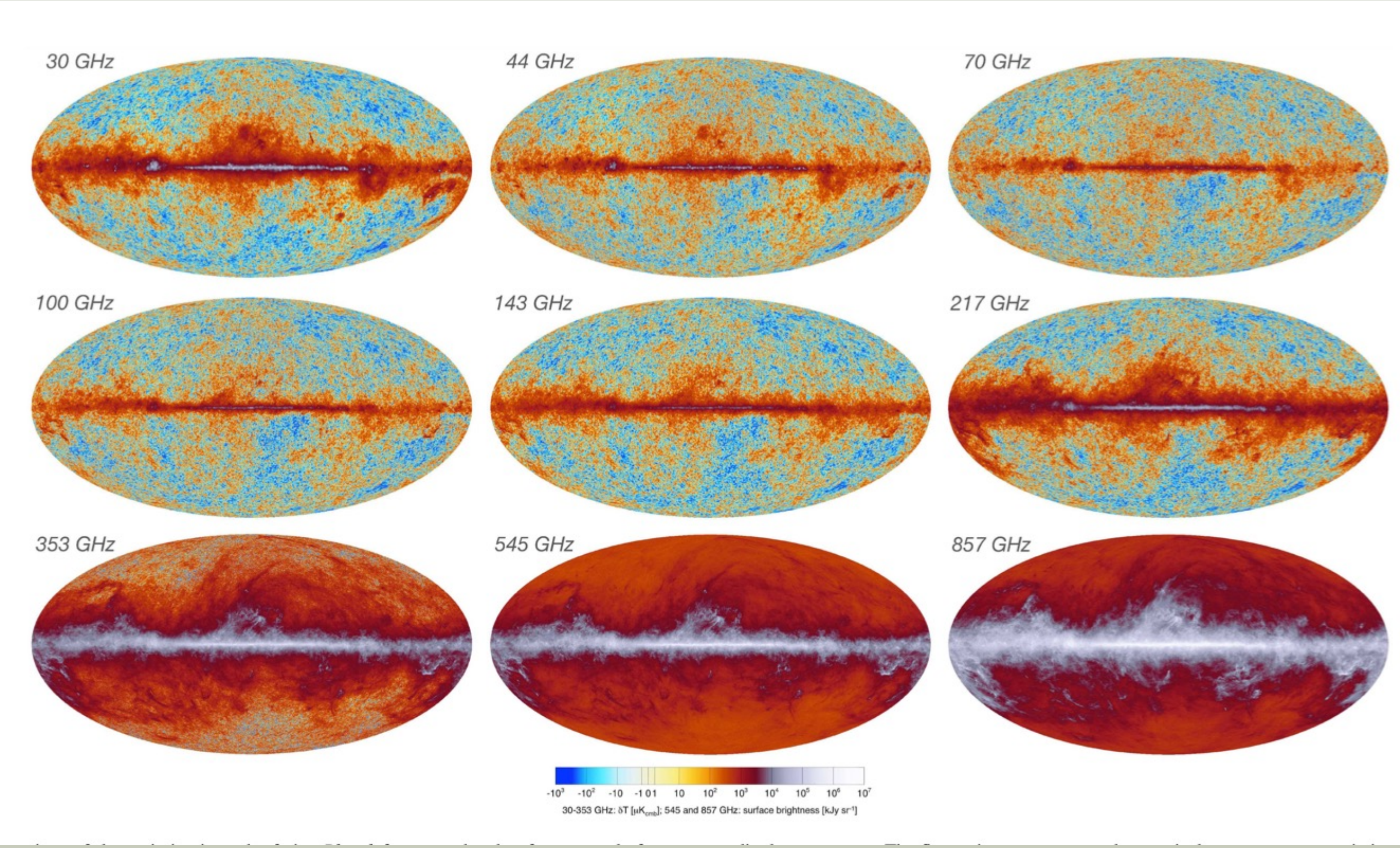
A TRAVEL THROUGH CMB SCIENCE: ACCOMPLISHMENTS AND PERSPECTIVES FOR THE NEXT DECADE



Elena Pierpaoli

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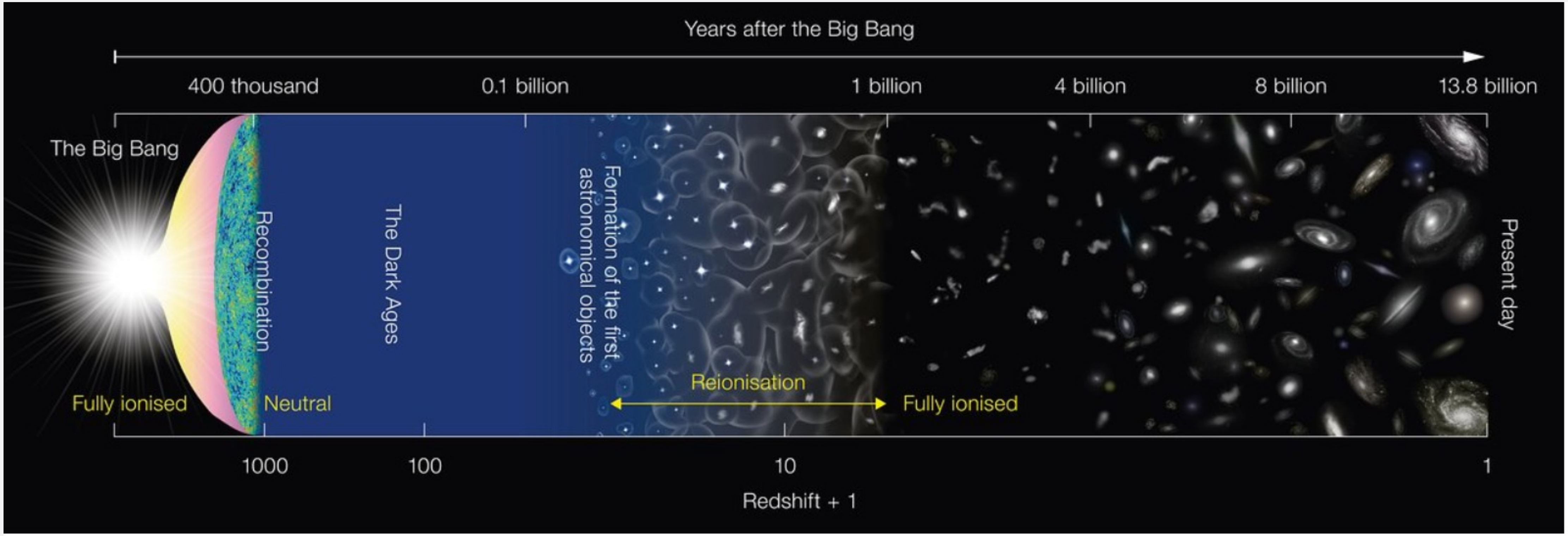
COSMO 22 Rio de Janeiro
8/22/22

THERMAL HISTORY OF THE UNIVERSE

Image credit: NAOJ



Primordial Gravitational waves

CMB Primary anisotropies

CMB secondary anisotropies

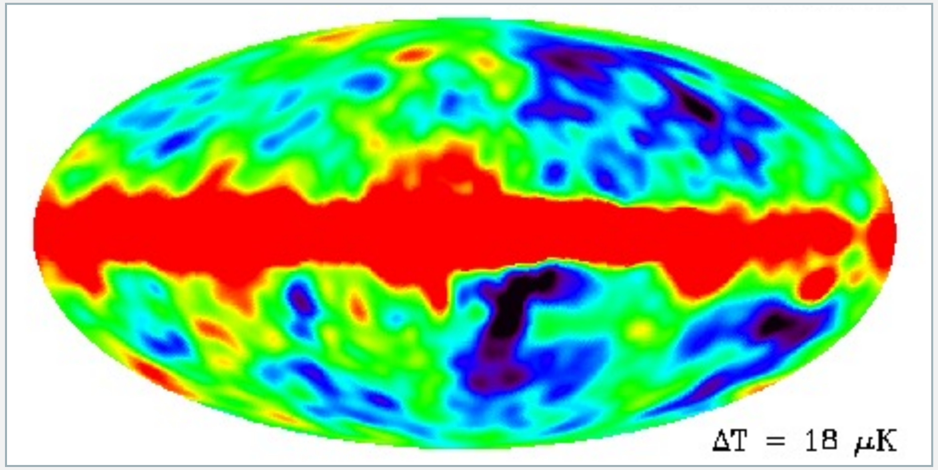
(Sunyaev Zeldovich, reionization, gravitational lensing, ISW)

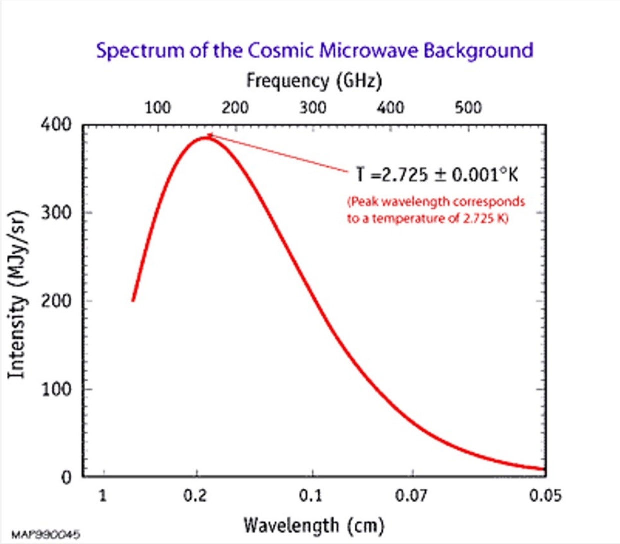
THE LAST 25 YEARS OF EPIC HISTORY

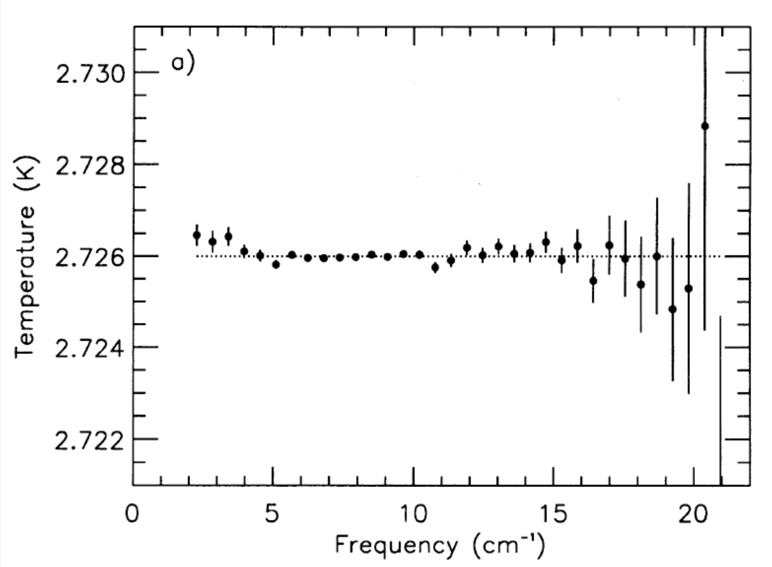
Discovery:1965 (Nobel in '78)

Confirmation of the big bang theory:
Is the spectrum a blackbody?
Does it shows anisotropies, as the matter distribution around us?

Answers provided by COBE (1994, Nobel 2006)

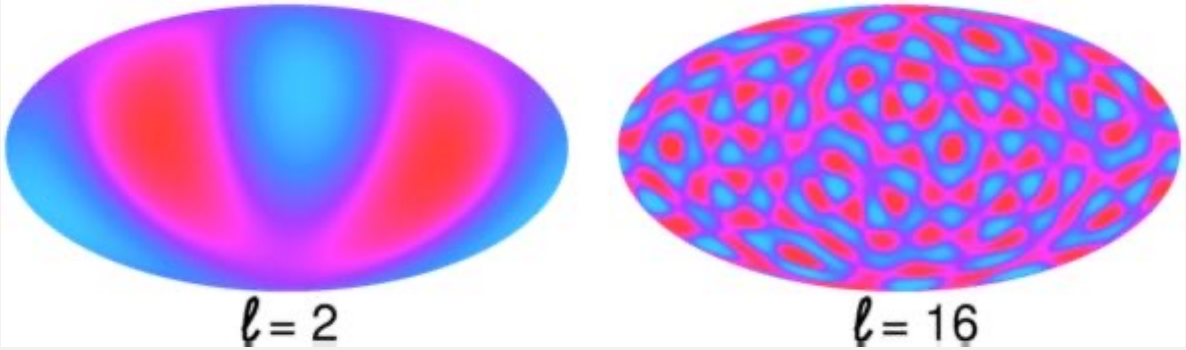






THE CMB POWER SPECTRUM

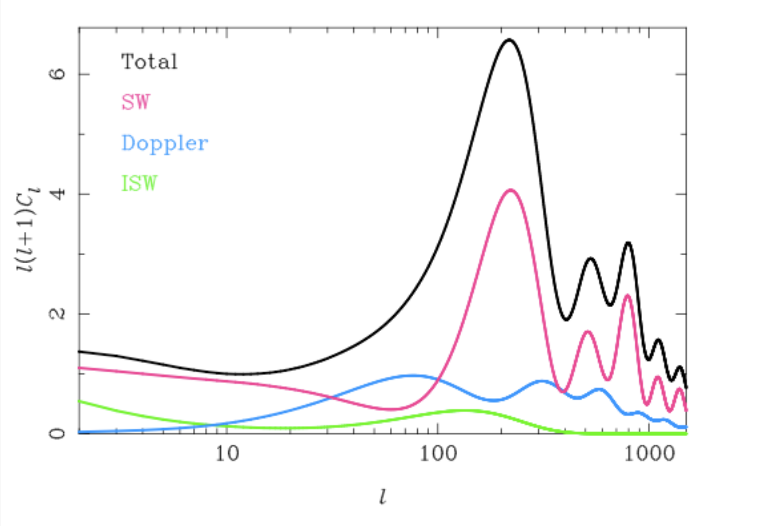
Examples of spherical harmonics



$$\Delta T(\theta,\phi) = \Sigma\, a_{l,m} Y_{l,m}(\theta,\phi)$$
$$C_l = \Sigma_m |a_{l,m}|^2$$

The power spectrum is the most compact way to describe (all or most of) the cosmological information in a sky map. It allows efficient comparison between theory and observation.

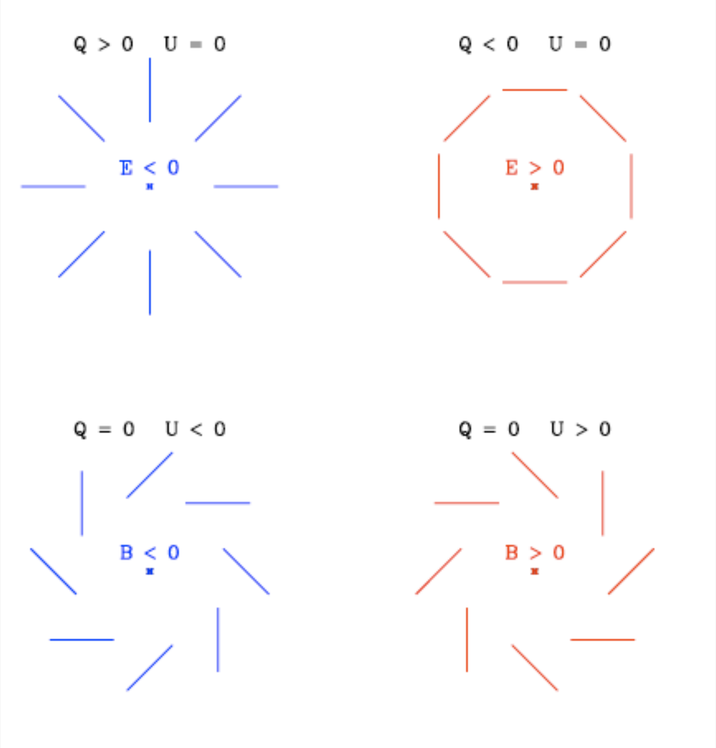
All: if perturbations are a Gaussian random field.

