Uncovering Physics Beyond the Standard Model in the Cosmic Microwave Background

Colin Hill

Columbia University

Research Progress Meeting
Lawrence Berkeley National Laboratory
12 March 2024

Work in progress with K. Surrao, B. Bolliet, S. Goldstein, F. McCarthy, D. Pirvu, J. Huang, M. Johnson, E. Calabrese/T. Louis/H. Jense/ACT Collaboration
2307.01043 + 2308.16260 w/ F. McCarthy
2303.01591 w/ B. Bolliet, A. Spurio Mancini, ++

Cosmic Microwave Background

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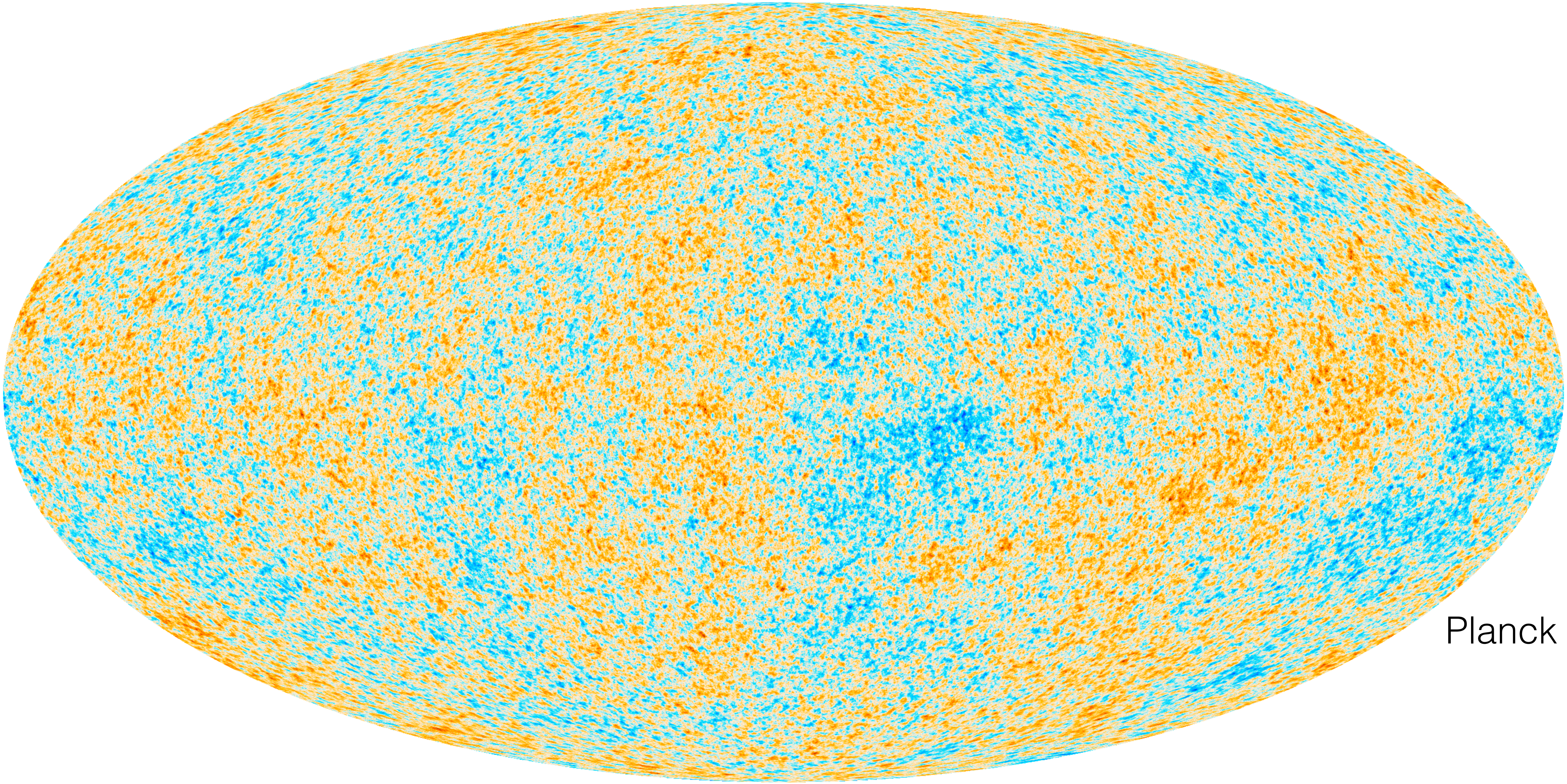


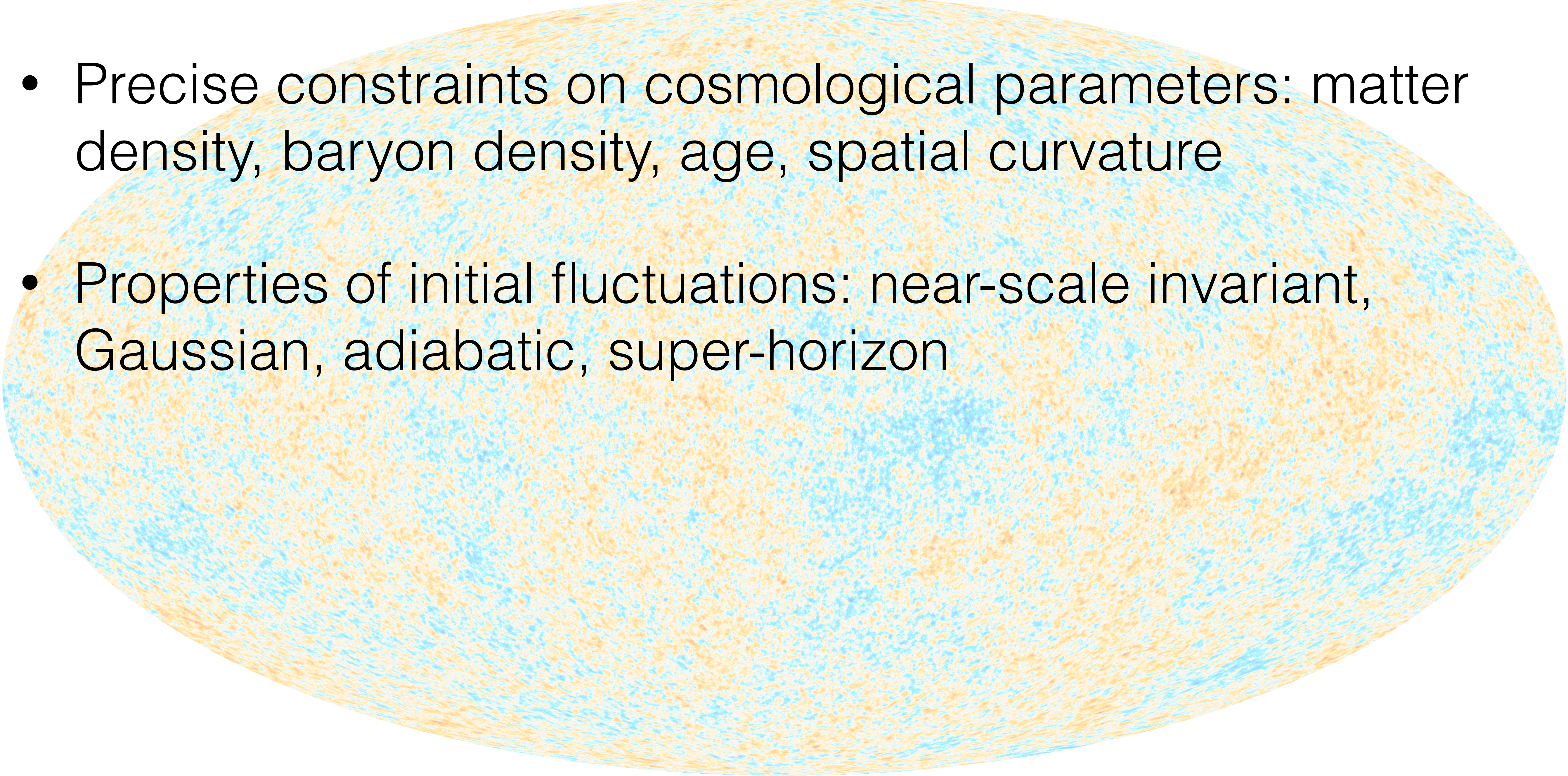
Planck

tens of millions of pixels: statistical properties fully described by six-parameter standard model

Planck Collaboration (2018)

Cosmic Microwave Background

What have we learned?



- Precise constraints on cosmological parameters: matter density, baryon density, age, spatial curvature
- Properties of initial fluctuations: near-scale invariant, Gaussian, adiabatic, super-horizon

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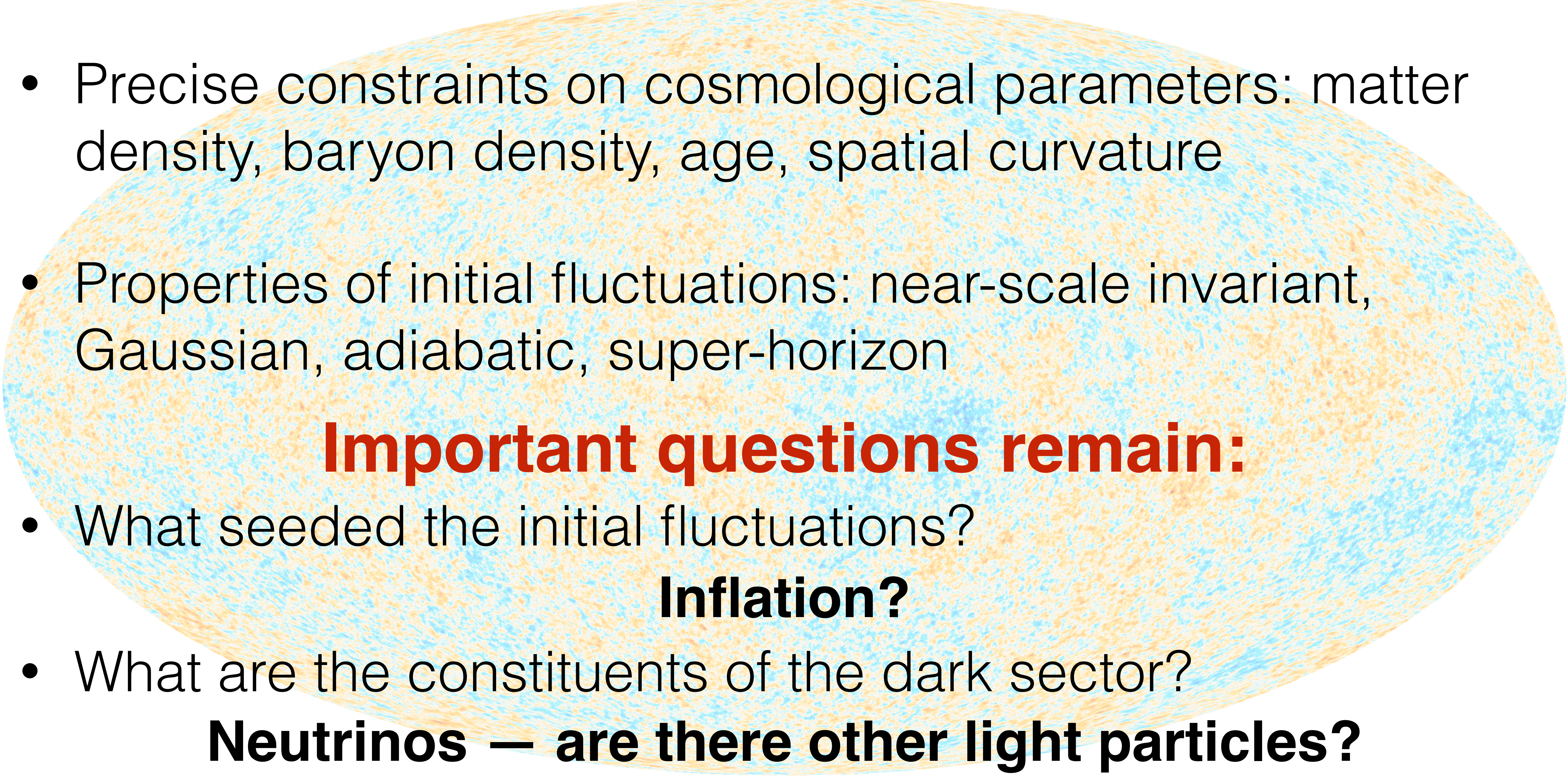
Cosmic Microwave Background

What have we learned?



- Precise constraints on cosmological parameters: matter density, baryon density, age, spatial curvature

- Properties of initial fluctuations: near-scale invariant, Gaussian, adiabatic, super-horizon

Important questions remain:

- What seeded the initial fluctuations?

  Inflation?

- What are the constituents of the dark sector?

  Neutrinos — are there other light particles?

- How can we use the CMB as a particle-physics detector?

  Beyond-Standard-Model physics signatures?

Outline

- BSM Physics in the Primary CMB
- BSM Physics in the Secondary CMB
- New Tools for New Physics
- Outlook: from SO to Advanced SO to CMB-S4

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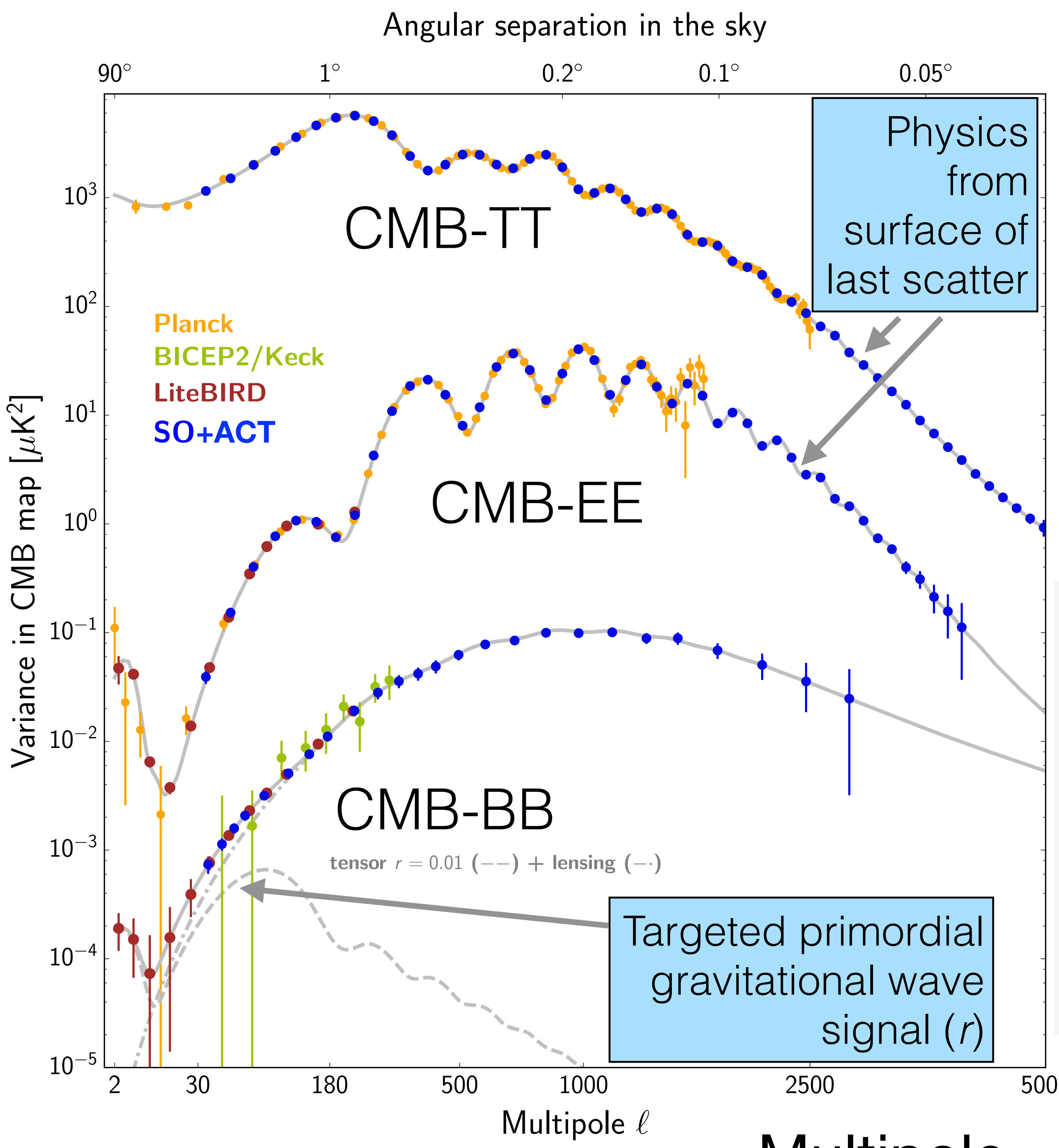
BSM Physics in the Primary CMB

Primary CMB: Landscape

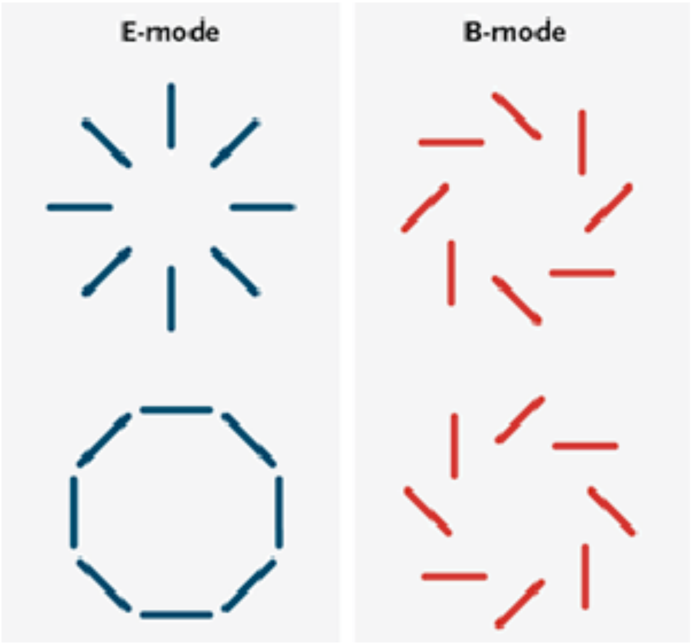


Physics from surface of last scatter

Targeted primordial gravitational wave signal (r)

Angular Power Spectrum

Multipole



Motivation

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- Primary CMB power spectra are sensitive to any light particles (mass < eV) that were *ever* in thermal contact with the primordial plasma ("dark radiation", e.g., neutrinos)

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- $N_{\rm eff}$: simple parameterization that captures a wide range of BSM theories, with SM value = 3.044 (neutrinos):

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

neutrino energy density (+DR)

photon energy density

CMB-S4: $\sigma(N_{\rm eff})$ = 0.03

CMB: Relativistic Particle Detector

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- CMB-S4 will rule out (or detect) at >95% CL *any* light spin-3/2 (e.g., gravitino) or spin-1 (e.g., dark photon) particle in thermal contact at any time back to reheating (t ~ 10^{-36} sec)

(cf. LHC: t ~ 10^{-15} sec)

- Detection would be the first direct cosmic signal from the epoch before neutrino decoupling (t ~ 1 sec)

External Motivation

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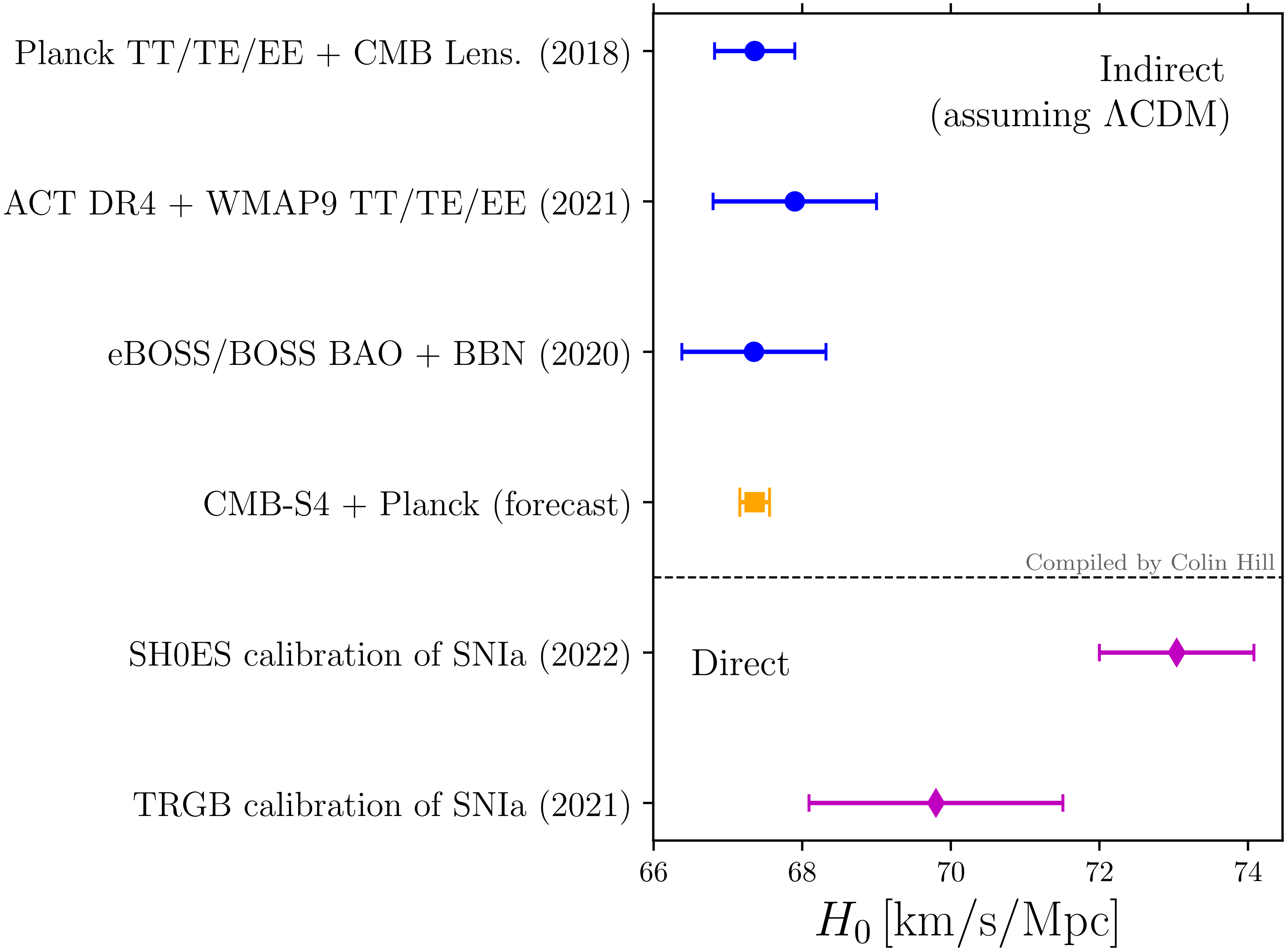
Hints of New Physics in H_0

Formal statistical discrepancy between Planck and SH0ES is ~5σ: if not a systematic (robust confirmation needed), requires new physics beyond ΛCDM



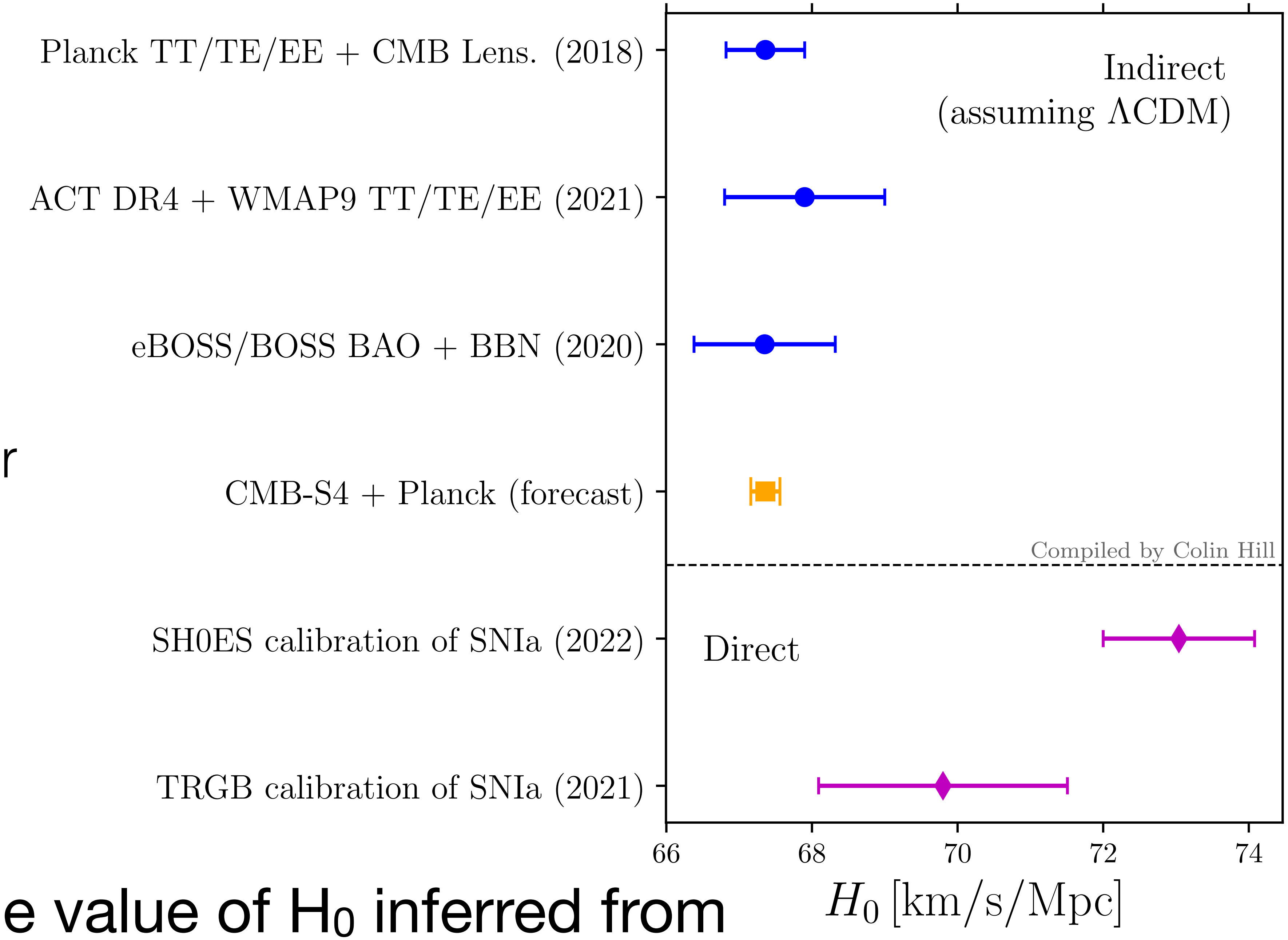
External Motivation

Hints of New Physics in H_0

Formal statistical discrepancy between Planck and SH0ES is ~5σ: if not a systematic (robust confirmation needed), requires new physics beyond ΛCDM

- Not a CMB systematic: Planck, ACT, SPT agree within ΛCDM

- Not specific to CMB: other cosmological probes (BOSS BAO+BBN+others) agree



How can we increase the value of H_0 inferred from CMB and large-scale structure data?

Classes of Models

Viable paths to increase CMB-inferred H_0

- Pre-recombination energy injection: e.g., early dark energy and its variants — all require new light field(s)

  Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); **JCH**+ (2020); Ivanov, McDonough, **JCH**+ (2020); **JCH**+ (2021); McDonough, Lin, **JCH**+ (2022); Lin, McDonough, **JCH**, Hu (2023)

- Modified recombination: e.g., primordial magnetic fields; increased m_e; or decreased T_{CMB}

  Jedamzik & Pogosian (2018); Sekiguchi & Takahashi (2020); Hart & Chluba (2020); Thiele, Guan, **JCH**+ (2021); Chiang & Slosar (2018); Lee+ (2022); Ivanov+ (2020); **JCH** & Bolliet (2023)

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- Additional dark radiation species (beyond usual three neutrinos) with non-trivial dynamics/interactions

  Buen-Abad+ (2015,2017); Aloni+ (2021,2022)

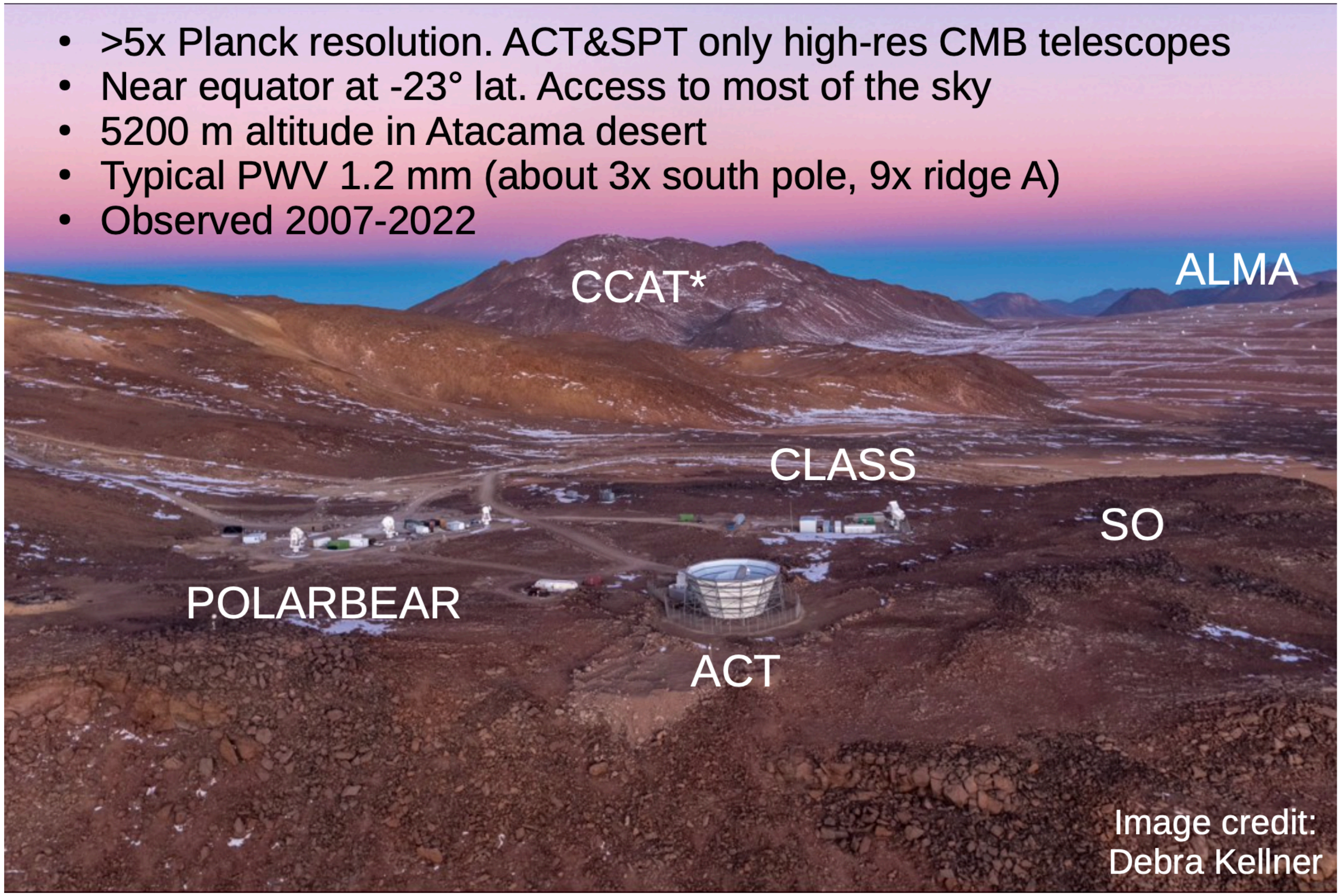
- Strong neutrino interactions (delay v free-streaming)

  Cyr-Racine & Sigurdson (2014); Lancaster+ (2017); Kreisch+ (2019); Escudero & Witte (2019); Kreisch,…,**JCH**+ (2024)

None of these models existed when Planck/ACT/SPT were proposed and built, yet these experiments have been absolutely crucial in searching for evidence of these signals of new physics

Current State of the Field: ACT

The Atacama Cosmology Telescope



- >5x Planck resolution. ACT&SPT only high-res CMB telescopes
- Near equator at -23° lat. Access to most of the sky
- 5200 m altitude in Atacama desert
- Typical PWV 1.2 mm (about 3x south pole, 9x ridge A)
- Observed 2007-2022

Image credit:
Debra Kellner

Planned future site for CMB-S4 wide-area survey

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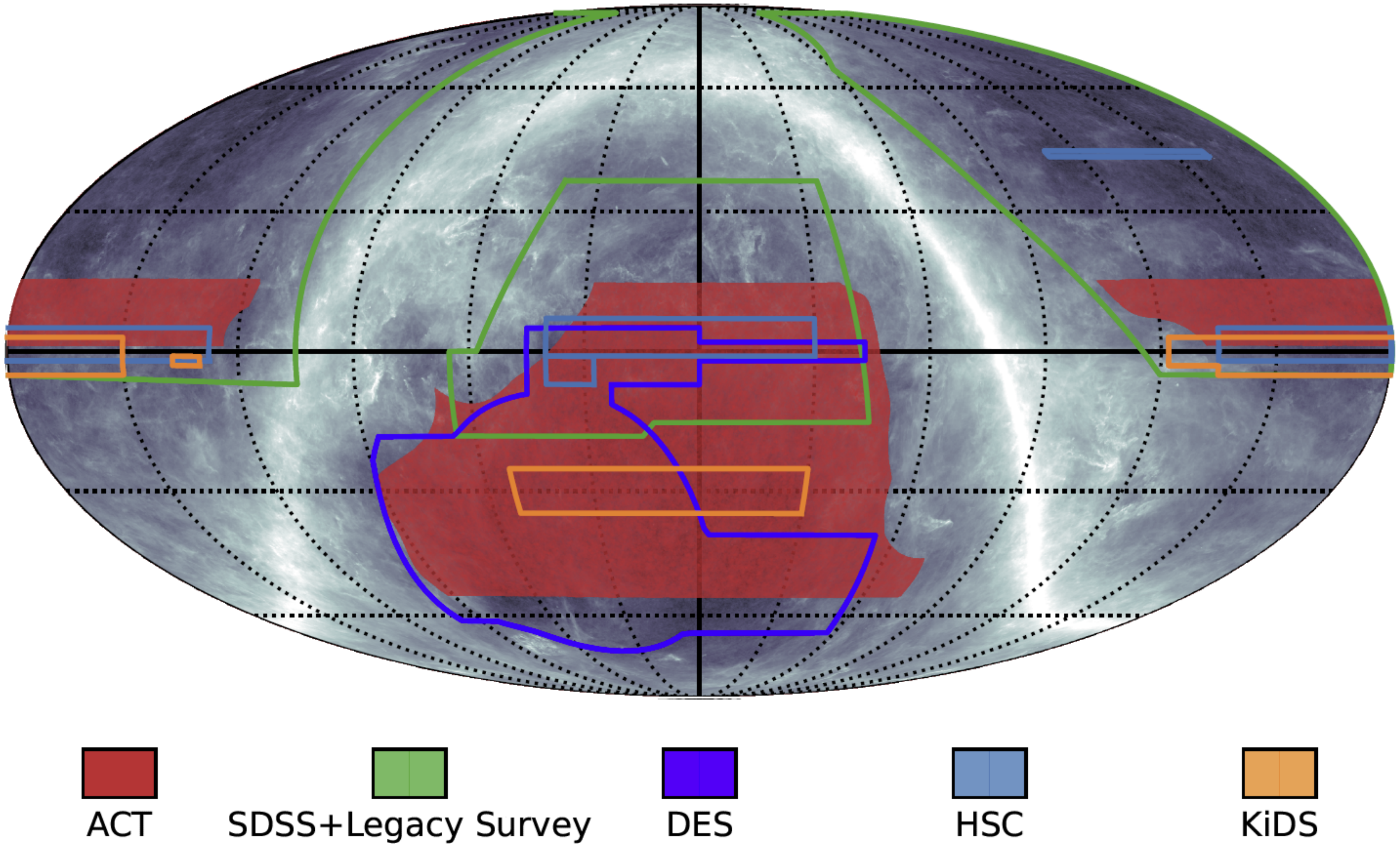

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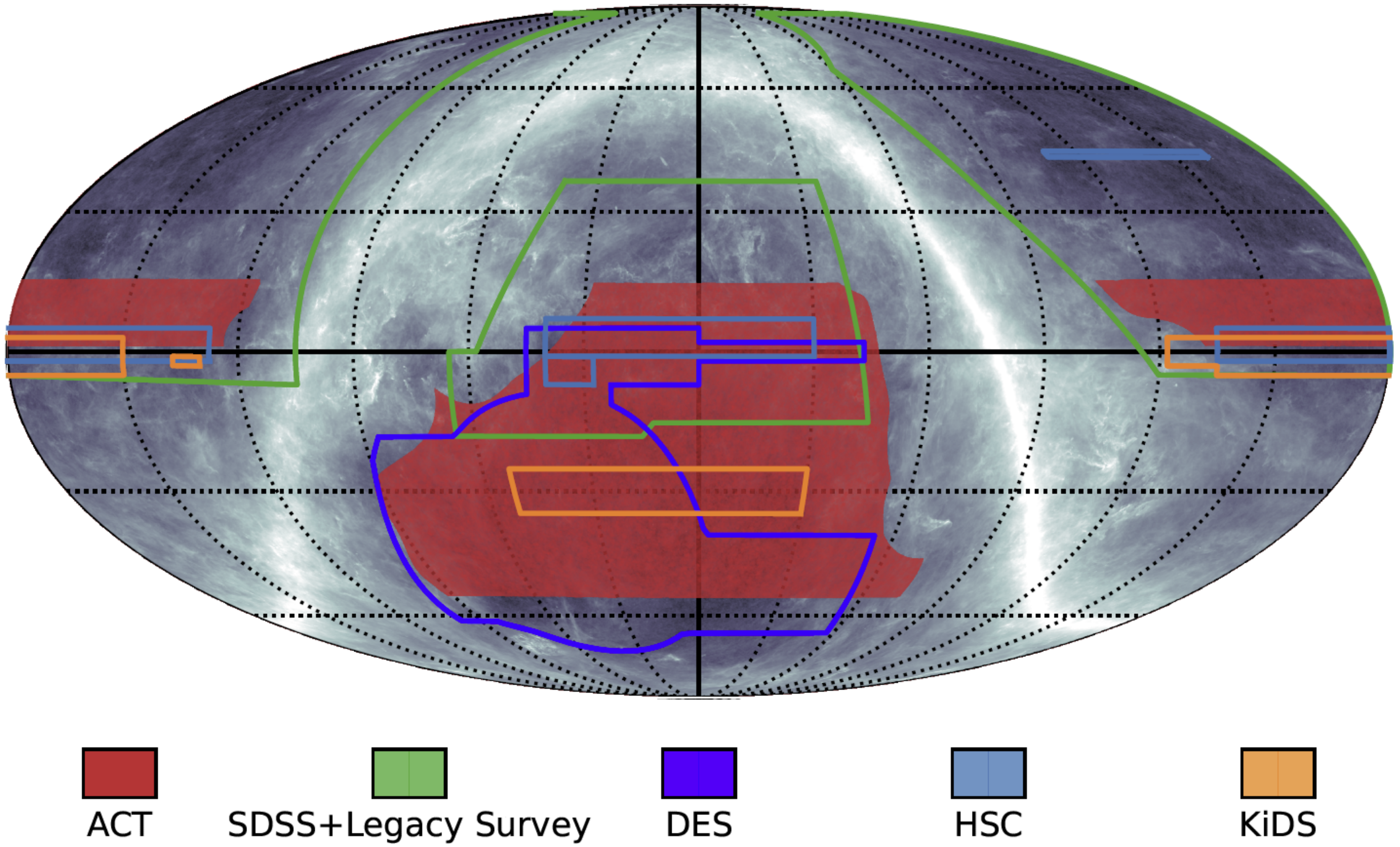

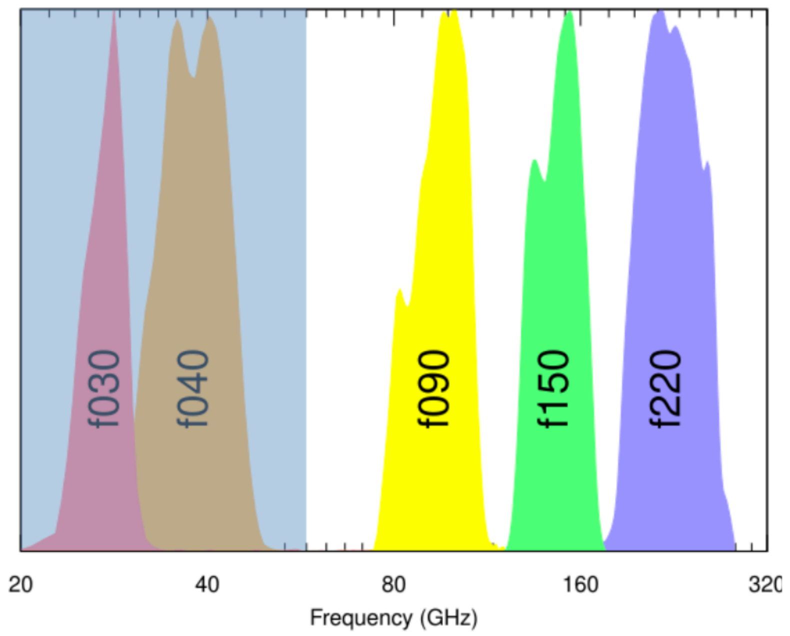

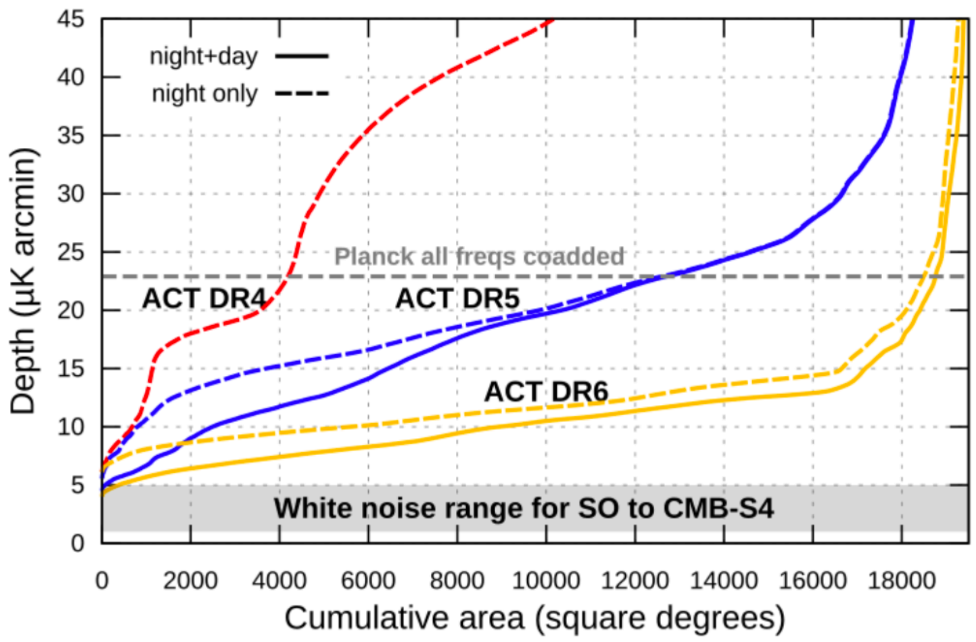

- Observed 2017-2022 in 5 bands
- Combined sensitivity of 6.1 μK√s (mostly in f090 and f150)
- ACT DR6 coming soonish 🙂
- Deeper than Planck over 19000°²
- Median depth of 10 μK arcmin
- 10x as much statistical power as DR4 (prev. cosmology release)

Data Release 6 (DR6) expected this year

Current State of the Field: ACT

T

E

B

F

DR6 map
example
(from 4-5 μK
arcmin region)

ACT DR6 Sensitivity

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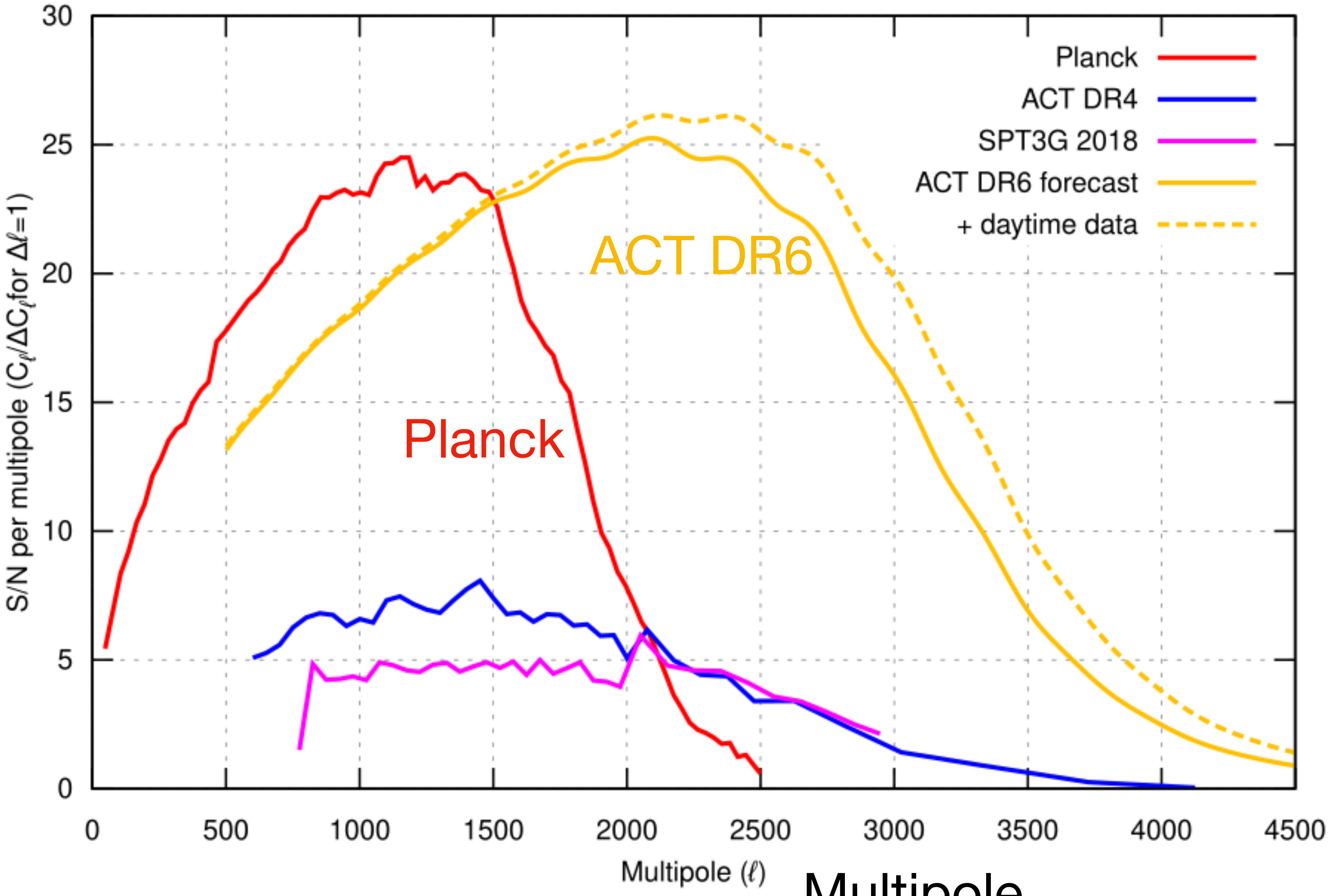
S/N per multipole in TT power spectrum

Preliminary!



