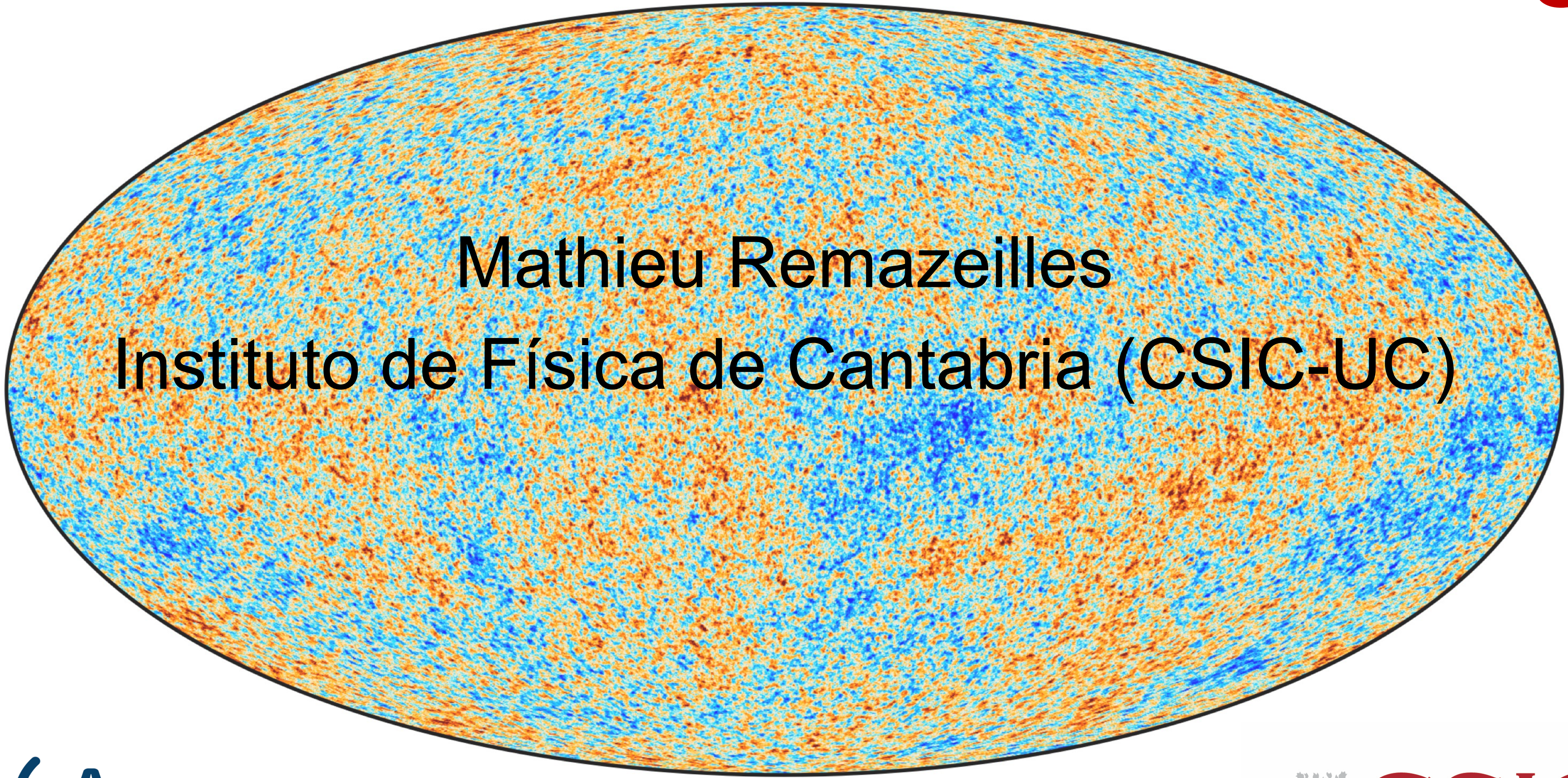
Cosmic Microwave Background: current status and next challenges



Mathieu Remazeilles
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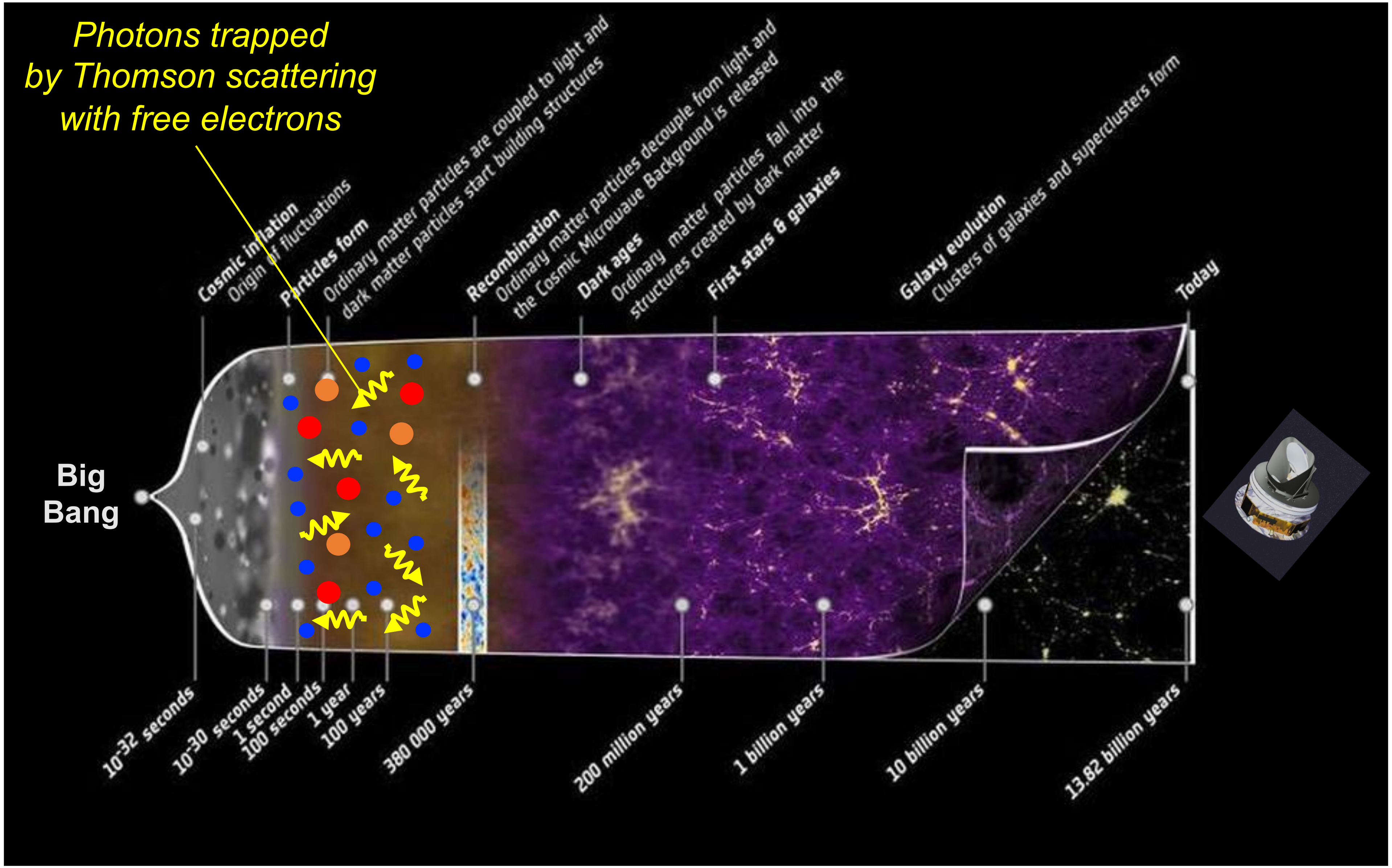
IFCA Instituto de Física de Cantabria

IX Meeting on Fundamental Cosmology
Tenerife, Nov 22nd - 24th , 2023

CSIC Consejo Superior de Investigaciones Científicas

UC Universidad de Cantabria

Cosmic Evolution



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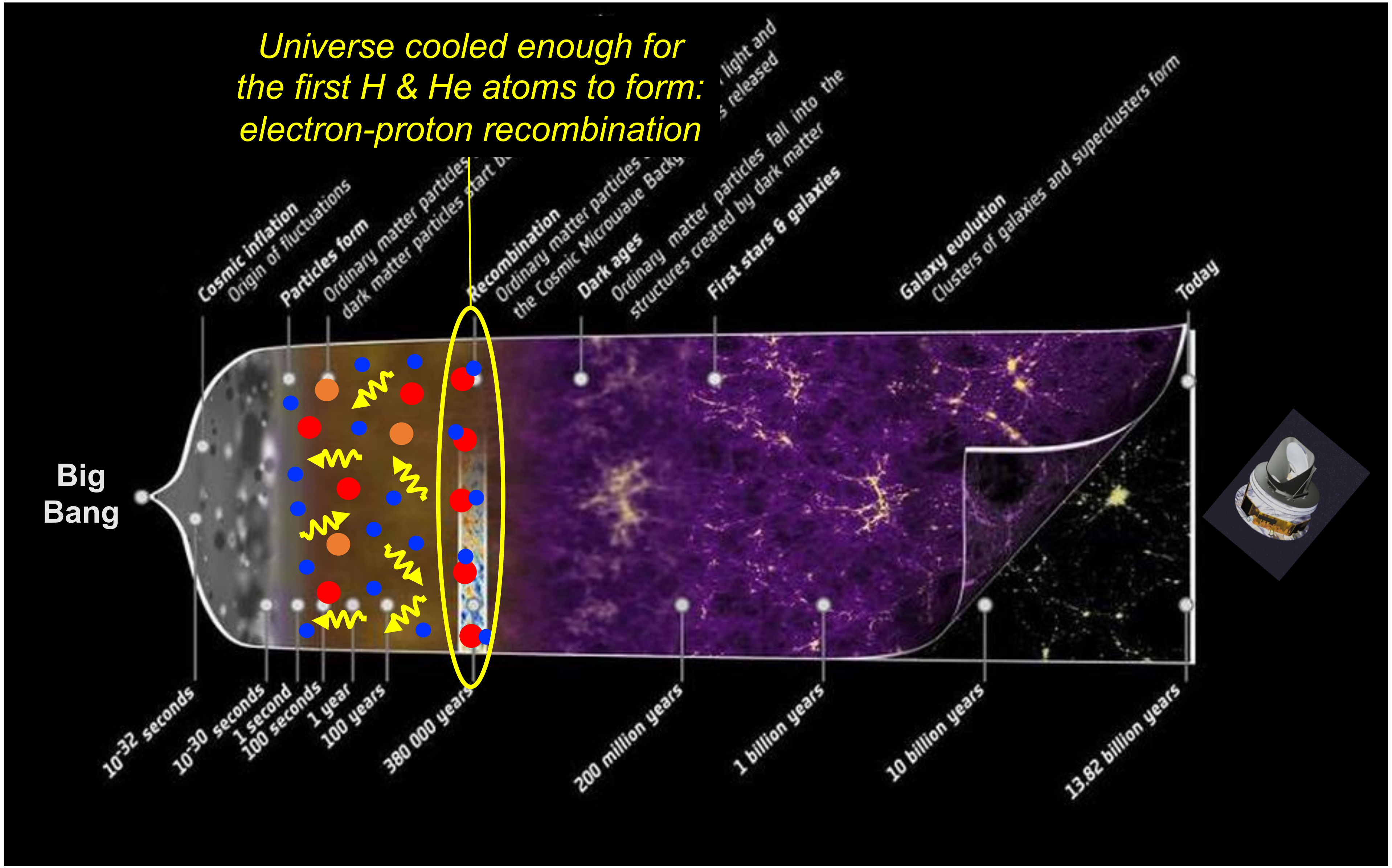
Cosmic Evolution