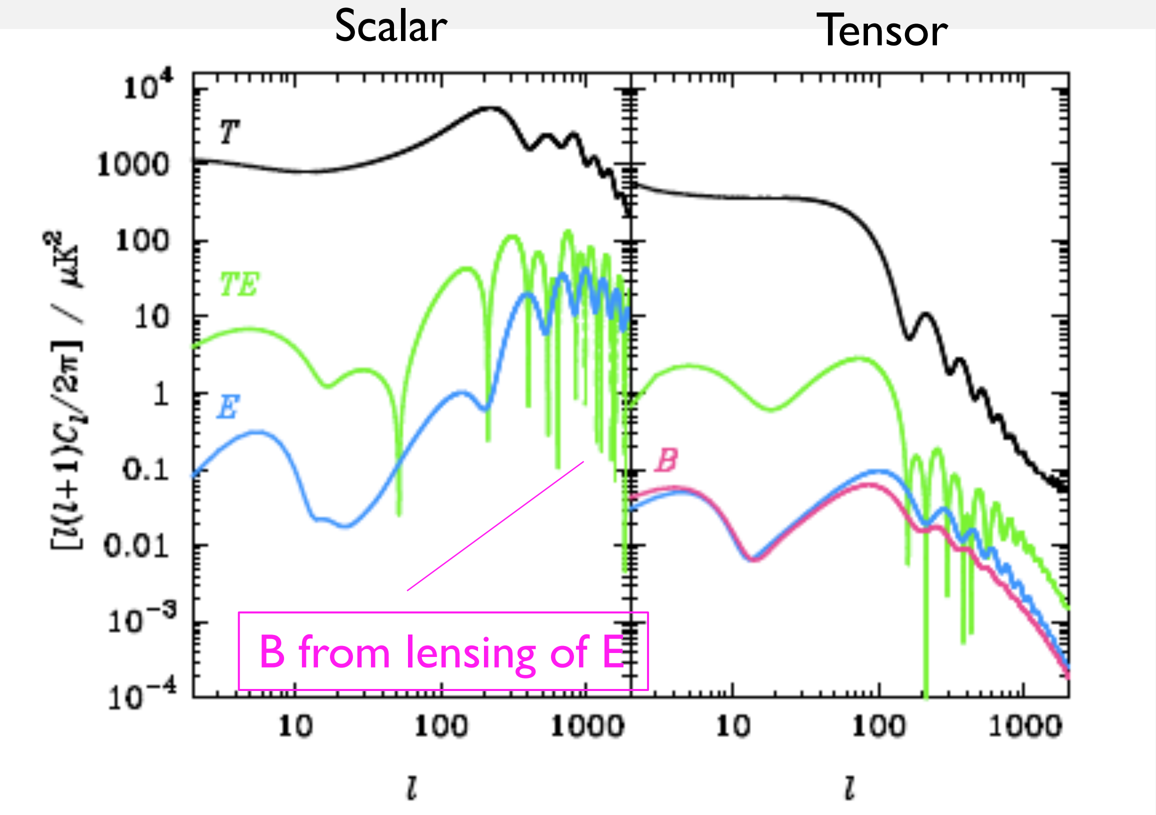


Small scale (angle on the sky)

POWER SPECTRA FOR SCALAR (=DENSITY, LEFT) AND TENSOR (= GRAVITY WAVES, RIGHT PANEL) PERTURBATIONS

Polarization is decomposed as below

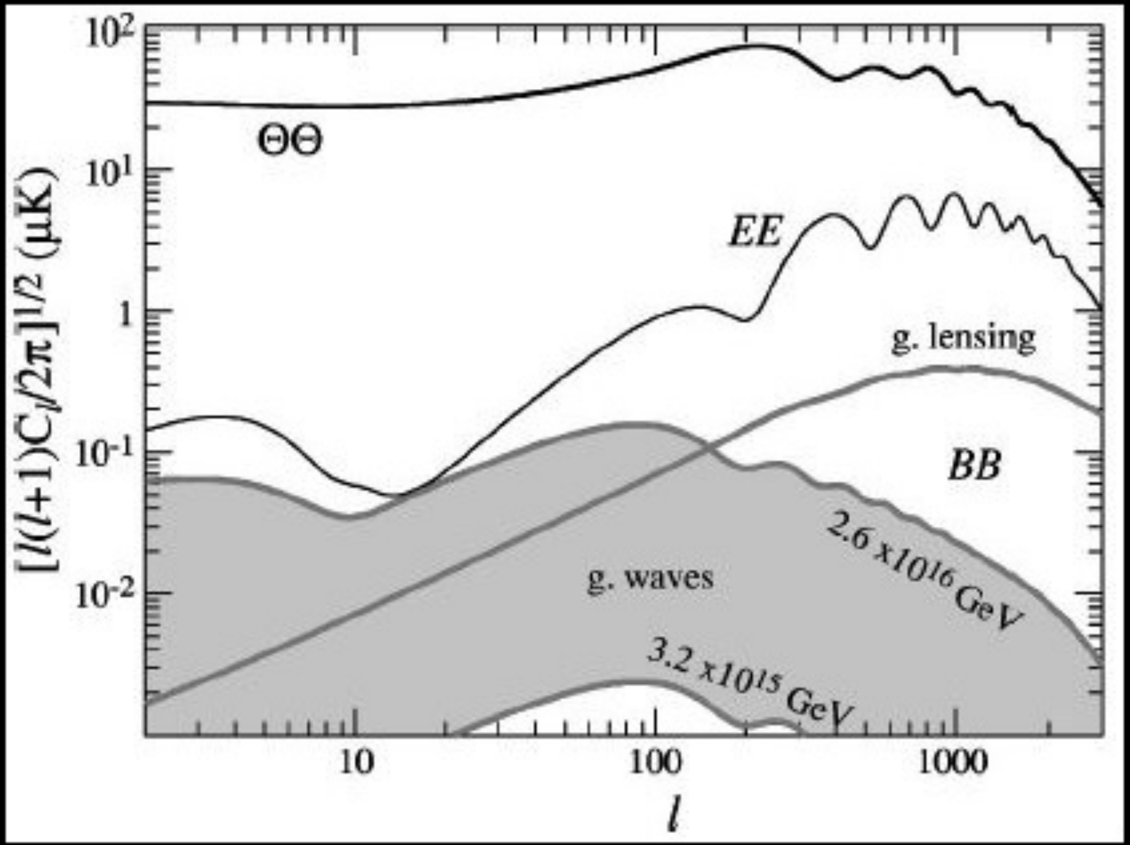




Here also B is produced!

Tensor to scalar ratio r=1

EXPECTED B MODES AND INFLATION

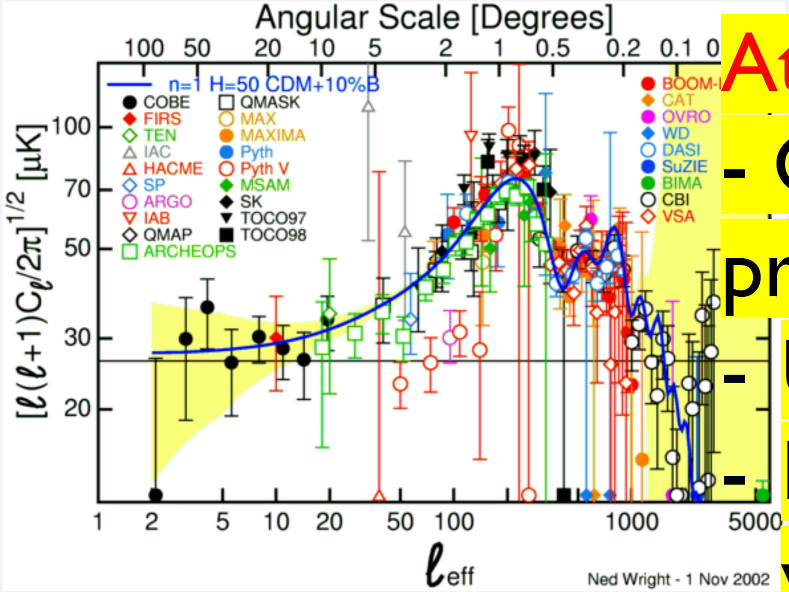


$$[l(l+1)C_{Bl}/2\pi]^{1/2} = 0.024(E_{\rm inf}/10^{16}{\rm GeV})^2\mu{\rm K}.$$

Hu et al 2003

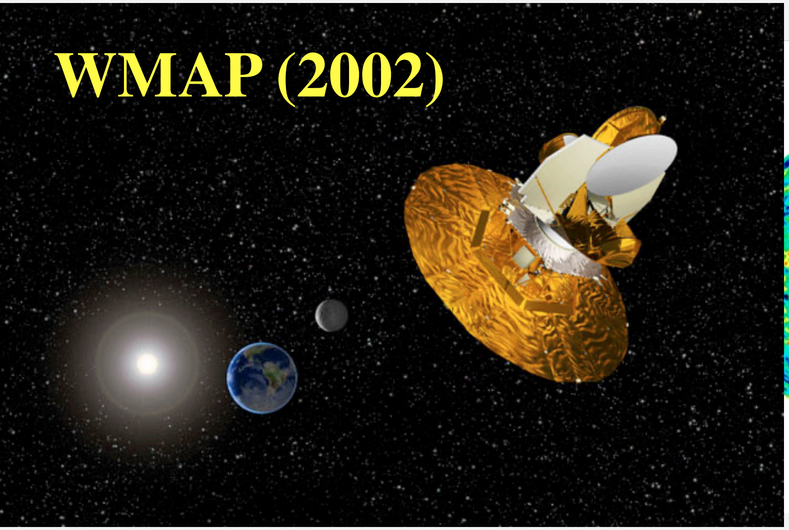
HISTOTY: MEASURING THE POWER SPECTRUM

Pierpaoli, Scott, White (2000)

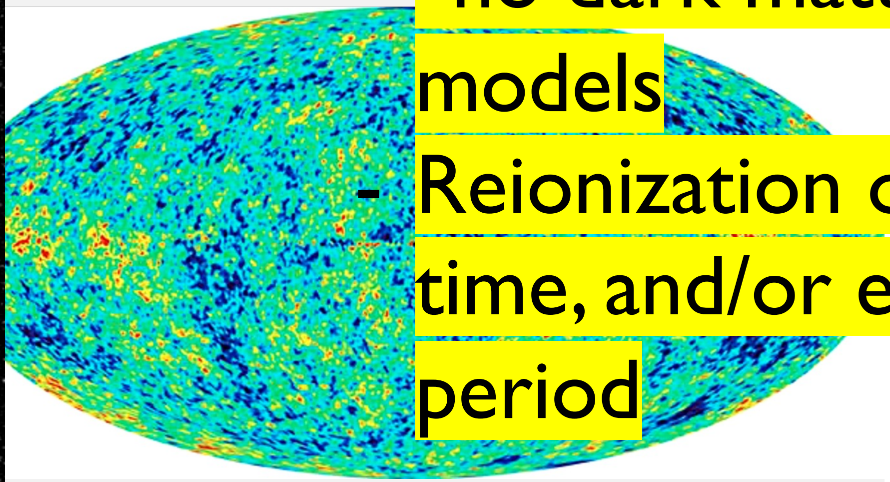


At this stage, we could exclude:

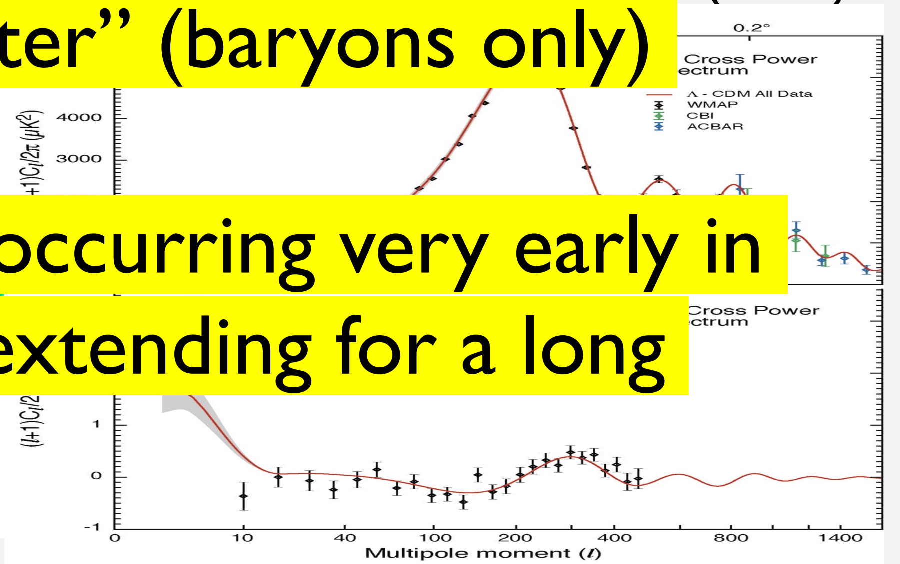
- Cosmic strings/topological defects as process to generate perturbations
- Universes with large curvatures
- Big amplitudes of primordial gravity waves, and related models
- “no dark matter” (baryons only) models
- Reionization occurring very early in time, and/or extending for a long period



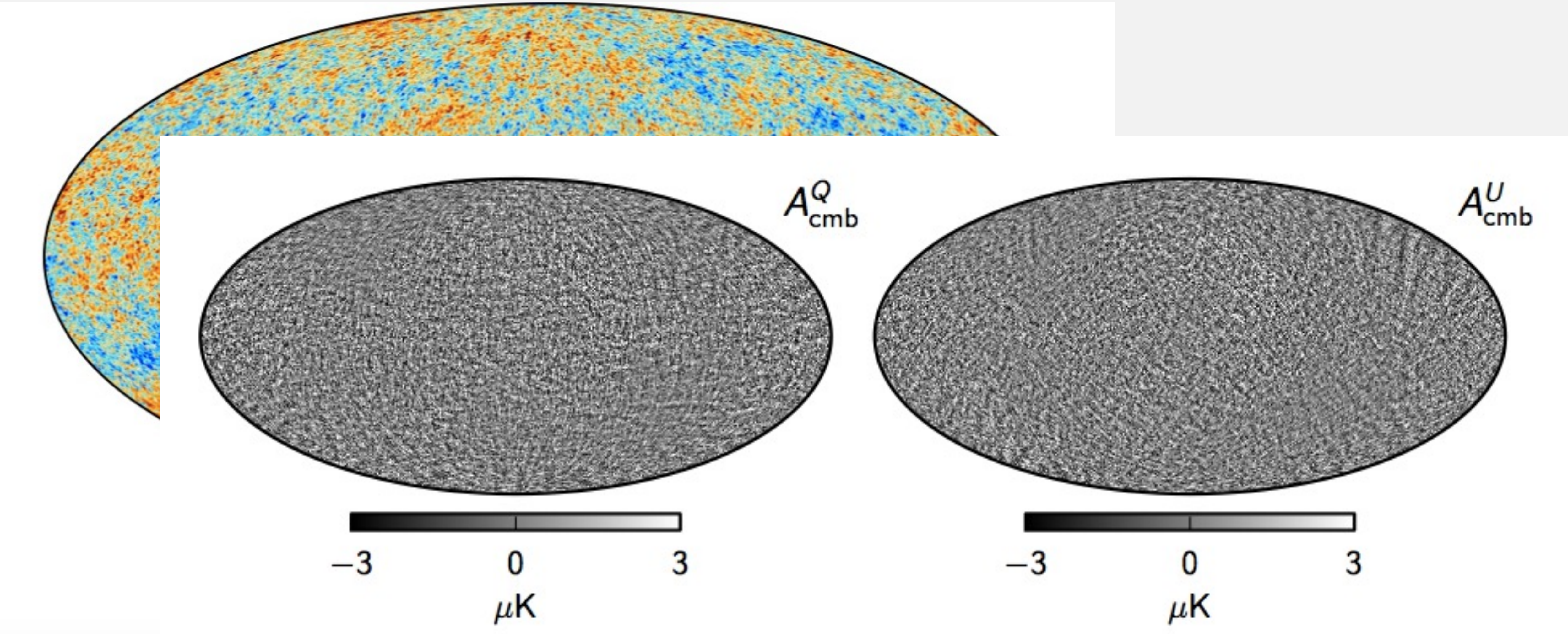
Temperature



...er spectrum (2003)