Multipole

ACT DR6 Sensitivity

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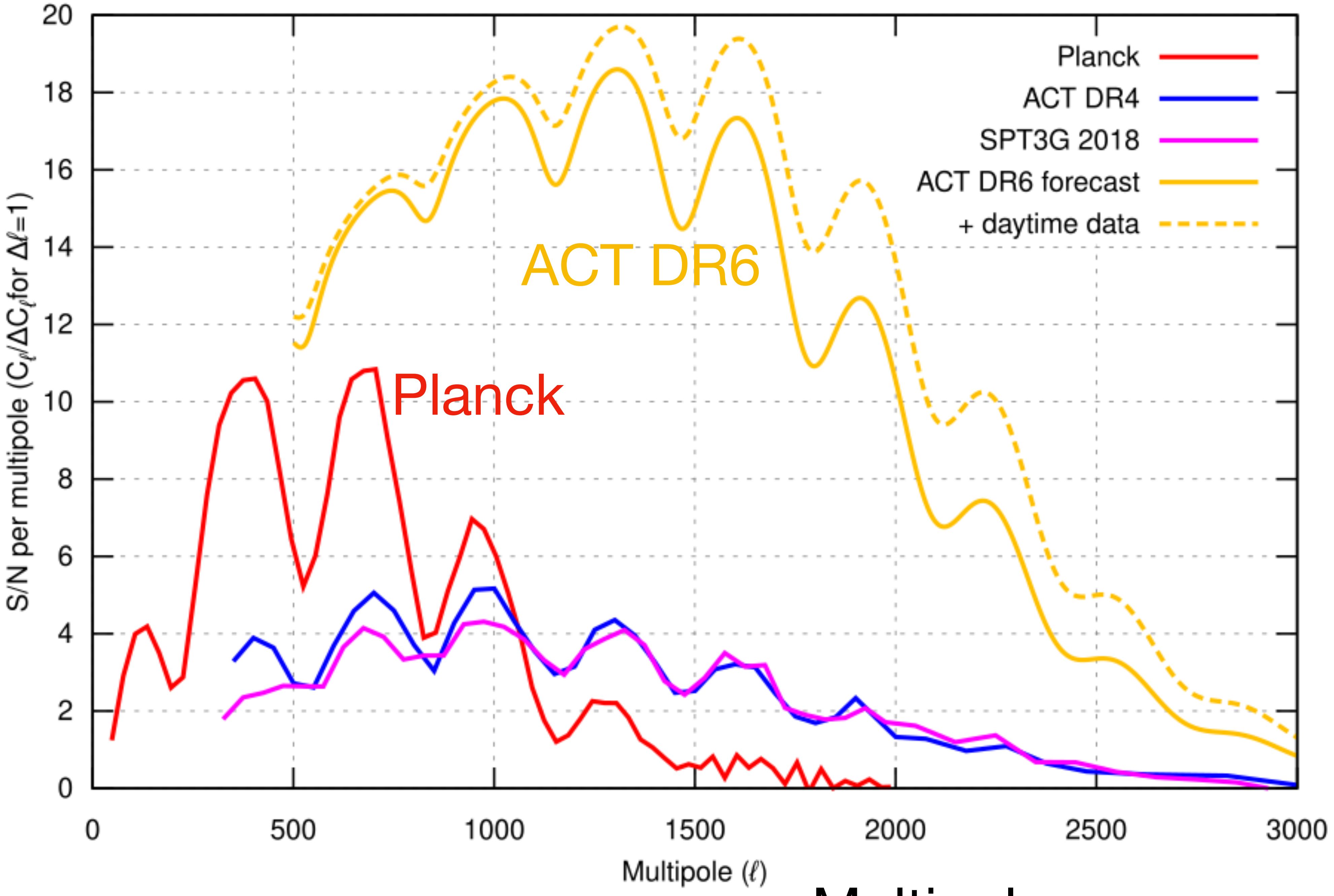
S/N per multipole in EE power spectrum

Preliminary!



EE

Multipole

Big step up from both DR4 and Planck!

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ACT DR6: Robustness

End-to-end validation from maps to parameters

- Standard in previous CMB power spectrum analyses: simulate gaussian random fields and run analysis pipeline with the same sky model

- More stringent test in DR6: infer parameters from ~realistic, non-gaussian sky maps with realistic instrument systematics, using analysis pipeline that does not contain models designed to match these simulations

ACT DR6: Robustness

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- Extragalactic fields = *Agora* (Omori 2022): N-body simulation post-processed with detailed models for secondary anisotropies, CIB, sources

- Galactic fields = *PySM3* (Thorne+2017, Zonca+2021)

- Maps for each ACT detector array are generated and processed with beams, passbands, and noise model built from data (Atkins+ 2023)

- Pipeline accelerated by >100x using neural-network-based Boltzmann code emulators (Bolliet, JCH,+ 2023)

ACT DR6: Robustness

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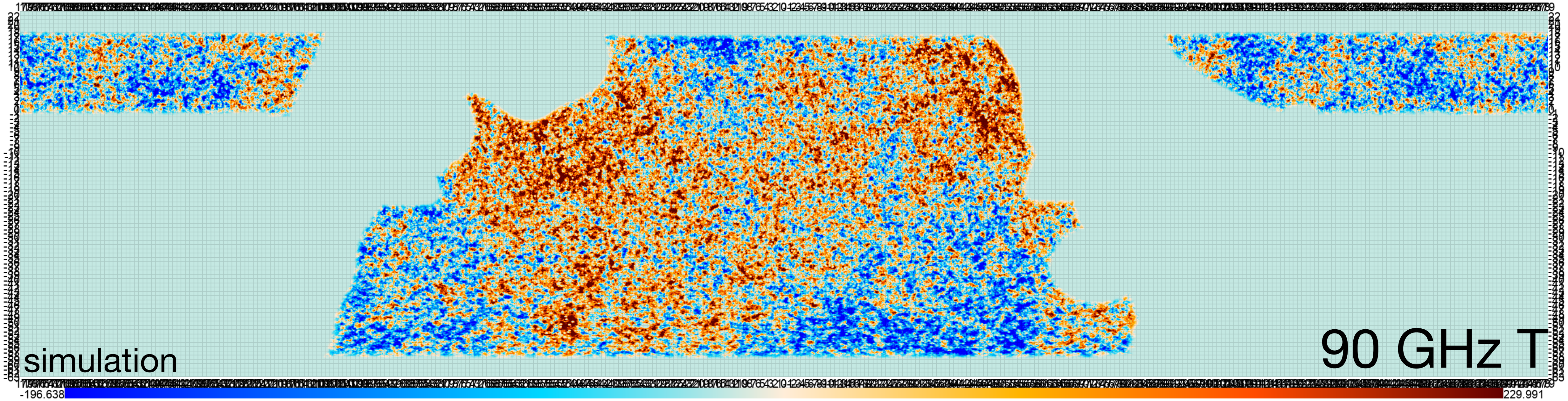

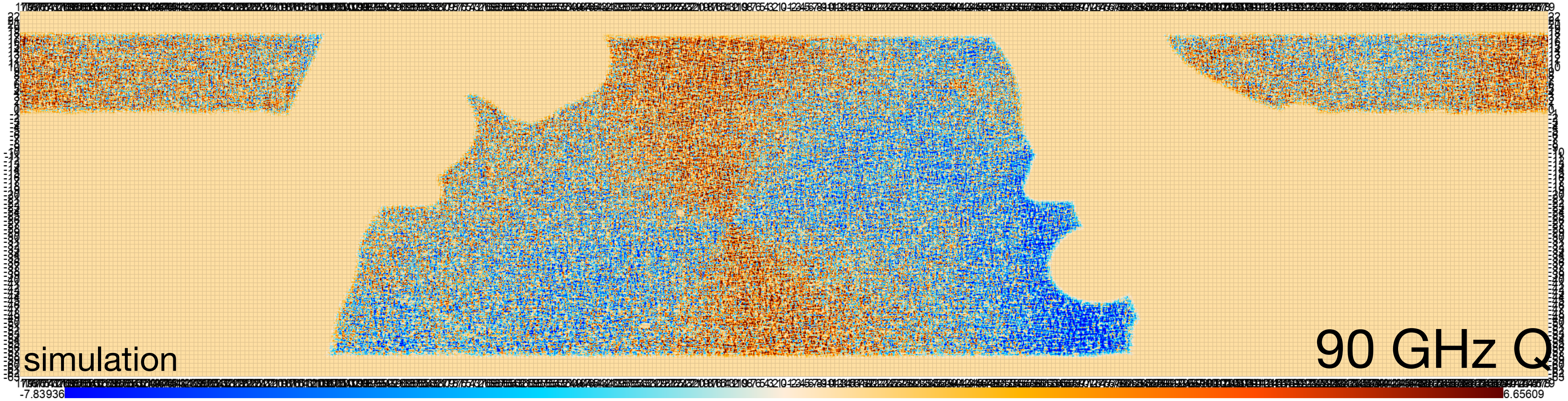

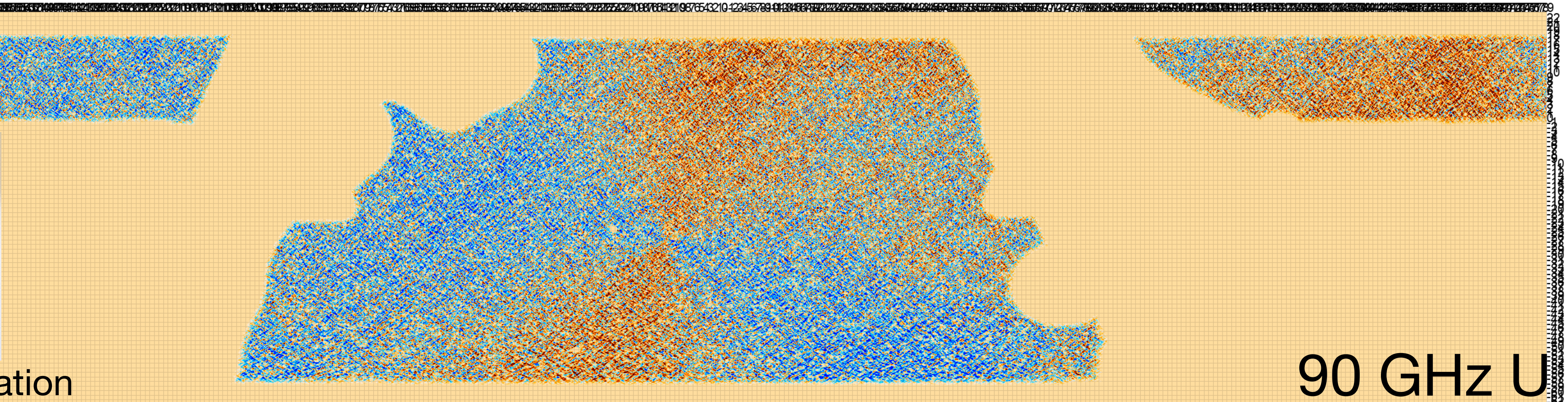

ACT DR6: Robustness

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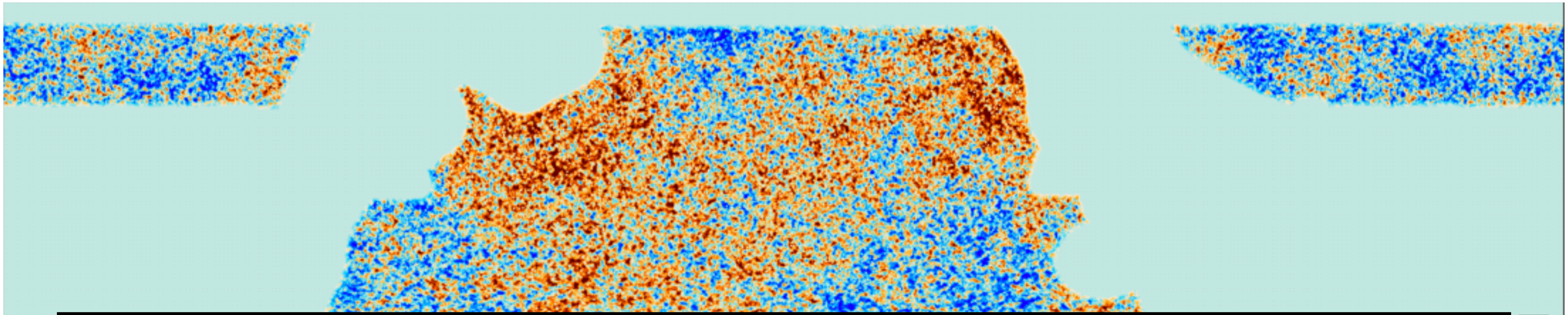
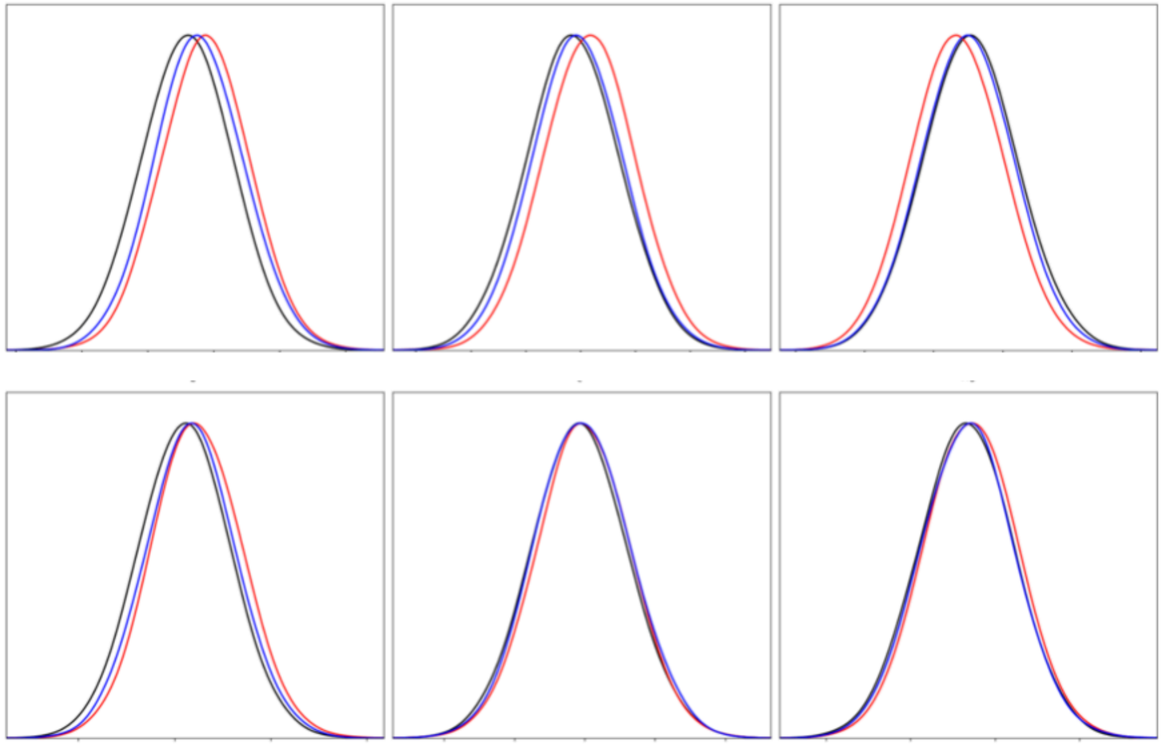


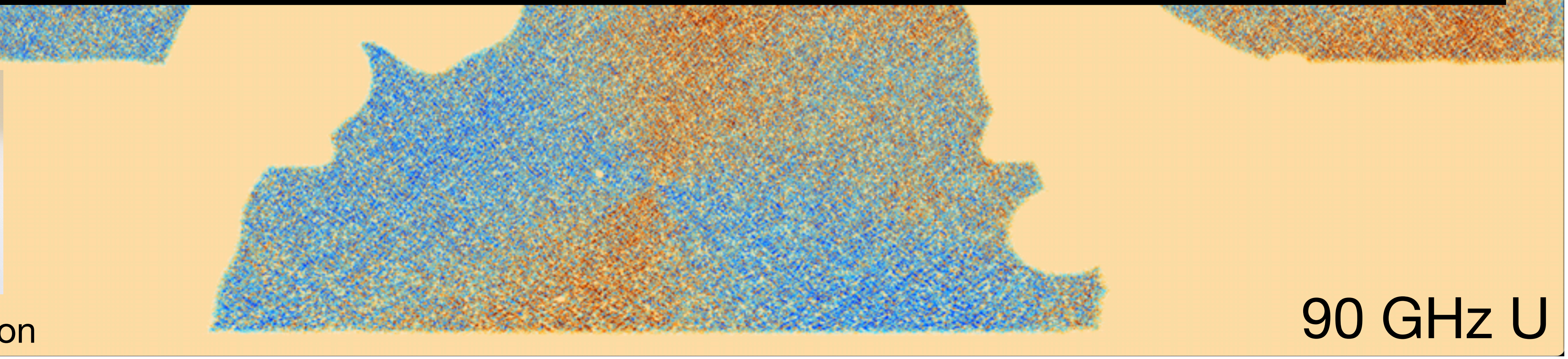
Data set = {TT: f90,f150,f220}
+ {TE,EE: f90,f150}

Analyze with pipeline (built for SO + CMB-S4) — MFLike

Infer parameters!
(not yet unblinded) →

https://github.com/simonsobs/LAT_MFLike





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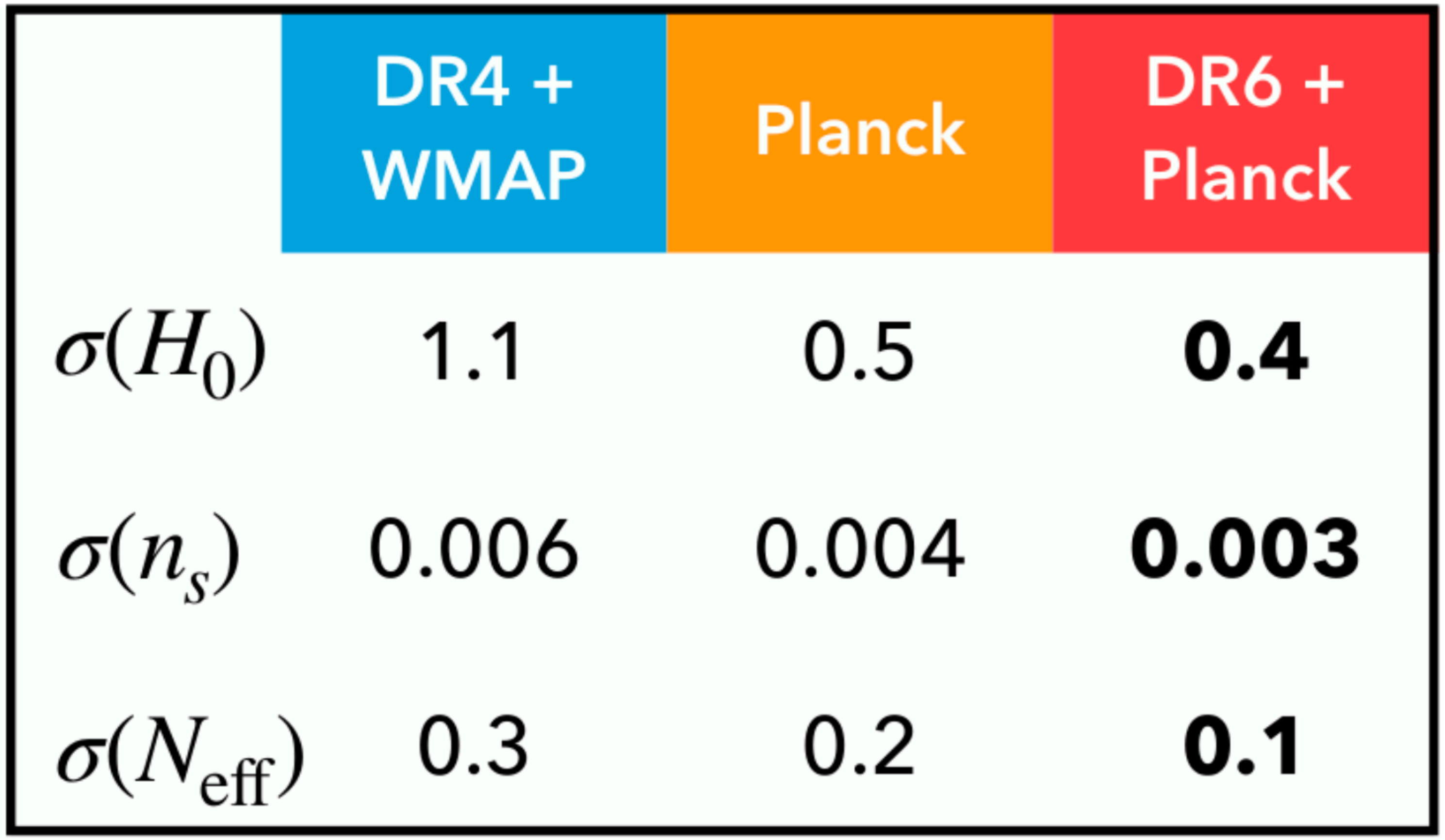
ACT DR6 Projections

ΛCDM + extensions



	DR4 + WMAP	Planck	DR6 + Planck
$\sigma(H_0)$	1.1	0.5	**0.4**
$\sigma(n_s)$	0.006	0.004	**0.003**
$\sigma(N_{\rm eff})$	0.3	0.2	**0.1**

Preliminary Forecast (rounded to 1 s.f.)

Also of interest — running of the spectral index:
cf. 3σ hint of running from eBOSS Ly-alpha forest at $\alpha_s \sim -0.01$
— could exclude/confirm this hint at moderate S/N in DR6

cf. Palanque-Delabrouille+ (2020)

ACT DR6 Projections

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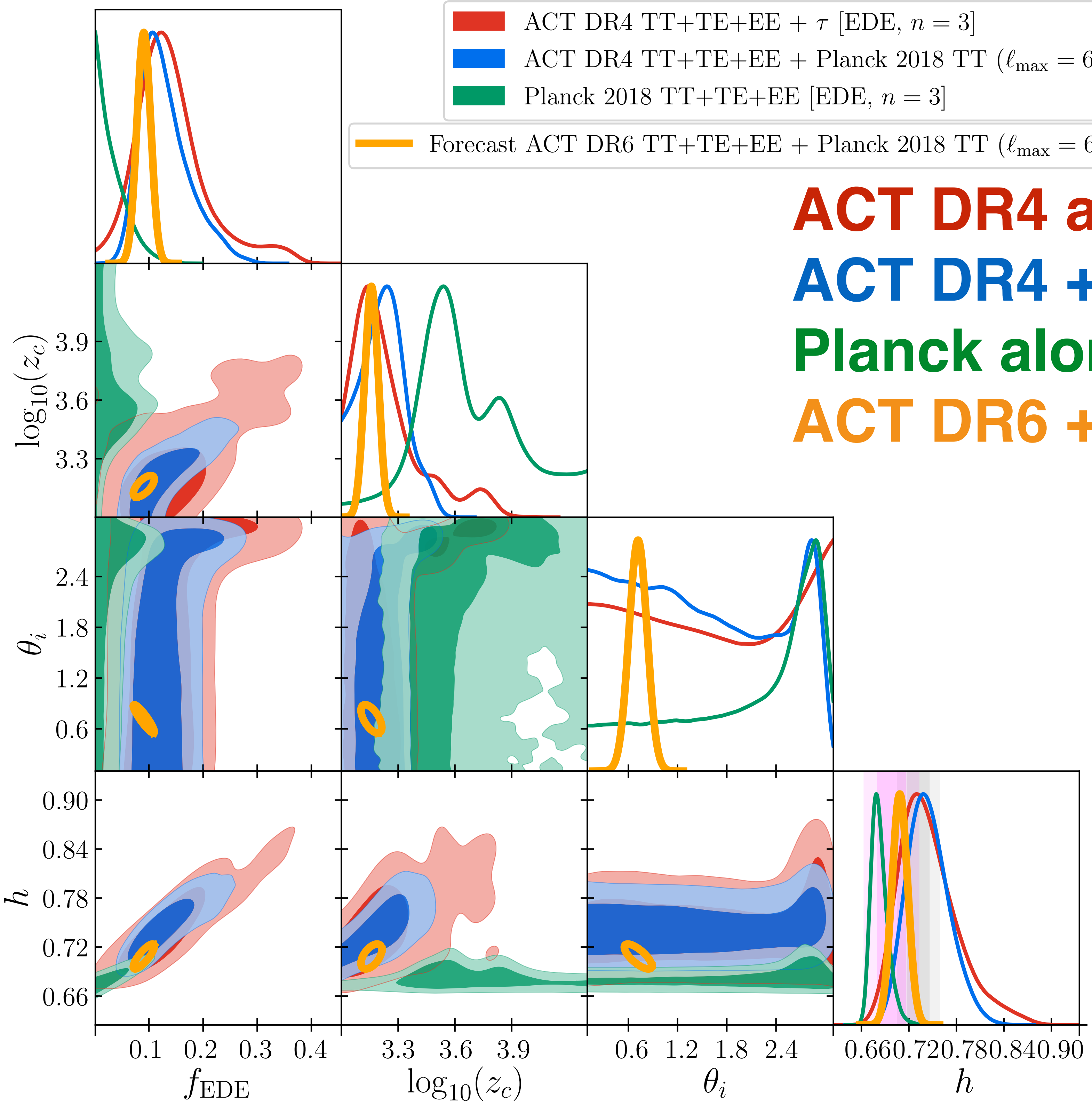
Axion-like early dark energy



ACT DR4 alone

ACT DR4 + Planck TT (ell<650)

Planck alone

ACT DR6 + WMAP forecast

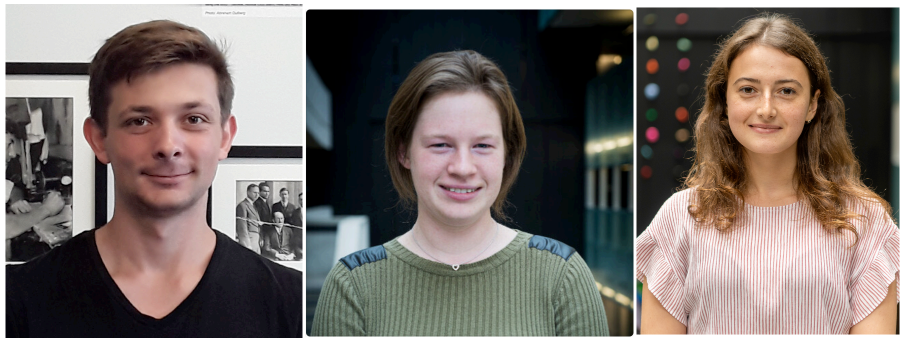
If H_0-tension-resolving EDE is present, we will detect it at ~10σ and constrain its dynamics

EDE fraction

Hubble

… stay tuned!

BSM Physics in the Secondary CMB



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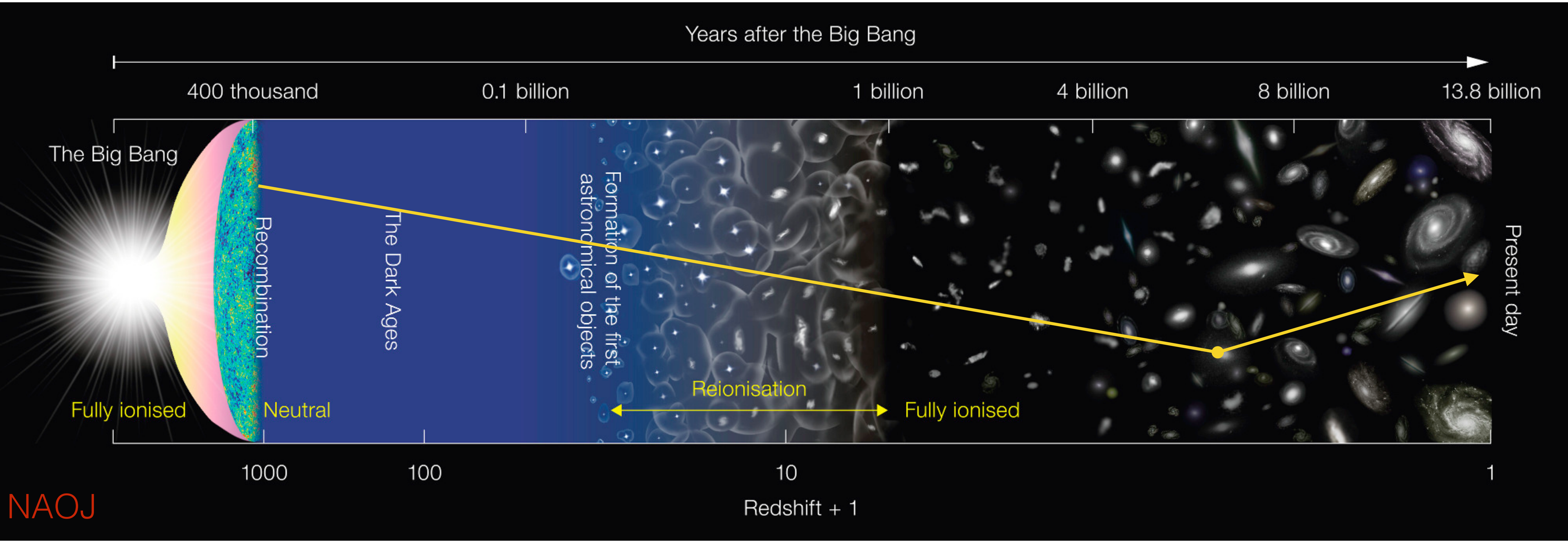
Cosmic Microwave Back*light*

Secondary Anisotropies



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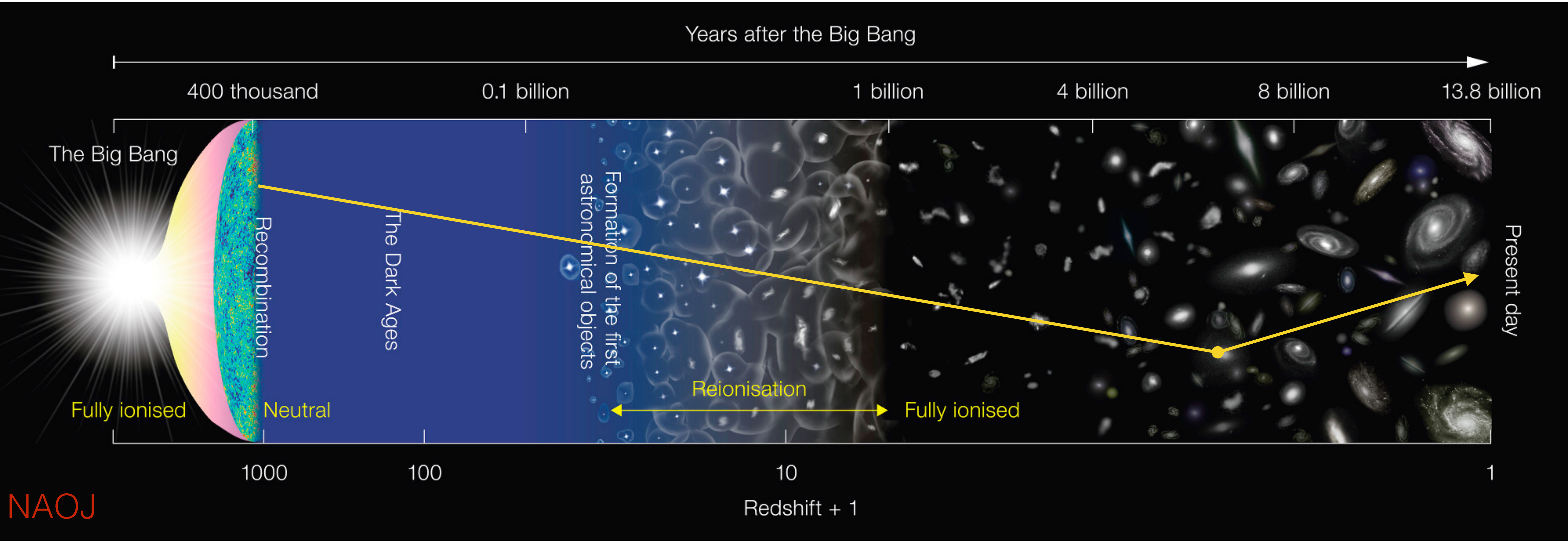

- Deflection: gravitational lensing

- Evolving potentials: integrated Sachs-Wolfe, Rees-Sciama effects

- Scattering: thermal / kinematic Sunyaev-Zel’dovich effects, patchy screening

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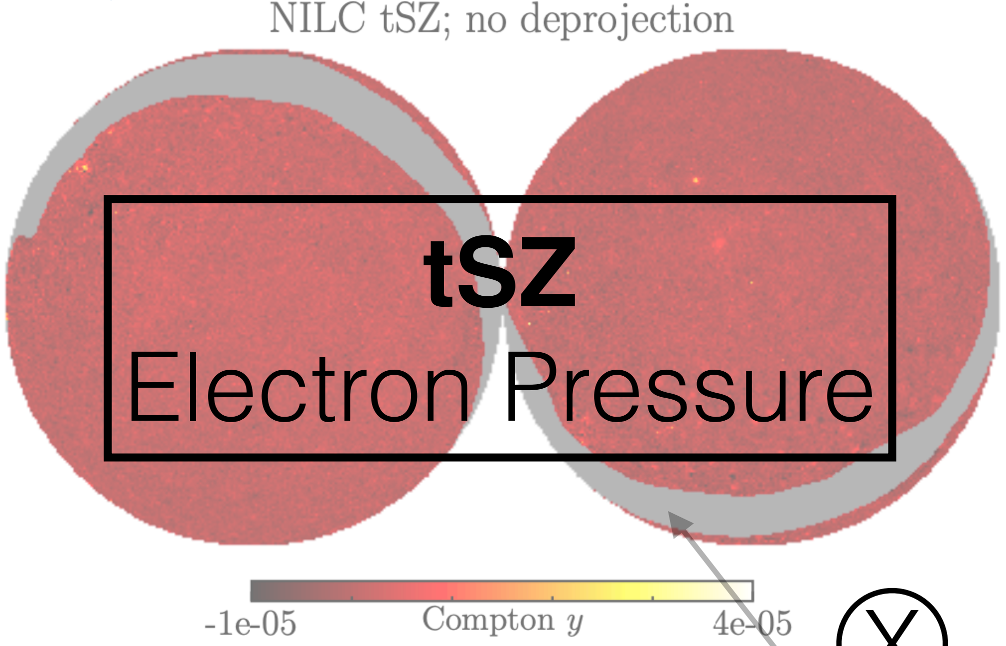
Cosmic Microwave Backlight

Secondary Anisotropies

McCarthy & JCH (2023a)

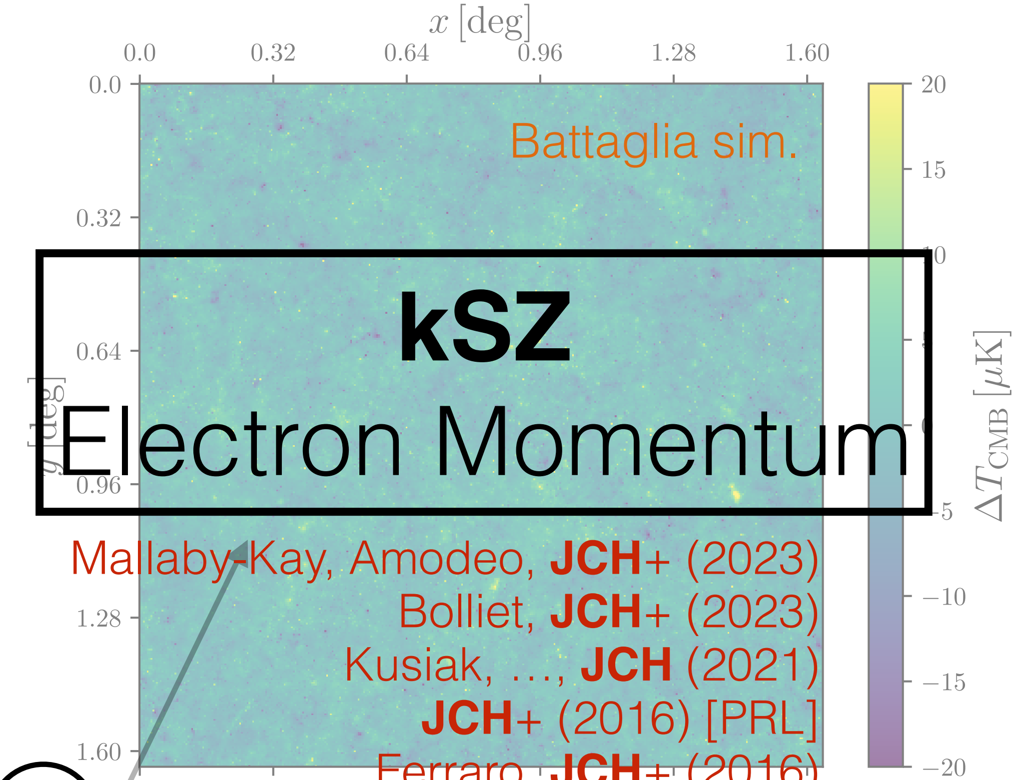


tSZ
Electron Pressure

McCarthy & **JCH** (2023a)
Coulton, Madhavacheril,
Duivenvoorden, **JCH**+ (2023)
Wadekar, Thiele, **JCH**+ (2023)
Thiele, Wadekar, **JCH**+ (2022)
Madhavacheril, **JCH**+ (2020)
Pandey, Baxter, **JCH** (2019)
Thiele, **JCH**, & Smith (2019)
JCH+ (2018)
Alonso, **JCH**+ (2018)
JCH+ (2015) [PRL]
Greco, **JCH**+ (2015)
JCH+ (2014)
JCH & Pajer (2013)
JCH & Sherwin (2013)
Wilson, Sherwin, **JCH**+ (2012)

⊗

McCarthy & **JCH** (2023b)
Madhavacheril & **JCH** (2018)
Battaglia, **JCH**, & Murray (2015)
JCH & Spergel (2014)



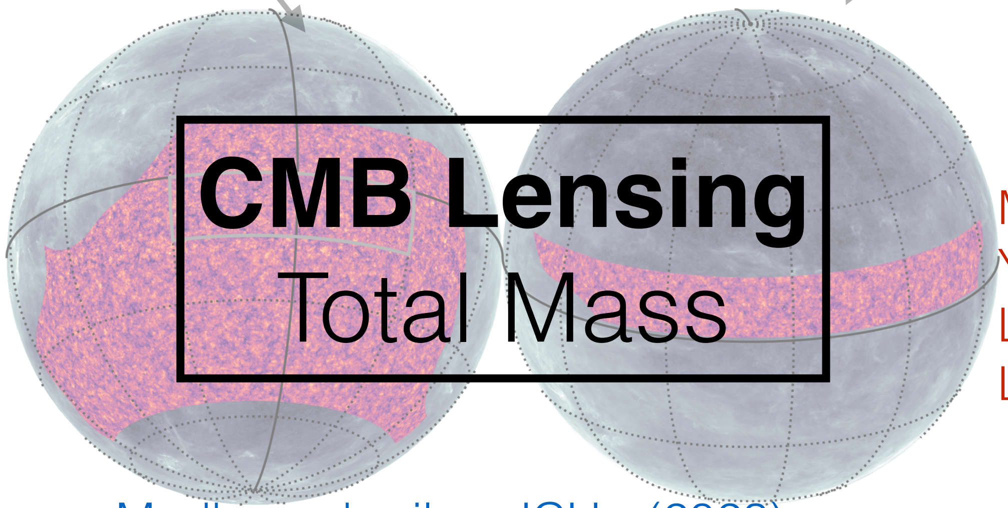
kSZ
Electron Momentum

Mallaby-Kay, Amodeo, **JCH**+ (2023)
Bolliet, **JCH**+ (2023)
Kusiak, …, **JCH** (2021)
JCH+ (2016) [PRL]
Ferraro, **JCH**+ (2016)

