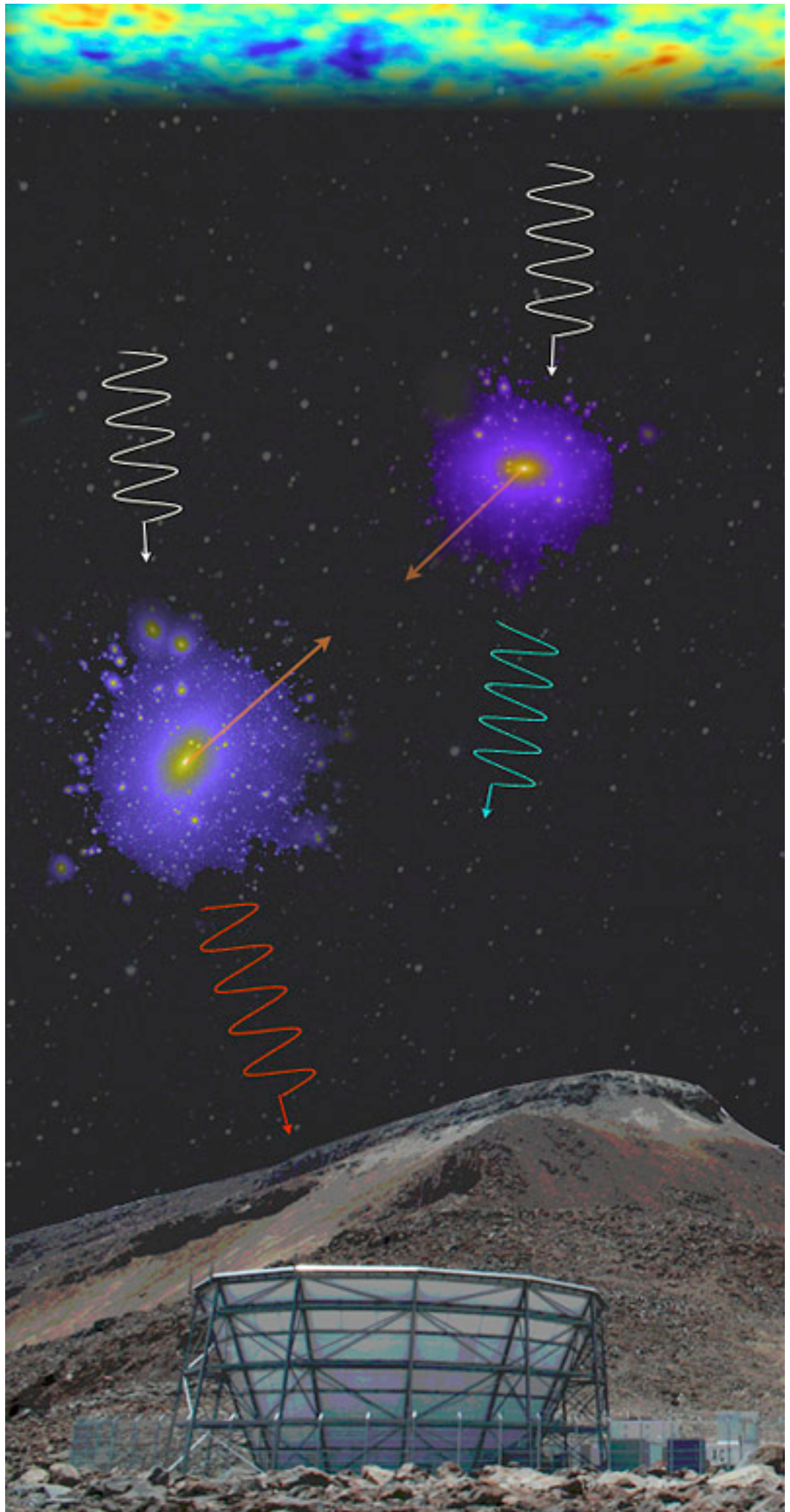
→ **Integrated Electron Momentum**



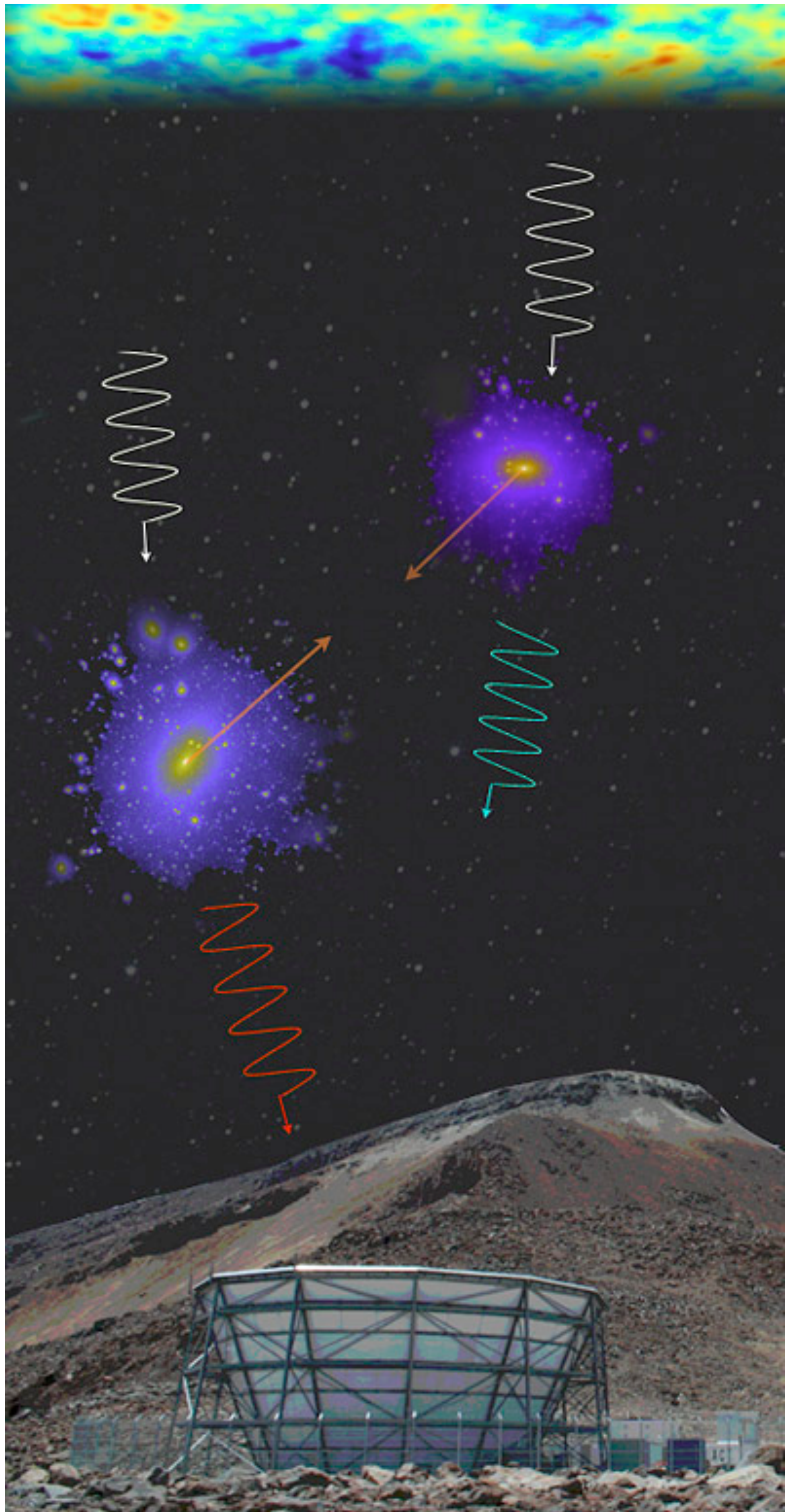
Sudeep Das/ACT

Kinematic Sunyaev-Zel'dovich Effect:
Doppler boosting of CMB photons
Compton-scattering off free electrons
with non-zero line-of-sight velocity

Colin Hill
Columbia/CCA

Kinematic SZ Effect

→ Integrated Electron Momentum



Sudeep Das/ACT

Kinematic Sunyaev-Zel'dovich Effect: Doppler boosting of CMB photons Compton-scattering off free electrons with non-zero line-of-sight velocity

- Preserves blackbody CMB spectrum
- Probe of electron momentum field

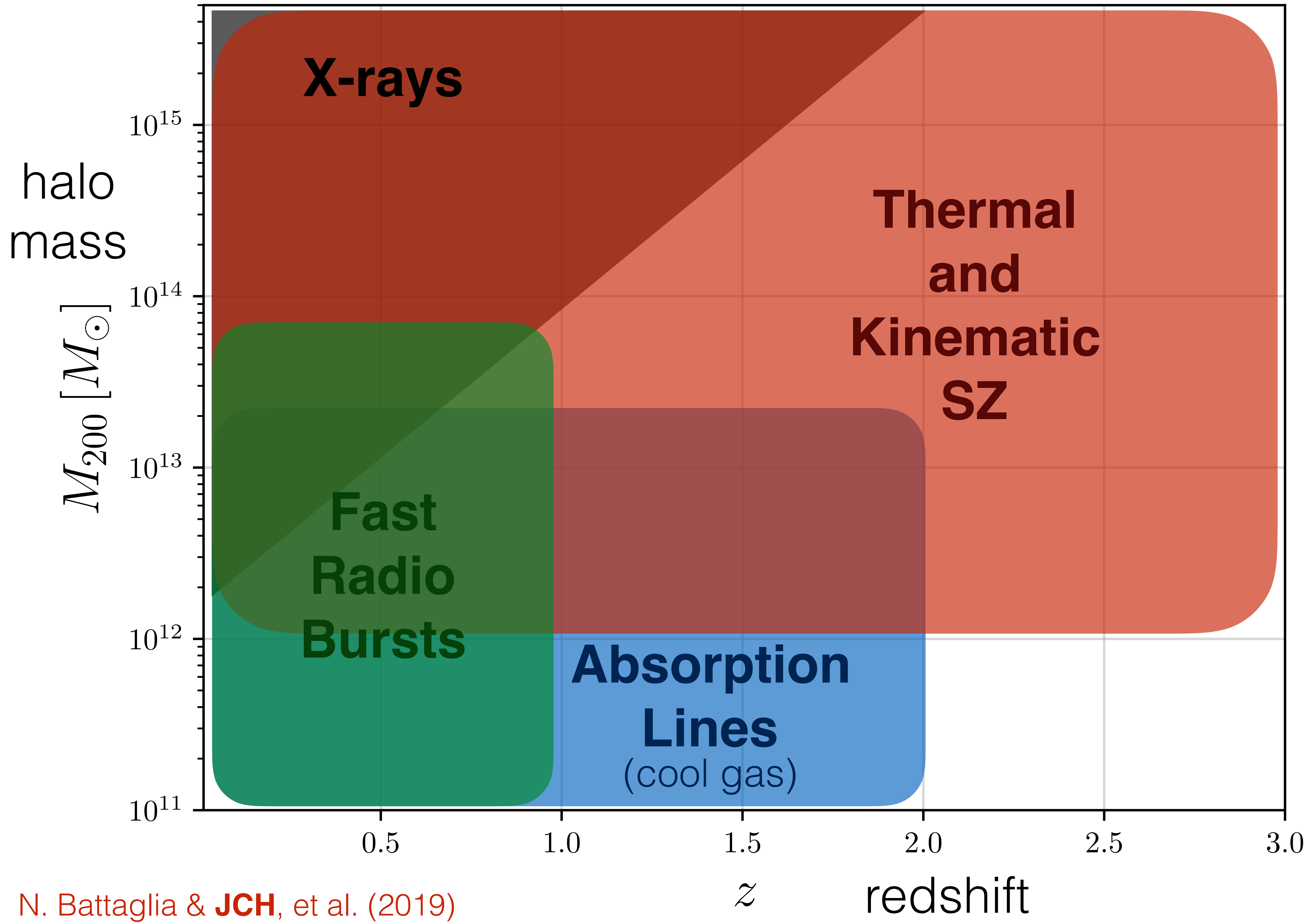
$$\frac{\Delta T_{\rm kSZ}(\hat{\mathbf{n}})}{T_{\rm CMB}} = -\frac{1}{c}\int_0^{\eta_{\rm re}} d\eta\, g(\eta)\, \mathbf{p}_e \cdot \hat{\mathbf{n}}$$

visibility function

- Unbiased tracer of free electrons — a precise tool to measure gas distribution (e.g., find "missing baryons")

Why tSZ/kSZ?

compare probes' sensitivity to gas properties near virial radius



N. Battaglia & **JCH**, et al. (2019)

Context

Why constrain feedback with tSZ/kSZ?

Unique advantages of tSZ/kSZ:

- Probe circumgalactic medium and intracluster medium (low-mass and high-mass systems)
- Probe low-z and high-z systems (z>1)
- Large samples of tSZ-detected groups and clusters are imminent: ~1000-2000 with AdvACT (on hand); ~20000 with SO
- Large sky coverage of ACT/SO (and Planck) allows cross-correlation with galaxy, cluster, and quasar samples at all other wavelengths
- Probe lower masses, higher redshifts, and larger radii than X-rays

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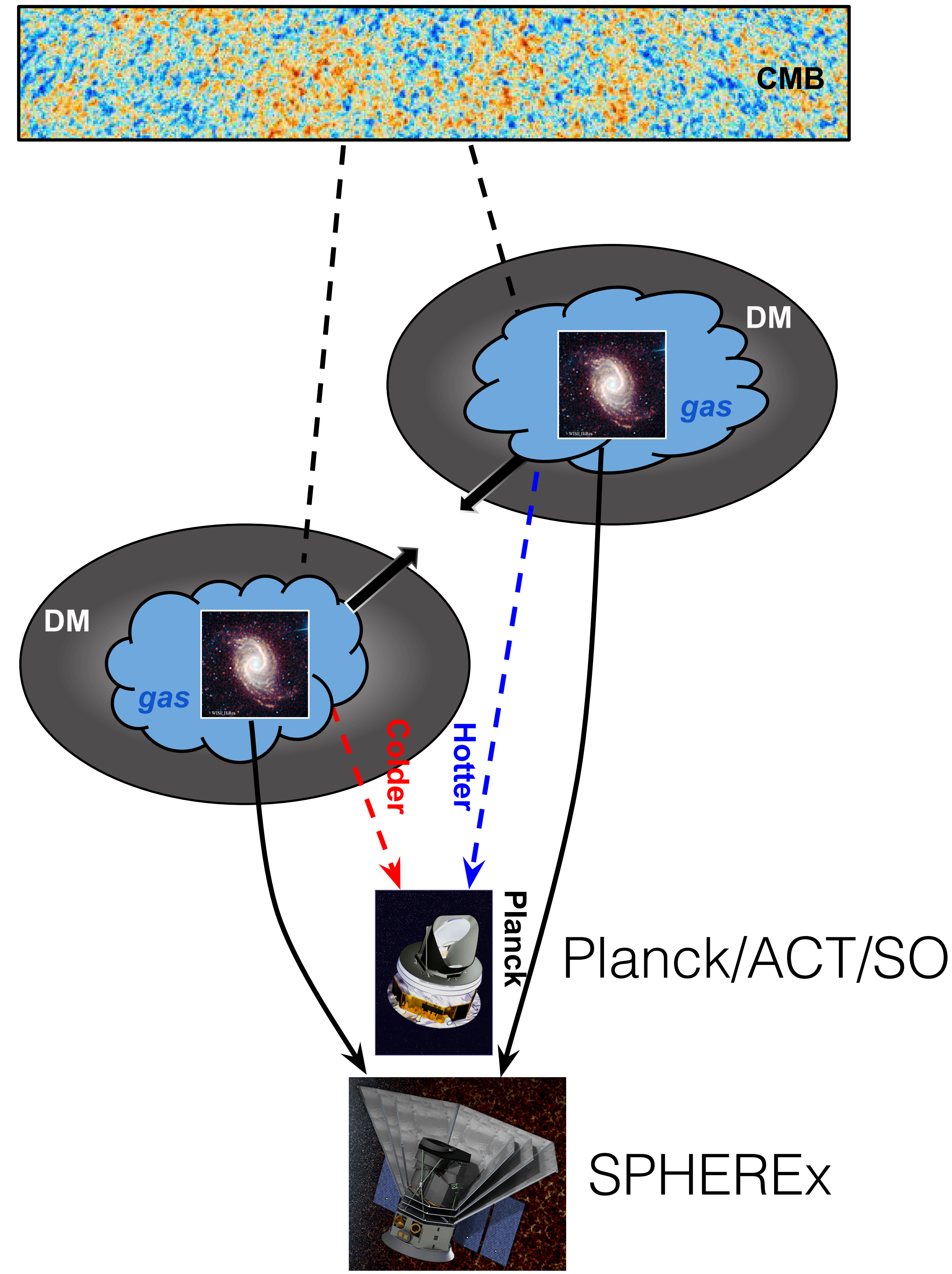
Kinematic SZ

Cross-Correlations

degenerate with primary CMB+lensing at power spectrum level

→ extract via cross-correlation with large-scale structure tracers



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Kinematic SZ

Cross-Correlations

degenerate with primary CMB+lensing at power spectrum level

→ extract via cross-correlation with large-scale structure tracers

Standard estimators (Smith+2019):

- mean pairwise momentum statistic

Ferreira+ (1999); Juszkiewicz+ (2000); Hand+ (2012)

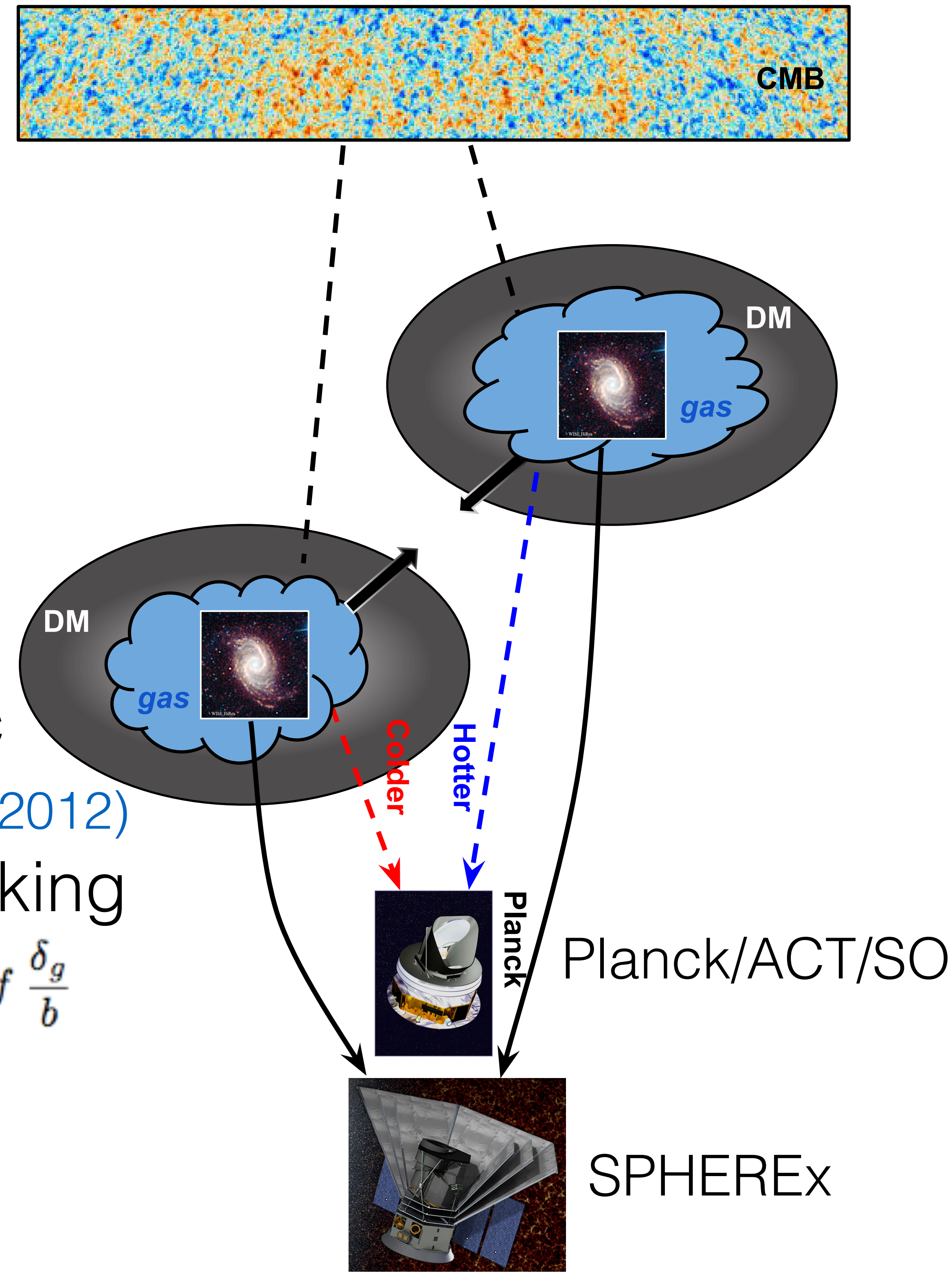
- velocity field reconstruction + stacking

Ho+ (2008)

$$\nabla \cdot \boldsymbol{v} + f \nabla \cdot [(\boldsymbol{v} \cdot \hat{\boldsymbol{n}})\, \hat{\boldsymbol{n}}] = -aHf\, \frac{\delta_g}{b}$$

→ require spectroscopic redshift data

Is there another way?



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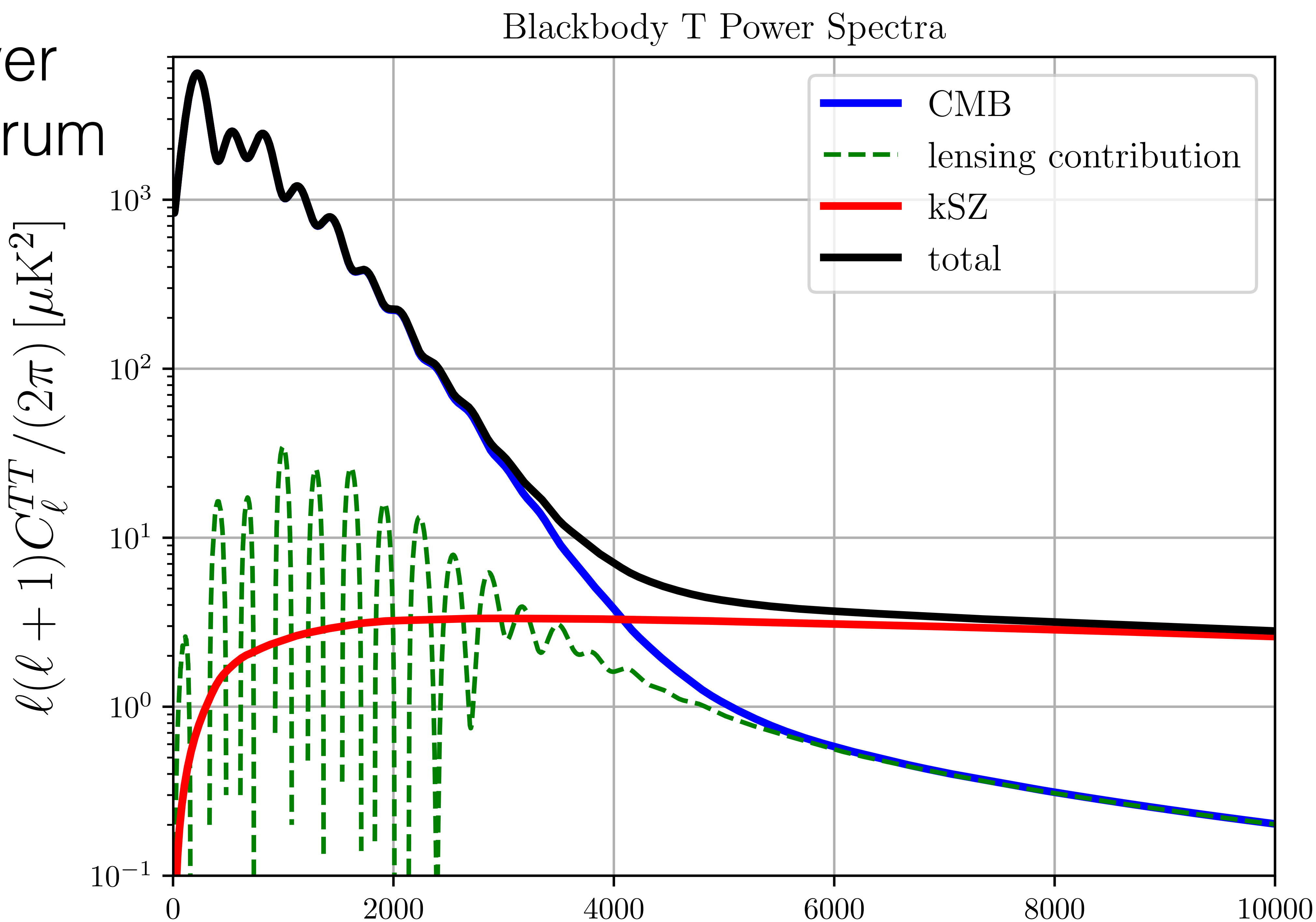
Novel kSZ Estimator

Main idea: blackbody T already contains kSZ information

Power Spectrum



Multipole ℓ

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Novel kSZ Estimator

Main idea: blackbody T already contains kSZ information

- Ideal frequency-cleaned CMB temperature map contains contributions from:
  - Primordial T (2<L<3000)
  - kSZ (primarily L>2000)
  - ISW (L<100) + RS/non-linear ISW (higher L, but small)

Dore+ (2004); DeDeo+ (2005); **JCH**+ (PRL 2016); Ferraro, **JCH**+ (2016)

Colin Hill
Columbia/CCA

Novel kSZ Estimator

Main idea: blackbody T already contains kSZ information

- Ideal frequency-cleaned CMB temperature map contains contributions from:
  - Primordial T ($2<L<3000$)
  - kSZ (primarily $L>2000$)
  - ISW ($L<100$) + RS/non-linear ISW (higher L, but small)

- Construct clean T map and apply a Wiener filter for kSZ

- Cross-correlate with LSS tracer (*projected* in 2D)
  - But <T x LSS> vanishes because of **v** ⟷ -**v** symmetry
  - Simplest fix: square in real space, measure <T^2 x LSS>
  - Measures a 3-pt function: <δ**pp**>
  - Caution: CMB lensing leakage (quadratic in T)

Dore+ (2004); DeDeo+ (2005); **JCH**+ (PRL 2016); Ferraro, **JCH**+ (2016)