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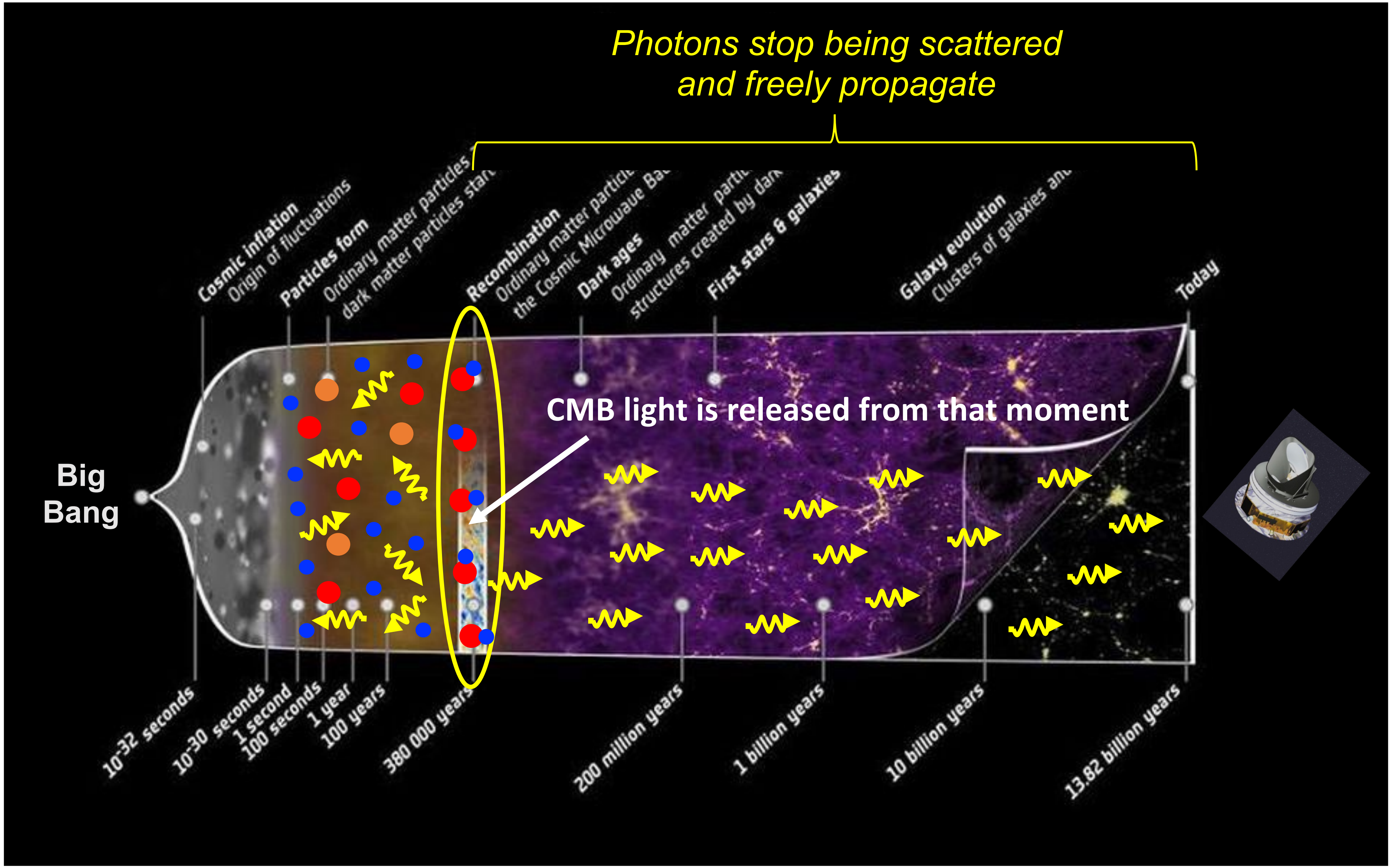
Cosmic Evolution



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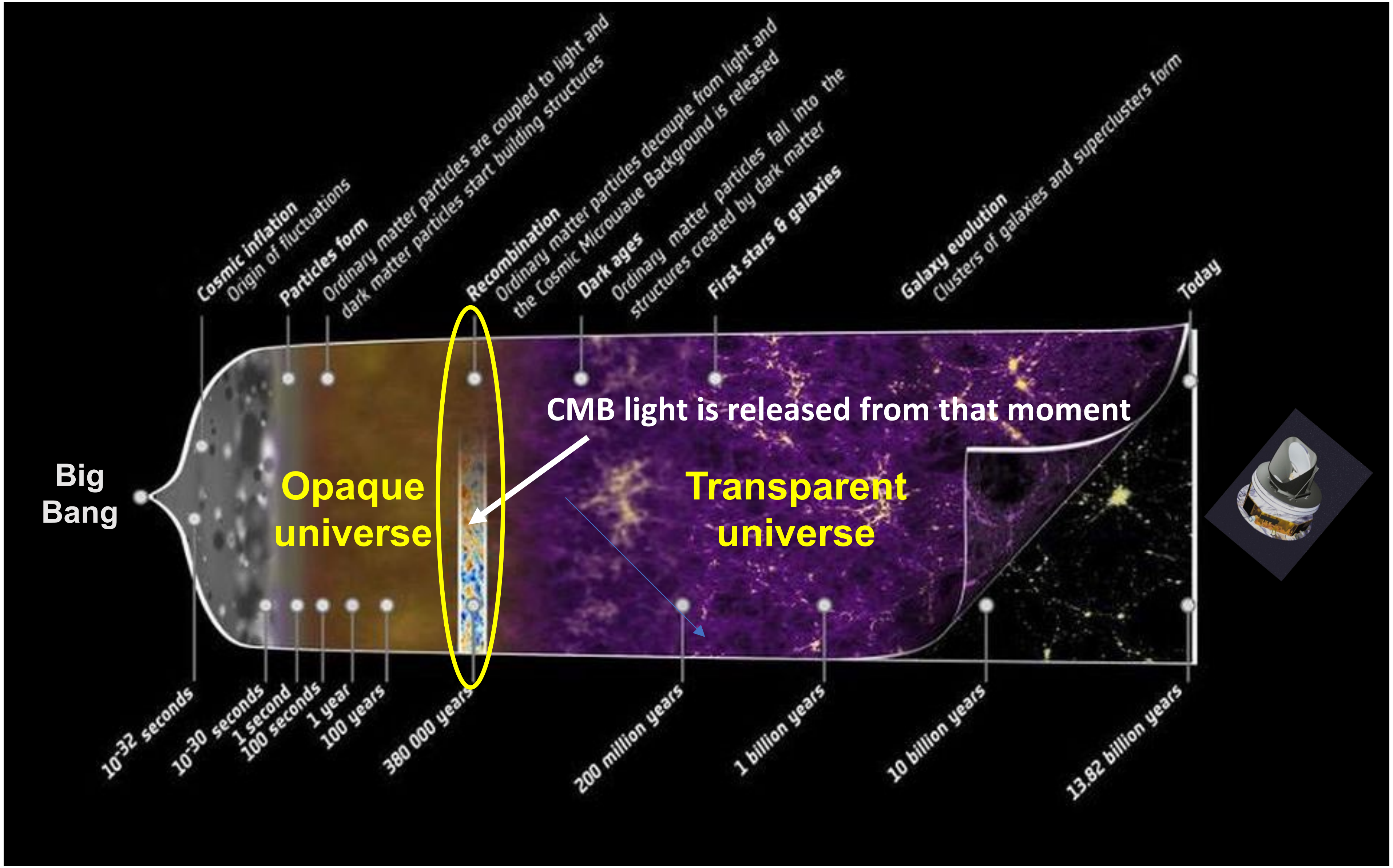
Cosmic Evolution



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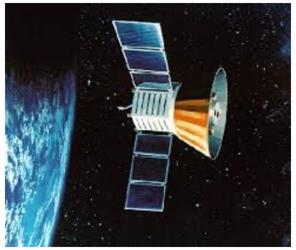
First light released in the Universe

