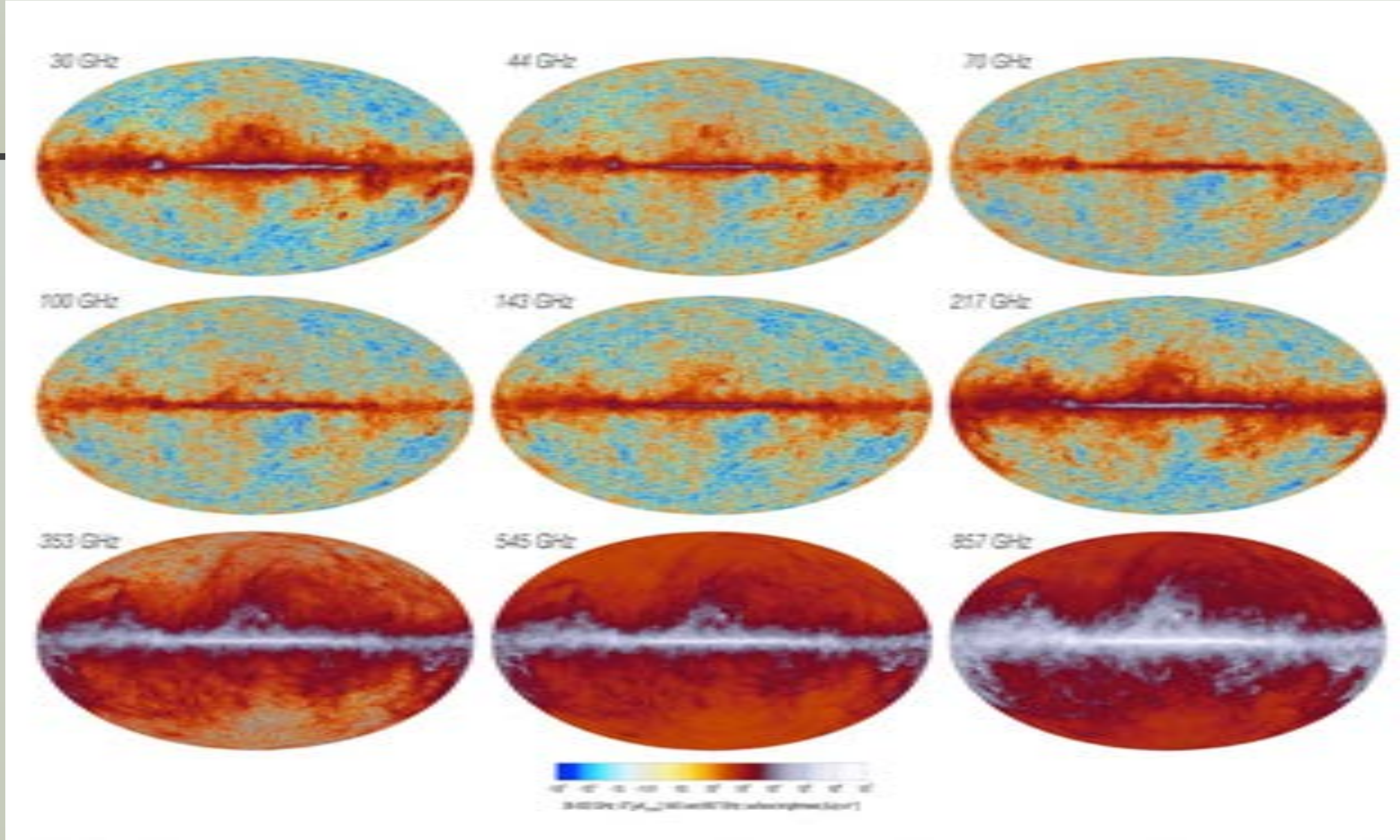
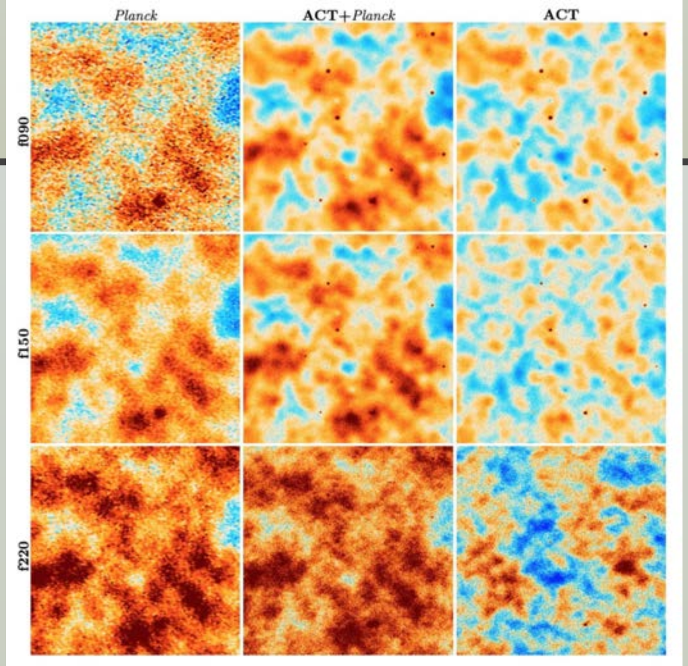
# WHAT DOES THE CMB STILL HAS TO SAY ON FUNDAMENTAL PHYSICS?




Planck frequency maps
(Credit: The Planck Collaboration)




CMB observations (ACT and Planck)
(Credit: Naess et al 2021)

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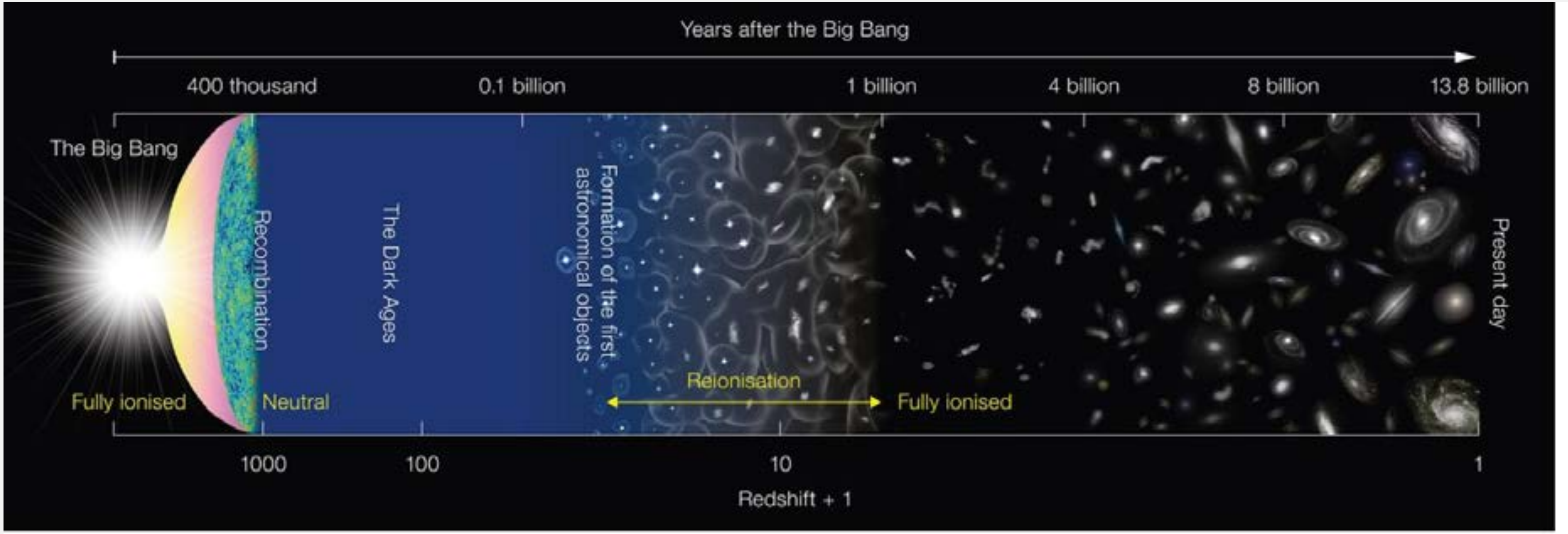
PACIFIC 2024 – Moorea 08/26/2024

# THERMAL HISTORY OF THE UNIVERSE

Image credit: NAOJ




Primordial Gravitational waves

CMB Primary anisotropies

CMB secondary anisotropies

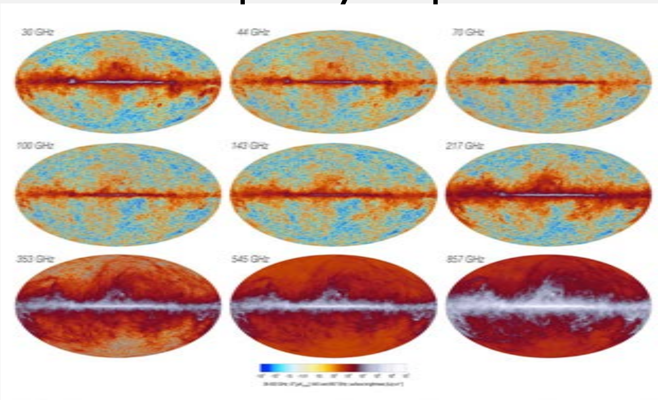
(Sunyaev Zeldovich, reionization, gravitational lensing, ISW)

Scattering processes

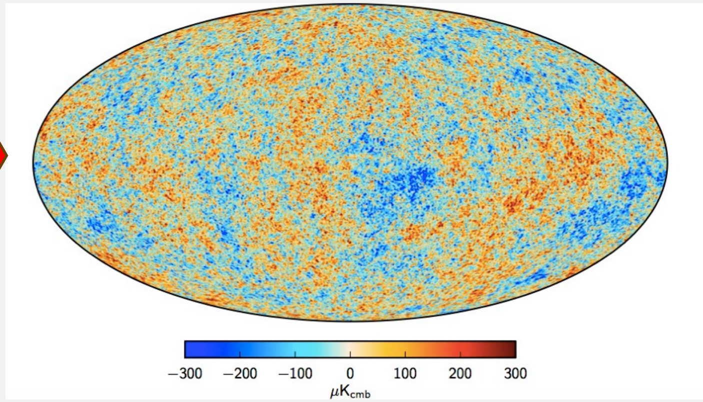
Gravitational processes

# FROM FREQUENCY MAPS TO PARAMETERS

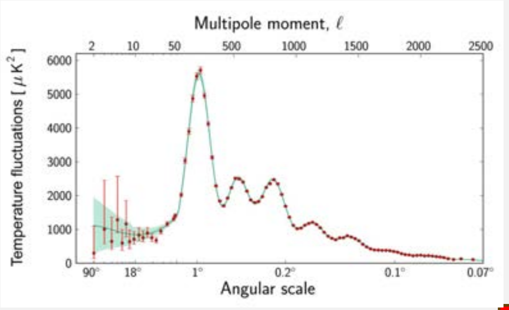
Frequency maps



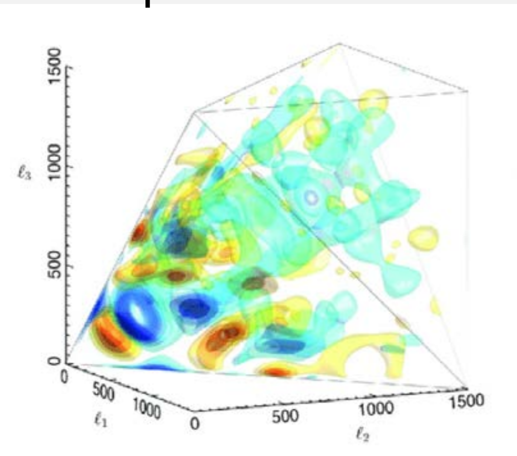

Black-body component  map(s)



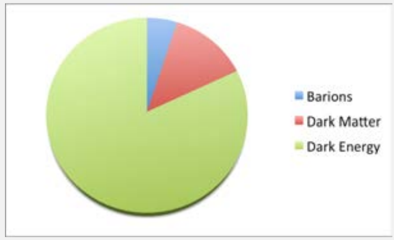

Powe spectrum




bispectrum

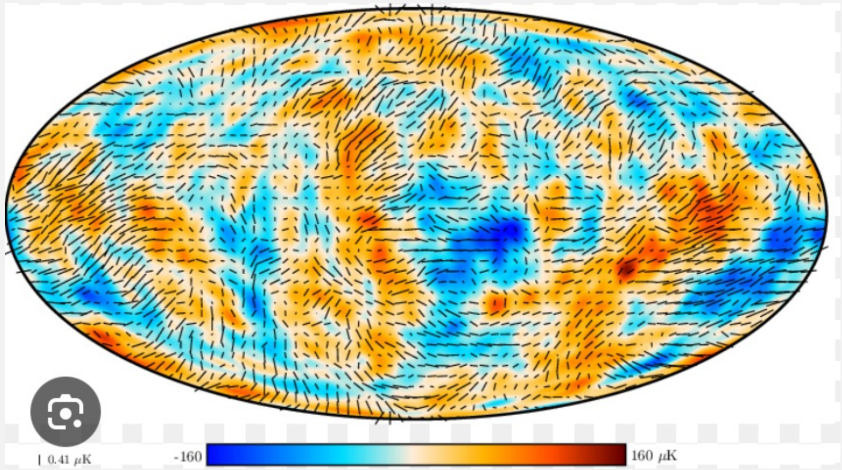



parameters



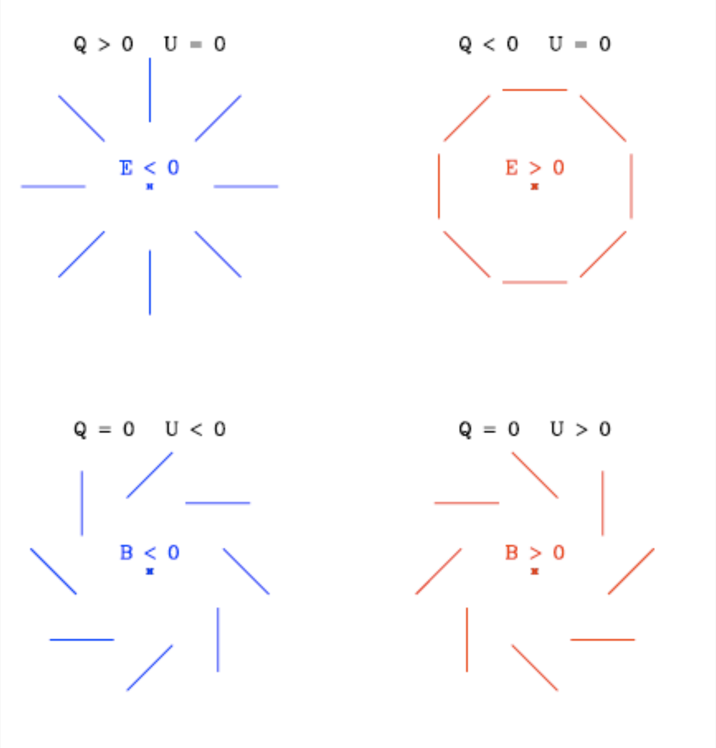

- There is more than  one statistical tool to derive parameters – power spectrum and bispectrum already used, but trispectrum will gain importance.

- Derived parameters depend on our ability to reconstruct the black-body component.  Component separation strategies are essential in your life, even if you are an early-universe scientist.