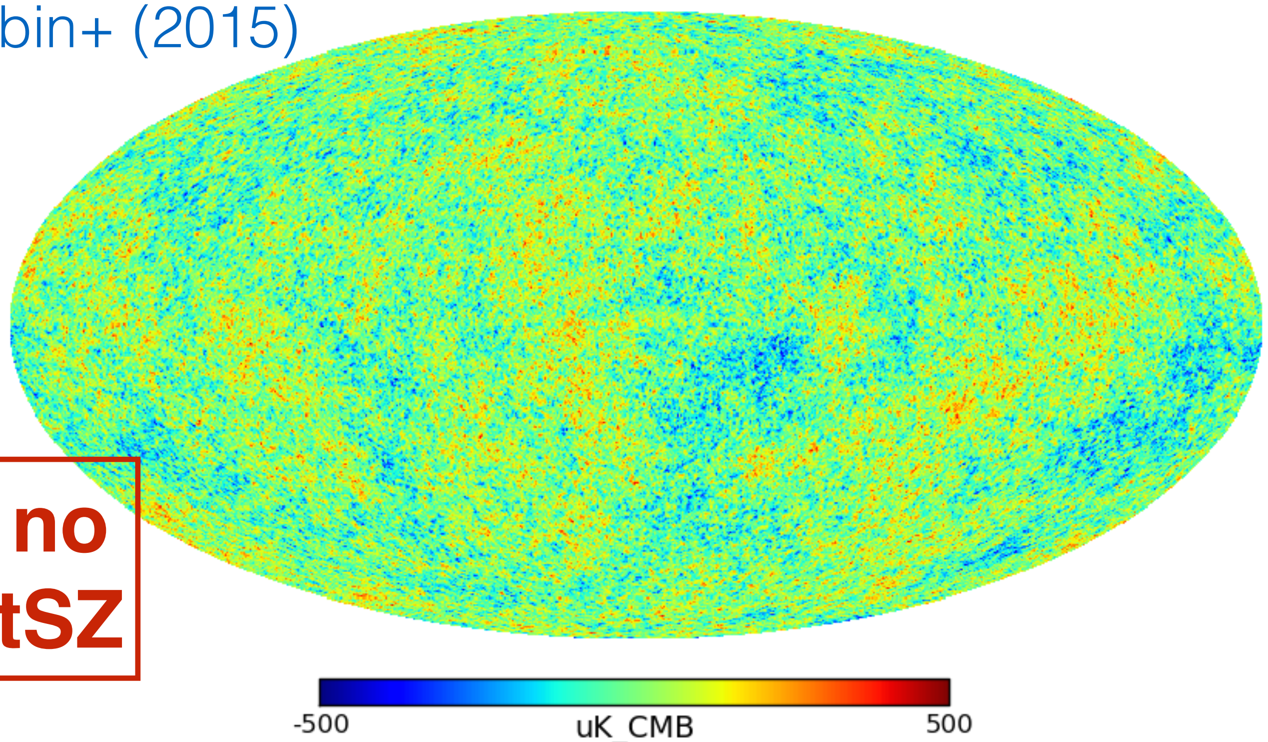
Colin Hill
Columbia/CCA

Novel kSZ Estimator

Planck/WMAP + WISE

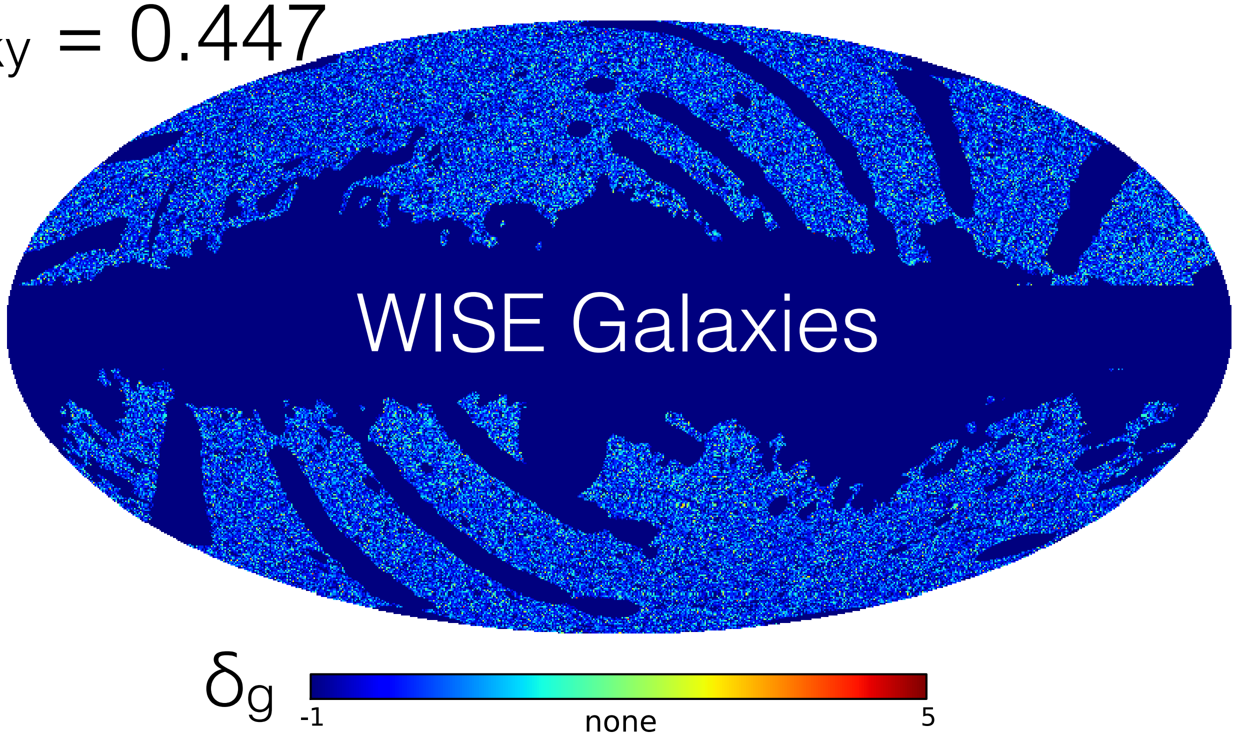
"LGMCA" CMB Map

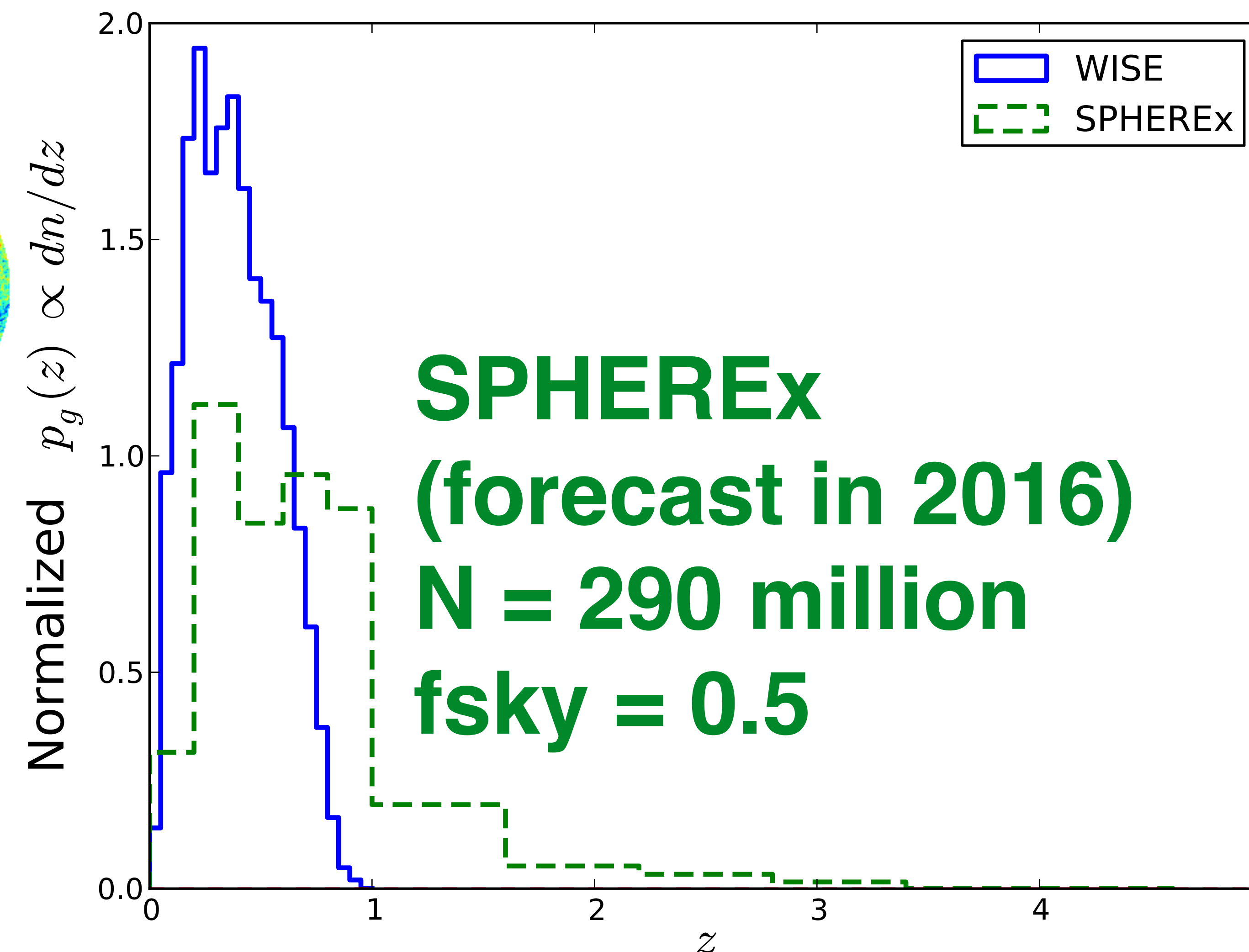
Bobin+ (2015)



no tSZ

f_{sky} = 0.447





N_{gal} ~ 46 million

<z> ~ 0.4 (dn/dz from SDSS cross-match)

L ~ L*

M ~ (1–5) x 10^{12} M_{sun}

JCH+ (PRL 2016)

Colin Hill
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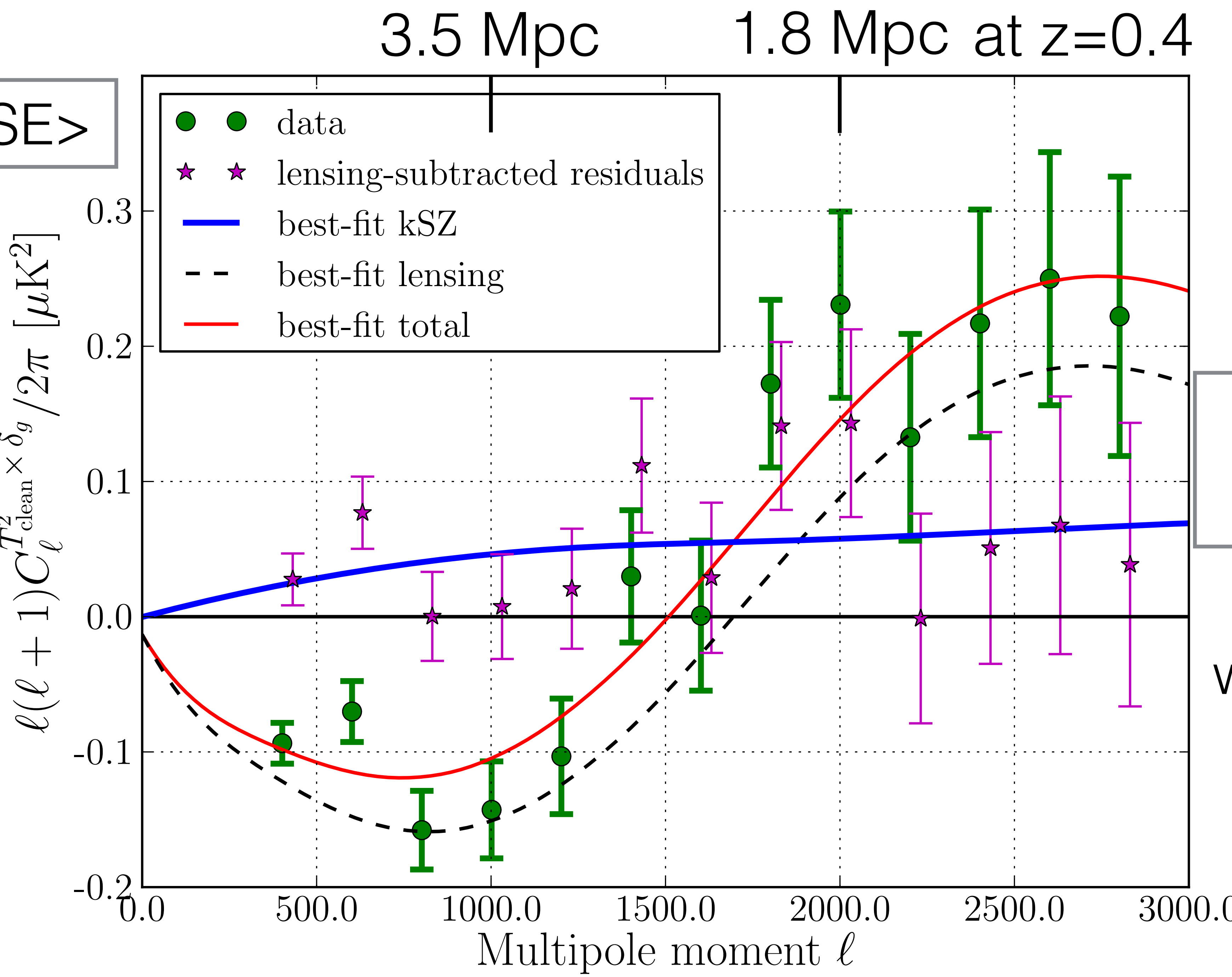
Novel kSZ Estimator

Detection with WISE (after further cleaning dust)

<T_{clean}^2 x WISE>



Multipole

3.8σ kSZ detection

model fits well (p=0.28)

JCH+ (PRL 2016)

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Forecasts/Outlook

Large improvement expected with higher res. + lower noise

CMB experiment	beam FWHM [arcmin]	effective noise[a] Δ_T [μK-arcmin]
Planck (2015 LGMCA map)	5	47
Simons Observatory	1.4	10

→ after foreground cleaning

	$f_{\rm sky}$	ℓ range	$\left(\frac{\Delta f_{\rm free}}{f_{\rm free}}\right)^{-1}$
Planck × *WISE*	0.7	100 - 3000	5.2
Planck × *SPHEREx*	0.7	100 - 3000	5.4
Simons Observatory × *WISE*	0.5	100 - 8000	232
Simons Observatory × *SPHEREx*	0.5	100 - 8000	280

Ferraro, **JCH**+ (2016)

Colin Hill
Columbia/CCA

Forecasts/Outlook

Large improvement expected with higher res. + lower noise

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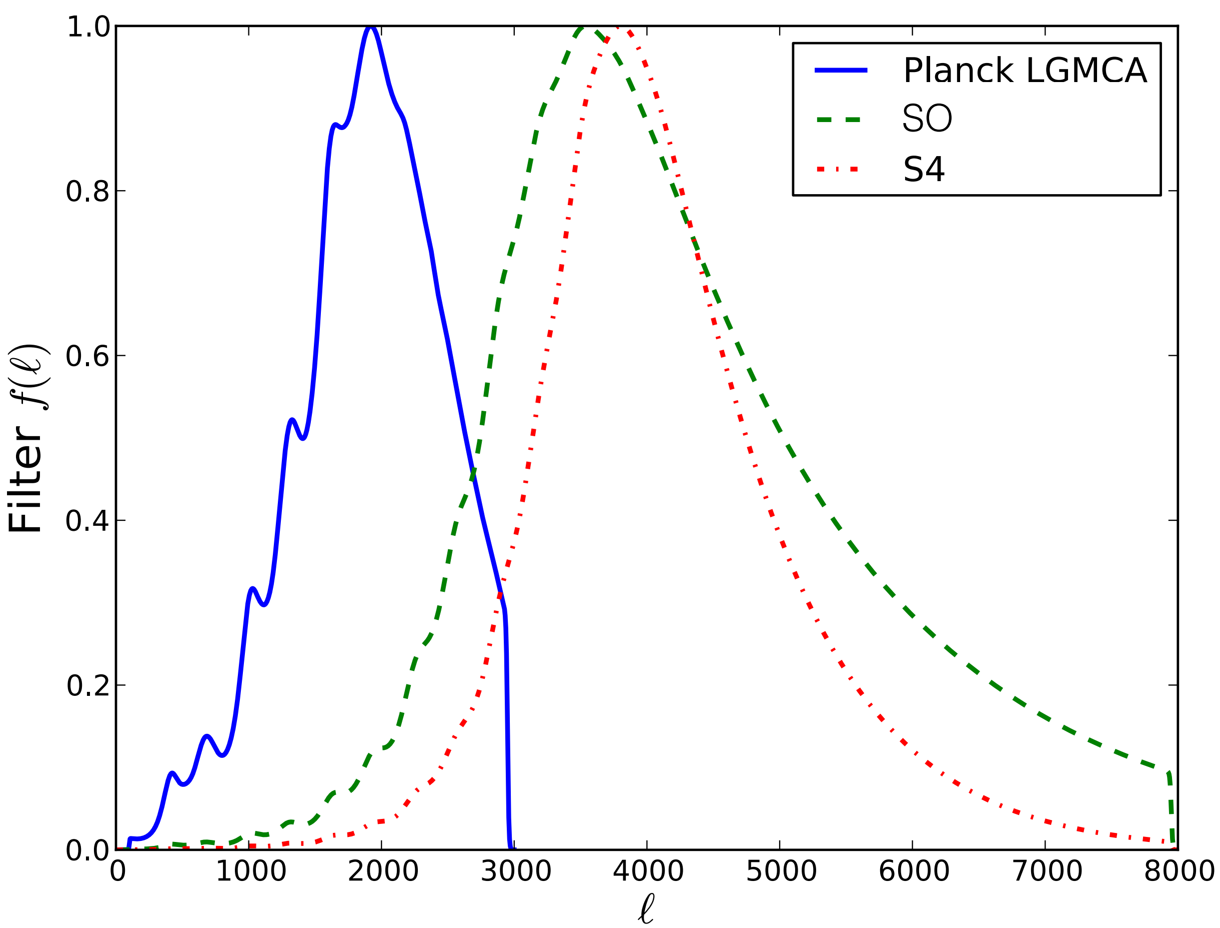
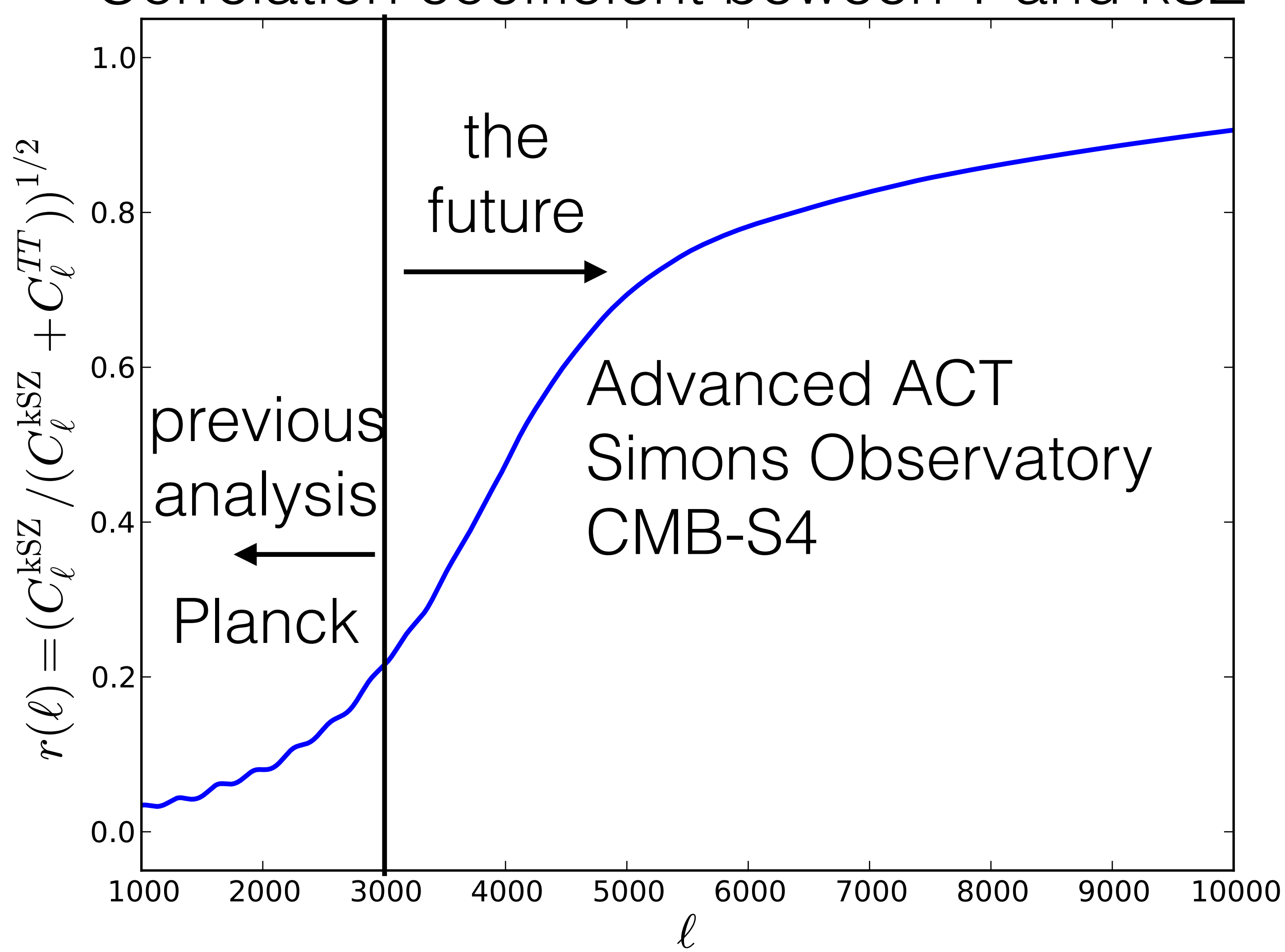
Simons Observatory × *WISE*	0.5	100 - 8000	232
Simons Observatory × *SPHEREx*	0.5	100 - 8000	280

Why? The kSZ signal dominates on small scales



Correlation coefficient beween T and kSZ



Ferraro, **JCH**+ (2016)

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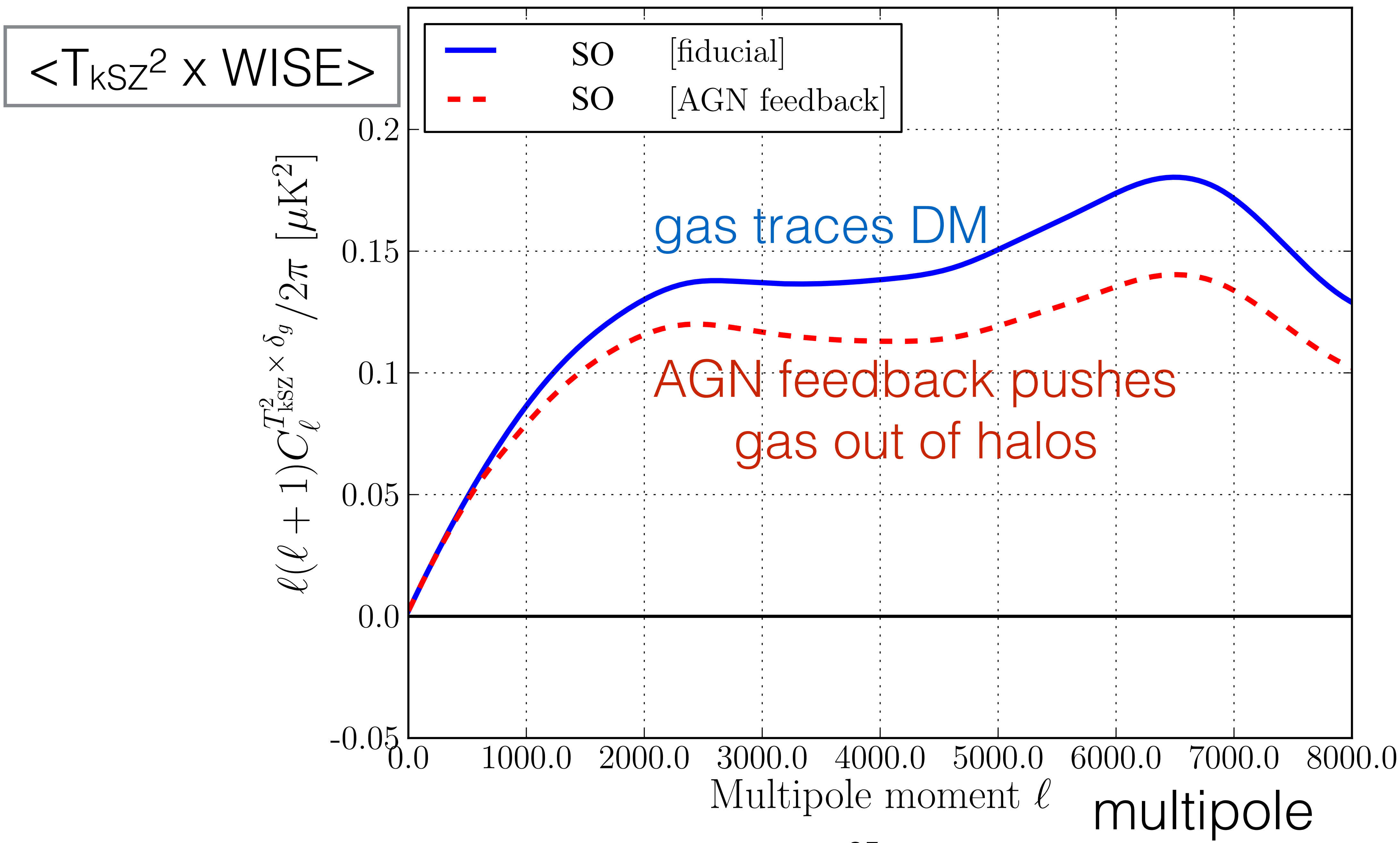
Columbia/CCA

Kinematic SZ: Feedback

Projected-field estimator opens a new window for kSZ measurements from non-spectroscopic surveys

Strong sensitivity to AGN feedback models via gas distribution



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kSZ: Project Pitches

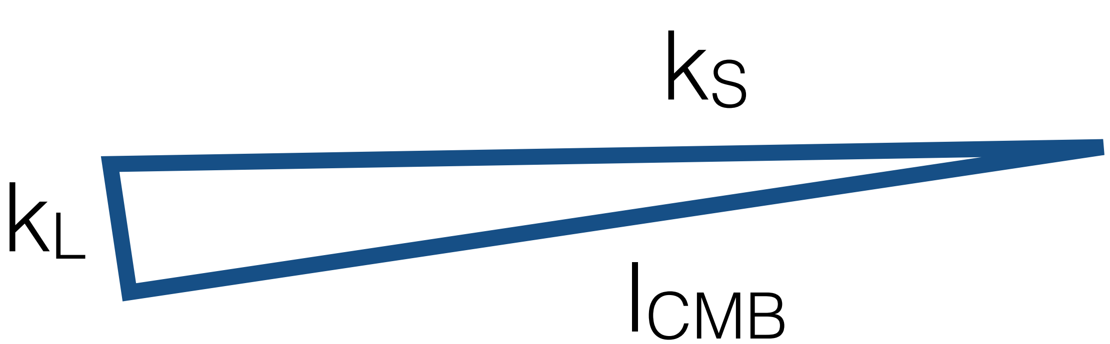
1) Improved Estimator

SPHEREx is an interesting limit in which the S/N from both spectroscopic <Tδδ> and non-spectroscopic <TTδ> estimators is substantial

<Tδδ>: SO x SPHEREx S/N ~ 70 using 24.5 million galaxies (Dore+2018)
<TTδ>: SO x SPHEREx S/N ~ 140 using 290 million galaxies

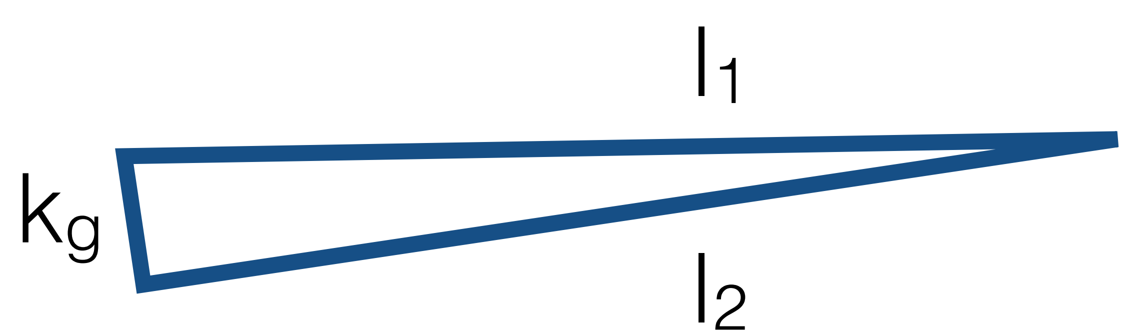
Pitch: develop an optimal estimator that combines information in these two limits to extract the full kSZ S/N in the SPHEREx data

<Tδδ>



<Tδδ> ~ $P_{gv}(k_L)P_{ge}(k_S)$

<TTδ>



<TTδ> ~ $\frac{1}{3} v_{\rm rms}^2 B_m^{\rm NL}$

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kSZ: Project Pitches

2) Improved Forecasts/Methodology for SPHEREx

SPHEREx dn/dz is sufficiently broad that optimal redshift weighting should increase S/N non-negligibly

[Also: forecasts can now be re-run using realistic component-separated noise curves for SO]

Astrophysics: the small-scale kSZ signal is expected to depend sensitively on galaxy properties, e.g., color, star formation rate, stellar mass, etc.