Credit: PICO Team

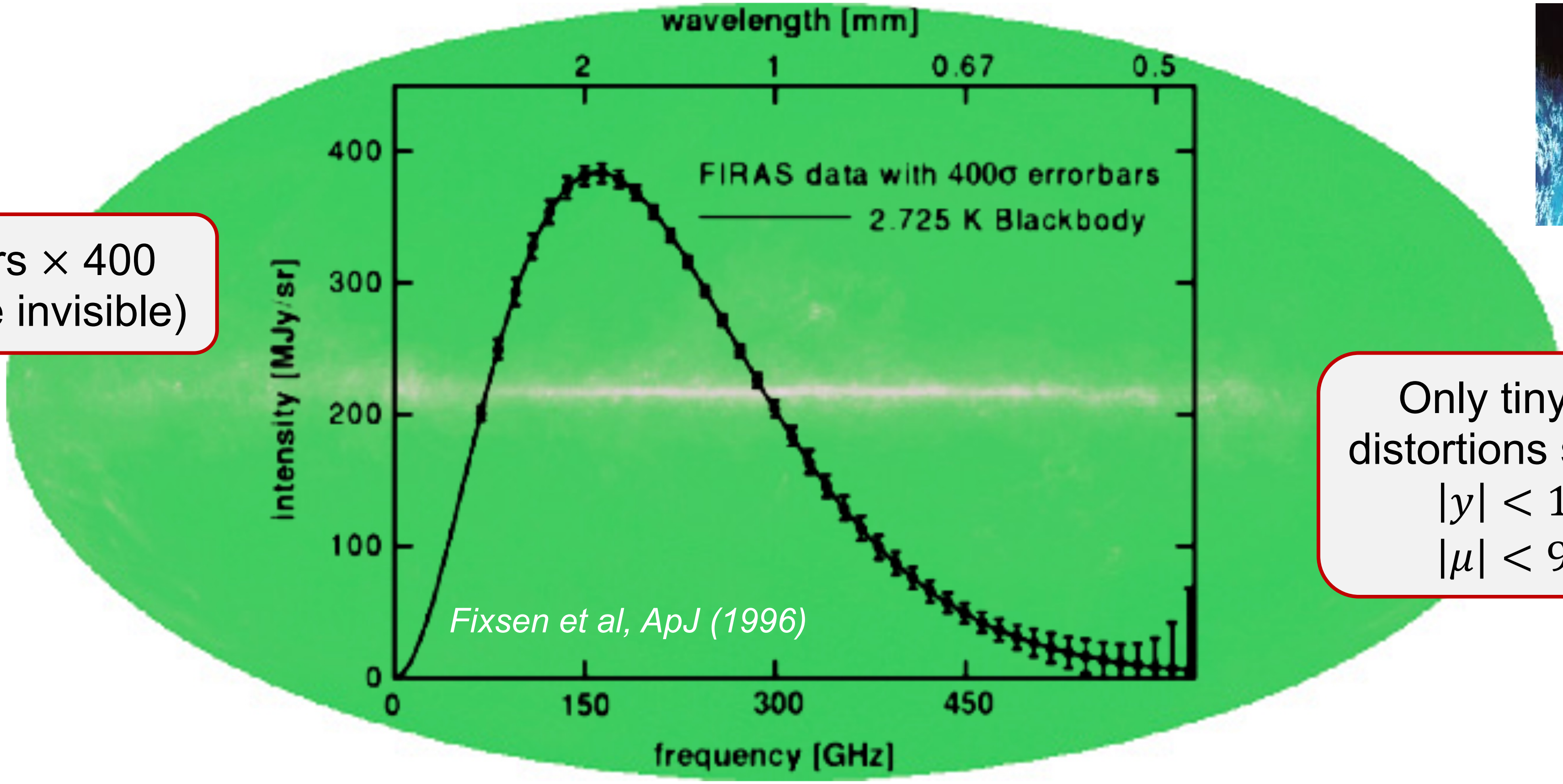
CMB radiation carries information about the Universe's initial conditions

Most perfect blackbody ever measured

COBE / FIRAS



Error bars × 400
(otherwise invisible)



Only tiny spectral distortions still allowed
$|y| < 1.5 \times 10^{-5}$
$|\mu| < 9 \times 10^{-5}$

No further measurement since COBE / FIRAS in the 90s!

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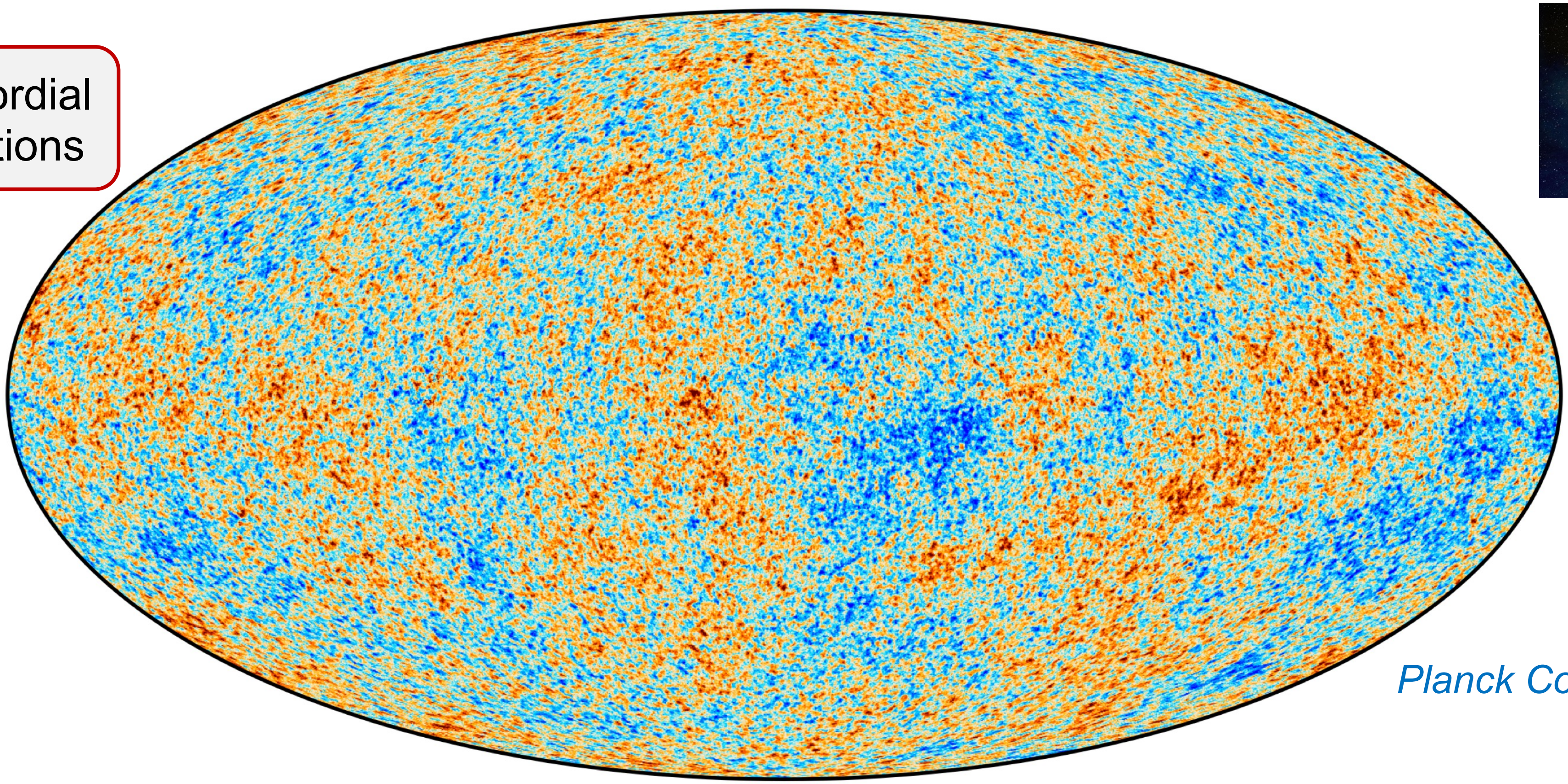
CMB temperature anisotropies from Planck