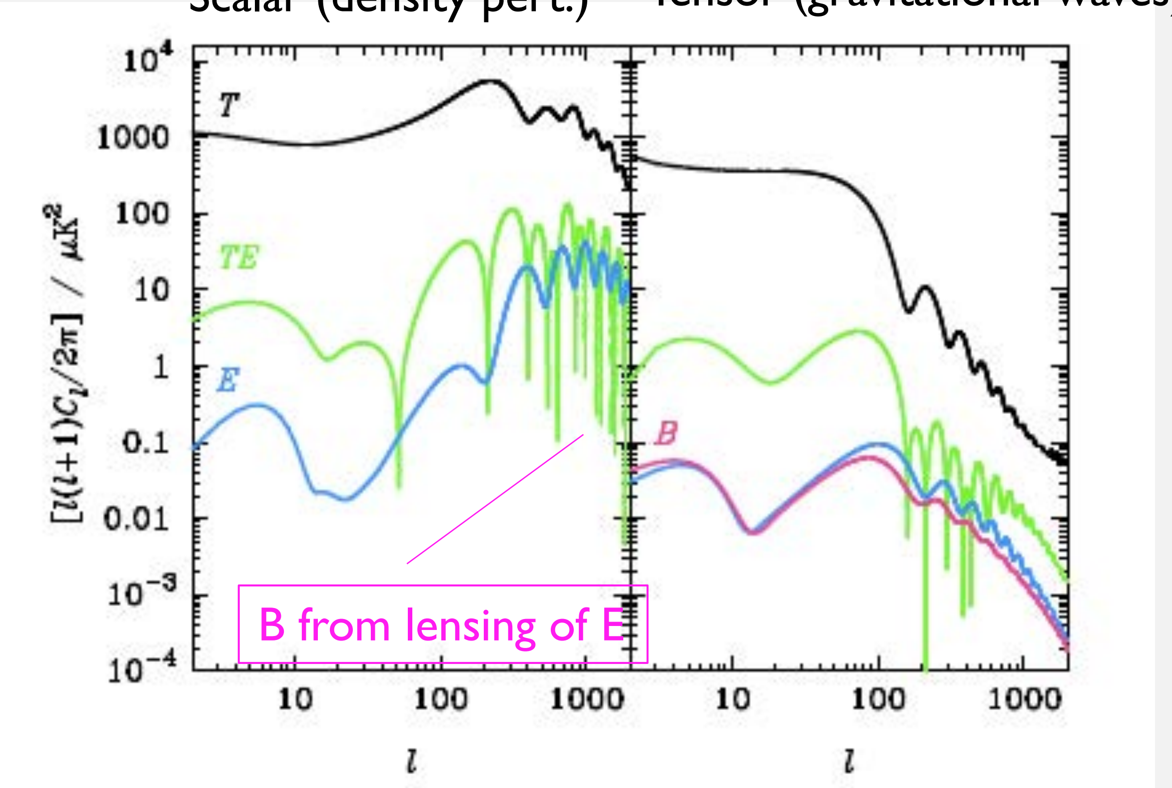

# POLARIZATION

Polarization is decomposed as below




Scalar (density pert.)

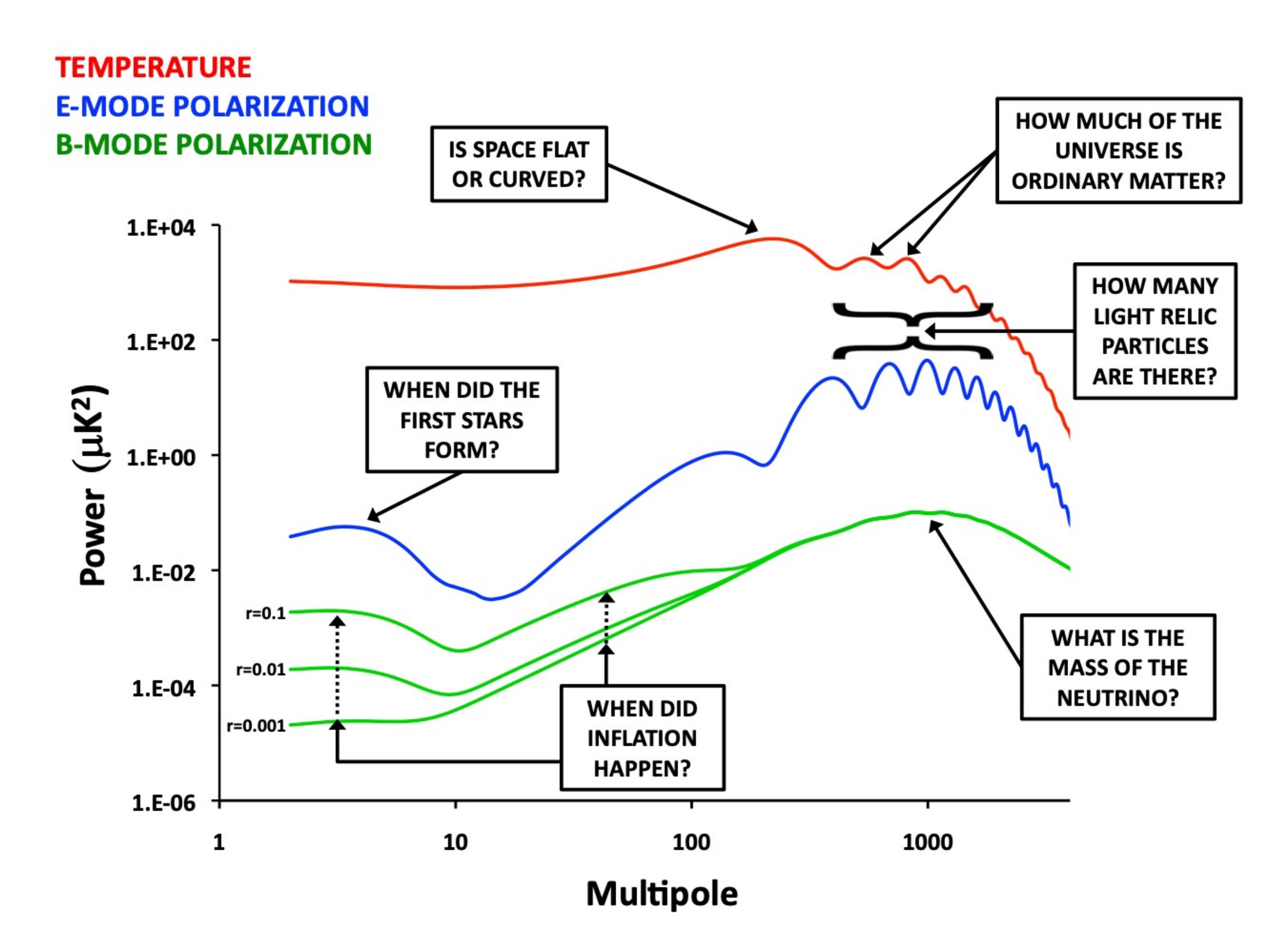
Tensor (gravitational waves)




Here also B is produced!

Tensor to scalar ratio r=1

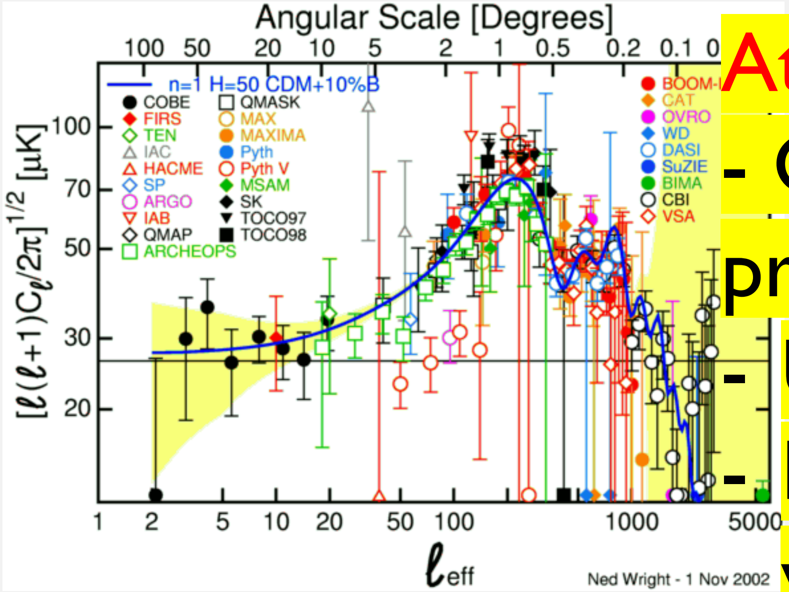
# WHERE TO LOOK FOR A GIVEN SCIENCE GOAL




Snowmass Cosmic Frontier: CMB experiments white paper

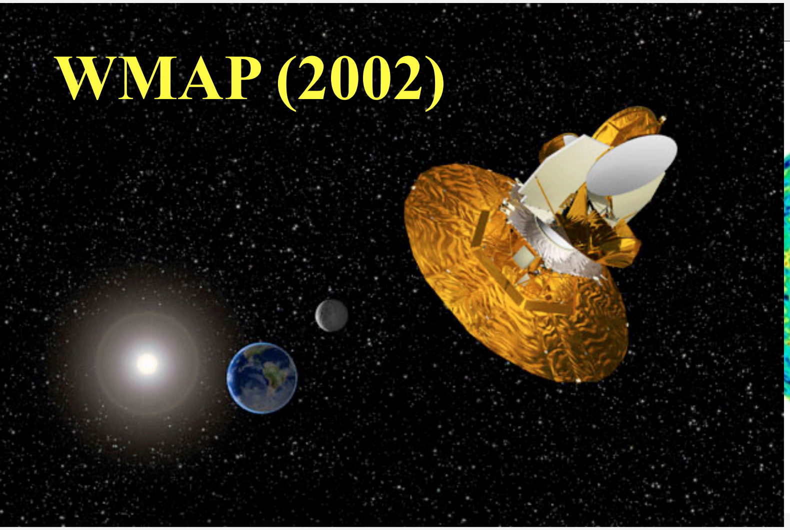
# HISTOTY: MEASURING THE POWER SPECTRUM

Pierpaoli, Scott, White (2000)

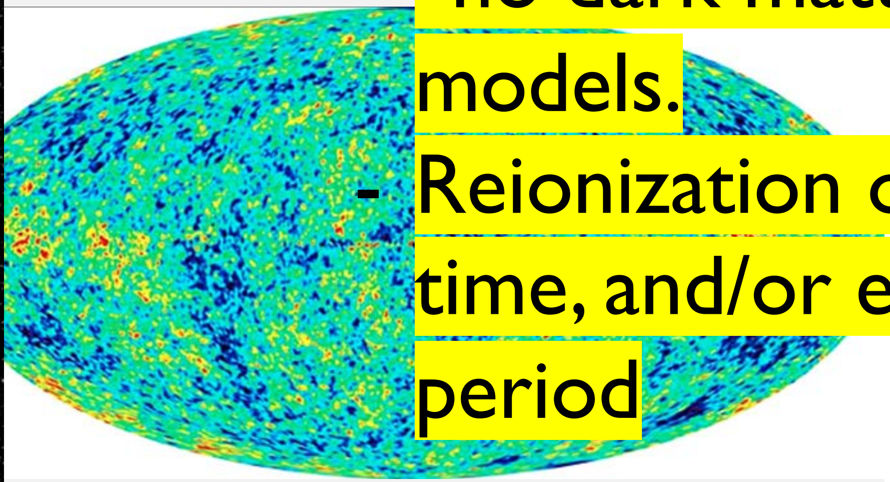



At this stage, we could exclude:

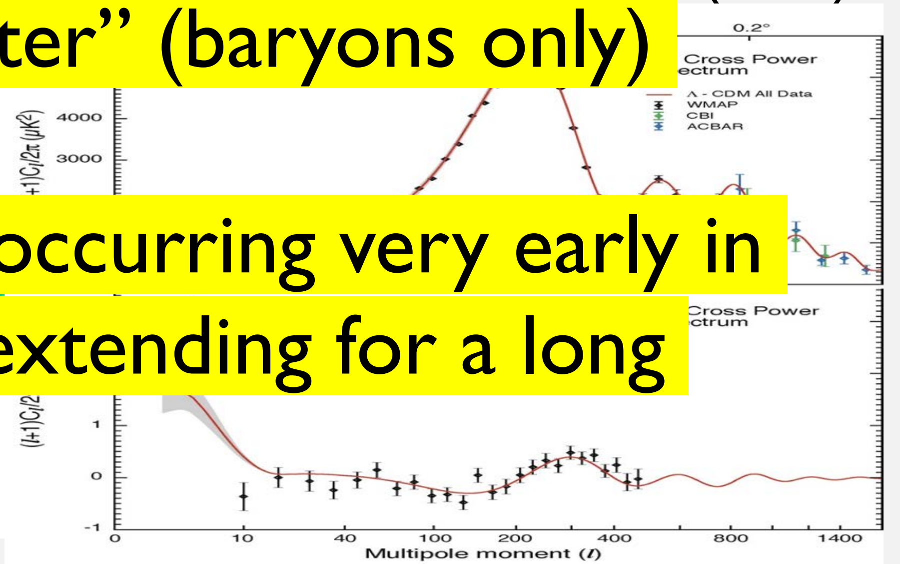
- Cosmic strings/topological defects as process to generate perturbations
- Universes with large curvatures
- Big amplitudes of primordial gravity waves, and related models
- “no dark matter” (baryons only) models.
- Reionization occurring very early in time, and/or extending for a long period



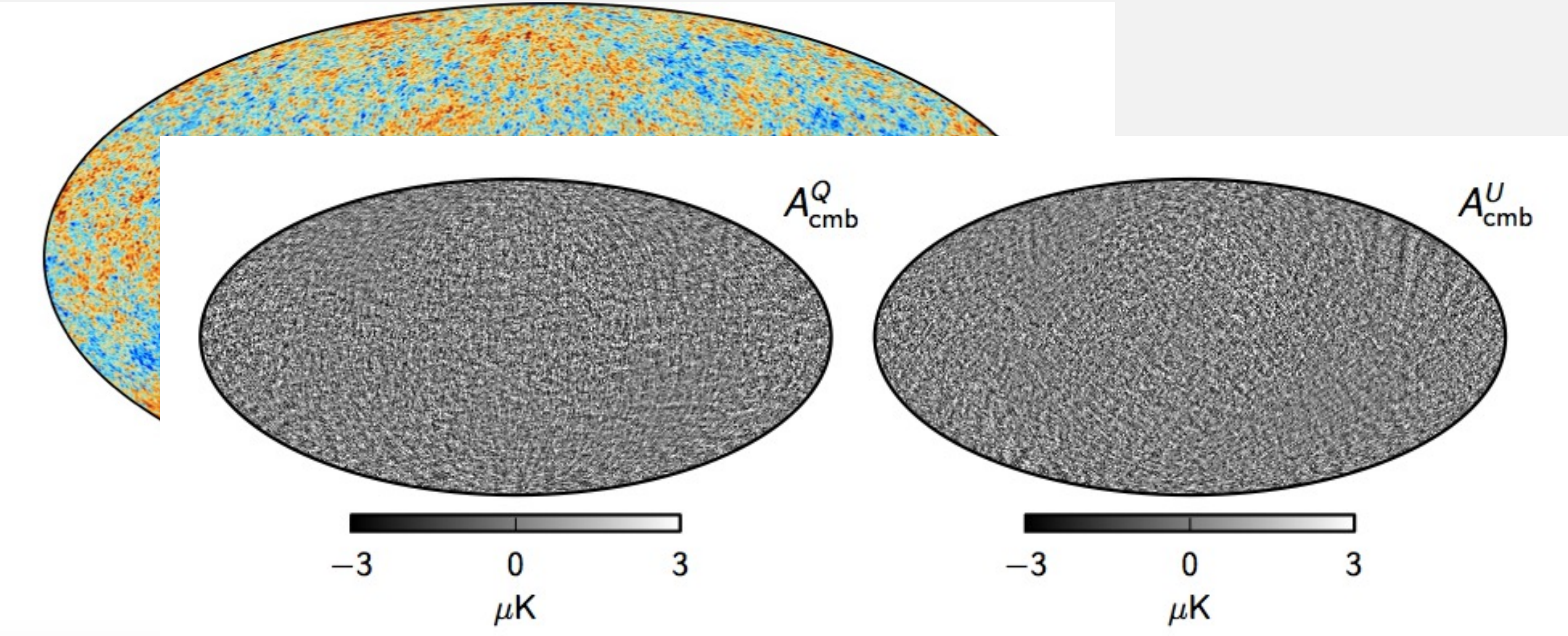

Temperature



...er spectrum (2003)