⊗

Cai, Madhavacheril, **JCH**, Kosowsky (2022)
Ferraro & **JCH** (2018)

ACT DR6 CMB lensing mass map



CMB Lensing
Total Mass

Madhavacheril,…,JCH+ (2023)

Marques, Liu, Huffenberger, **JCH**+ (2021)
Yu, **JCH**, & Sherwin (2017)
Liu, **JCH**+ (2016)
Liu & **JCH** (2015)

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Cosmic Microwave Backlight

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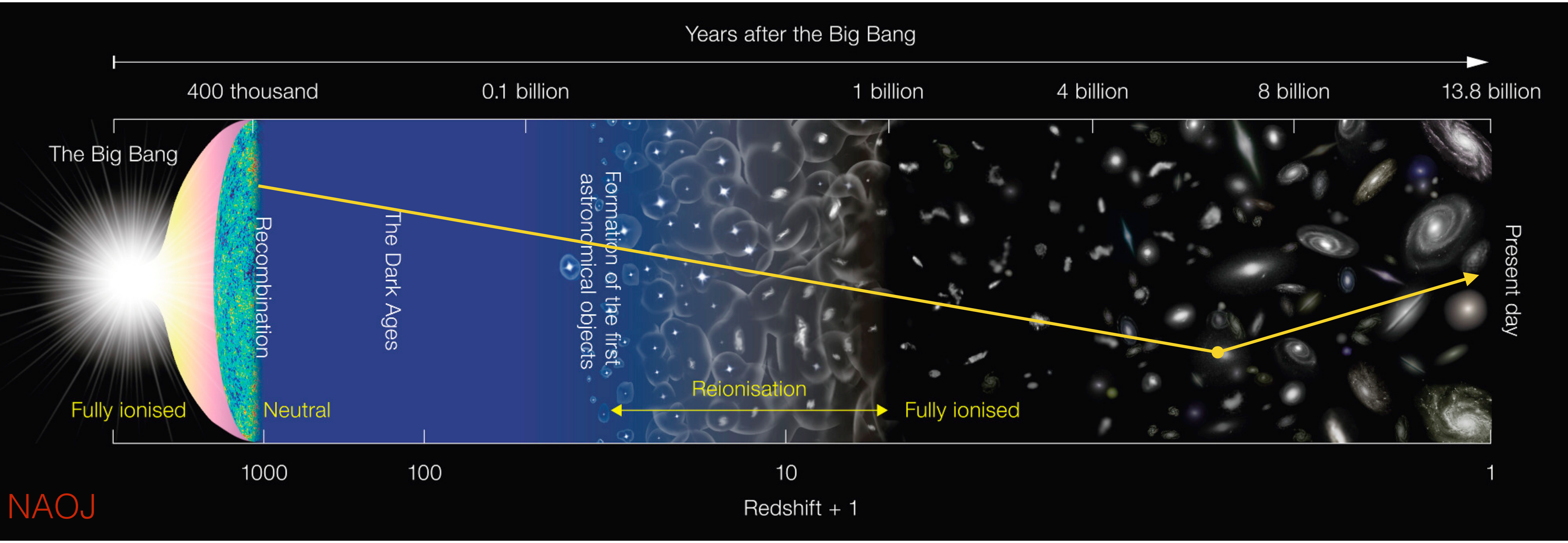

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+ BSM conversion: dark screening

Dark Screening in the CMB

BSM Portals

Only a few well-motivated, renormalizable interactions allowed by SM symmetries that provide a portal between the SM and the dark sector:

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

(e.g.) Essig+2013

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Dominant effect relevant to CMB: resonant conversion when "plasma mass" of CMB photon = dark photon mass or axion mass

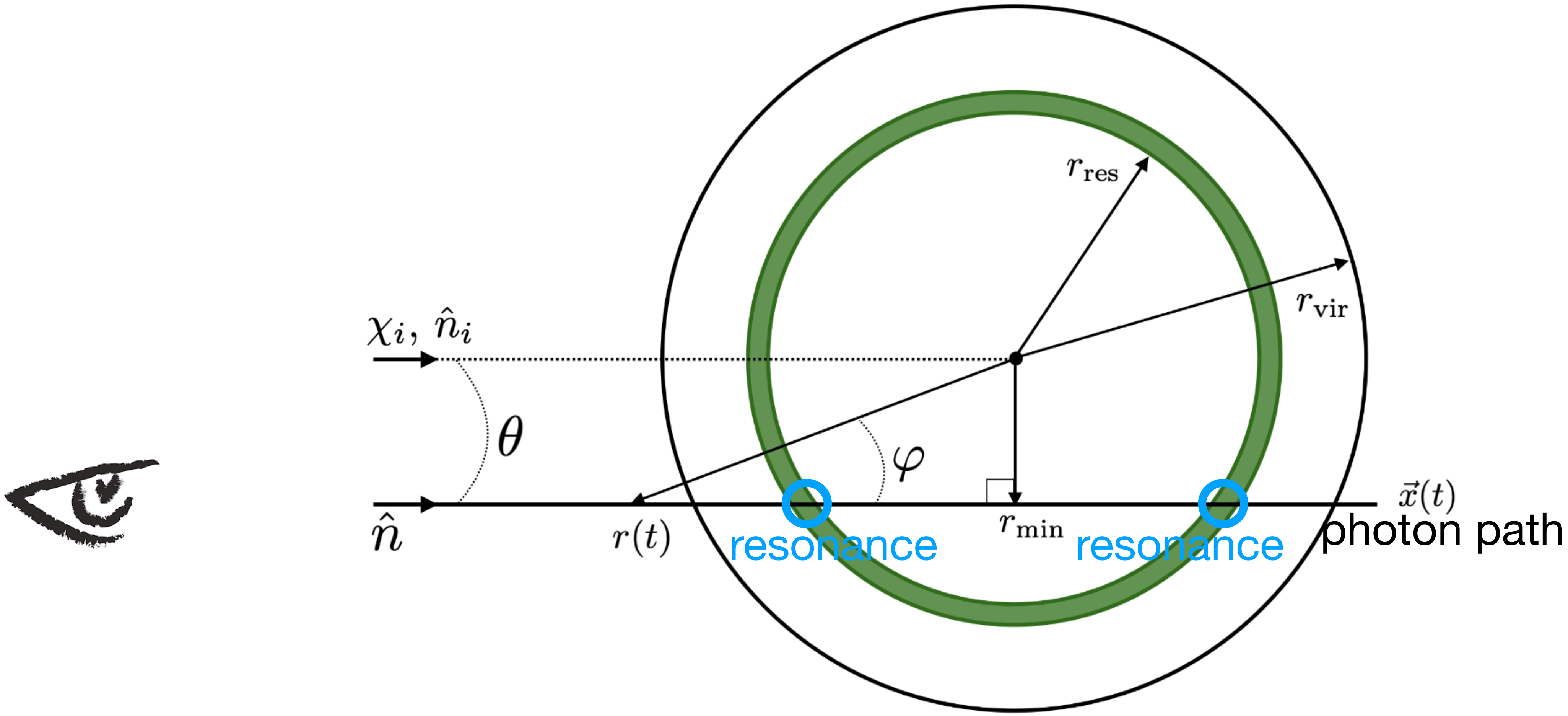
→ Sensitive to mass range ~ 10^{-13} eV — 10^{-11} eV

Mirizzi+ (2009); McDermott & Witte (2020); Caputo+ (2020); Pirvu, Huang, Johnson (2023); +++

Dark Screening in the CMB

(Massive) Dark Photon

Halo model viewpoint:



resonance location depends on DP mass and electron density profile of halo

⟶ **Spatially varying spectral distortion in the CMB, which traces LSS**

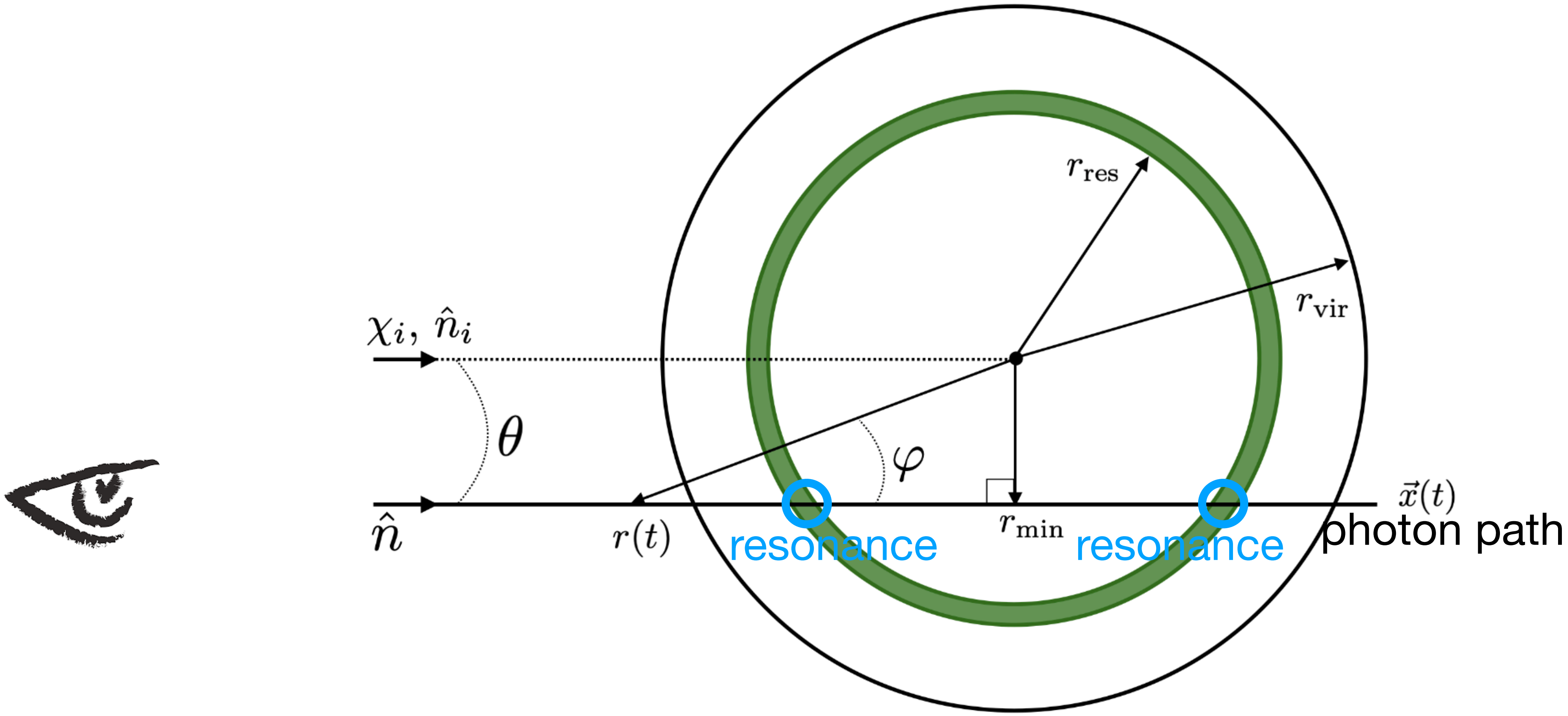
(just like, e.g., the thermal SZ effect)

Pirvu, Huang, Johnson (2023); McCarthy, Pirvu, **JCH**, Huang, Johnson, Rogers (in prep.)

Dark Screening in the CMB

Axion-Like Particle

Halo model viewpoint:



resonance location depends on axion mass and electron density profile of halo

signal strength depends on magnetic field within halo

→ **Spatially varying spectral distortion in the CMB, which traces LSS**

(just like, e.g., the thermal SZ effect)

Goldstein, McCarthy, Pirvu, **JCH**, Huang, Johnson, Rogers (in prep.)

Dark Screening in the CMB

Distortion SEDs

Dark photon: $$\frac{\Delta T(x)}{T_{\mathrm{CMB}}} \propto -\frac{\epsilon^2 m_{A'}^2}{x}\left(\frac{1-e^{-x}}{x}\right)$$

Axion: $$\frac{\Delta T(x)}{T_{\mathrm{CMB}}} \propto -\frac{g_{a\gamma\gamma}^2 B^2}{m_a^2}\, x\left(\frac{1-e^{-x}}{x}\right)$$

$$x \equiv h\nu/(k_{\mathrm{B}}T_{\mathrm{CMB}})$$

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Dark Screening in the CMB

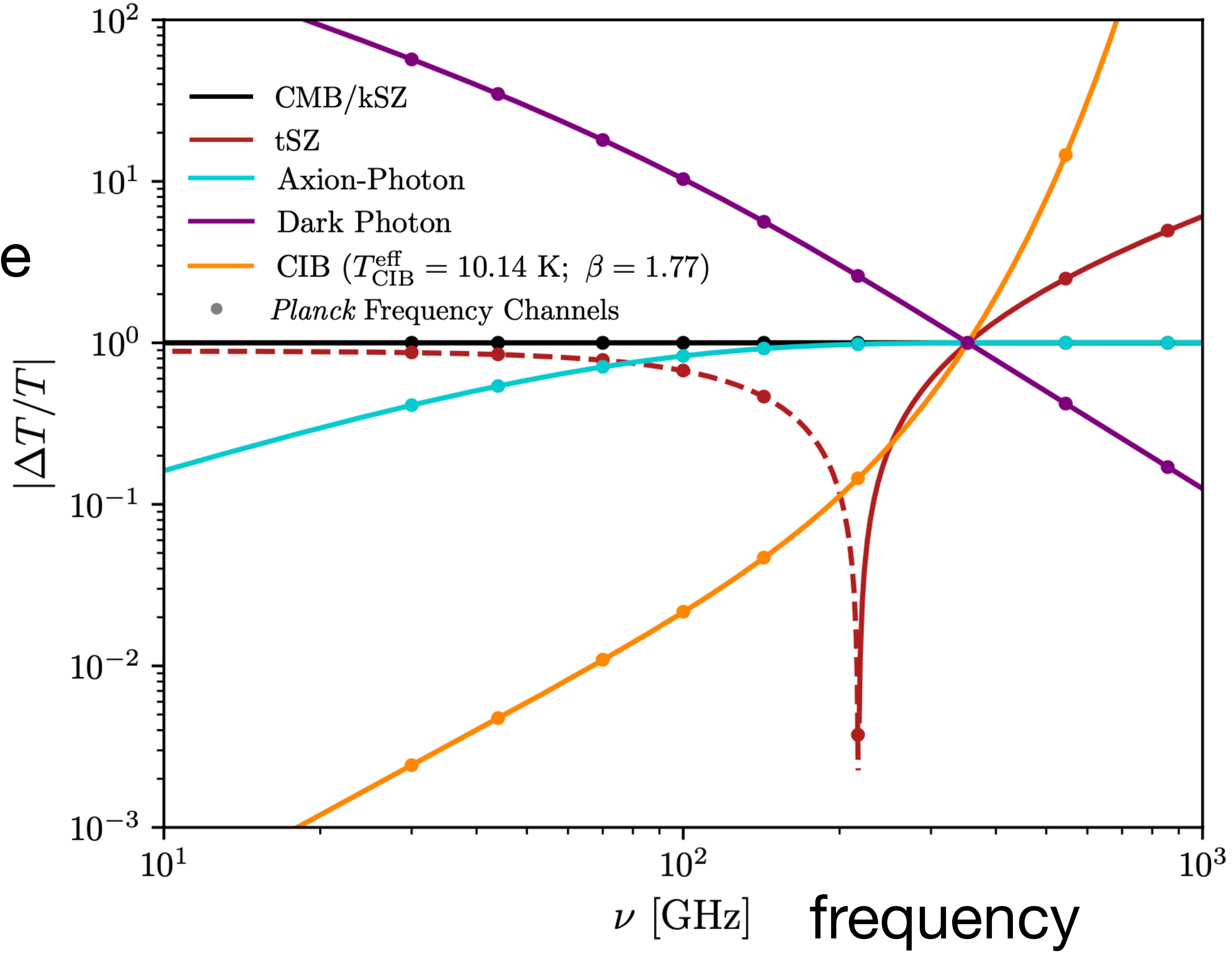
Distortion SEDs

Dark photon: $\frac{\Delta T(x)}{T_{\rm CMB}} \propto -\frac{\epsilon^2 m_{A'}^2}{x}\left(\frac{1-e^{-x}}{x}\right)$

Axion: $\frac{\Delta T(x)}{T_{\rm CMB}} \propto -\frac{g_{a\gamma\gamma}^2 B^2}{m_a^2}\, x \left(\frac{1-e^{-x}}{x}\right)$

$x \equiv h\nu/(k_{\rm B}T_{\rm CMB})$

CMB temperature fluctuation



frequency

all SEDs normalized to 1 at 353 GHz

Colin Hill
Columbia

Dark Screening in the CMB

Distortion SEDs

Dark photon: $$\frac{\Delta T(x)}{T_{\rm CMB}} \propto -\frac{\epsilon^2 m_{A'}^2}{x}\left(\frac{1-e^{-x}}{x}\right)$$

Axion: $$\frac{\Delta T(x)}{T_{\rm CMB}} \propto -\frac{g_{a\gamma\gamma}^2 B^2}{m_a^2}\, x\left(\frac{1-e^{-x}}{x}\right)$$

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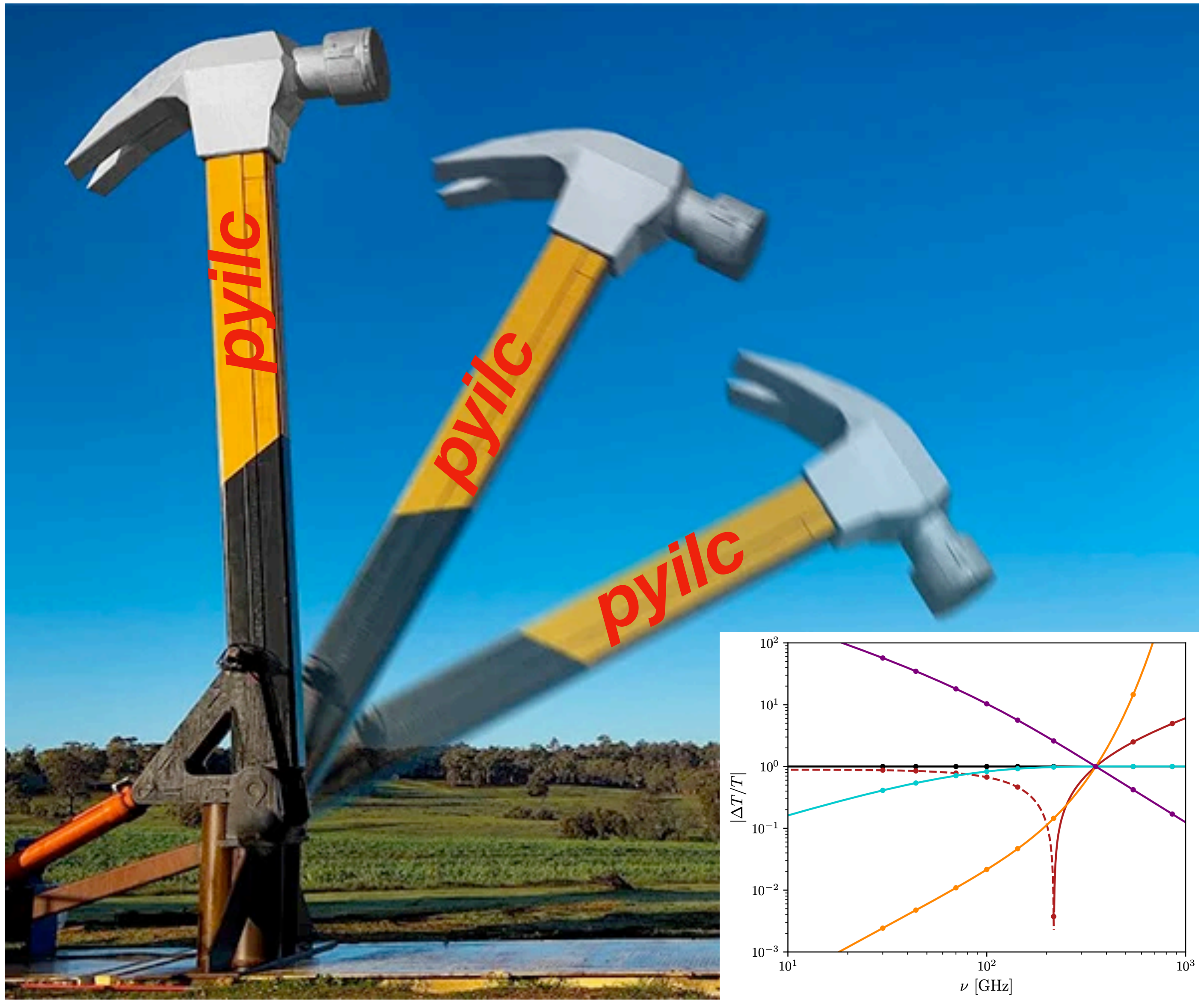


<u>Crucial</u>: instrument passbands and beams

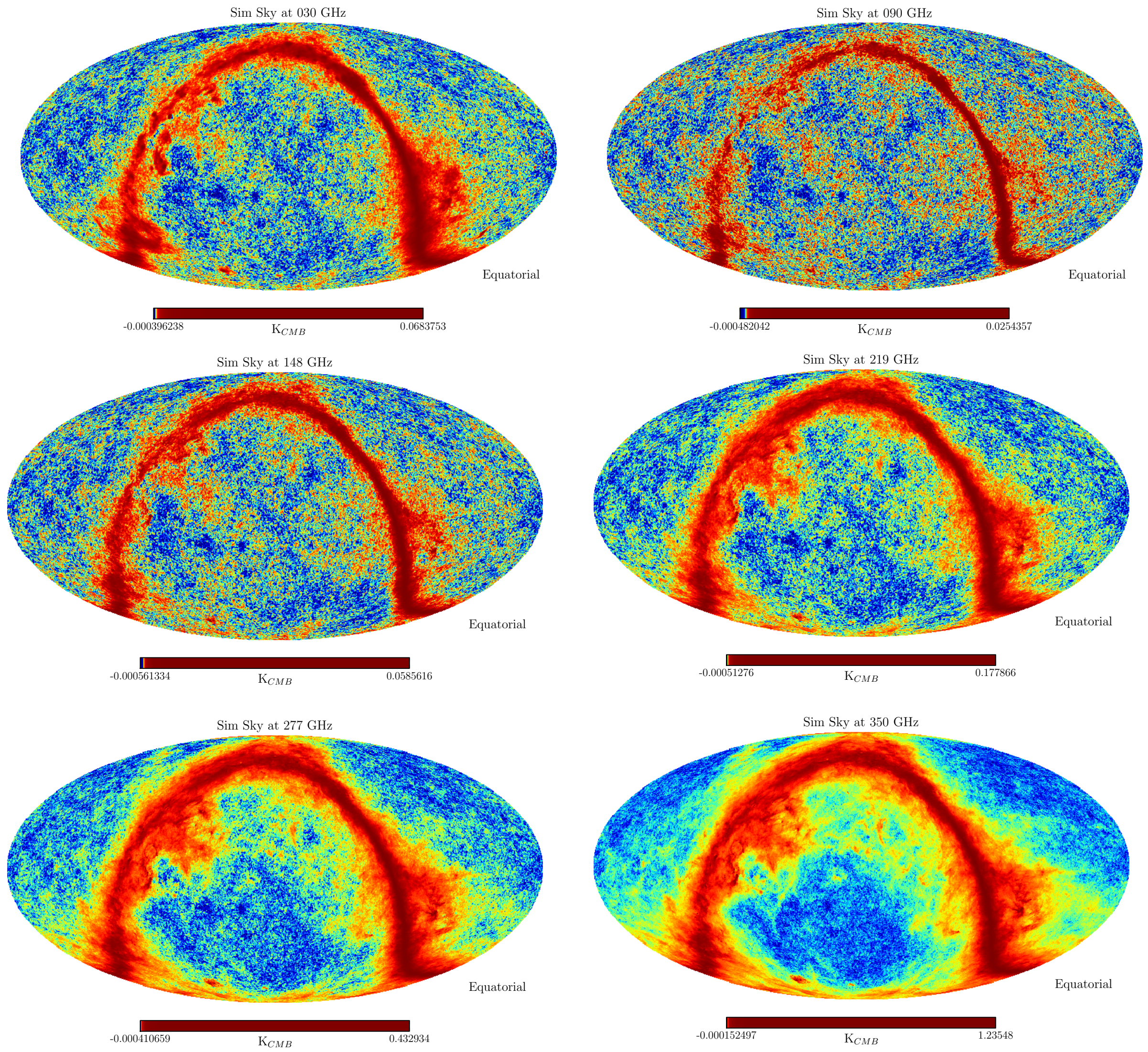
https://github.com/jcolinhill/pyilc

McCarthy & **JCH** (2023a)

Dark Screening: Extraction

Internal Linear Combination

“semi-blind” approach to component separation



frequency maps

e.g., Eriksen+(2004); Delabrouille+(2009); Remazeilles+(2011); JCH & Spergel (2014)

Dark Screening: Extraction

Colin Hill
Columbia

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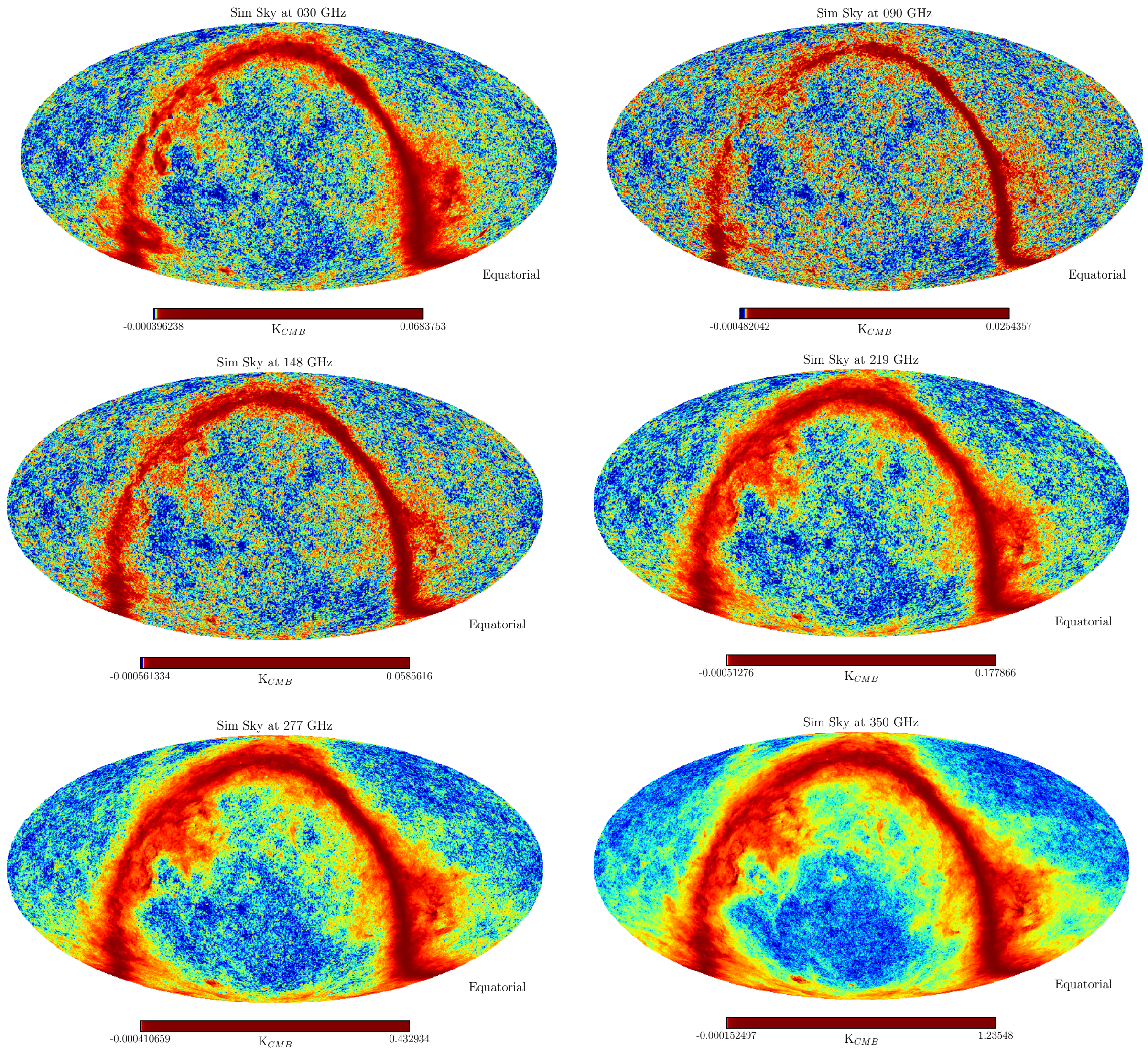
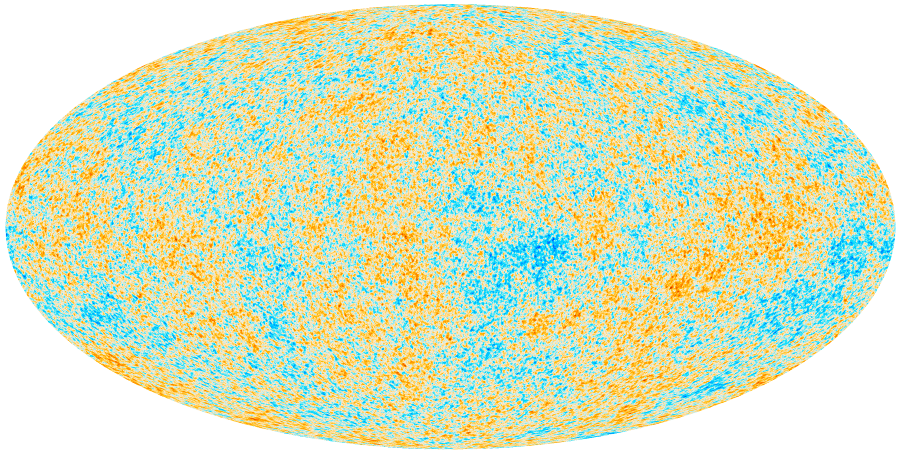


frequency maps

find linear combination with

minimum variance and unbiased response to signal of interest



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Columbia

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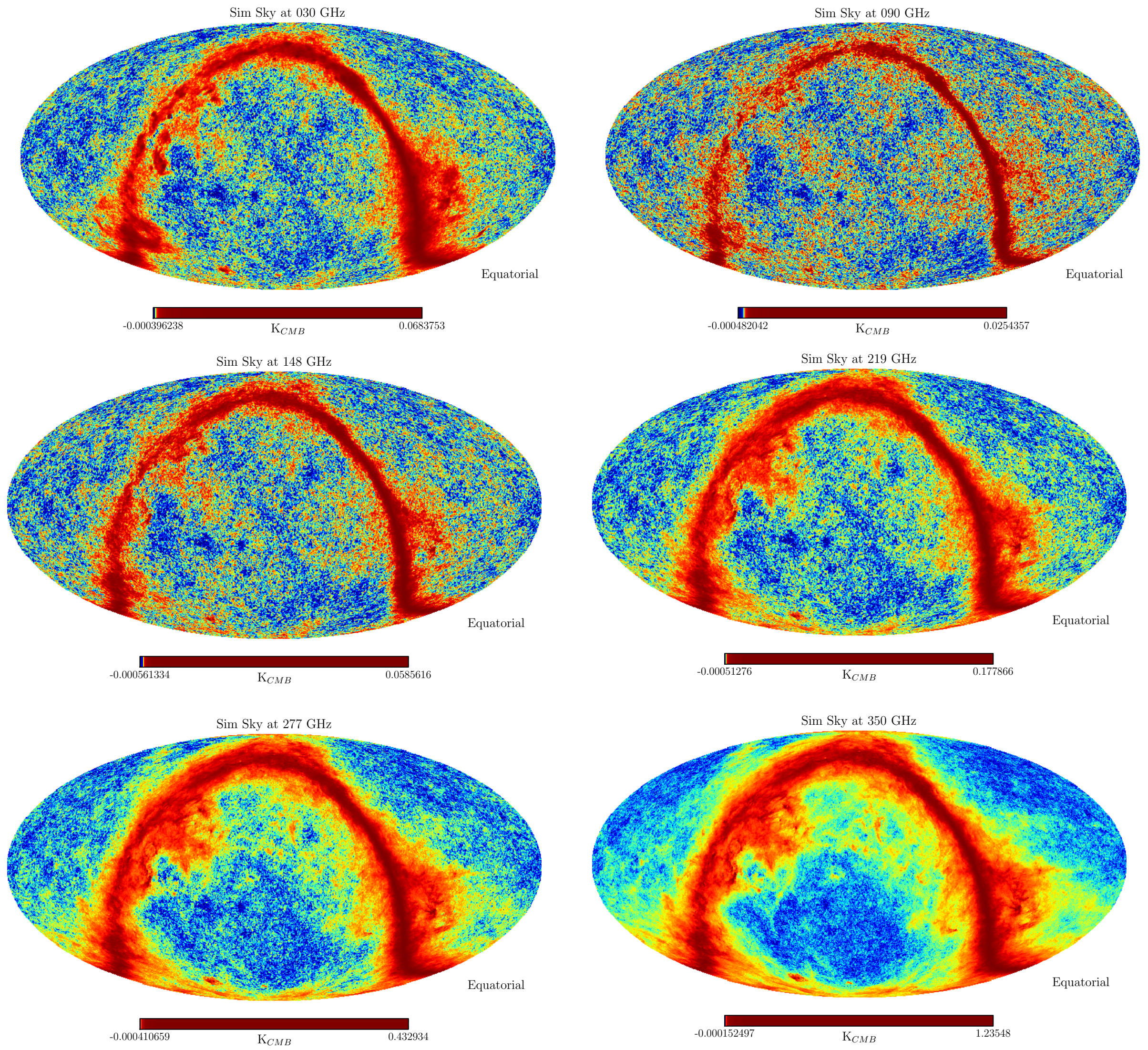

find linear combination with

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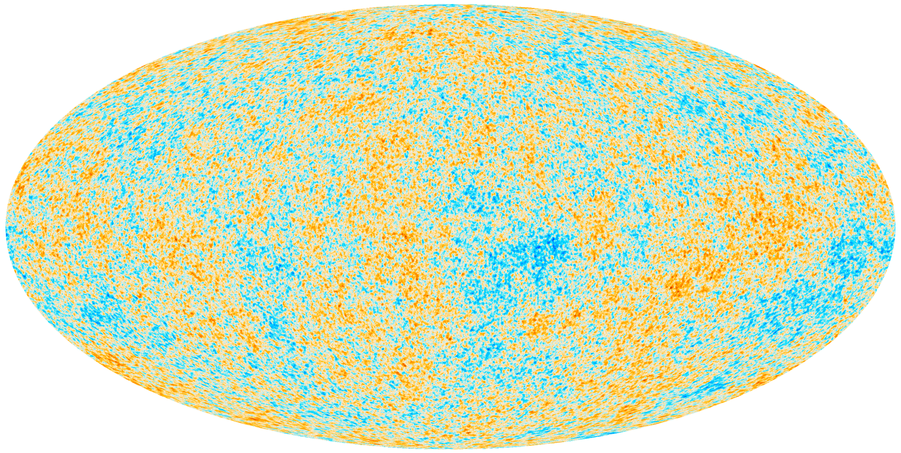


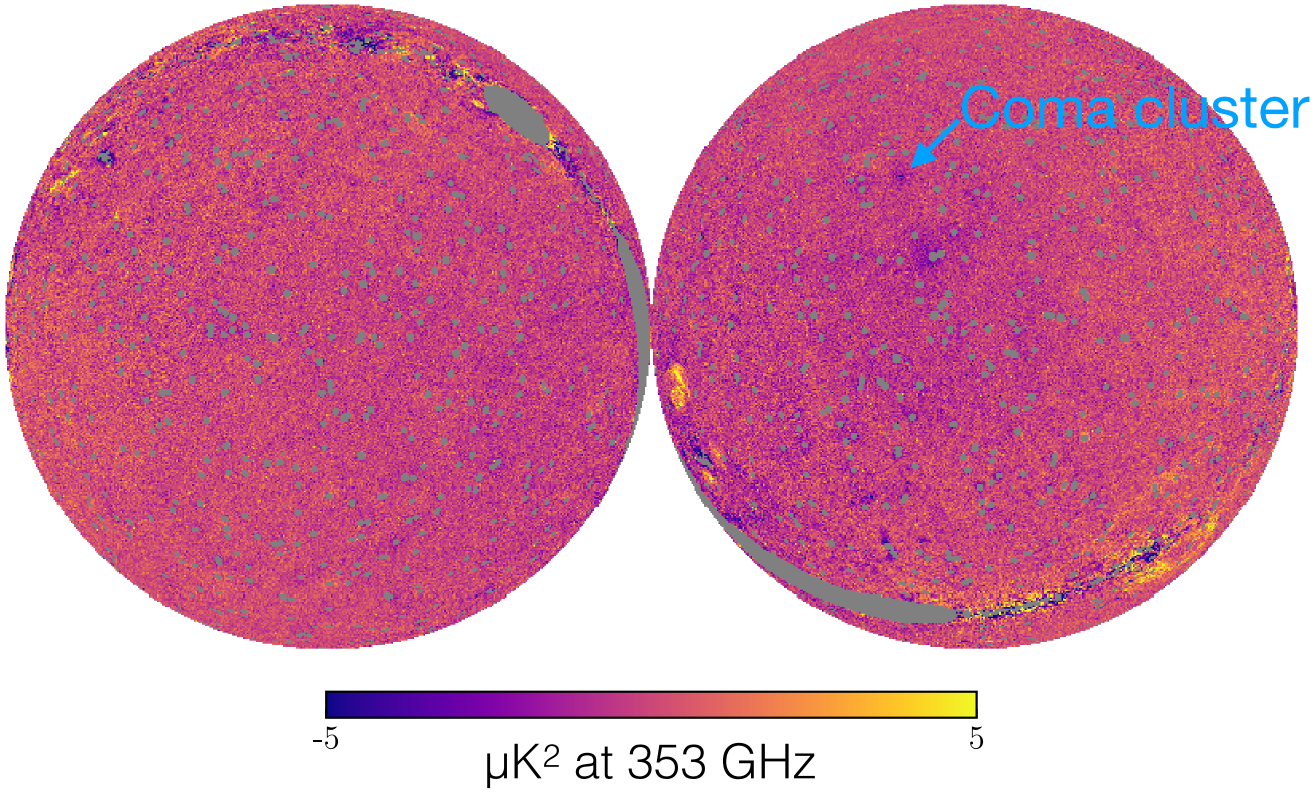
Flexibility: domain on which to do linear combination (we use needlets)
Extension: impose constraints to null ("deproject") contaminants

Delabrouille+(2009); Remazeilles+(2011); **JCH** & Spergel (2014); McCarthy & **JCH** (2023a)

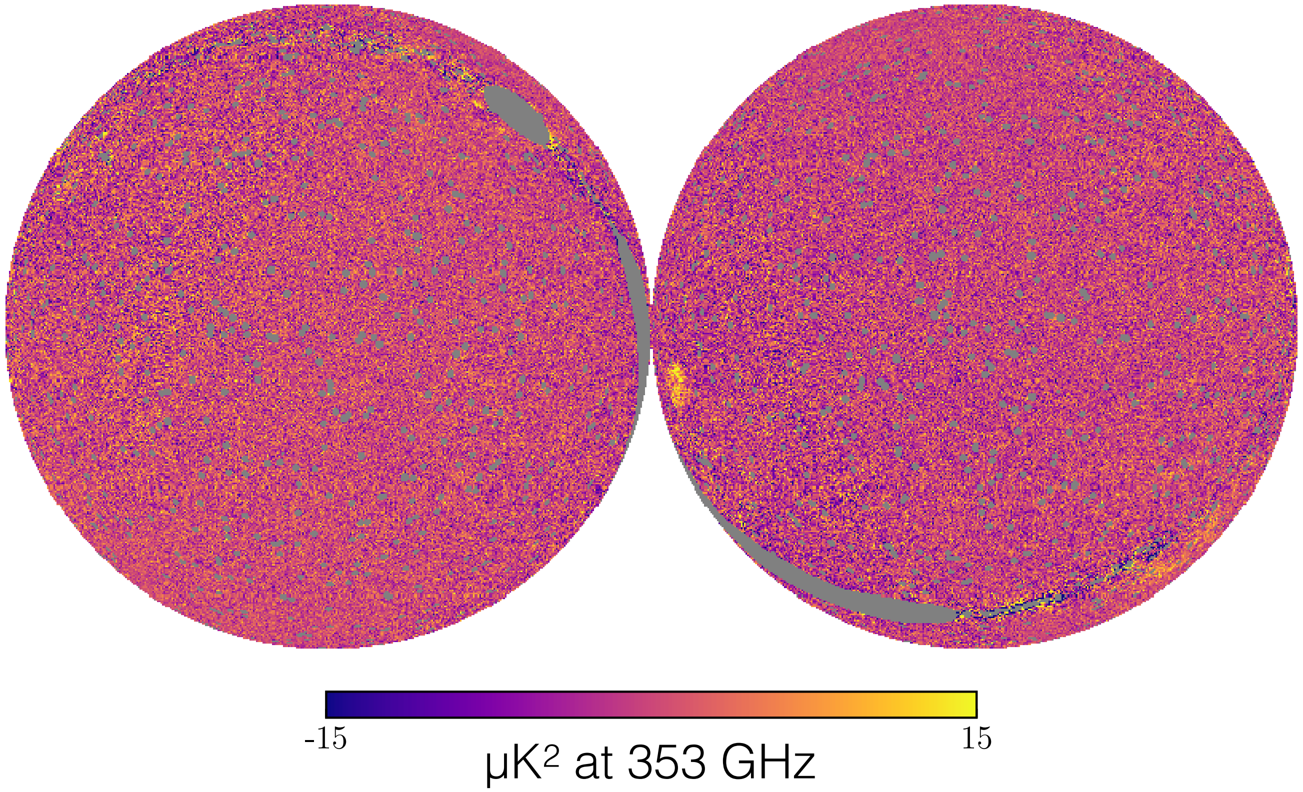
Dark Screening: Extraction

First Maps of Dark Photon-Induced Patchy Screening

No deprojection constraints



tSZ+CIB+dCIB/dβ deprojection constraints



https://github.com/jcolinhill/pyilc

McCarthy, Pirvu, **JCH**, Huang, Johnson, Rogers (in prep.)