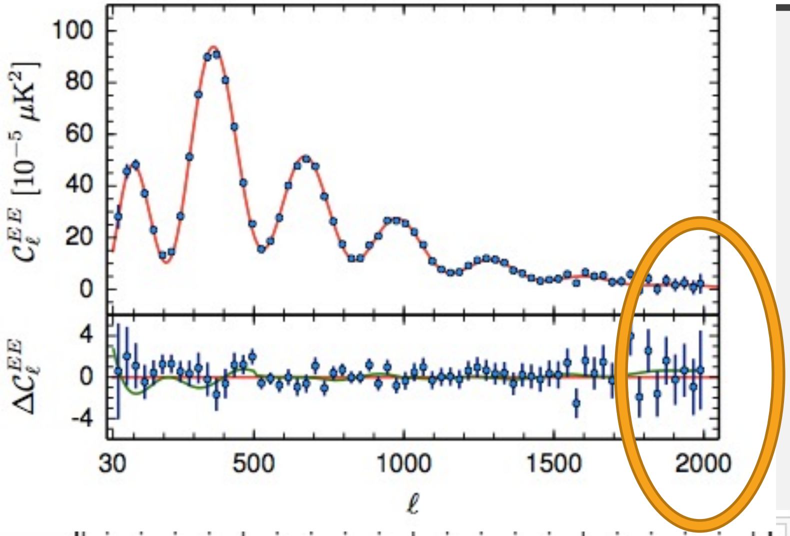
THEN CAME PLANCK….. (2009)



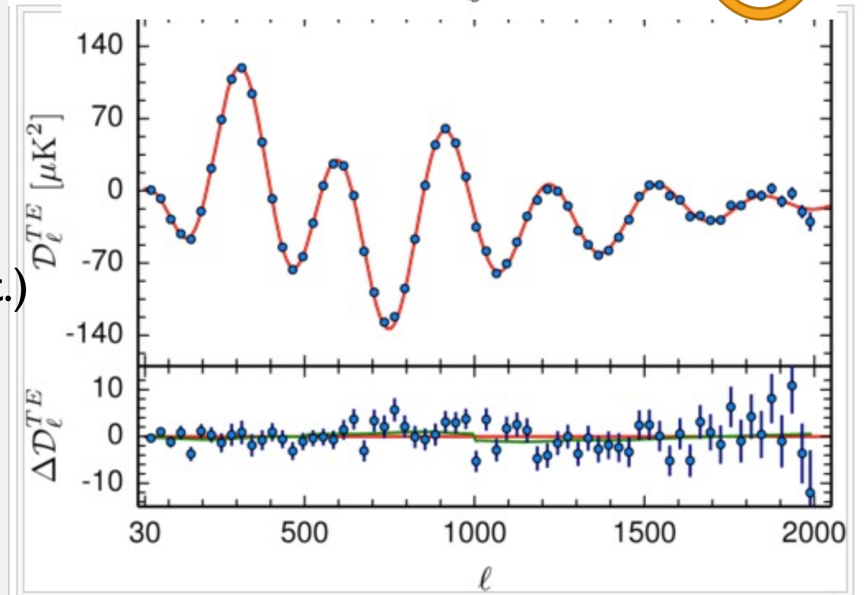
anisotropy intensity map ((5' resolution)

TT AND TE SPECTRA FORM WMAP AND PLANCK

Planck 2015
(intensity: TT)

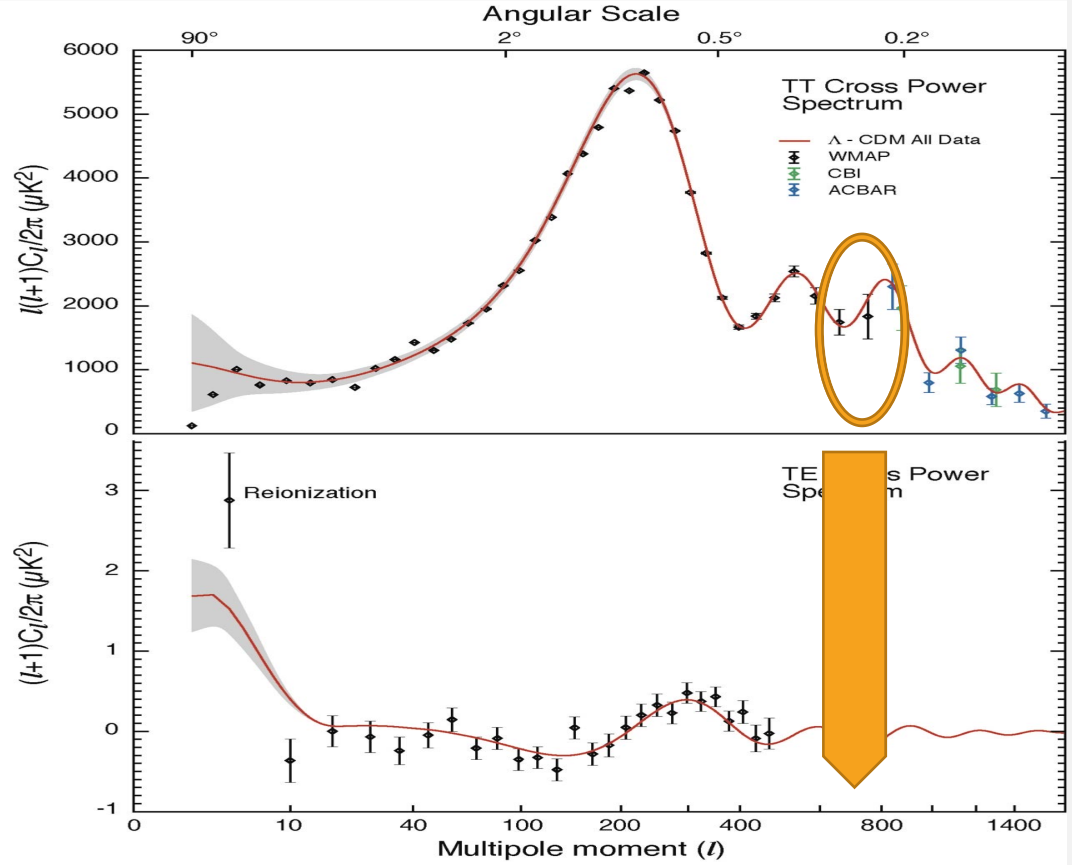


Planck 2015
(TE cross correlat.)



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)

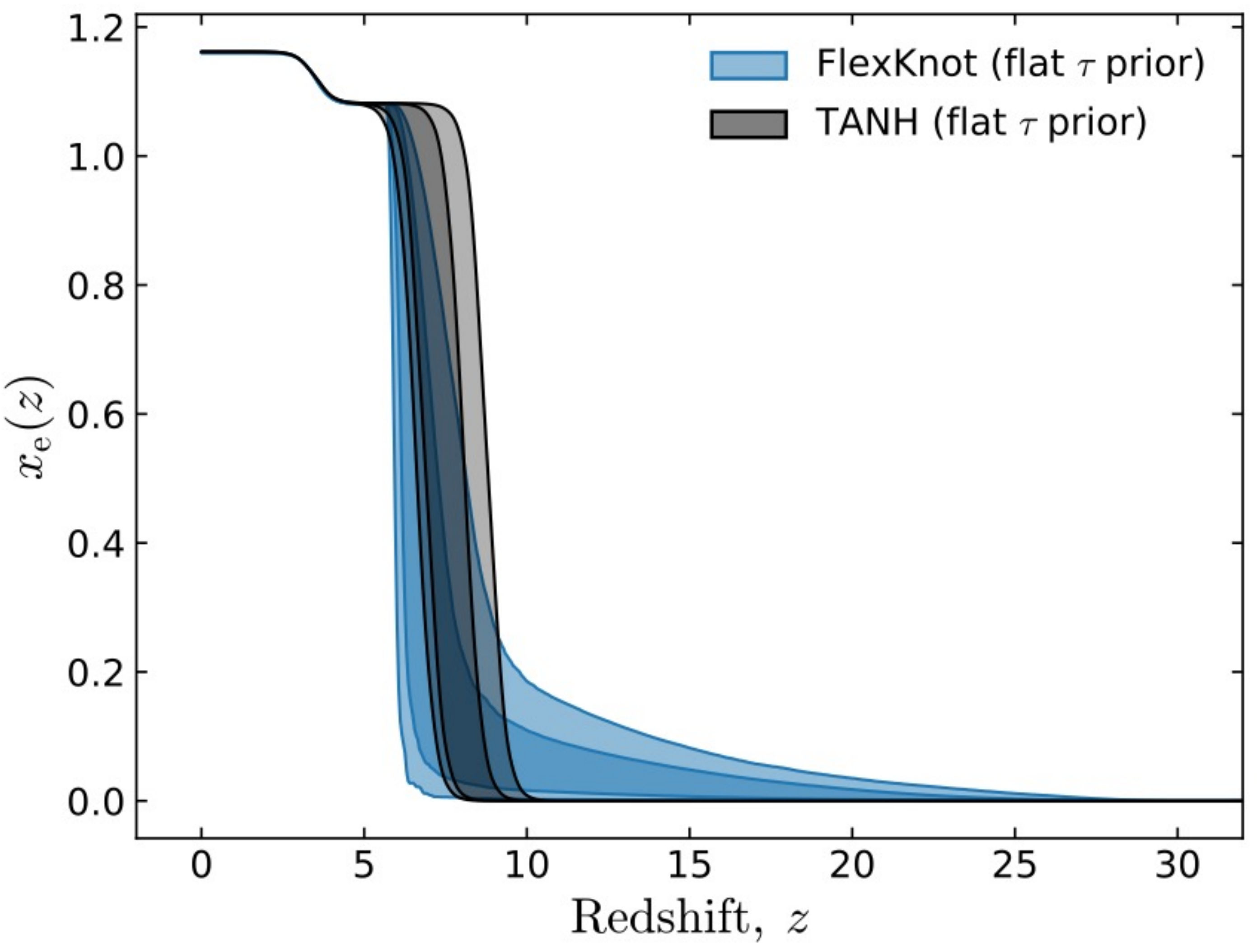


WMAP
TT

WMAP
TE

COSMOLOGICAL PARAMETERS – WHAT WE LEARNED

- 1) Geometry: the Universe is close to flat
  - $\Omega_K = 0.001 \pm 0.002$, Planck+BAO (Alam et al 2021)
- 2) Composition: ΛCDM 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: Σm_ν <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~8
- 4) Inflation is the favorite mechanism for producing perturbations (see next slide)



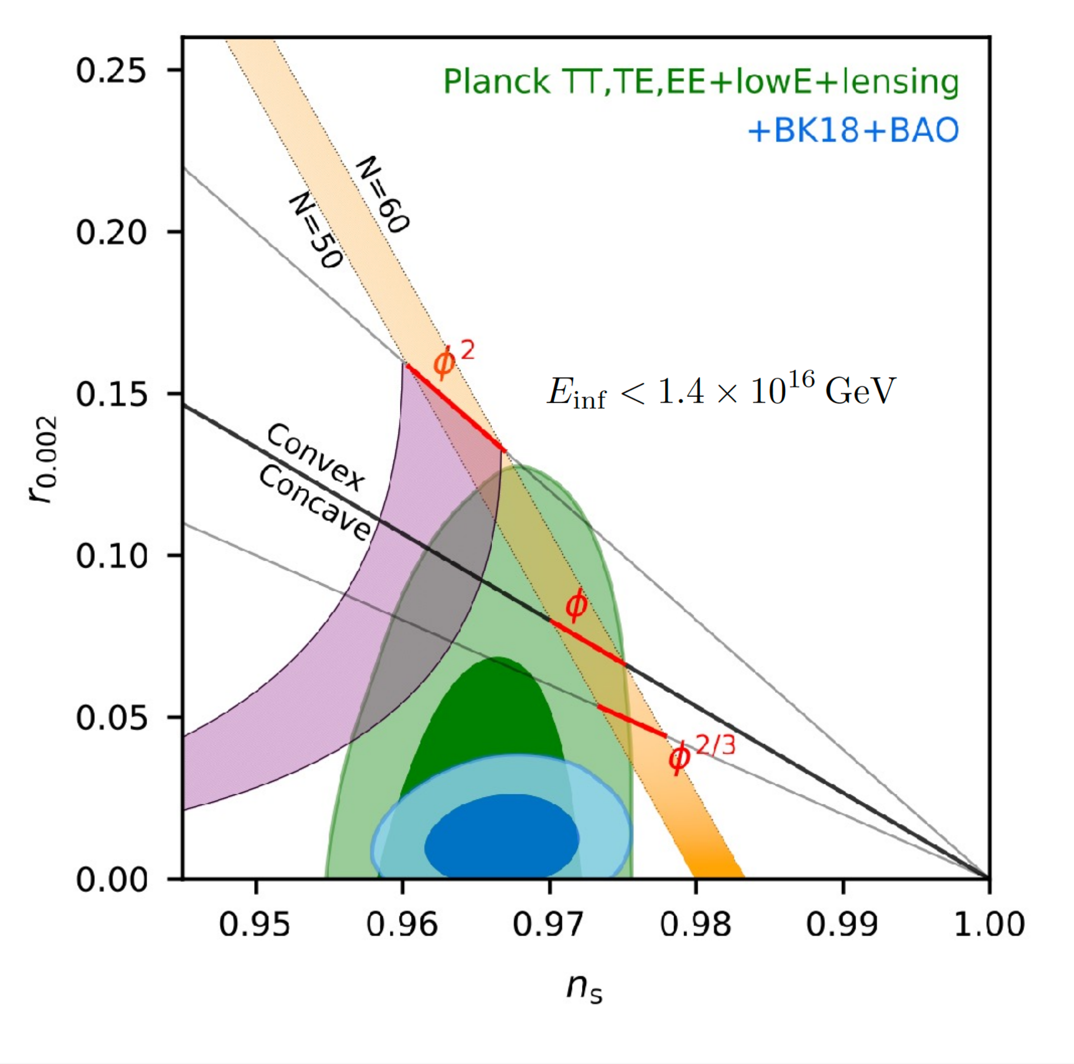
INITIAL CONDITIONS AND LIMITS ON INFLATION

- 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.