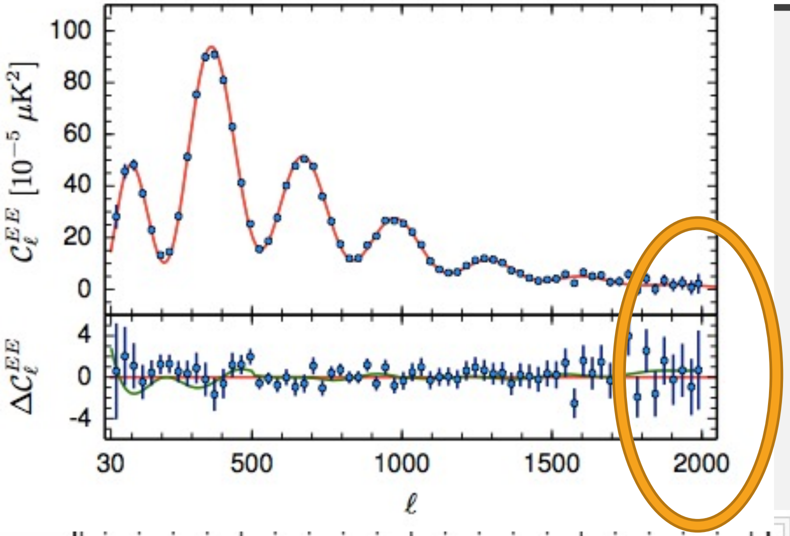
# THEN CAME PLANCK….. (2009)



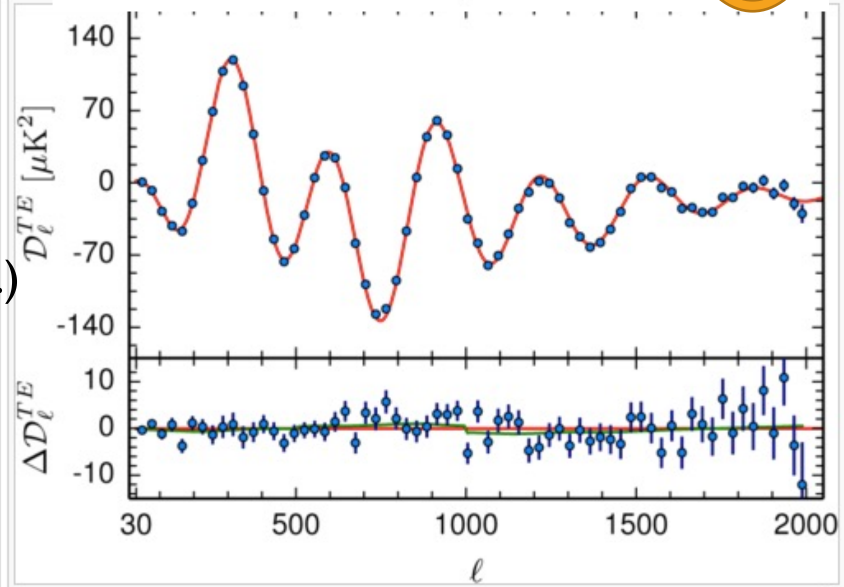

anisotropy intensity map ((5' resolution)

# TT AND TE SPECTRA FORM WMAP AND PLANCK

Planck 2015
(intensity: TT)

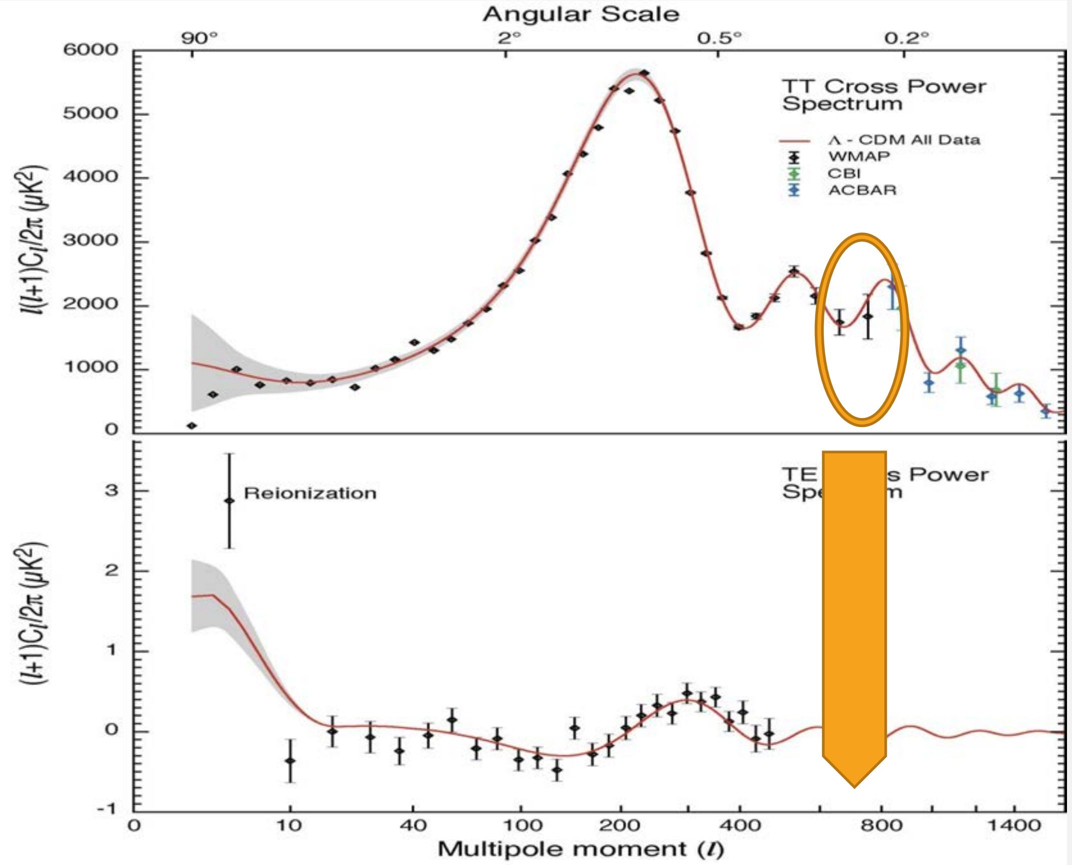



Planck 2015
(TE cross correlat.)




Planck 2015 *TE* power spectrum. The red line is the Planck best-fit primordial power spectrum (cf. Planck TT+lowP in table 3 of Planck-2015-A15[3]). Residuals with respect to this model are shown in the lower panel. The error bars show ±1σ uncertainties.

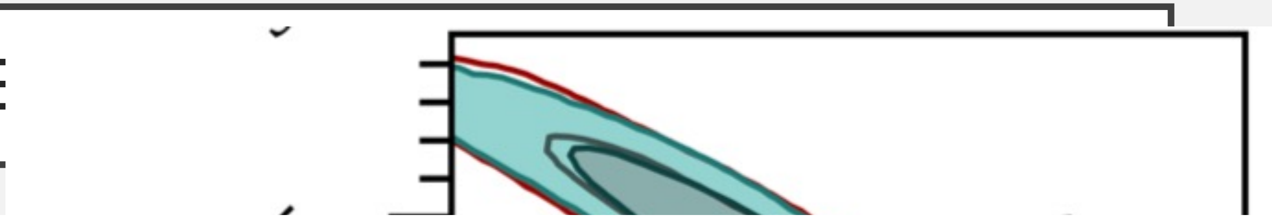
The WMAP power spectrum (2003)



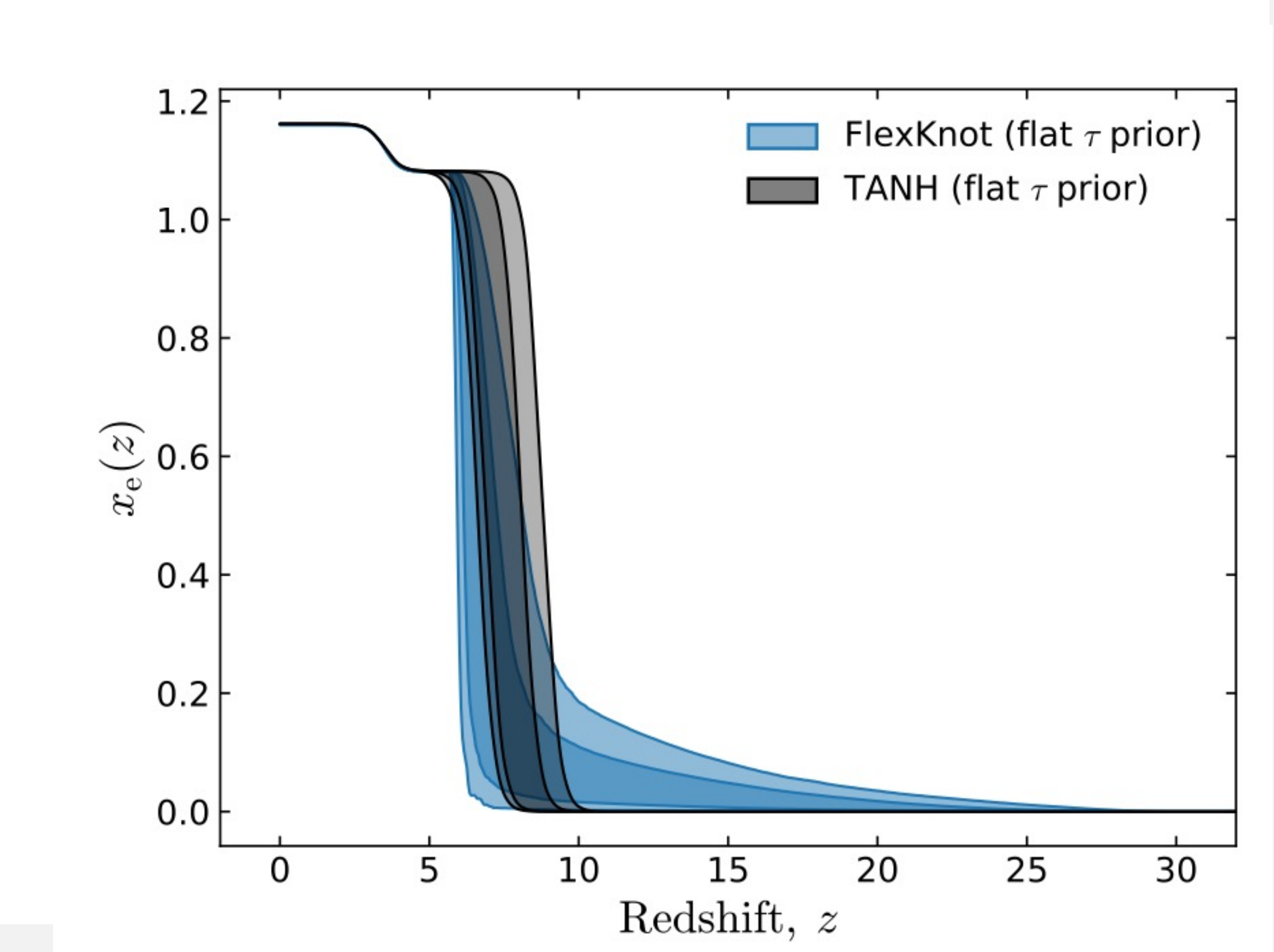

WMAP
TT

WMAP
TE

# COSMOLOGICAL PARAME



- 1) Geometry: the Universe is close to flat
  - $\Omega_K = 0.001 \pm 0.002$, Planck+BAO (Alam et al 2021)
- 2) Composition: $\Lambda$CDM is (still) the best fitting model
- Dark energy is consistent with cosmological constant ($w = -0.978 \pm 0.03$, Brout et al 2022, Planck+SN)
- Limits on neutrino masses: $\Sigma m\nu < 0.12$ eV (95%) Planck+BAO
- Relativistic species: $N_{eff} = 3.0 \pm 0.2$, Planck
- 3) Reionization constraints ($\tau = 0.058 \pm 0.012$, Planck), reionization occurs at $z \sim 8$
- 4) Inflation is the favorite mechanism for producing perturbations (see next slide)



# INITIAL CONDITIONS AND LIMITS ON INFLATION

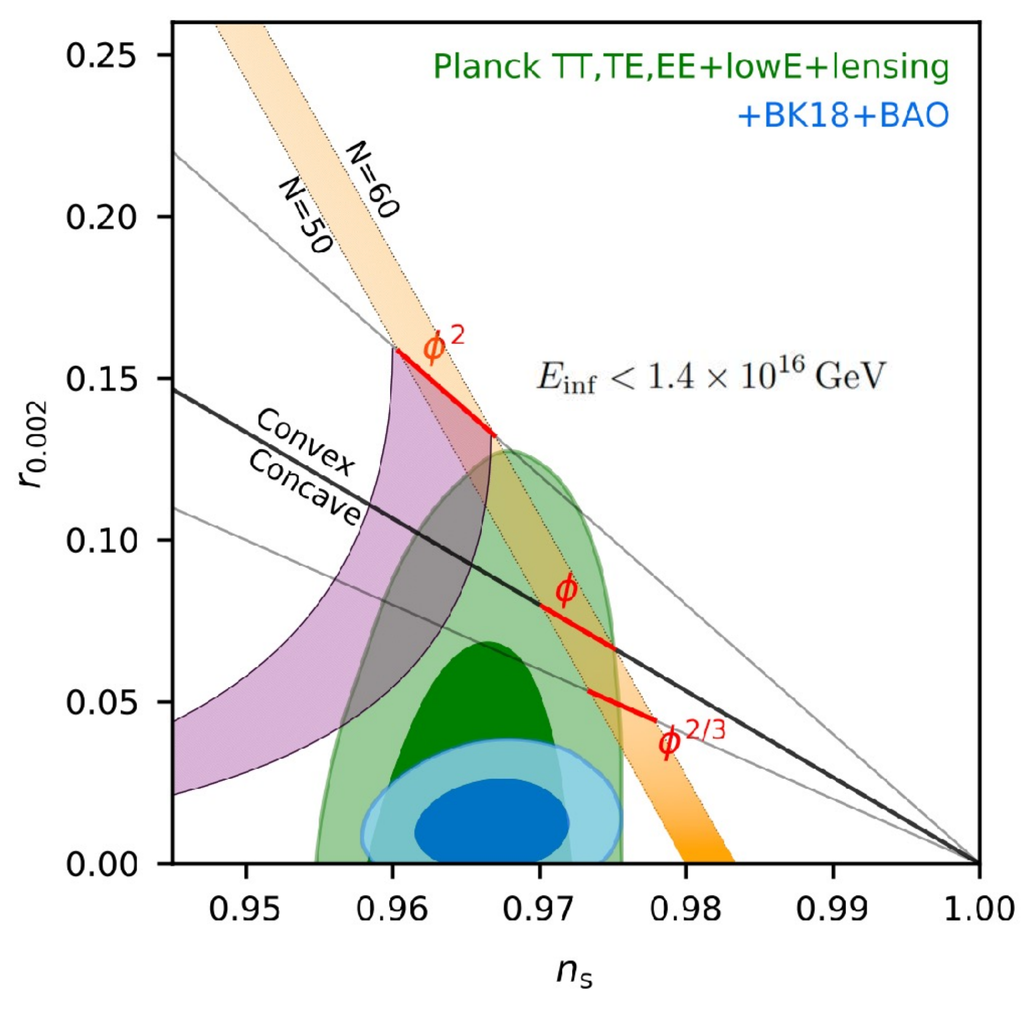
- Perturbations are largely Gaussian: $f_{NL\text{-}Local}$= -1 ± 5 (Planck)
- Perturbations are largely adiabatic (within a few percent, Planck)
- The initial power spectrum slope does not show departure from a power law dn/dlnk = −0.005 ± 0.007 (Planck)
- The slope of density perturbations $n_s$ is close to one: $n_s$ = 0.9665 ± 0.0038
- There is no detection of gravitational waves (tensor perturbations): r= $P_T/P_S$ < 0.056 (Planck) and r< 0.036 (Planck+BICEP/Keck 2021, 95% CL)

ALL OF THE ABOVE IS COMPATIBLE WITH SINGLE FIELD INFLATION

$$\mathcal{P}_\zeta(k) = \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot\phi}\right)^2\Bigg|_{k=aH} = \frac{1}{8\pi^2}\frac{H^4}{M_{\rm Pl}^2|\dot H|}\Bigg|_{k=aH} \approx A_s\left(\frac{k}{k_*}\right)^{n_s-1}$$

And some constraints on the shape of the potential can already been determined.