Imprint of primordial density fluctuations

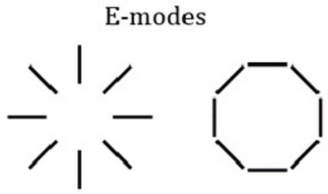


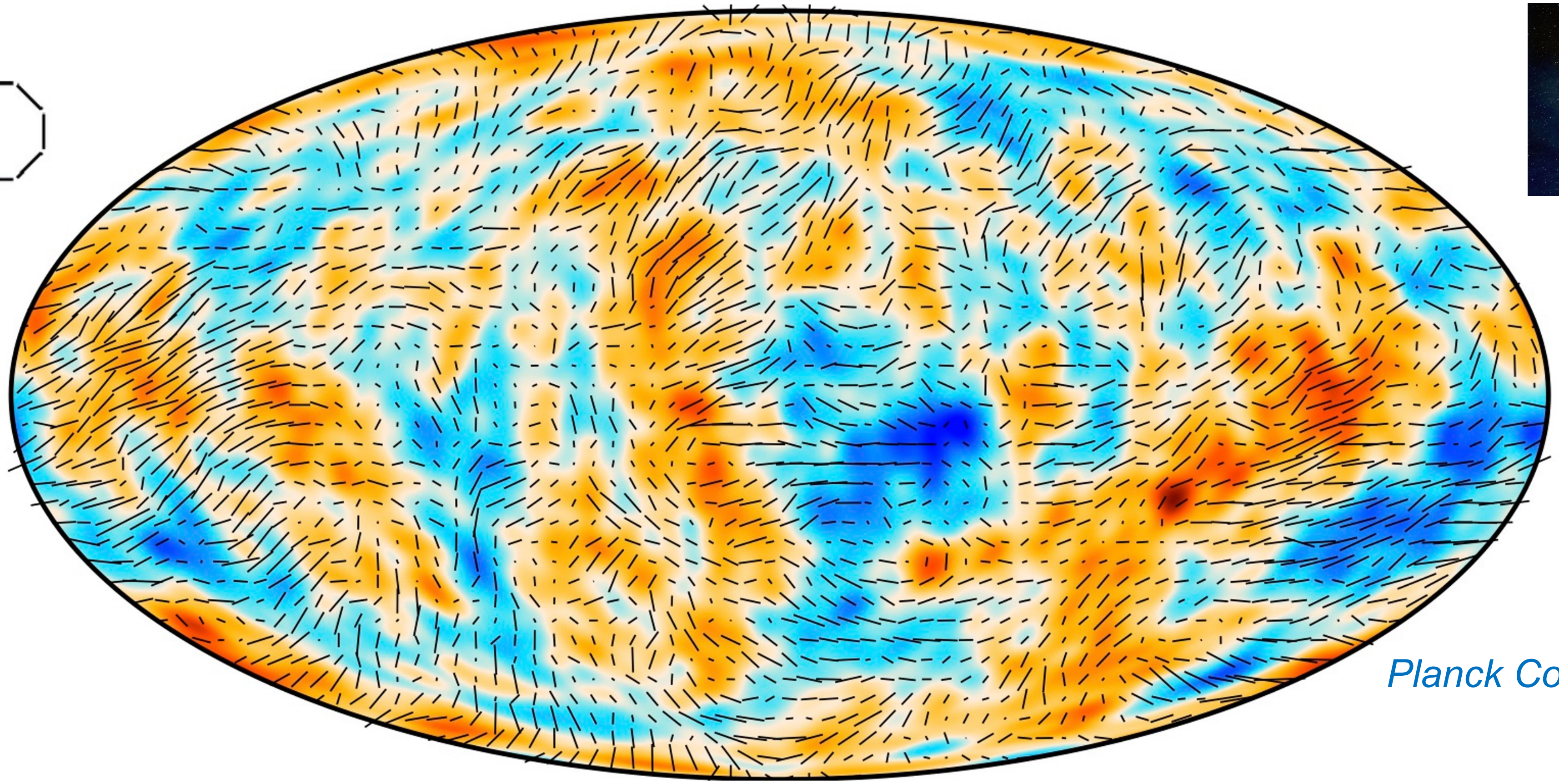
ESA's Planck

Planck Collaboration I (2020)

Temperature anisotropies $\delta T/T \sim 10^{-5}$
around the mean blackbody at $T = 2.725$ *K*

CMB polarization anisotropies from Planck



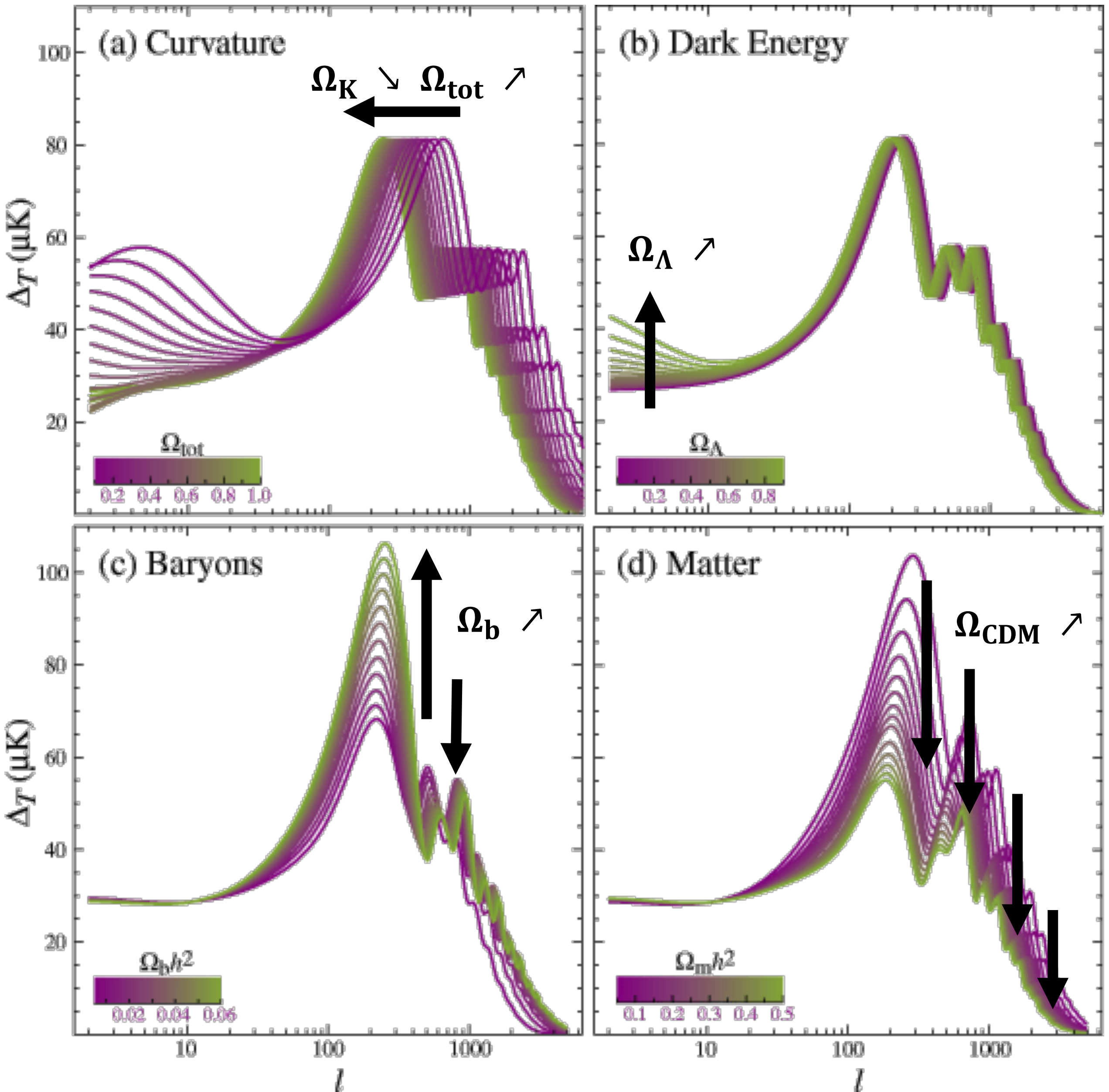


ESA's Planck

Planck Collaboration I (2020)

E-mode dominated, tracing mostly scalar (density) primordial perturbations

CMB statistics: A sensitive cosmological probe



Hu & Dodelson, 2002

The CMB power spectrum is shaped by the underlying cosmological parameters

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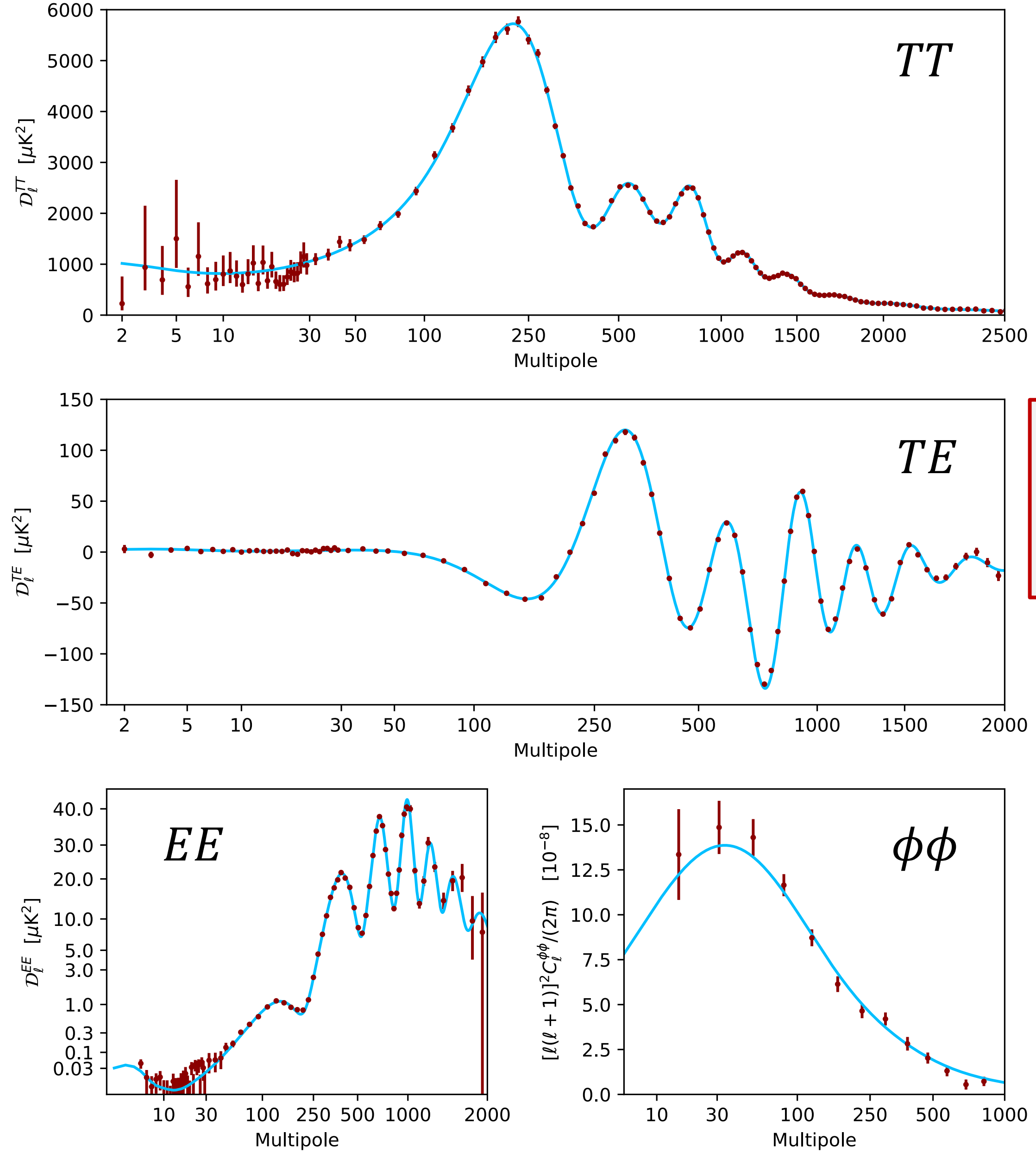
6-parameter ΛCDM model perfectly fits the data

Planck Collaboration I, A&A (2020)



Sub-percent precision on many parameters!