Pitch: determine optimal redshift weighting and most interesting SPHEREx observable proxies on which to split samples in order to probe feedback with kSZ (and tSZ)

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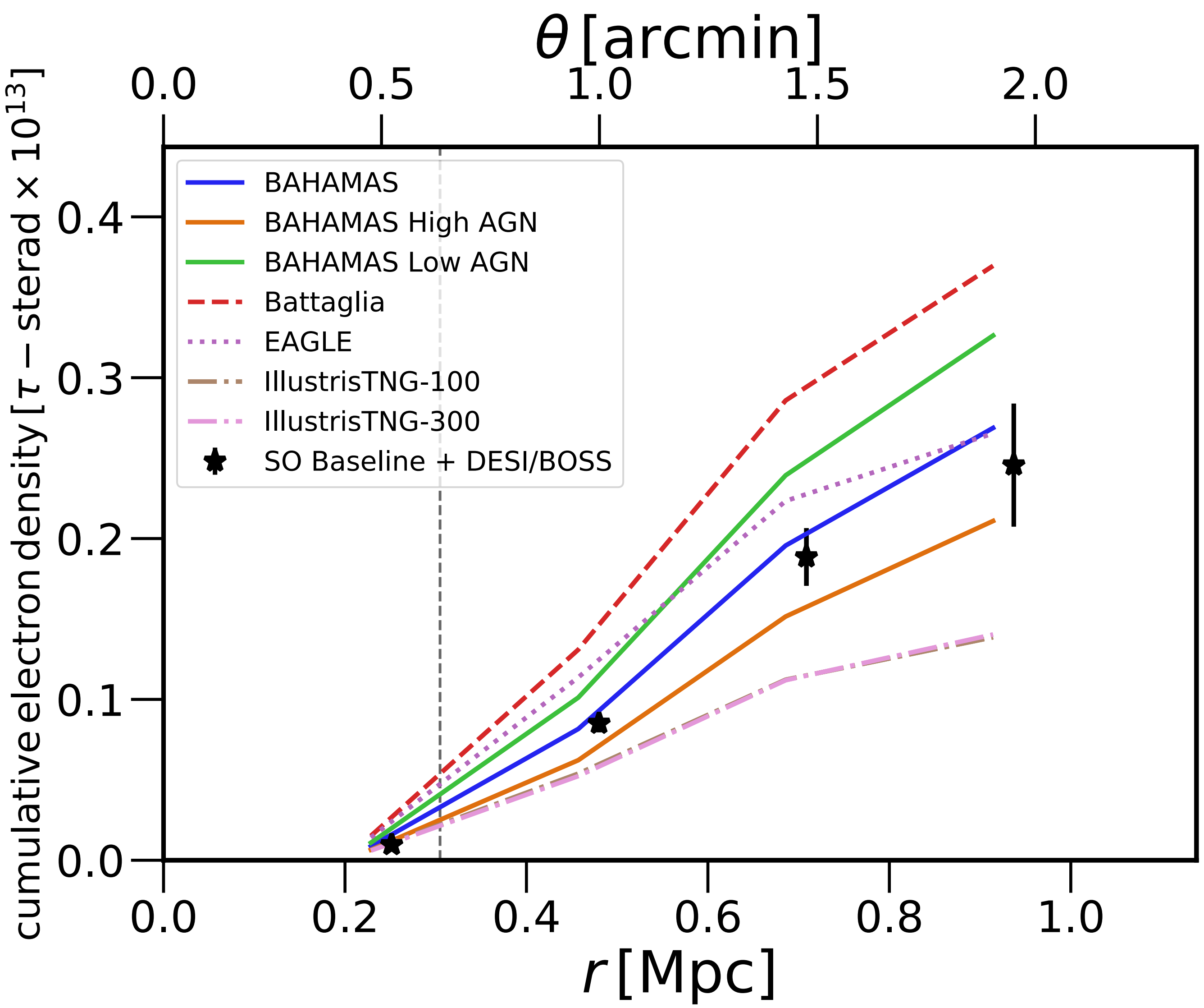
kSZ: Project Pitches

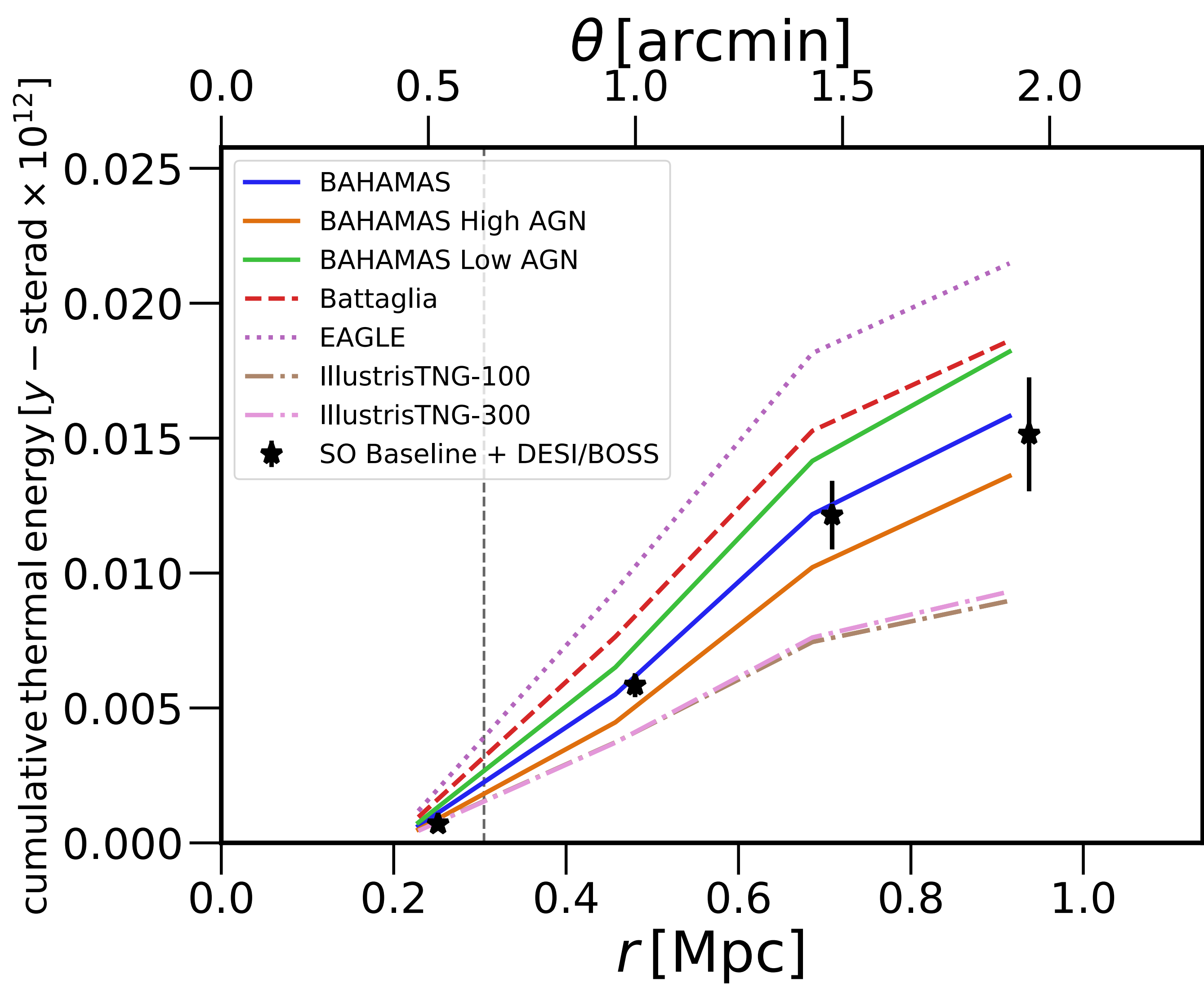
3) Joint tSZ+kSZ Analysis Using SO and SPHEREx Data

Example: stacking 250,000 LRGs at z=1 (M_{200} = 10^{13} M_{sun})

Gas Density via kSZ



Gas Pressure via tSZ



JCH+ (in prep) + CMB-S4 Decadal Survey Report (1907.04473)

Thanks!

https://simonsobservatory.org/

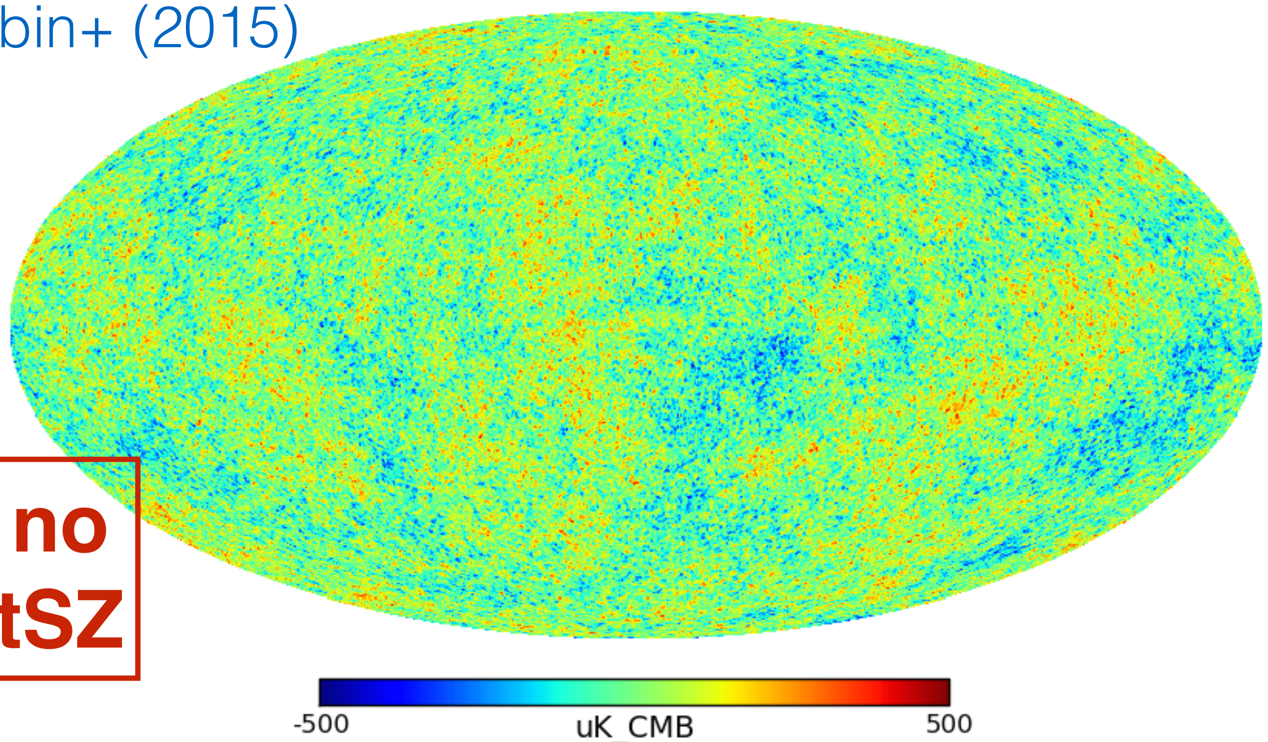
Colin Hill
Columbia/CCA

Novel kSZ Estimator

Planck/WMAP + WISE

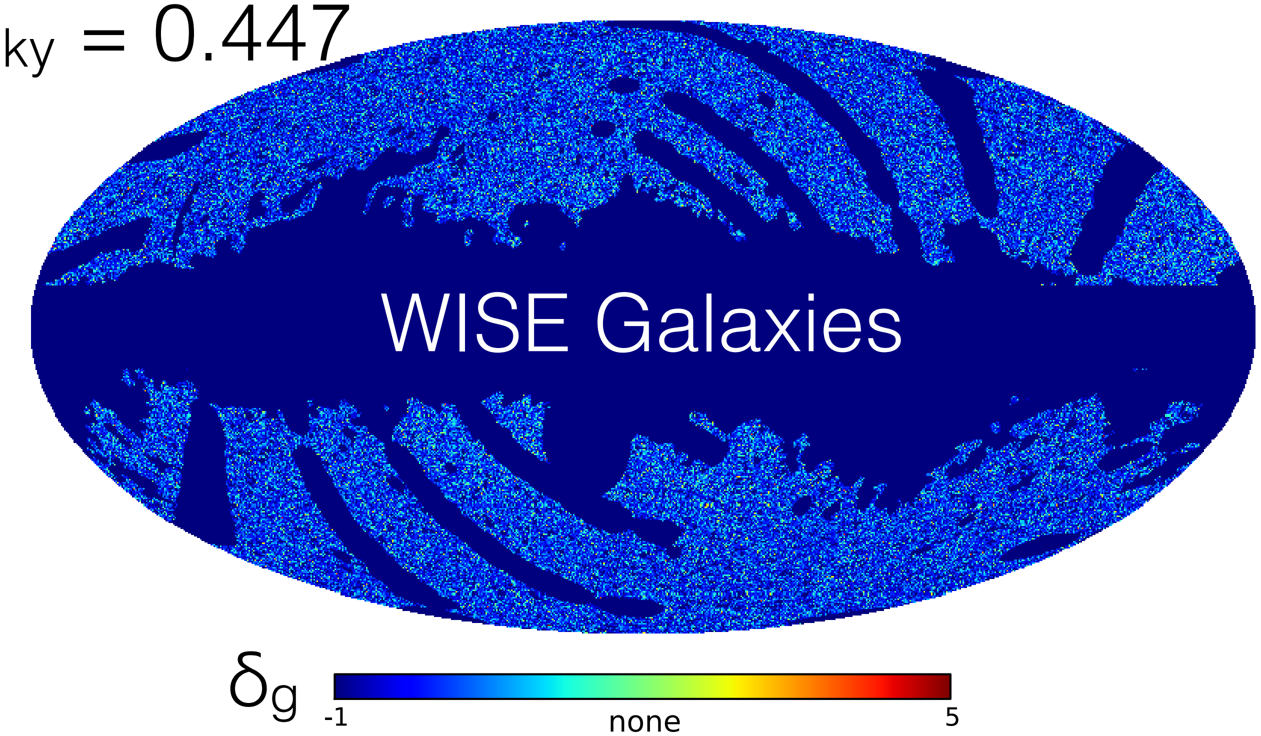
"LGMCA" CMB Map

Bobin+ (2015)



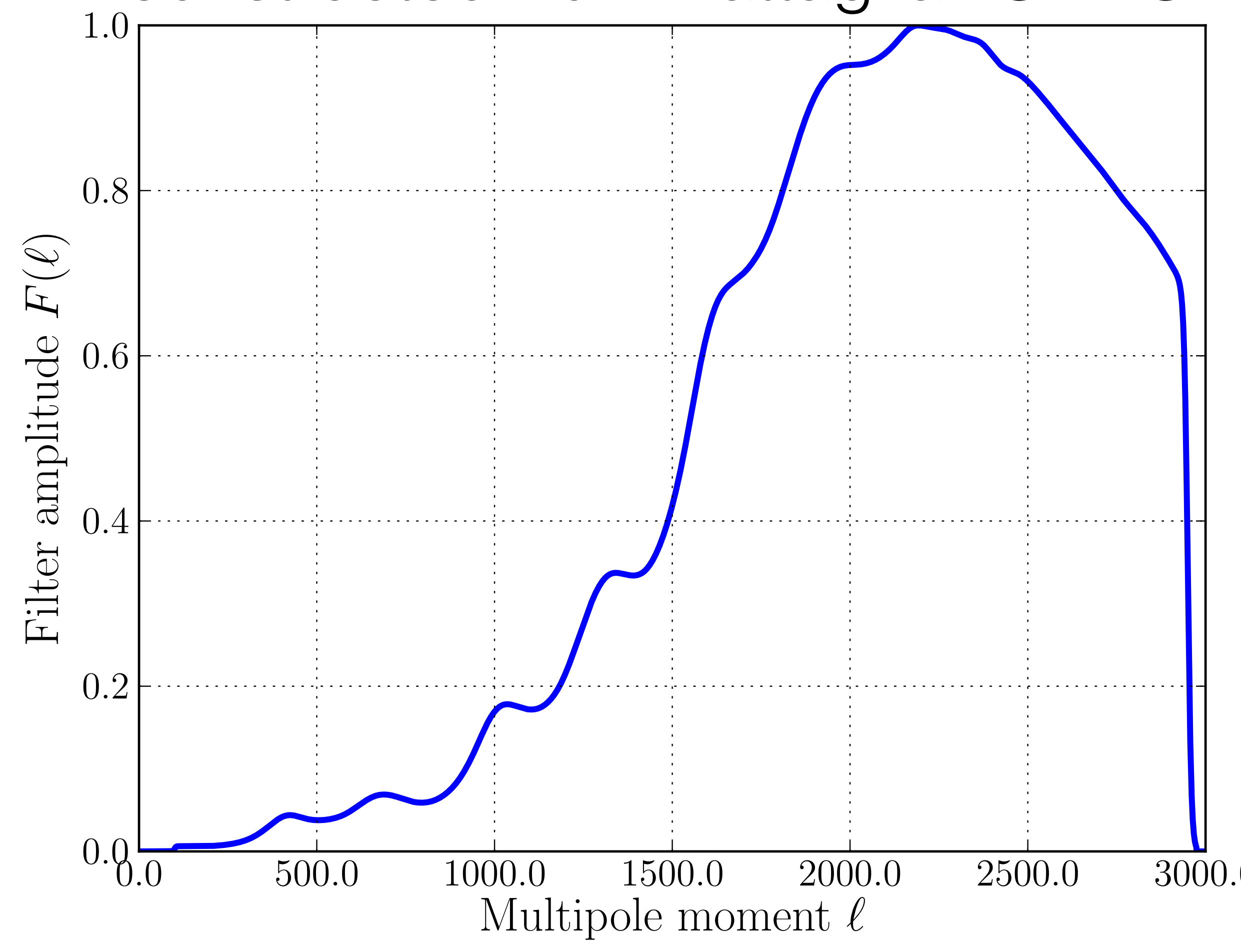
no tSZ

$f_{sky} = 0.447$



Wiener filter

constructed from Battaglia kSZ PS



N_{gal} ~ 46 million

<z> ~ 0.4 (dn/dz from SDSS cross-match)

L ~ L*

M ~ (1–5) x 10^{12} M_{sun}

JCH+ (PRL 2016)

Data Analysis

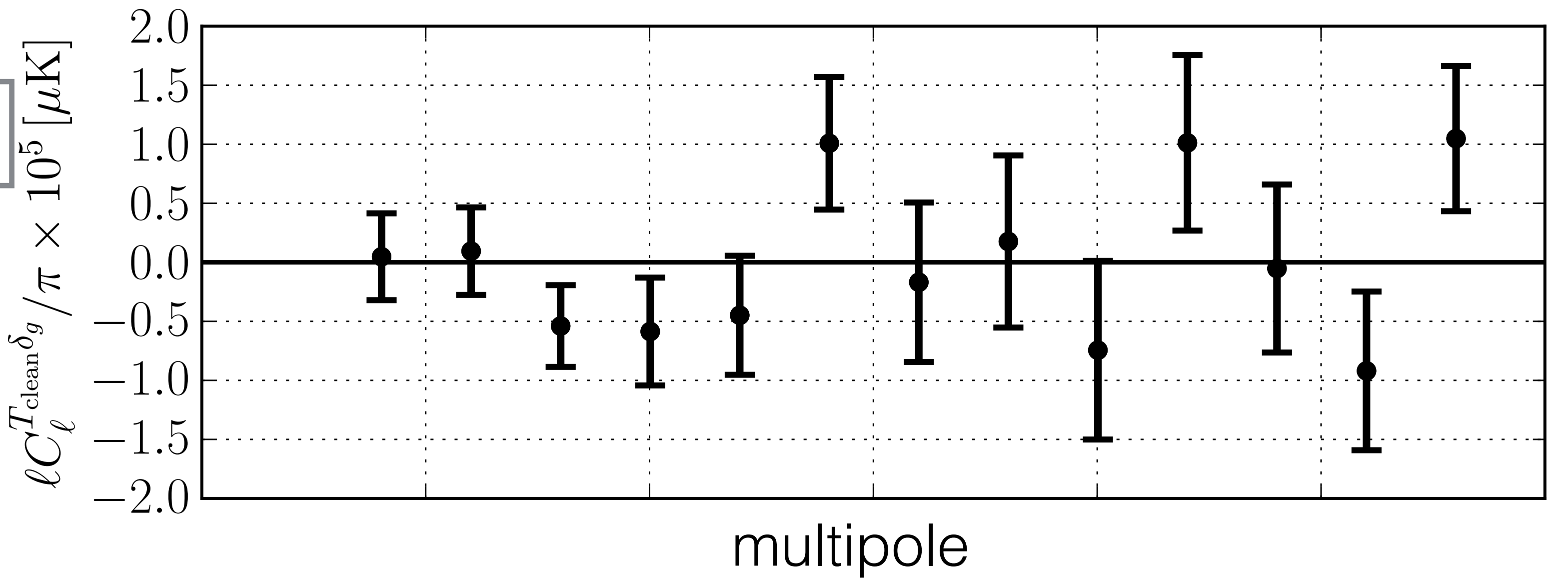
Extra Cleaning: Dust

Colin Hill
Columbia

- T_{dust} = CMB-free combination of 545 and 217 GHz (SFH14)
- $T_{clean} = (1+\alpha)T_{LGMCA} - \alpha^* T_{dust}$ where α minimizes $\langle((1+\alpha)T_{LGMCA} - \alpha^* T_{dust}) \times \mathrm{WISE}\rangle$ ($\alpha_{min} = -0.0002$)

$\langle T_{clean} \times \mathrm{WISE}\rangle$

Test for any mean residual emission



p = 0.20
(p=0.08 w/ no cleaning)

Data Analysis

Colin Hill
Columbia

Extra Cleaning: Dust

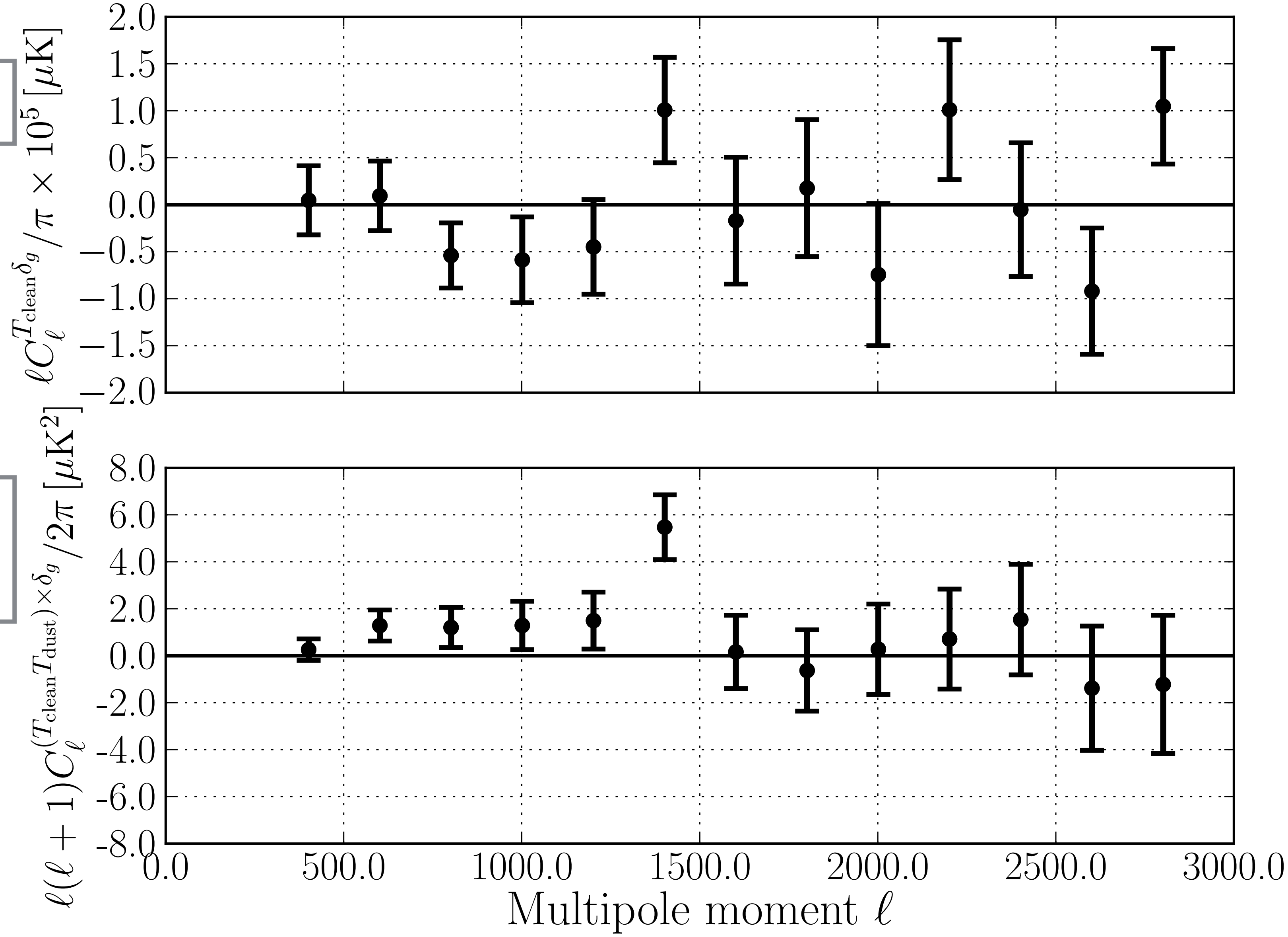
- T_{dust} = CMB-free combination of 545 and 217 GHz (SFH14)
- $T_{clean} = (1+\alpha)T_{LGMCA} - \alpha^* T_{dust}$ where α minimizes $\langle((1+\alpha)T_{LGMCA} - \alpha^* T_{dust}) \times \text{WISE}\rangle$ ($\alpha_{min} = -0.0002$)

<T_{clean} x WISE>

Test for any mean residual emission

<(T_{clean}*T_{dust}) x WISE>

Test for residual dust emission, including fluctuations



p = 0.20 (p=0.08 w/ no cleaning)

p = 0.02 **but** must rescale amplitude from 545 GHz to CMB channels a factor ~400-500

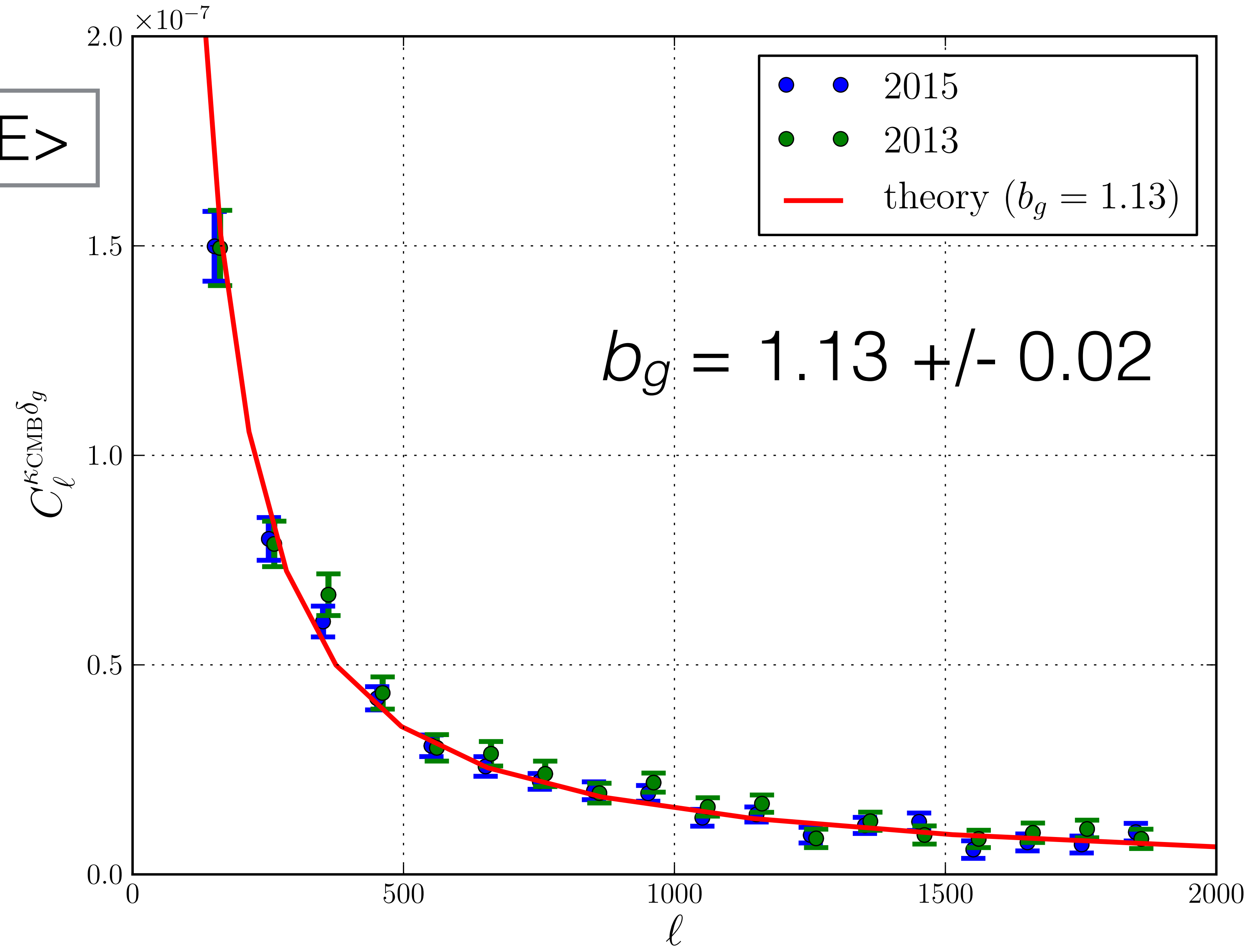
+other null tests

Colin Hill
Columbia

Data Analysis

External constraint on WISE galaxy bias from κ_{CMB}

<κ_{CMB} x WISE>

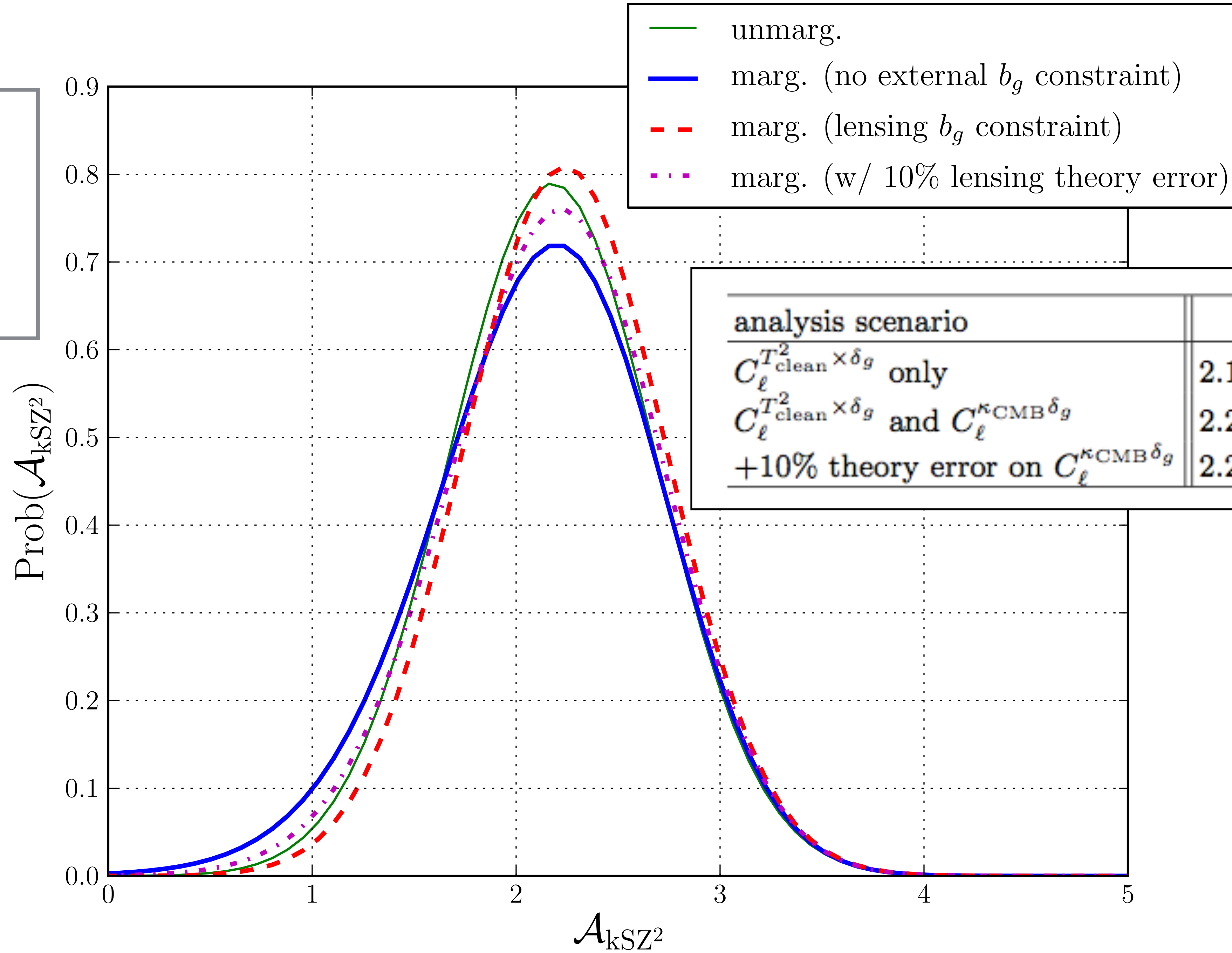


Consistent bias values are also an important test for the <T² x WISE> framework

Colin Hill
Columbia

Interpretation

3.8-4.5σ
kSZ^2
detection



analysis scenario	$\mathcal{A}_{\mathrm{kSZ}^2}$	b_g
$C_\ell^{T^2_{\mathrm{clean}} \times \delta_g}$ only	2.18 ± 0.57	1.10 ± 0.11
$C_\ell^{T^2_{\mathrm{clean}} \times \delta_g}$ and $C_\ell^{\kappa_{\mathrm{CMB}} \delta_g}$	2.24 ± 0.50	1.13 ± 0.02
+10% theory error on $C_\ell^{\kappa_{\mathrm{CMB}} \delta_g}$	2.21 ± 0.53	1.11 ± 0.08

consistent with expected cosmic baryon abundance: $(f_b/0.155)\,(f_{\mathrm{free}}/1.0) = 1.48 \pm 0.19$

N.B. theoretical systematics at ~10s% (e.g., NL bispectrum, σ_8/parameters, …)