Elena Pierpaoli (USC)



# SMALL-SCALE EXPERIMENTS

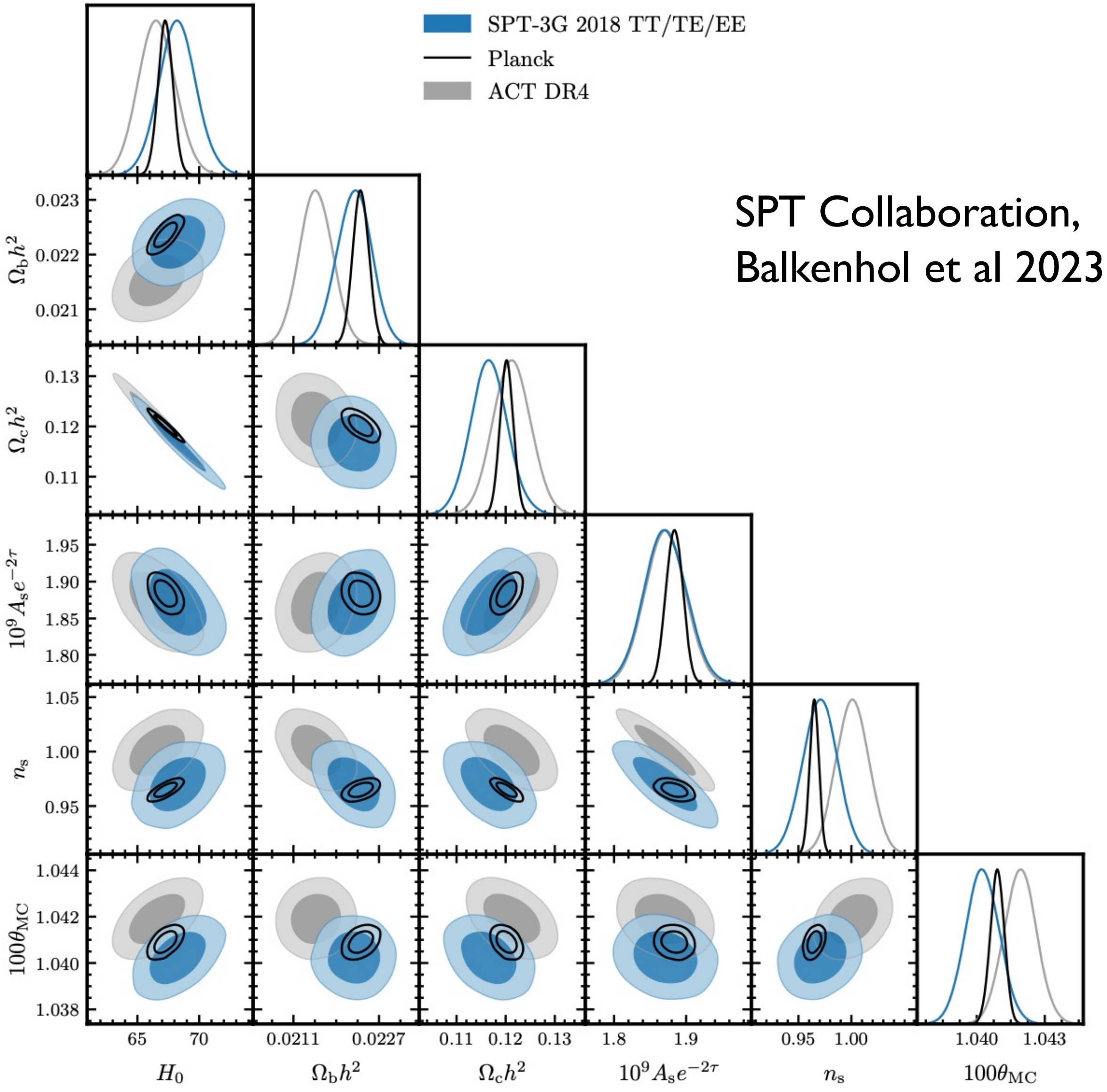
-- Added information on small scale
 (currently l~4000 in TT and TE)

--Added information on the BB power spectrum
 (gravitational lensing measurement, and Gravitational waves upper limits)

-- In addition: a lot of secondary anisotropies science (Sunyaev Zeldovich, lensing)

- Cosmological results on mail cosmological parameters from Planck and small scale experiments are largely consistent.






SPT Collaboration, Balkenhol et al 2023

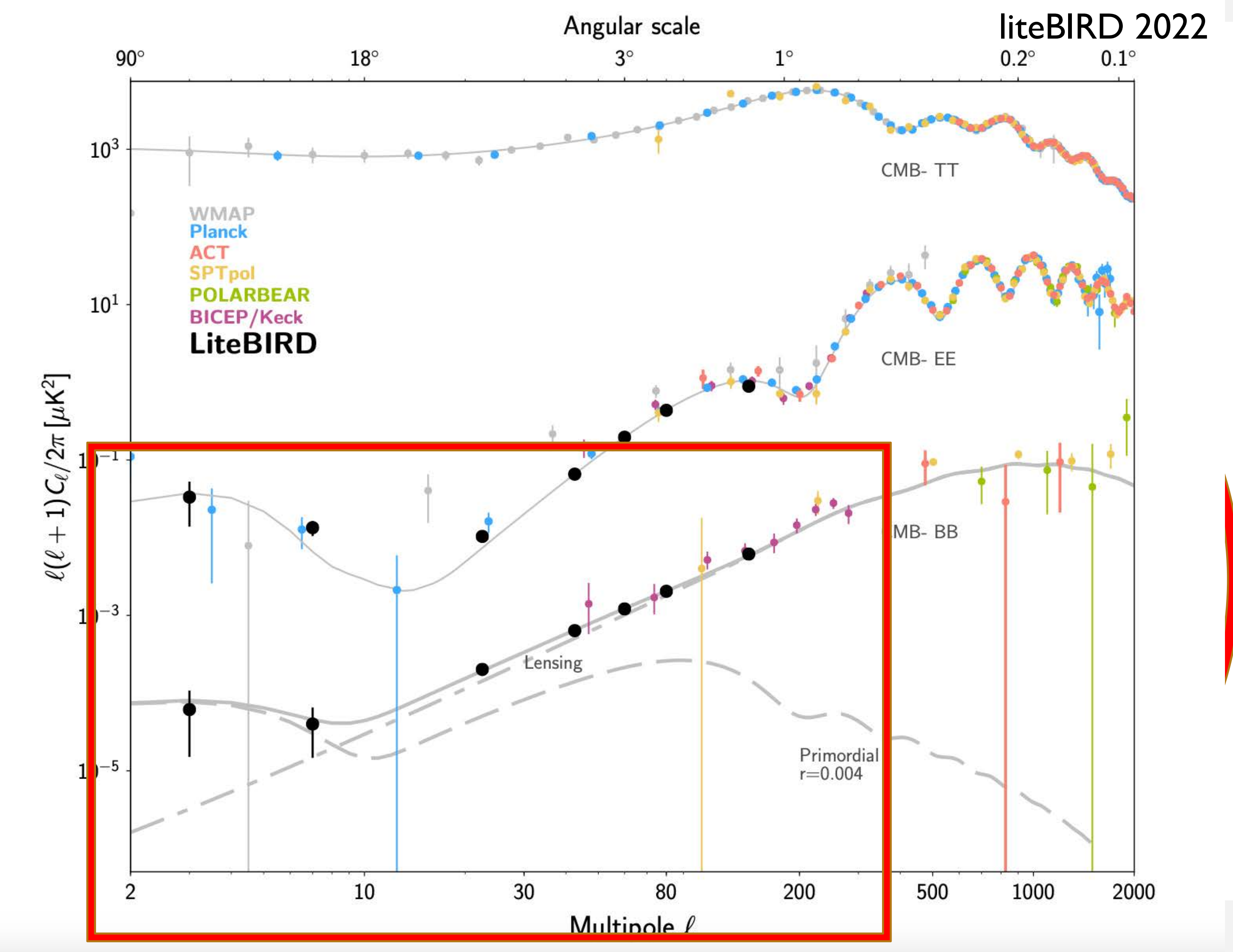
FIG. 7. Marginalized one- and two- dimensional posterior distributions for the SPT-3G 2018 $TT/TE/EE$ data set (blue contours), *Planck* (black line contours), and ACT DR4 (gray contours) in ΛCDM. The constraints derived from SPT-3G data are in excellent agreement with the *Planck* constraints, including for $H_0$. The SPT-3G and ACT data have similar constraining power and the differences in their constraints are compatible with statistical fluctuations.

# FUTURE CMB EXPERIMENTS

General directions of new observations:

1) Higher spatial resolution, larger area
2) Better polarization measurements (higher s
3) Sufficient frequency coverage to separate c

- Simons Observatory (2023-24, ground)
  - ~1 arcmin resol., freq: 27-280GHz, $f_{sky}$=0.4
- CMB-S4 (2027-2028, ground)
  - ~1 arcmin resol. Noise:1-10 muK-arcmin, $f_{sky}$=0.7
- CMB-HD (>2030, ground)
  - 0.15 arcsec res, Noise: -0.5-5 muK-arcmin, $f_{sky}$=0.5, freq:30-350GHz
  - Lensing measurement. Dark matter, small scales
- LiteBIRD (2027-28, satellite, L2)
  - Low noise, large frequency coverage, large beam.
  - Tensor modes + reionization, large scale BB



# SCIENCE QUESTIONS FOR THE FUTURE (OF THE CMB COMMUNITY)

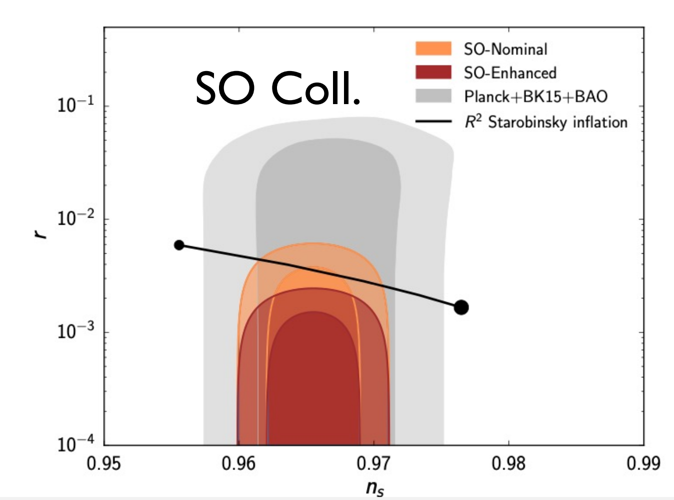
- Which inflation?
  - Can we put a tighter limit on the amplitude of primordial gravitational waves?
  - How "Gaussian" are the perturbations?
  - Can we extend the information on the initial power spectrum to smaller scales?

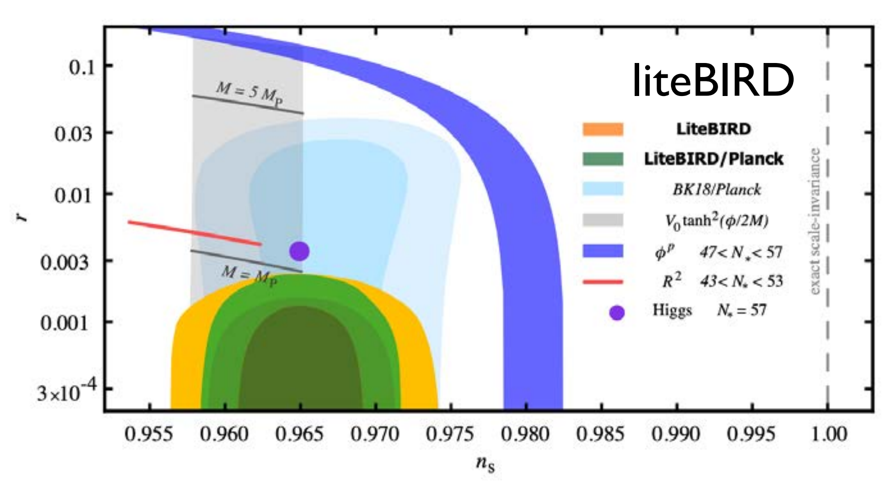
- Which specific content of the Universe?
  - Can we detect the neutrino mass?
  - Are there new light relics?

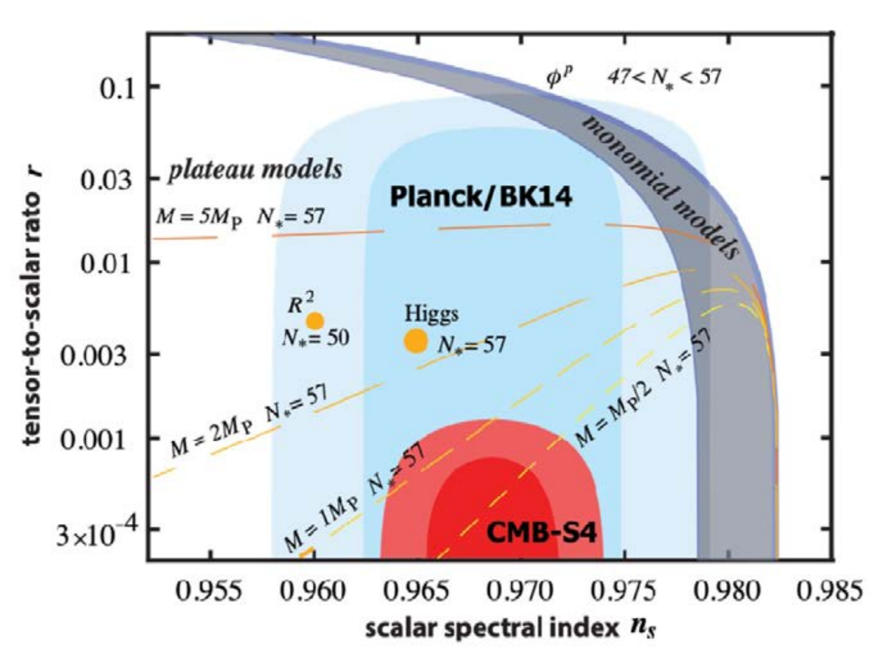
- How did structure formation occur?
  - How did reionization occurred, specifically?
  - How is the gas distributed in the Universe in general (around galaxies and within clusters)?

# EARLY UNIVERSE SCIENCE: GRAVITATIONAL WAVES

- Inflationary models that are compatible with the observed scalar spectral index naturally also imply $r > 10^{-3}$
- Simons Observatory goal: $r < 10^{-2}$
- CMB-S4 upper limit goal: $r < 10^{-3}$ at 95% C.L.
- Similar upper limits from liteBIRD
- a non-detection of r will rule out the leading inflationary models, and motivate alternate models for the origin of the universe.