SMALL-SCALE EXPERIMENTS (CURRENT: SPT AND ACT)

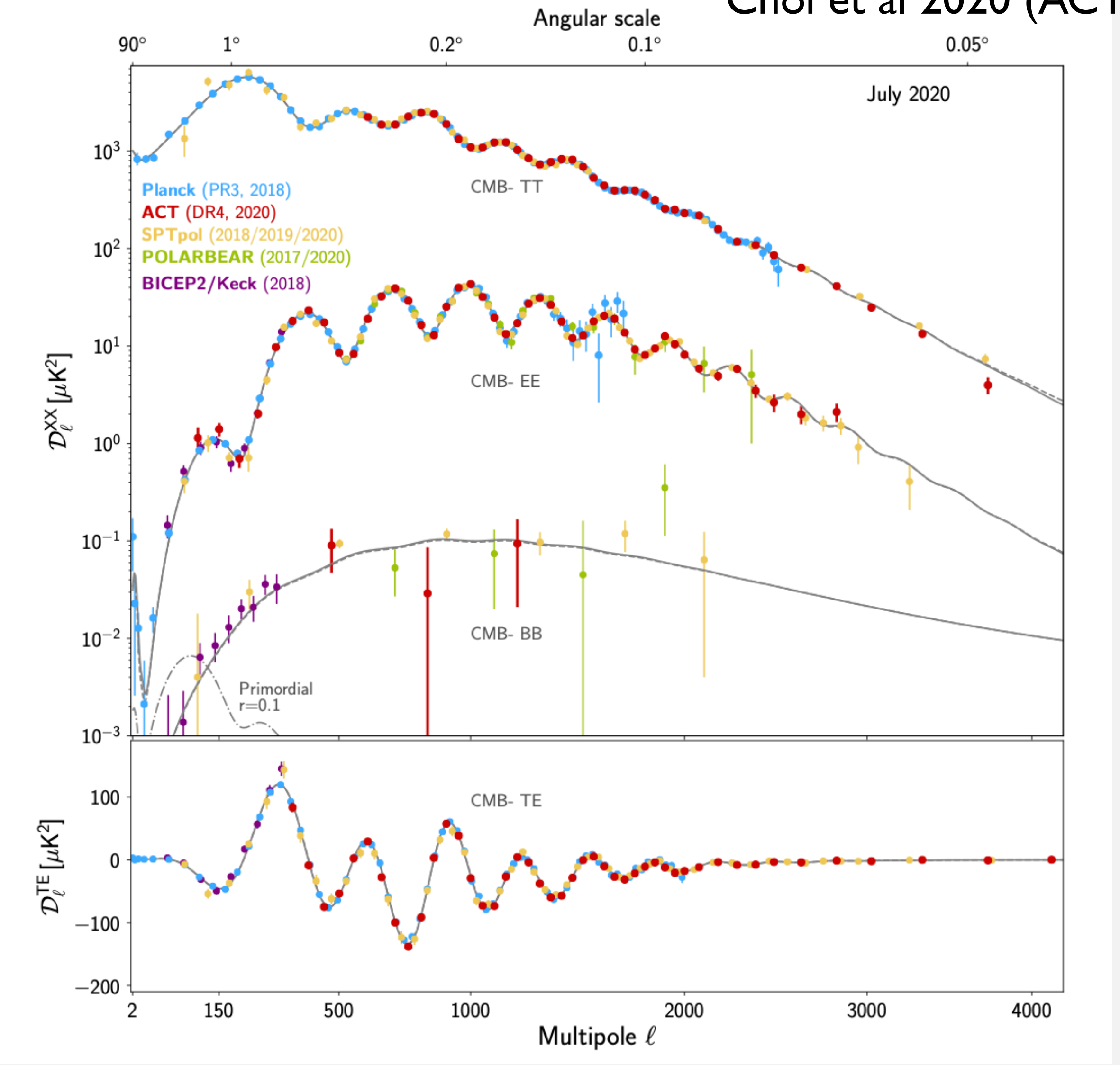
-- Added information on small scale
(currently l~4000 in TT and TE)

--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)

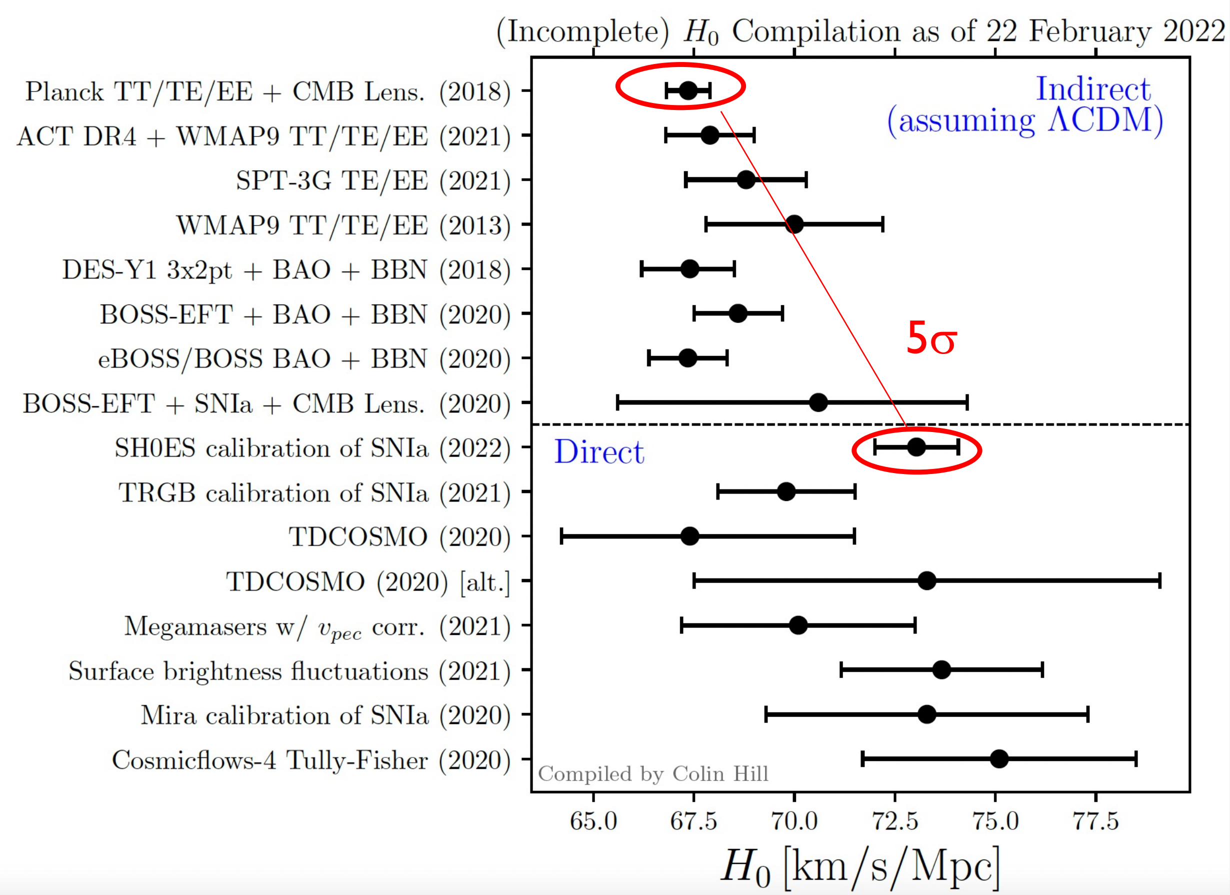
[See also Dutcher et al 2021 for updated SPT results]

Choi et al 2020 (ACT coll)

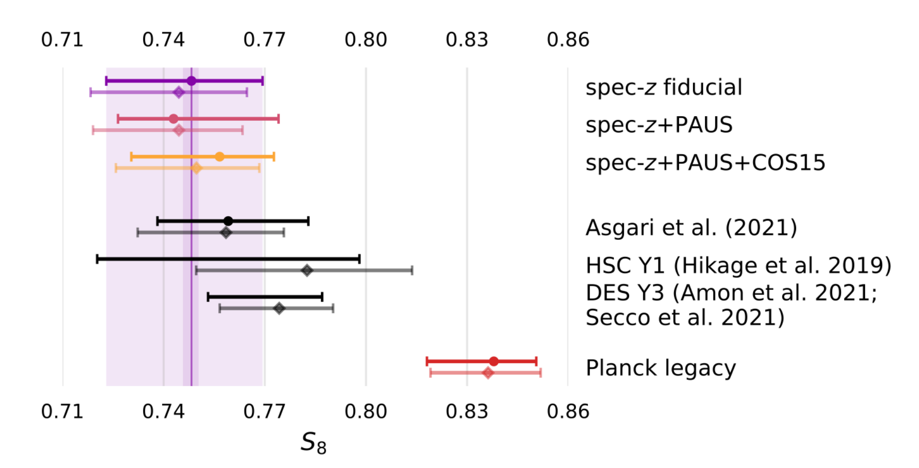


CURRENT "PUZZLES" INVOLVING THE CMB AND OTHER PROBES

- **H_0 tension**: SNIA measurement of the "local" H_0 value are in disagreement with what derived from Planck (and most other CMB experiments), which assume, however, ΛCDM. BAO+ BBN measurements are also lower than SNIA (SHOES).



- **S_8 tension**: Cosmic sheer (galaxy lensing) predicts a lower value of the clustering of matter compared with what derived from Planck (3.4σ discrepancy).



van den Busch 2022 (KIDS collab.)

WILL WE HAVE TO REVISE ΛCDM?

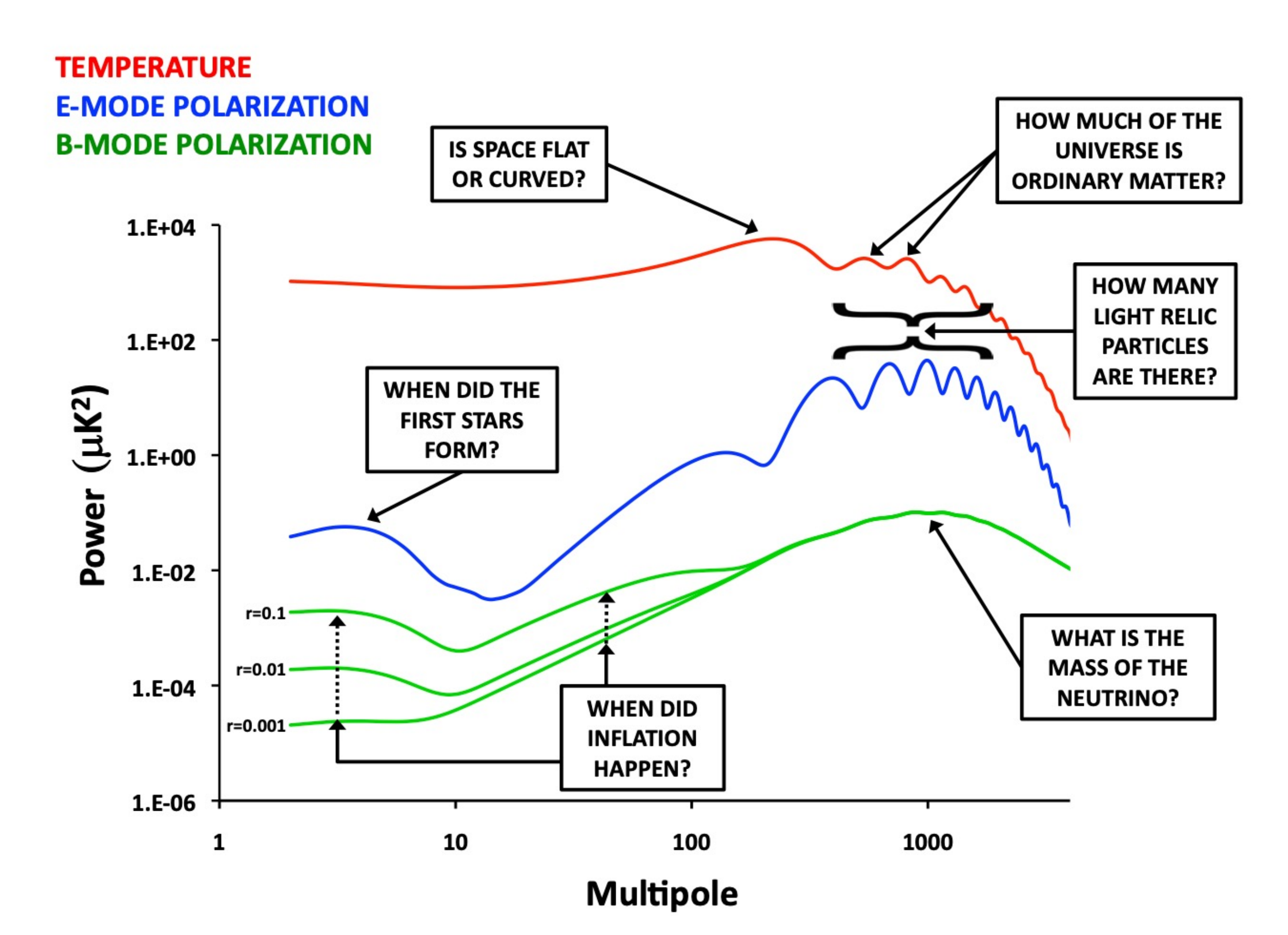
SCIENCE QUESTIONS FOR THE FUTURE (OF THE CMB COMMUNITY)

- 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)?

WHERE TO LOOK FOR A GIVEN SCIENCE GOAL

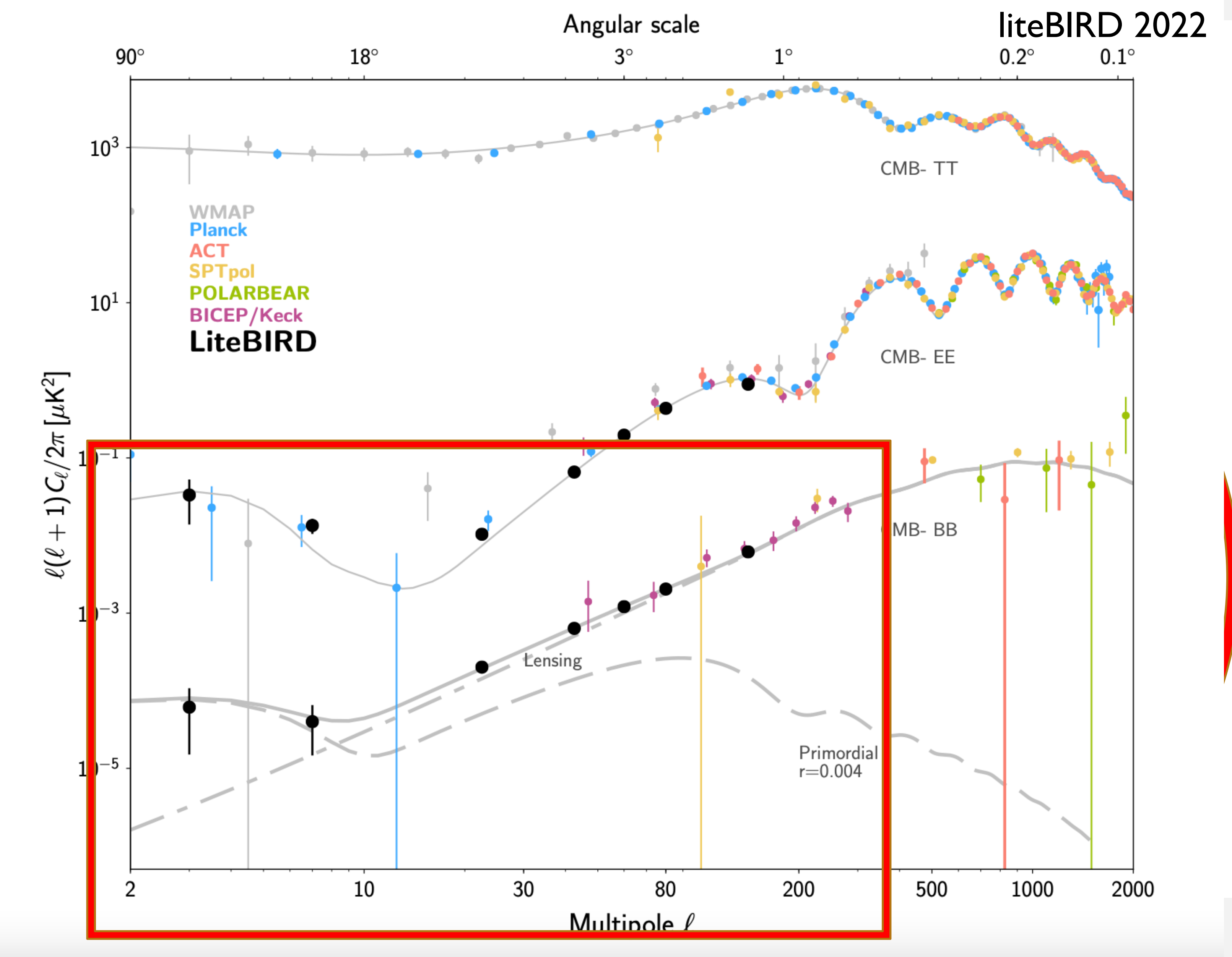


Snowmass Cosmic Frintier: CMB experiments white paper

FUTURE CMB EXPERIMENTS

General directions of new observations:

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



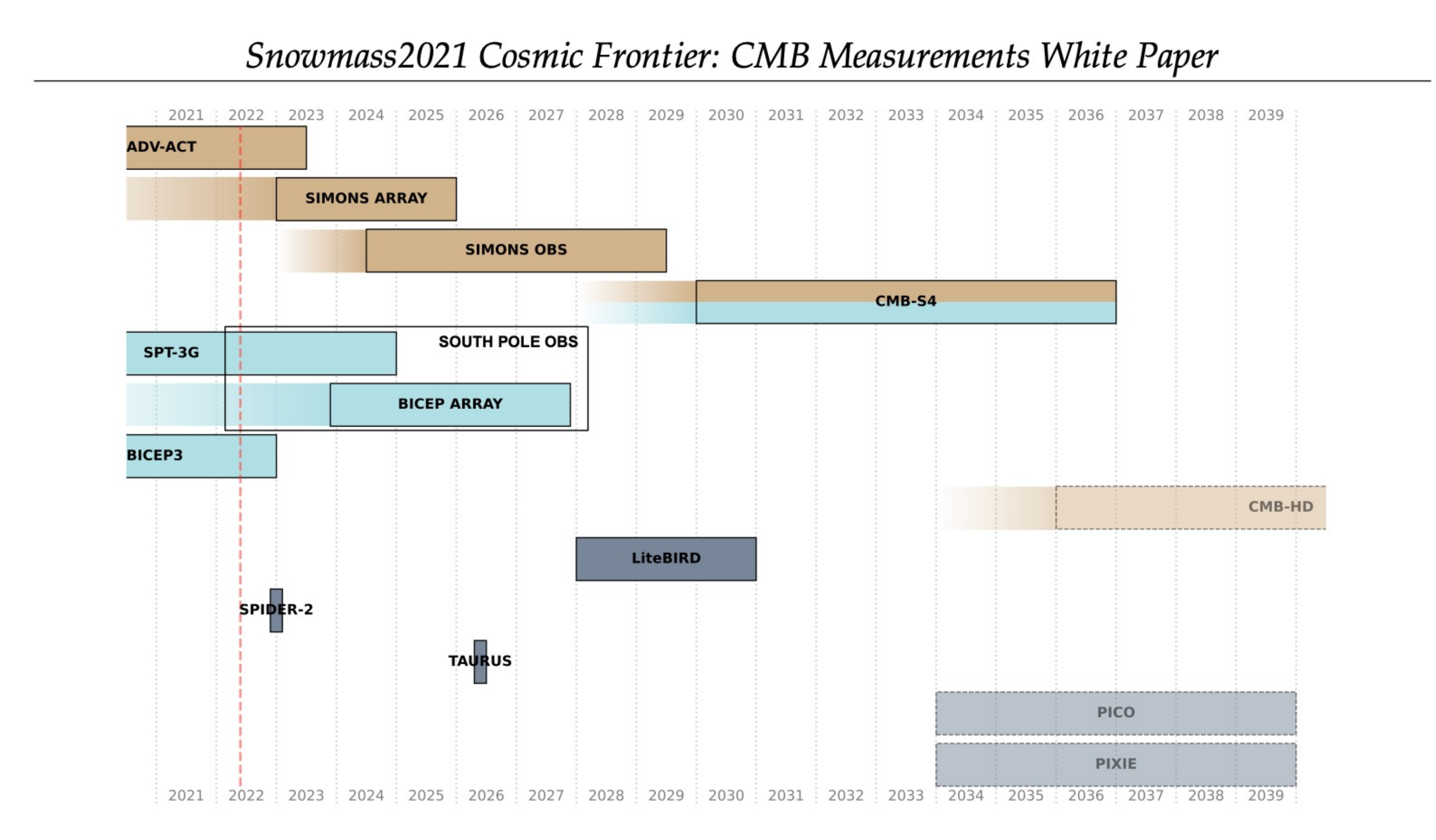
- Simons Observatory (2023-24, ground)
  - ~1 arcmin resolution
- CMB-S4 (2027-2028, ground)
  - ~1 arcmin resol. Noise:1-10 muK-arcmin
- CMB-HD (>2030, ground)
  - 0.15 arcsec res, Noise: -0.5-5 muK-arcmin
  - Lensing measurement. Dark matter, small scales
- LiteBIRD (2027-28, satellite, L2)
  - Low noise, large frequency coverage, large beam.
  - Tensor modes + reionization, large scale BB

TIMELINE OF EXPERIMENTS

Atacama desert

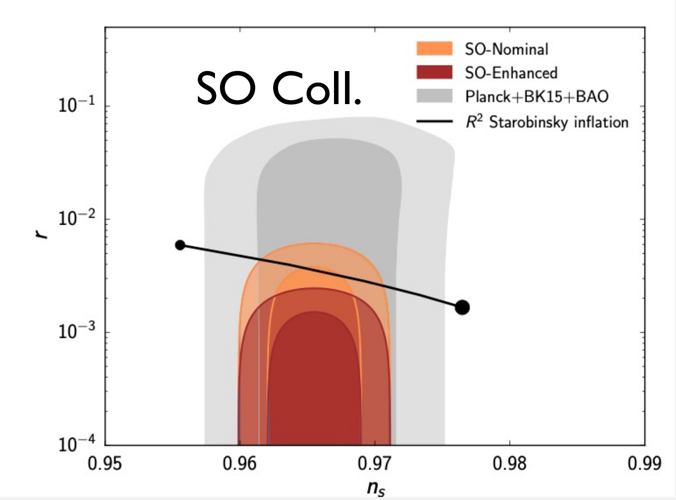
South Pole

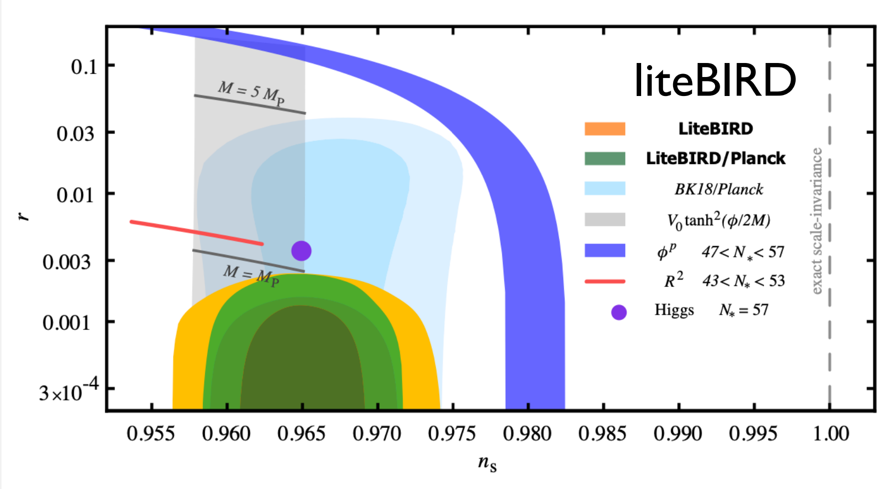
Space

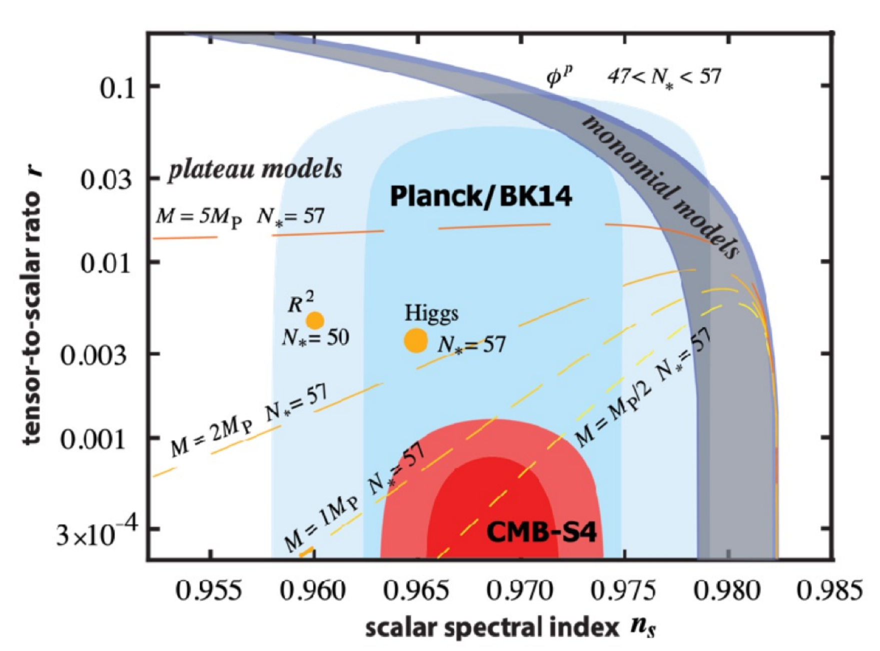


EARLY UNIVERSE SCIENCE: GRAVITATIONAL WAVES

- 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.



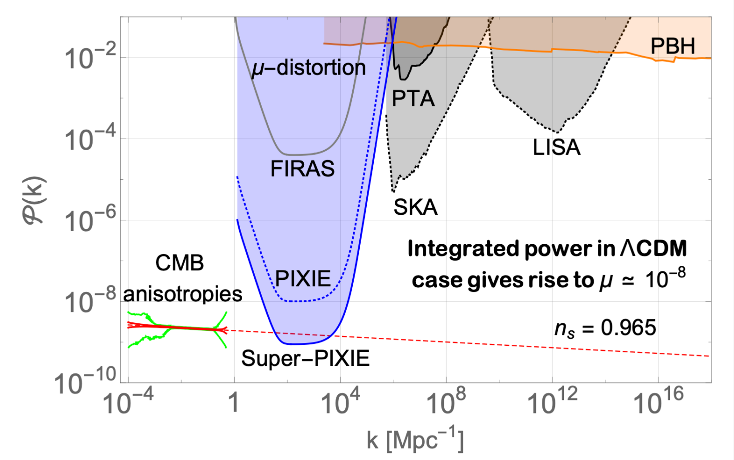


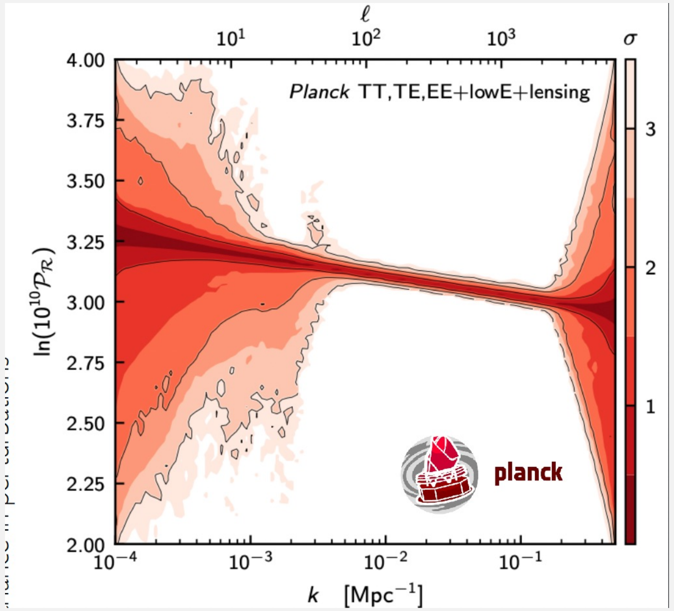


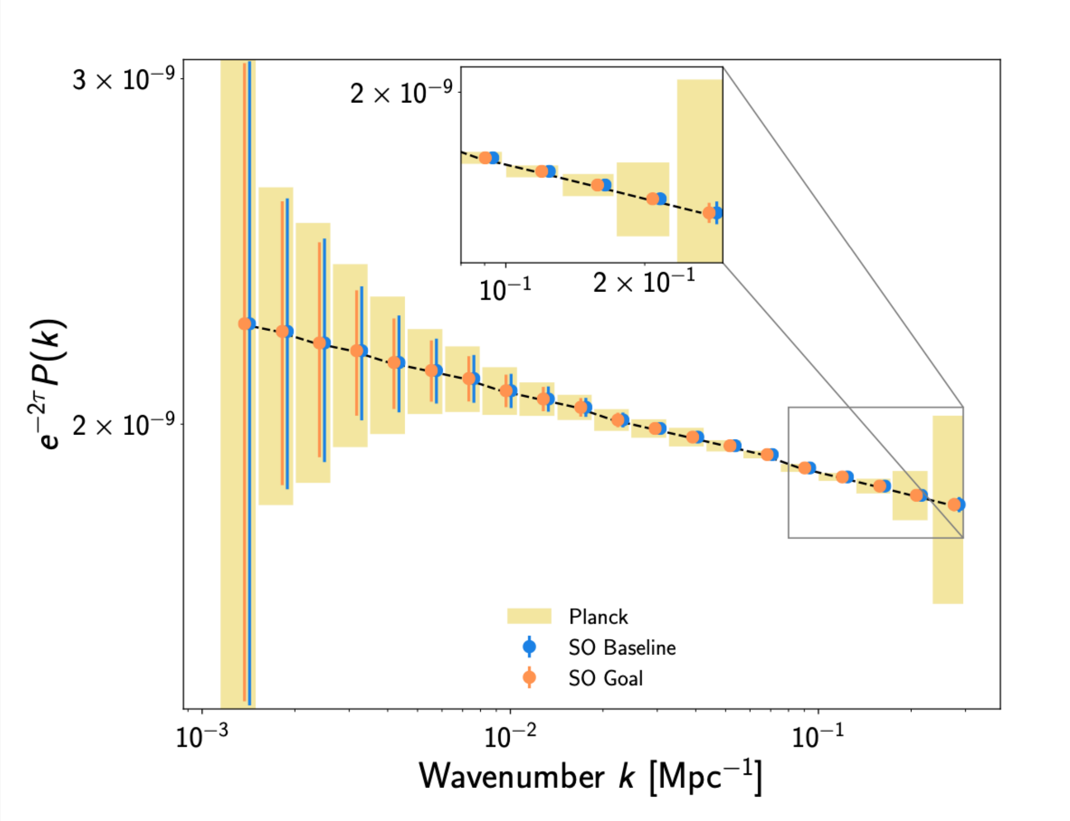
CMB-S4 collaboration

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.