McCarthy & **JCH** (2023a)

Dark Screening: Extraction

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Columbia

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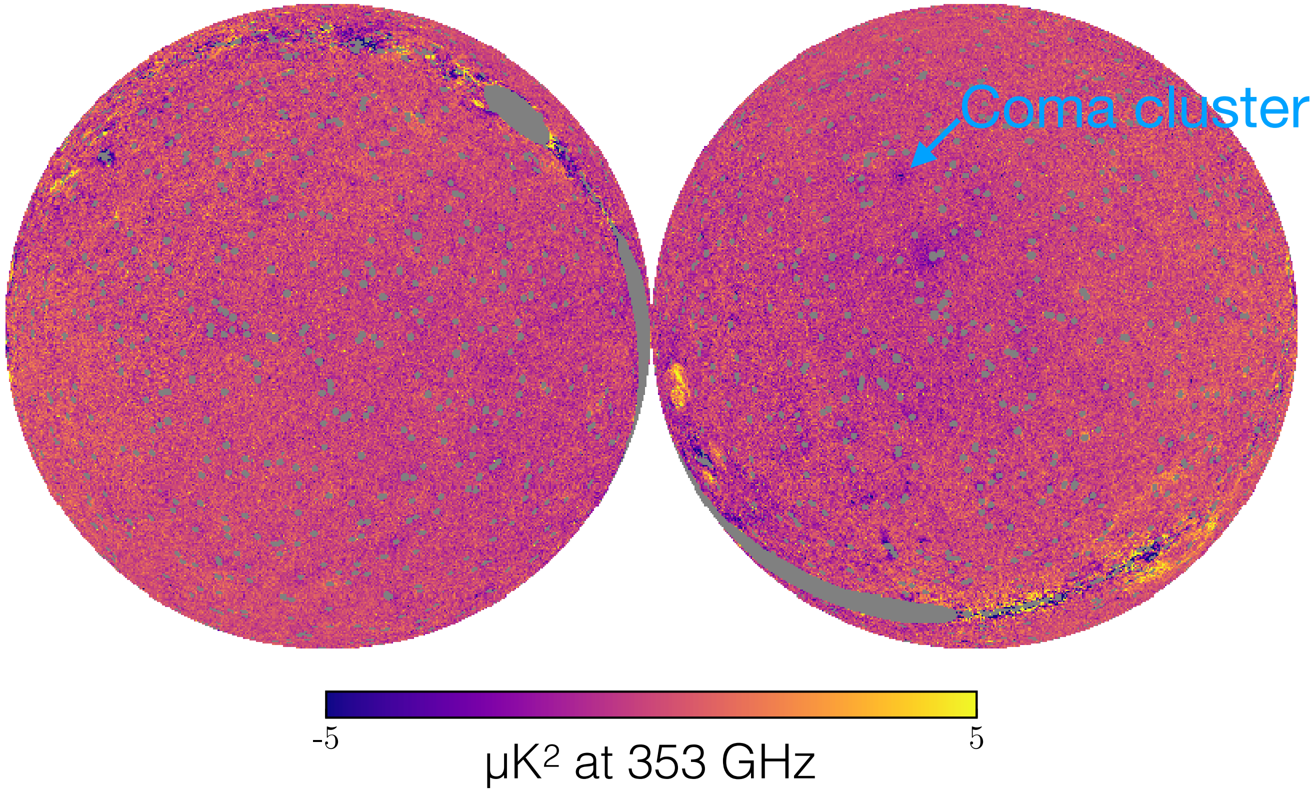

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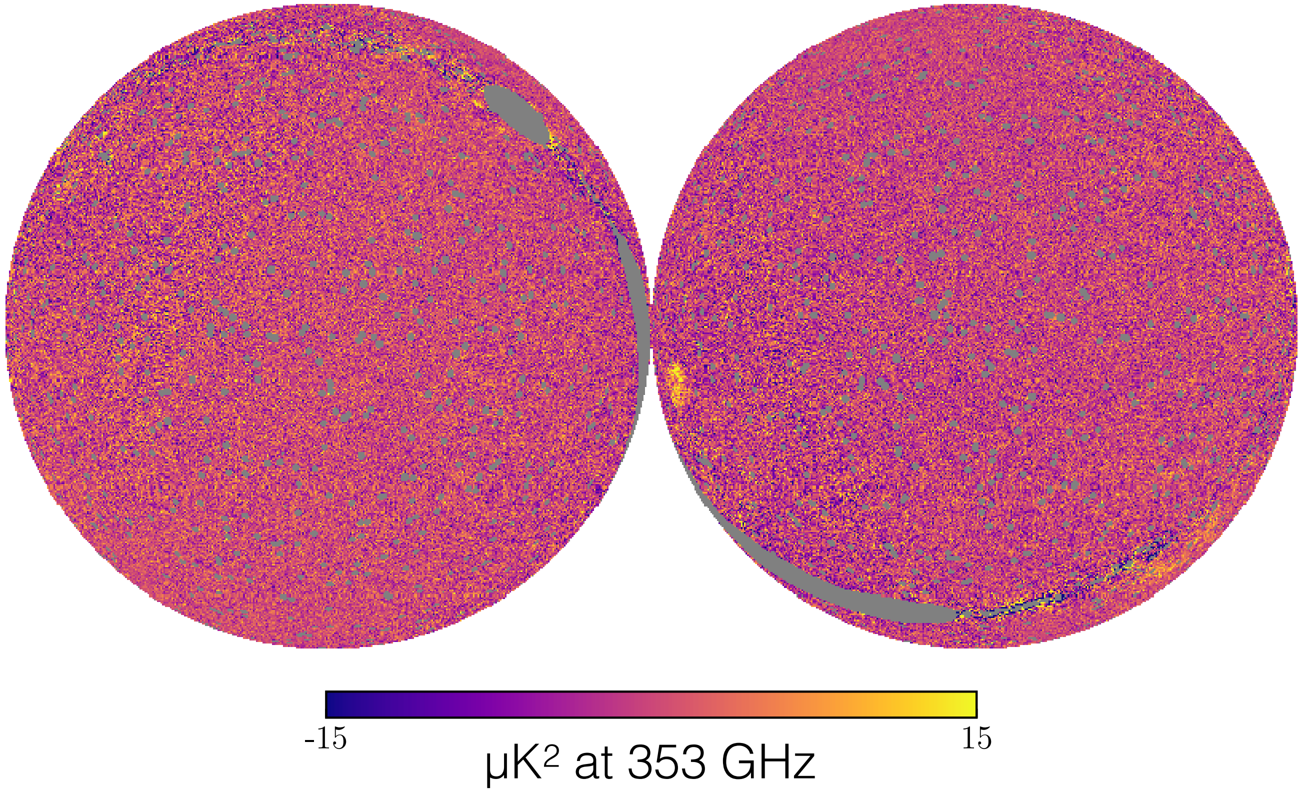
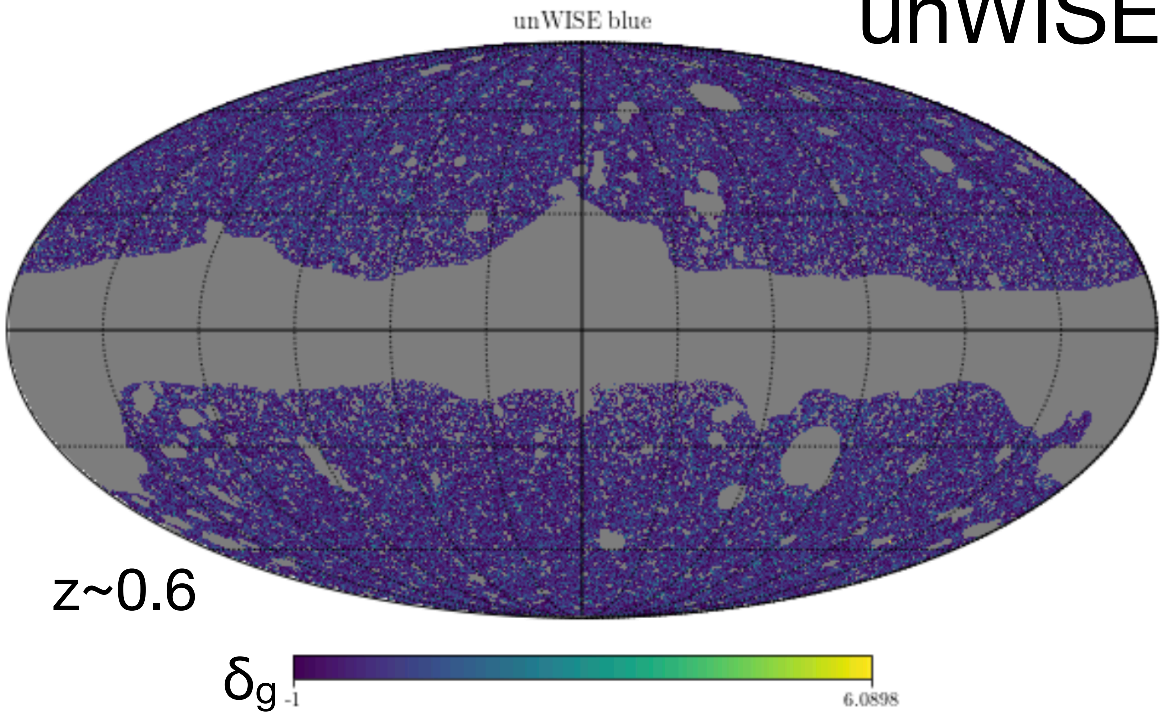
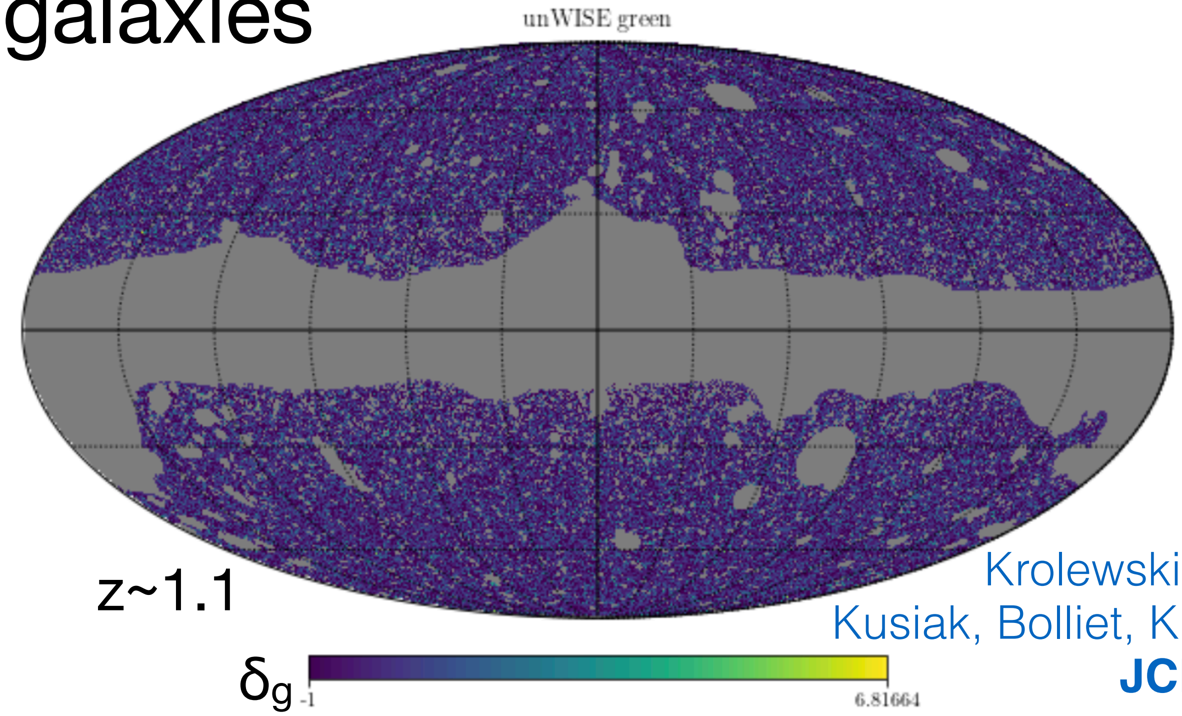


x

unWISE galaxies





Krolewski+ (2020)
Kusiak, Bolliet, Krolewski, **JCH** (2022)

Dark Photon Screening

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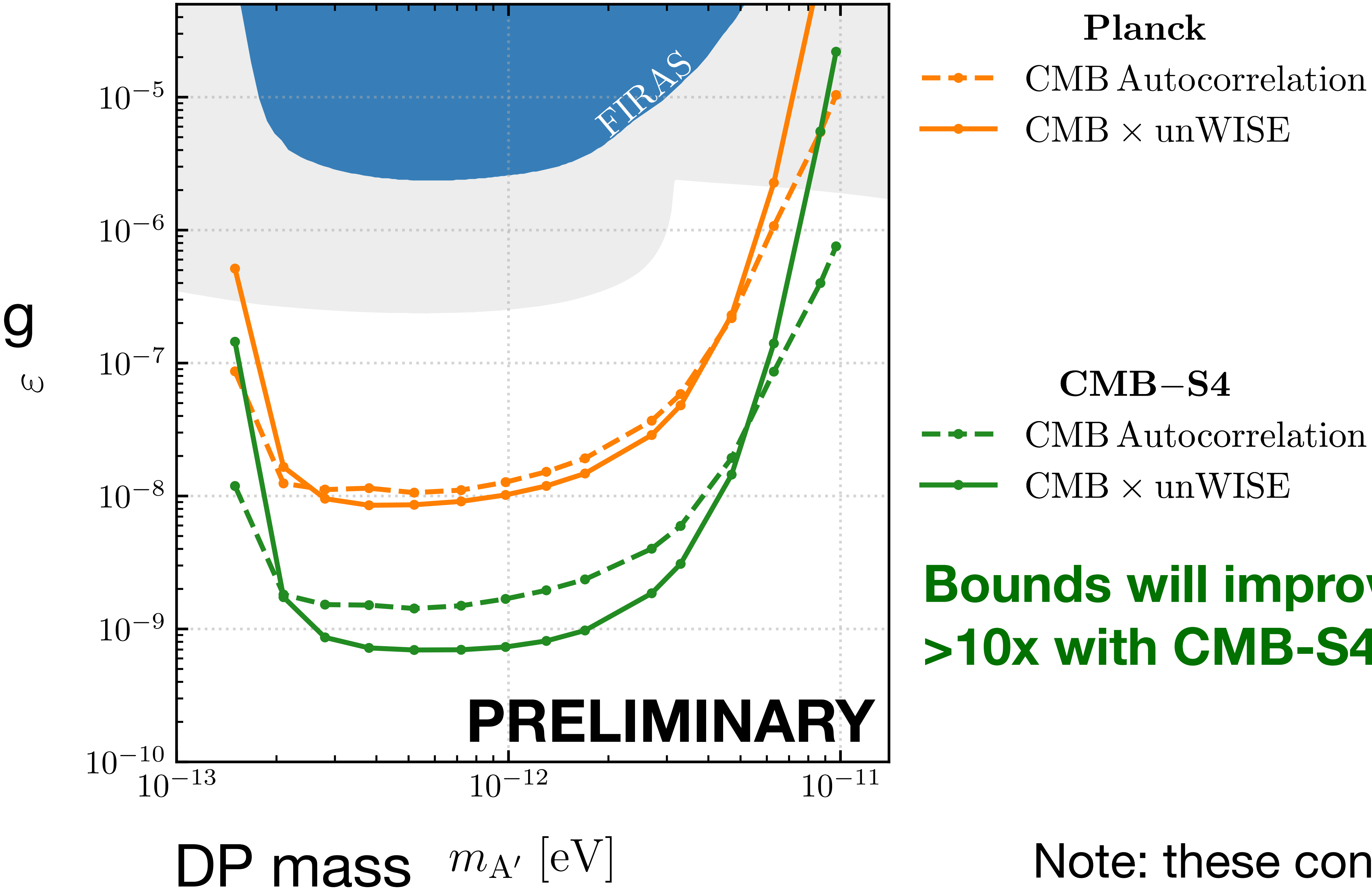
Columbia

Constraints on SM photon - DP coupling

Tightest constraints on this coupling in the mass range accessible to CMB

coupling



DP mass

Bounds will improve by >10x with CMB-S4!

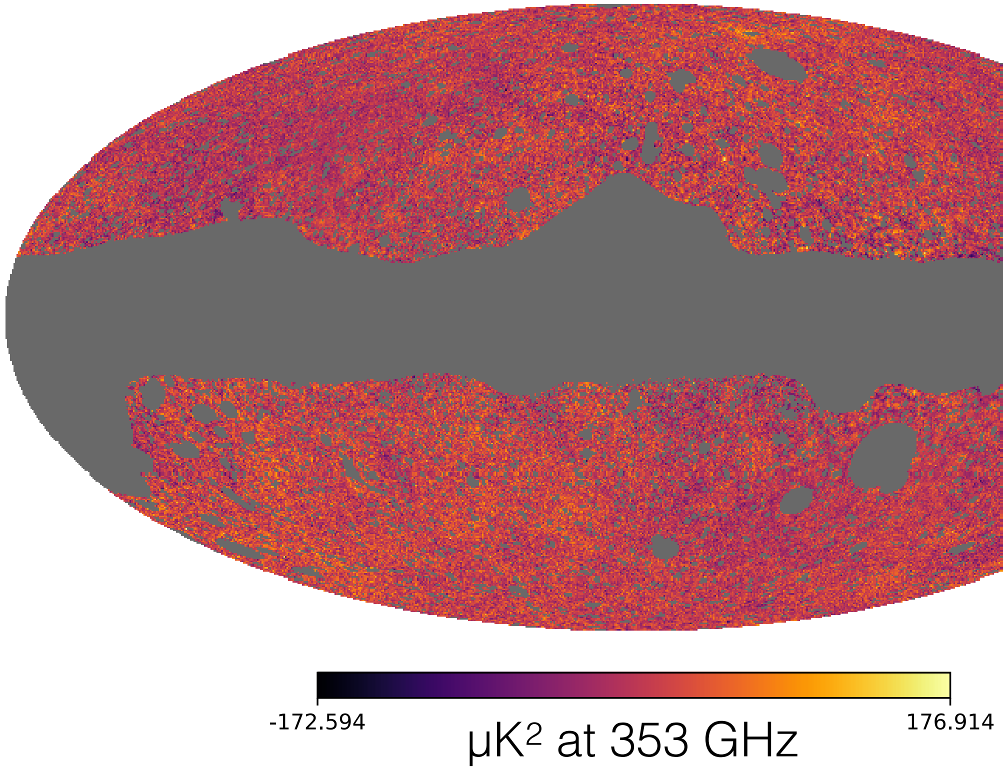
Note: these constraints do *not* require the DP to comprise the dark matter

McCarthy, Pirvu, **JCH**, Huang, Johnson, Rogers (in prep.)

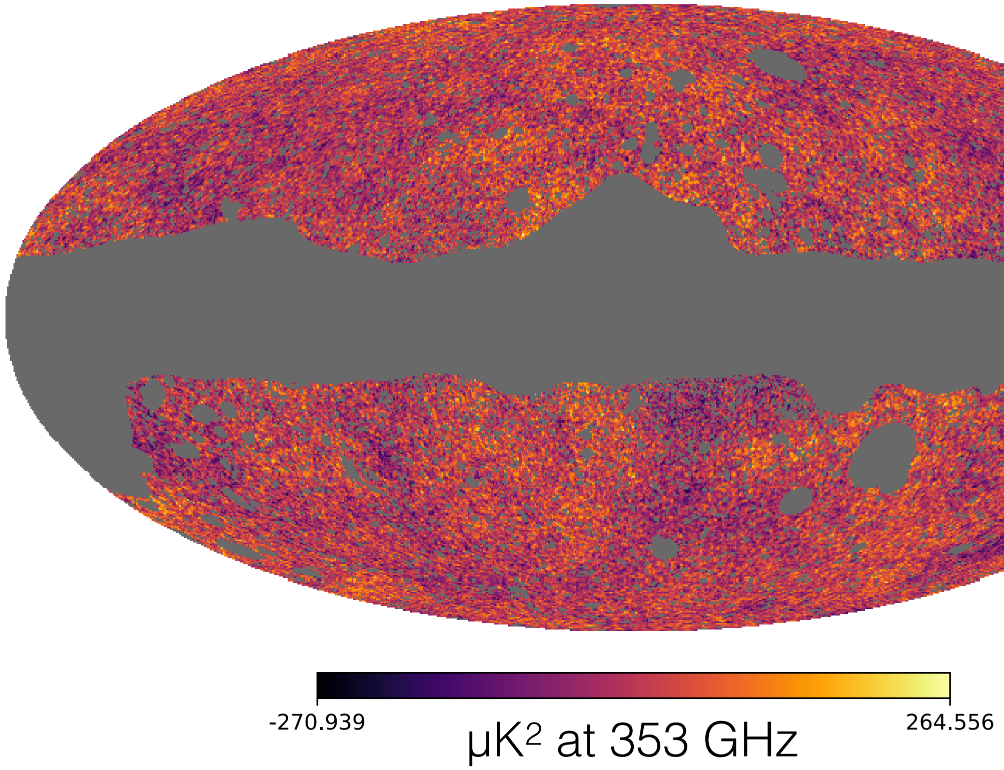
Axion Screening: Extraction

First Maps of Axion-Induced Patchy Screening

No deprojection constraints



tSZ+CIB+dCIB/dβ deprojection constraints



https://github.com/jcolinhill/pyilc

Goldstein, McCarthy, Pirvu, **JCH**, Huang, Johnson, Rogers (in prep.)

McCarthy & **JCH** (2023a)

Axion Screening: Extraction

Colin Hill
Columbia

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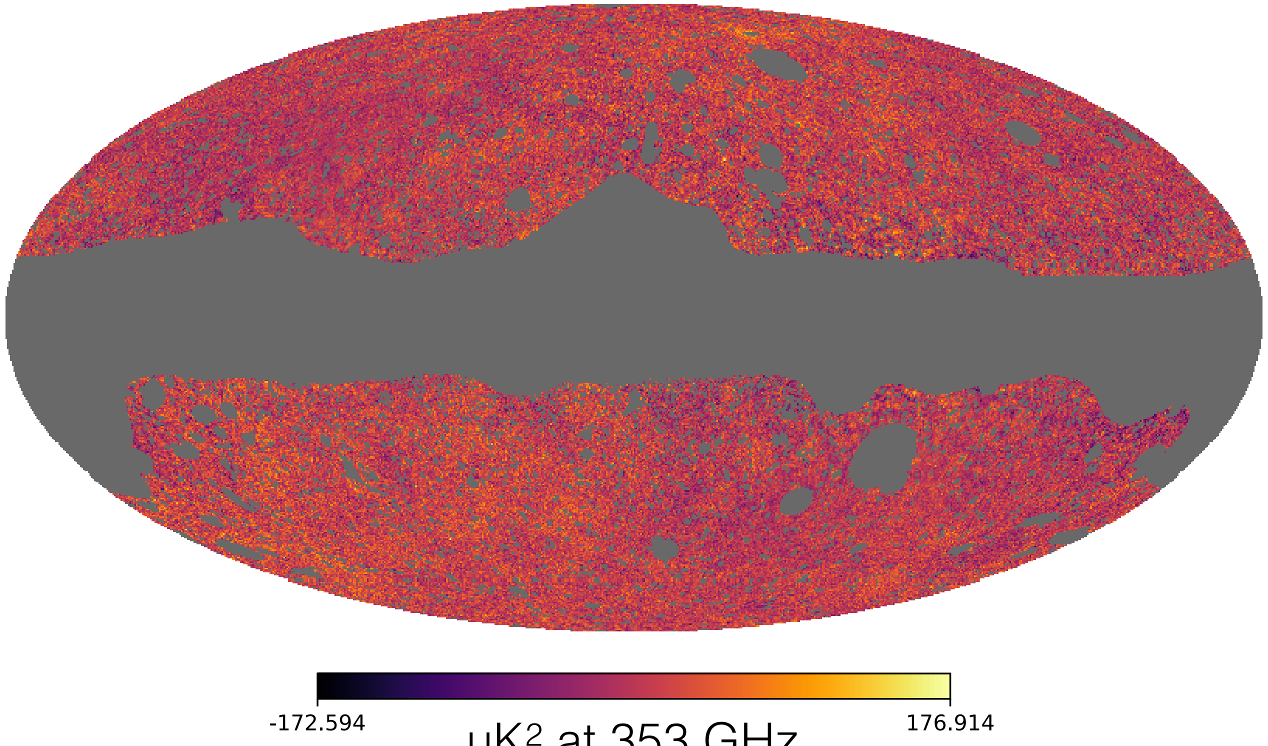

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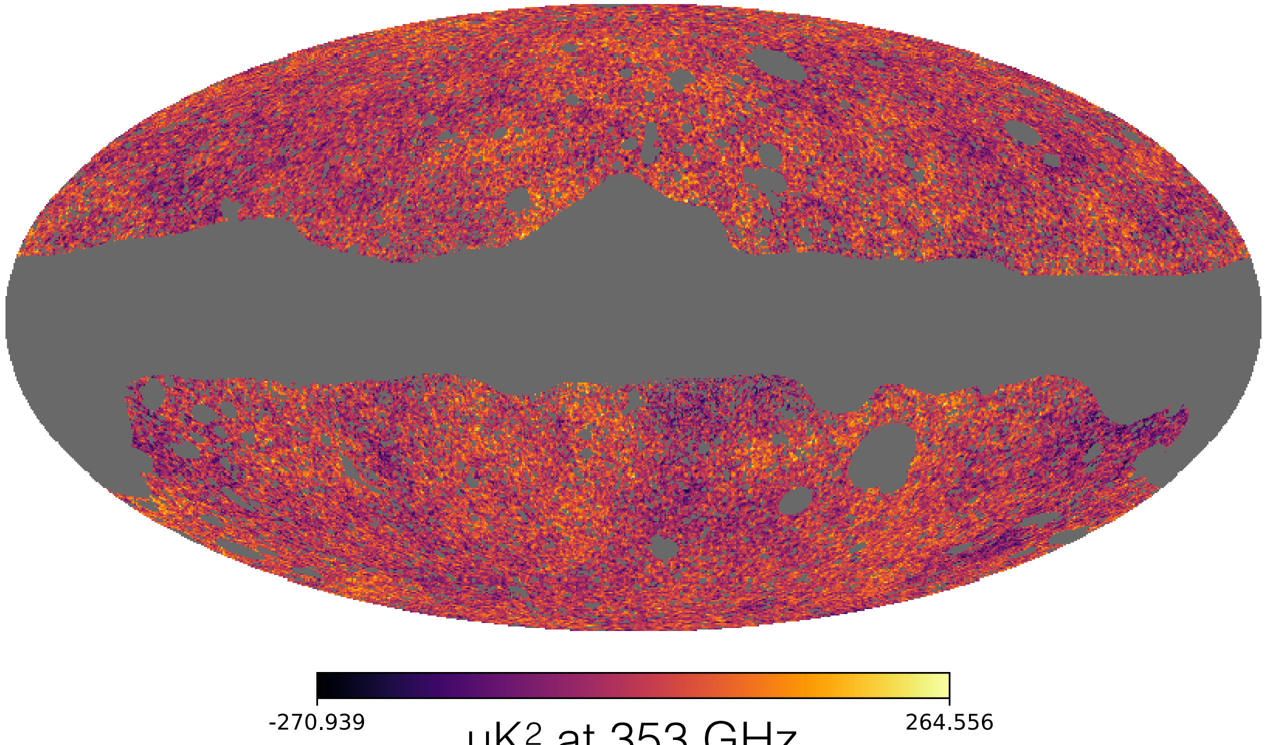
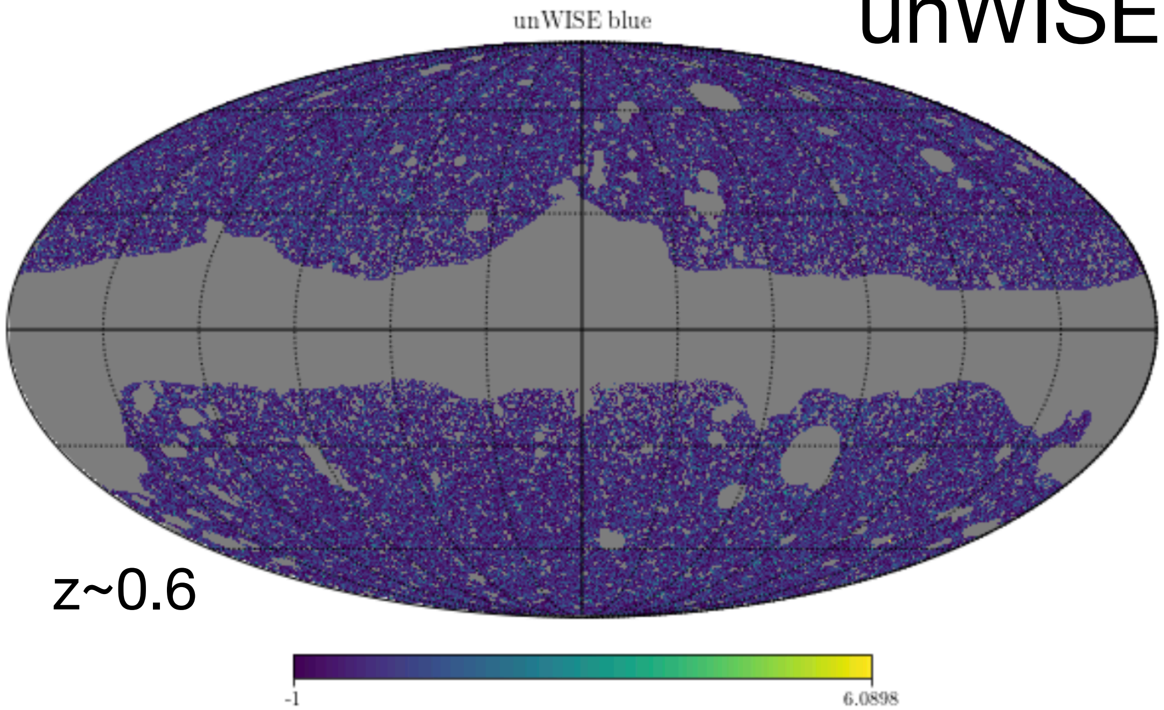
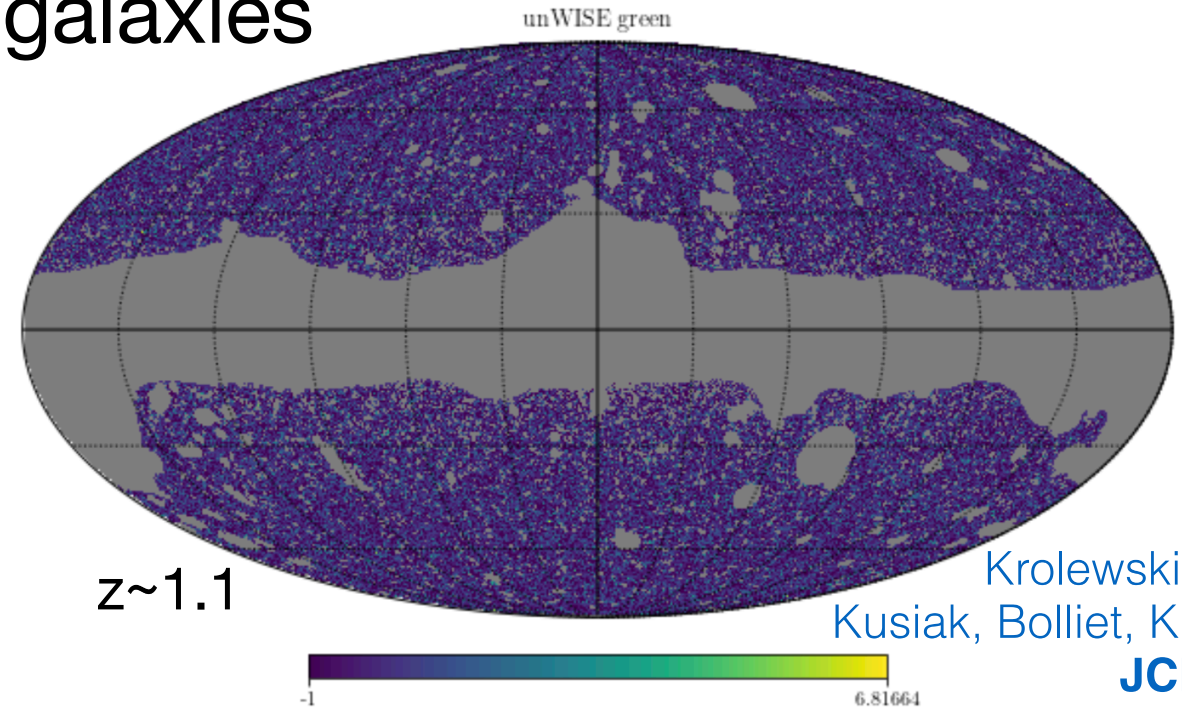


x

unWISE galaxies



z~0.6



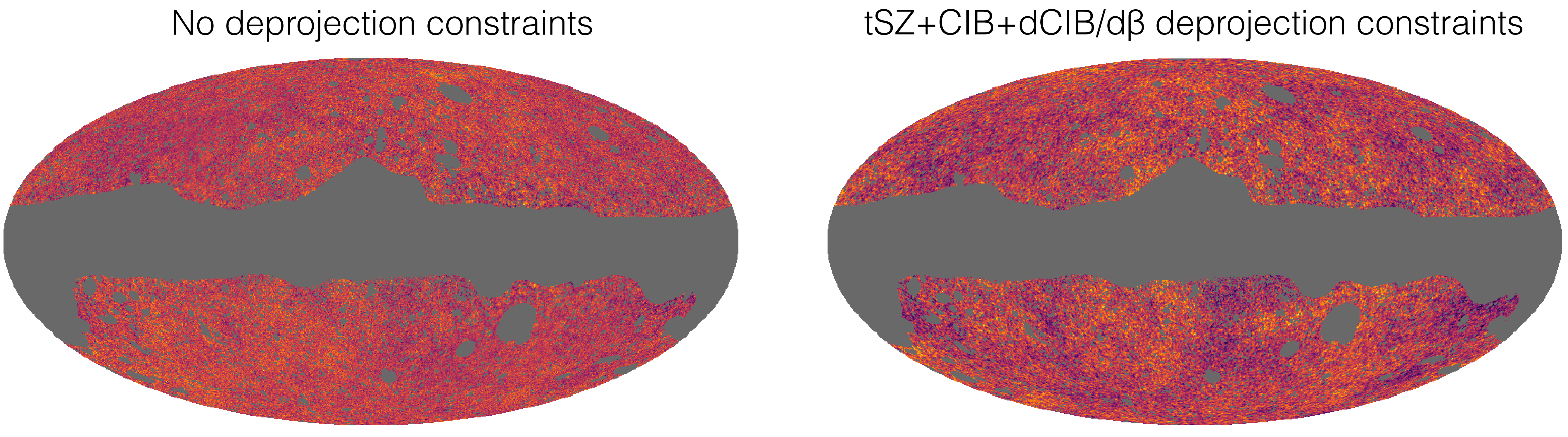
z~1.1

Krolewski+ (2020)
Kusiak, Bolliet, Krolewski, **JCH** (2022)

Axion Screening: Extraction

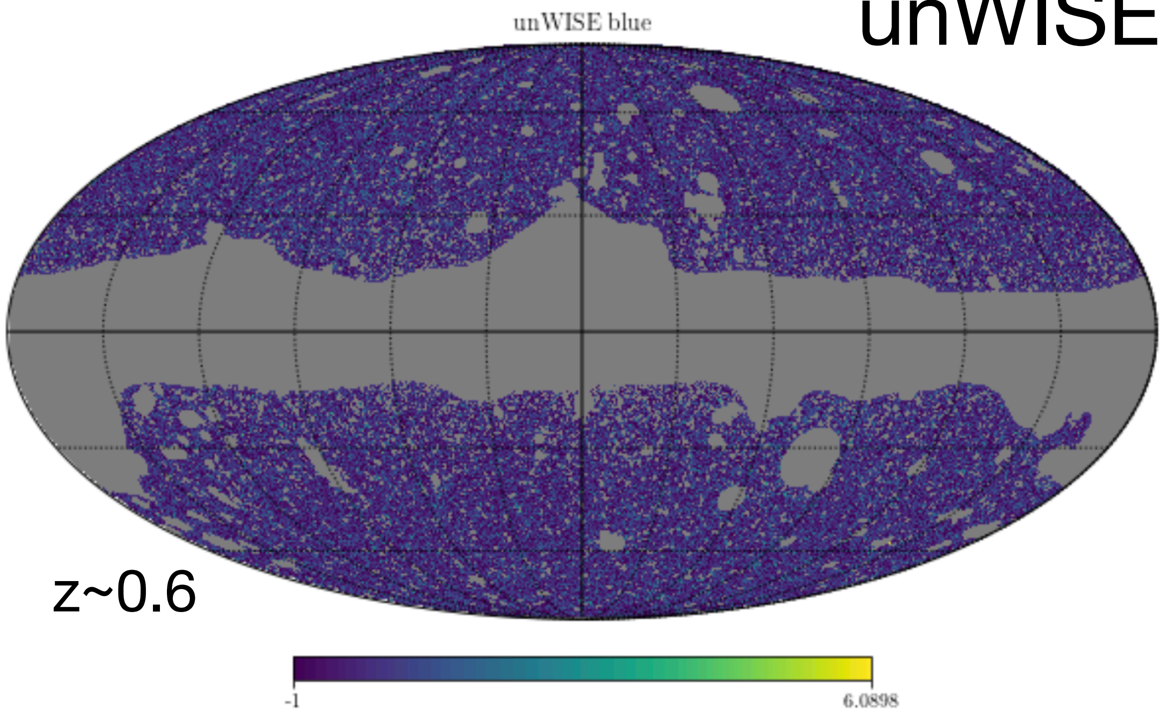
Colin Hill
Columbia

First Maps of Axion-Induced Patchy Screening



Work in progress to extract bound on axion-photon coupling

unWISE galaxies



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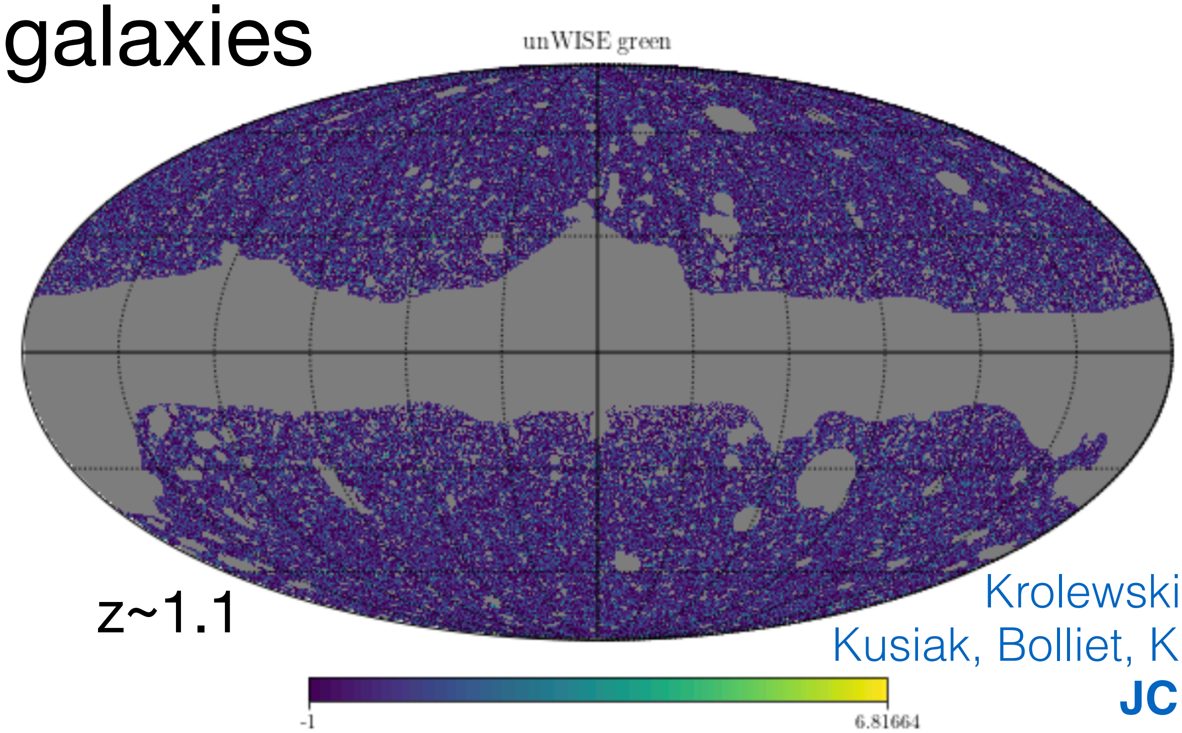

z~1.1

Krolewski+ (2020)
Kusiak, Bolliet, Krolewski,
JCH (2022)

BSM Physics in CMB Secondary Anisotropies

Takeaways

- CMB is a uniquely powerful probe of well-motivated BSM models

- We have just started to scratch the surface of this line of research — these are the very first such constraints! Much more to do: e.g., axion spectral distortions also affect polarization. Other signals are possible directly in the time-ordered data (Fedderke+19)

BSM Physics in CMB Secondary Anisotropies

Takeaways

- CMB is a uniquely powerful probe of well-motivated BSM models
- We have just started to scratch the surface of this line of research — these are the very first such constraints! Much more to do: e.g., axion spectral distortions also affect polarization. Other signals are possible directly in the time-ordered data (Fedderke+19)
- Expect at least order of magnitude gains with CMB-S4
- Robustness of these constraints (or a detection) is directly coupled to understanding of the instrument:
  - **Passbands: frequency-dependent BSM physics**
  - **Beams: power spectrum interpretation**
  - **Polarization angles: birefringence**

New Tools for New Physics

McCarthy, **JCH**, Coulton, Hogg (in prep.)

Motivation

Foregrounds are non-Gaussian, but our semi-blind methods (e.g., ILC) generally use only two-point information

Can we do better?

Motivation

Can we do better?

Signal-preserving CMB component separation with machine learning

Simple, but naive, approach:

$$\hat{T}^{\mathrm{pred,\,coi}} = f(T^i)$$

predicted map of component of interest (e.g., CMB B-modes)

arbitrary non-linear function of frequency maps

One can train a machine learning model (e.g., a CNN) to learn $f(T^i)$

However, this approach is unlikely to be robust:

- Results would be highly sensitive to mismatch between simulations and data
- No guarantee of unbiasedness/signal preservation
- Lacks the interpretability of the ILC or similar methods

McCarthy, **JCH**, Coulton, Hogg (in prep.)

Our Approach

Colin Hill
Columbia

Signal-preserving CMB component separation with machine learning

Consider the usual ILC estimate: $\hat{T}^{\rm ILC}(p) = T^{\rm coi}(p) + \Delta T^{\rm ILC}(p)$

ILC residual w.r.t. true signal

We seek an estimate of the ILC residual: $\Delta \hat{T}^{\rm ILC}(p)$

We can then obtain a cleaner final map by subtracting this estimate

McCarthy, **JCH**, Coulton, Hogg (in prep.)

Our Approach

Signal-preserving CMB component separation with machine learning

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ILC residual w.r.t. true signal

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We can then obtain a cleaner final map by subtracting this estimate

Our approach:

- Compute ILC estimate and subtract it from each frequency map:

$$\hat{F}_i \equiv T_i - \hat{T}^{\rm ILC}$$

- Use simulations to train a CNN to predict $\Delta\hat{T}^{\rm ILC}(p)$ using $\hat{F}_i$
- Subtract this estimate to obtain a cleaner — and still unbiased — map of the component of interest: $\hat{T} = T^{\rm ILC} - \Delta\hat{T}^{ILC}$

McCarthy, **JCH**, Coulton, Hogg (in prep.)