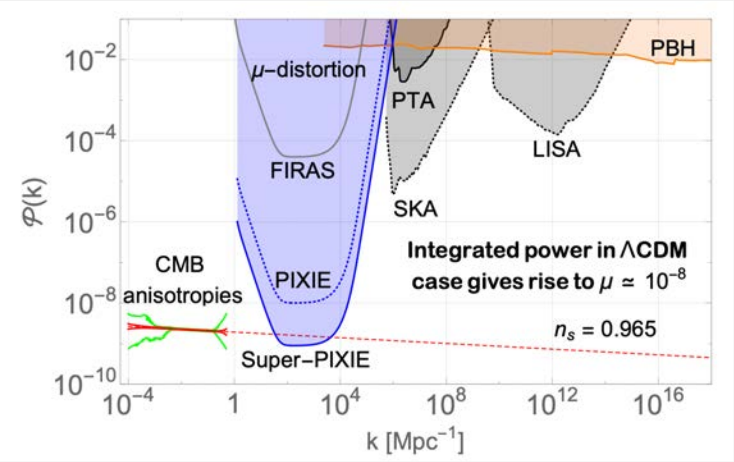



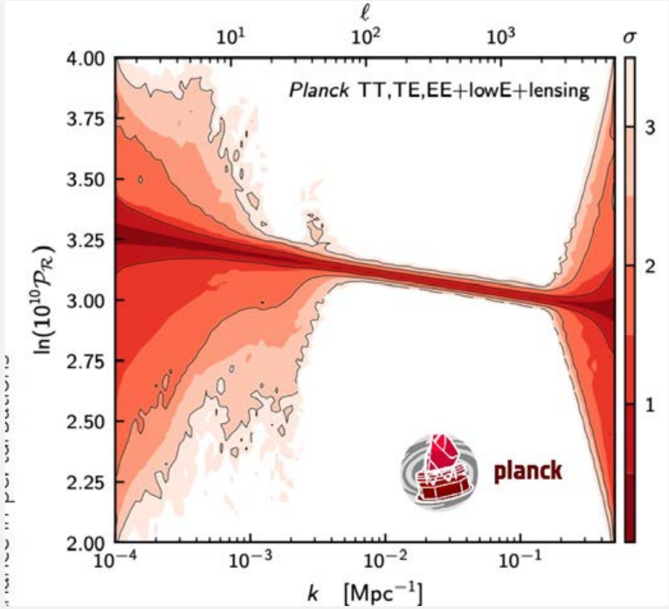

CMB-S4 collaboration

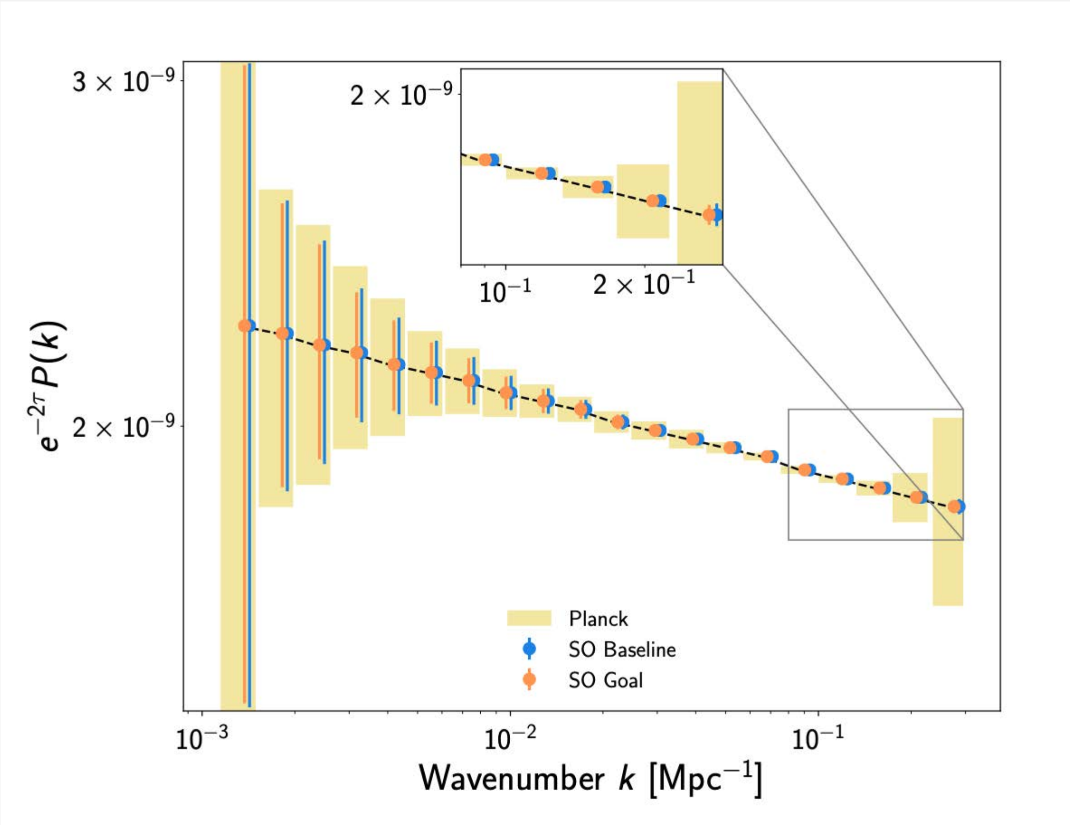
# EARLY UNIVERSE: PROBING THE PRIMORDIAL DENSITY SPECTRUM

- Simons Observatory will improve 10 times over Planck at small scales ($k \sim 0.2$ Mpc$^{-1}$), thanks to small-scale polarization
- It will also help in better characterizing larger scales $\sim 0.001$ Mpc$^{-1}$
- Possible new venue for the measurement of the small scale ($k \sim 10^3$ Mpc) spectrum: spectral distortions.



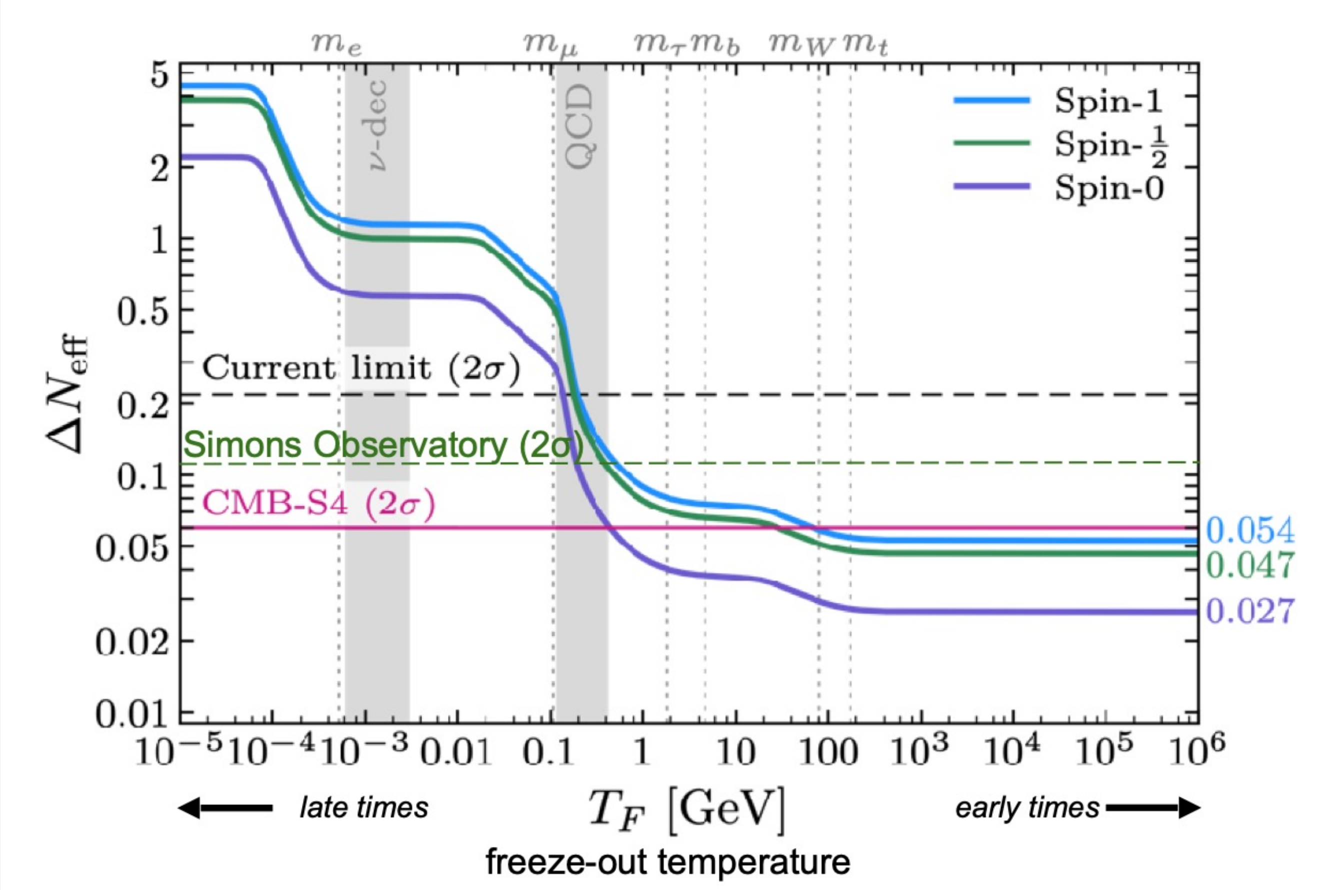

Chluba et al 2019
(Voyage 2050 science paper)



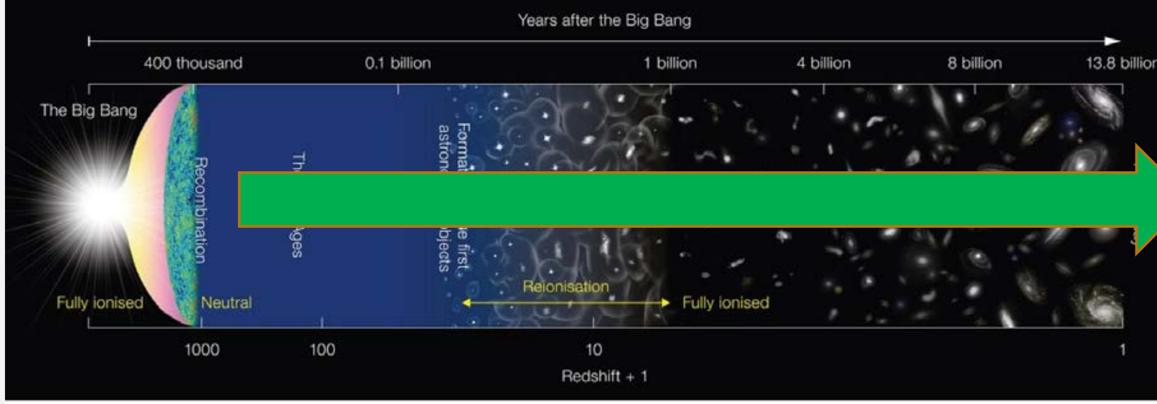
# LIGHT RELICS

- $N_{eff}$ is expected to be 3.046 if only neutrinos contribute to this number. Other light particles present in the early Universe will alter this value.
- The earlier the freeze-out of the particle, the smaller their contribution to the radiation energy density
- CMB-S4 will be able to detect any kind of particle that froze-out after ~0.3 GeV [start of QCD]




CMB-S4 science book

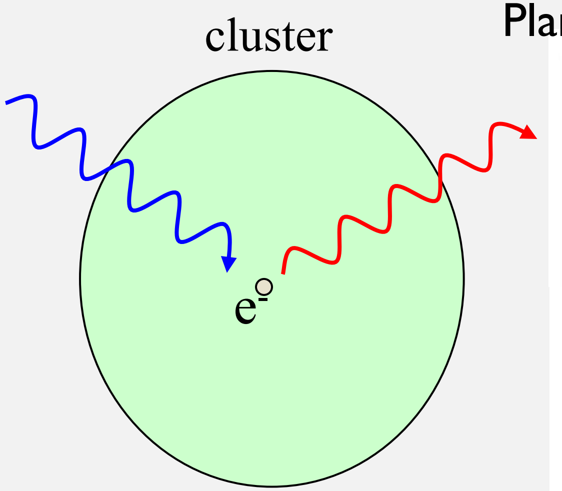
# SECONDARY ANISOTROPIES

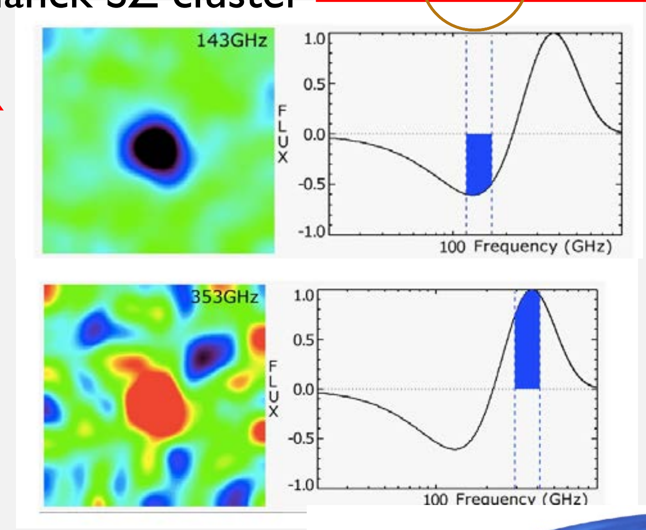



Thermal and kinetic Sunyaev Zeldovich
(CMB scattering off hot/free electrons)

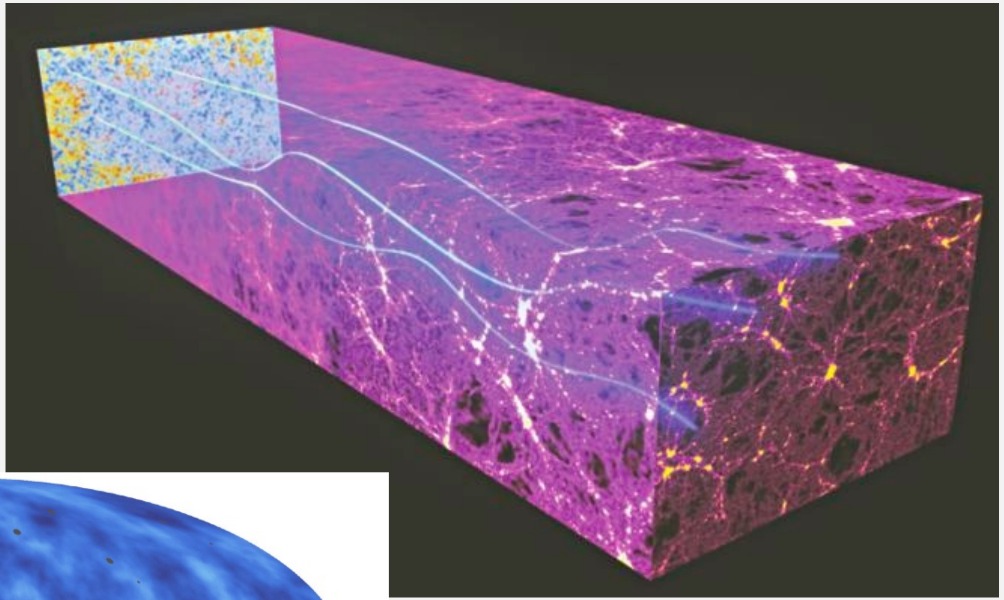
$$\Delta T/T = f(\nu)\, y$$
$$y \propto T_e\, n_e$$