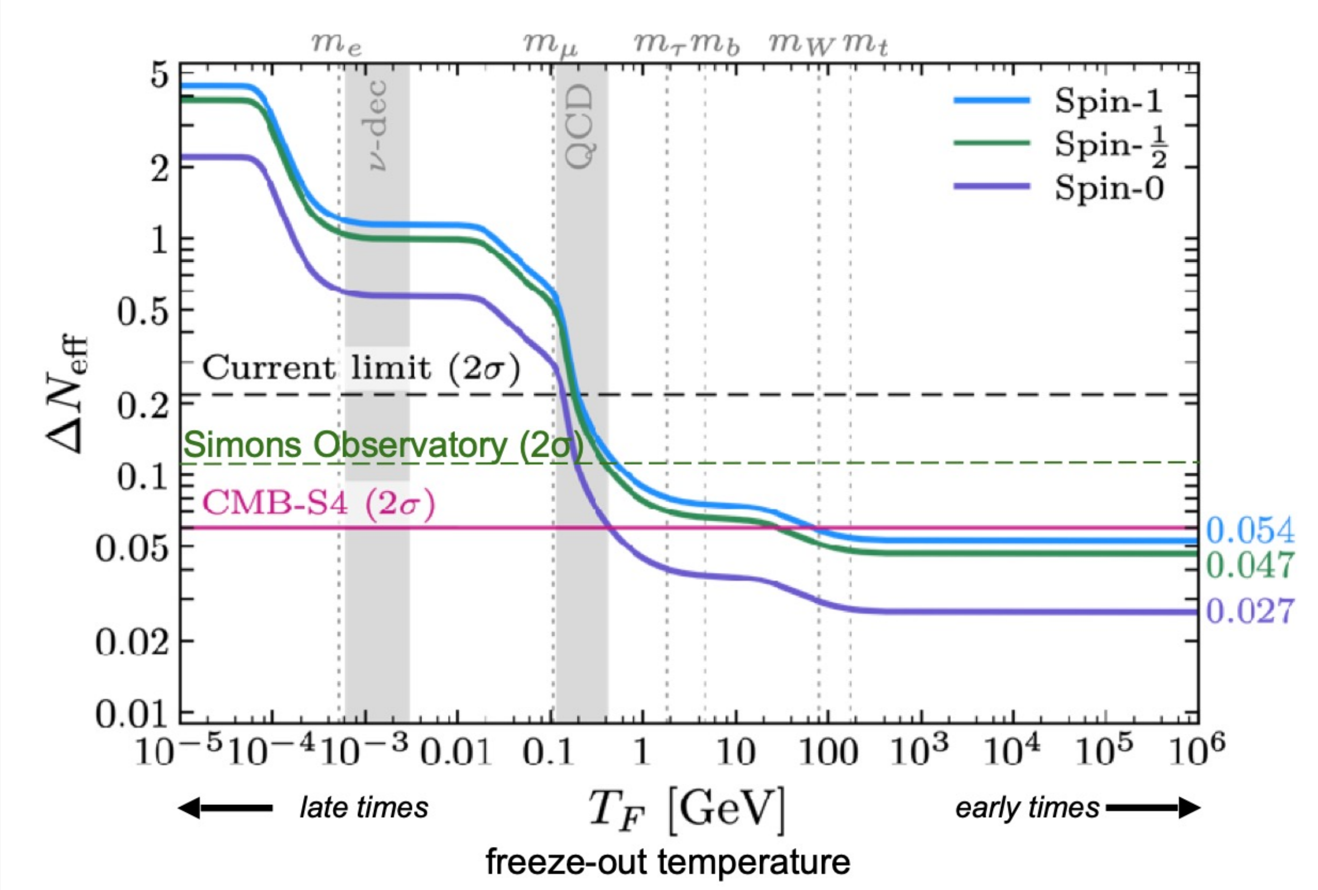




Chluba et al 2019
(Voyage 2050 science paper)

LIGHT RELICS

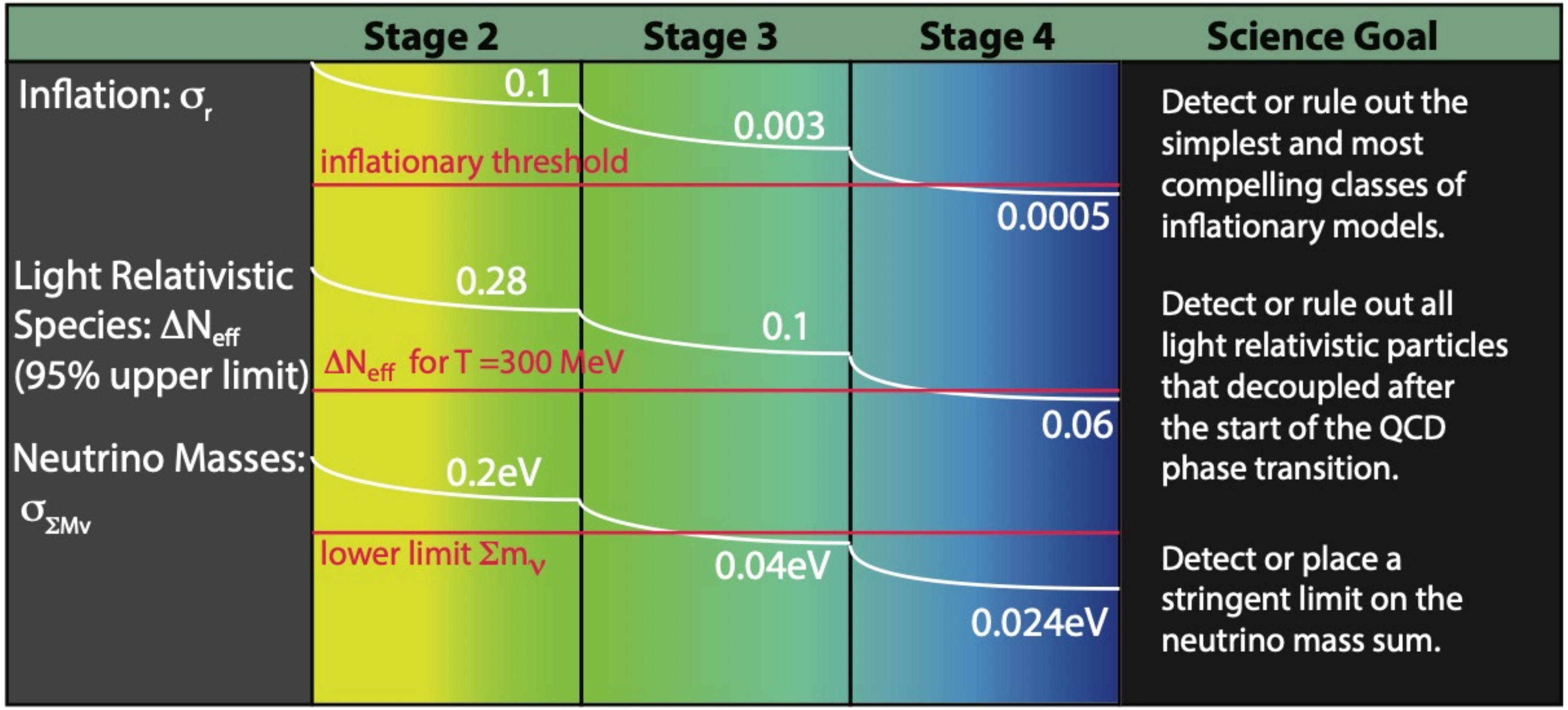
- N_{eff} is expected to be 3.046 if only neutrinos contribute to this number. Other light particles present in the early Universe will alter this value.
- The earlier the freeze-out of the particle, the smaller their contribution to the radiation energy density
- CMB-S4 will be able to detect any kind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



CMB-S4 science book

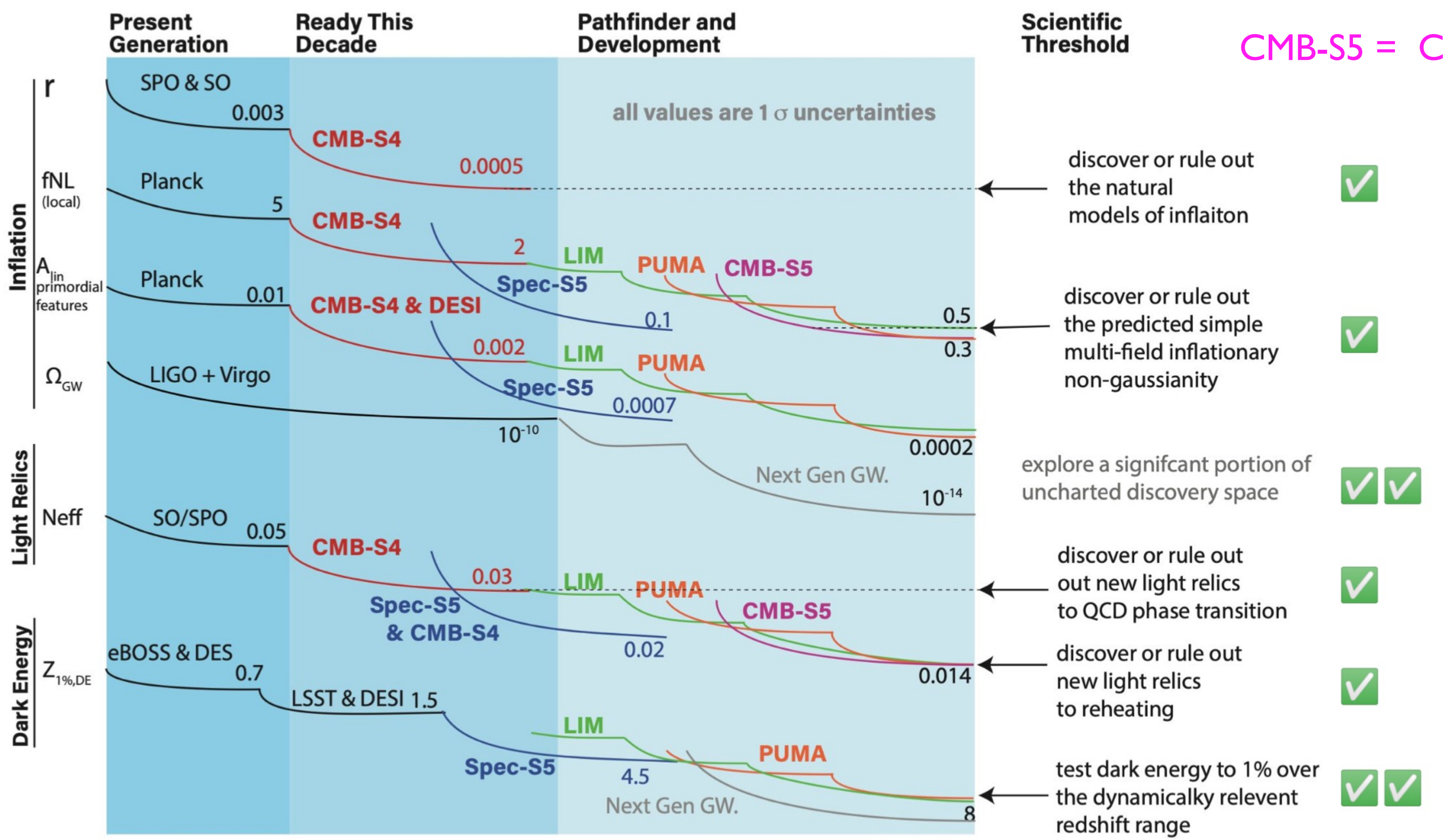
SUMMARY OF EXPECTED RESULTS

Snowmass2021 Cosmic Frontier: CMB Measurements White Paper



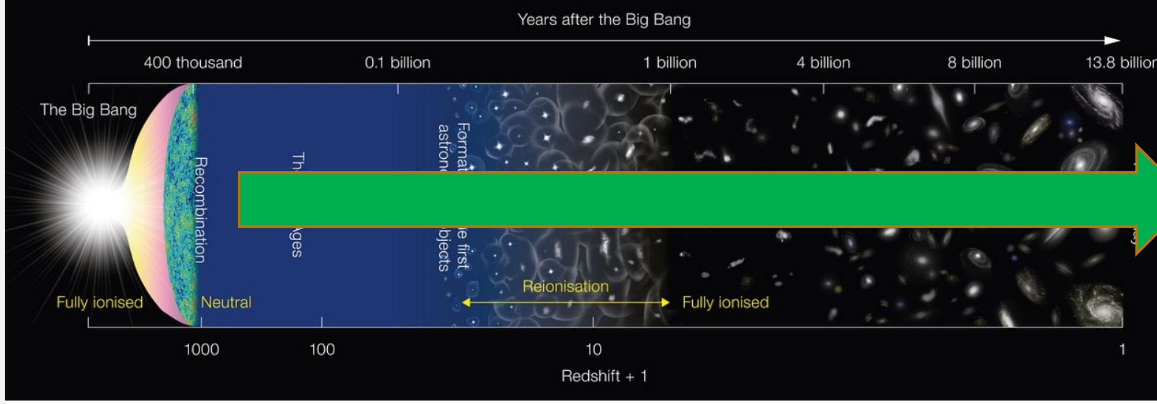
OTHER VERSION

CMB-S5 = CMB-HD



Elena P

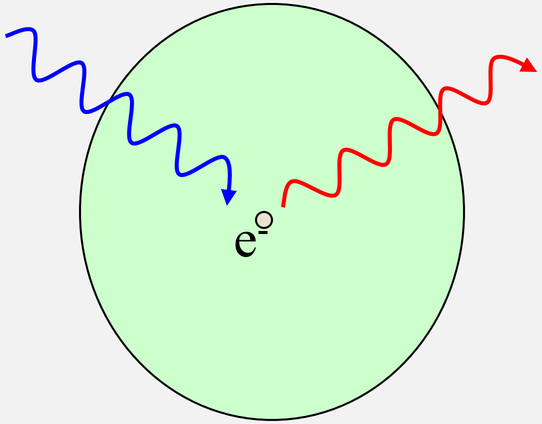
SECONDARY ANISOTROPIES



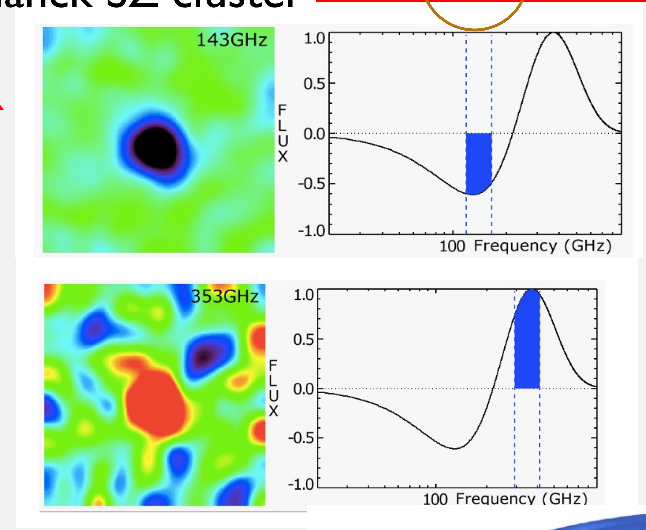
Thermal and kinetic Sunyaev Zeldovich
(CMB scattering off hot/free electrons)

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

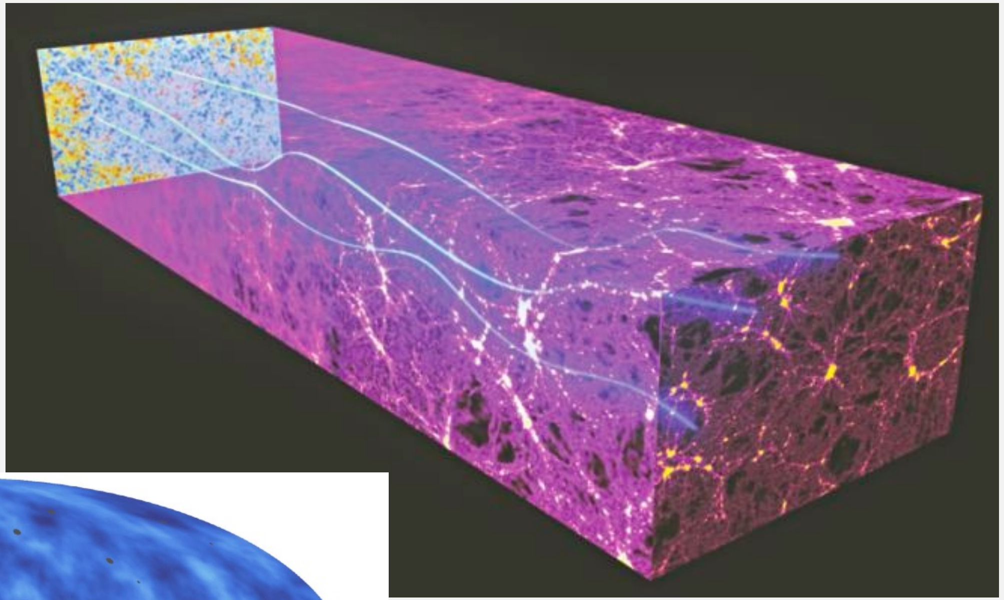
cluster



Planck SZ cluster

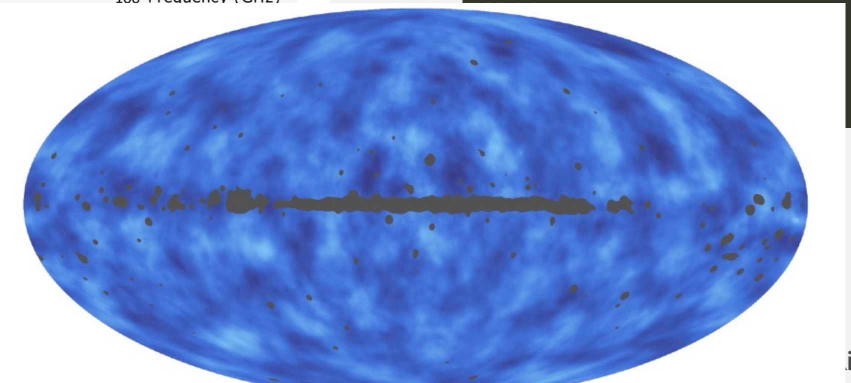


Gravitational lensing (and ISW)