Colin Hill
Columbia

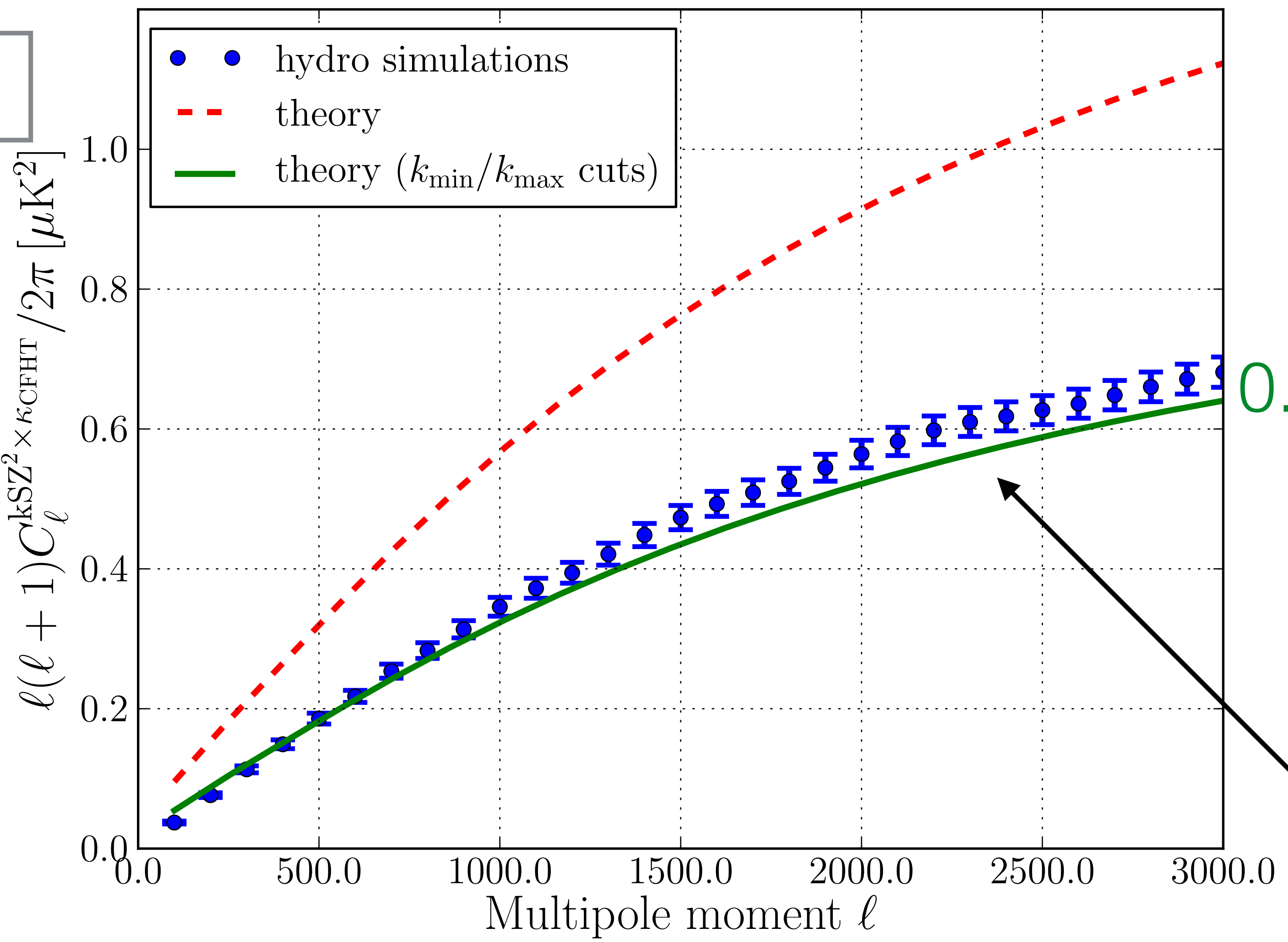
Simulation Tests

Comparison to Battaglia+ cosmological hydro sims.

sim. LSS tracer = CFHTLenS lensing convergence

<kSZ^2 x κ_{CFHT}>

(unfiltered)



0.038 *h*/Mpc < *k* < 76 *h*/Mpc

must account for the effect of missing super-box long-wavelength modes on the velocity field (c.f. Park+ 2013)

(50% of <v_{rms}^2> comes from *k* < 0.06 *h*/Mpc)

Colin Hill
Columbia

Simulation Tests

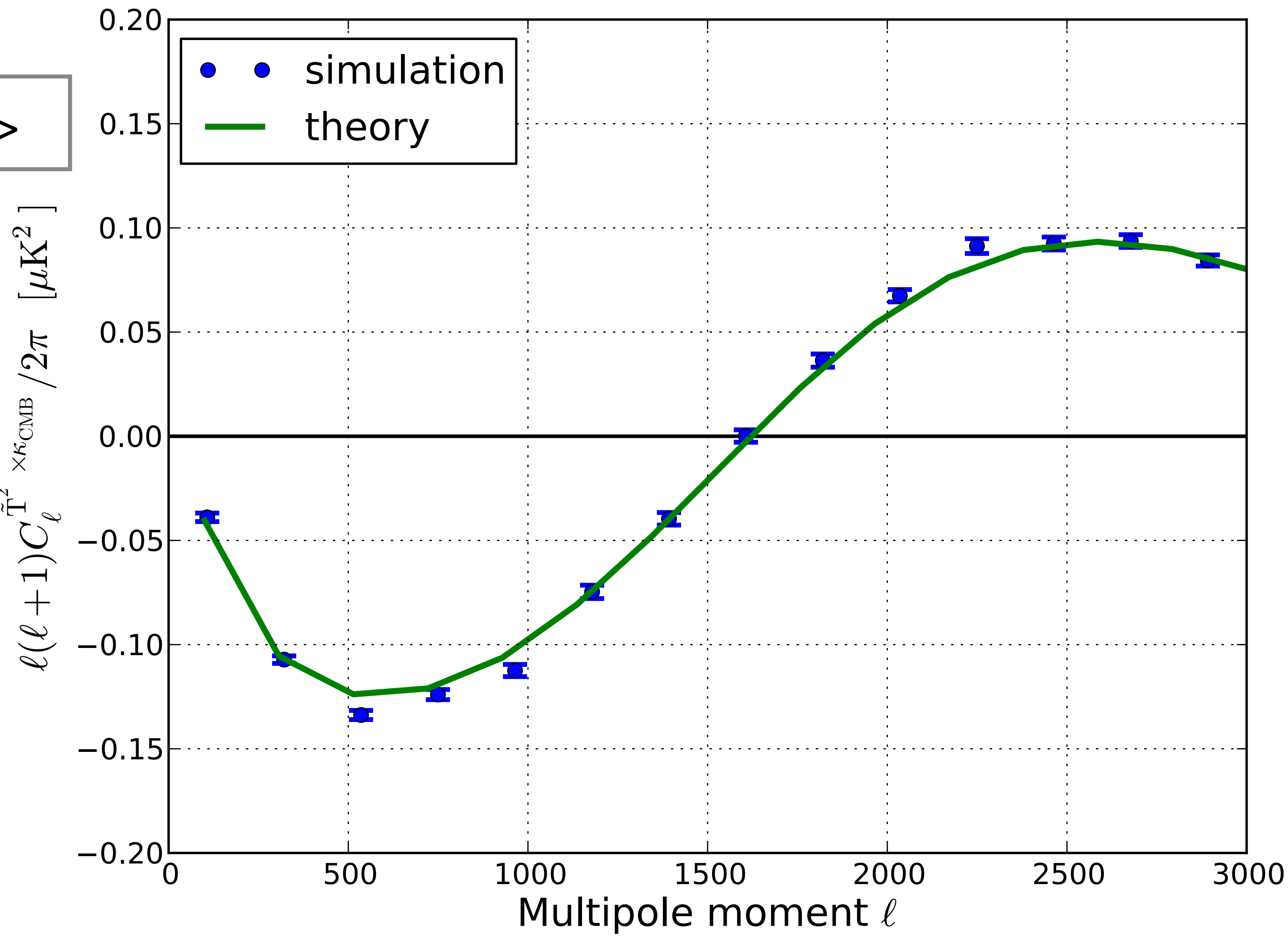
Comparison to Sehgal+ sims (N-body/“painted gas”)

sim. LSS tracer = CMB lensing convergence

verification of CMB lensing “leakage” calculation for kSZ^2

<T^2 x κ_{CMB}>

(filtered)

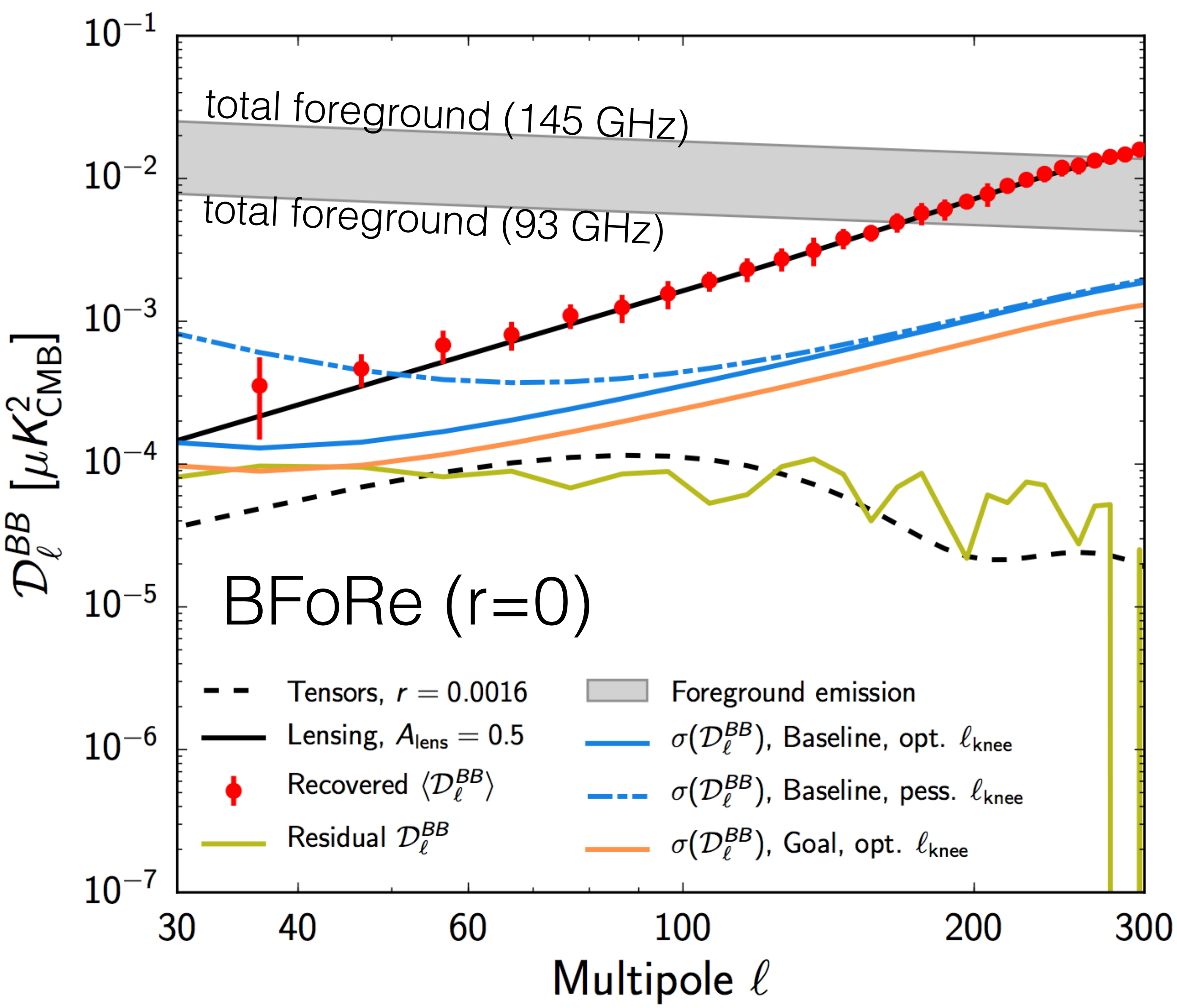


SO SAT Science: Primordial Tensor Modes

Colin Hill
Columbia/CCA

SAT BB forecasting based on full-sky simulated maps (PySM) w/ multiple sets of realistic foregrounds

Sky models are combined with SO SAT noise model, then coupled to several foreground mitigation schemes (cross-spectrum analysis, xForecast, BFoRe, harmonic-space ILC) to infer *r*



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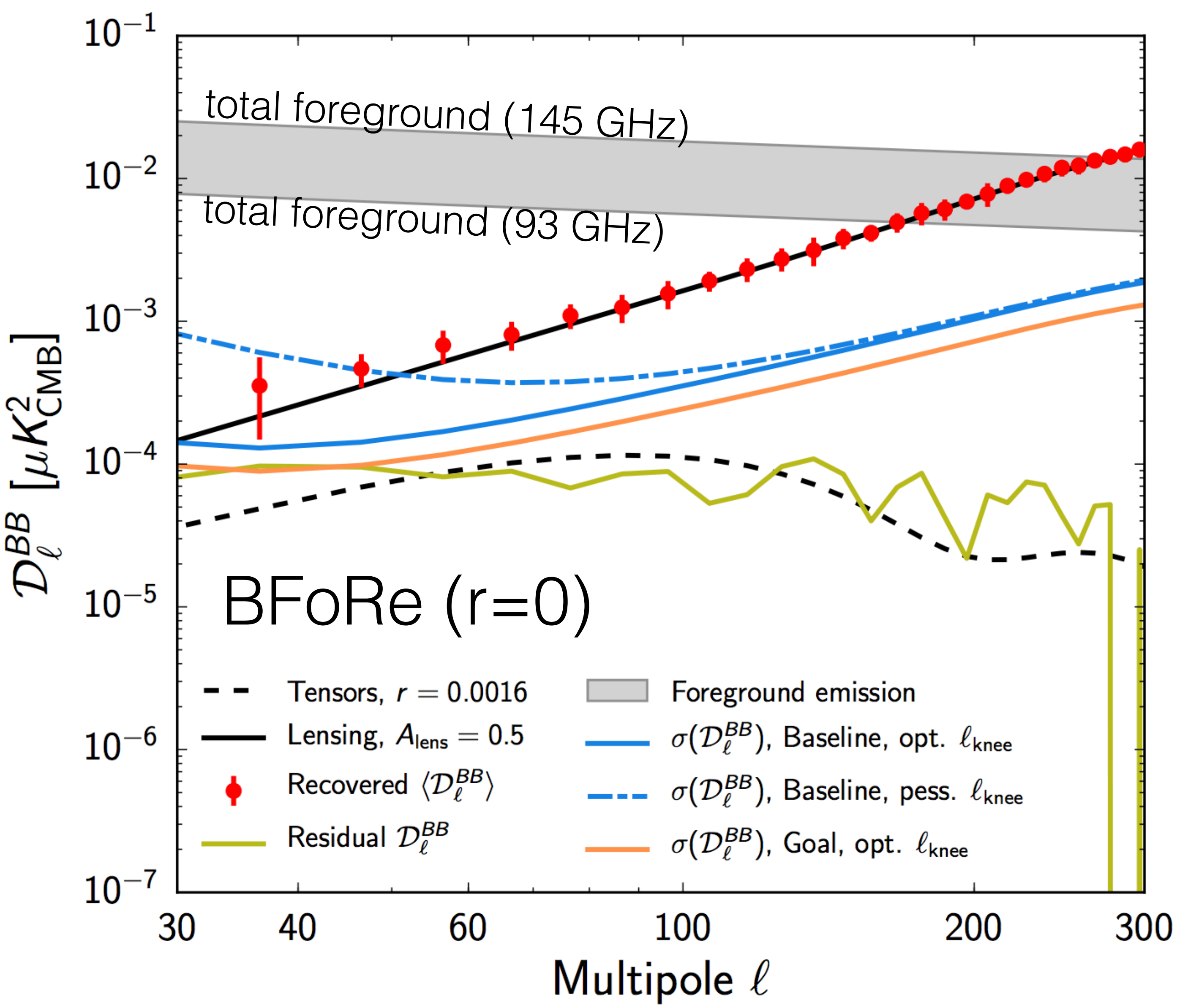

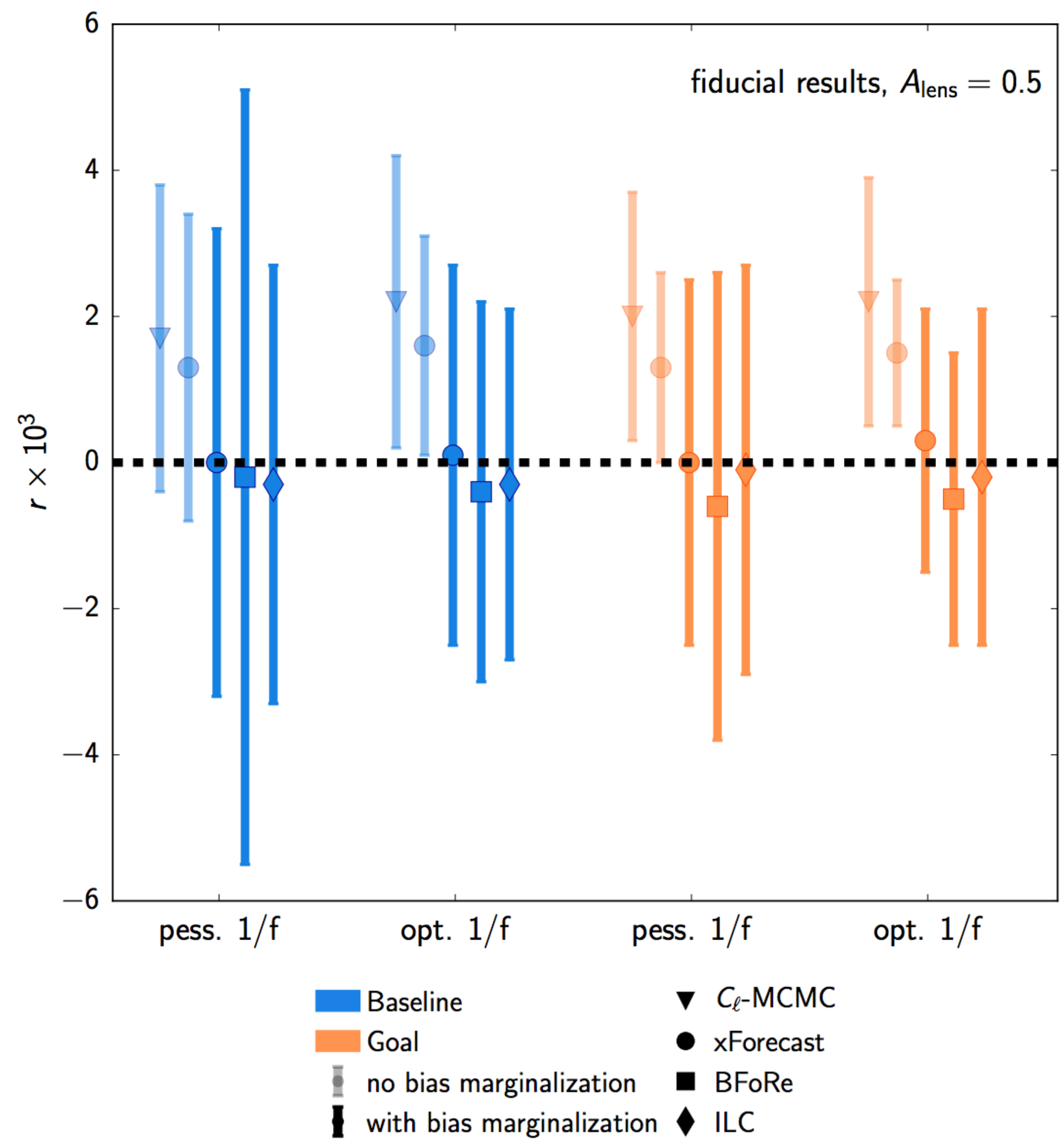

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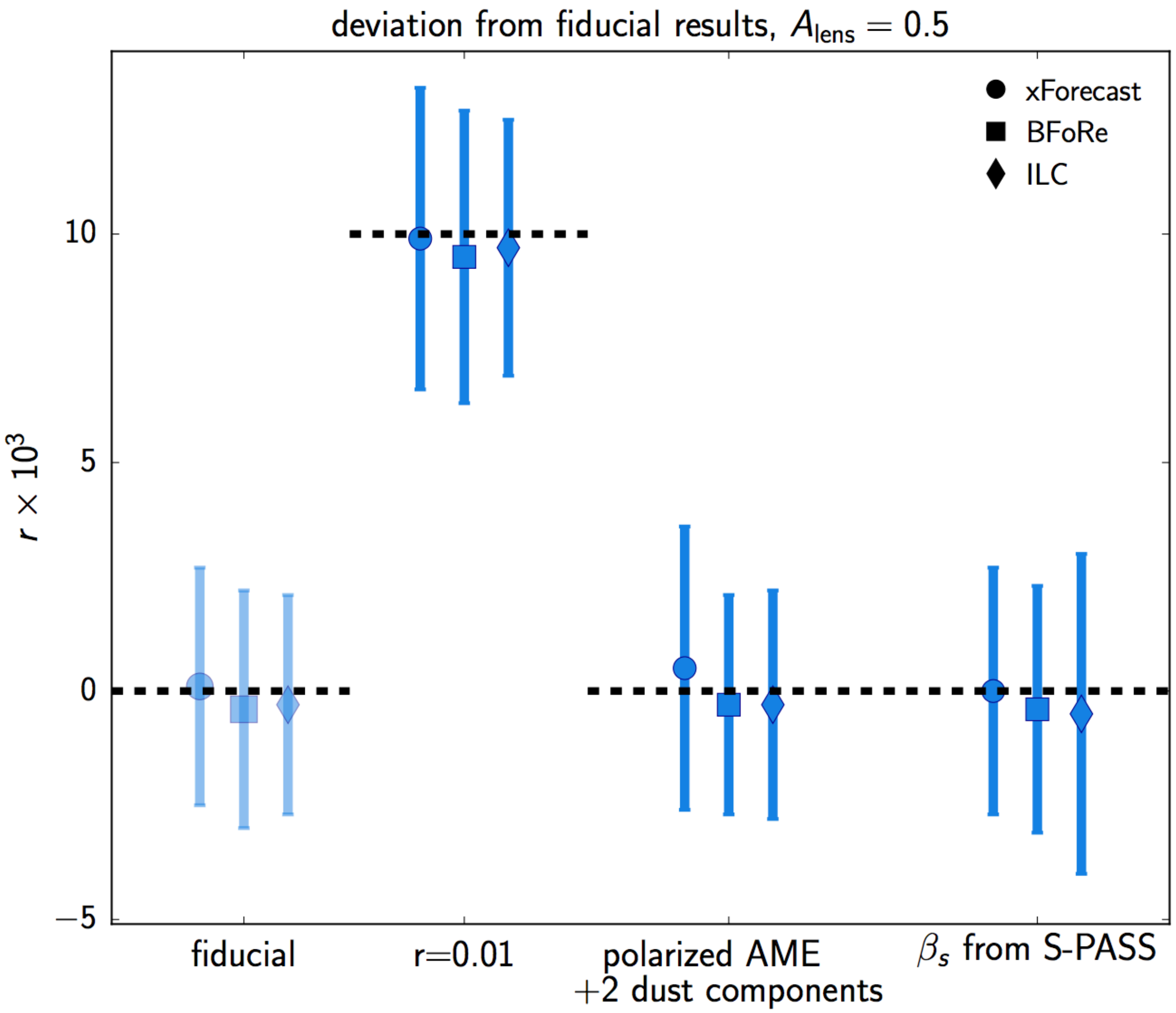
SO SAT Science: Primordial Tensor Modes

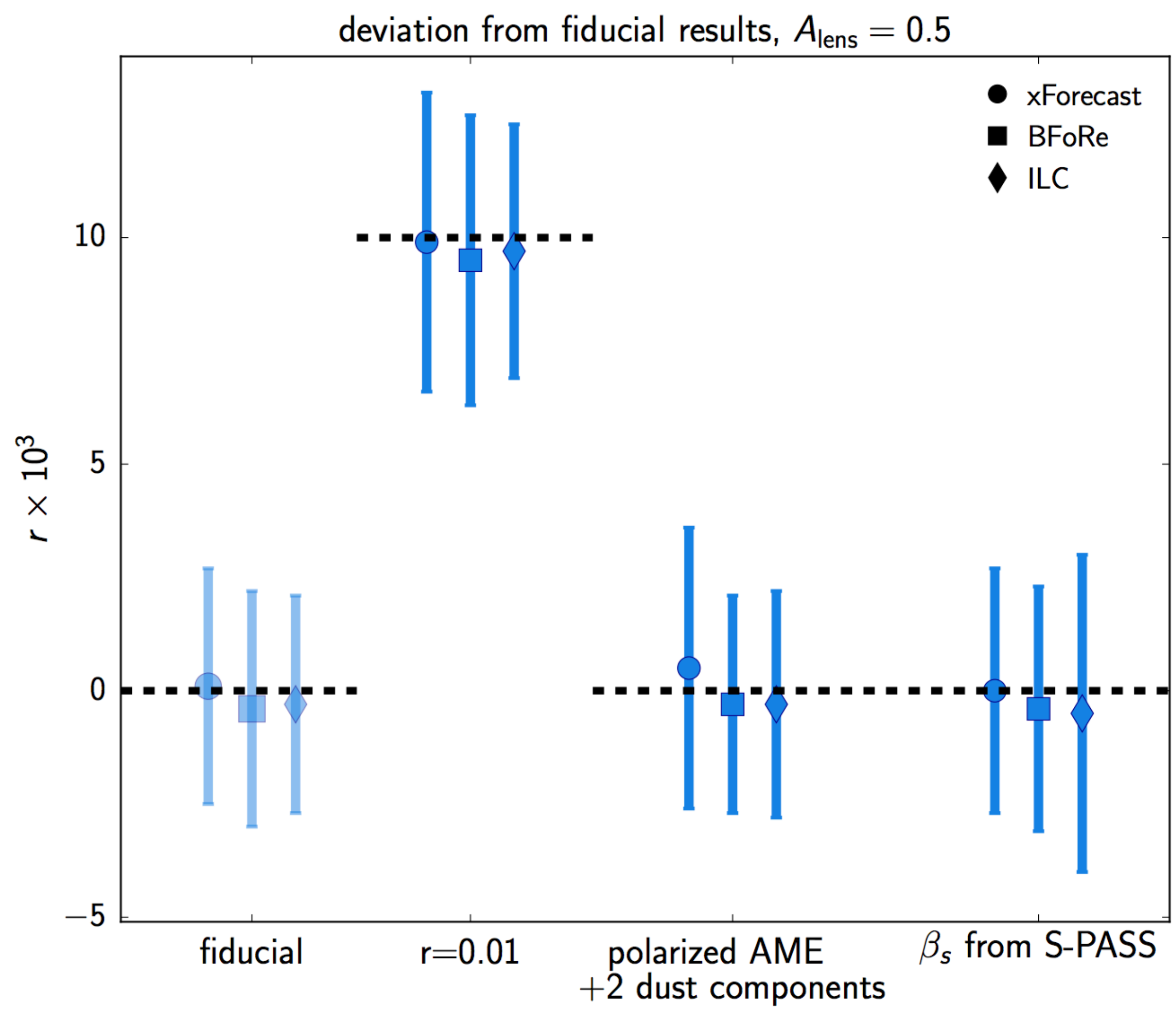
Robust to variations in foreground model complexity (within the space of models explored)



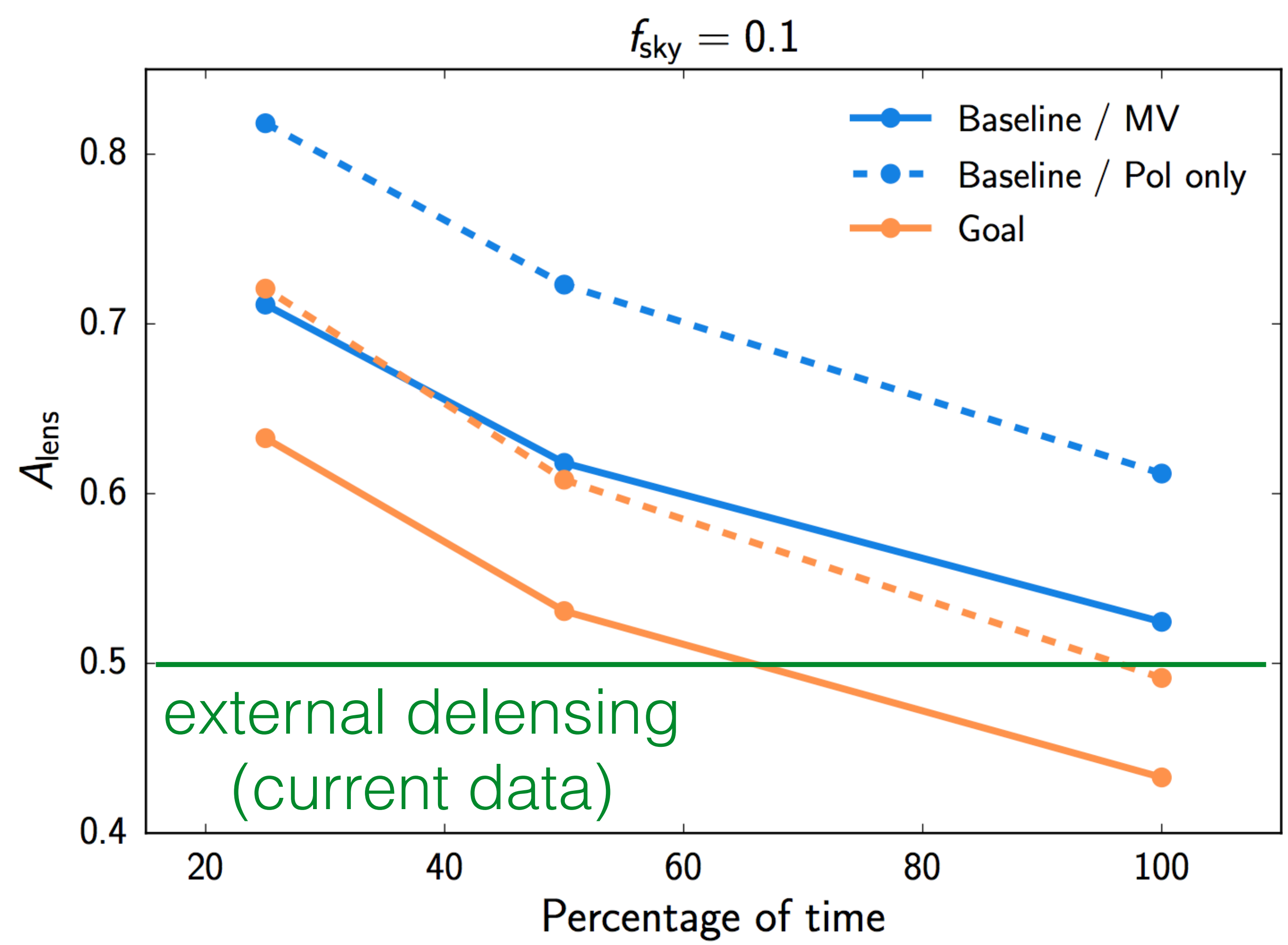
SO SAT Science: Primordial Tensor Modes

Colin Hill
Columbia/CCA

Robust to variations in foreground model complexity (within the space of models explored)