Planck SZ cluster



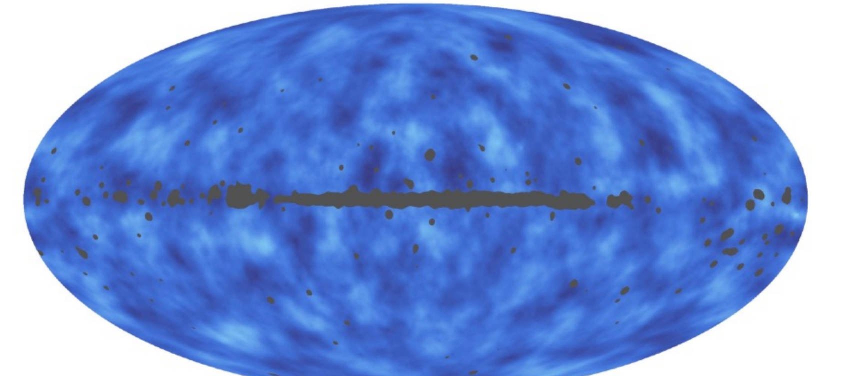




Gravitational lensing (and ISW )



Detection of galaxy clusters (tSZ)
Characterization of reionization
Peculiar velocity fields (kSZ)

$$\frac{\delta T}{T_0}(\hat{n}) = -\int dl\, \sigma_T\, n_e \frac{v_e \cdot \hat{n}}{c}$$

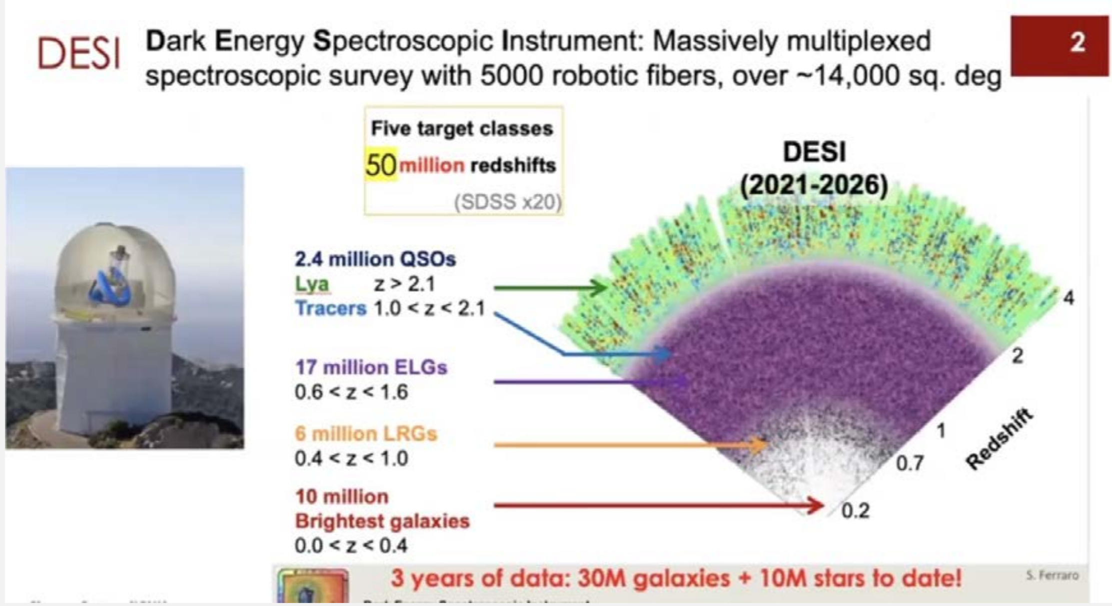


Planck lensing potential map

Growth of structures at early/late times
Dark matter characterization

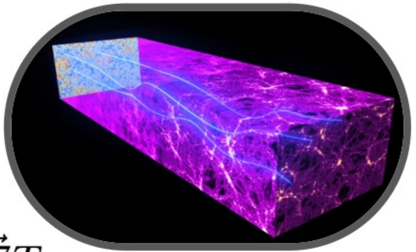
# WHY STUDYING SECONDARY ANISOTROPIES?

- Powerful tool, as it provides integrated information along the line of sight – small effects ”add up” and become large.
- Information from  CMB maps only,  and  cross correlations
  - Cross-correlations between the CMB (unbiased tracer of the density field) ang galaxies (biased tracer) helps reducing sample variance (e.g. measurement of f_NL)
- What science?
  - Cosmology
    - Dark energy properties and neutrino masses
    - Low-redshift measurements, to be compared with high-redshift (e.g. S8)
    - Inflation – large scale spectral index
    - Cosmology from velocity fields
  - Astrophysics
    - Galaxy evolution (reionization)
    - Clusters’ evolution (ICM properties, gas-DM distributions, galaxy population in clusters)



# LIST OF "SECONDARY" EFFECTS

**Imprints of LSS on the CMB**



**Sourced by gravitational potentials:**

| | |
|---|---|
| Lensing, | $\propto \vec{\theta}_{\rm lens} \cdot \vec{\nabla} T$ |
| ISW, | |
| Rees-Sciama, | $\propto \dot{\Phi}$ |
| Moving Lens | $\propto \vec{v}_\perp \cdot \nabla\Phi$ |

**Sourced by Thomson scattering:**

| | |
|---|---|
| Screening, | $\propto e^{-\tau}\, T$ |
| kinetic SZ, | $\propto v_{\parallel}\, \tau$ |
| rotational kSZ, turbulent SZ | $\propto v_{\rm rot}\, \tau$ , $v_{\rm therm}\, \tau$ |
| thermal SZ, relativistic SZ | $\propto f(z)\, y_{\rm compt}$ |
| polarized SZ, | $\propto \tau\, a^T_{2m}$ |
| kinetic polarized SZ | $\propto \tau\, v_\perp^2$ |

**Sourced by Dust:**

| | |
|---|---|
| Cosmic infrared background | $\propto I_\nu$ |

2

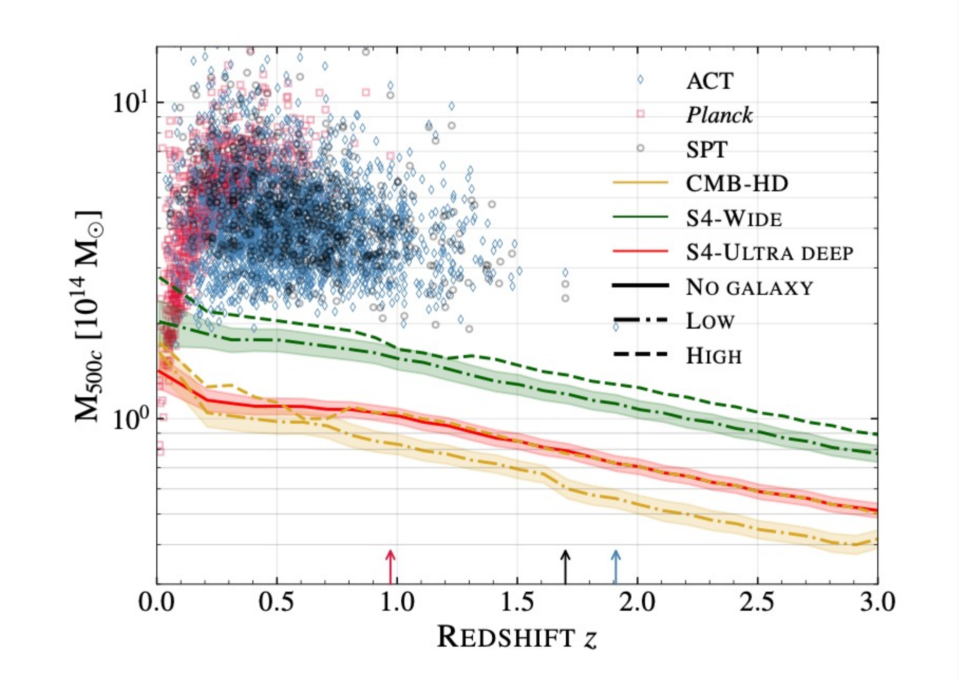
Optical depth

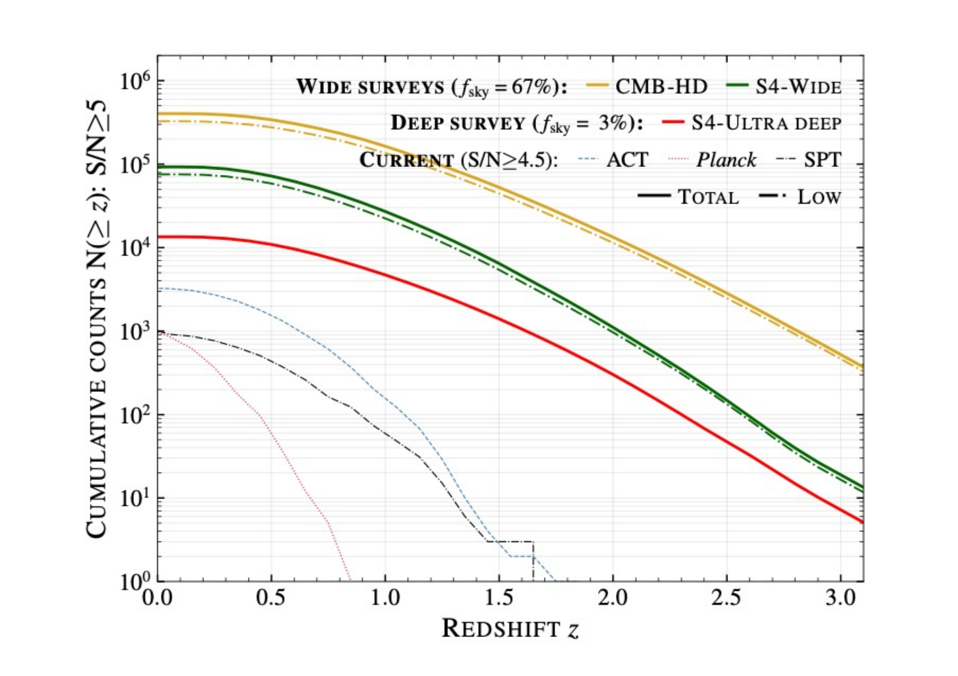
$$\tau(z) = \sigma_T n_{e0} \int_0^z dz' \frac{cdt}{dz'} x_e(z')(1+z')^3$$

# CLUSTER DETECTION AND NUMBER COUNTS (TSZ)

1653 Planck detected clusters
~4000 objects with ACT and SPT

Raghunathan et al 2022



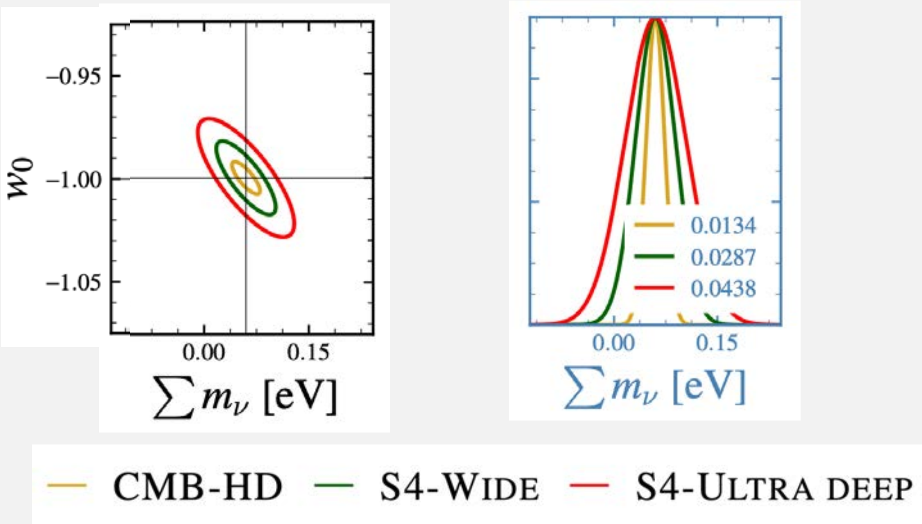




- Detection expected down to very low mass and z~3
- Enabled science:
  - Study of the growth factor (dark energy, modified gravity)
  - Neutrino masses

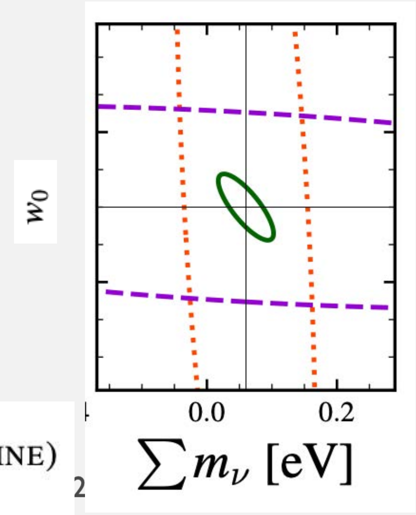
# NEUTRINO MASSES AND DARK ENERGY

Raghunathan et al 2022

- Oscillation experiments determine a minimum mass of 0.06 eV for at least one neutrino.
- Neutrinos contribute to the total dark matter budget, but at most by 2%, given current constraints (and at least 0.5%)
- Their presence suppresses the growth of perturbation on small scales and over a large redshift range.

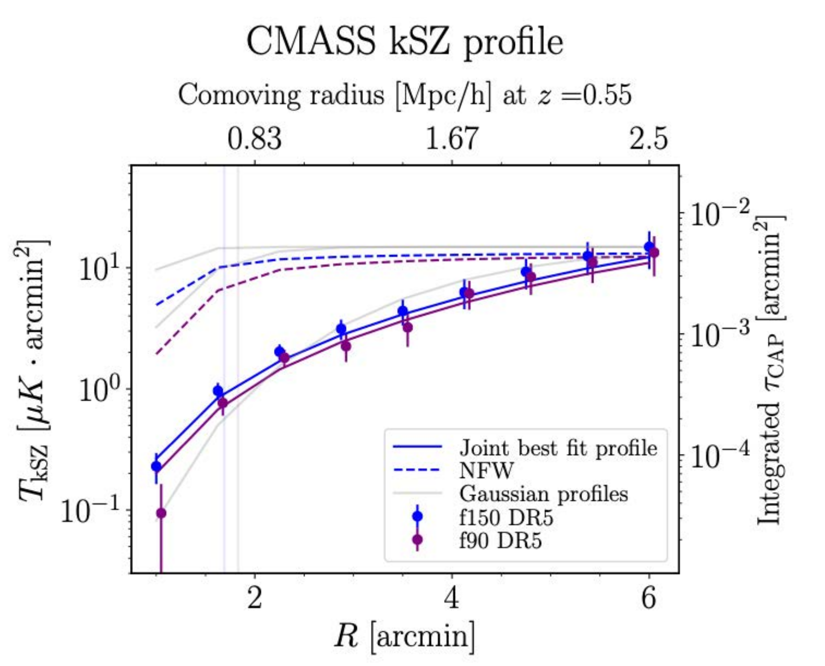



- Current limits: $\Sigma m_\nu < 0.12$ eV (95% CL, Planck + BAO)
- Future limits: $\Sigma m_\nu < 0.03$ eV from SZ cluster counts (with mass calibration from CMB lensing)
- Result are somewhat degenerate with the  the dark energy equation of state
- CMB power spectrum and cluster counts are highly complementary