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

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



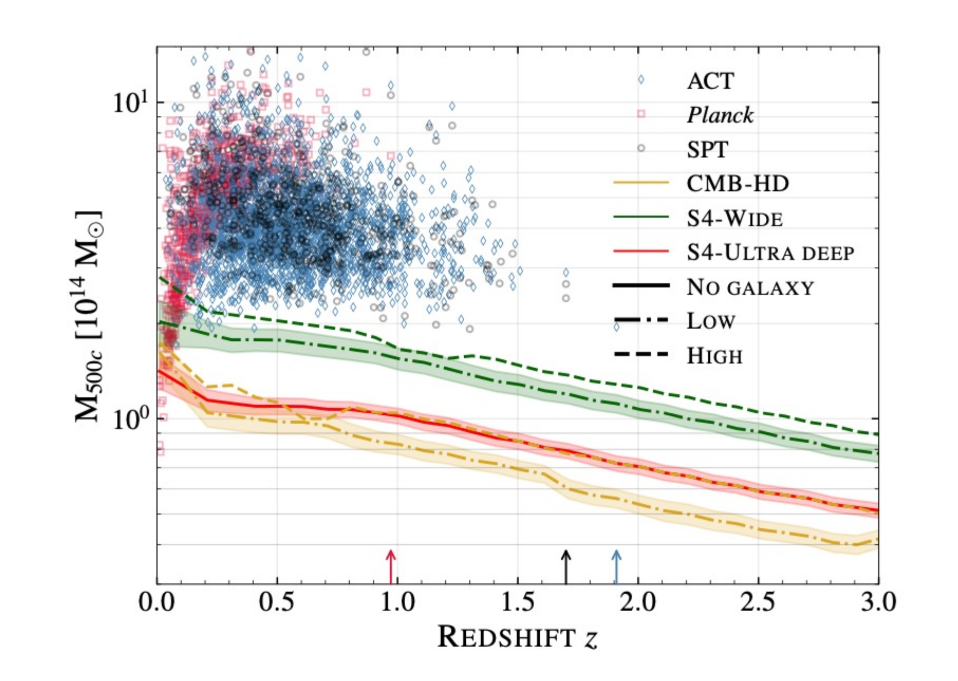
Planck lensing potential map

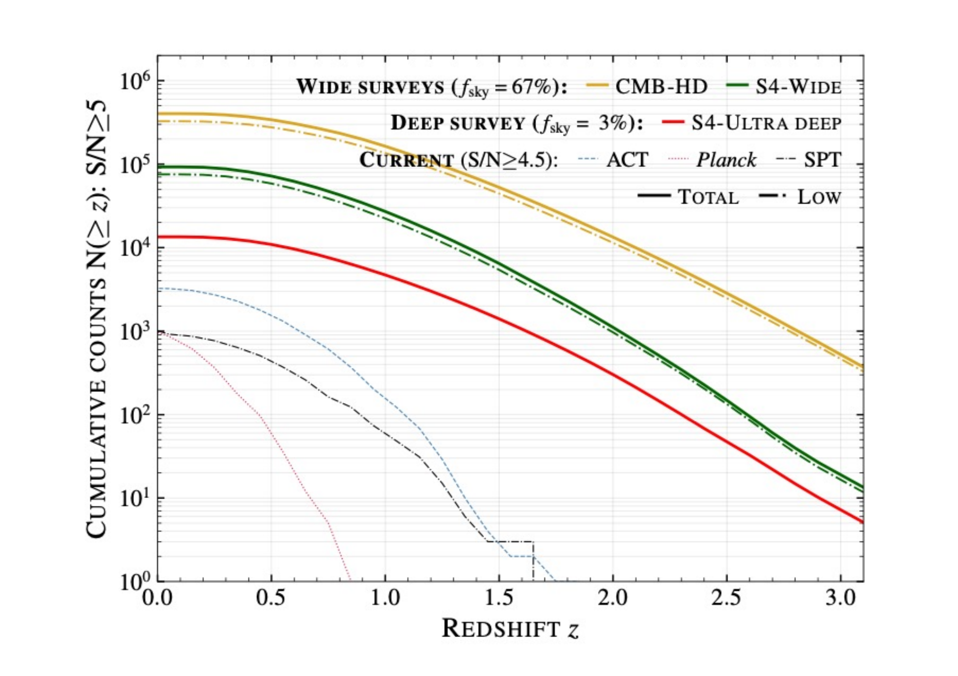
Growth of structures at
early/late times
Dark matter characterization

CLUSTER DETECTION AND NUMBER COUNTS (TSZ)

1653 Planck detected clusters
~4000 objects with ACT and SPT

Raghunathan et al 2022



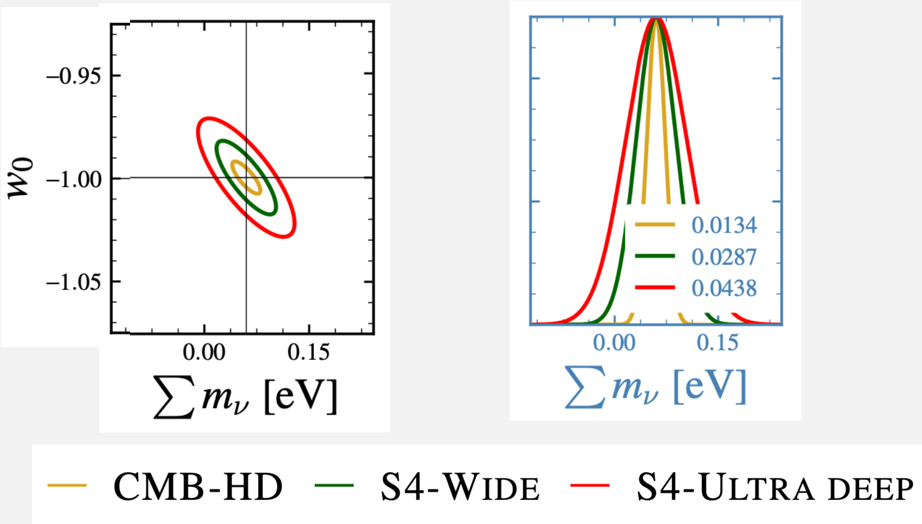


- Detection expected down to very low mass and z~3
- Enabled science:
  - Study of the growth factor (dark energy, modified gravity)
  - Neutrino masses

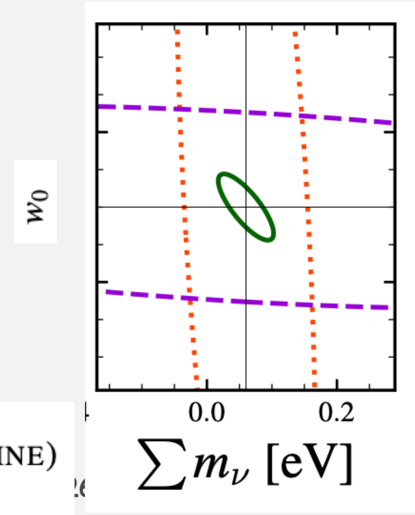
NEUTRINO MASSES AND DARK ENERGY

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.

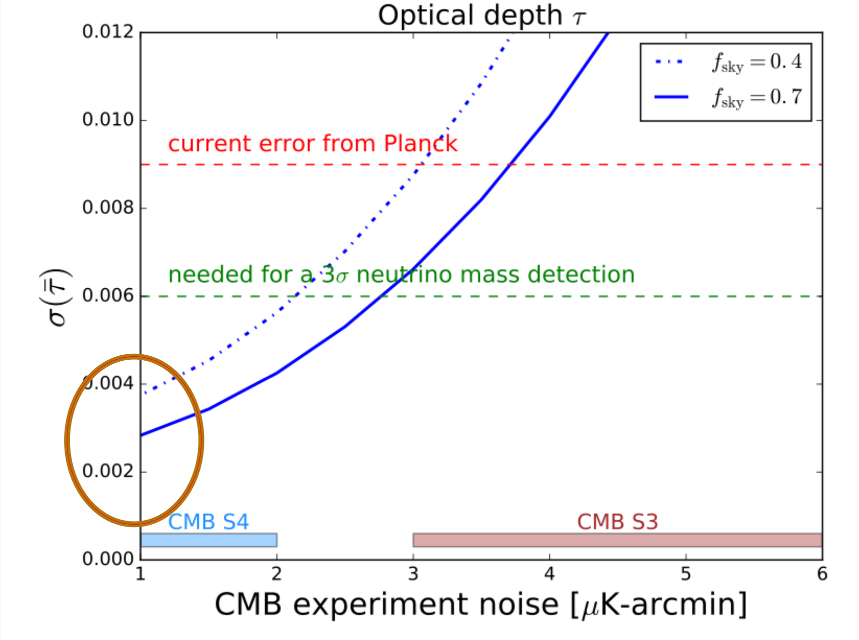


- Current limits: $\Sigma m_\nu < 0.13$ eV (95% CL, Planck + BAO)
- Future limits: $\Sigma m_\nu < 0.03$ eV (from SZ cluster counts (mass calibration from CMB lensing)
- Result are somewhat degenerate with the the dark energy equation of state
- CMB power spectrum and cluster counts are highly complementary

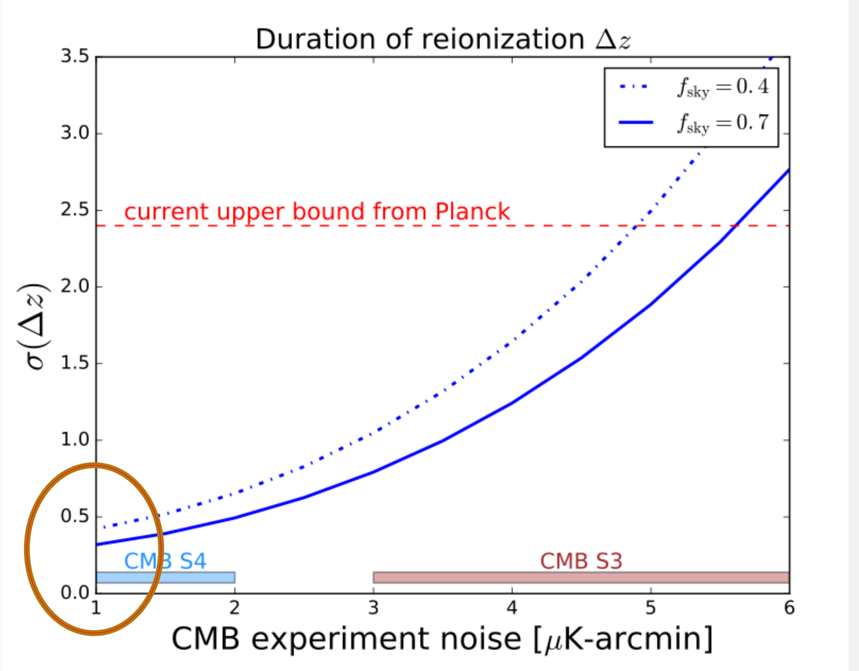


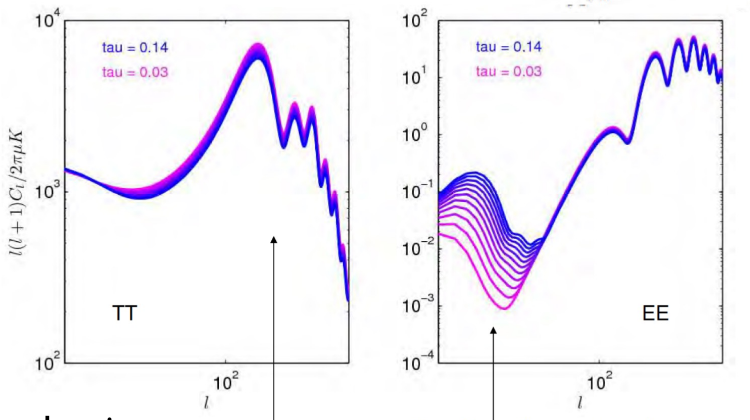
REIONIZATION

Ferraro and Smith 2018



- Reionization leaves an imprint in polarization at large scale and temperature at all scales
- Current "width" of reionization (from Planck): Δz~2
- Expected width from τ measurements with CMB-S4: Δz~0.3
- NB: Better optical depth measurements also needed for best neutrino mass determination



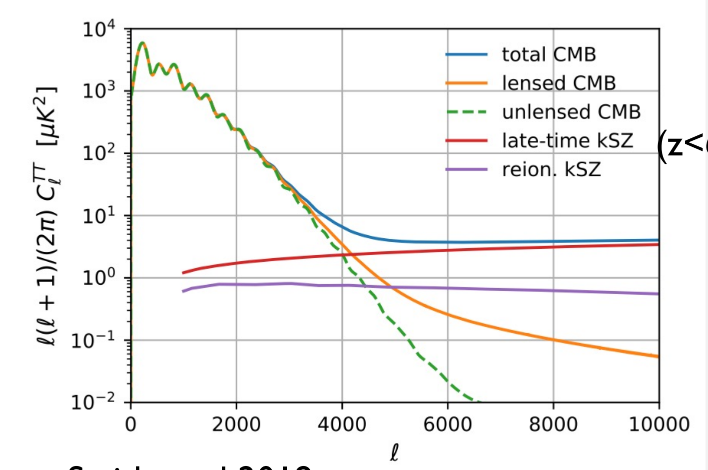


Anthony Lewis

$e^{-2\tau}$ suppression

Quadropole scattered power scales as $\sim\tau^2$

Elena Pierpaoli (USC)

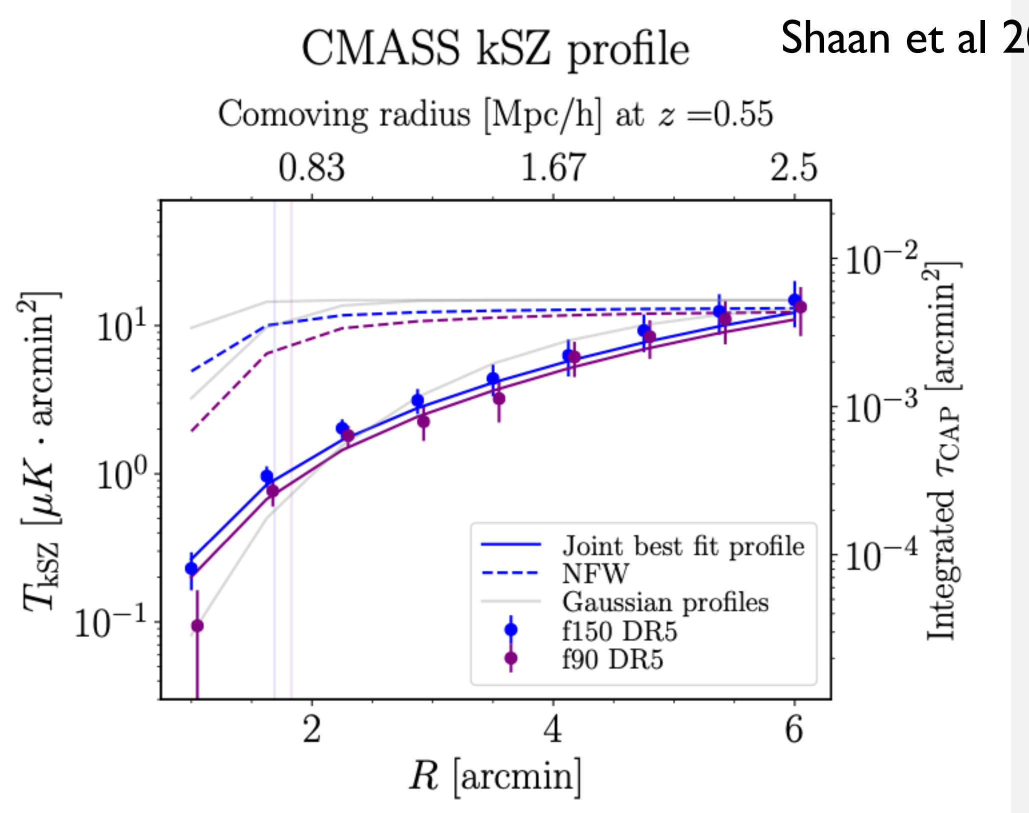


(z<6)