A dedicated delensing survey is not necessary; external delensing suffices

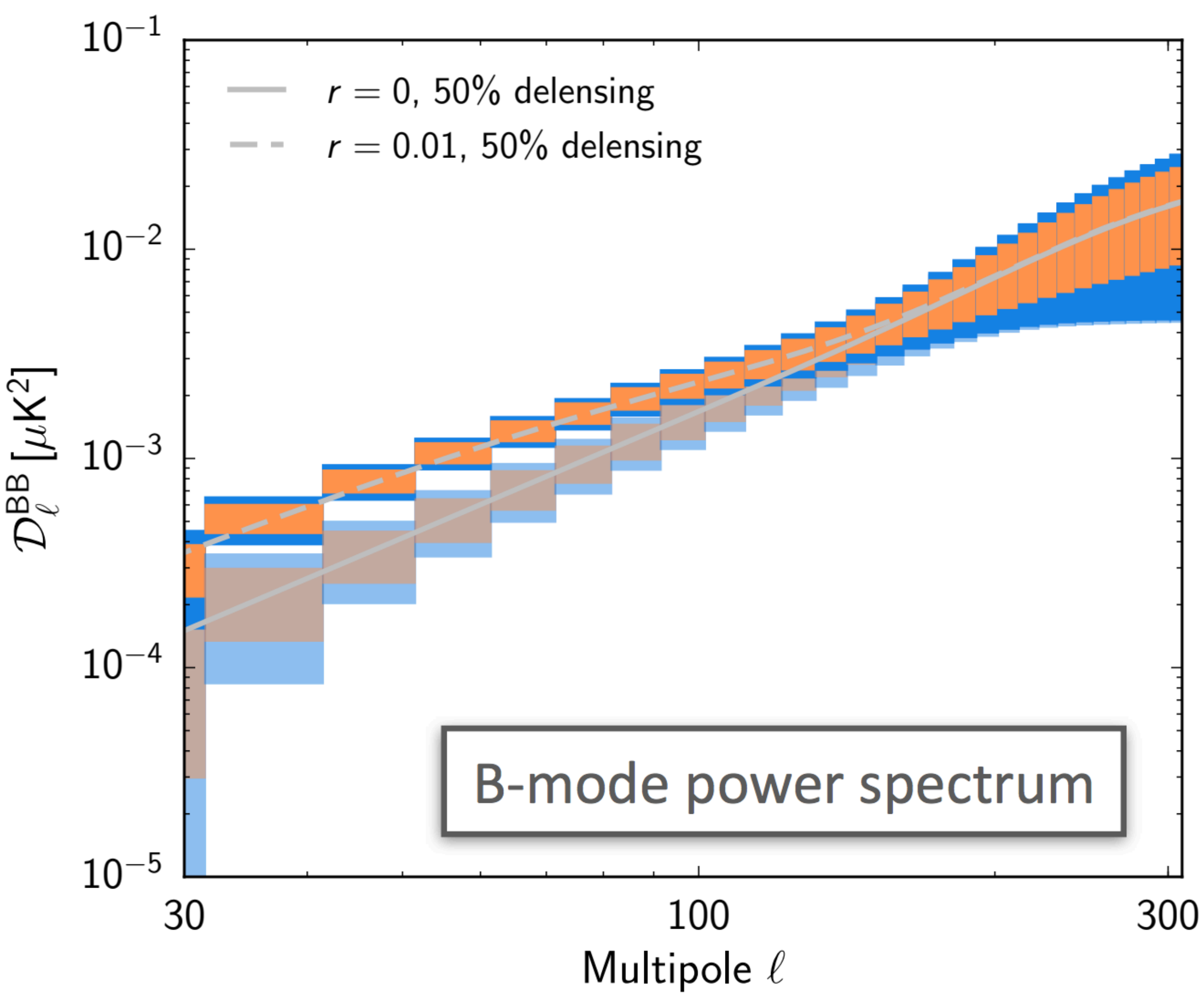


Conclusion: σ(r) = 0.003 (SO Baseline)

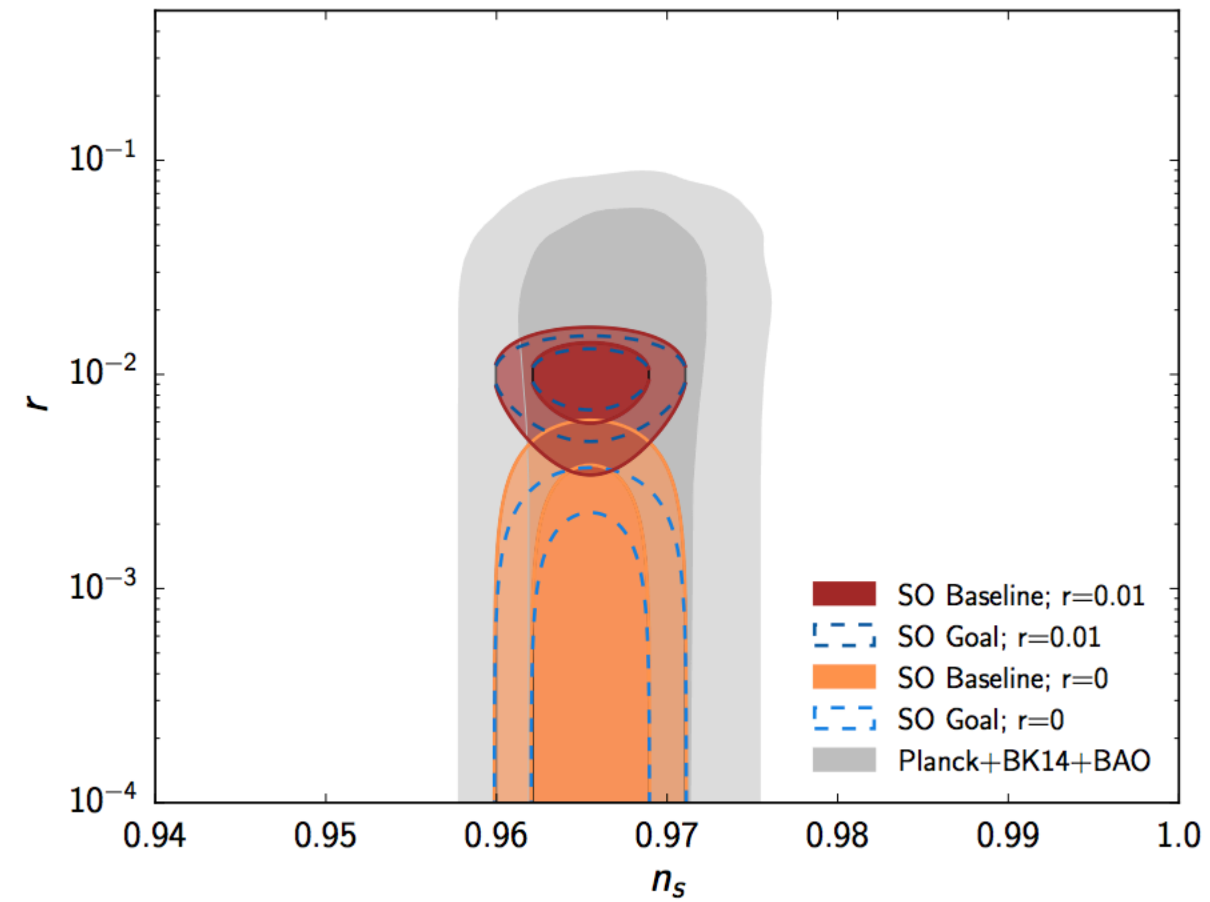
assuming r=0

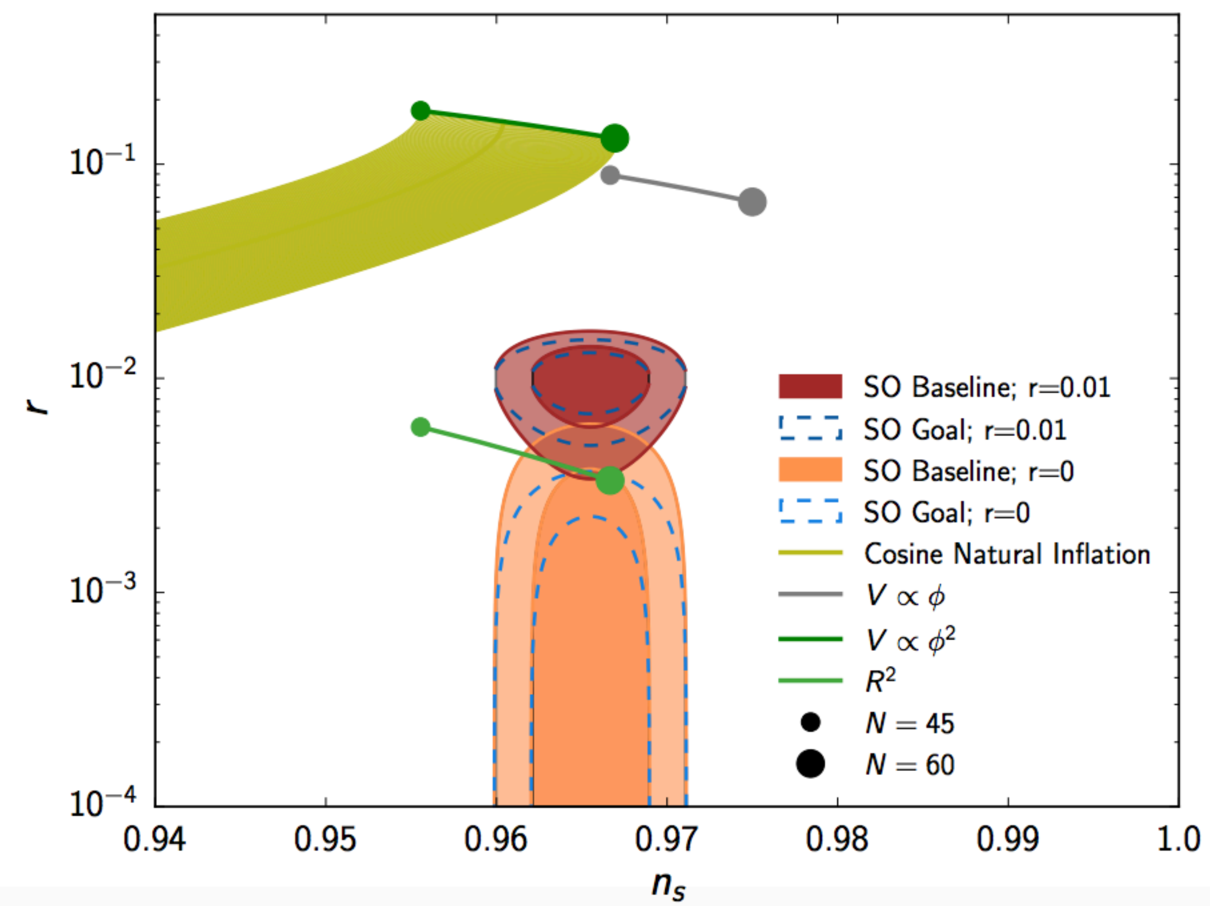
SO SAT Science: Primordial Perturbations

Colin Hill
Columbia/CCA



SO will detect or rule out models with r >= 0.01 at 3σ or greater





SO LAT Forecasting Methodology

Colin Hill
Columbia/CCA

LAT T forecasting based on high-resolution, full-sky simulated maps w/ realistic foregrounds and signals (e.g., correlated extragalactic fields)

LAT E/B forecasting based on simulated power spectra, calibrated to match SAT BB assumptions at degree scales

SO LAT Forecasting Methodology

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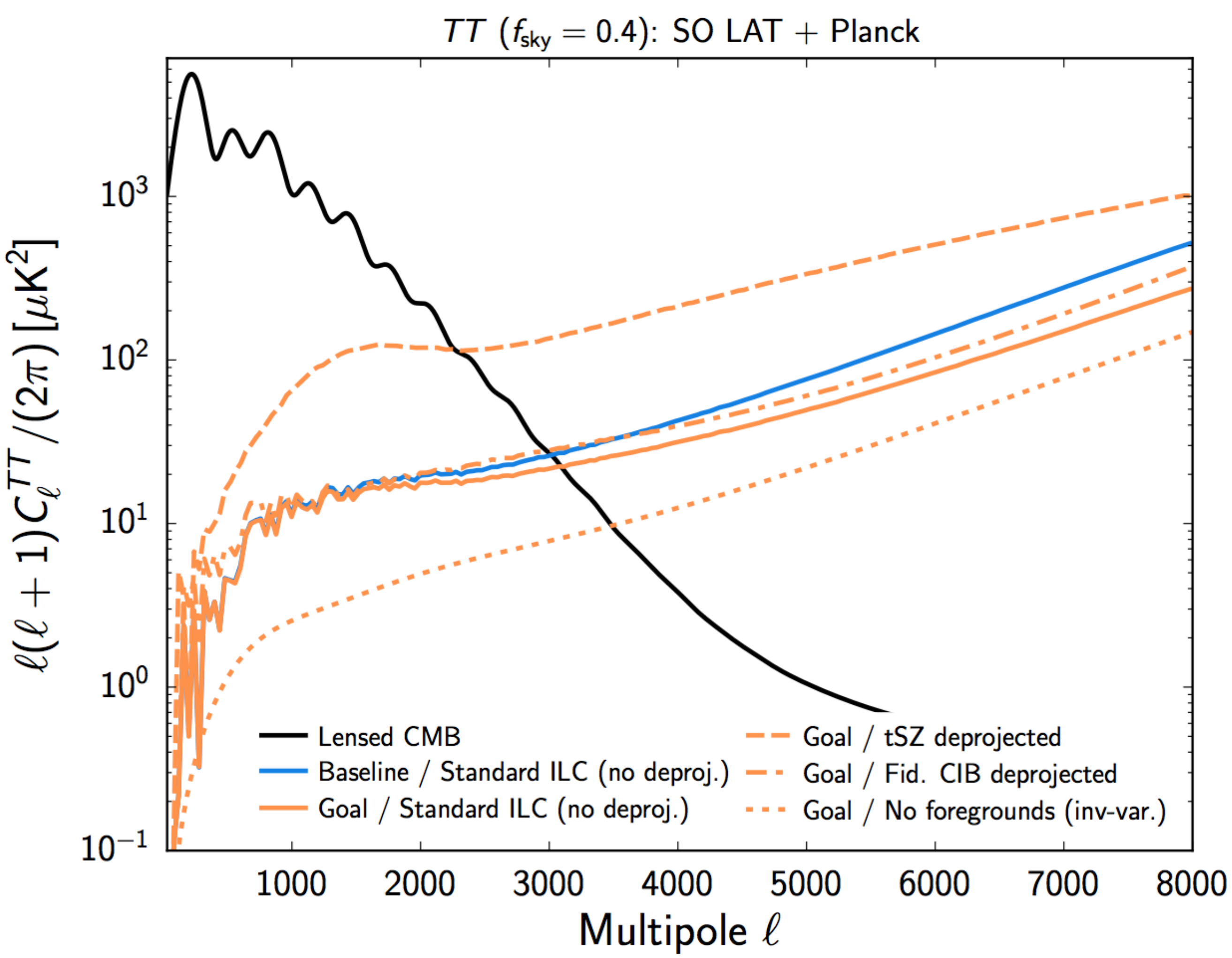
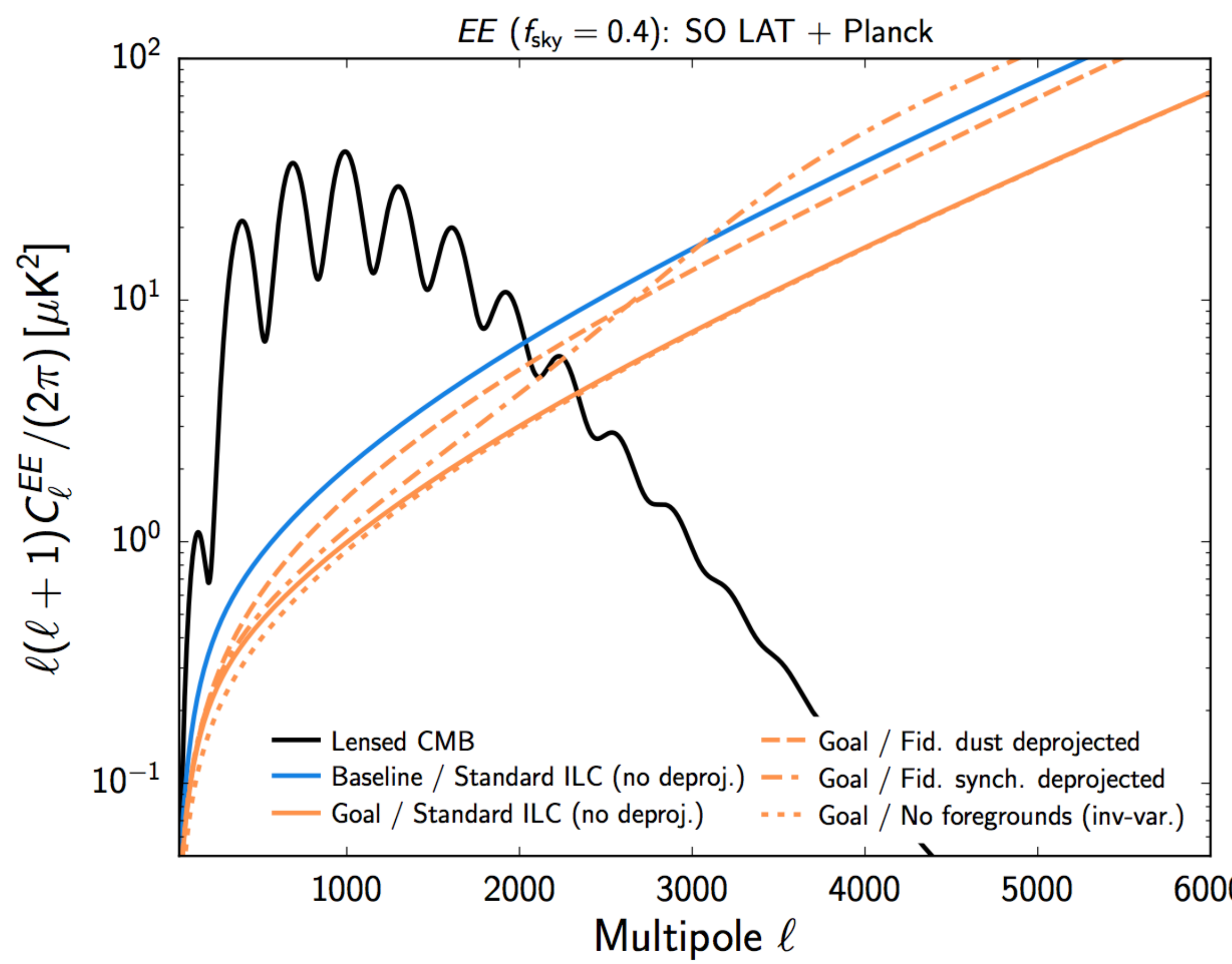
Columbia/CCA

LAT T forecasting based on high-resolution, full-sky simulated maps w/ realistic foregrounds and signals (e.g., correlated extragalactic fields)

LAT E/B forecasting based on simulated power spectra, calibrated to match SAT BB assumptions at degree scales

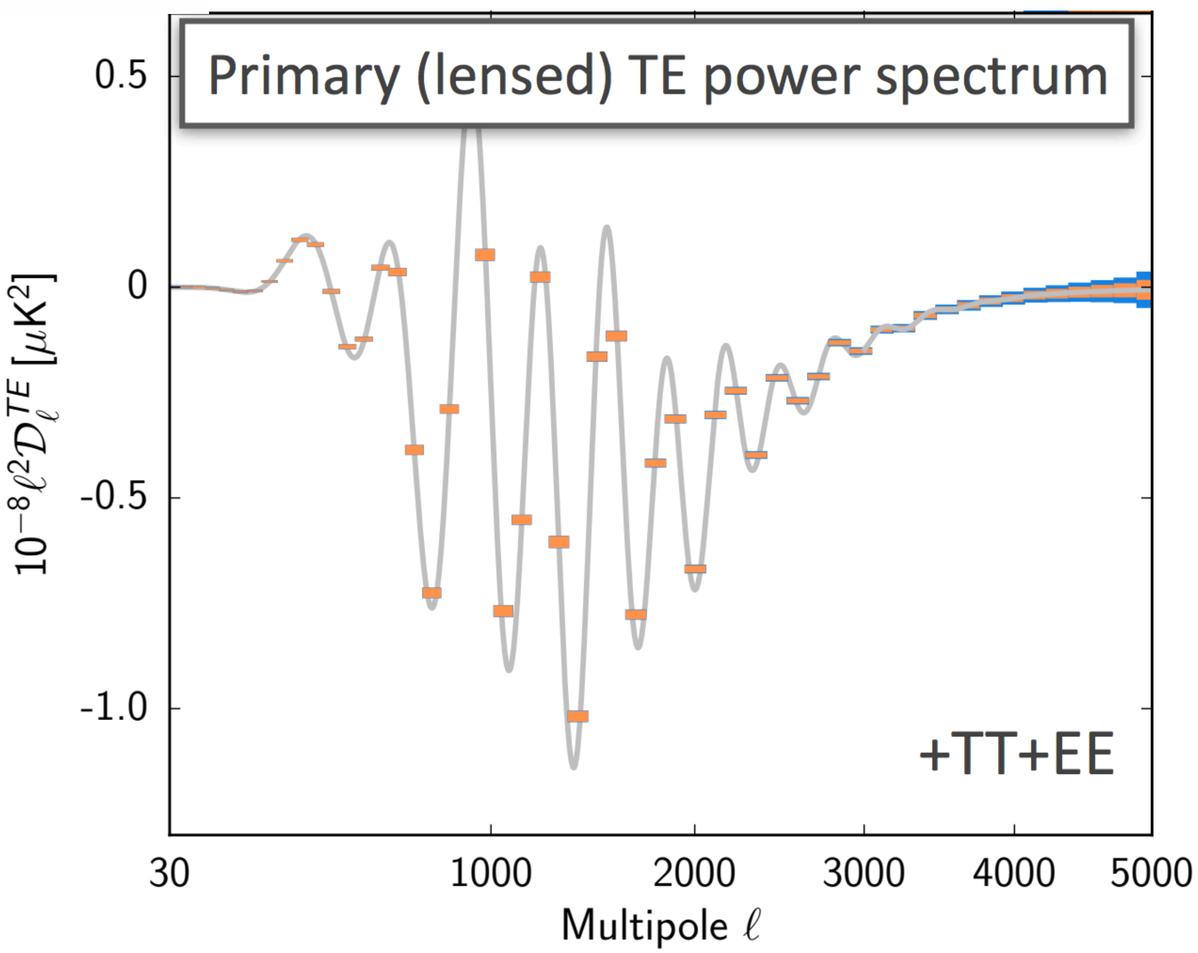
Sky models are combined with SO LAT noise model (and Planck), then coupled to (constrained) harmonic-space internal linear combination (ILC) to derive component-separated noise curves