Application: B-modes

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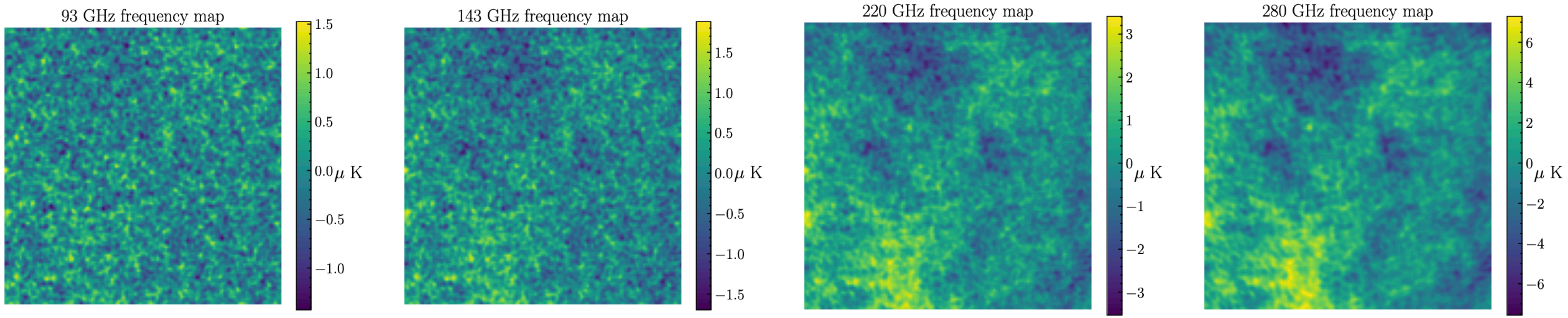
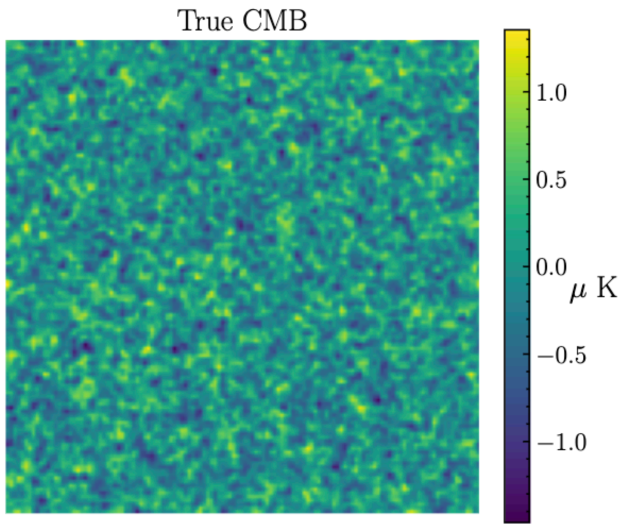
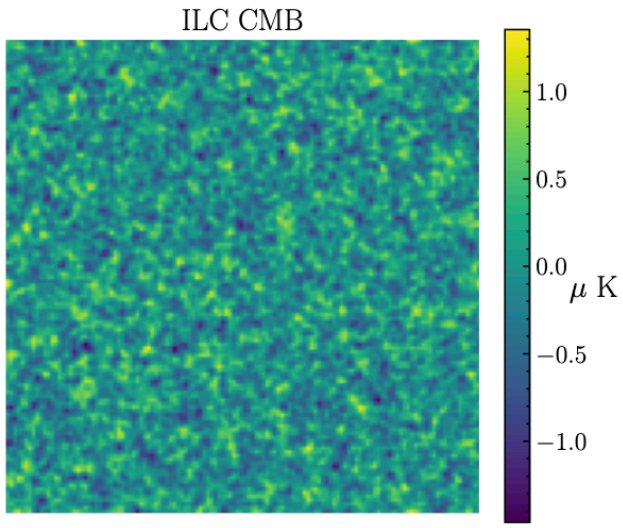
Columbia

Simulations: dust + synchrotron + CMB (~1000 maps, 10x10 deg^2)

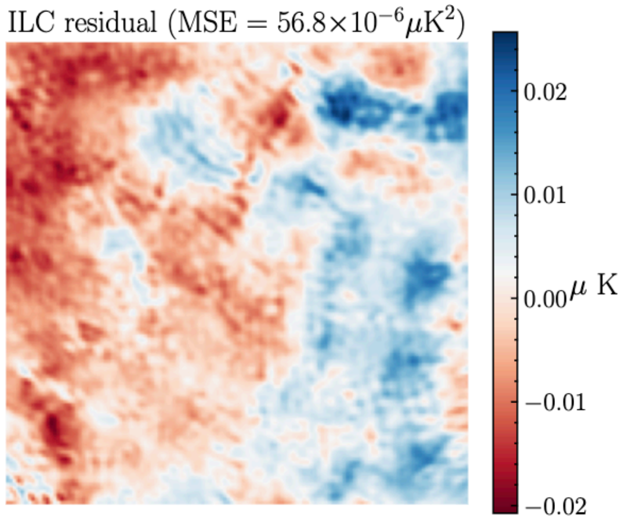




Truth



ILC



residual

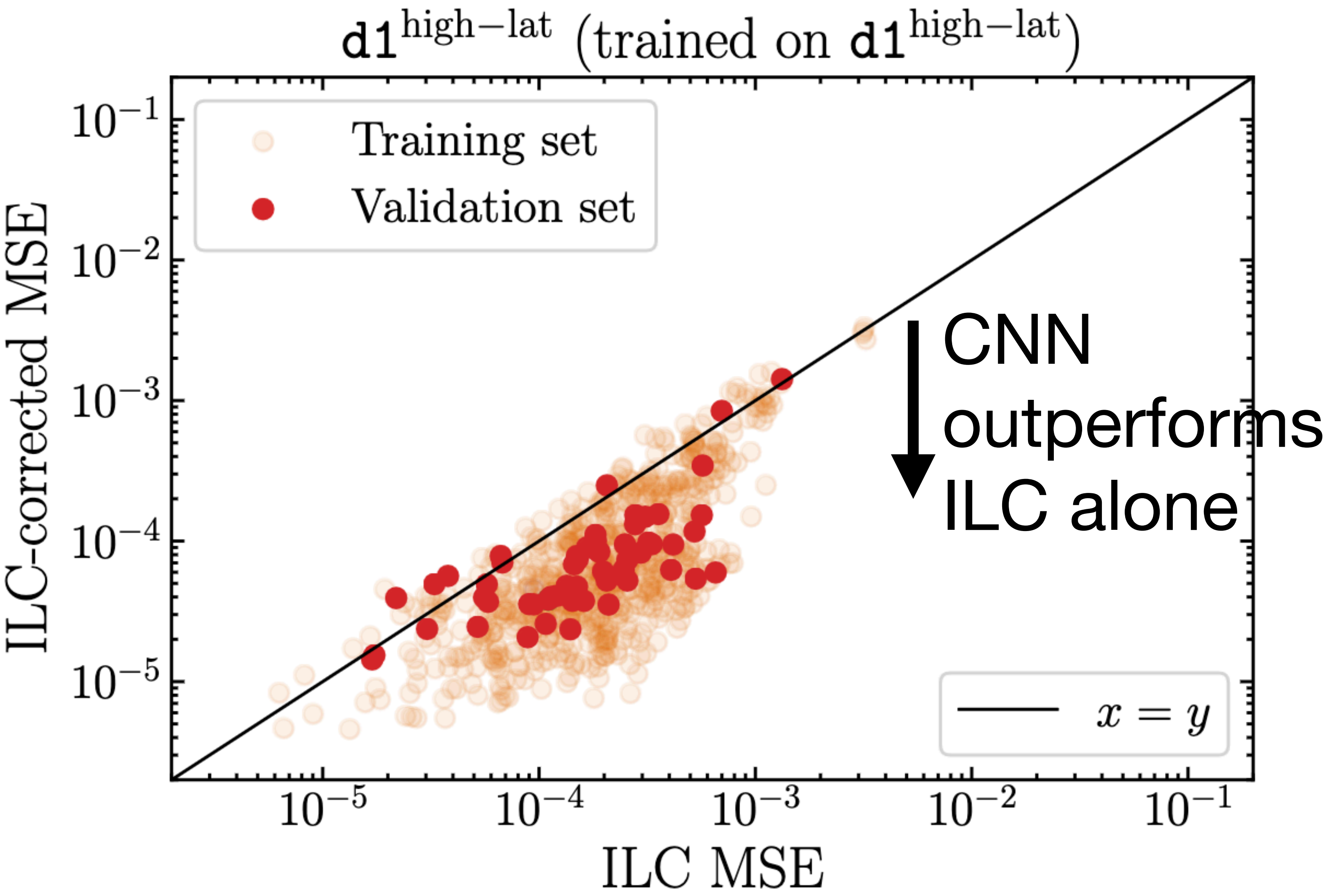
ILC clearly leaves anisotropic residuals

McCarthy, **JCH**, Coulton, Hogg (in prep.)

Application: B-modes

Loss function: $L = \sum_i \frac{1}{N_i} \sum_p \left(\Delta \hat{T}^{\rm ILC}(p) - \Delta T^{\rm ILC}(p) \right)^2$ $N_i \equiv \sum_p \Delta T_i^{\rm ILC}(p)$

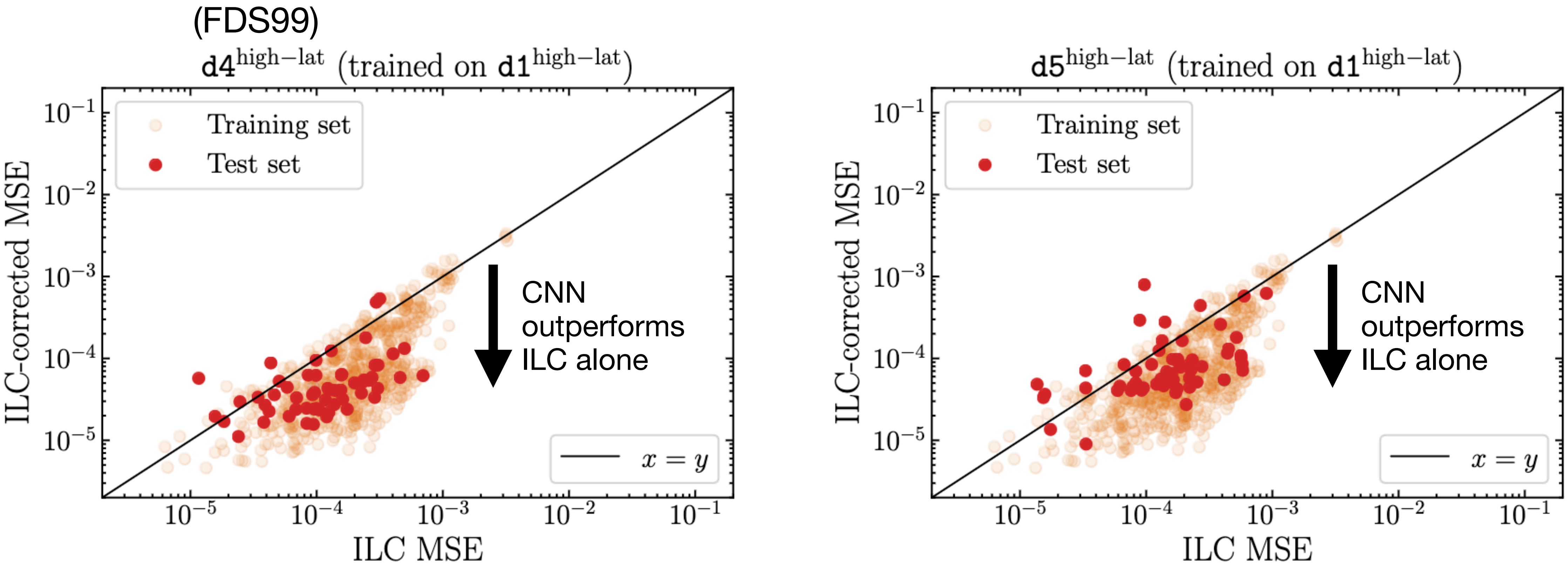
Assess performance via mean-squared error on 10x10 deg^2 maps:



McCarthy, **JCH**, Coulton, Hogg (in prep.)

Application: B-modes

Does it work for dust models on which the CNN was not trained?



(FDS99)

$\mathtt{d4}^{\rm high-lat}$ (trained on $\mathtt{d1}^{\rm high-lat}$)

$\mathtt{d5}^{\rm high-lat}$ (trained on $\mathtt{d1}^{\rm high-lat}$)

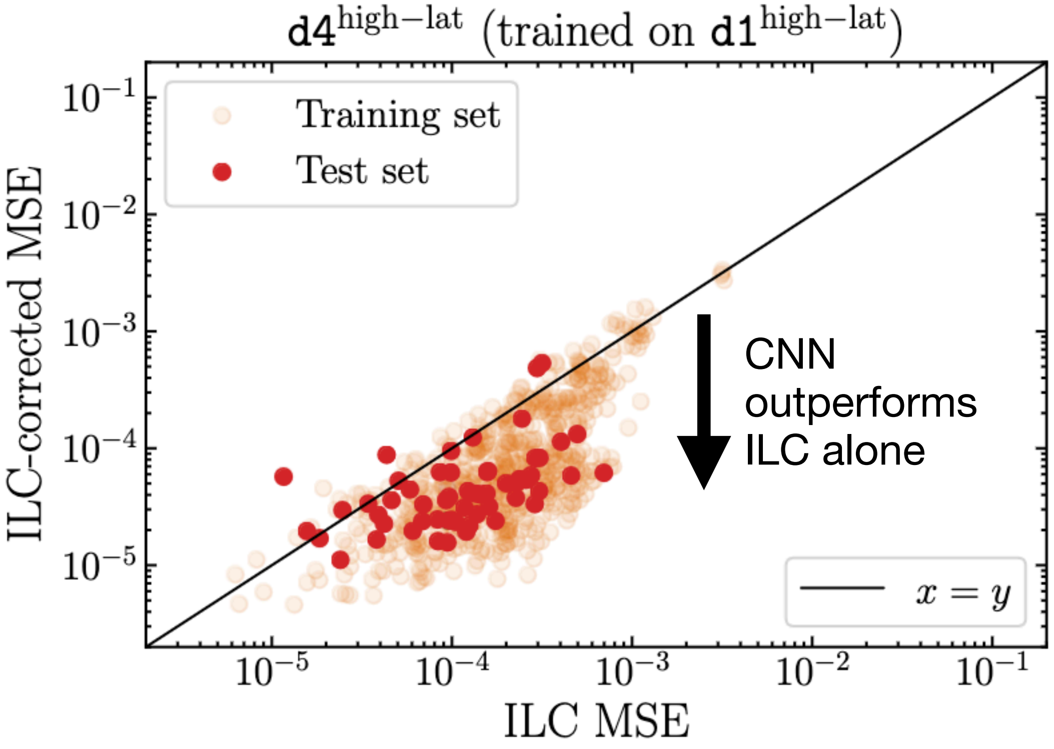
CNN outperforms ILC alone

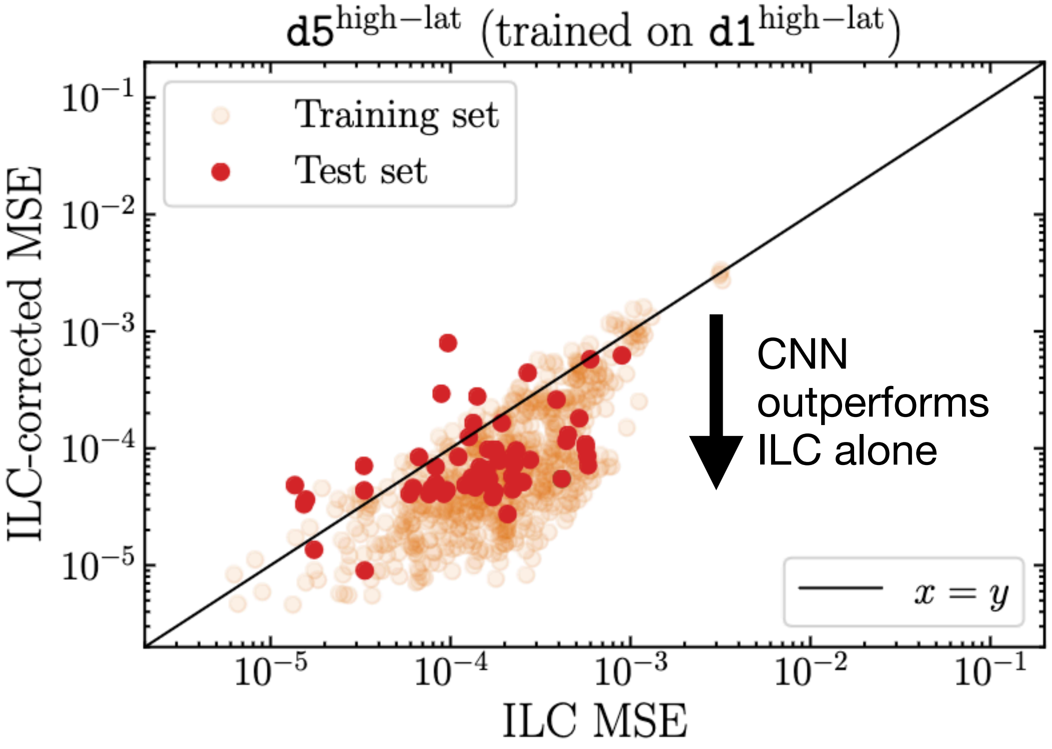
CNN outperforms ILC alone

McCarthy, **JCH**, Coulton, Hogg (in prep.)

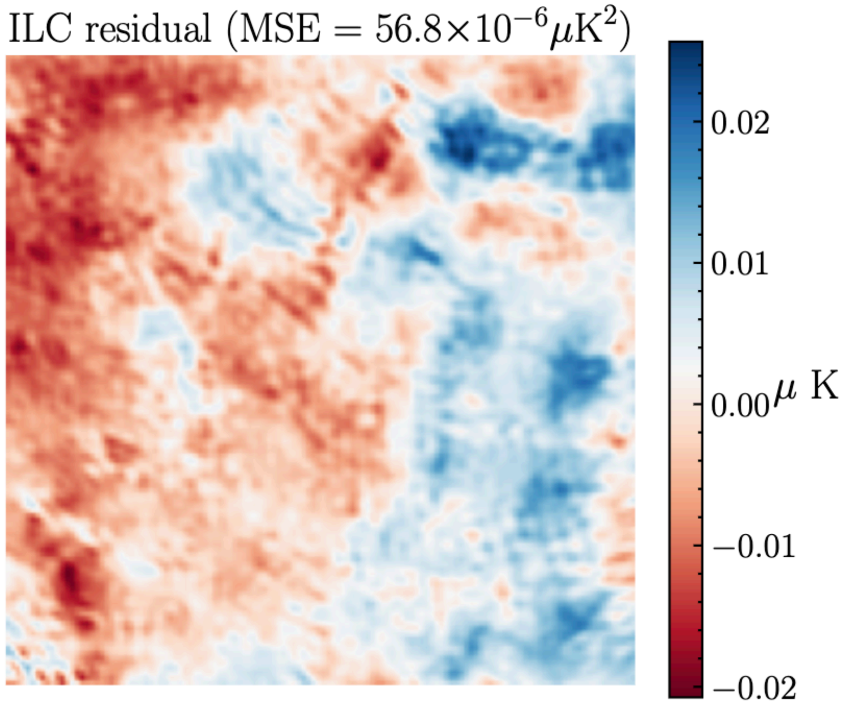
Application: B-modes

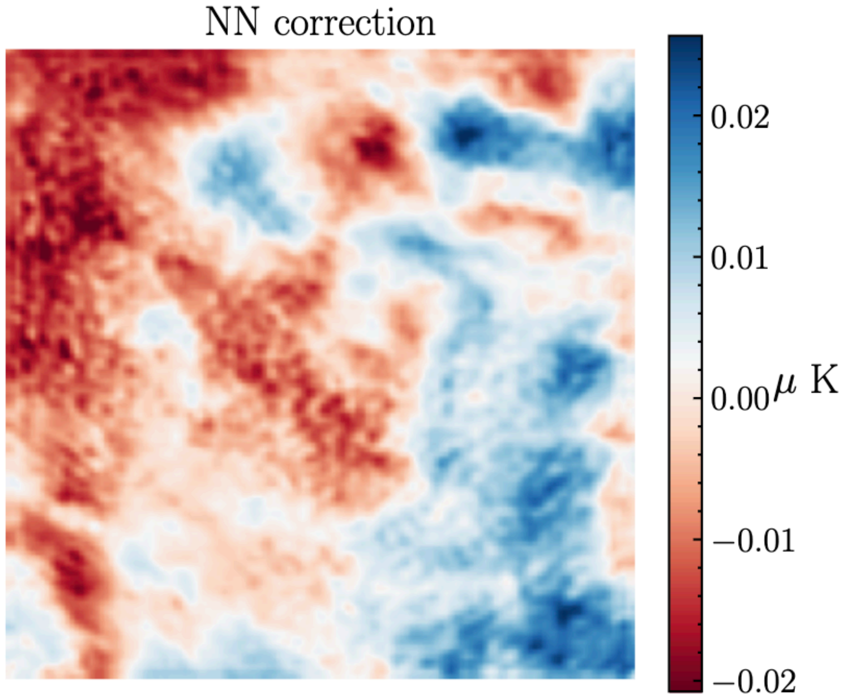
Does it work for dust models on which the CNN was not trained? Yes

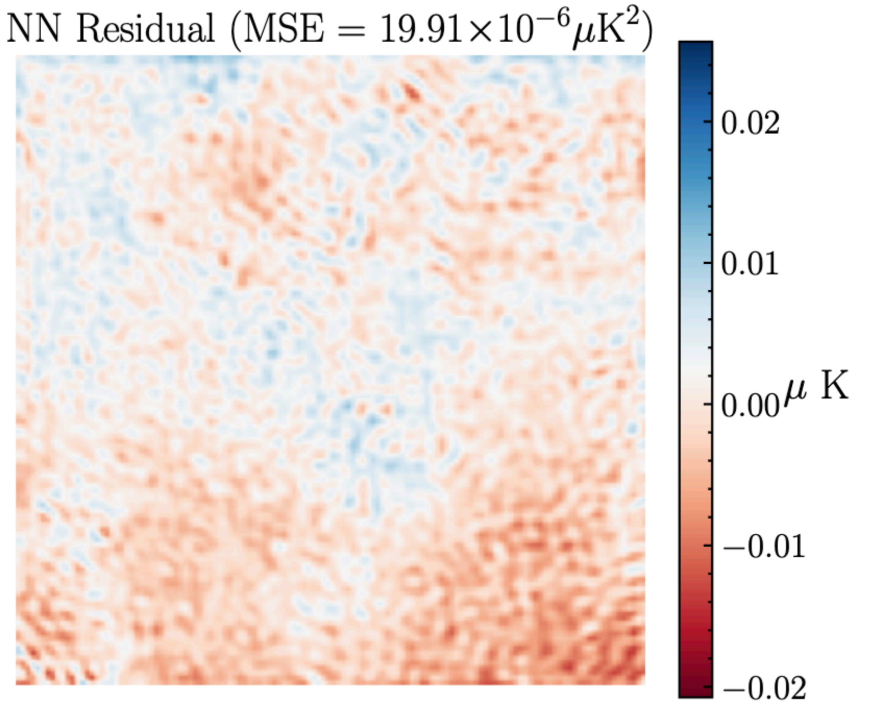




Is it learning the residual successfully? Yes







New Tools

Takeaways

- In the foreground-dominated era, large gains may be wrought from new methods (we see up to ~3x reduction in foreground “noise”)

Crucial to maximize CMB-S4 primordial B-mode science

- We also find similar success in application to CMB+tSZ simulations

New Tools

Takeaways

- In the foreground-dominated era, large gains may be wrought from new methods (we see up to ~3x reduction in foreground "noise")

Crucial to maximize CMB-S4 primordial B-mode science

- We also find similar success in application to CMB+tSZ simulations

- Much more still to do:
  - Inclusion of noise and instrumental systematics
  - Scale up the model to realistic map sizes
    - This will require additional simulations — need new methods
  - Determine what the ML model is learning
    - Can we build a simple analytic statistic that performs nearly as well?

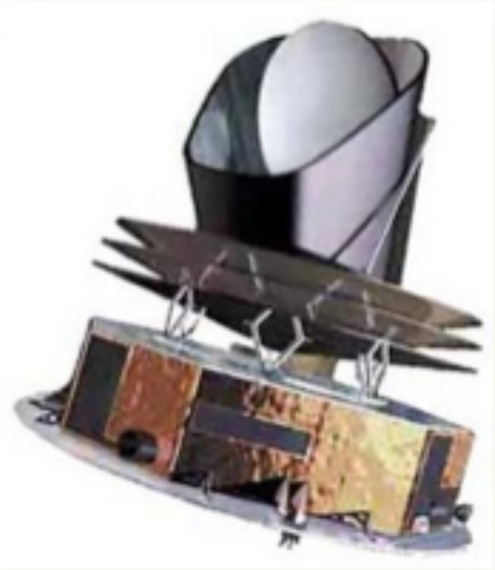
Related work in progress: tools to enable cosmological parameter inference from needlet ILC CMB maps (2403.02261 + to appear)

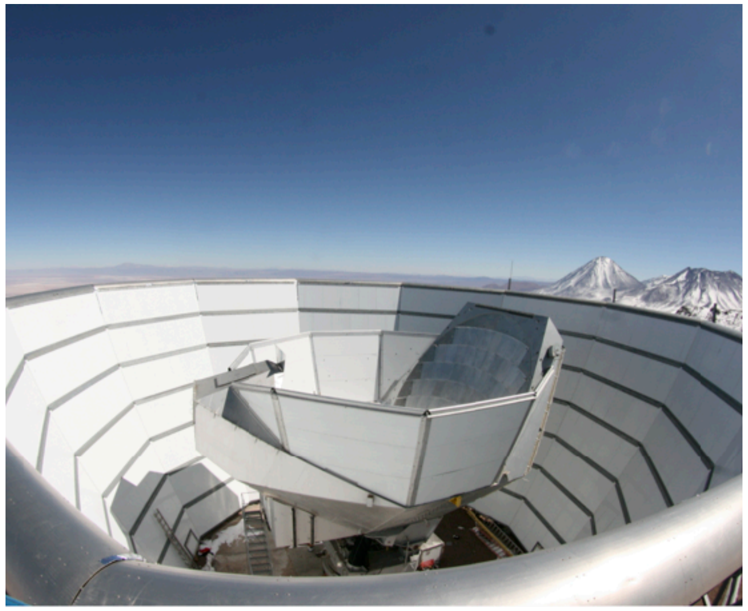
Outlook:
Simons Observatory
Advanced SO
CMB-S4

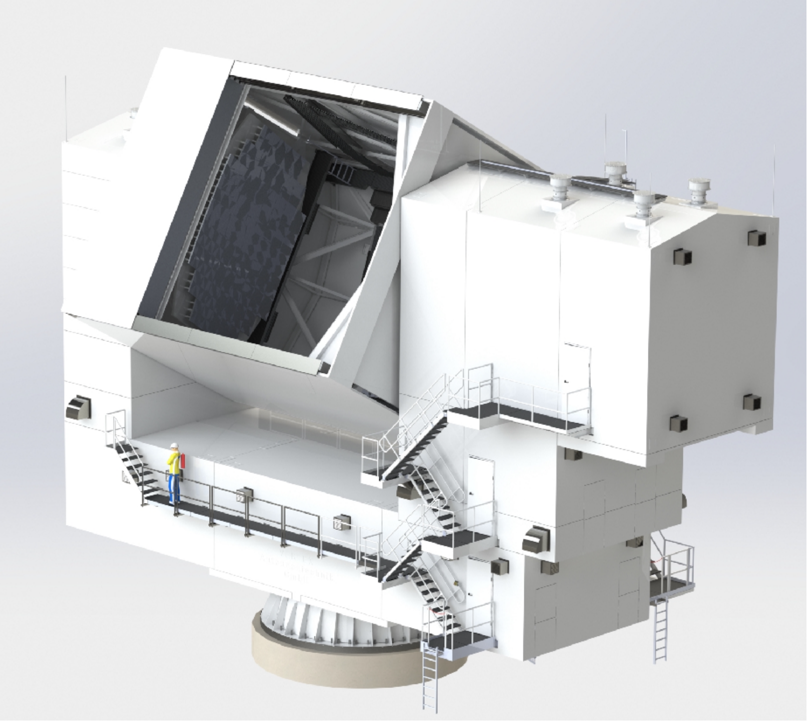
Colin Hill
Columbia

Landscape

Planck → ACT → **SO** Large Aperture Telescope







Final data 2018/2020
100% sky

0.35 — 10 mm (9 bands)
5 — 33' resolution

Observations through 8/2022
40% sky
Noise ~3 times < Planck
1.4 — 10 mm (5 bands)
1 — 7' resolution

[South Pole Telescope - same timeframe]

Observations 2024 - ~29
40% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7' resolution

+ ~6 low-resolution SATs
with additional bands

Landscape

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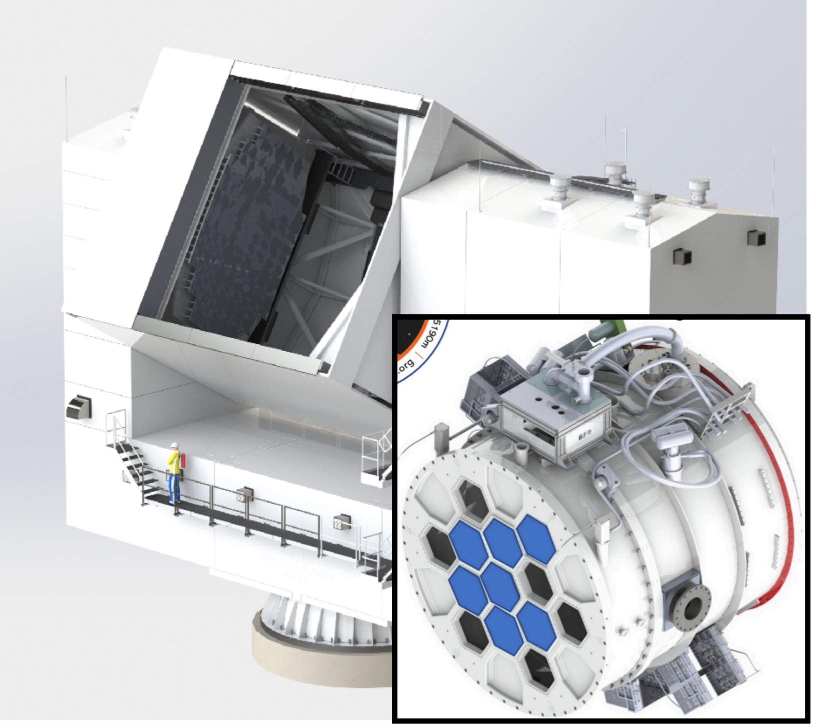
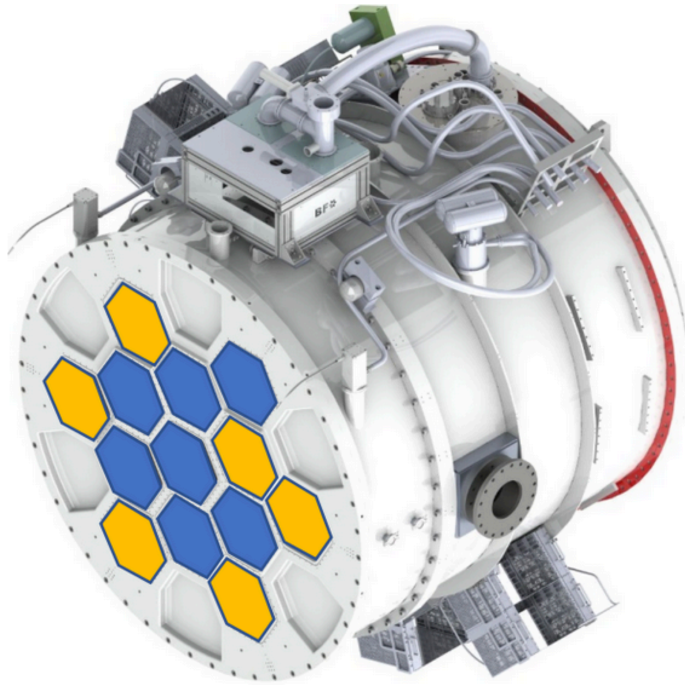
Columbia

SO →



Observations 2024 - ~29
40% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7' resolution

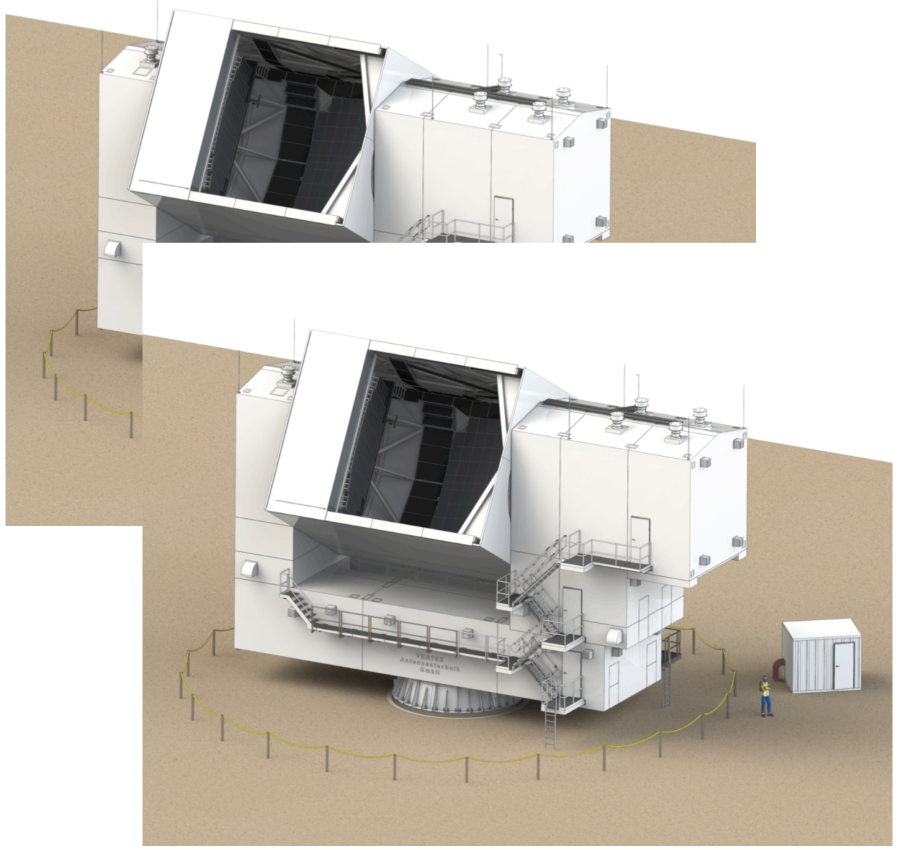
Advanced SO →



Observations ~2028 - 2033
40% sky
Noise ~1.7 times < SO
1 — 10 mm (6 bands)
1 — 7' resolution

JCH: Co-Project Scientist

CMB-S4 Large Aperture Telescopes



Observations ~2030 - 2037
70% sky
Noise ~2.4 times < Adv. SO
1 — 10 mm (6 bands)
1 — 7' resolution

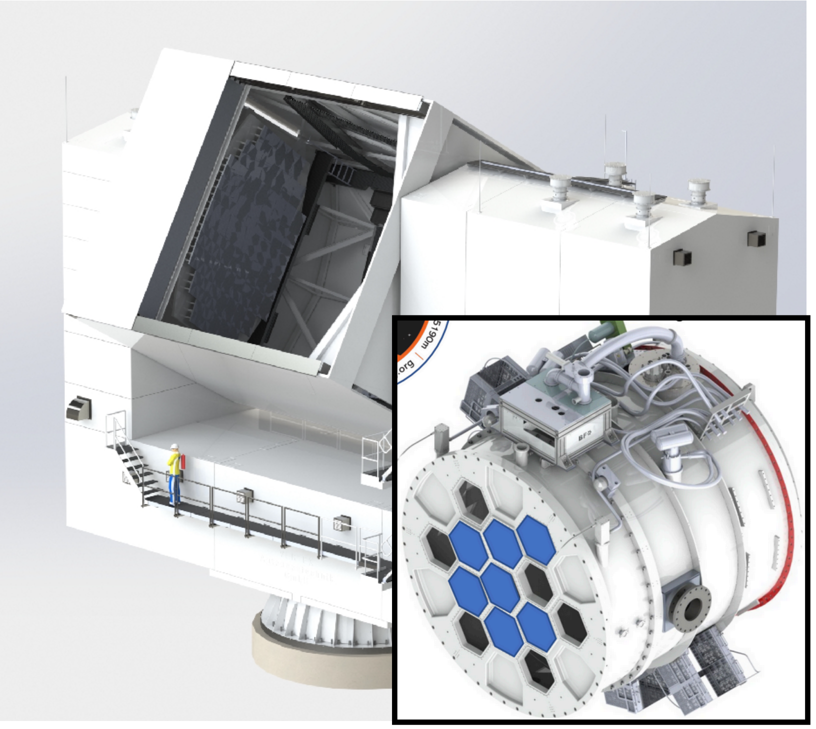
+ ~9 low-resolution SATs
with additional bands

Colin Hill
Columbia

Landscape

SO → Advanced SO → **CMB-S4** Large Aperture Telescopes

SO



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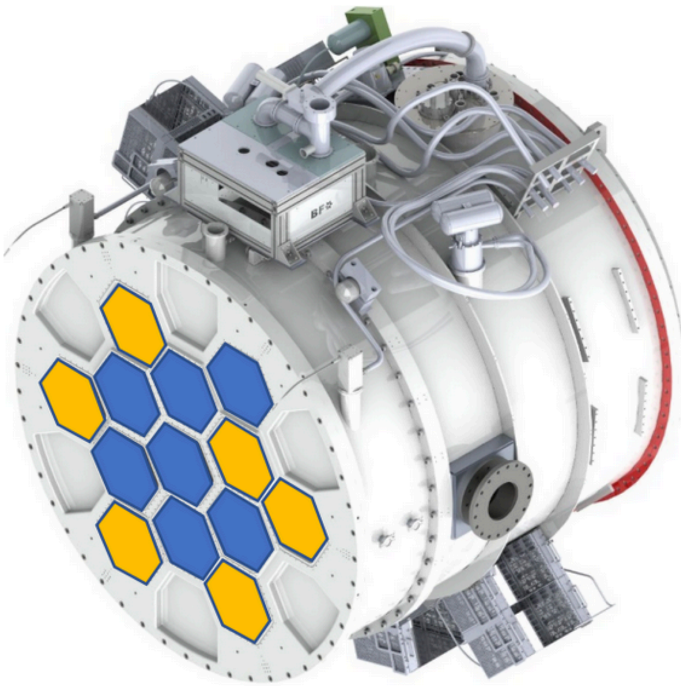
Advanced SO



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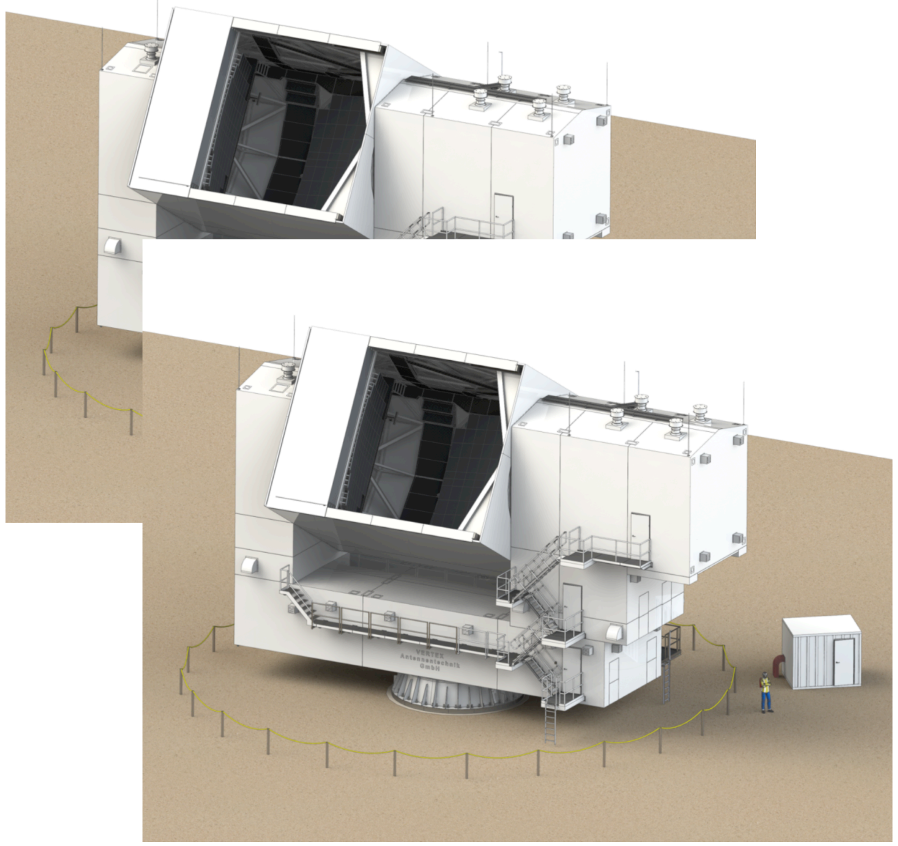
CMB-S4 Large Aperture Telescopes



Observations ~2030 - 2037
70% sky
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1 — 10 mm (6 bands)
1 — 7’ resolution

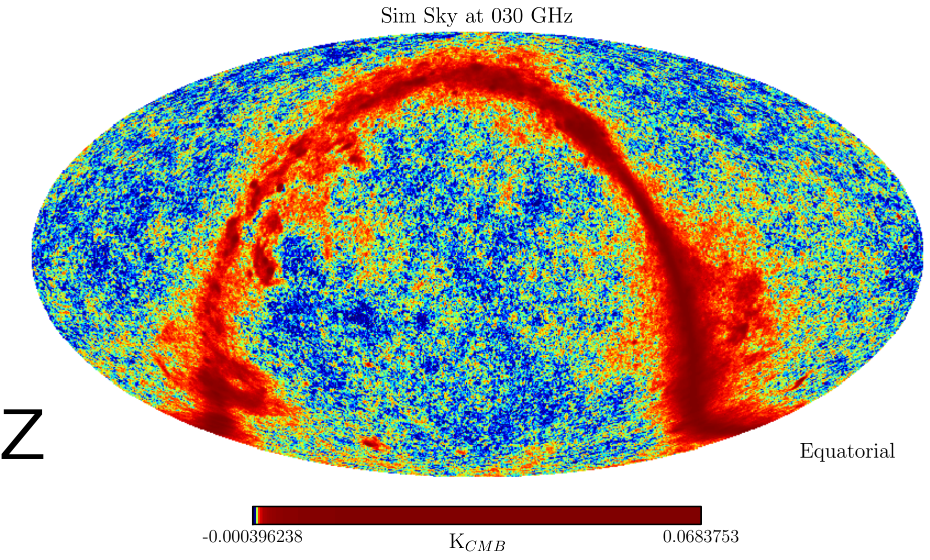
+ ~9 low-resolution SATs
with additional bands