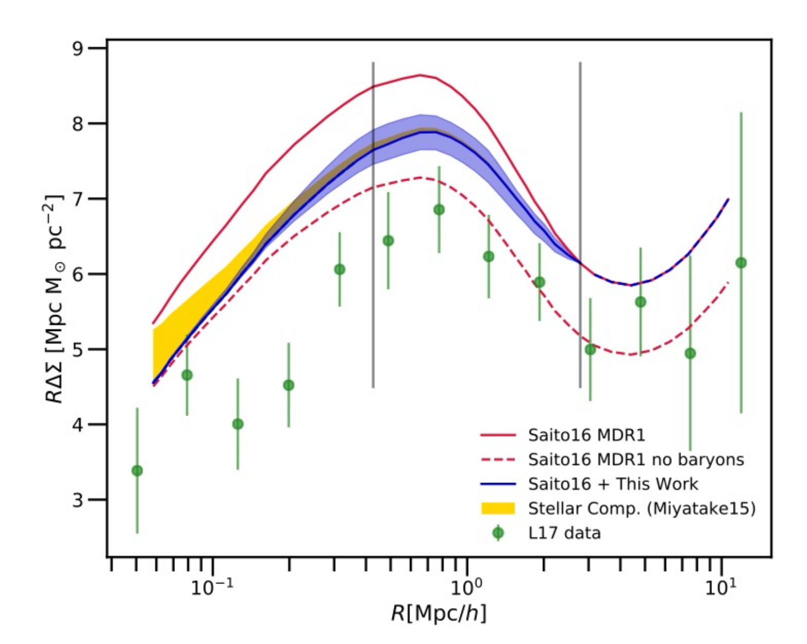

# KSZ: GAS (VERSUS DM) DISTRIBUTION IN CLUSTERS

Shaan et al 2020 (ACT)



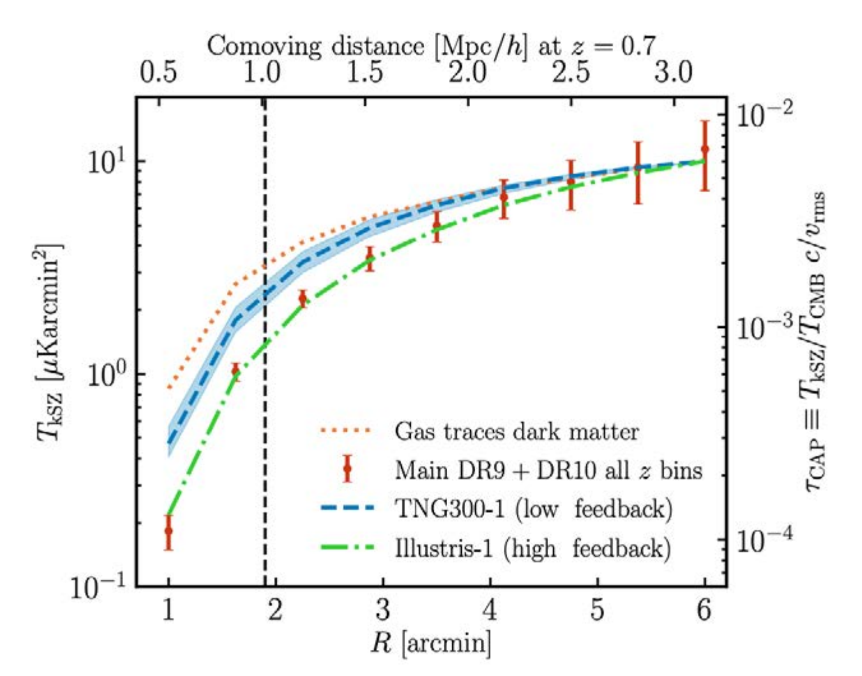

- The profile of the baryon for stacked kSZ clusters does not seem to follow an NFW profile. Gas is way more extended.

Amodeo et al 2020 (ACT)




The correction of the baryon profiles helps in reconciling galaxy lensing data with halo models used for the interpretation

Hadzhiyska et al 2024 (ACT+DESI)



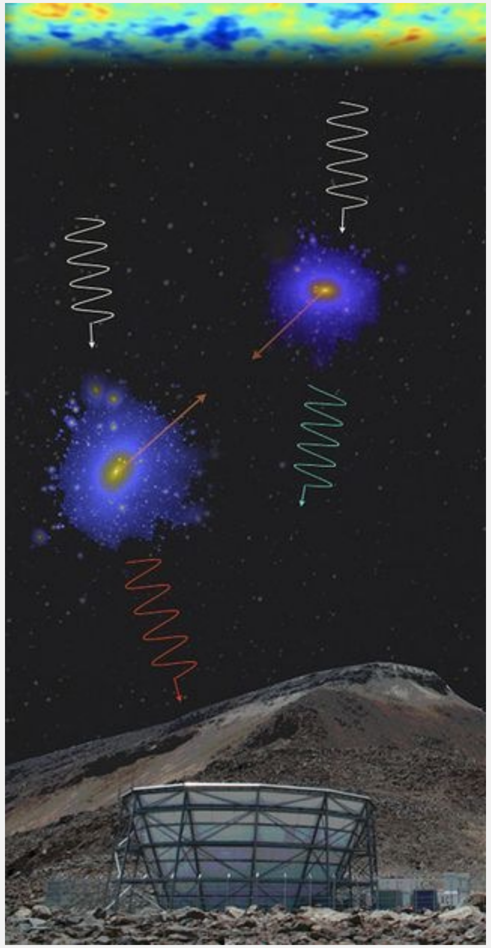

Gas is more extended than DM (at 40 σ).
Constraints on feedback models
(low feedback disfavored for z<1 objects)

# MAPPING VELOCITY FIELDS WITH SECONDARY ANISOTROPIES: KSZ

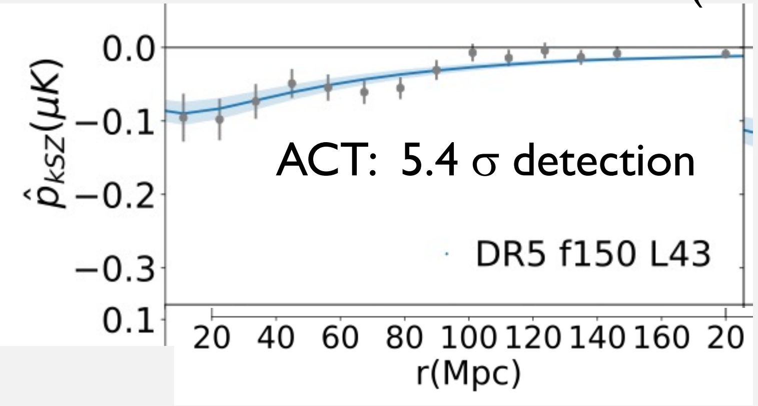
- Pairwise veolicties: Galaxies/clusters at a given separation tend, on average, to move towards one another.
- Current surveys already allow to measure pairwise velocities through the kSZ effect.
- At the moment, there is a detection but the significance is too low to use this probe to infer cosmological parameters.
- A mean value of the optical depth of the sample is computed.
- Future surveys will have enough sensitivity to measure parameters this way (Muller et al 2014)

The kSZ effect measures radial velocity
And optical depth:

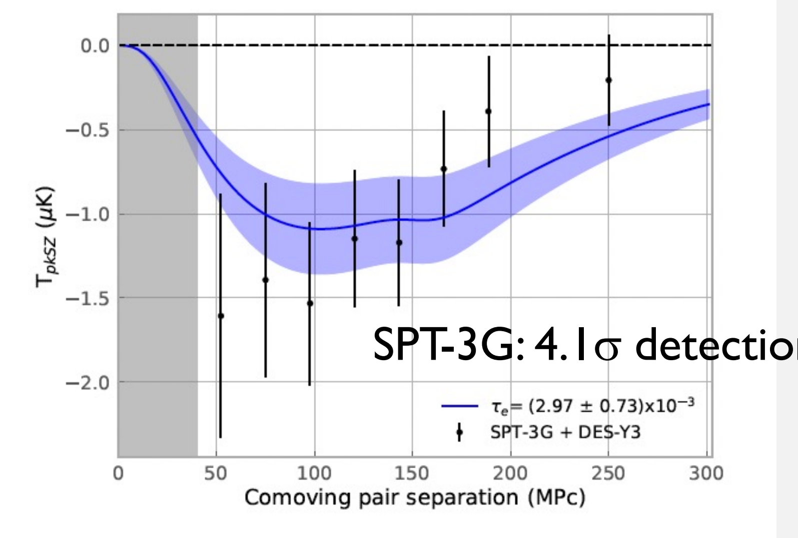
$$\frac{\delta T}{T_0}(\hat{n}) = -\int dl\, \sigma_T\, n_e \frac{v_e \cdot \hat{n}}{c}$$



Calafut et al 2021 (ACT)



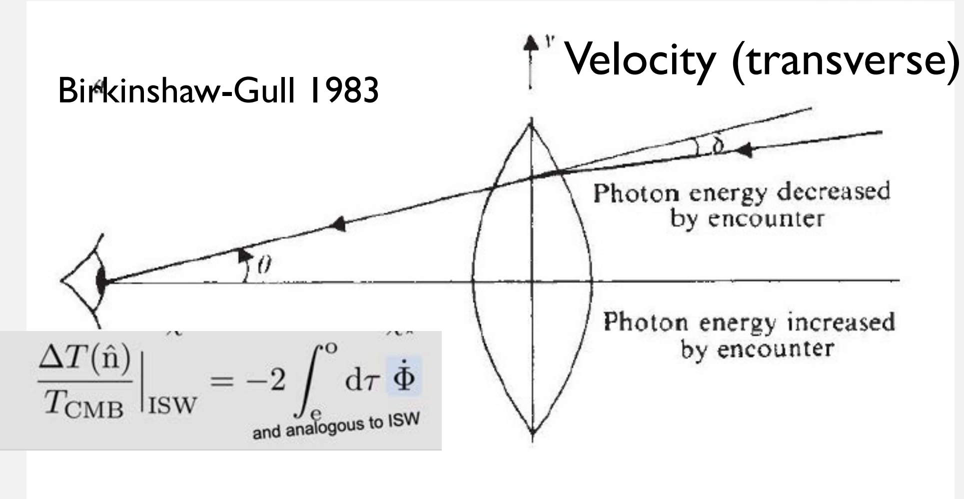

Schiappucci et al 2022 (SPT)

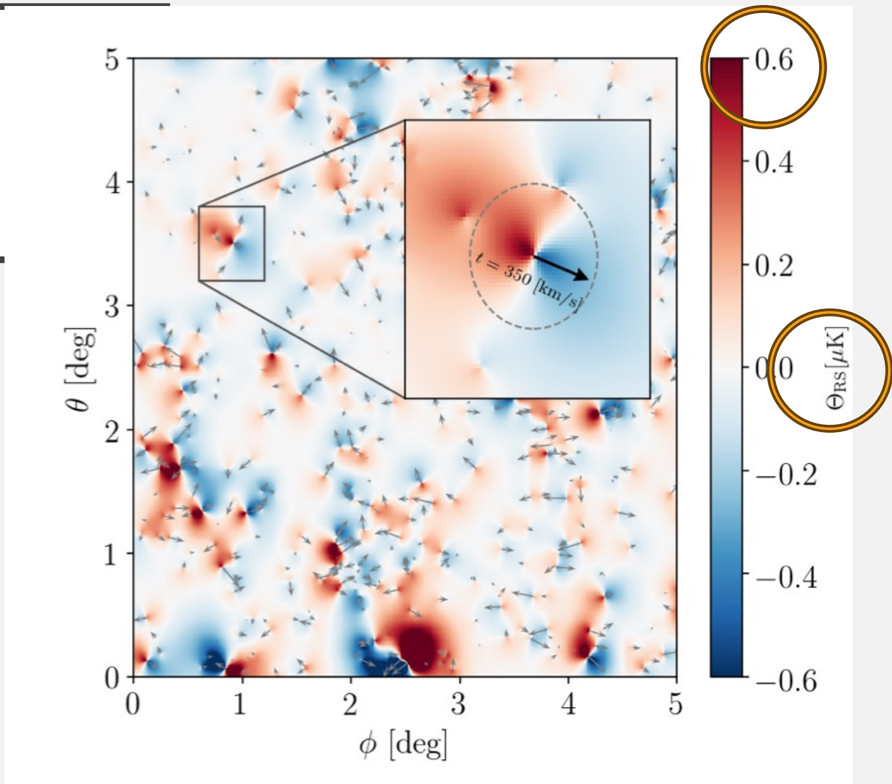



$$\bar{\tau}_e = (2.97 \pm 0.73) \times 10^{-3}$$

# MAPPING VELOCITIES WITH LENSING

- What: dipolar temperature change in the direction of a halo:



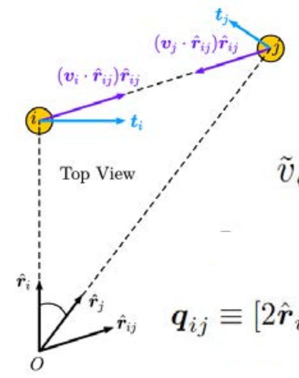




- **Small** dipolar signal
- Same frequency dependence as CMB
- Extended (beyond the virial radius)
- It depends on mass and velocity of halos

- Why:
  - one of the two ways of measuring transverse velocities (other: polarized SZ, affected by different systematic effects)
  - Potential for making 3D velocity reconstruction
  - Potential of constraining cosmology (e.g. modified gravity)

Small, but detectable with upcoming surveys (Yasini, Mirzatuny, EP 2019, Hotinli et al 2019)

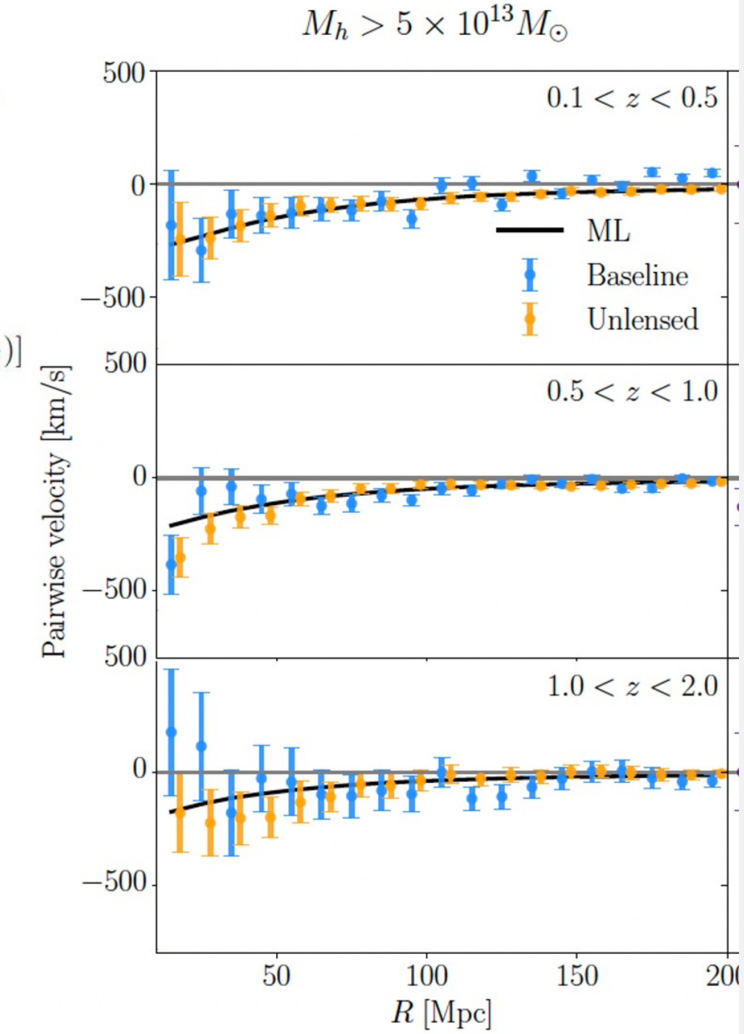
# PAIRWISE VELOCITIES FROM MOVING LENS




$$v_{\langle ij \rangle}(r) \equiv \langle \boldsymbol{v}_{ij}(r) \cdot \hat{\boldsymbol{r}}_{ij} \rangle$$

$$\tilde{v}_{\langle ij \rangle} = \frac{\sum_{ij} (\tilde{\boldsymbol{t}}_i - \tilde{\boldsymbol{t}}_j) \cdot \boldsymbol{q}_{ij}}{\sum_{ij} |\boldsymbol{q}_{ij}|^2}$$

$$\boldsymbol{q}_{ij} \equiv [2\hat{\boldsymbol{r}}_{ij} - \hat{\boldsymbol{r}}_i(\hat{\boldsymbol{r}}_{ij} \cdot \hat{\boldsymbol{r}}_i) - \hat{\boldsymbol{r}}_j(\hat{\boldsymbol{r}}_{ij} \cdot \hat{\boldsymbol{r}}_j)]$$




Hotinli & Pierpaoli 2024

- NB: This is NOT kSZ pairwise! (transverse velocities, and lensing - not baryon physics).
- Same procedure as for stacking, plus matched filtering to get velocities.
- CMB-S4 + LSST will be able to detect the transverse velocities. SO+DESI no.
- CIB and tSZ less (or not) of an issue. Main problem: halo lensing.
- Mass and redshift determination don't seem to be very relevant
- VERY computationally demanding - better strategy needed?