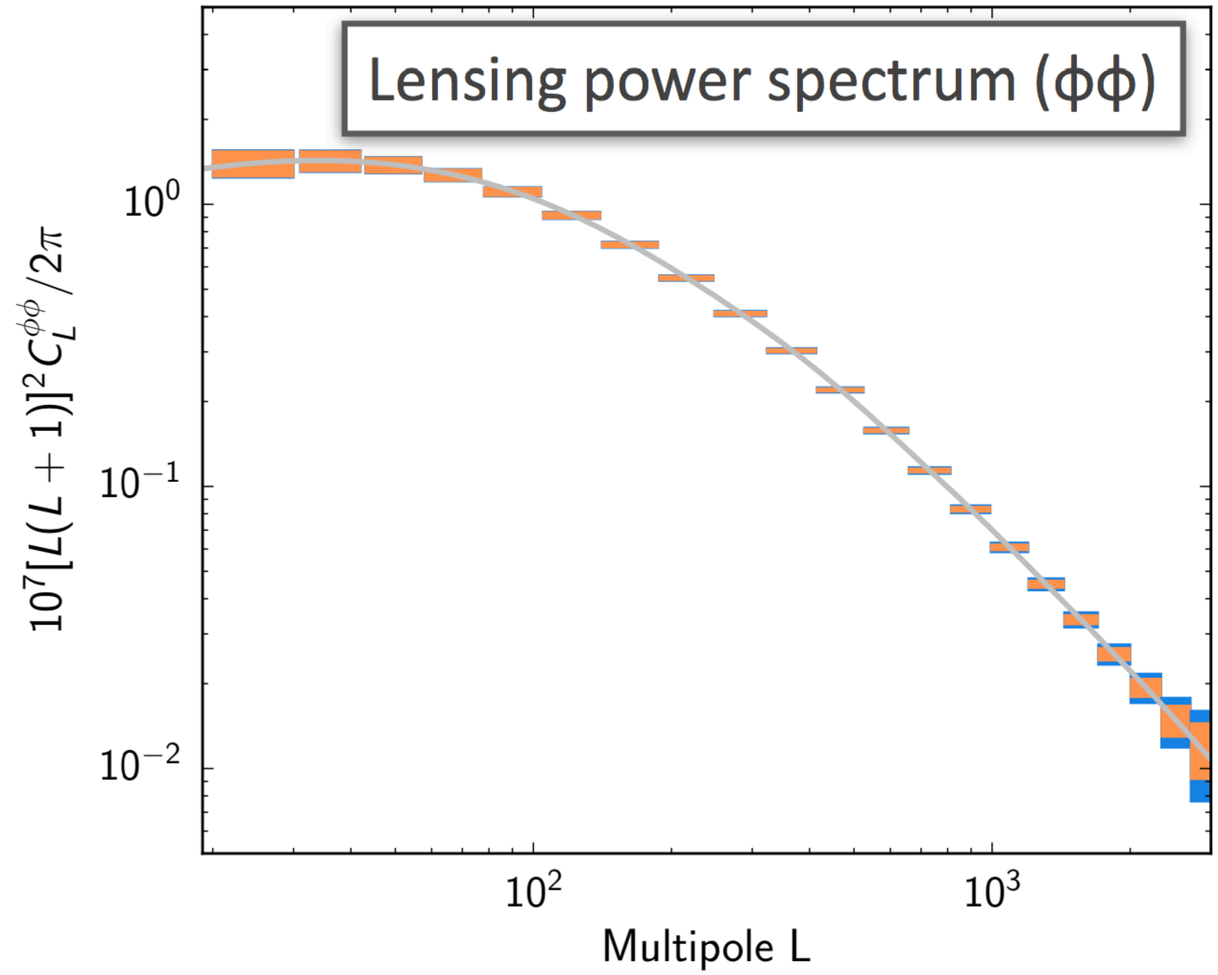


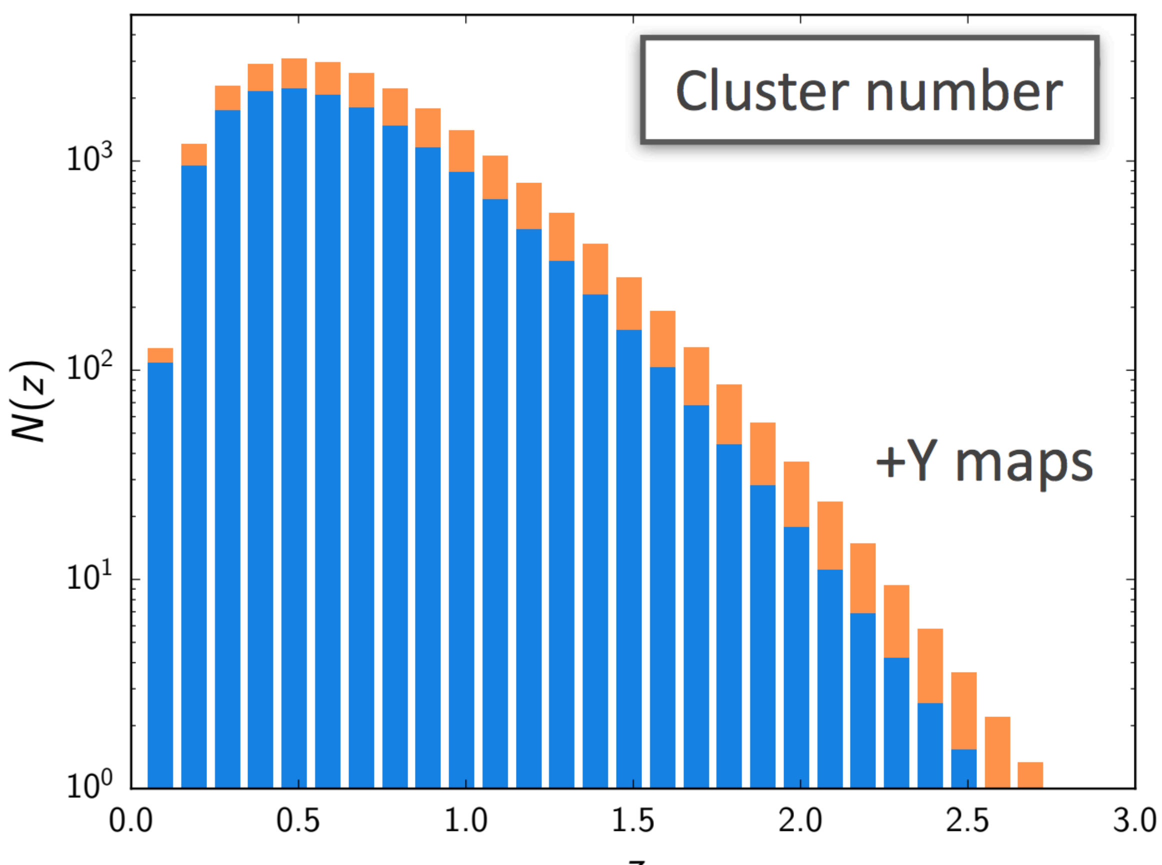


SO LAT Science Observables

Colin Hill
Columbia/CCA







SO Baseline Sensitivity

SO Goal Sensitivity

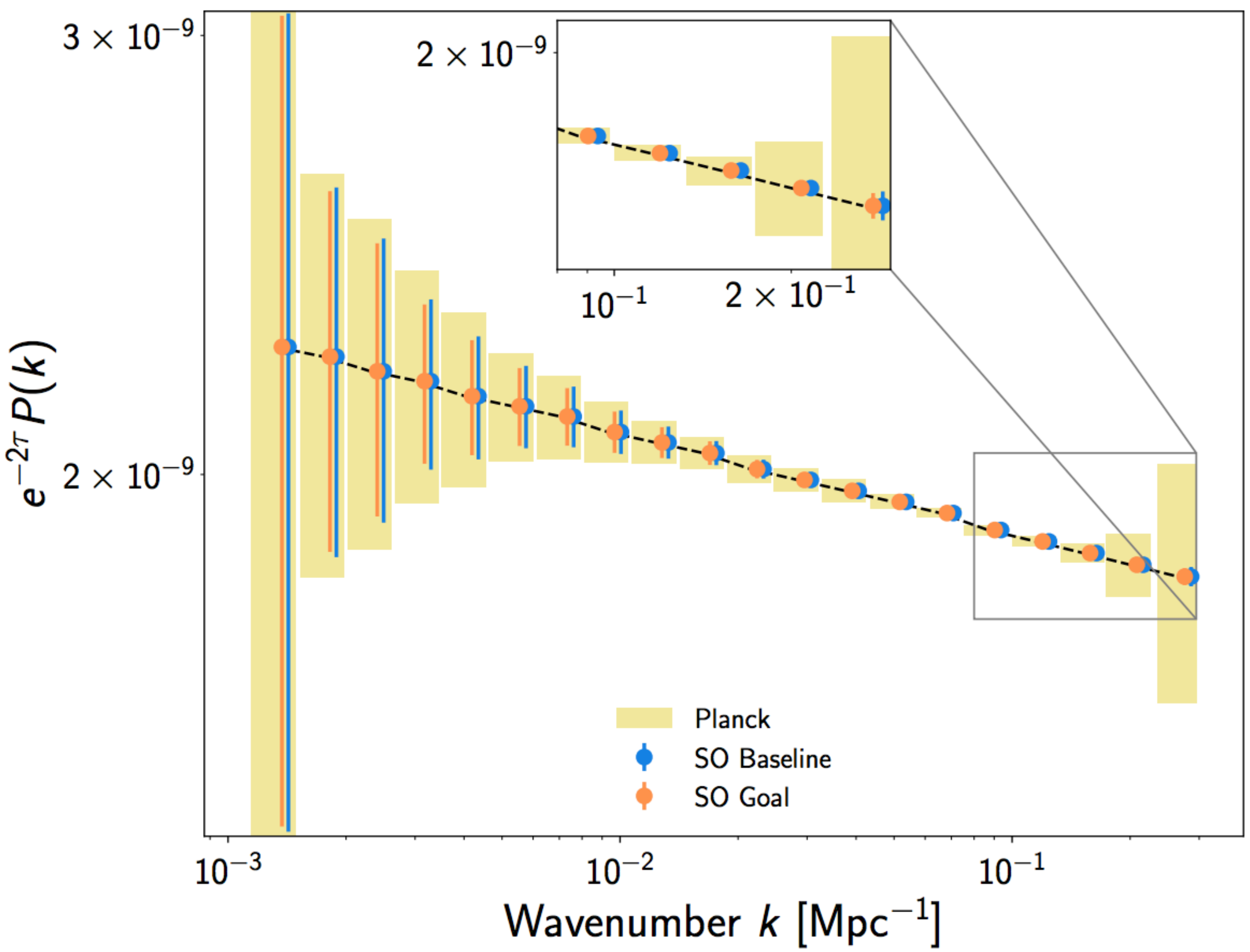
+kSZ signal + bispectrum

+ cross-correlations
+ source counts

SO LAT Science: Primordial Perturbations

Colin Hill
Columbia/CCA

Primordial scalar power spectrum

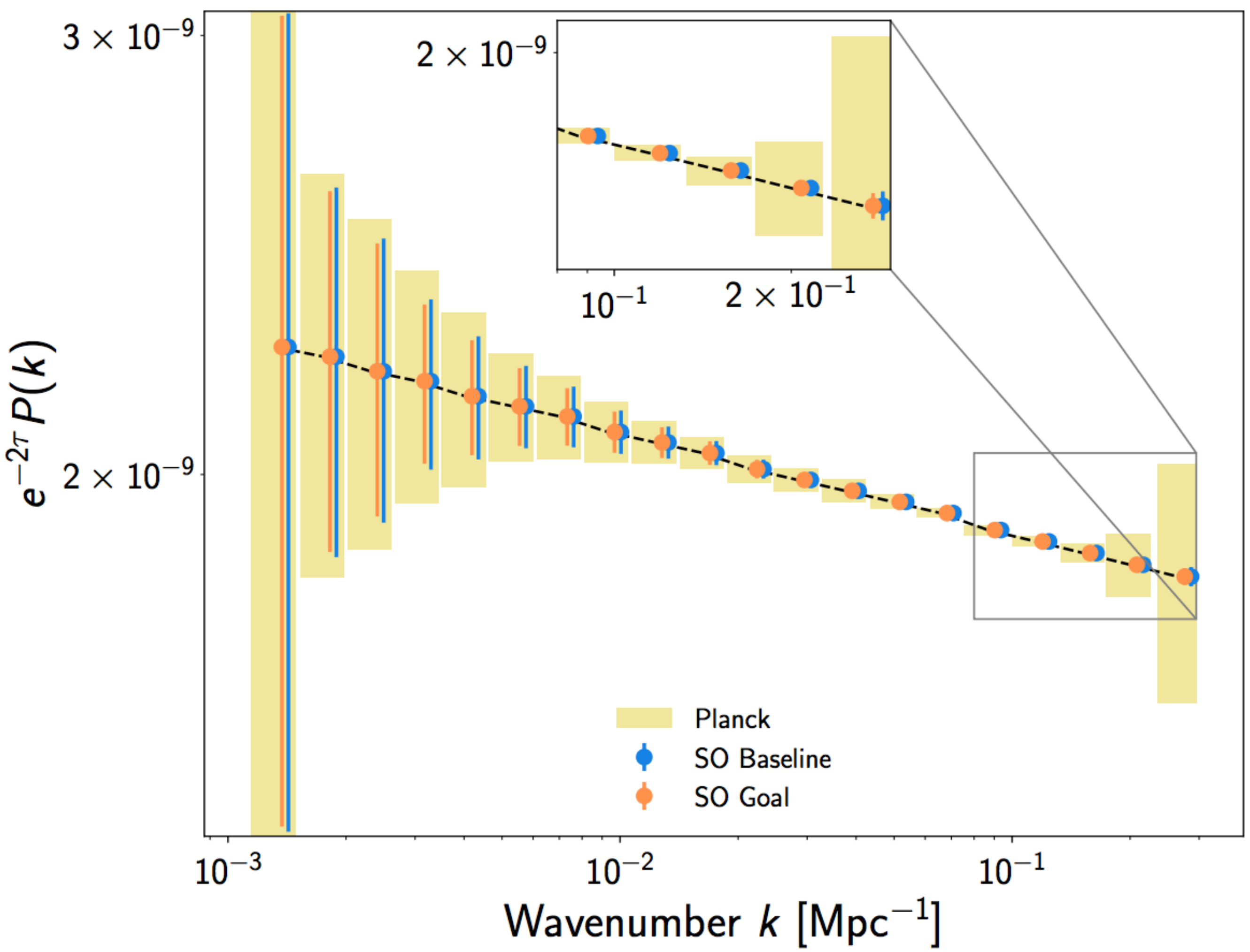


0.4% constraint at k~0.2/Mpc
(10x improvement over Planck)

Colin Hill
Columbia/CCA

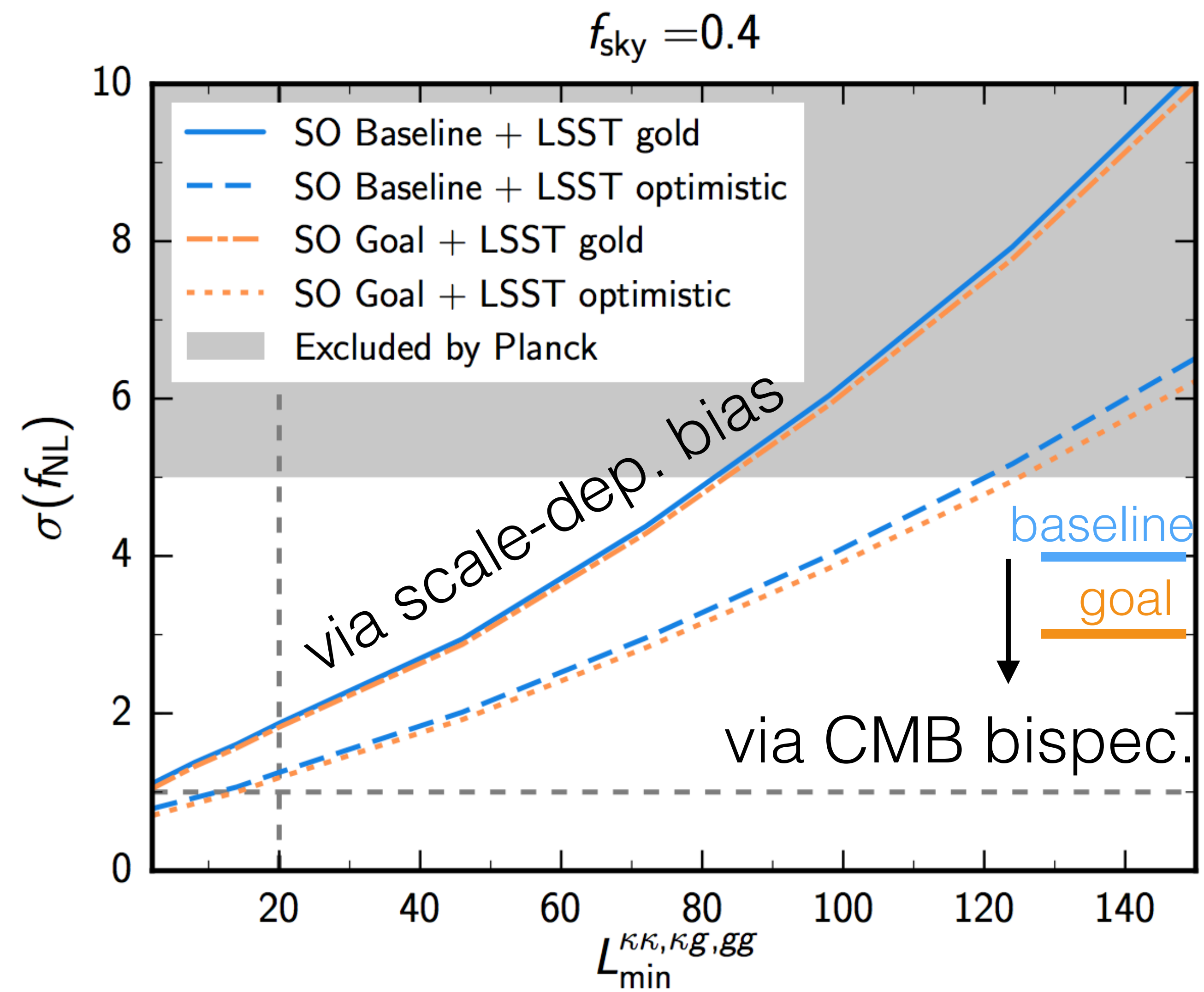
SO LAT Science: Primordial Perturbations

Primordial scalar power spectrum



0.4% constraint at k~0.2/Mpc
(10x improvement over Planck)

Local-type primordial non-Gaussianity

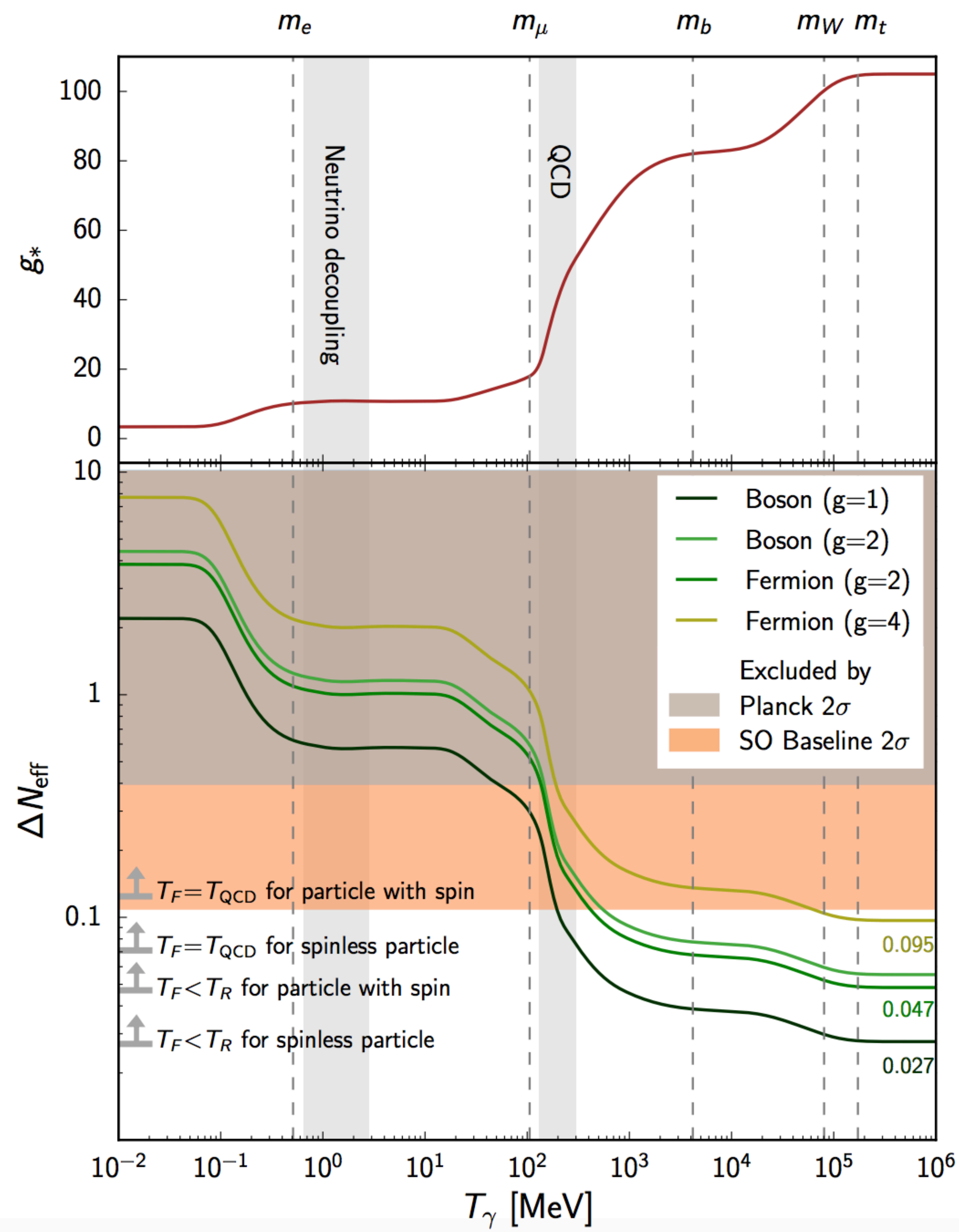


Shape ($\langle\zeta\zeta\zeta\rangle$) $\langle TTT\rangle$,$\langle TTE\rangle$, $\langle TEE\rangle$,$\langle EEE\rangle$	Current (*Planck*)	SO Baseline	SO Goal
local	5	4	3
equilateral	43	27	24
orthogonal	21	14	13

+ tensor NGs

SO LAT Science: Light Relics

Colin Hill
Columbia/CCA



SO can detect any particle with spin that decoupled after the start of the QCD phase transition (at 2σ)

$\sigma(N_{\rm eff}) = 0.07$

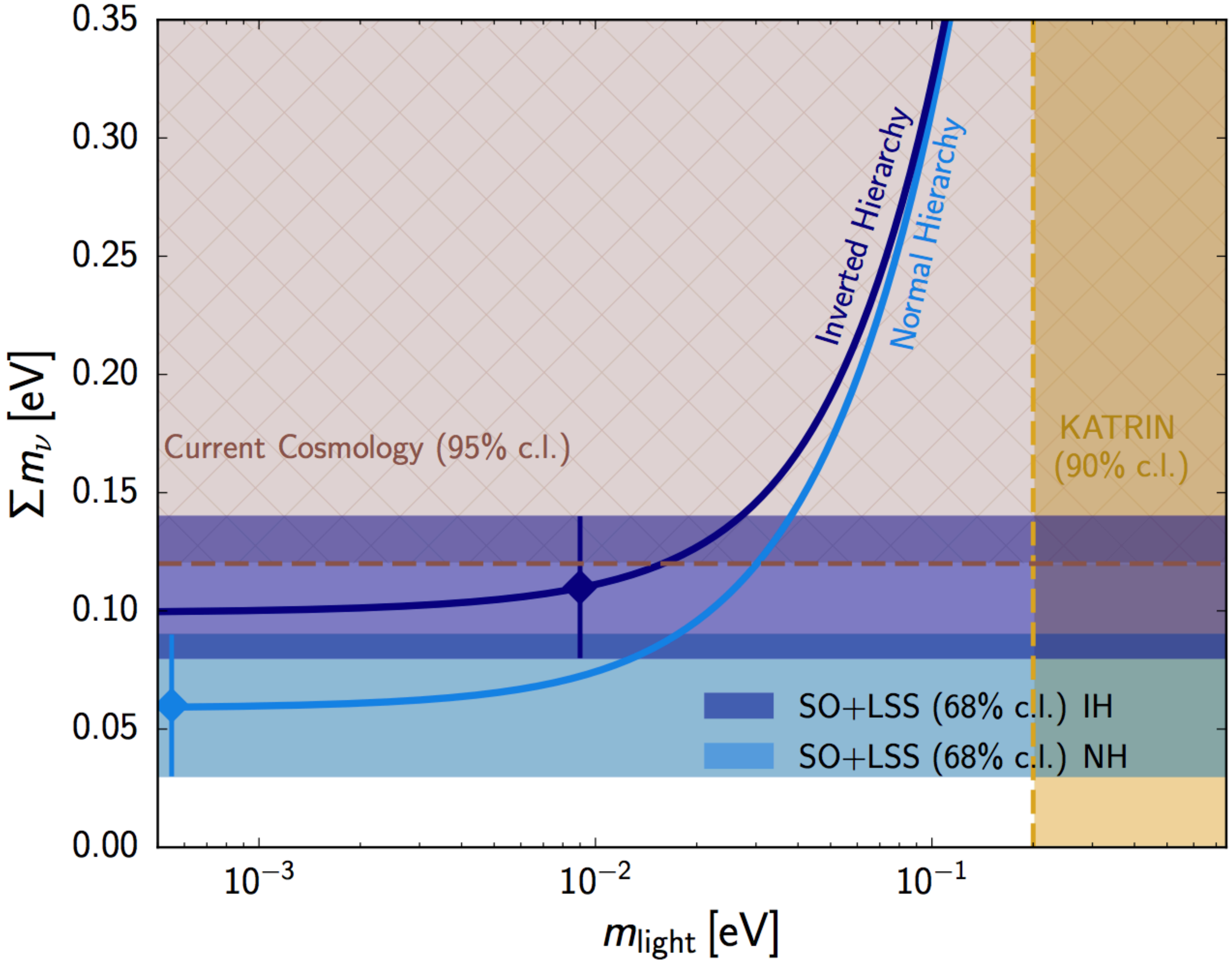
Forecasts are strongly robust to foregrounds (driven by TE + EE)

Other damping tail science:
- BBN (Y_p)
- H_0 improvement (~2x)
- Dark matter interactions
- Ultra-light axions
- and more

SO LAT Science: Neutrino Masses

Colin Hill
Columbia/CCA

Constraints derived from CMB lensing power spectrum (+DESI BAO), tSZ cluster counts (+LSST WL), and tSZ power spectrum (+DESI BAO)



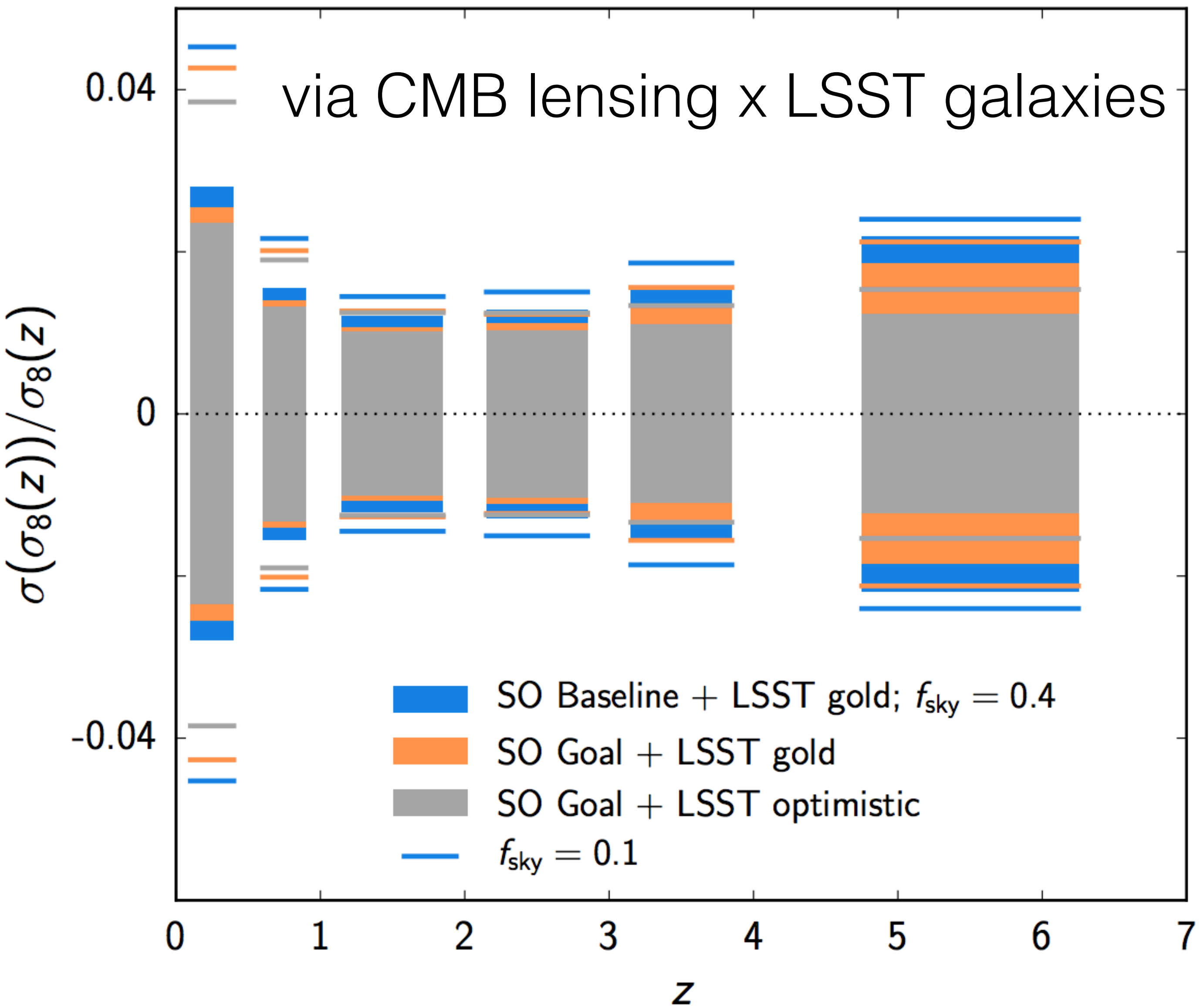
$\sigma(\Sigma M_\nu) = 0.04$ eV ⟶ 0.02 eV w/ CV-limited τ

SO LAT Science: Dark Energy

Colin Hill
Columbia/CCA

Constraints derived from tSZ cluster counts (+LSST WL and/or SO CMB lensing), and CMB lensing cross-correlations w/ LSST galaxies

Amplitude of fluctuations as a function of redshift



DE equation of state (via tSZ cluster counts)

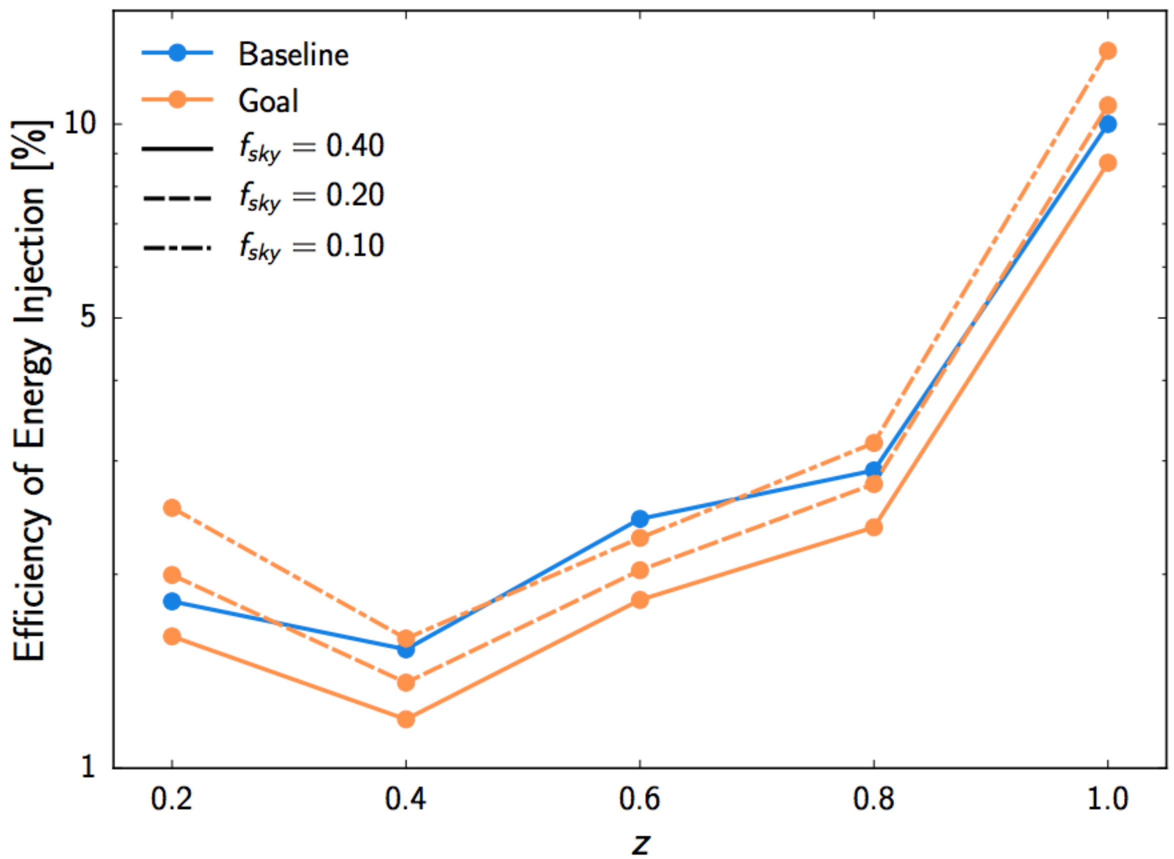
$$\sigma(w_0) = 0.06, \quad \Lambda\mathrm{CDM} + w_0 + w_a$$
$$\sigma(w_a) = 0.20,$$
$$\sigma(w_0) = 0.08, \quad \Lambda\mathrm{CDM} + w_0 + w_a + \Sigma m_\nu$$
$$\sigma(w_a) = 0.32,$$

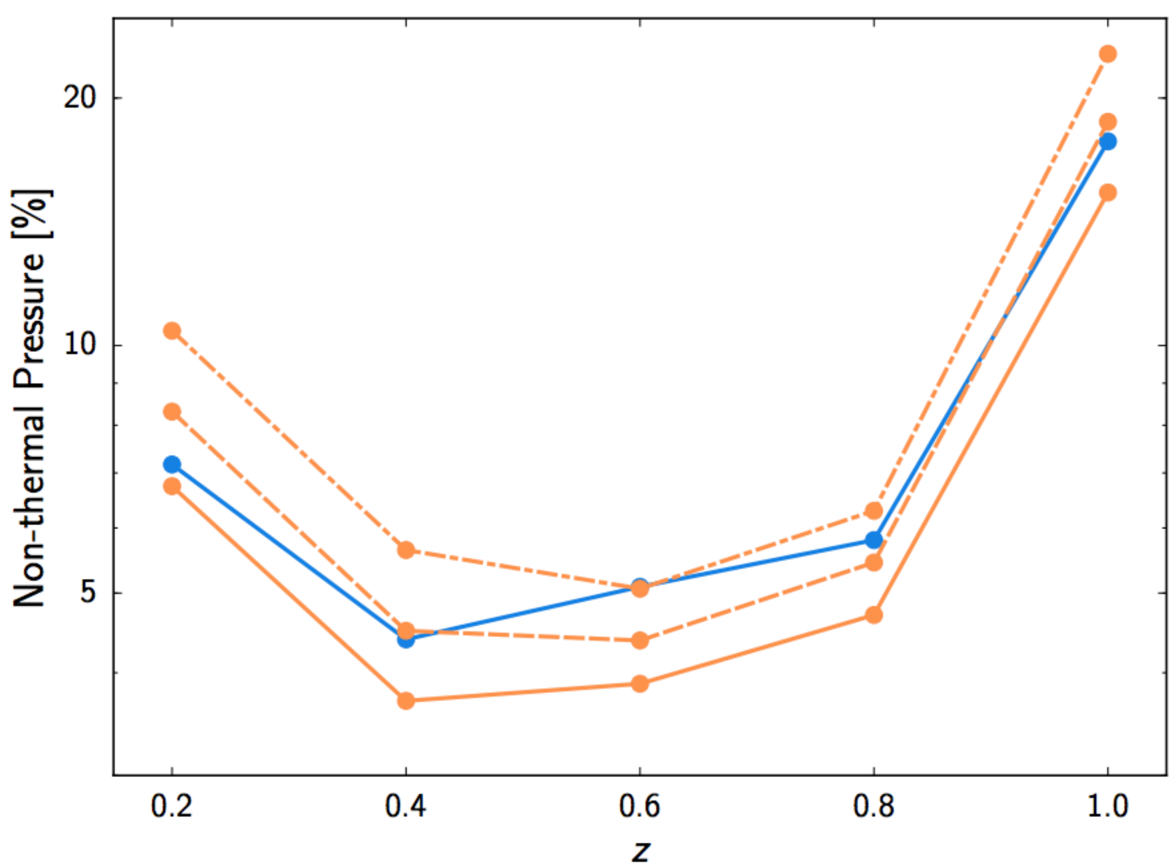
Unique ability to search for deviations from Λ at $z > 1$ (complementary to lower-redshift WL and galaxy surveys)

c.f. also improved $\sigma(H_0)$

SO LAT Science: Galaxy Formation/Evolution

Colin Hill
Columbia/CCA





Constraints derived from joint analysis of tSZ and kSZ measurements of DESI Luminous Red Galaxies (just one example cross-correlation!)