ΛCDM parameters

derived parameters

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

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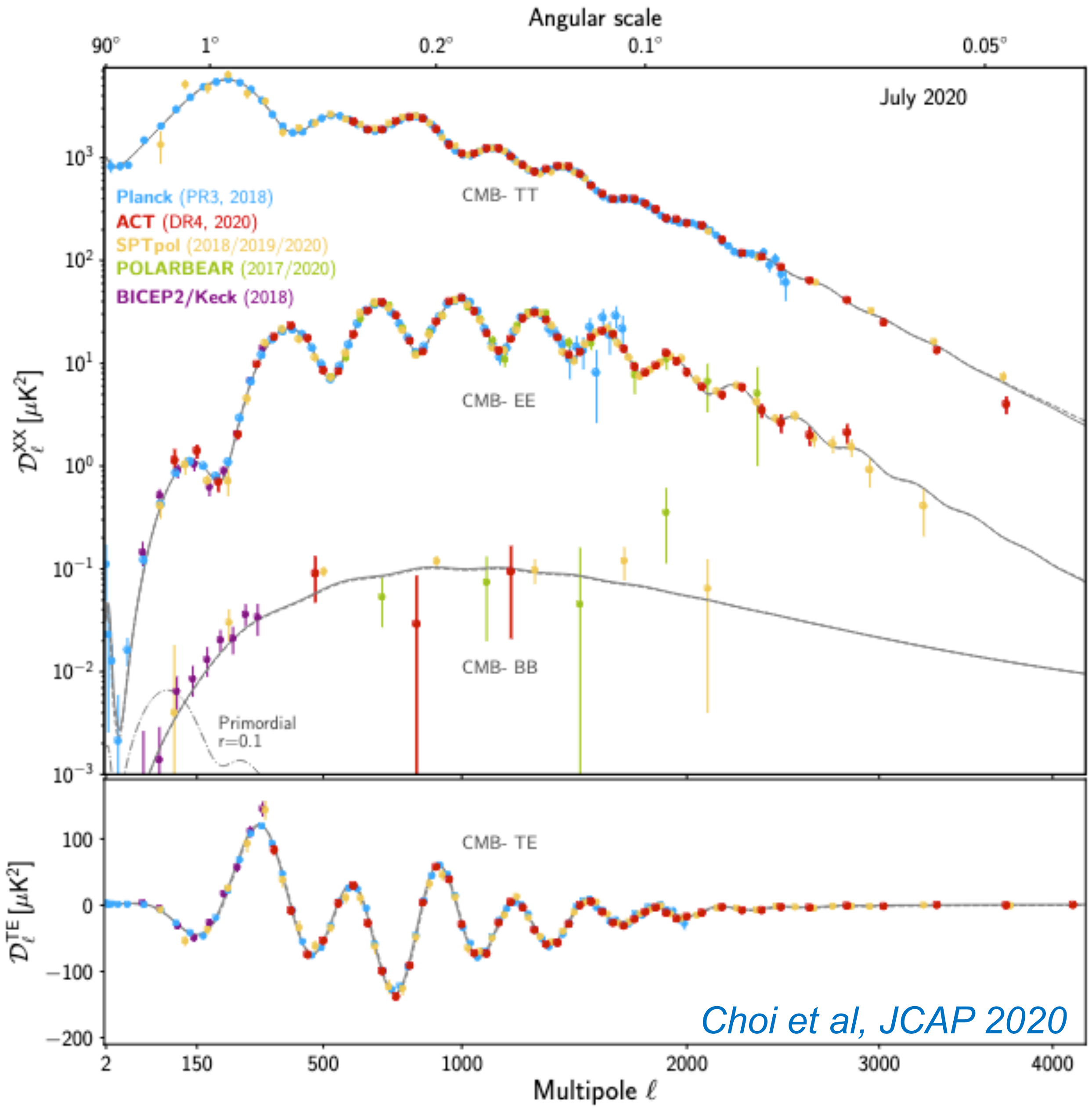
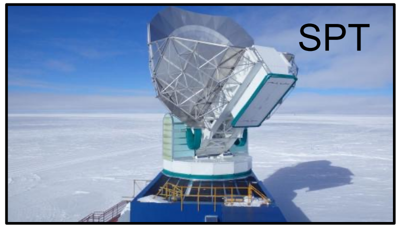
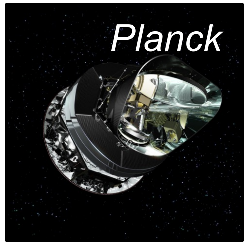
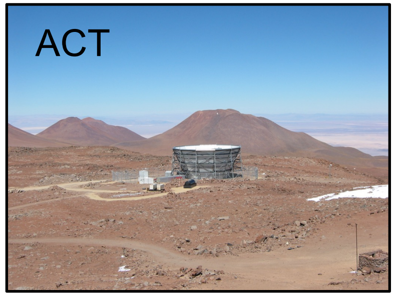
Current state of CMB observations

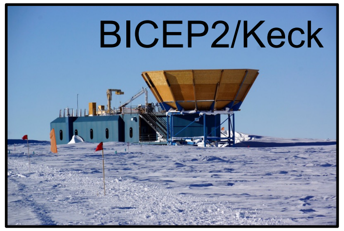


- TT cosmic-variance limited
- Total of 24 acoustic peaks in TT, EE, and TE
- Lensing BB signal successfully observed
- Primordial BB signal (GWs) not yet detected
- All CMB data consistent with standard ΛCDM









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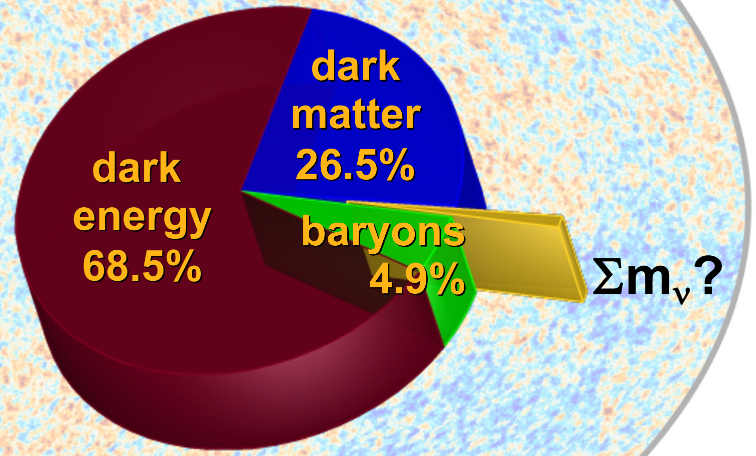
Geometry & Content

- Spatially flat Universe: $\Omega_K = 0.0007 \pm 0.002$
- Slightly slower-expanding Universe: $H_0 = (67.7 \pm 0.4)$ km s^{-1} Mpc^{-1}
- Slightly more baryonic (4.9%) and dark (26.5%) matter
- Slightly less dark energy: 68.5%
- Only three neutrino species: $N_{eff} = 3.0 \pm 0.2$
- No sign of neutrino mass: $\Sigma m_\nu < 0.13$ eV (95% CL)
- No sign of primordial gravitational waves: $r < 0.11$ (95% CL)



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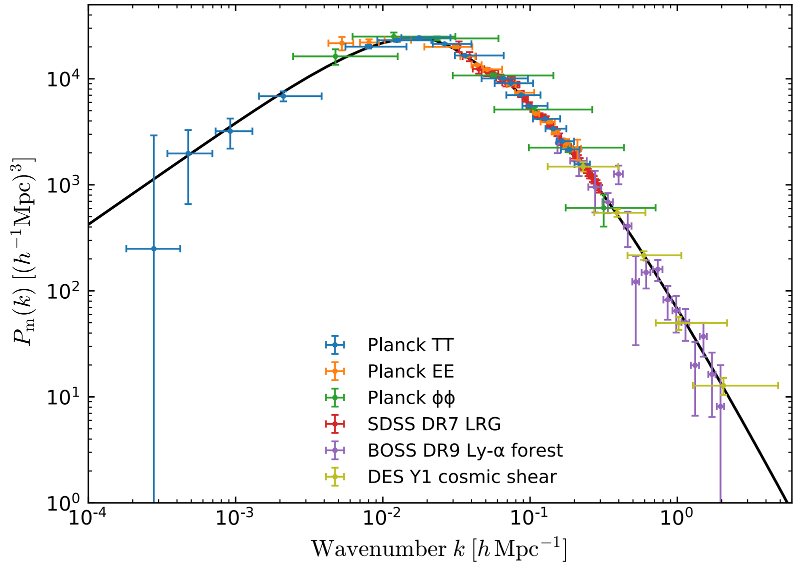
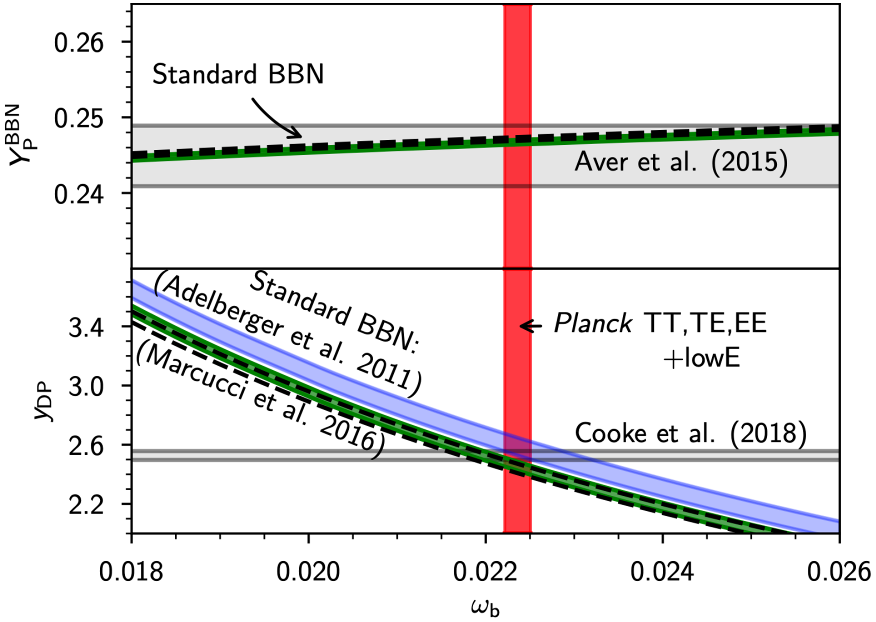
Consistency with other cosmological data…