SO analysis = essential training ground + preparation for CMB-S4

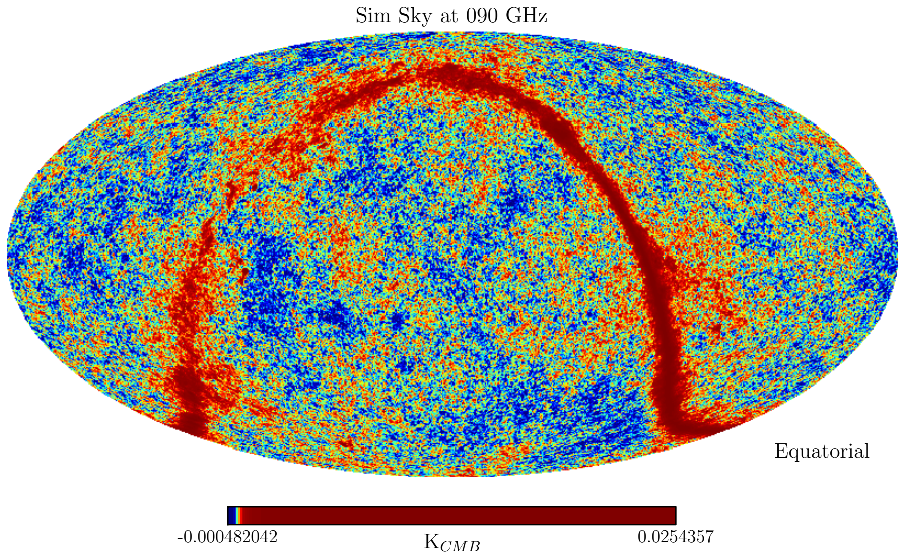
CMB-S4: Optimization

Colin Hill
Columbia

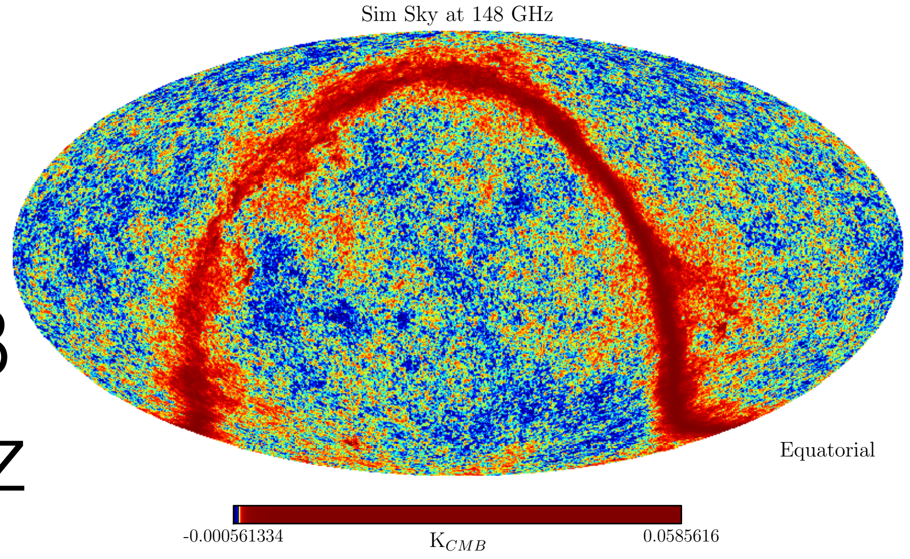
Baseline LAT design for allocation of detectors across frequencies was determined by my work



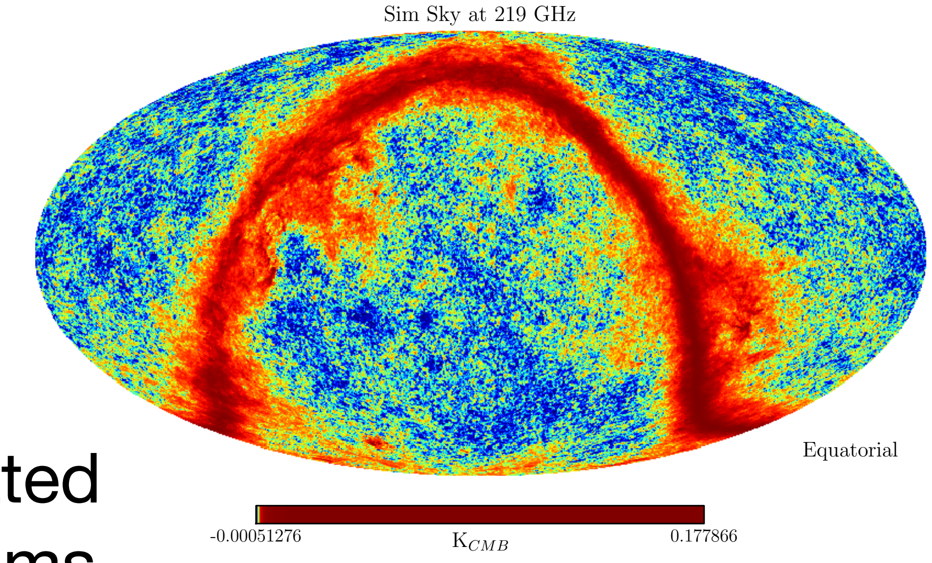
30
GHz



90
GHz

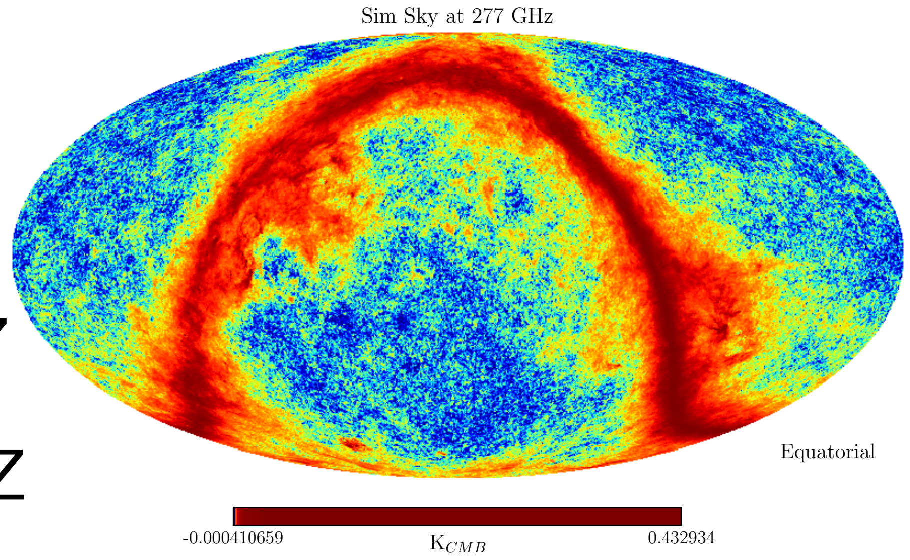


148
GHz

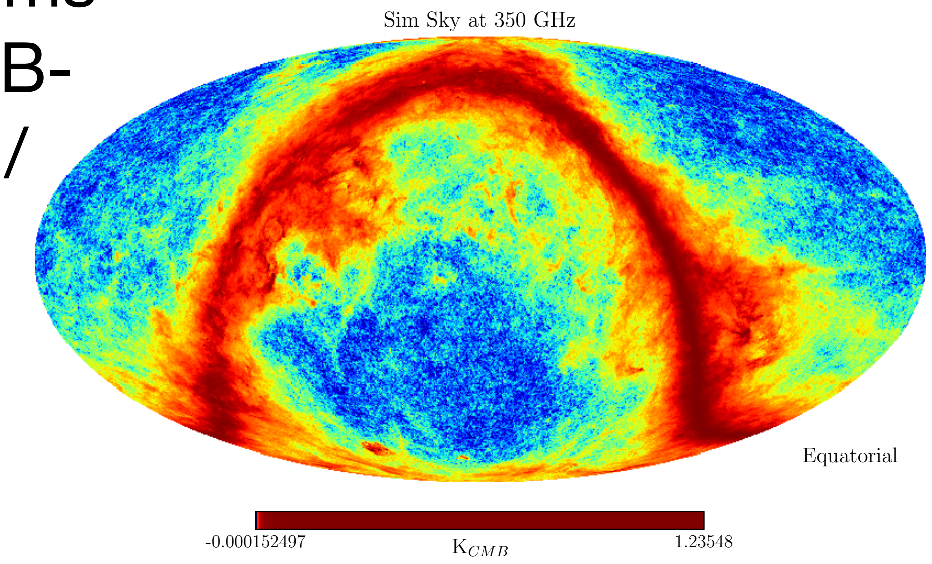


219
GHz

Built from updated Sehgal+2009 sims + PySM1 + CMB-S4 noise model/ calculator



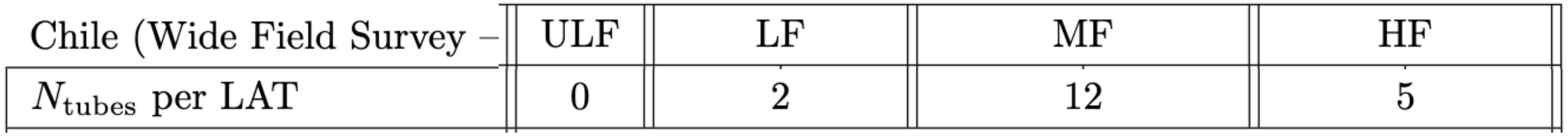
277
GHz



350
GHz

CMB-S4: Optimization

Sampling over ~10^5 possible detector distributions, performing component separation, and obtaining S/N on key science targets yielded the baseline CMB-S4 LAT configuration



Chile (Wide Field Survey –	ULF	LF	MF	HF
N_{tubes} per LAT	0	2	12	5

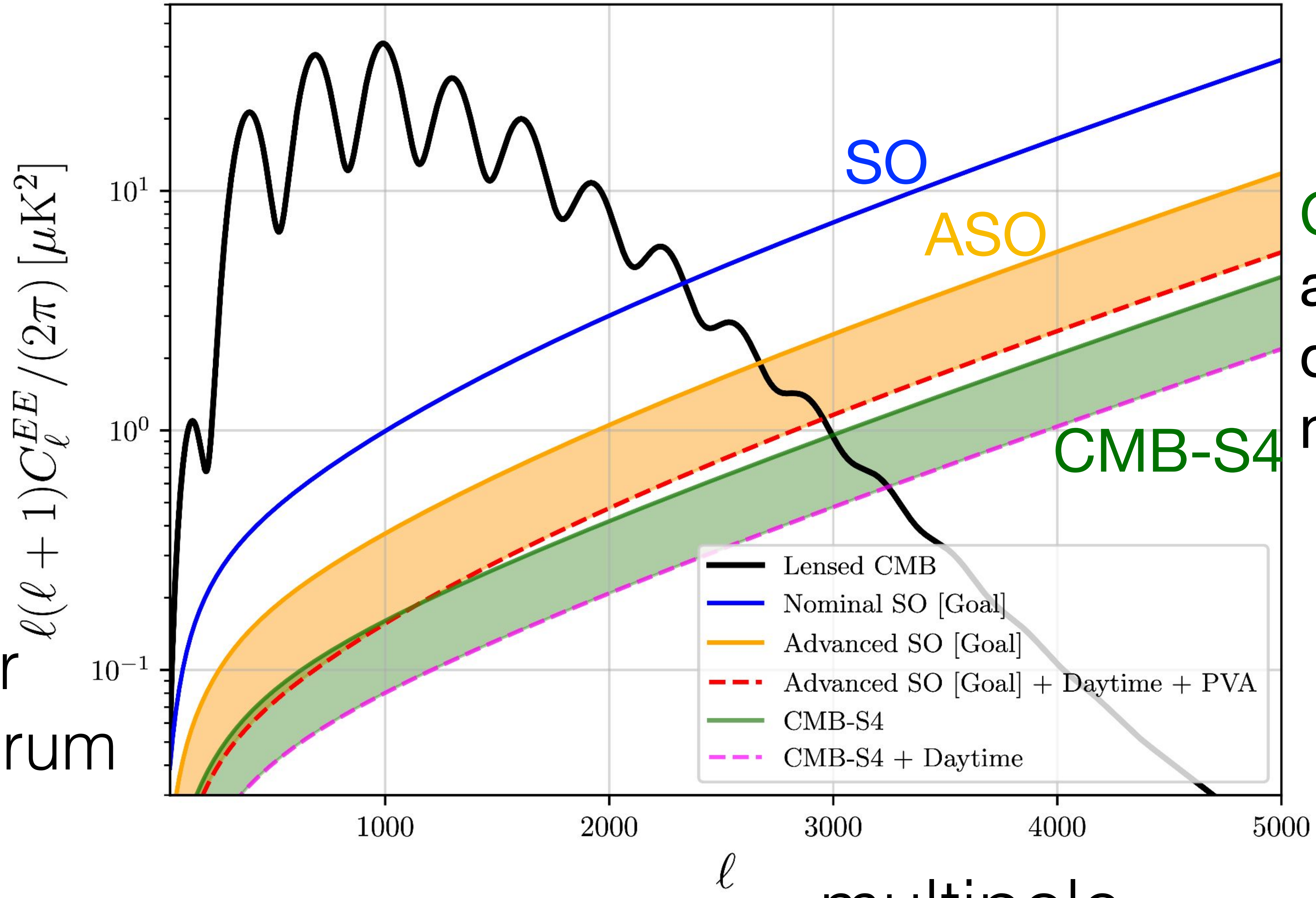
See appendices of CMB-S4 Decadal Survey Report (2019); results used in dozens of forecasts (e.g., Alvarez, Ferraro, **JCH**,+ 2021)

CMB-S4: Optimization

Colin Hill
Columbia

Sampling over ~10^5 possible detector distributions, performing component separation, and obtaining S/N on key science targets yielded the baseline CMB-S4 LAT configuration

EE (post-component-separation noise curves)



EE power spectrum

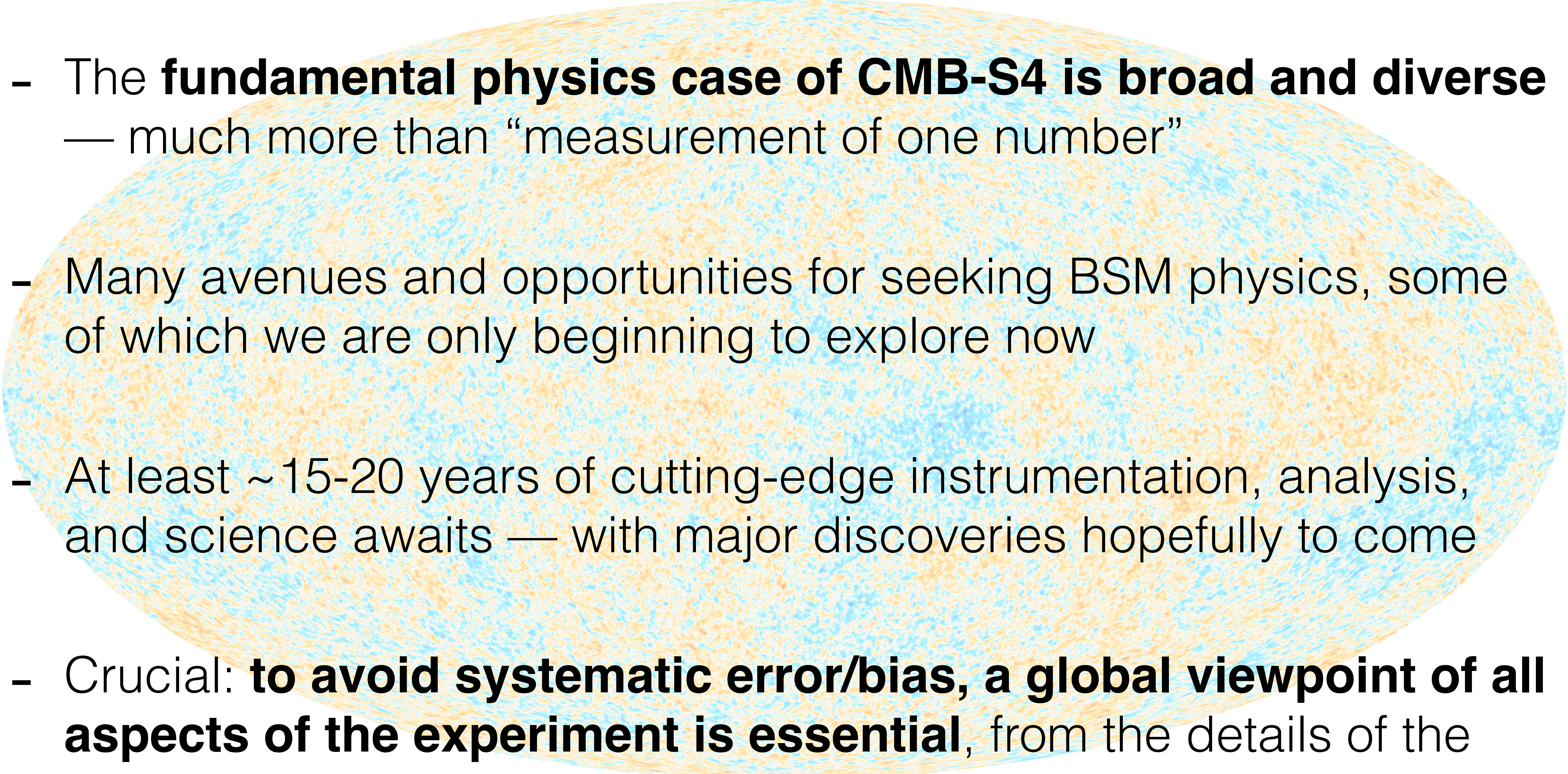
multipole

CMB-S4: ~3x as many signal-dominated E-modes as SO!

Immense discovery potential

Outlook

Takeaways

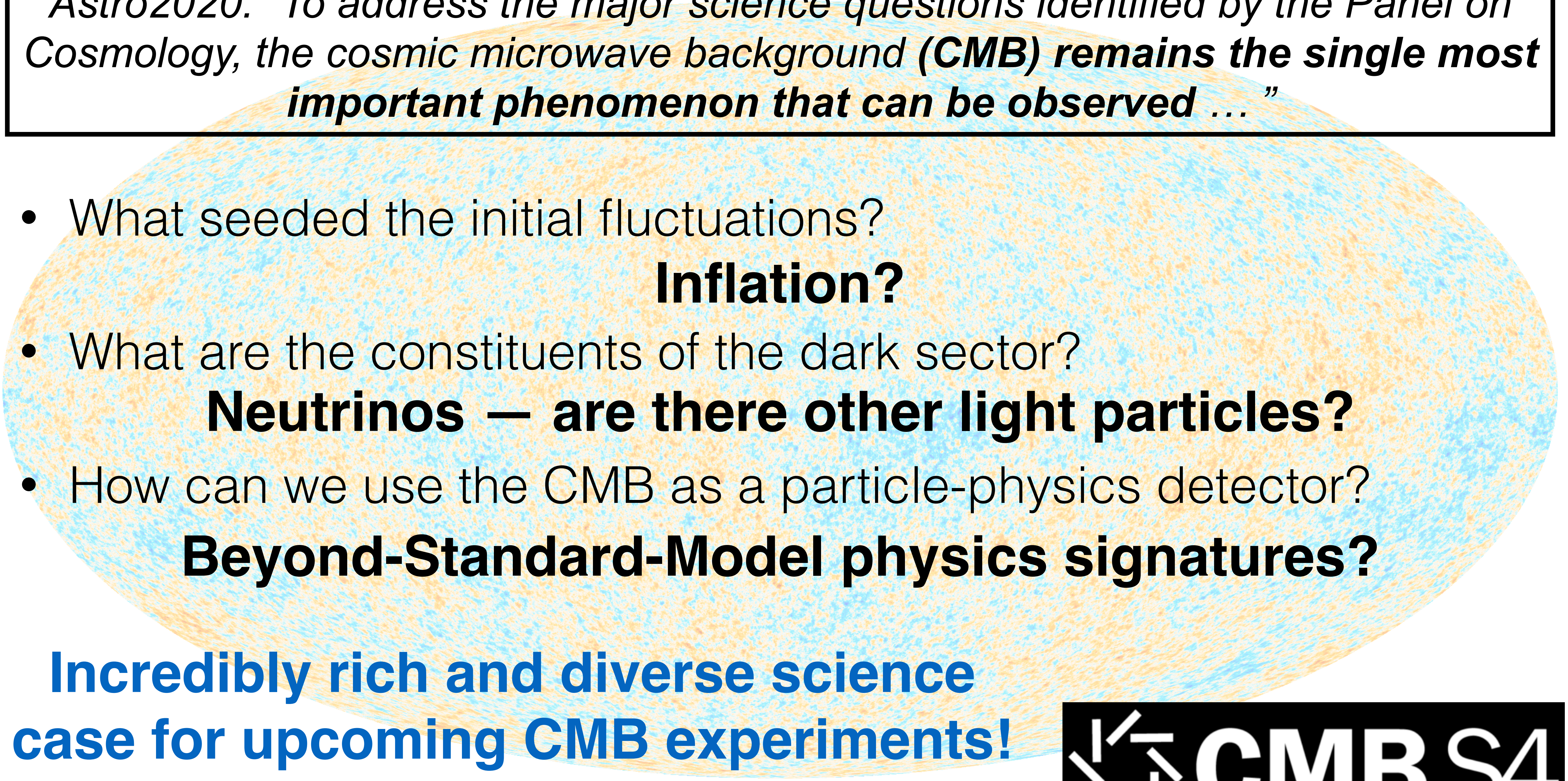


- The **fundamental physics case of CMB-S4 is broad and diverse** — much more than “measurement of one number”
- Many avenues and opportunities for seeking BSM physics, some of which we are only beginning to explore now
- At least ~15-20 years of cutting-edge instrumentation, analysis, and science awaits — with major discoveries hopefully to come
- Crucial: **to avoid systematic error/bias, a global viewpoint of all aspects of the experiment is essential**, from the details of the hardware to the final scientific interpretation.

Colin Hill
Columbia

Cosmic Microwave Background

> *Astro2020: "To address the major science questions identified by the Panel on Cosmology, the cosmic microwave background* ***(CMB) remains the single most important phenomenon that can be observed*** *… "*



- What seeded the initial fluctuations?

Inflation?

- What are the constituents of the dark sector?

Neutrinos — are there other light particles?

- How can we use the CMB as a particle-physics detector?

Beyond-Standard-Model physics signatures?

Incredibly rich and diverse science case for upcoming CMB experiments! New tools and close interface between analysis and instrumentation will enable breakthroughs.

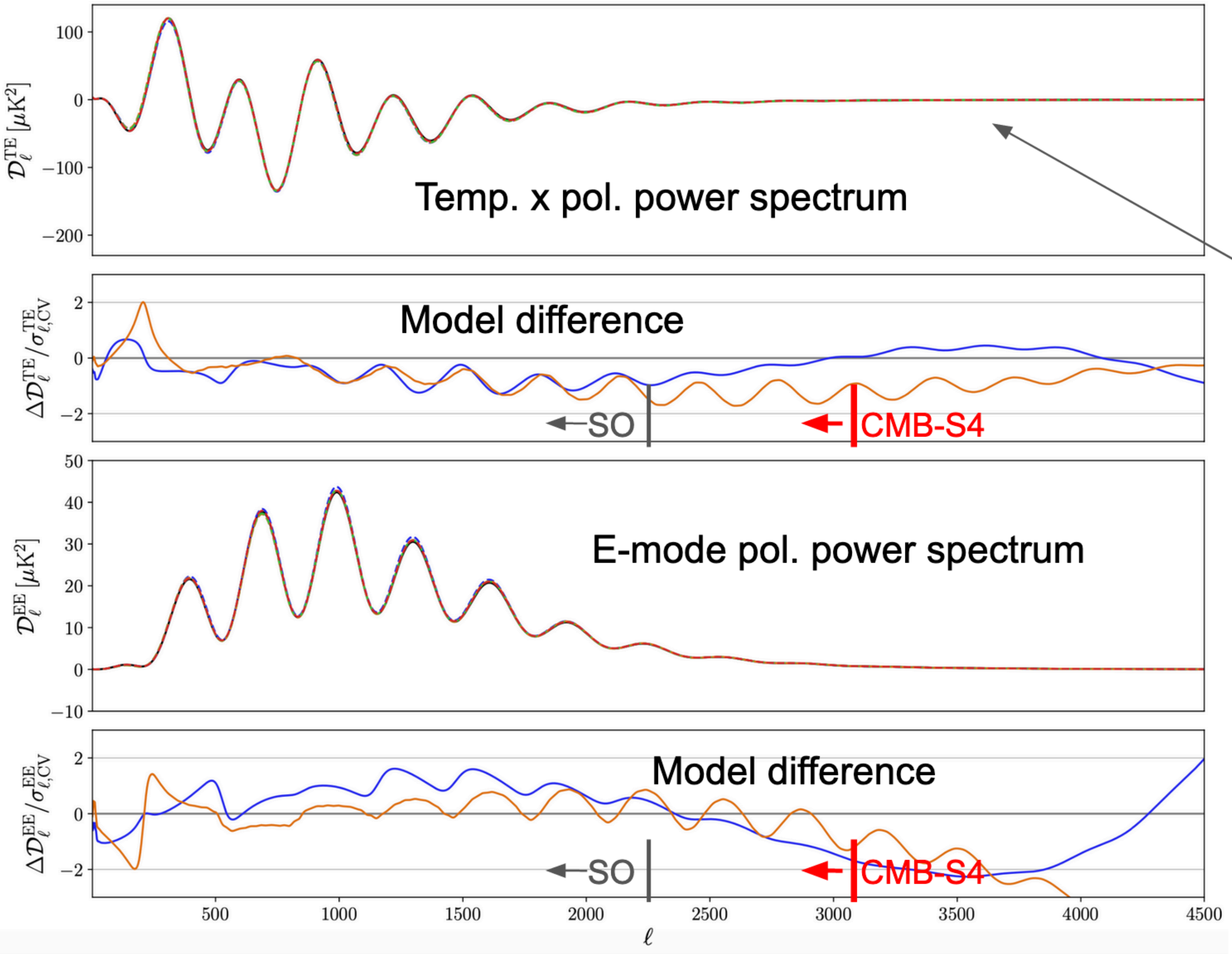
CMB S4

SIMONS OBSERVATORY

Bonus

CMB-S4: Opening Up Discovery Space

Colin Hill
Columbia



Example: early dark energy (EDE) scenario

Idea: brief period of cosmic acceleration just prior to recombination

Best-fit EDE and ΛCDM models to various data sets

ACT best-fit EDE - Planck best-fit ΛCDM

ACT+low-ell-TT best-fit EDE - Planck best-fit ΛCDM

Key differences are seen in pol. power spectra – but signal is tiny

We need as many high-S/N modes as possible to maximize discovery potential – low noise and wide area:

~2σ hint in ACT DR4 → 60σ in CMB-S4

Hill et al. [ACT] (2021)

We are looking for tiny signals — detailed characterization of instrument will be essential to avoid systematic error

Dark Screening in the CMB

(Massive) Dark Photon

Kinetic mixing between SM photon and dark photon (DP):

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{m^2_{\mathrm{A}'}}{2}\mathrm{A}'_{\mu}\mathrm{A}'^{\mu} - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \mathrm{A}^{\mu}J_{\mu}$$

SM photon   DP   DP mass term   SM-DP kinetic mixing

Holdom (1986); recent review: Caputo+ (2021)

Dark Screening in the CMB

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SM photon DP DP mass term SM-DP kinetic mixing

Dominant effect relevant to CMB: resonant conversion

SM photon acquires "plasma mass" post-reionization:

$$m_\gamma = \sqrt{4\pi\alpha n_e/m_e} = 3.7\times10^{-11}\ \mathrm{eV}\sqrt{\frac{n_e}{\mathrm{cm}^{-3}}}$$

If this plasma mass = DP mass, resonant conversion occurs (~ε^2):

$$P_{\gamma\to\mathrm{A}'} = \sum_{t_{\mathrm{res}}} \frac{\pi\varepsilon\, m_{\mathrm{A}'}^2}{\omega(t_{\mathrm{res}})} \times \varepsilon \left|\frac{\mathrm{d}}{\mathrm{d}t}\ln m_\gamma^2(\vec{x}(t))\right|^{-1}_{t=t_{\mathrm{res}}}$$

Mirizzi+ (2009); McDermott & Witte (2020); Caputo+ (2020); Pirvu, Huang, Johnson (2023); +++

Dark Screening in the CMB

Axion-Like Particle

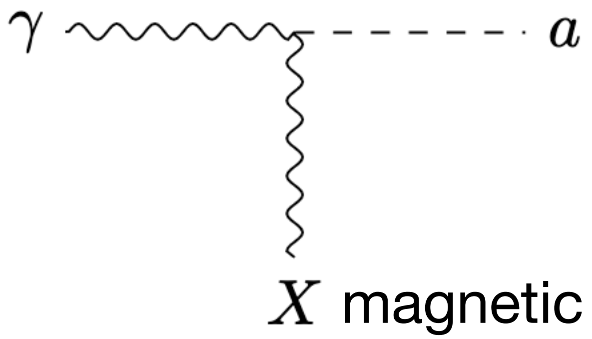
Axion-photon coupling:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}\, a$$

axion

SM photon

Photon-axion
conversion in
magnetic field:



magnetic field

Raffelt & Stodolsky (1988); Csaki+ (2002); Mirizzi+ (2008); D'Amico & Kaloper (2015); +++

Colin Hill
Columbia

Dark Screening in the CMB

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axion

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If this plasma mass = axion mass, resonant conversion occurs in a background magnetic field (~$B^2 g_{a\gamma\gamma}^2$):

$$P(A_\parallel \to a)_{\mathrm{res}} \simeq \frac{\pi \omega g_{a\gamma\gamma}^2 B^2}{m_a^2} \left| \frac{d \ln m_\gamma^2}{dt} \right|_{t_{\mathrm{res}}}^{-1}$$

Raffelt & Stodolsky (1988); Csaki+ (2002); Mirizzi+ (2008); D'Amico & Kaloper (2015); +++

How do we measure H_0?

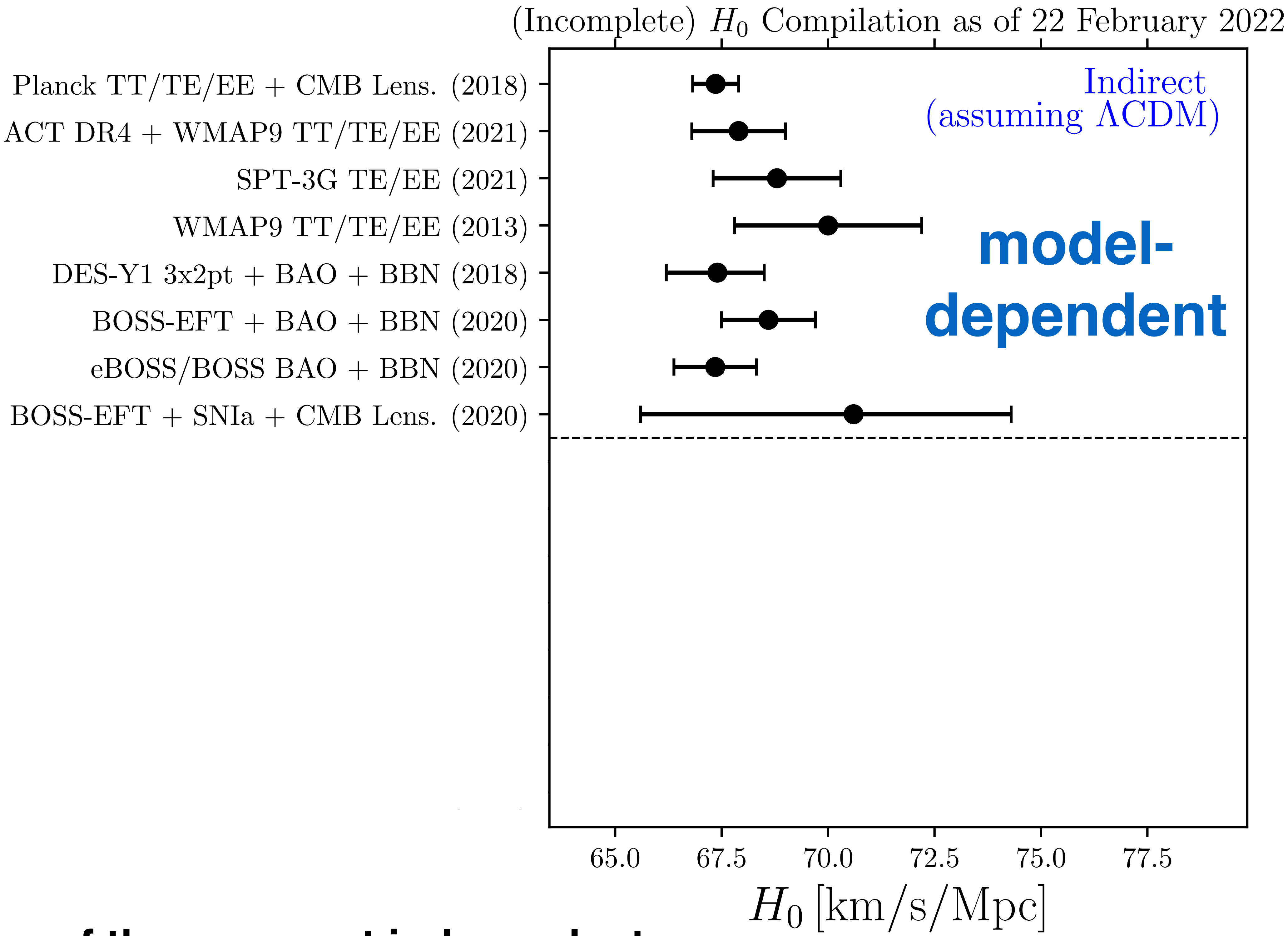
Method 1: measure the distance-redshift relation in the nearby universe, e.g., using the classical distance ladder (same method as Hubble himself) — infer H_0 “directly”

Method 2: fit a detailed cosmological model to data from cosmic microwave background and/or large-scale structure surveys — infer H_0 “indirectly”

The Hubble Situation

Colin Hill
Columbia

My personal view: observational situation remains unclear



N.B. many of these are not independent

Original discussion: https://twitter.com/jcolinhill/status/1319415667095949312

Colin Hill
Columbia

The Hubble Situation

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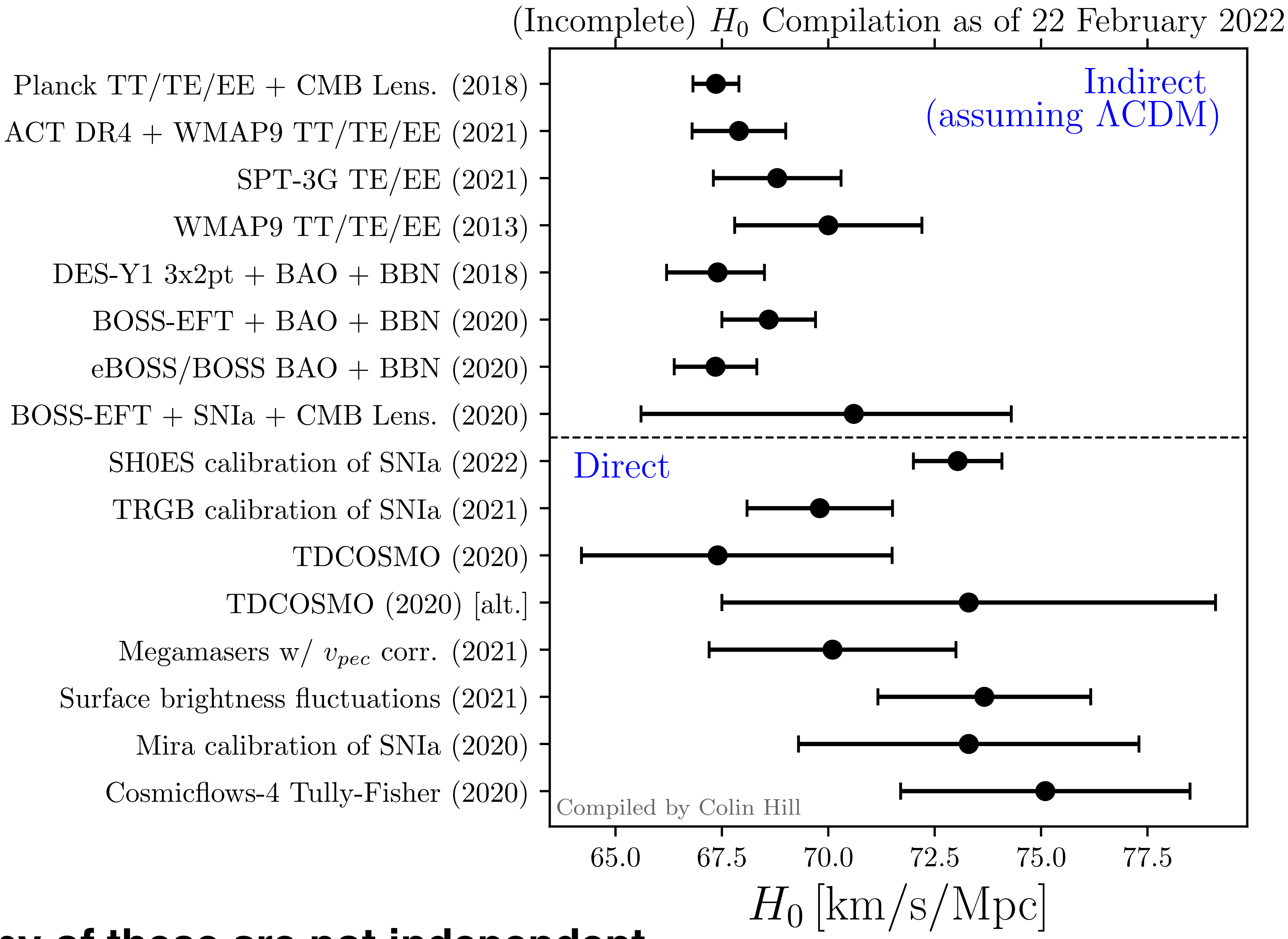

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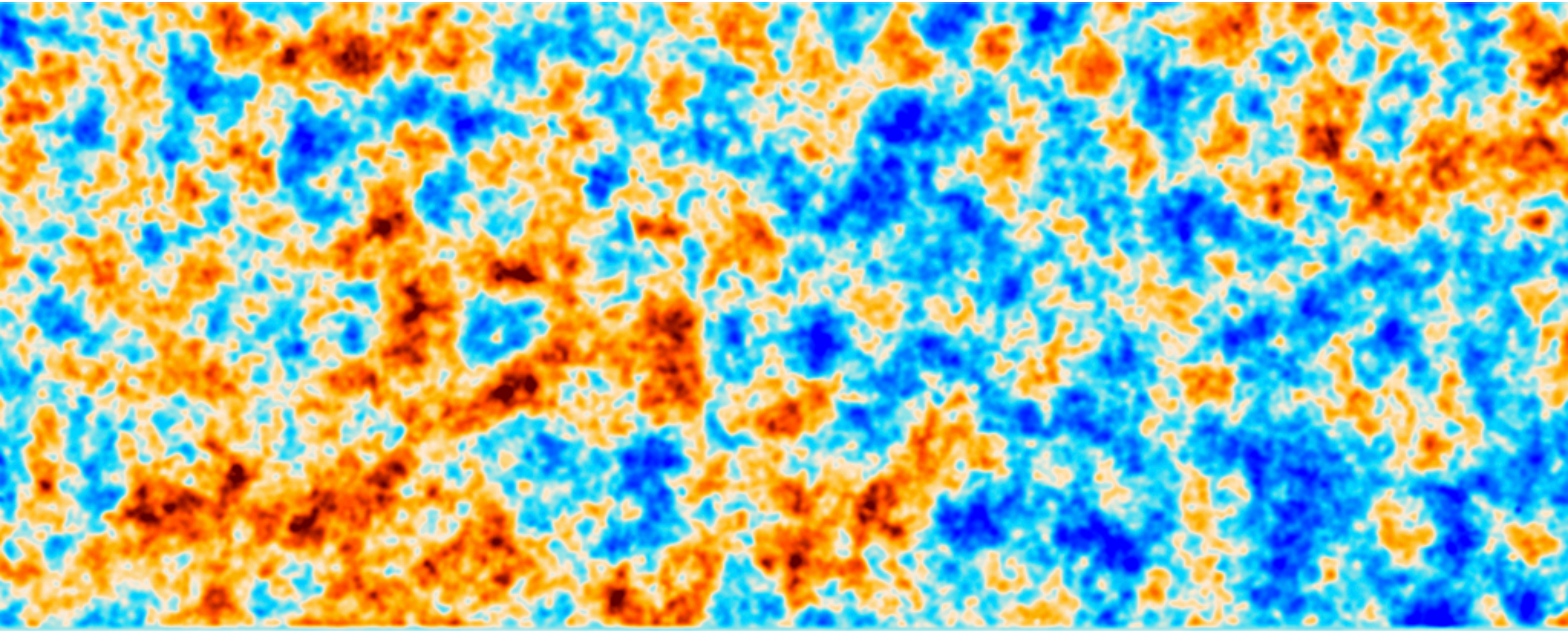
Original discussion: https://twitter.com/jcolinhill/status/1319415667095949312

How Do We Infer H_0 from the Cosmic Microwave Background?

The Sound Horizon

Colin Hill
Columbia/CCA

There is a “standard ruler” of known physical size imprinted in CMB maps. It is the distance that a sound wave could propagate in the plasma that filled the universe, starting at t=0 (Big Bang) until redshift $z = 1100$



A small patch of a CMB temperature map made from combination of Planck and ACT DR4 data (25x10 deg^2)

Naess et al. (2020)

The Sound Horizon

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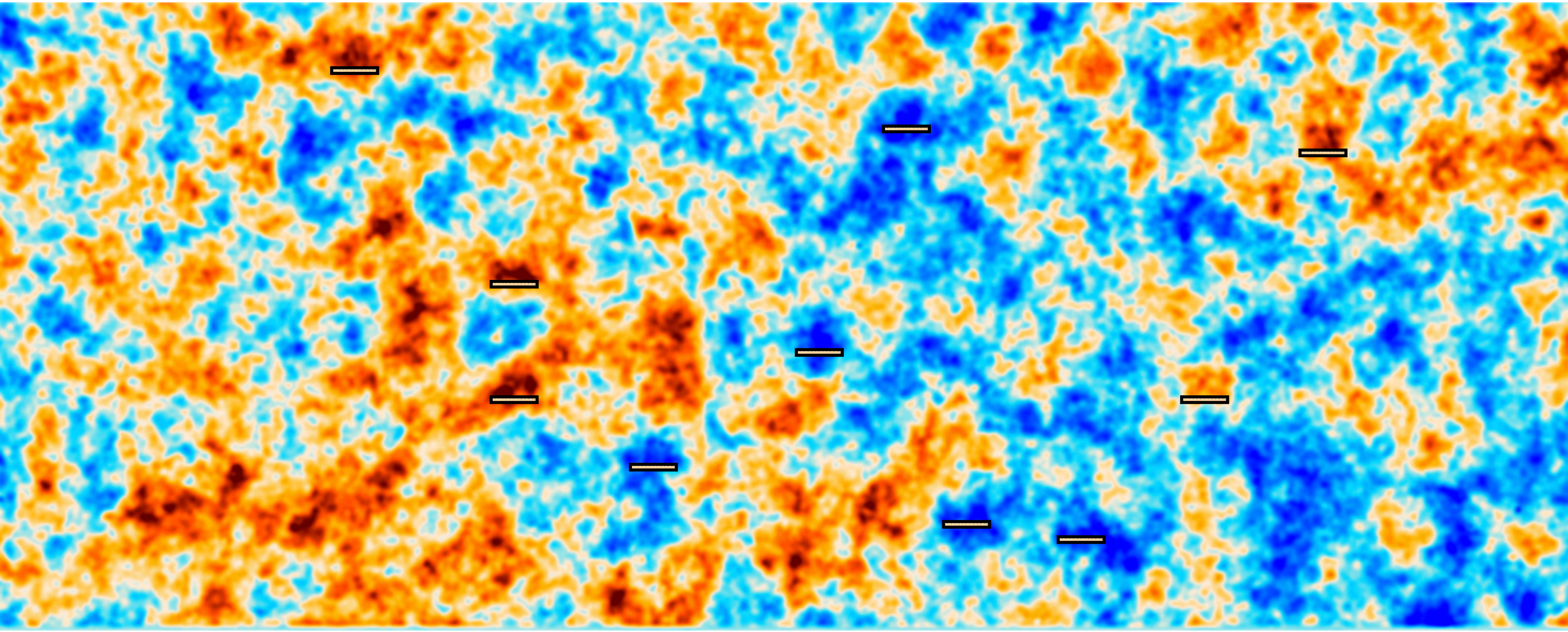

We measure the angular size of this ruler on the sky (θ_s^*), and thus infer the distance to the CMB — therefore we have a **distance** and a **redshift**.