~Few percent constraints on feedback efficiency and non-thermal pressure support

>200σ detection of tSZ PS
>100σ detections of kSZ cross-corrs.

Legacy catalogs

SZ clusters	20000
AGN galaxies	10000
Dusty star-forming galaxies	10000

+transient sources

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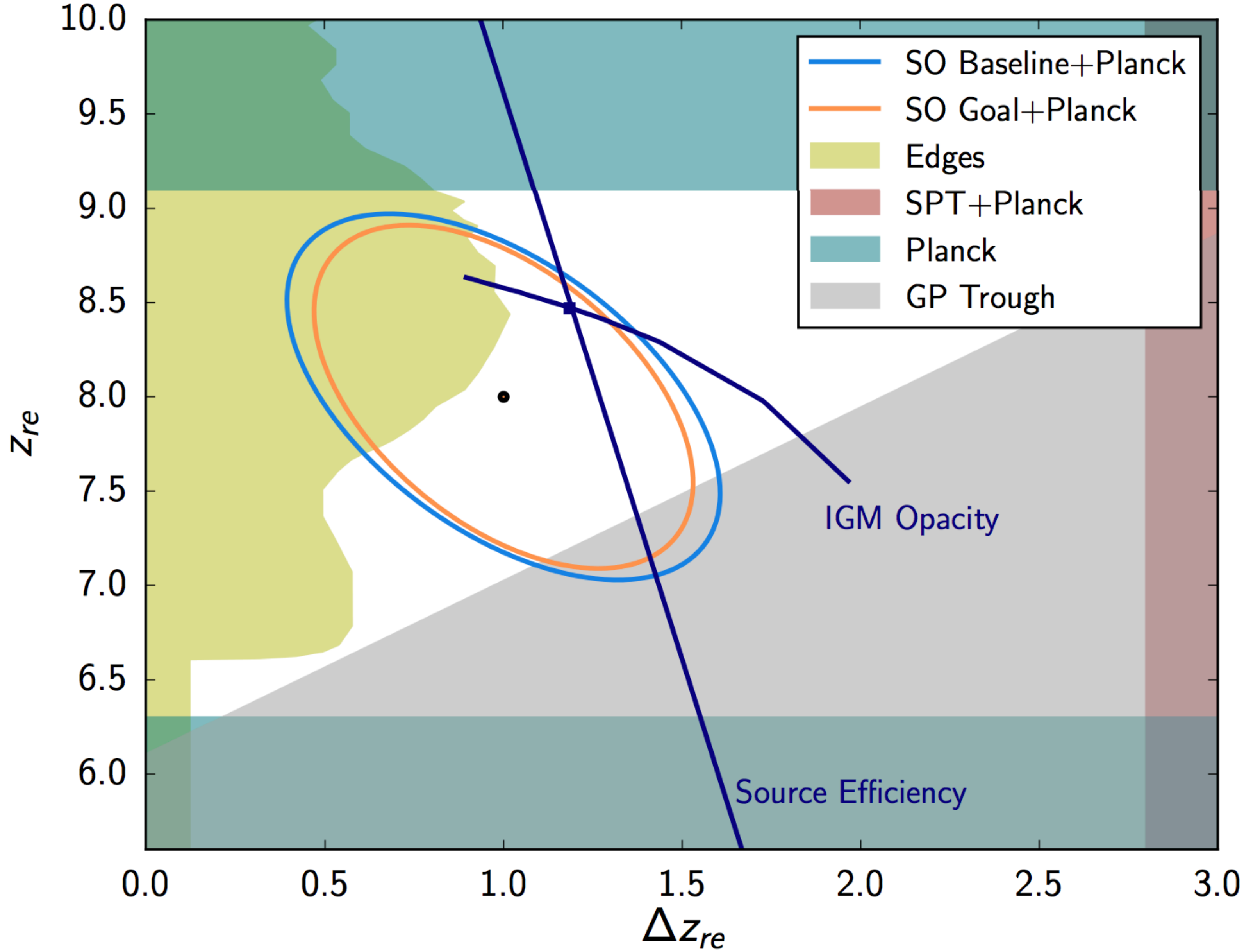
SO LAT Science: Reionization

Constraints derived from kSZ power spectrum via TT combined with TE/EE (also, potentially from higher-order kSZ statistics)



$$\sigma(\Delta z_{\rm re}) = 0.40$$

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Columbia/CCA

Simons Observatory Science Goals and Probes

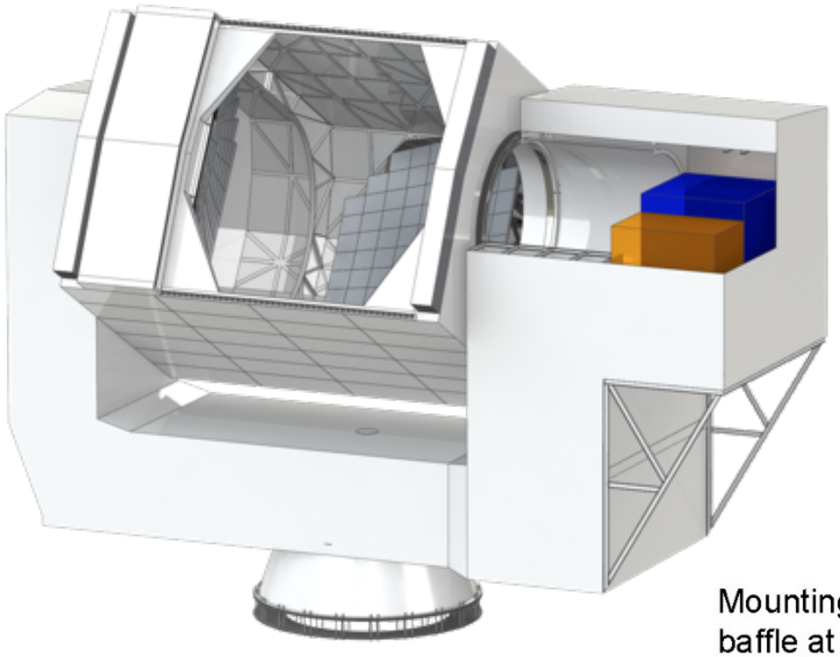
	Parameter	SO-Baseline[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt
		2	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.04	0.03		tSZ-N $\times$ LSST-WL
		0.05	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS + DESI-BAO
		2%	1%		tSZ-N $\times$ LSST-WL
	H_0 (ΛCDM)	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	**0.6**	0.3	1.4	TT (kSZ)

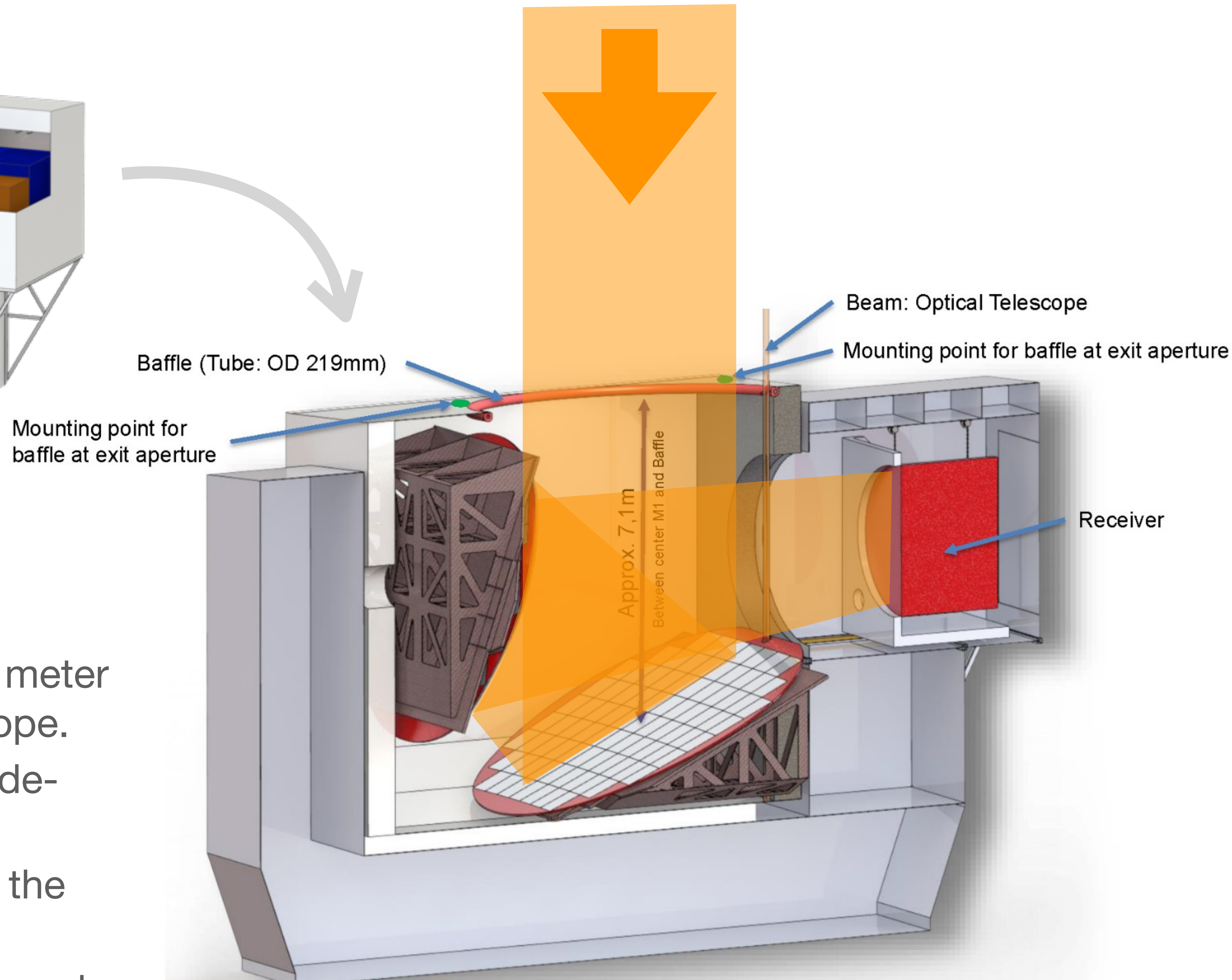
All quoted errors are 1σ

All forecasts assume SO + Planck

Baseline SO forecasts include systematic error budget

The Simons Observatory Large Aperture telescope





3D Cross-section of Yoke Structure and Elevation Housing (view towards M1)

- The SO will baseline a 6 meter Cross Dragone telescope.
- 2-mirror design with a side-looking camera.
- The camera rotates with the elevation axis.
- The back of the camera can be accessed while installed on the telescope.
- Developed in collaboration with CCAT and built by Vertex
- The telescope is capable of > 100,000 detectors

The Simons Observatory Large Aperture receiver

total weight ~ 5000kg (!) when
populated with 13 tubes

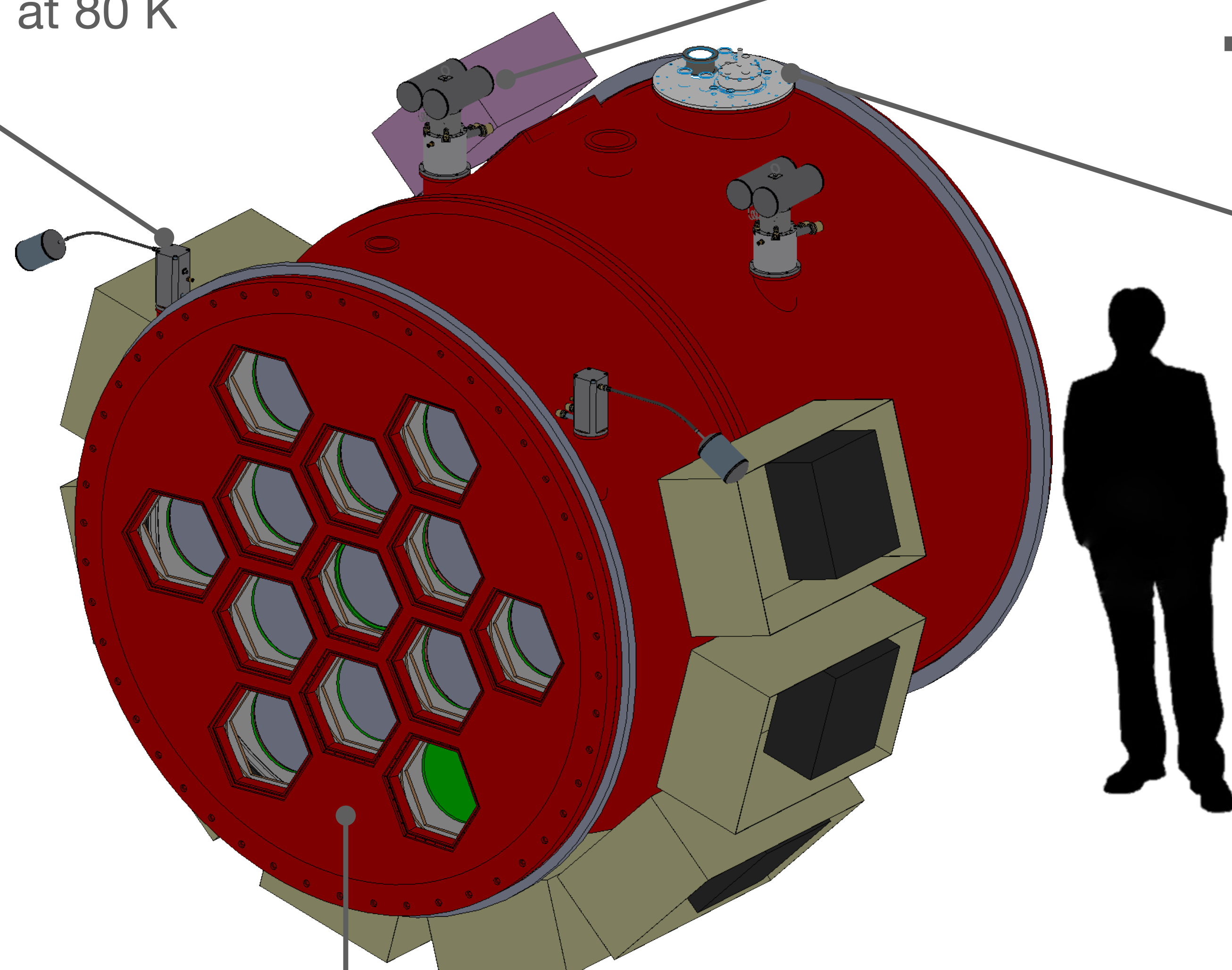
2 PT90s

➡180 W of cooling at 80 K

3 PT420 coolers

➡ 165 watts of cooling at 40 K

➡ 6 watts of cooling at 4 K



Dilution Refrigerator

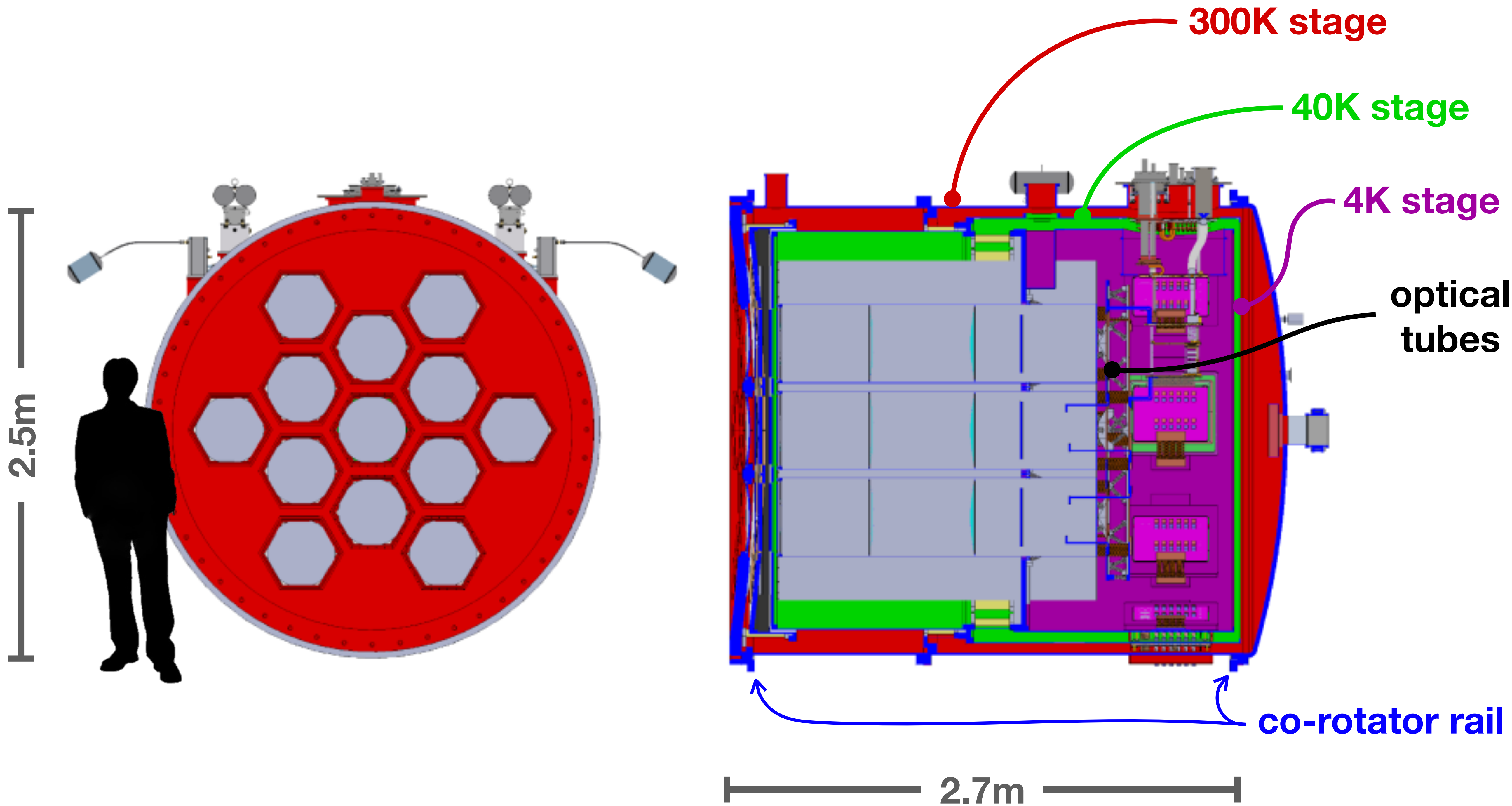
➡17 mW at 1K

➡500 uW at 100 mK

- 1200 kg cooled to 4K
- 200 kg cooled to 100 mK
- **Up to 13 optics tubes**
  ➡7 currently planned for SO

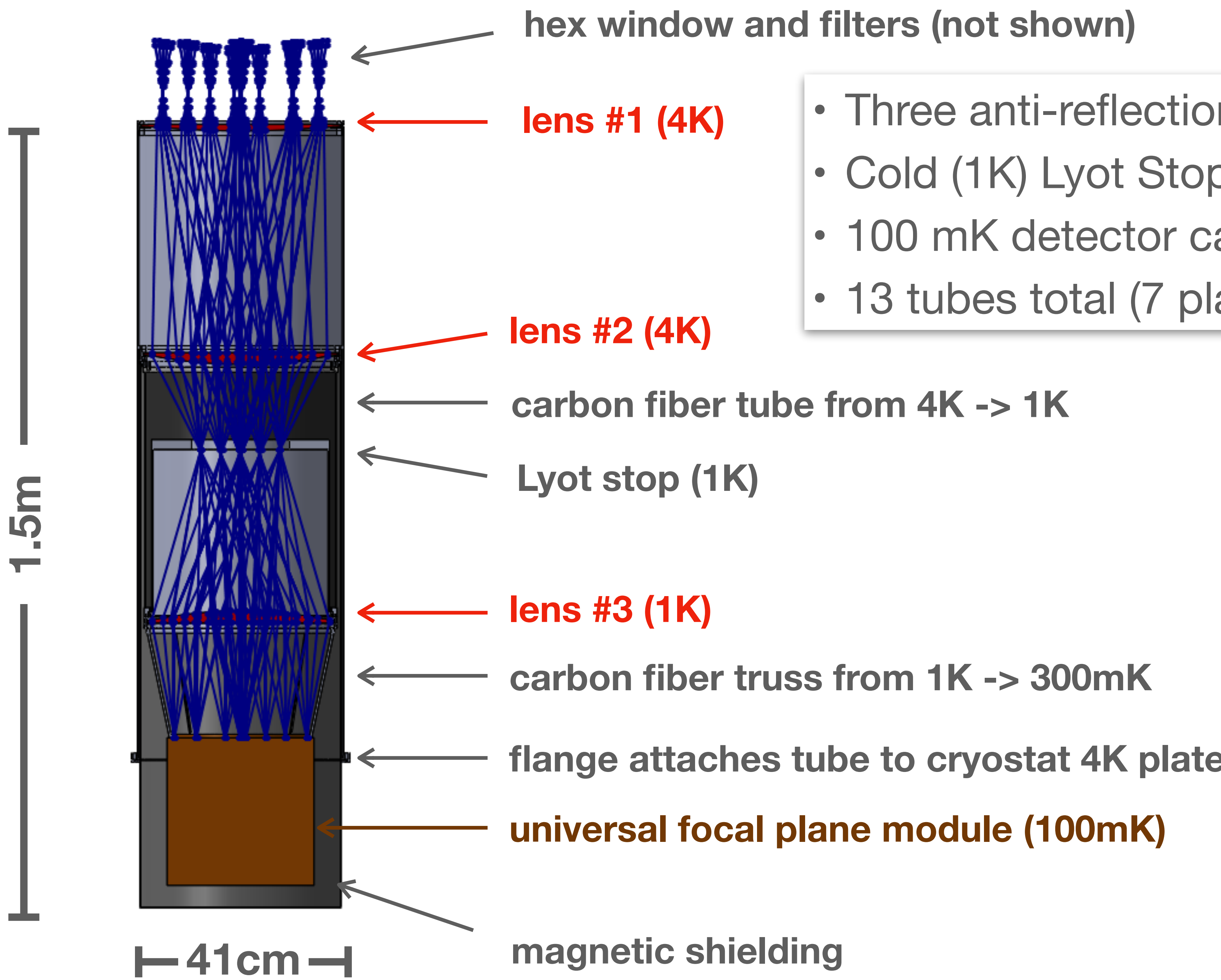
- **70,000+ detector capacity *in this cryostat***
  ➡ 30,000 planned for SO
- The optics tubes can be replaced while cryostat is installed.

The Simons Observatory Large Aperture receiver

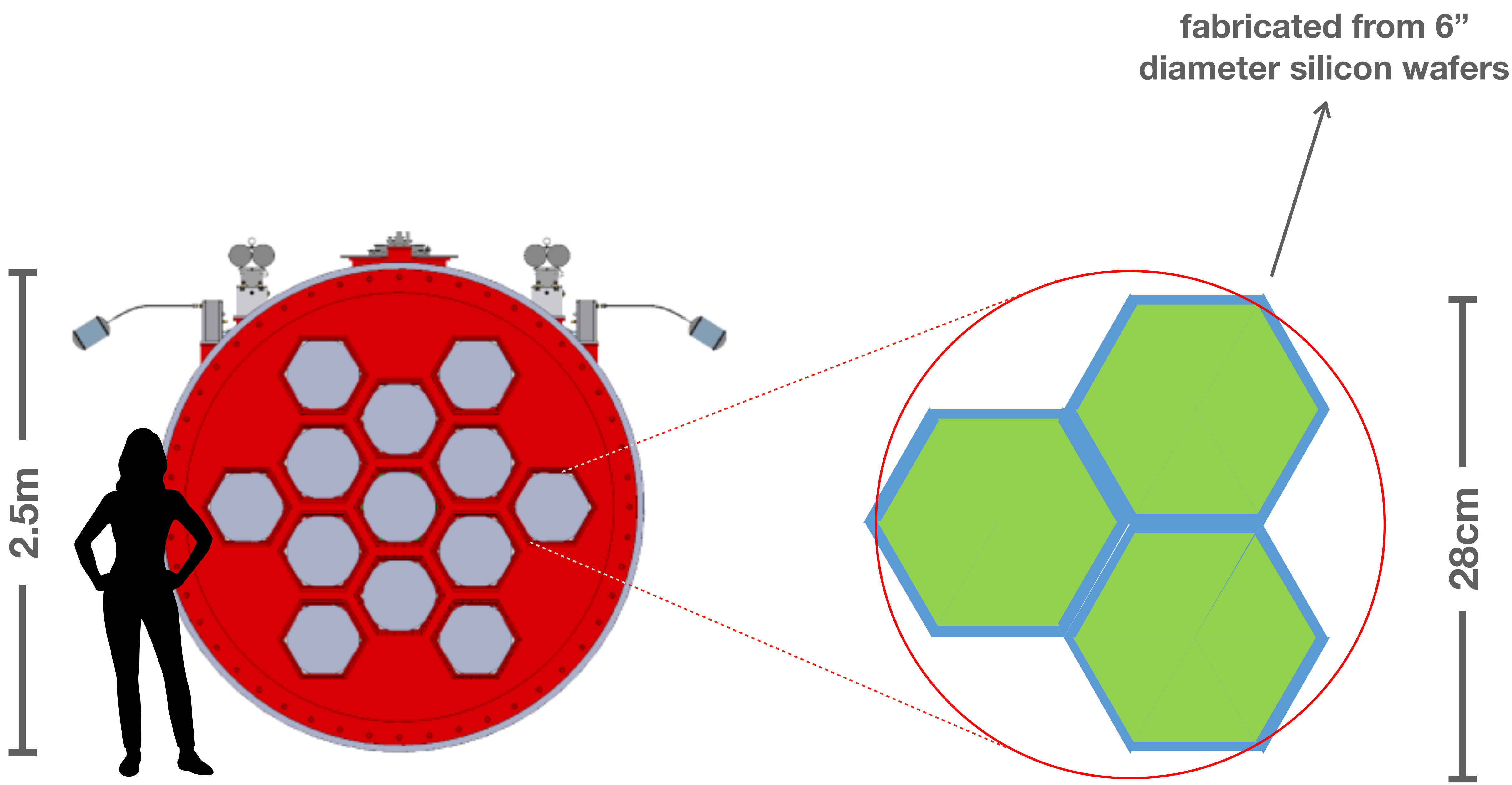


The Simons Observatory Large Aperture receiver

- Three anti-reflection coated silicon lenses
- Cold (1K) Lyot Stop
- 100 mK detector cavity
- 13 tubes total (7 planed for SO)