LSST+CMB-S4

$M_h > 5 \times 10^{13} M_\odot$.

| SNR | $z \in [0.1, 0.5]$ | | | $z \in [0.5, 1.0]$ | | | $z \in [1.0, 2.0]$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $R \in$ | $< 150$Mpc | $> 150$Mpc | All | $< 150$Mpc | $> 150$Mpc | All | $< 150$Mpc | $> 150$Mpc | All | Total |
| baseline | 5.17 | - | 5.17 | 6.31 | 2.84 | 7.11 | 3.14 | 0.99 | 3.25 | 9.4 |
| unlensed | 9.2 | 3.82 | 9.72 | 8.38 | 3.76 | 9.23 | 4.11 | 1.71 | 4.38 | 14.1 |

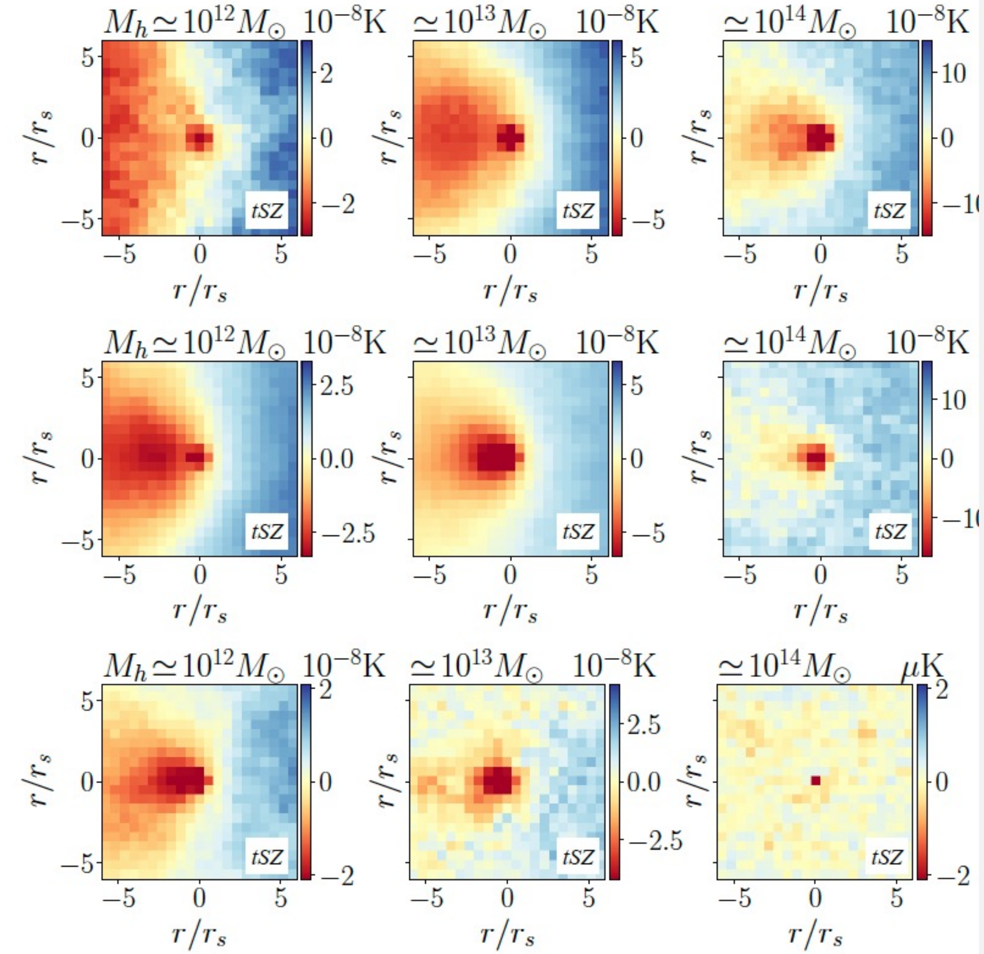
# THIS PHYSICAL EFFECT IS IN THE SIMULATIONS, AND IT IS MASS AND REDSHIFT DEPENDENT

If ignored: substantial potential bias on velocity determination from single-frequency observation.

SZ Clusters @ 150 GHz

Hotinli, EP, Ferraro, Smith 2023

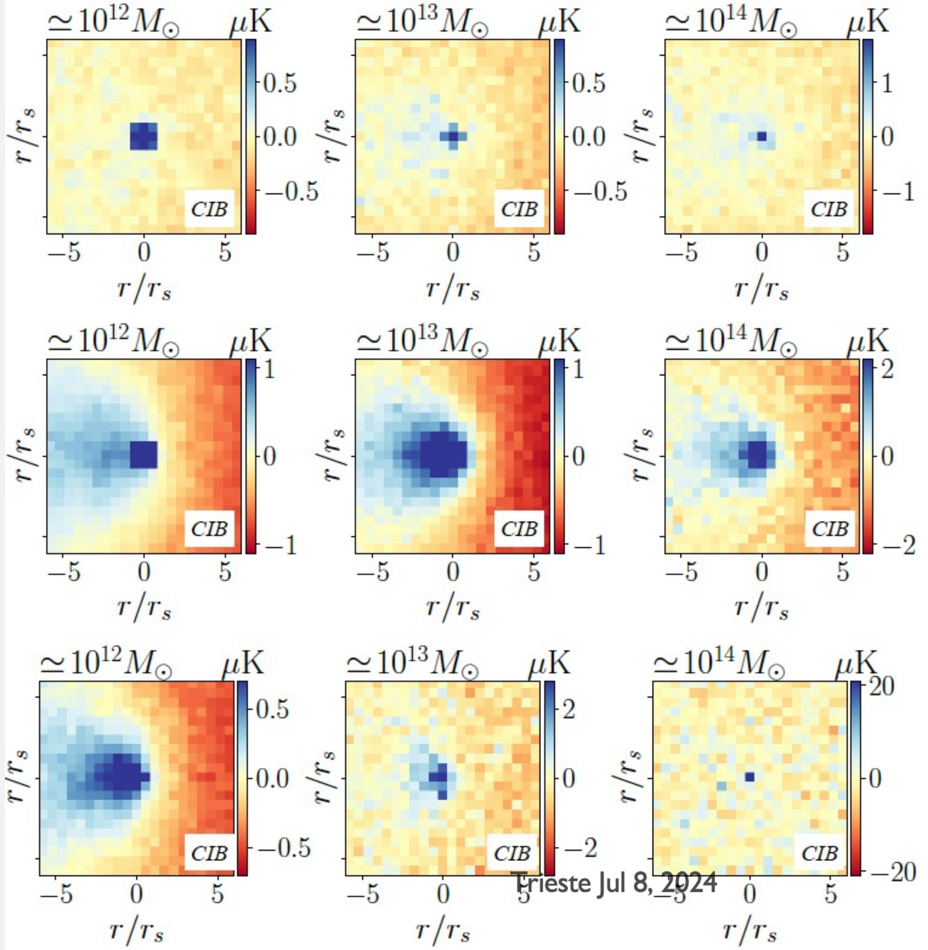
CIB @ 220 GHz



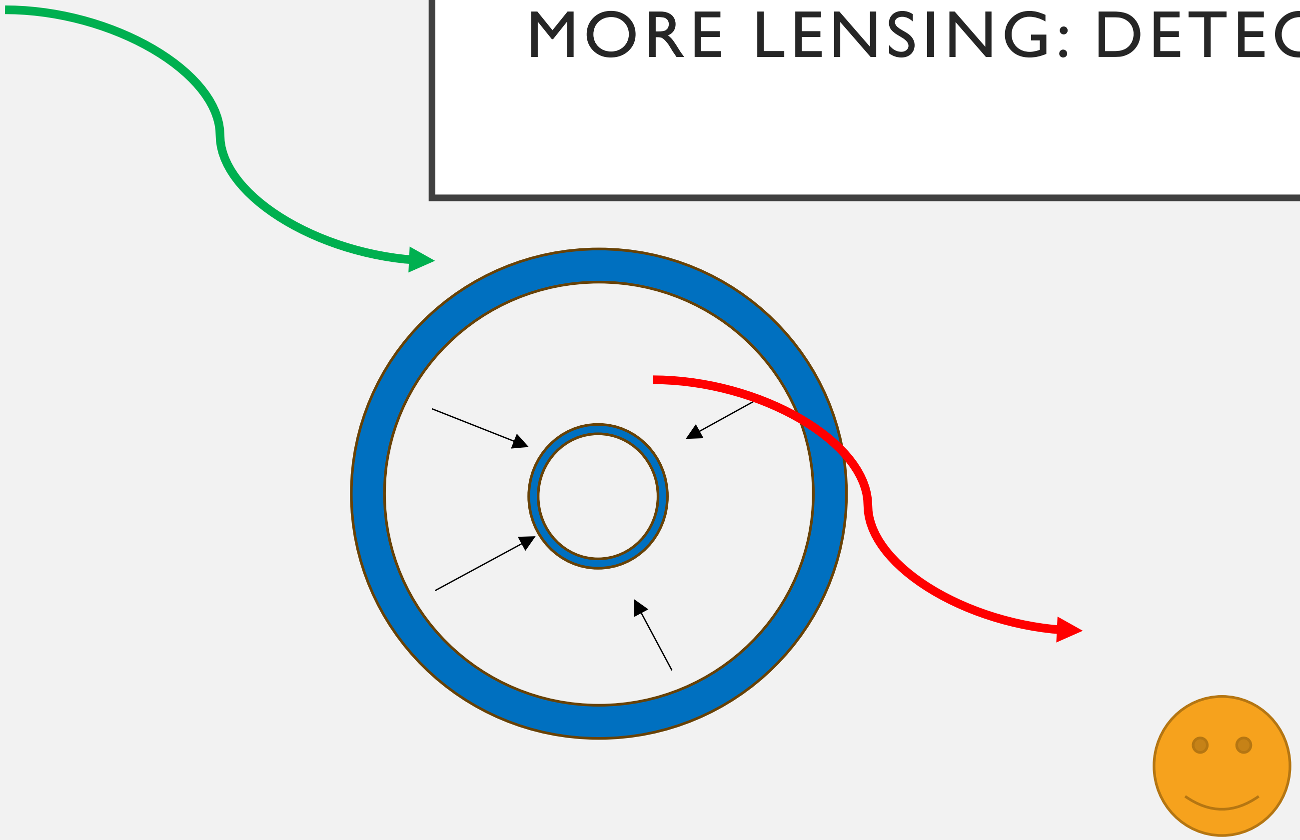

0<z<0.5

1.4<z<1.8

2.5<z<3

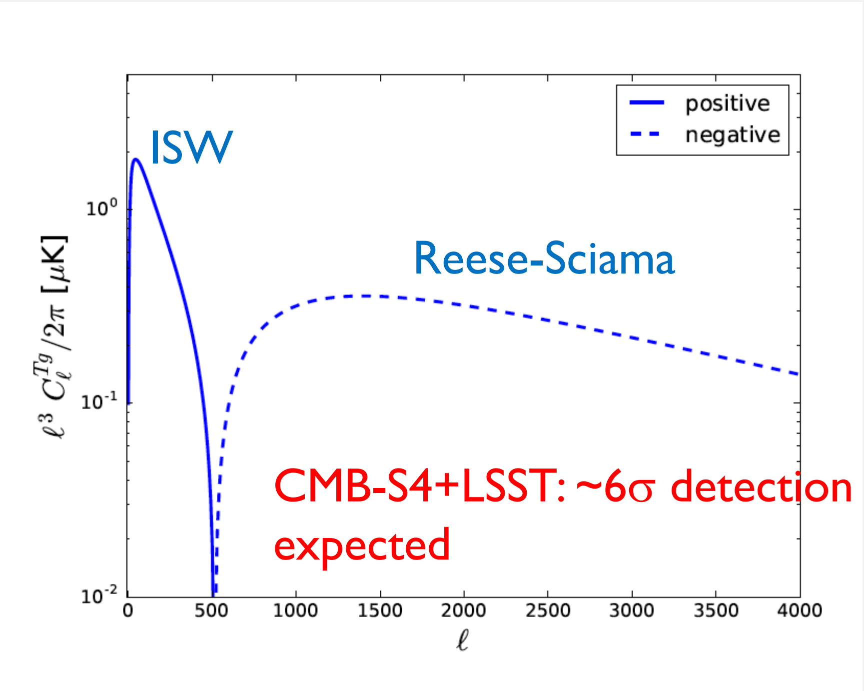


# MORE LENSING: DETECTING THE REESE-SCIAMA EFFECT



- Reese-Sciama: photons passing through a structure which is growing in the non-linear regime will show an altered energy, observable in the temperature map (non-linear ISW).
- Future cross-correlations between CMB maps and galaxy surveys will detect, for the fist time, the Reese-Sciama effect.

Ferraro, Schaan, EP (2022)




$$\left(\frac{\Delta T}{T}\right)_{\rm ISW}(\hat{n}) \propto \dot{\Phi}$$

# THE END - SUMMARY

- In the past ~25 years, the CMB has set/confirmed a very precise cosmological framework, confirming $\Lambda$CDM, and pointing towards single-field inflation, measuring the redshift of reionization quite precisely.
- In the next 10 years we shall expect:
  - Detection of primordial gravitational waves from B modes
  - Detection of the hierarchy for neutrino masses
  - Better characterization of inflation (primordial power spectrum etc)
  - Better understanding of particle physics beyond the standard model
  - Detection of many clusters/massive halos up to redshift 3
  - Detection of transverse velocities and Reese-Sciama effect
  - Better characterization of structure formation, including:
    - the reionization period
    - Dark matter and gas mass distribution in clusters

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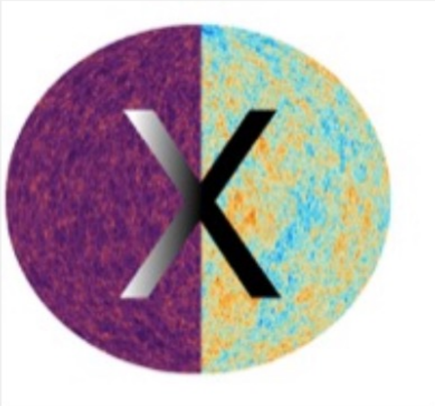
Kavli Institute for Theoretical Physics

**Exploring New Boundaries in Cosmology and Astrophysics: Cosmic Microwave Background and Large Scale Structure Surveys**

**Coordinators:** Stefano Borgani, Tzu-Ching Chang, Matthew Johnson, and Elena Pierpaoli



**DATES**

Jan 12, 2026 - Mar 5, 2026

**INFORMATION**

Apply

**Application deadline is:**
*Dec 8, 2024.*