Matter power spectrum

Consistent picture between CMB and LSS on linear matter power spectrum and BAOs

Planck Collaboration I (2020)



BBN primordial He & D abundance

Consistent picture between BBN and CMB on primordial element abundance and baryon density

Planck Collaboration VI (2020)

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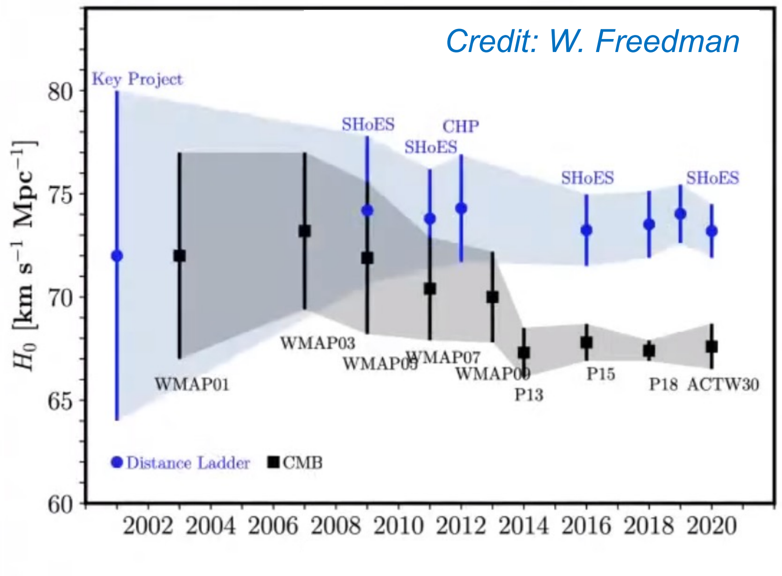
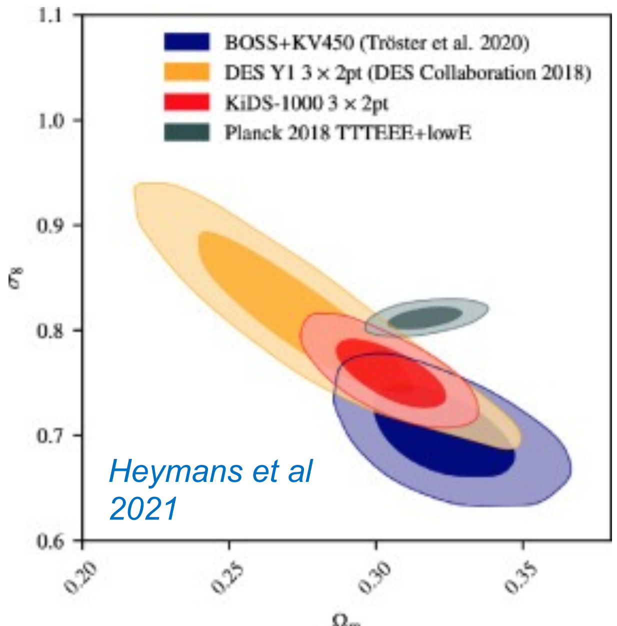
But some intriguing tensions





H_0

(See V. Poulin's talk)

5σ tension between CMB (ΛCDM) and low-redshift direct probes

- New physics beyond ΛCDM?
- Systematics?

σ_8

2σ tension between CMB and low-redshift LSS probes

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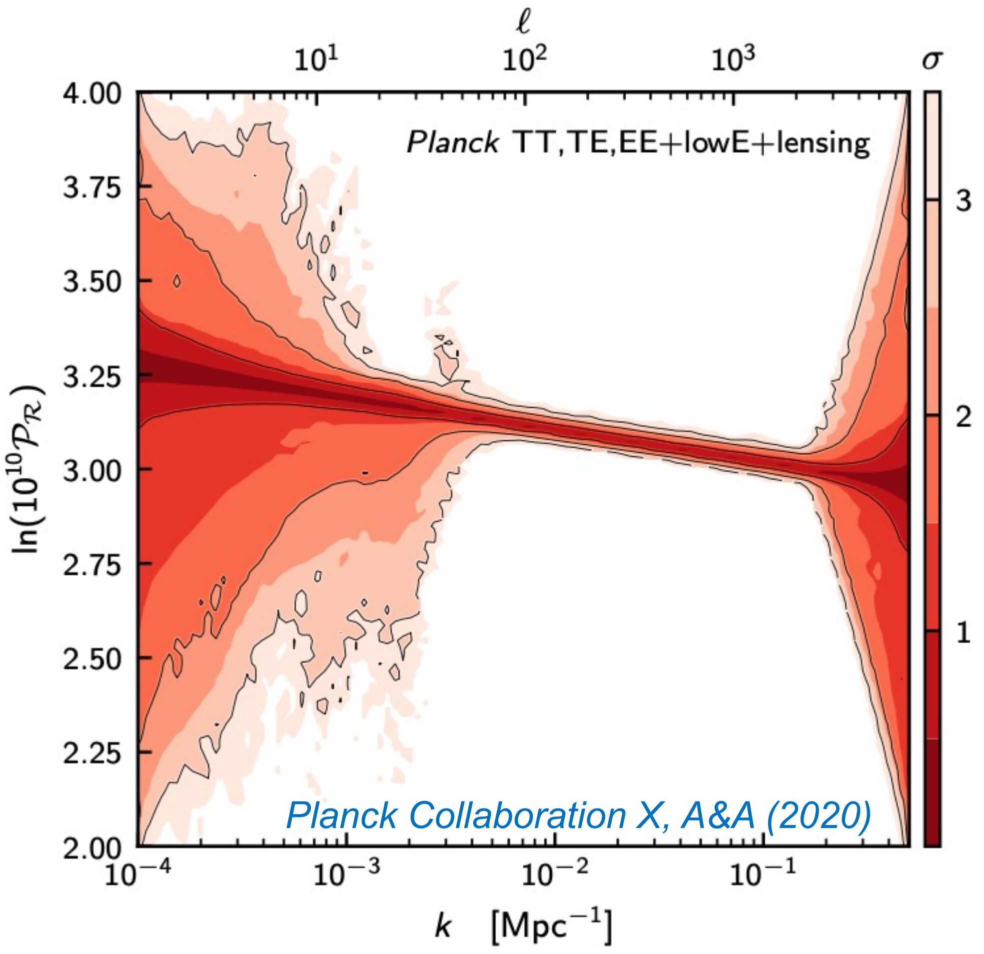
Initial Conditions



- Spatially **flat** Universe, $\Omega_K = 0.0007 \pm 0.0019$
- where scalar (density) perturbations are **Gaussian** $f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$
- and **adiabatic**, $\alpha_{-1} = 0.0001 \pm 0.0004$
- with **nearly scale-invariant** (red) power spectrum $n_s = 0.9649 \pm 0.0042$
- following a **power-law** $dn_s/d\ln k = 0.004 \pm 0.007$

Evidence towards single-field slow-roll inflation…

But no reported detection of primordial gravitational waves yet

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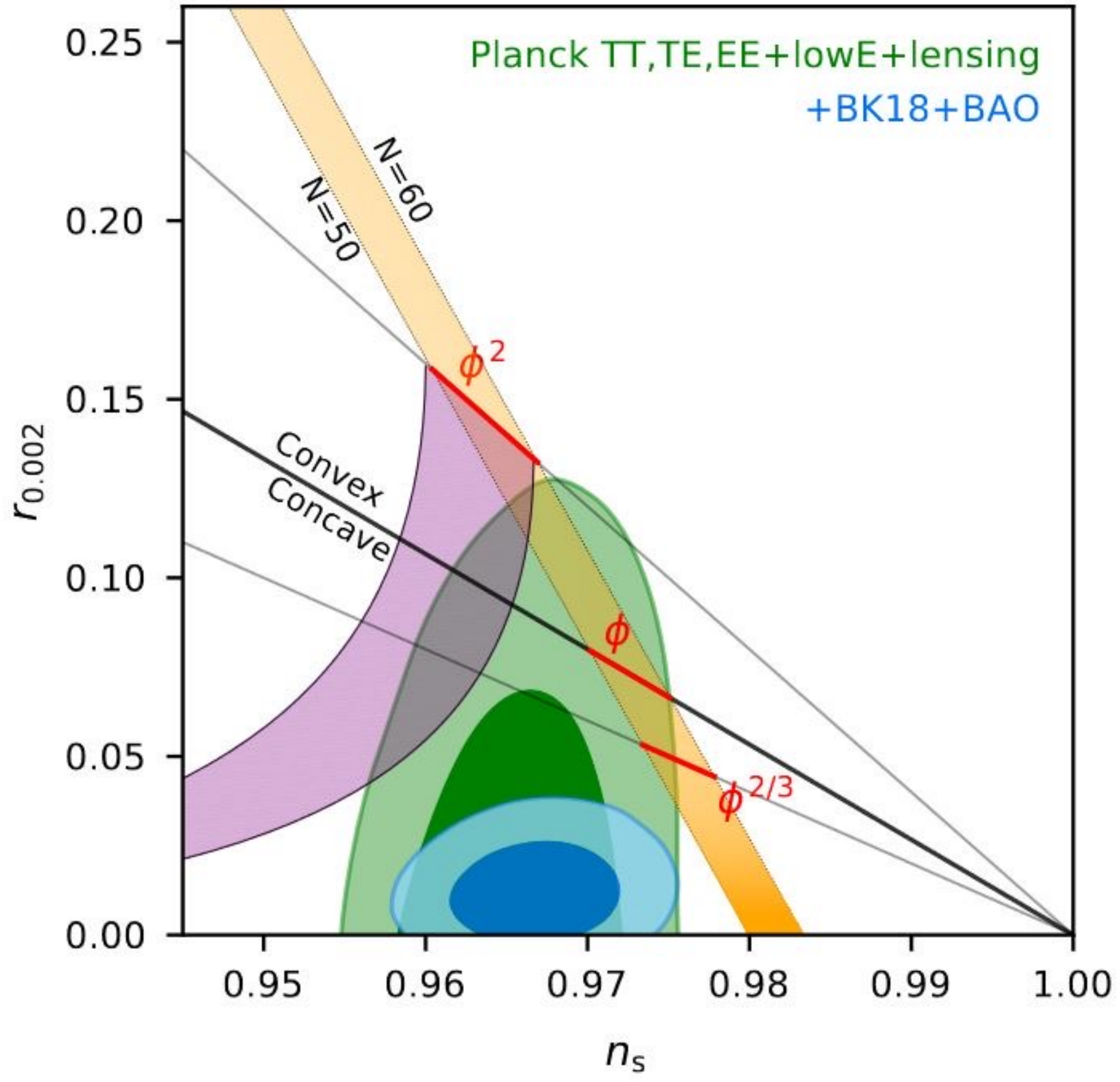
Initial Conditions