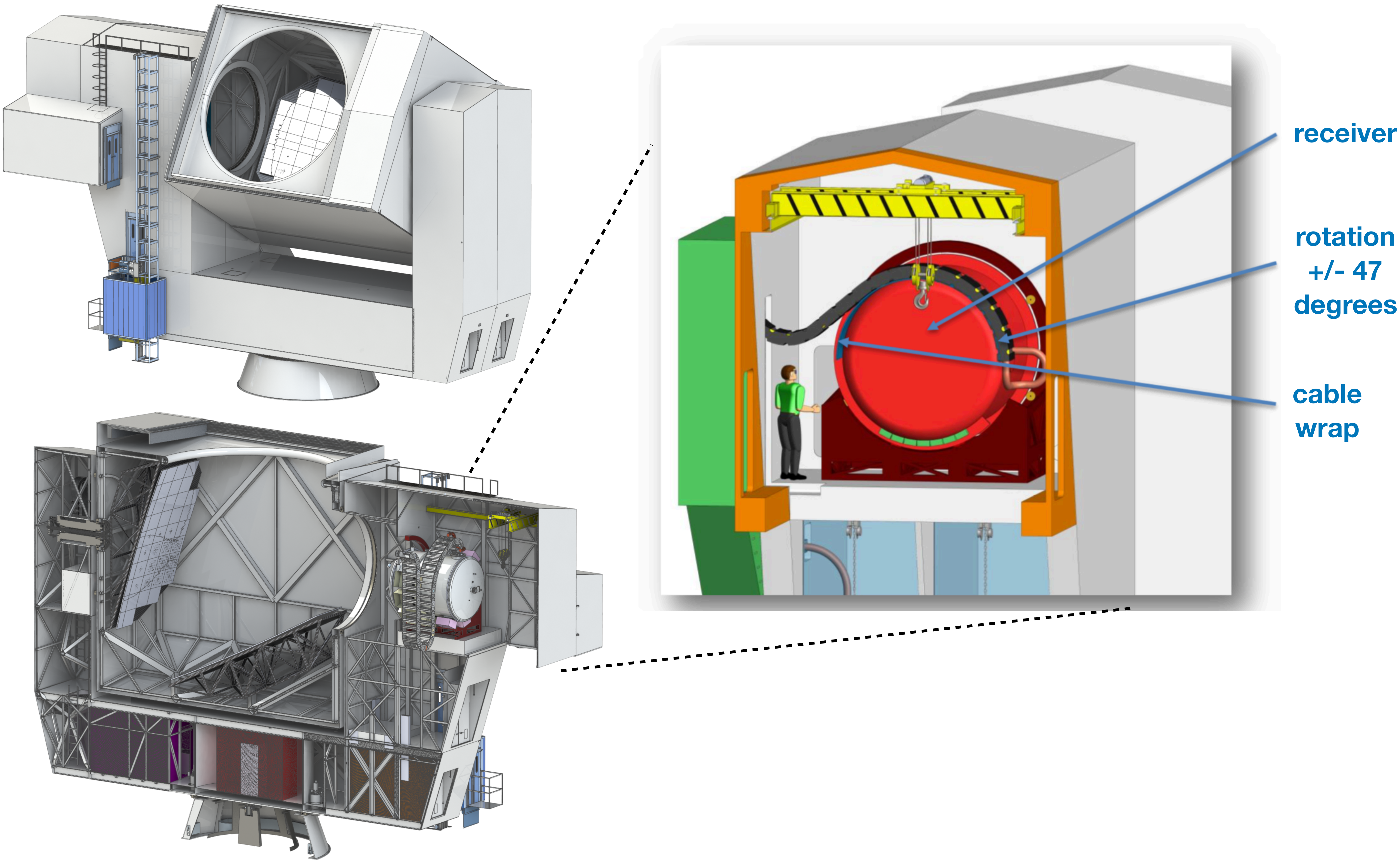


The Simons Observatory Large Aperture receiver

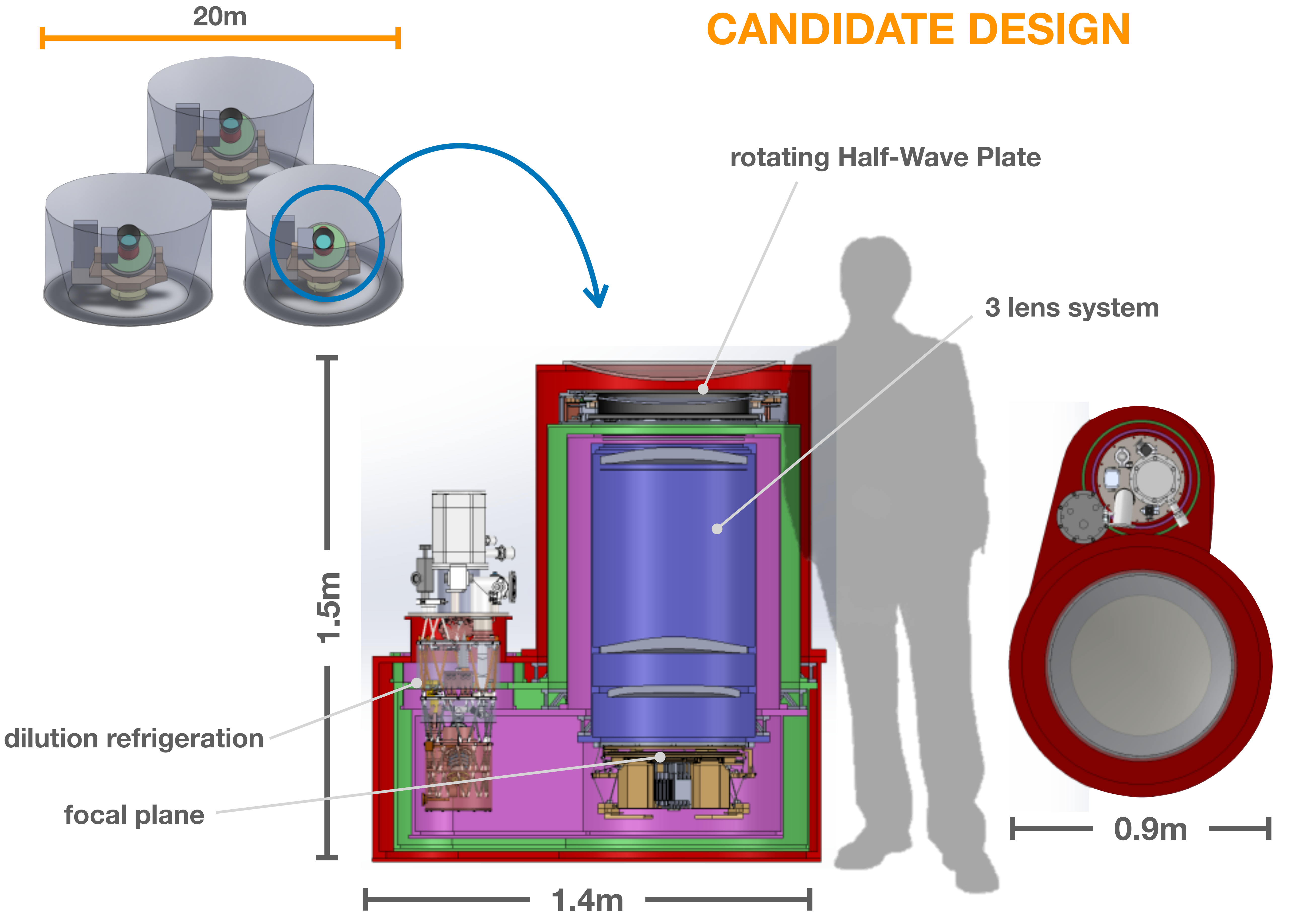


for Simons Observatory Large Aperture:
~21 wafers ➔ ~30,000 detectors

The Simons Observatory Large Aperture receiver

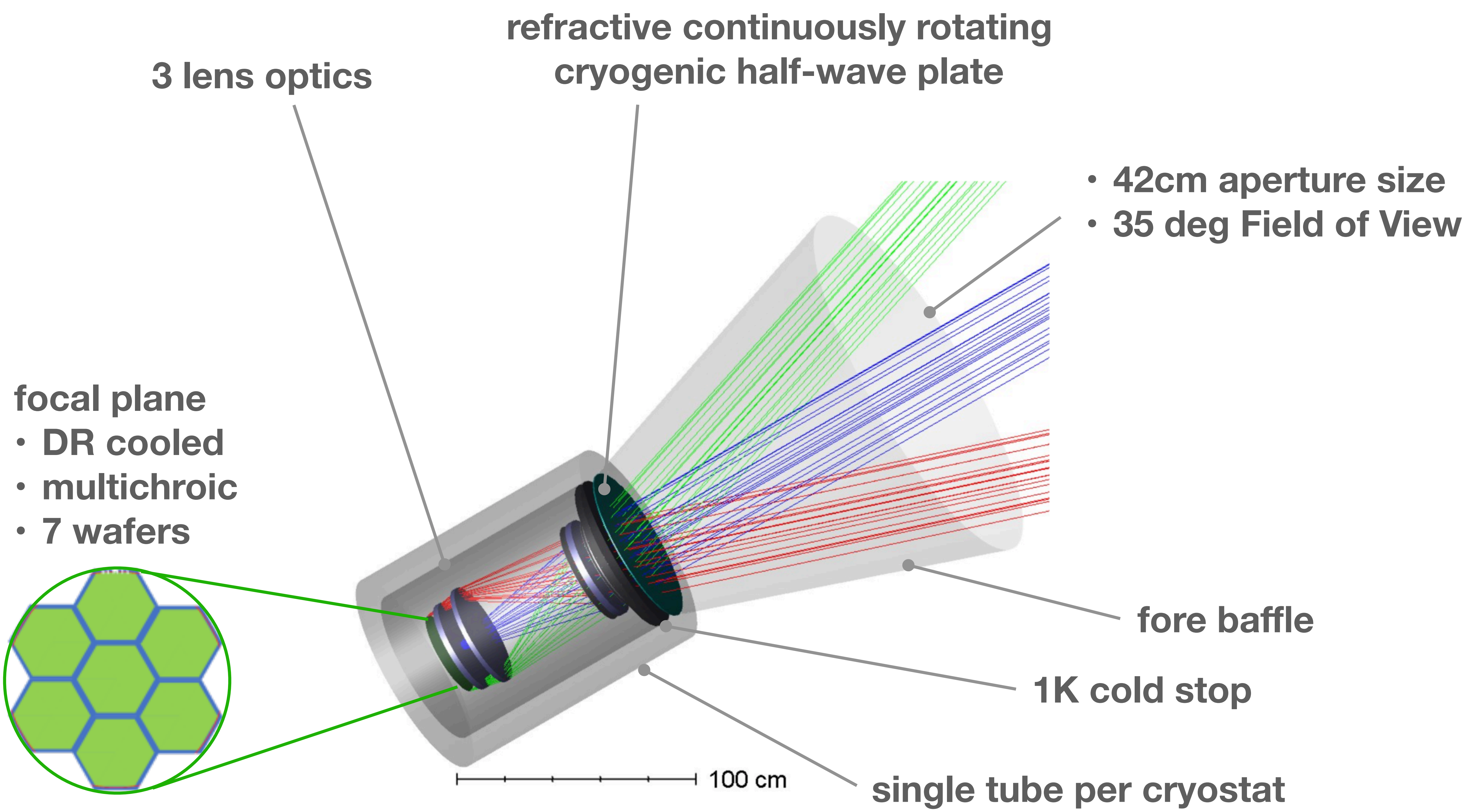


The Simons Observatory Small Aperture Camera



The Simons Observatory Small Aperture Camera

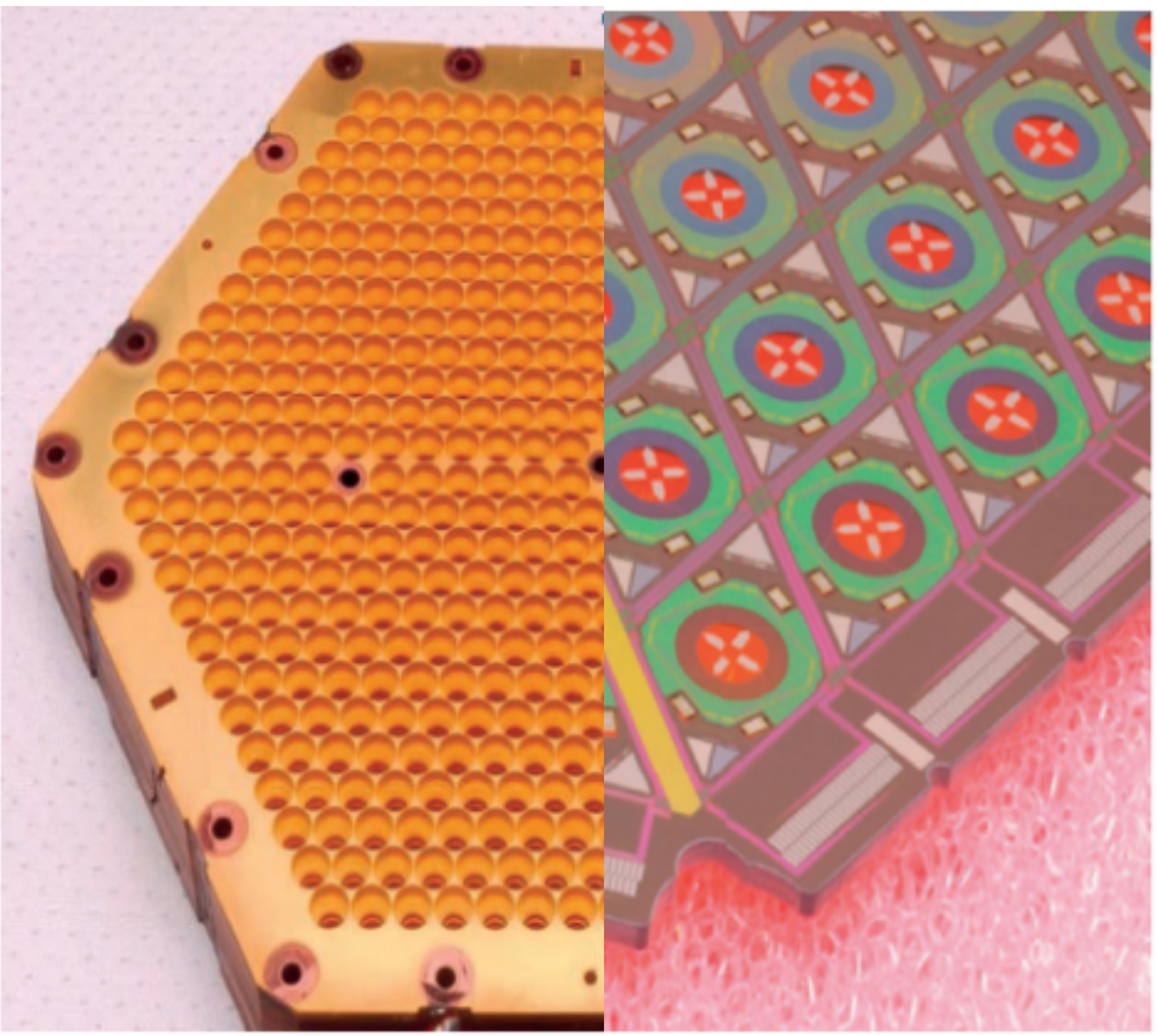
PRELIMINARY DESIGN



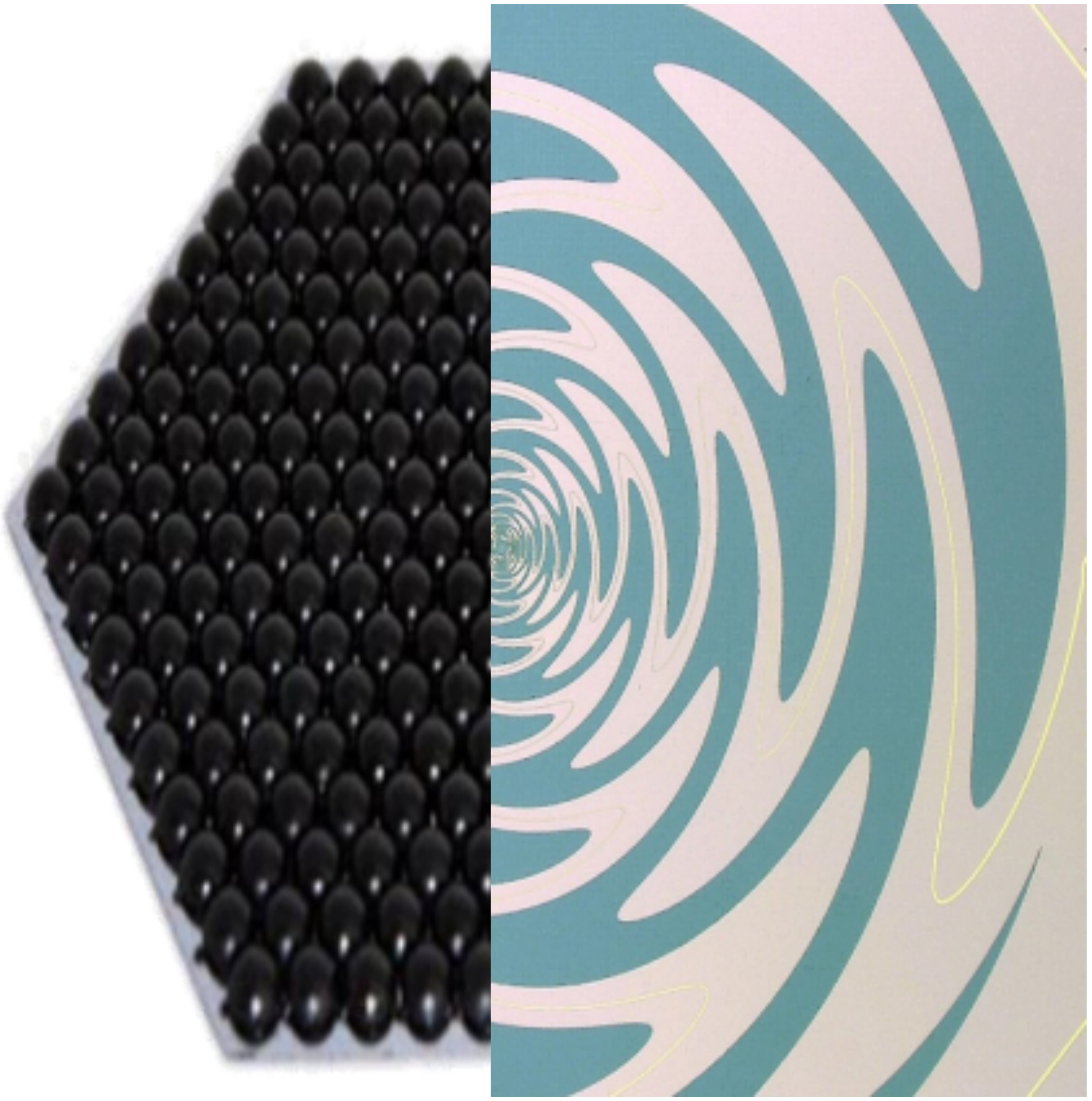
for Simons Observatory: ~21 wafers ➔ ~30,000 detectors

The Simons Observatory Detectors

two detector architectures



Spline Horn Array
(NIST)

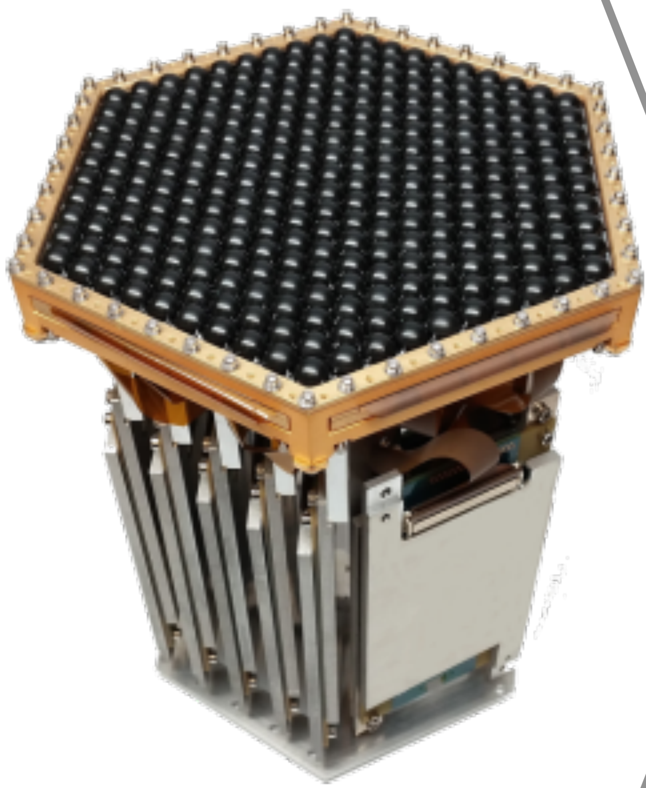


Sinuous antenna + lenslet array
(Berkeley)

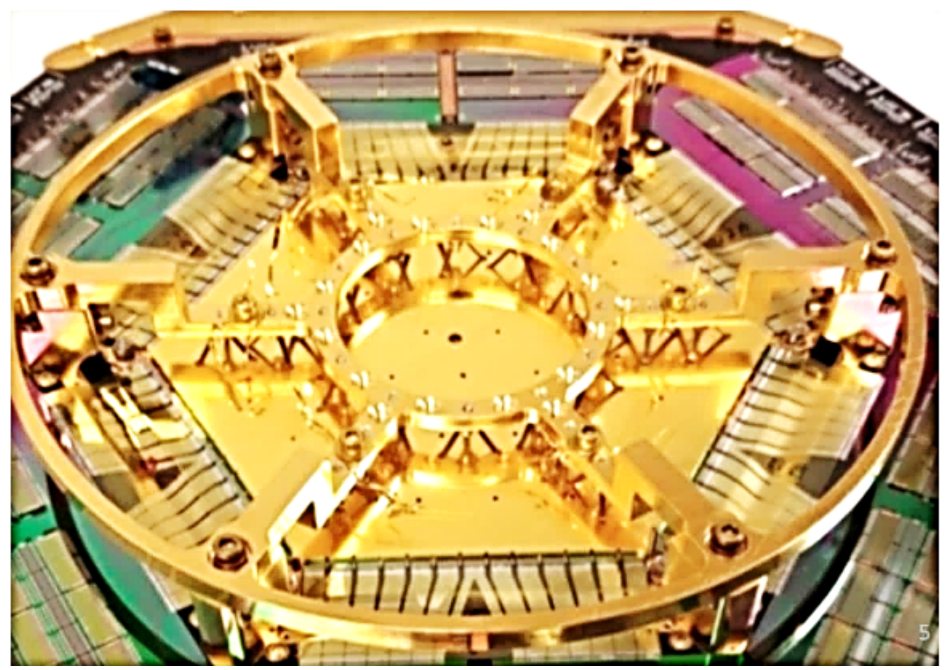
The Simons Observatory Detectors

universal focal plane module (UFM)

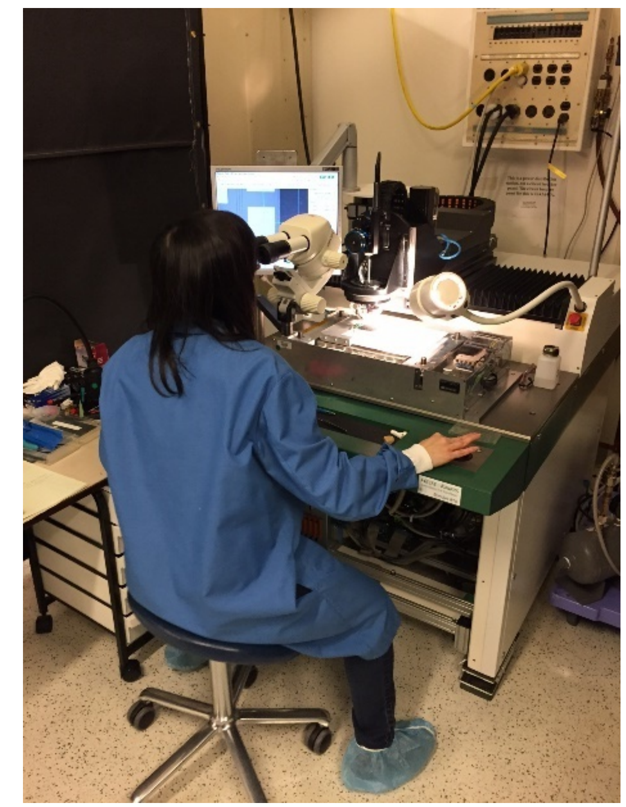
both horn and sinuous/lenslet arrays



detector module



detectors with readout cables

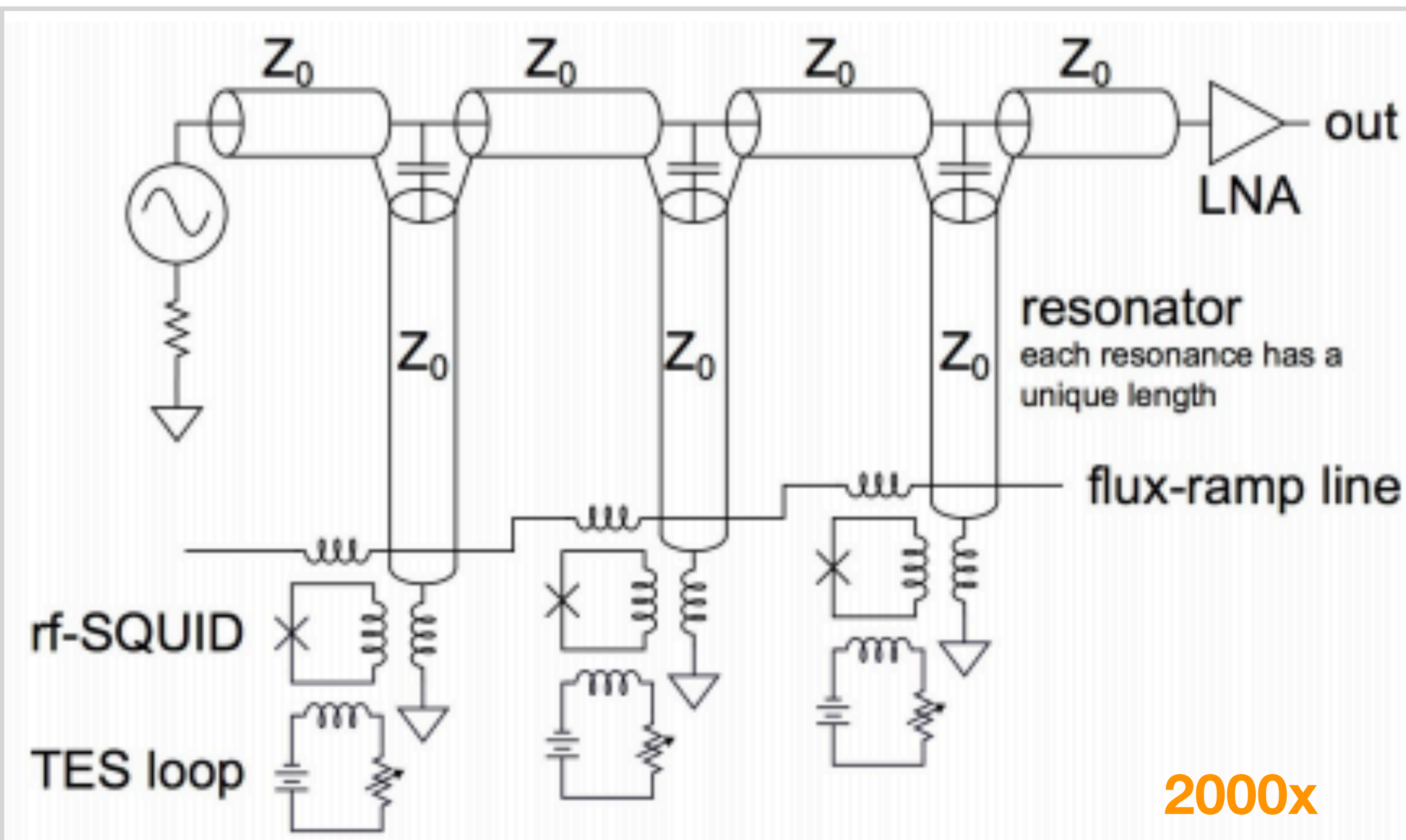


automatic wire bonder

both detector technologies can be read out with the same frequency multiplexing system

The Simons Observatory Detector Readout

- Frequency domain multiplexing
- Send in a comb of narrow frequency bands (tones)
- Each detector is coupled to a resonant circuit such that its output signal is converted to a change in the resonance of the circuit



uMux – current through the TES couples flux into a flux-variable inductor in an LC circuit

The Simons Observatory Calibration

we are working on requirements for bandpass measurements, gain, beams and polarization angles

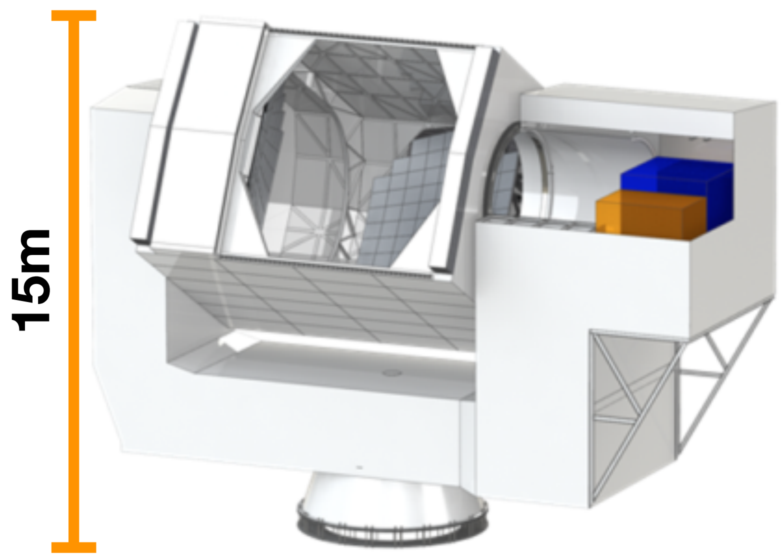
examples of recent studies

POLOCALC: a Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background
F. Nati et al (2017)

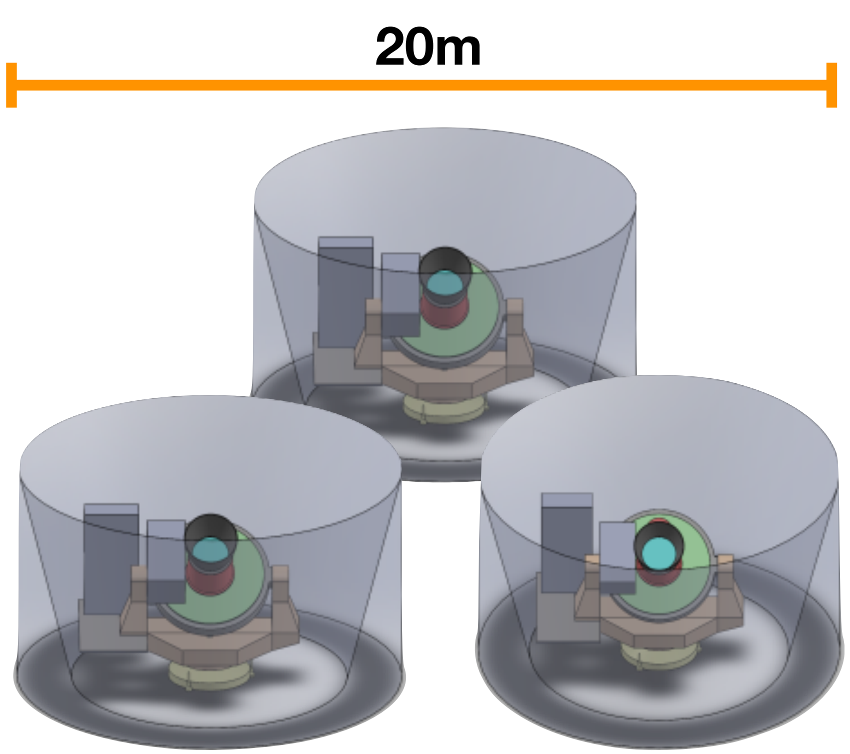
Fig. 1. Three different configurations for POLOCALC (starting from the left): 1) from a ground tripod 2) from a flying drone and 3) from a high-altitude balloon.

The Effects of Bandpass Variations on Foreground Removal Forecasts for Future CMB Experiments
Ward, Alonso, Errard, Devlin, Hasselfield [arXiv:1803.07630]

The Simons Observatory — technical summary



- 6-meter diameter Cross Dragone telescope
- 2-mirror design with a side-looking camera
- the camera rotates with the elevation axis
- the back of the camera can be accessed while installed on the telescope
- constructed by Vertex, in collaboration with CCAT
- 1.4’ FWHM @ 150GHz
- 2.8 m x 2.5 m / 5,000kg cryostat
- 70,000+ detector capacity (30,000 planned for SO)
- modular design receiver for optics tube



- 42 cm aperture size, 35 degree FoV
- 30,000 detectors for SO
- continuously rotating HWP
- 4.2 meter high, 7 meter diameter ground shield

SO deliverables for small + large apertures
~ 42 wafers → 60,000 detectors