The Sound Horizon

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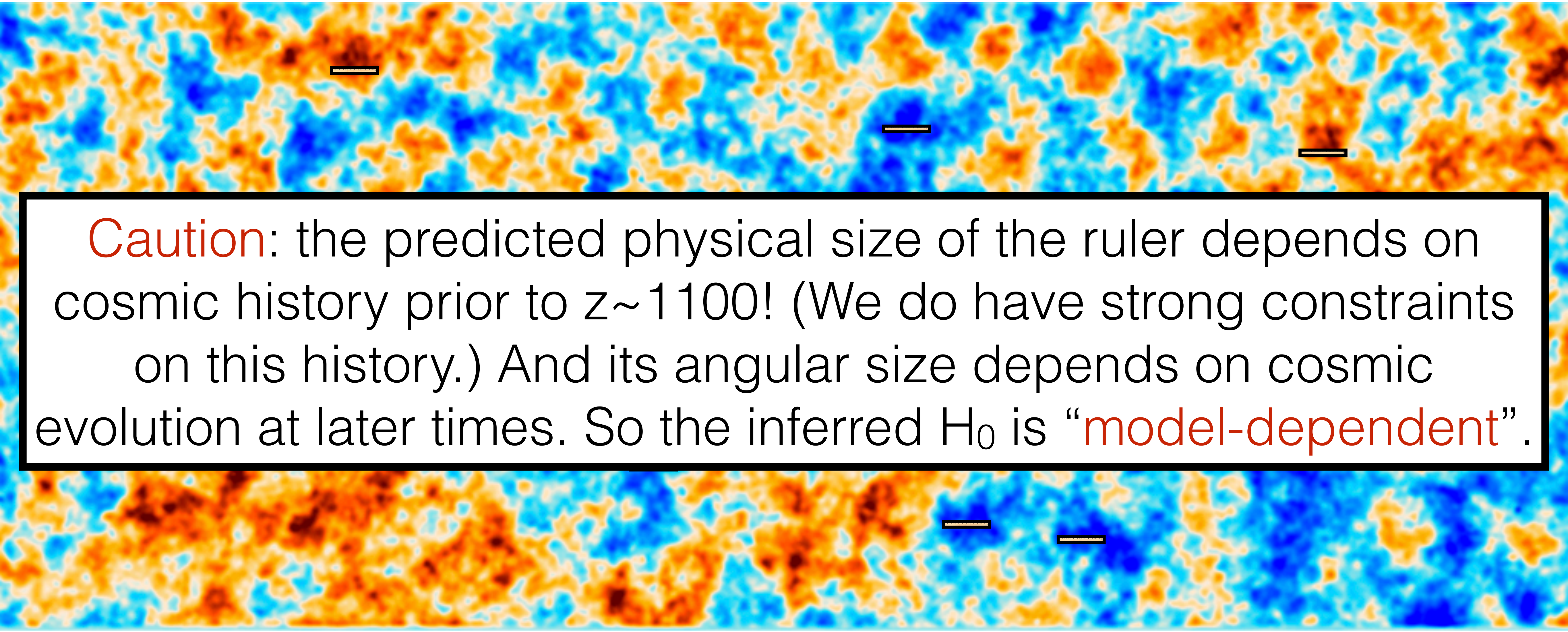


Caution: the predicted physical size of the ruler depends on cosmic history prior to z~1100! (We do have strong constraints on this history.) And its angular size depends on cosmic evolution at later times. So the inferred H_0 is “model-dependent”.

We measure the angular size of this ruler on the sky (θ_s^*), and thus infer the distance to the CMB — therefore we have a **distance** and a **redshift**.

The Hubble Situation

Colin Hill
Columbia

How can we increase H_0 inferred from the CMB and large-scale structure?

Can we preserve the angular size of the sound-horizon ruler on the sky while modifying cosmic evolution at late times to increase H_0?

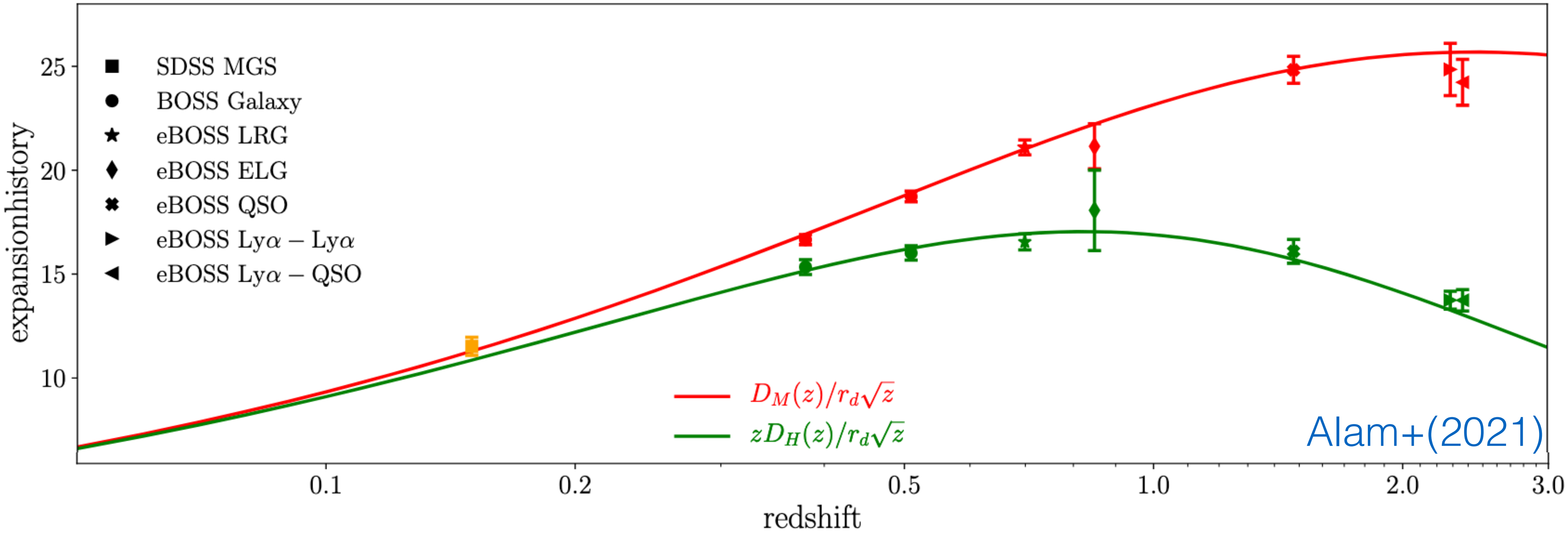
The Hubble Situation

How can we increase H_0 inferred from the CMB and large-scale structure?

Can we preserve the angular size of the sound-horizon ruler on the sky while modifying cosmic evolution at late times to increase H_0?

No

Late-time (z<few) theoretical modifications are highly constrained by (relative) expansion history data, e.g., BAO distances and SNIa distances



Alam+(2021)

Such models often also conflict with integrated Sachs-Wolfe effect and CMB lensing data (e.g., McCarthy & JCH (2022): 2210.14339)

The Hubble Situation

My personal view: observational situation remains unclear

Regardless, the situation has motivated us to think about many types of new physics in the cosmos that we otherwise (likely) would not have

↓

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"We single out the set of solutions that increase the expansion rate in the decade of scale factor expansion just prior to recombination as the least unlikely [to be successful]." — Knox & Millea (2020)

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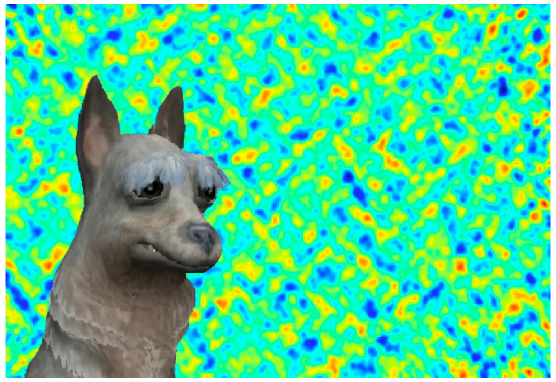
→ **Generic consequence: new signals in the cosmic microwave background**



The Hubble Situation

If the H_0 discrepancy is not due to systematic error(s), how can we explain it?

One possibility: some (exotic) new physics altered the physical size of the “ruler” in the CMB

e.g., extra “dark radiation” in the early universe or “early dark energy”

Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

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Goal of many such proposals: the new physics acts to *decrease* the physical size of the standard ruler (the sound horizon), so that the distance to the CMB that we infer is also decreased, and our inferred H_0 is *increased*

Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

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$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(z)$$

sound
horizon

scale
factor

sound
speed

idea: increase H(z)
just prior to z*~1100

Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

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sound horizon

scale factor

sound speed

idea: increase H(z) just prior to z*~1100

Then to keep $\theta_s^* = r_s^*/D_A^*$ fixed, H_0 must increase ($D_A \sim 1/H_0$)

Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

The Hubble Situation

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The Hubble Situation

If the H_0 discrepancy is not due to systematic error(s), how can we explain it?

Another possibility: some new physics altered the dynamics of the epoch of recombination

e.g., primordial magnetic fields or varying fundamental constants

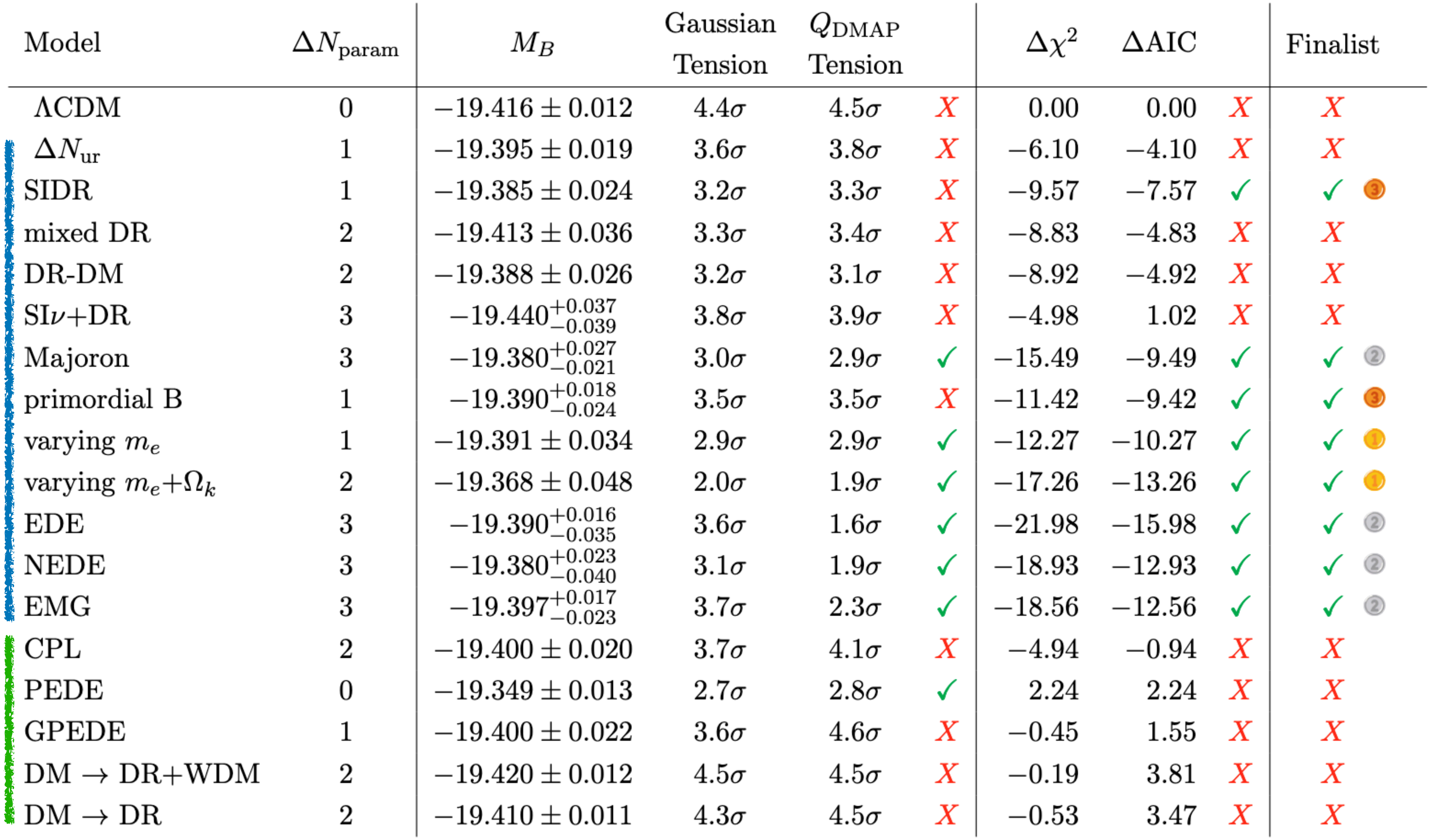
Goal of many such proposals: the new physics acts to *accelerate* the process of recombination, so that recombination happens earlier (i.e., at higher redshift)

In some such models (but not all), r_s^* is decreased due to higher z^*

Jedamzik & Pogosian (2018); Sekiguchi & Takahashi (2020); Hart & Chluba (2020); JCH & Bolliet (2023)

“H_0 Olympics”

Very useful systematically organized global study
(N.B. no S_8 data considered, apart from Planck CMB lensing)



Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓	③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	②
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓	③
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	①
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	①
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	②
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	②
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓	②
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X	
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X	
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X	
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X	
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X	

early universe

late universe

Schoenberg+21

Dark Screening: Extraction

Colin Hill
Columbia

Needlet Internal Linear Combination

Needlets allow localization of ILC weights in both harmonic and pixel space

Steps:

1) Filter each frequency map with each harmonic-space needlet filter

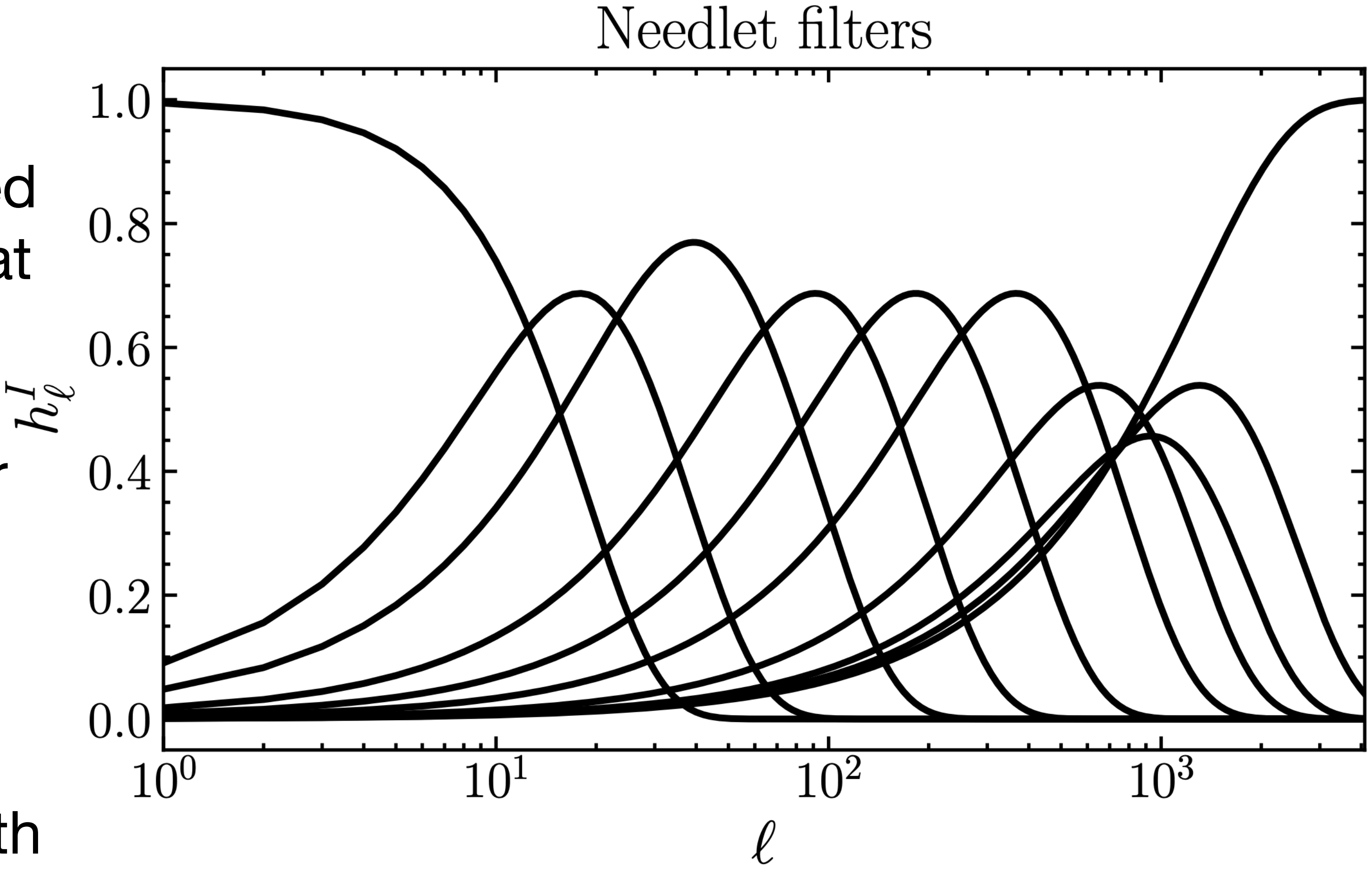
2) Compute the freq.-freq. covariance matrix in real-space domain of specified size centered on each pixel (for maps at each needlet scale)

3) Compute ILC weights at each pixel (for maps at each needlet scale)

4) Obtain per-scale ILC maps

5) Filter each per-scale ILC map again with the needlet filters

6) Co-add ILC maps from all needlet scales to obtain final NILC map



e.g., Eriksen+(2004); Delabrouille+(2009); Remazeilles+(2011); JCH & Spergel (2014)

Dark Screening: Extraction

pyilc

flexible, extensible NILC code in Python

Needlet ILC in Python

Features:

- Trivial installation, requires only healpy
- Many component SEDs available (CMB, tSZ, CIB, synchrotron, ..) + easy to add more
- Easy to define any type of needlet filters
- Delta-function or realistic passbands can be used
- Gaussian beams or arbitrary ell-dependent beams can be used
- Automatically determines which frequency maps to use at a given needlet scale, given their beams
- Covariances are computed only once and then cached for future use, allowing many constrained ILCs (“deprojections”) to be run at ~zero additional computational expense
- Automatically determines the size of the real-space domains to be used in computing the freq.-freq. covariance matrix at each needlet scale, by requiring the number of modes to be large enough to keep the “ILC bias” below a fixed tolerance:

$$\frac{b_{\mathrm{ILC}}}{\langle s^2 \rangle} = \frac{|1 + N_{\mathrm{deproj}} - N_{\mathrm{freq}}|}{N_{\mathrm{modes}}}$$

McCarthy & JCH (2023a)

https://github.com/jcolinhill/pyilc

Thermal SZ Extraction

CIB cleaning: moment deprojection

Idea: suppose the fundamental SED describing dust emission is indeed a modified blackbody (MBB). Variations in the MBB parameters (β,T) across the sky and along the line of sight will generically produce new spectral shapes that are described by higher-order moments in a Taylor expansion of the fundamental SED.

Chluba, JCH, Abitbol (2017); McCarthy & JCH (2023a)

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MBB:

$$I_\nu^{\mathrm{CIB}}(\hat{n}) = \left(\frac{\nu}{\nu_0}\right)^{\beta+3} \frac{1}{e^{x_{\mathrm{CIB}}}-1} A^{\mathrm{CIB}}(\hat{n})$$

First-order moments:

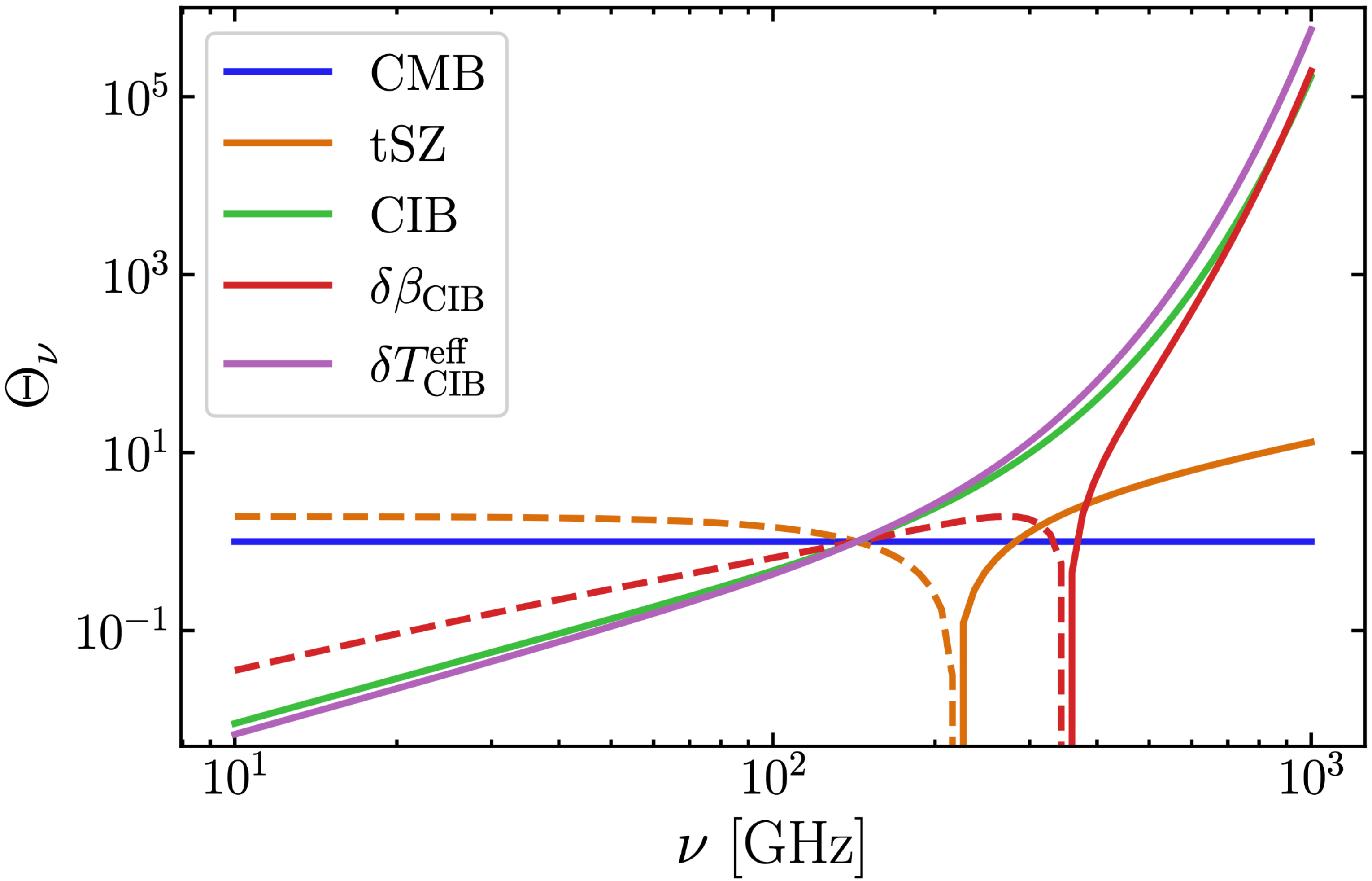
$$\frac{\partial I_\nu^{\mathrm{CIB}}(\hat{n})}{\partial \beta} = \ln\left(\frac{\nu}{\nu_0}\right) I_\nu^{\mathrm{CIB}}(\hat{n})\,;$$

$$\frac{\partial I_\nu^{\mathrm{CIB}}(\hat{n})}{\partial T_{\mathrm{CIB}}^{\mathrm{eff}}} = I_\nu^{\mathrm{CIB}}(\hat{n}) \frac{x_{\mathrm{CIB}}}{T_{\mathrm{CIB}}^{\mathrm{eff}}} \frac{e^{x_{\mathrm{CIB}}}}{e^{x_{\mathrm{CIB}}}-1}$$

$$x_{\mathrm{CIB}} \equiv \frac{h\nu}{k_B T_{\mathrm{CIB}}^{\mathrm{eff}}}$$

ν_0 = 353 GHz

Component SEDs [normalized]



Chluba, JCH, Abitbol (2017); McCarthy & JCH (2023a)

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MBB fit to CIB monopole SED predicted by best-fit halo model to CIB power spectra

McCarthy & JCH (2023a); Planck Collaboration XXX (2014)

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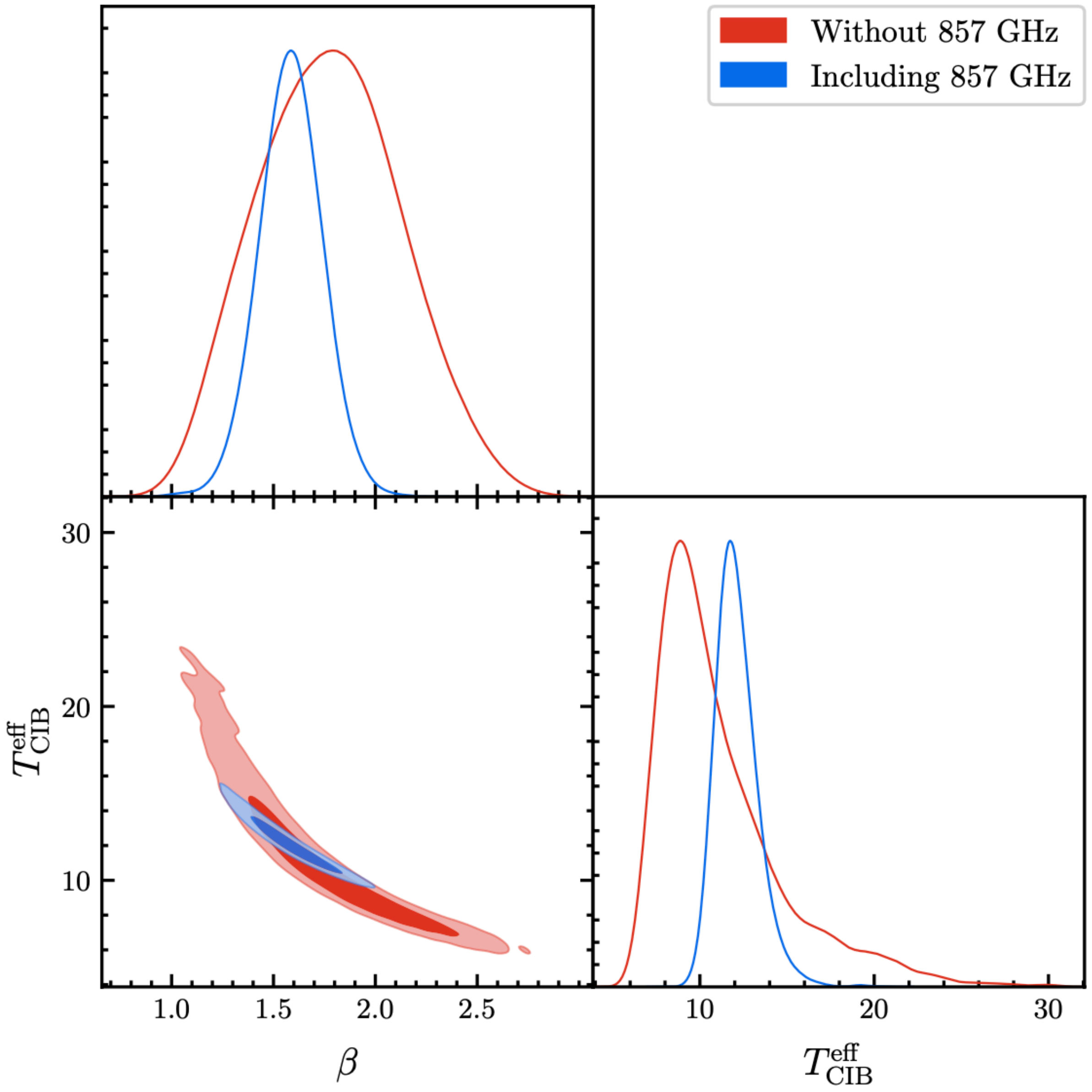
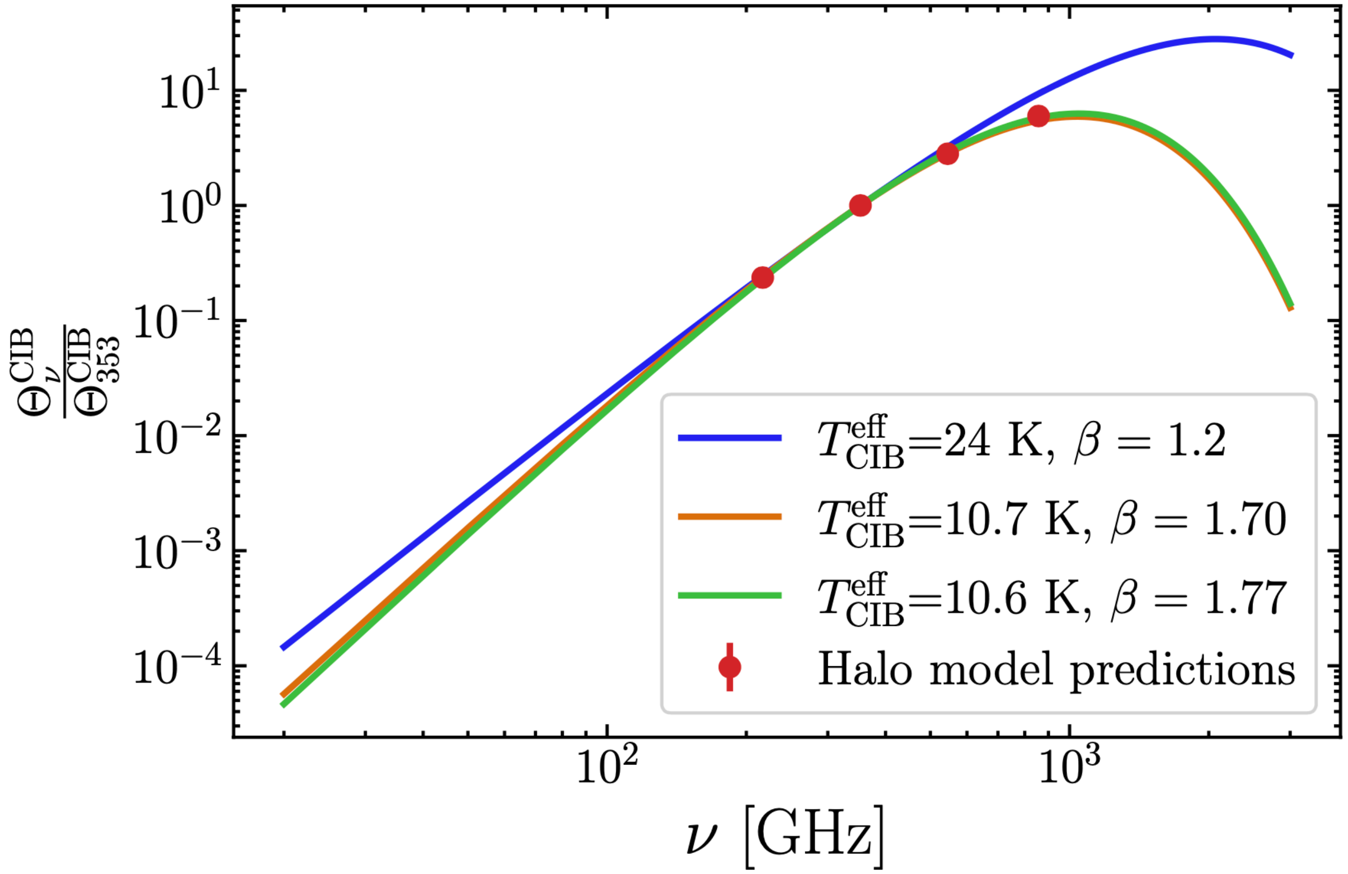
CIB cleaning: moment deprojection

MBB fit to CIB monopole SED predicted by best-fit halo model to CIB power spectra





Later in our analysis we will draw (β,$T^{\rm eff}$) samples from this posterior to test the sensitivity of our CIB deprojections to the assumed MBB SED

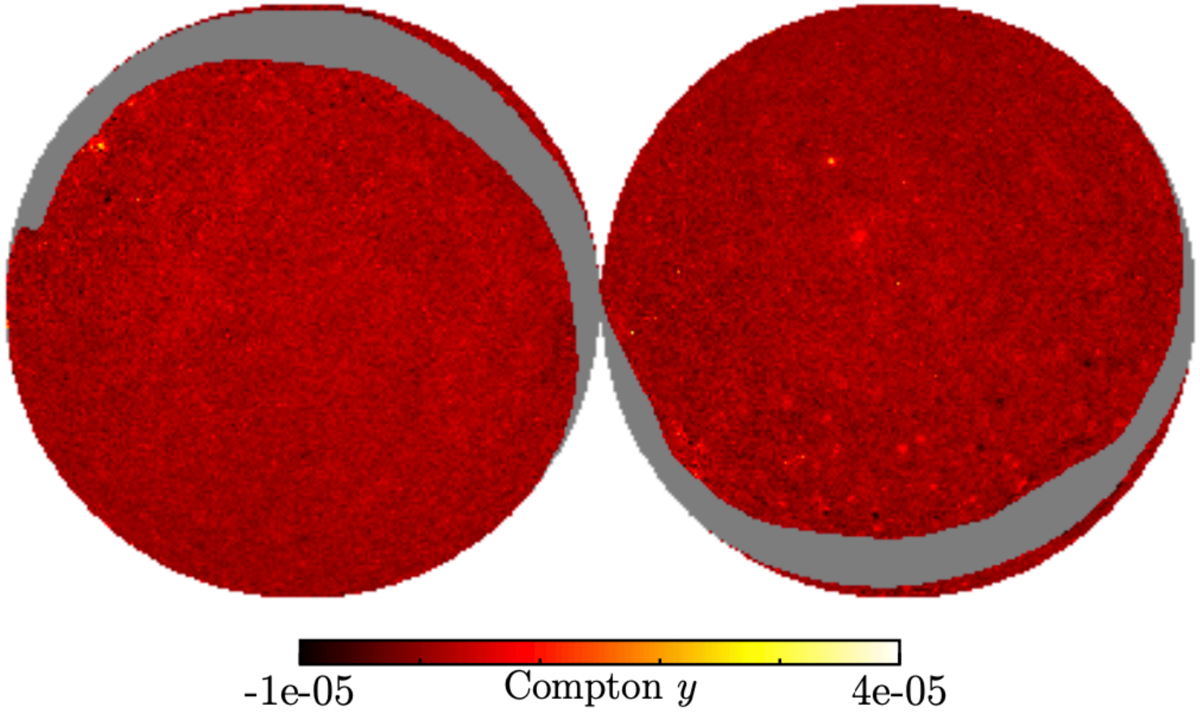
McCarthy & JCH (2023a)

Thermal SZ Extraction

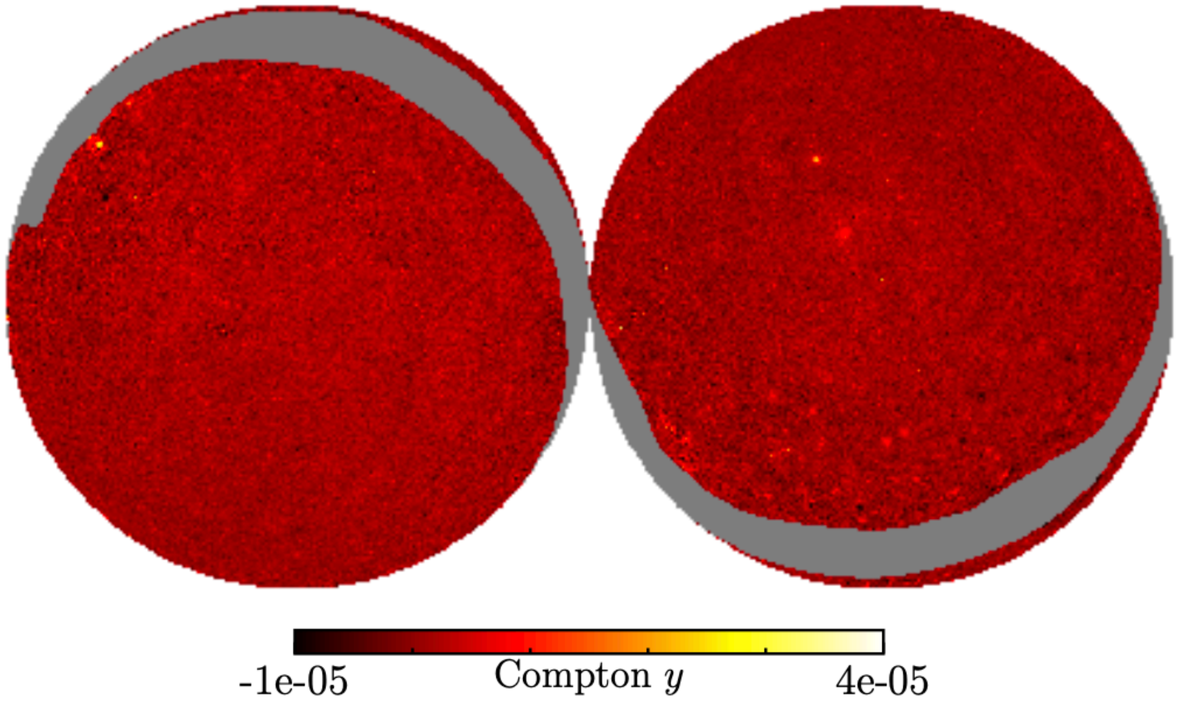
Colin Hill
Columbia

Application to Planck PR4 (NPIPE) maps

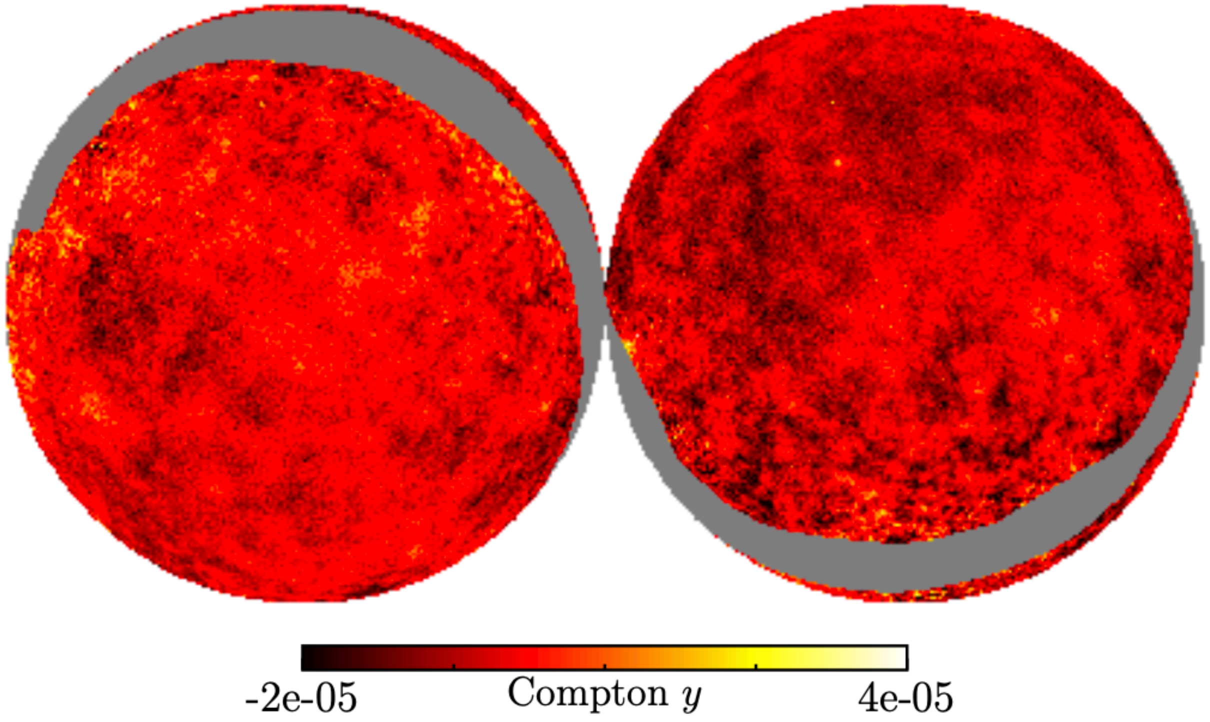
NILC tSZ; no deprojection



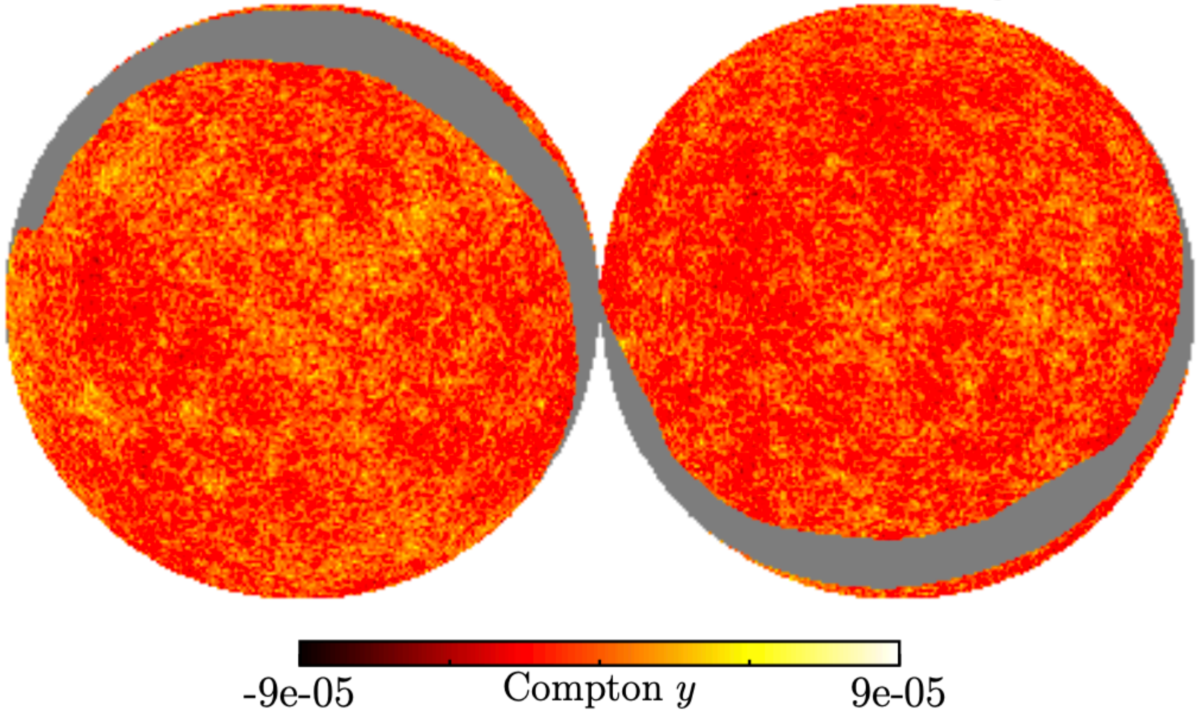
NILC tSZ; deprojection of CIB



NILC tSZ; deprojection of CIB+$\delta\beta$



NILC tSZ; deprojection of CIB+$\delta\beta$+$\delta T_{\mathrm{CIB}}^{\mathrm{eff}}$