- CMB data rule out many inflation models (convex inflaton potentials now excluded)
- $r = P_T/P_S < 0.032$ (95% CL) BK18+Planck PR4 (Tristram et al 2022)
- Starobinsky's R^2 and Higgs inflation models with $r \sim 0.003$ still allowed

BICEP2/Keck Collaboration, PRL 2021

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Outstanding Questions

- What is missing in ΛCDM that explains current tensions?
- Did inflation happen in the early Universe and produce a background of primordial gravitational waves?
- When did the Universe reionize to form the first stars?
- What are the neutrino masses and their hierarchy?
- Are there extra light relics besides neutrinos?
- What is the relationship between baryonic and dark matter?

Exploring new CMB observables

- CMB E- and B-mode polarization
- CMB secondary anisotropies
- CMB spectral distortions

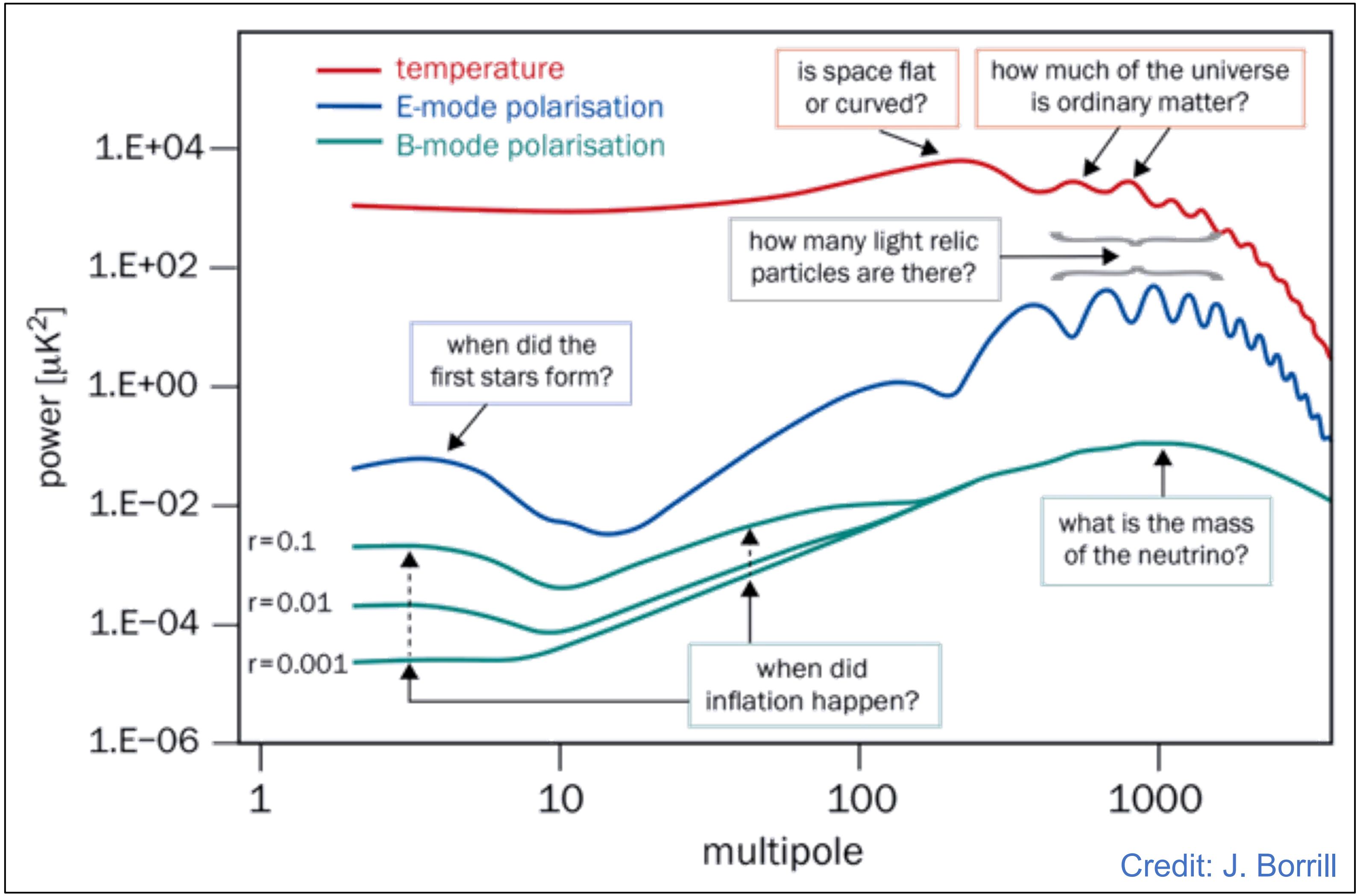
Primary CMB E-/B-mode anisotropies

τ

Deficit of large-scale E-mode if delayed reionization

Excess of large-scale B-mode depending on inflation energy scale

r



N_{eff}

Additional light relics further smooth and shift acoustic peaks

Small-scale deficit of lensing B-mode if $\Sigma\, m_\nu \neq 0$

Σm_ν

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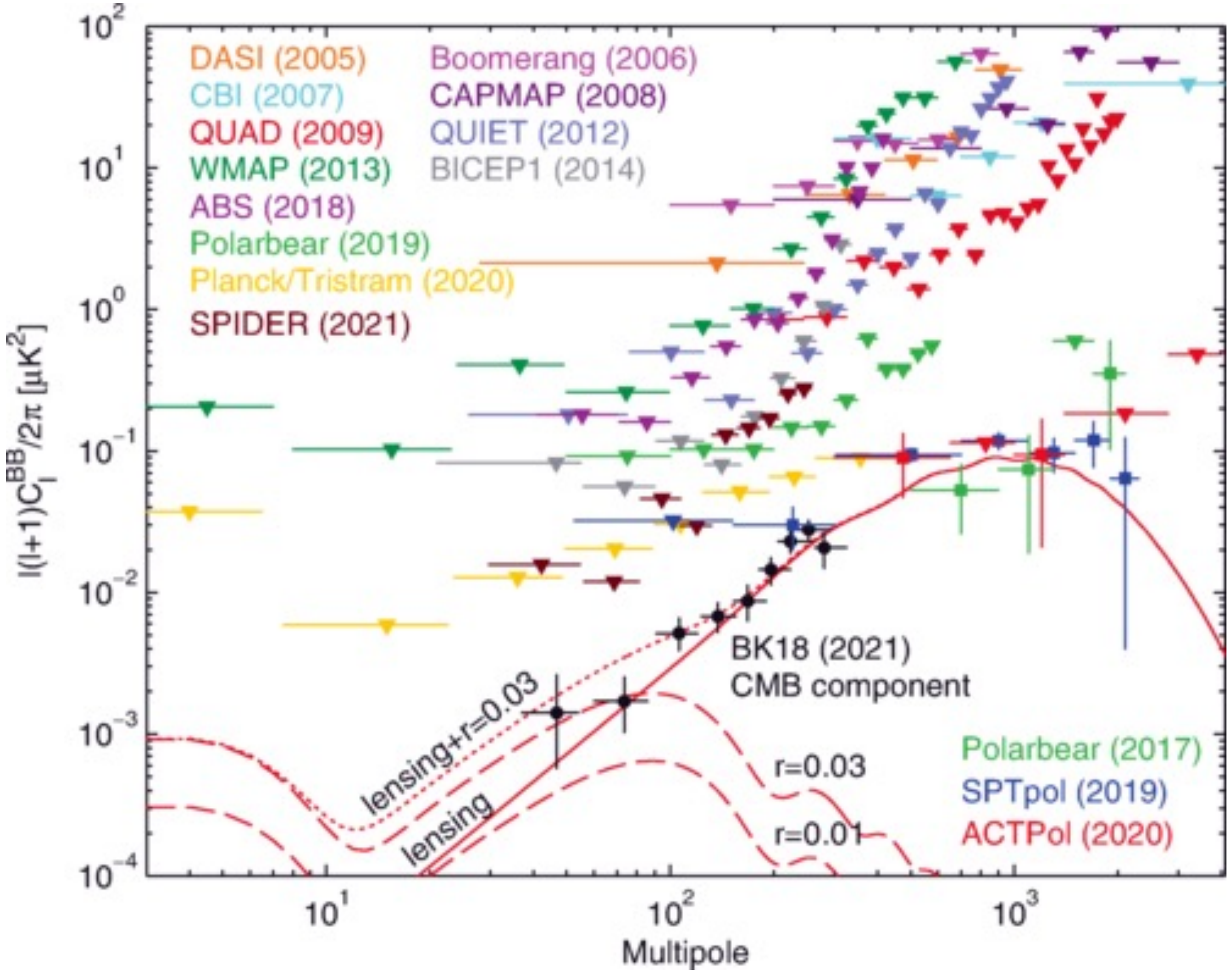
Current state of B-mode observations