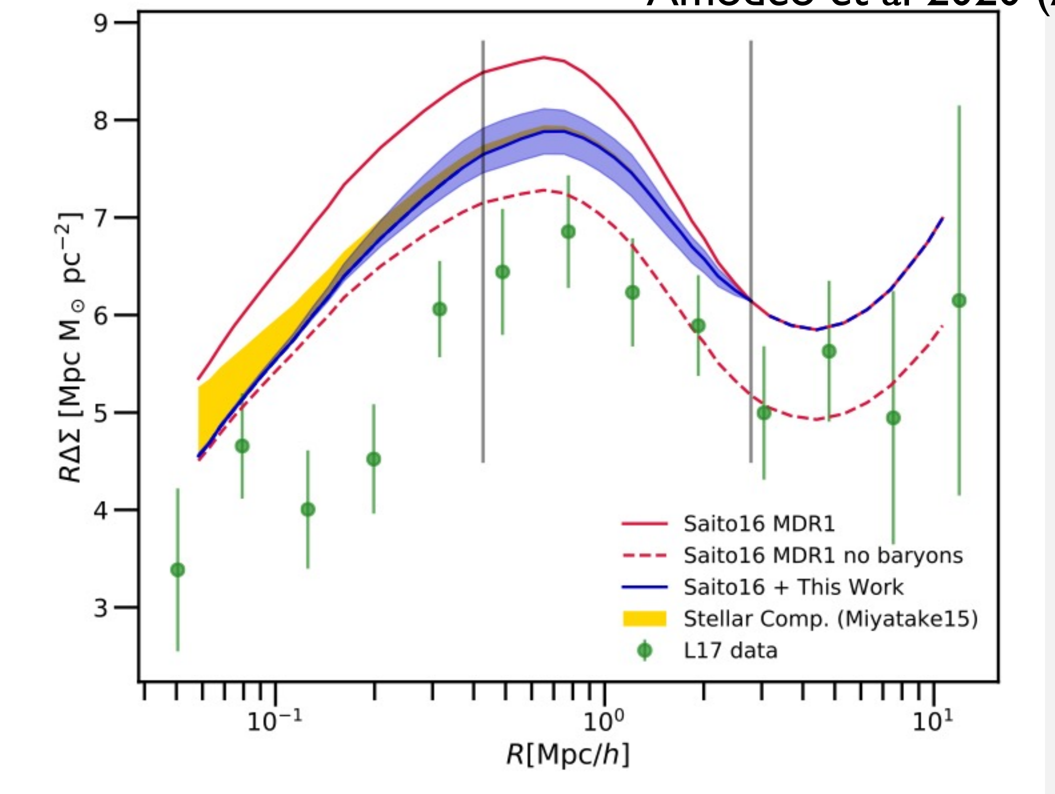
Smith et al 2018

KSZ: GAS DISTRIBUTION IN CLUSTERS

Shaan et al 2020 (ACT)



Amodeo et al 2020 (ACT)



- The profile of the baryon for stacked kSZ clusters does not seem to follow an NFW profile

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

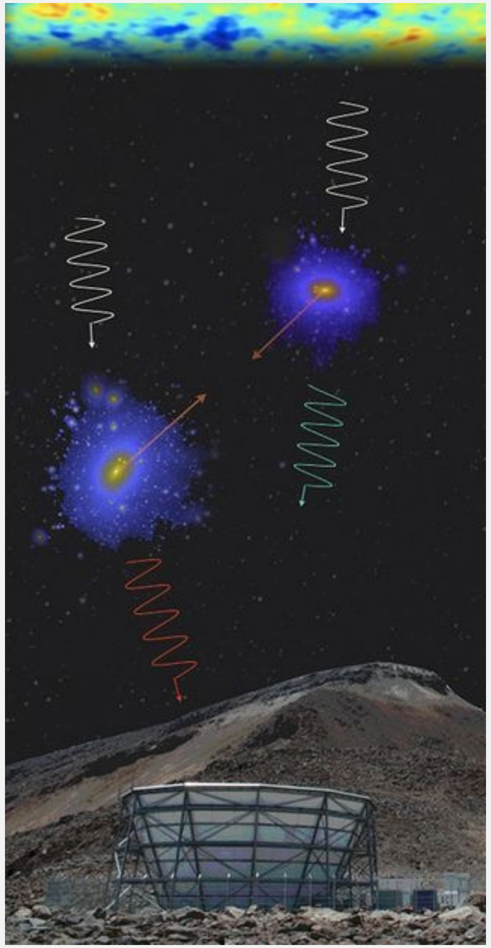
Higher resolution experiments will improve on all the

MAPPING VELOCITY FIELDS WITH SECONDARY ANISOTROPIES: KSZ

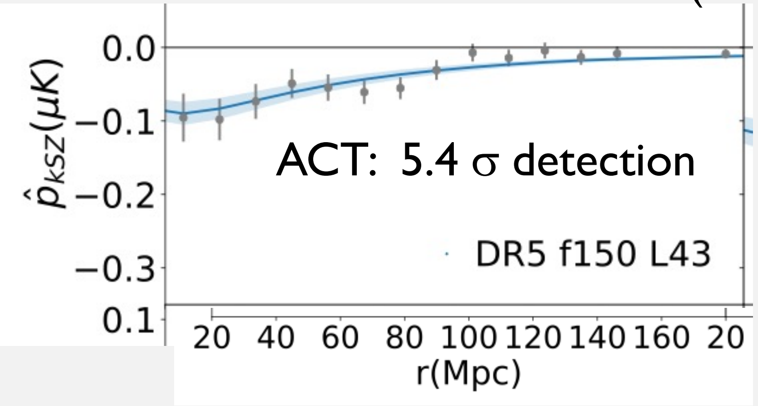
- Pairwise veolicties: Galaxies/clusters at a given separation tend, on average, to move towards one another.
- Current surveys already allow to measure pairwise velocities through the kSZ effect.
- At the moment, there is a detection but the significance is too low to use this probe to infer cosmological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

The kSZ effect measures radial velocity
And optical depth:

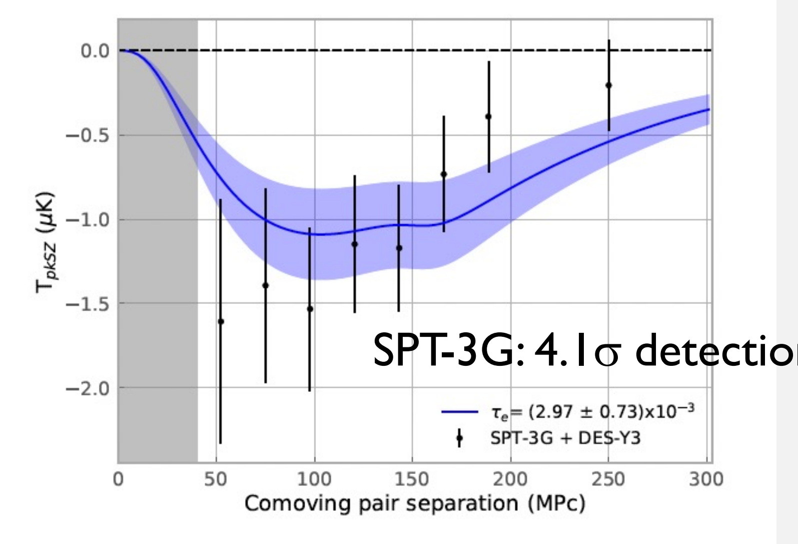
$$\frac{\delta T}{T_0}(\hat{n}) = -\int dl\, \sigma_T\, n_e \frac{v_e \cdot \hat{n}}{c}$$



Calafut et al 2021 (ACT)



Schiappucci et al 2022 (SPT)



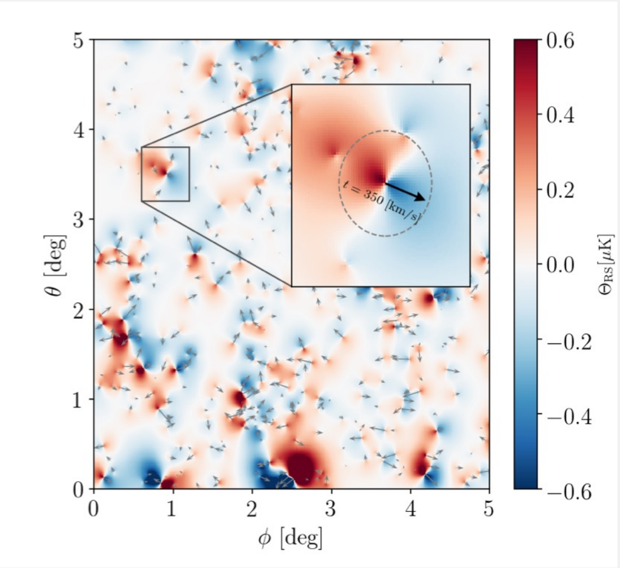
$$\bar{\tau}_e = (2.97 \pm 0.73) \times 10^{-3}$$

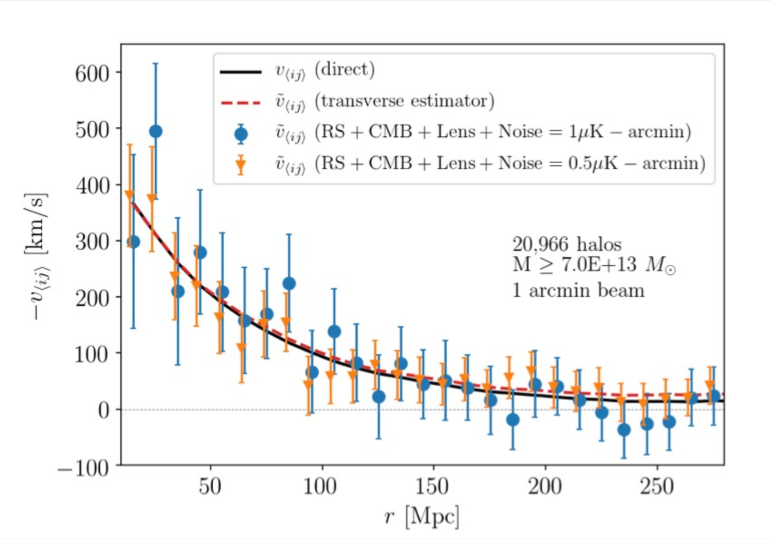
NEW VENUES FOR CMB IMPRINTS OF GRAVITATIONAL LENSING

Detecting the transverse peculiar velocities

- Moving lens effect: photons passing in front of behind a cluster moving across the line of site will experience a different changing gravitational potential.
- Future surveys will detect, for the fist time, the transverse velocities via the "moving lens" effect, visible in the CMB sky.
- Lower detection significance than pairwise kSZ, but different systematics.

Yasini, Mirzatuny, EP (2019)



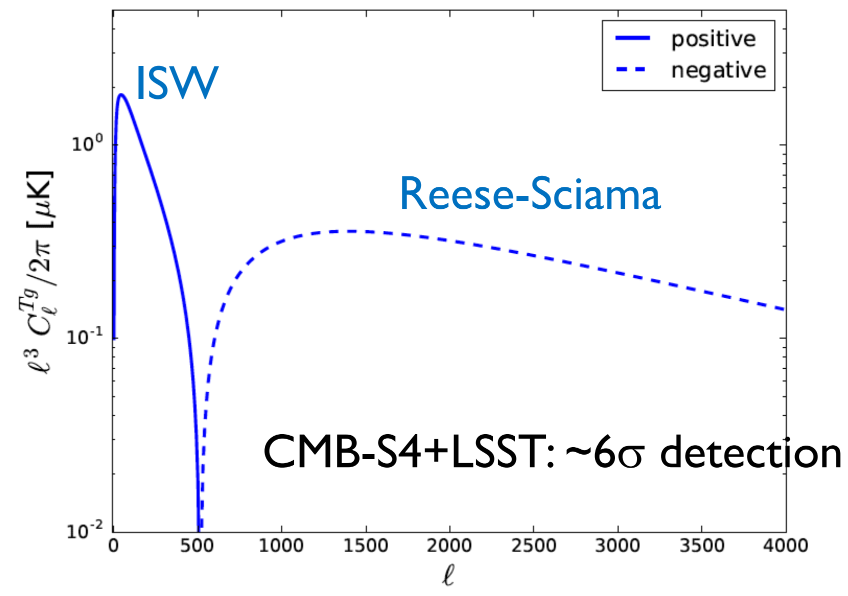


CMB-S4: 5.4 σ detection of pairwise (due to transverse velocity)

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)

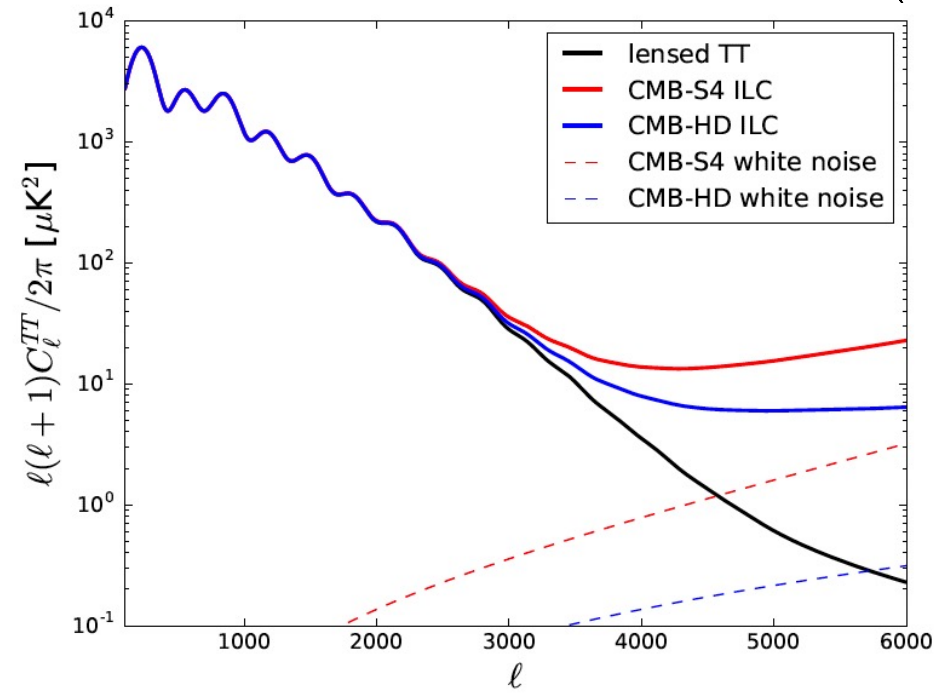


CHALLENGES AND OPPORTUNITIES

- Challenges:
  - The signals we are after are small (polarization,
  - There are many competing signals, especially at small scales

- Opportunities (non-discussed potential science):
  - CMB: alterative measurements of the Milky-way peculiar velocity
  - Galactic science
  - Transient sources in the mm (gamma-ray bursts,
  - Variable AGN
  - Dusty star-forming galaxies
  - Planet 9?

Ferraro, Schaan, EP (2022)



SUMMARY

- In the past ~25 years, the CMB has set/confirmed a very precise cosmological framework, confirming ΛCDM, 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
    - ….And much more, for any Astrophysical taste!

THANK YOU FOR YOUR ATTENTION!