McCarthy & JCH (2023a)

Thermal SZ Extraction

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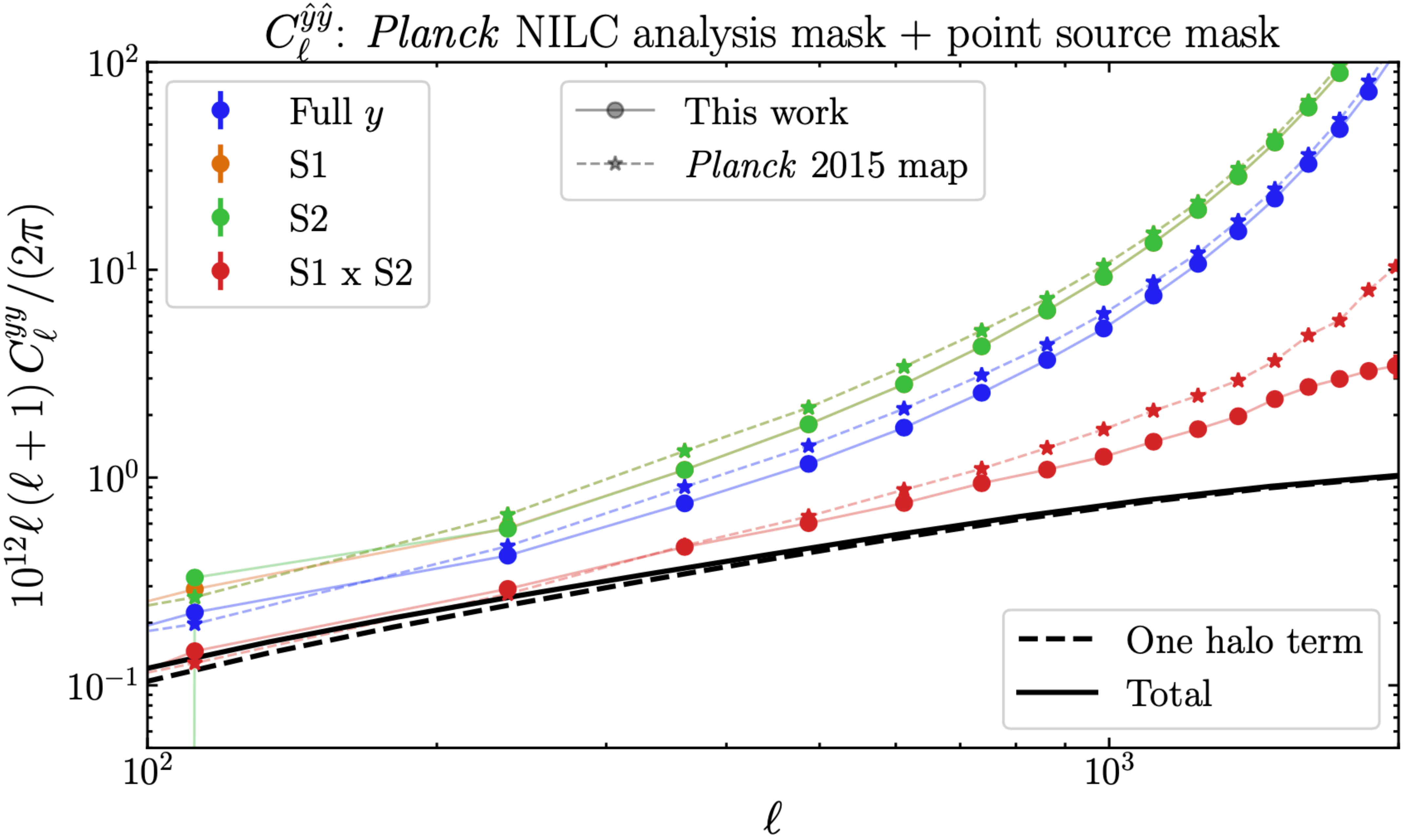
Application to Planck PR4 (NPIPE) maps

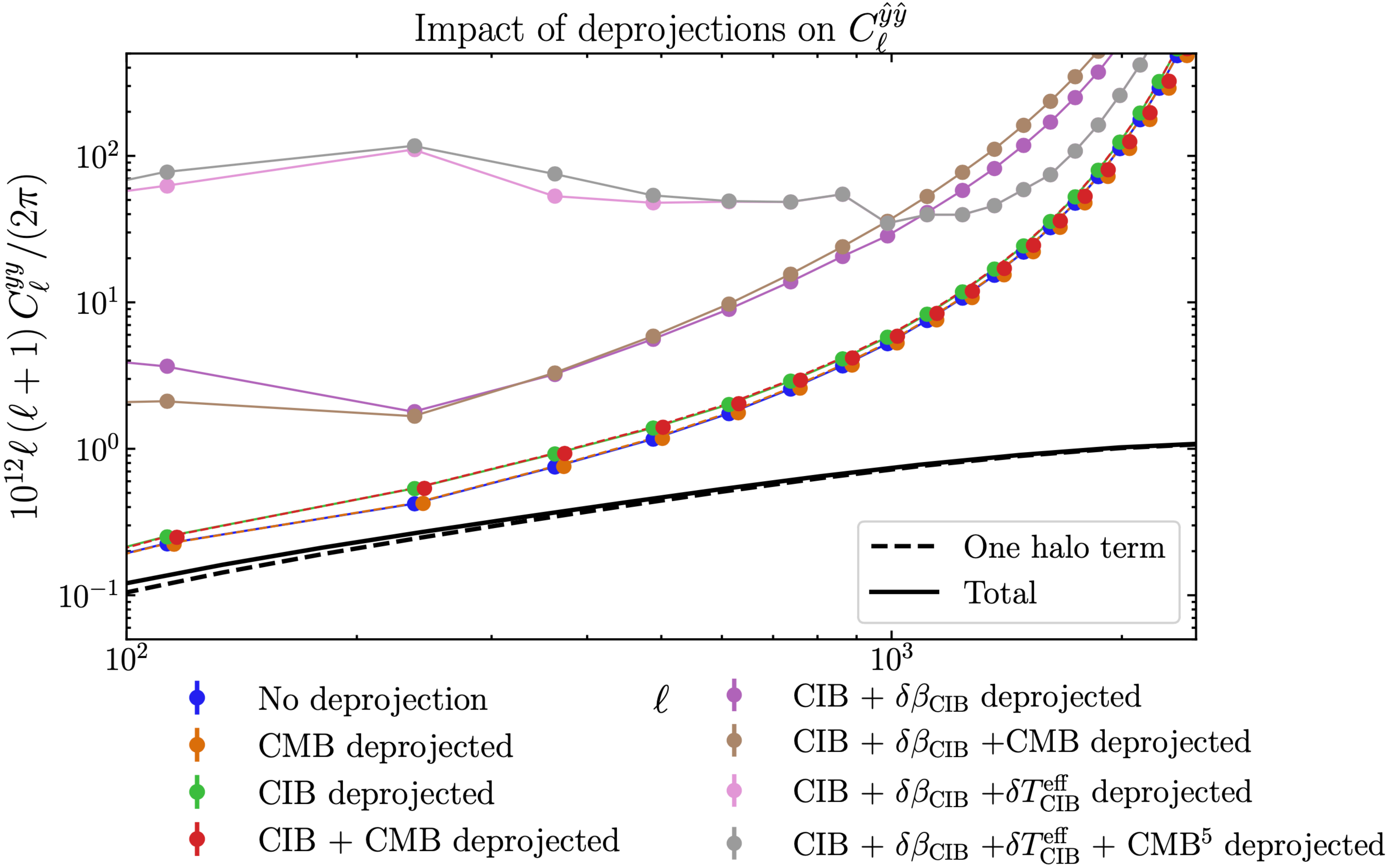


~10-20% lower noise visible on small scales in auto-spectrum, and improved foreground cleaning visible in S1xS2 cross-spectrum (free of noise bias)

McCarthy & JCH (2023a); see also Tanimura+(2022) and Chandran+(2023) [consistent results]

Thermal SZ Extraction

Application to Planck PR4 (NPIPE) maps



Impact of deprojections on $C_\ell^{\hat{y}\hat{y}}$

McCarthy & JCH (2023a)

unWISE Properties

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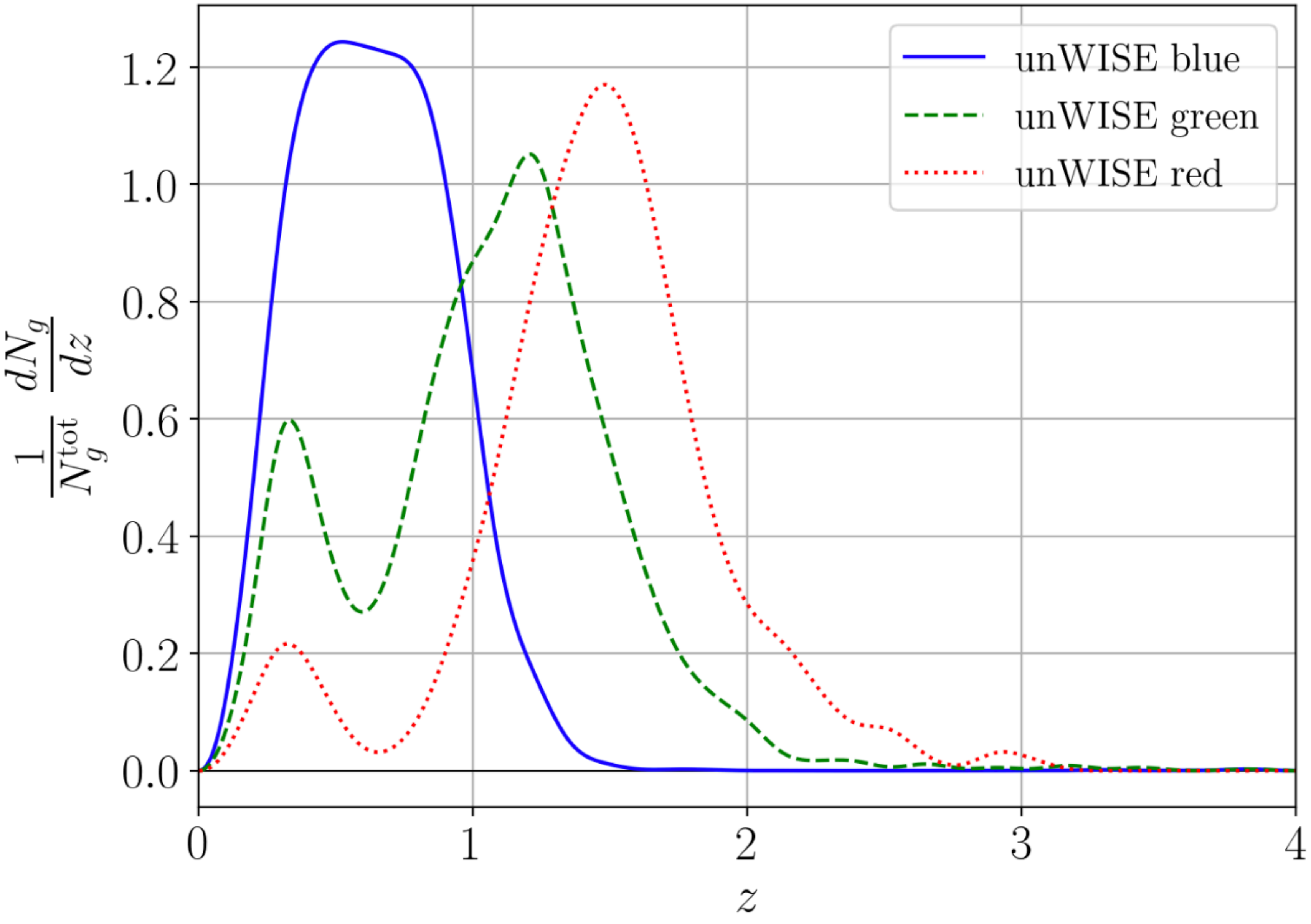
Columbia

Redshift distributions



Krolewski+ (2020); Krolewski+ (2021); Kusiak, Bolliet, Krolewski, **JCH** (2022)

unWISE Properties

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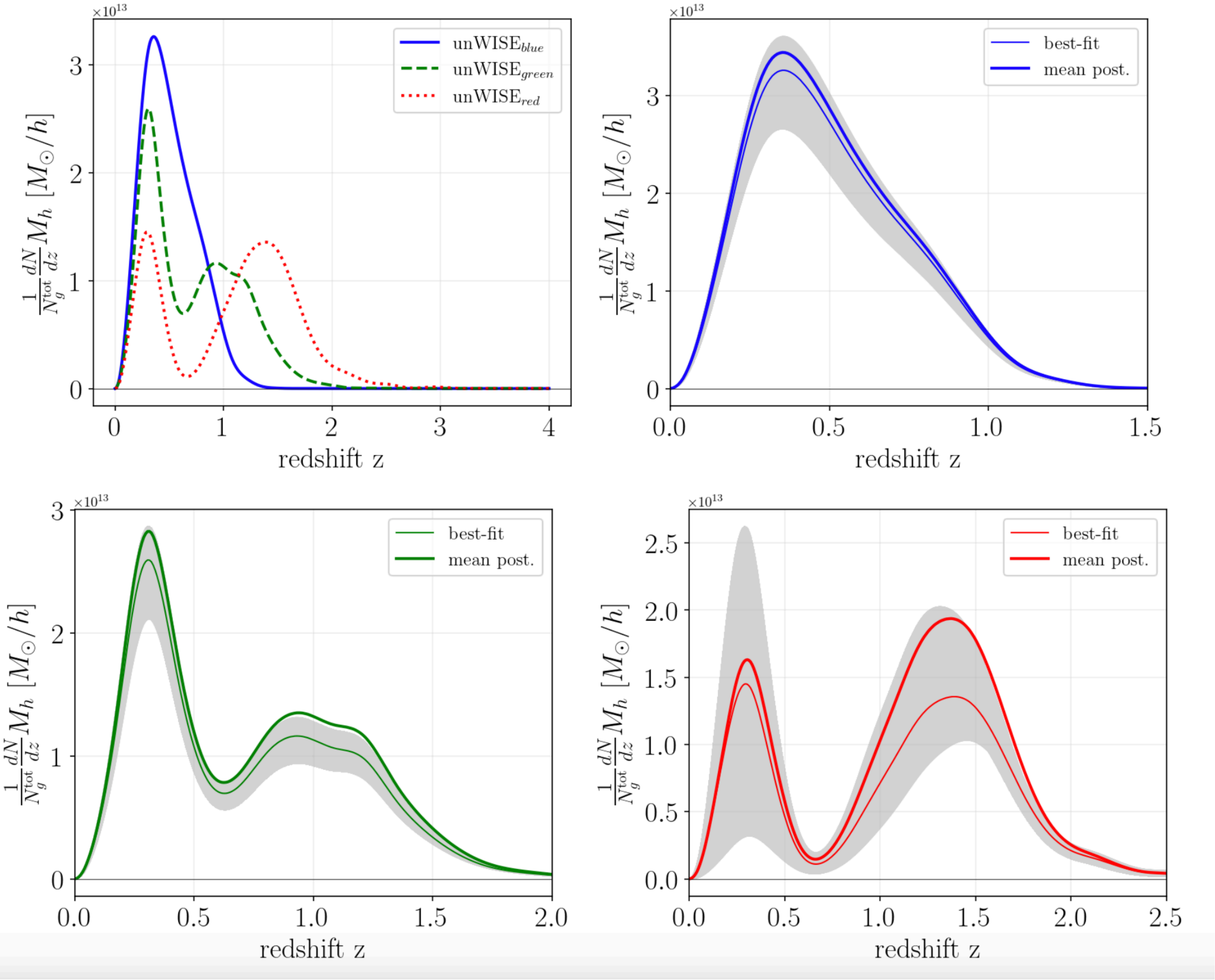
Mean halo mass

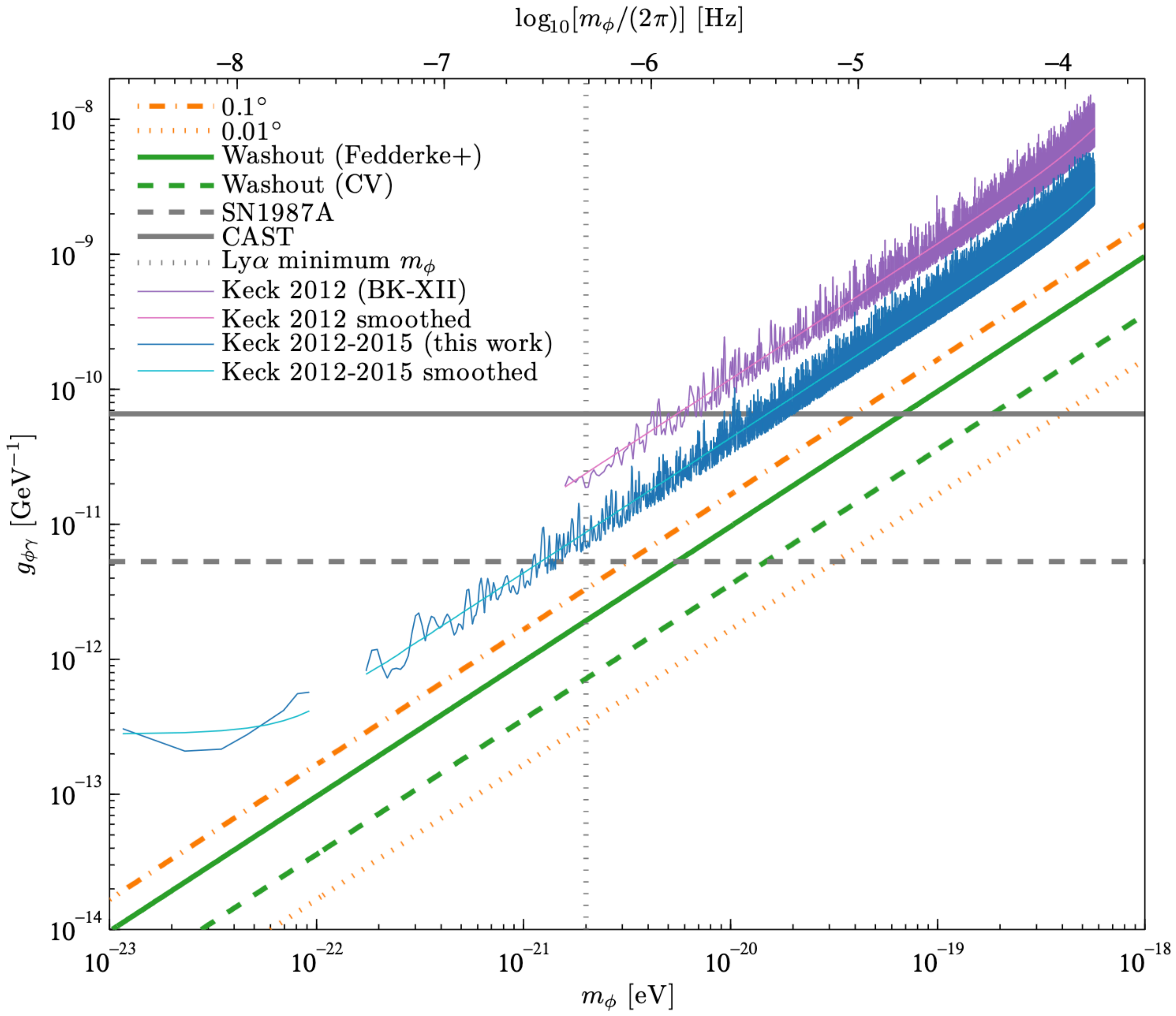


Kusiak, Bolliet, Krolewski, **JCH** (2022)

Other Axion CMB Limits

Other effects in CMB polarization due to axion-photon coupling:

- all-sky oscillation of CMB polarization (in real time)
- "washout" of polarization at last-scattering surface



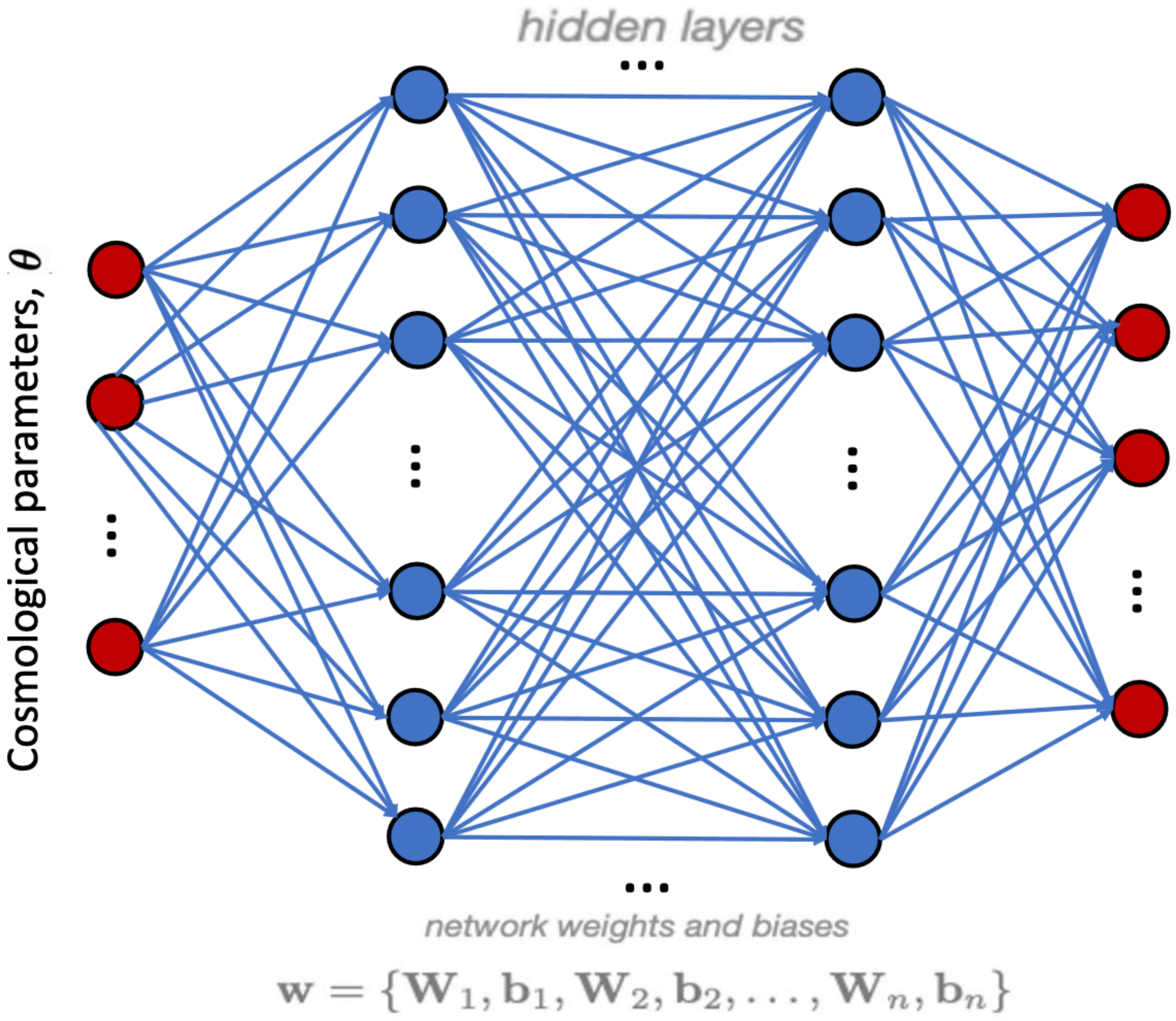
Fedderke+ (2019); BICEP/Keck XIV (2022); see also recent papers from POLARBEAR and SPT-3G

CosmoPower

Cosmological observables are smooth functions of the input parameters: easy to emulate at high accuracy with modern neural networks, thereby massively accelerating standard calculations

input

ω_b
ω_c
θ_s
A_s
n_s
τ



output

C_l^{TT}
C_l^{TE}
C_l^{EE}
$P(k)$
$H(z)$
…

Spurio Mancini et al. (2022)

Theoretical Accuracy

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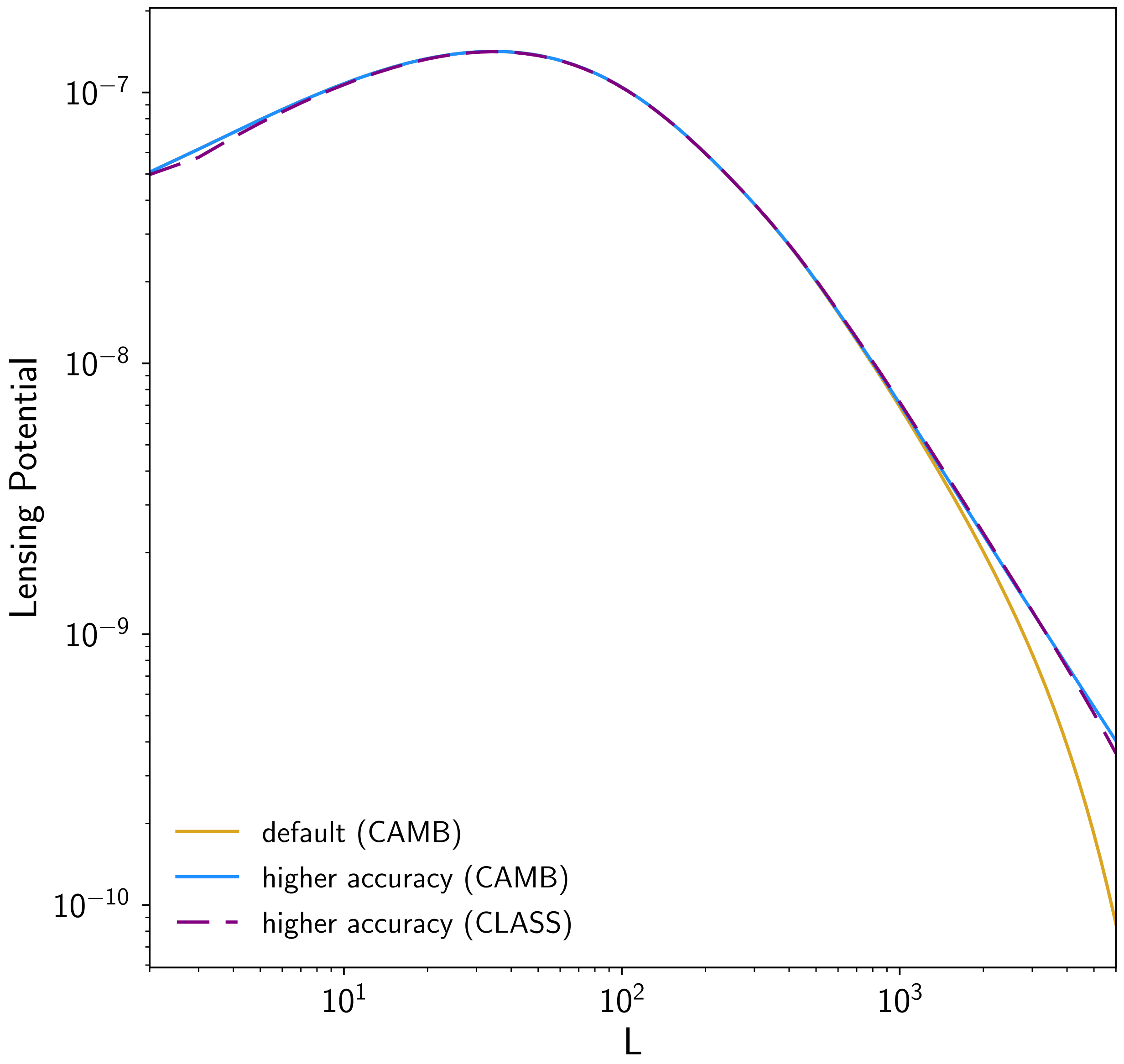
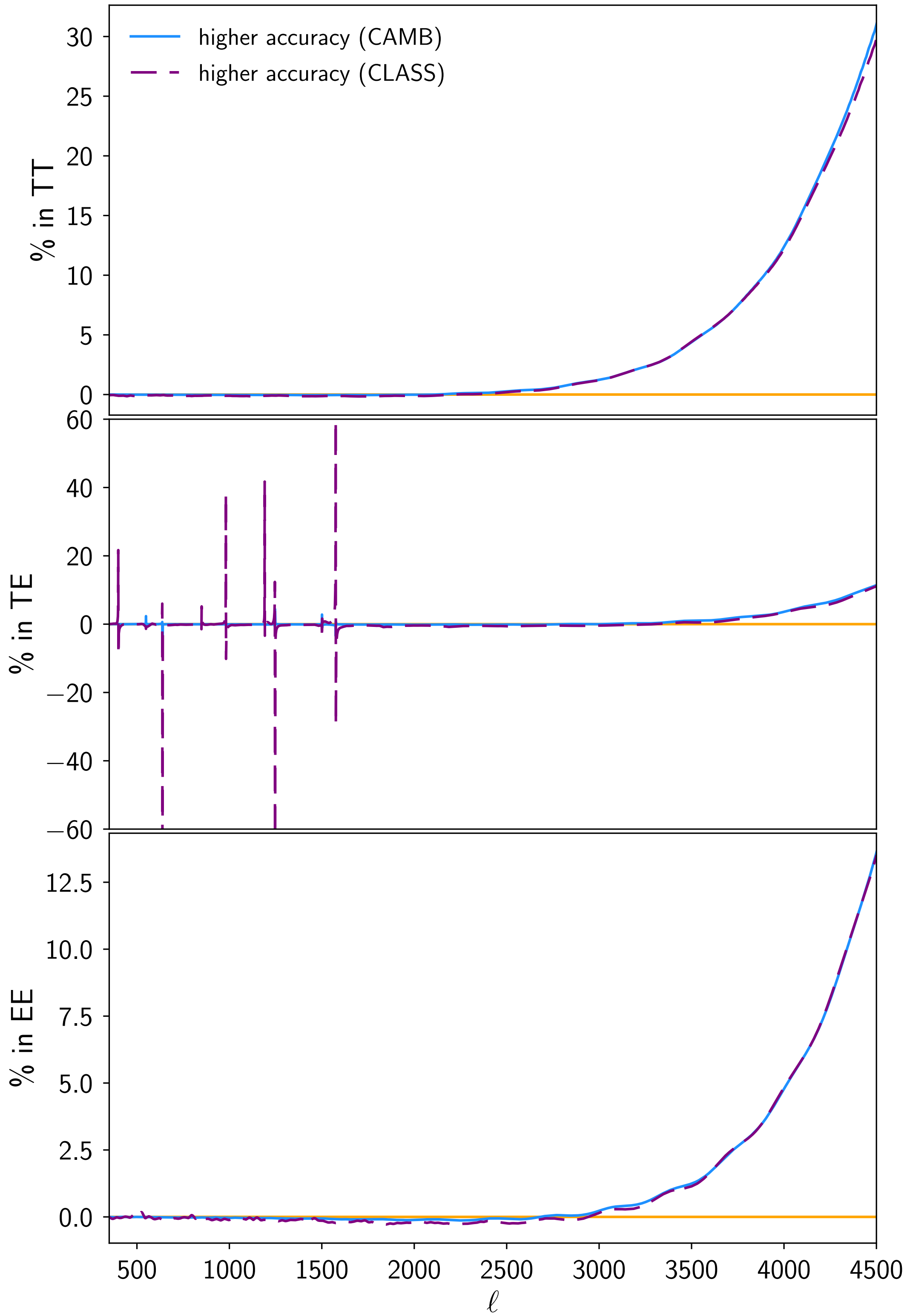
Are the default accuracy settings in CAMB/CLASS OK for ACT/SO?
Almost, but not quite — higher accuracy needed in lensing calc.





JCH et al. (2021); McCarthy, JCH, Madhavacheril (2021)

CosmoPower++

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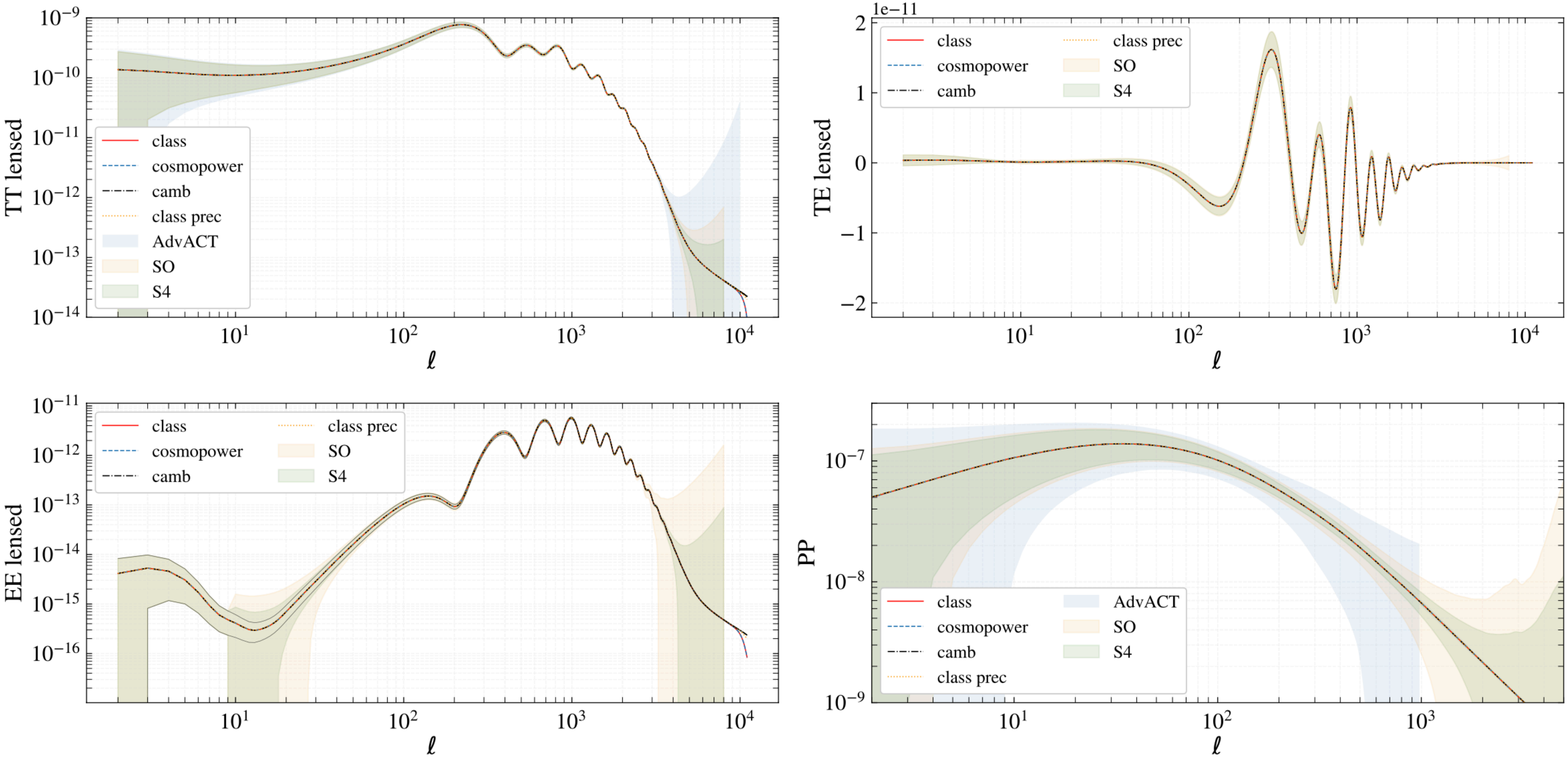
Columbia

Goal of new work: build emulators using very high-accuracy CLASS calculations — these require ~1 minute per evaluation (~10-20x slower than default settings)



It works: emulator reproduces correct results in < 10 ms per evaluation

Bolliet, Spurio Mancini, JCH, Madhavacheril, Jense, Calabrese, Dunkley (2023): 2303.01591

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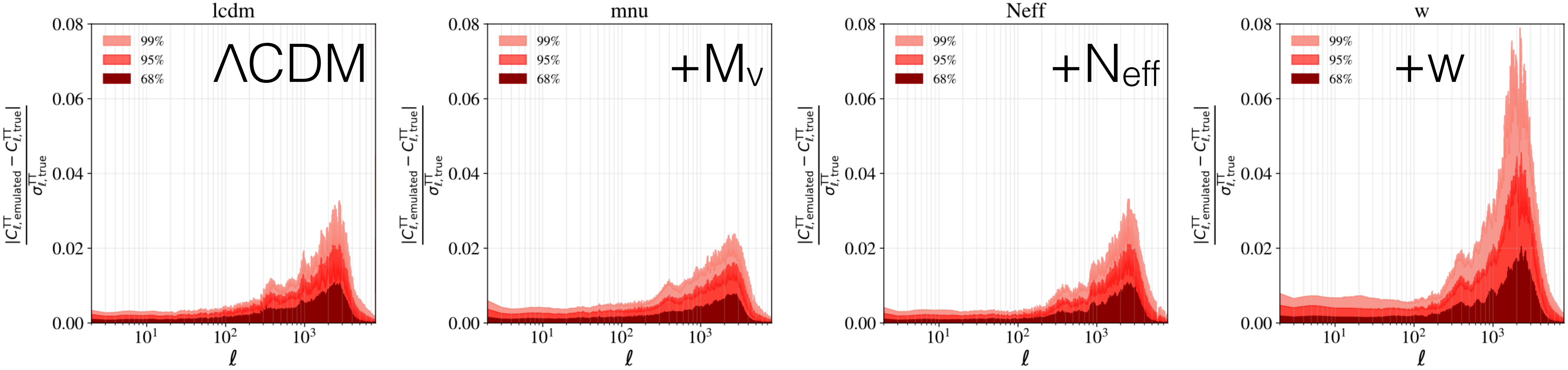
Emulator Validation on Test Set

Assess accuracy in terms of forecast CMB-S4 error bars: $< 0.07\sigma$ at all ell<10^4

CMB TT power spectrum



- Factor of 100-1000 speedup per Boltzmann call in MCMC runs
- NNs are fully differentiable: can be used in gradient-based inference
- Can be run on GPUs for further acceleration

Models run thus far (128,000 parameter sets each):
ΛCDM, $+N_{\rm eff}$, $+M_\nu$, +w

Bolliet, Spurio Mancini, JCH, Madhavacheril, Jense, Calabrese, Dunkley (2023): 2303.01591

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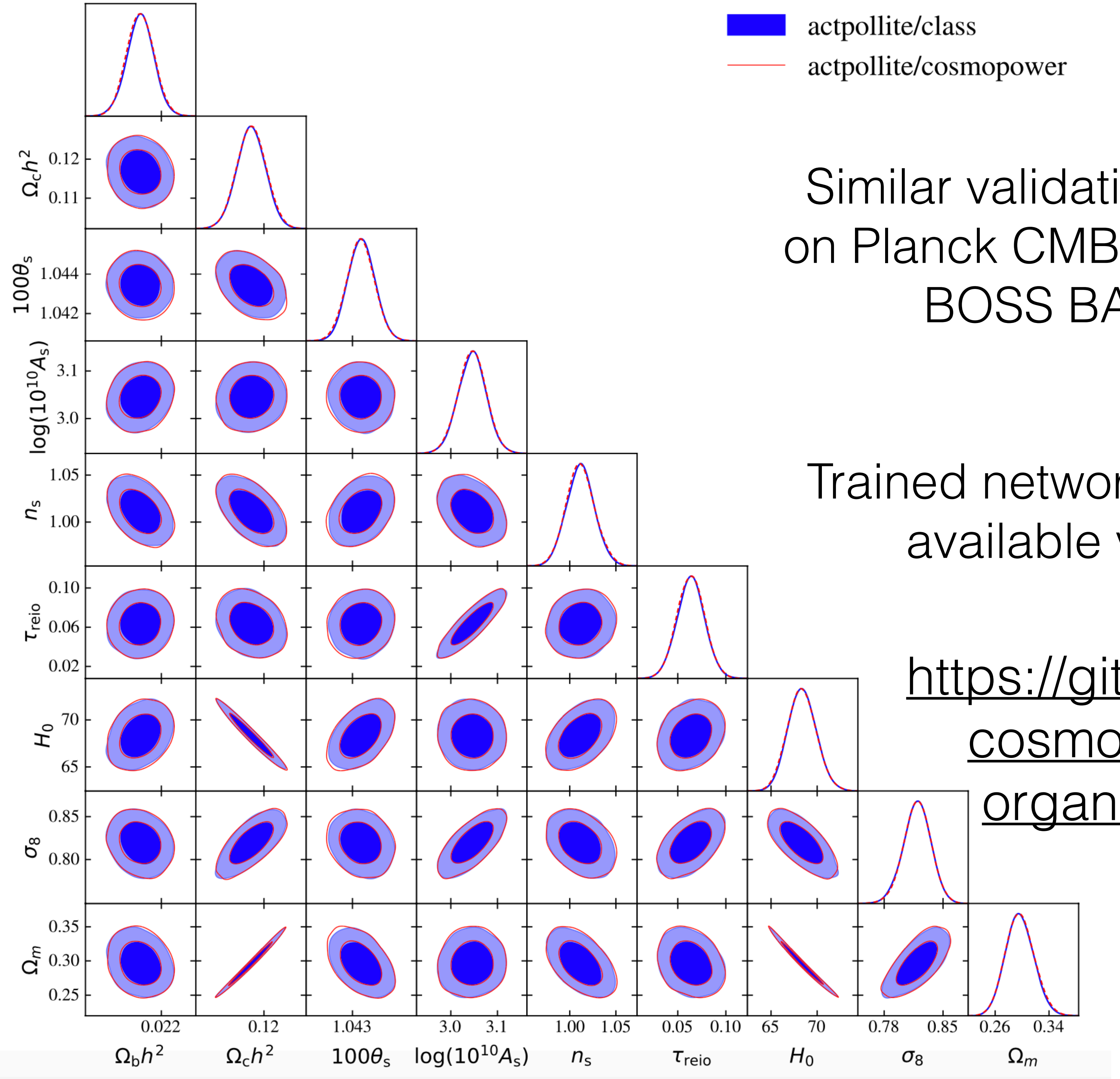
ACT DR4 ΛCDM Reproduction

~few minutes on laptop vs. ~few days on CCA cluster (!)



Similar validation performed on Planck CMB, CMB lensing, BOSS BAO+RSD

Trained networks are publicly available via GitHub

https://github.com/cosmopower-organization

Follow-up paper in prep: interface with Cobaya, Cosmosis, Monte Python, etc.