BICEP2/Keck Collaboration, PRL 2021



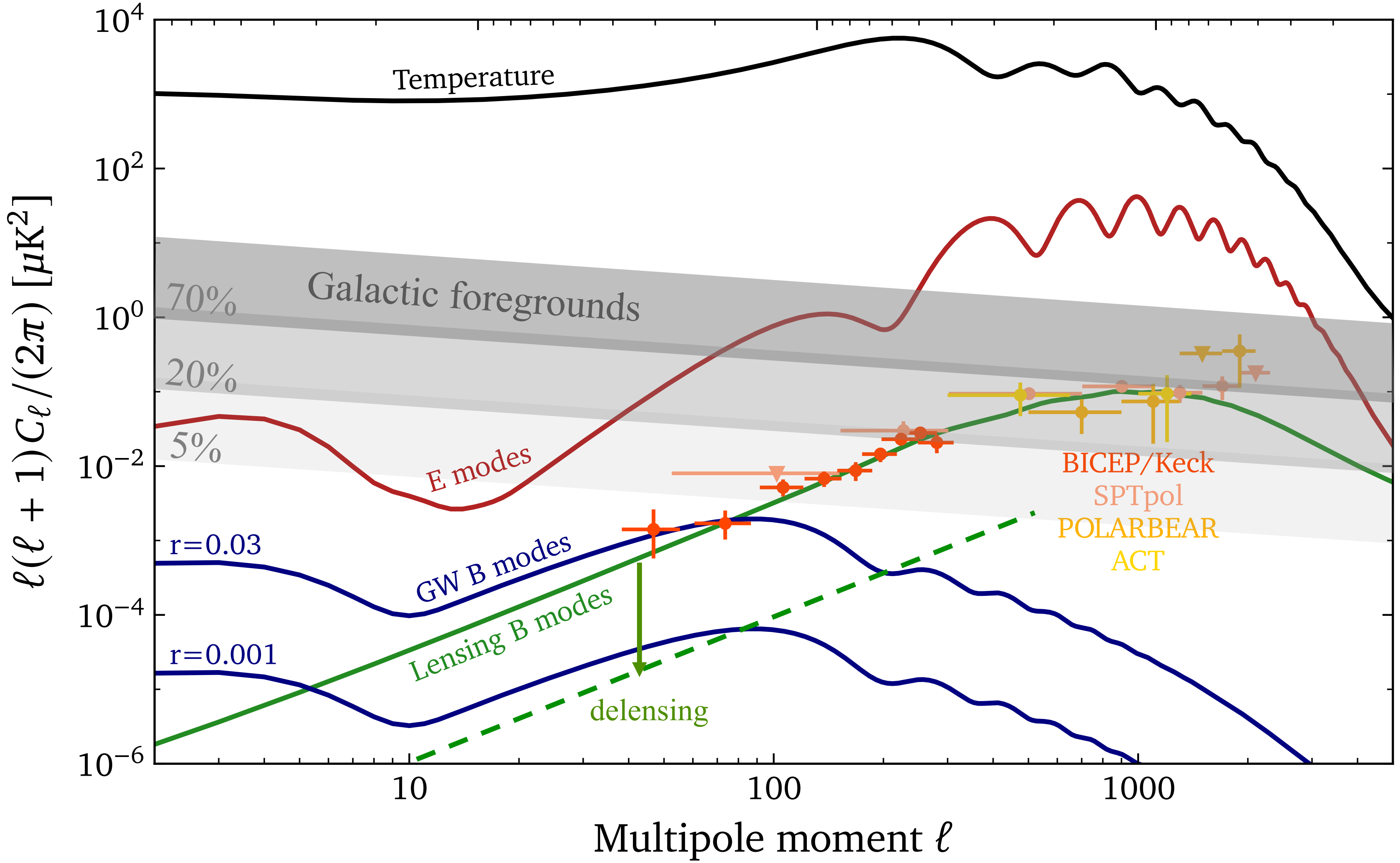
BK18 + Planck PR4

$r < 0.032$ (95% CL)

Tristram et al, PRD 2022

The B-mode polarization challenge

Evidence for primordial GWs requires detecting both reionization and recombination peaks



- Subtract > 99% foregrounds (reionization peak)
- Achieve ~ 90% delensing (recombination peak)
- Reionization peak achievable only from full-sky space survey

Adapted from Achúcarro et al (2022)

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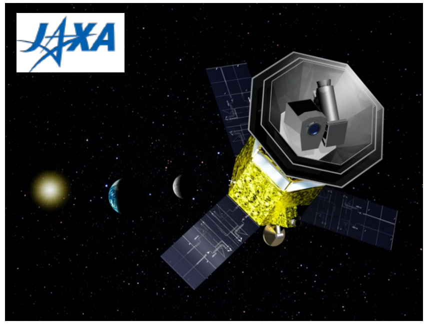
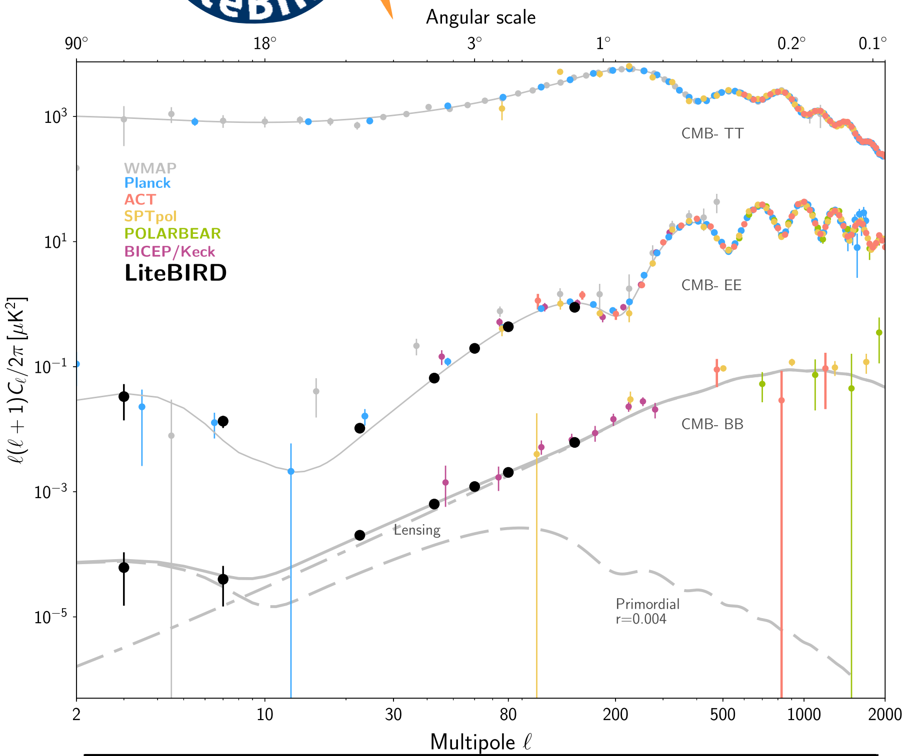
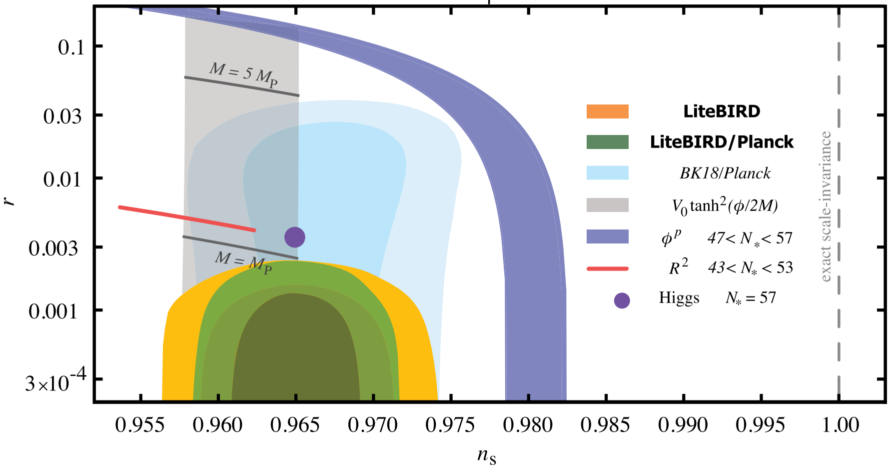
The LiteBIRD space mission

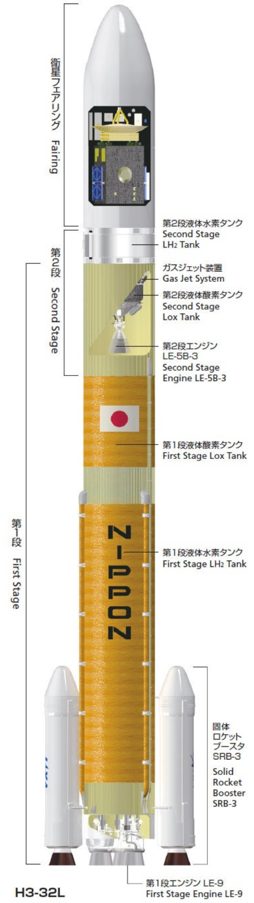






(See M. Lattanzi's talk)

- Both reionization and recombination peaks of the B-mode spectrum
- 5σ detection of both peaks if $r = 0.01$
  Total uncertainty $\delta r < 0.001$ if $r = 0$
- 15 frequency bands over 40-402 GHz to control foregrounds
- Expected launch in 2032 (JFY)



LiteBIRD Collaboration, PTEP 2023

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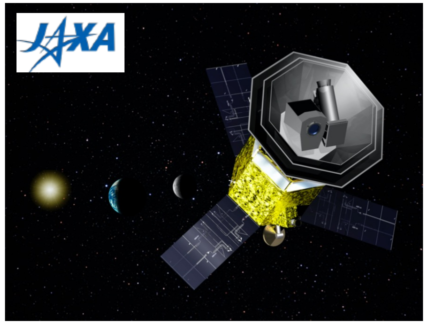
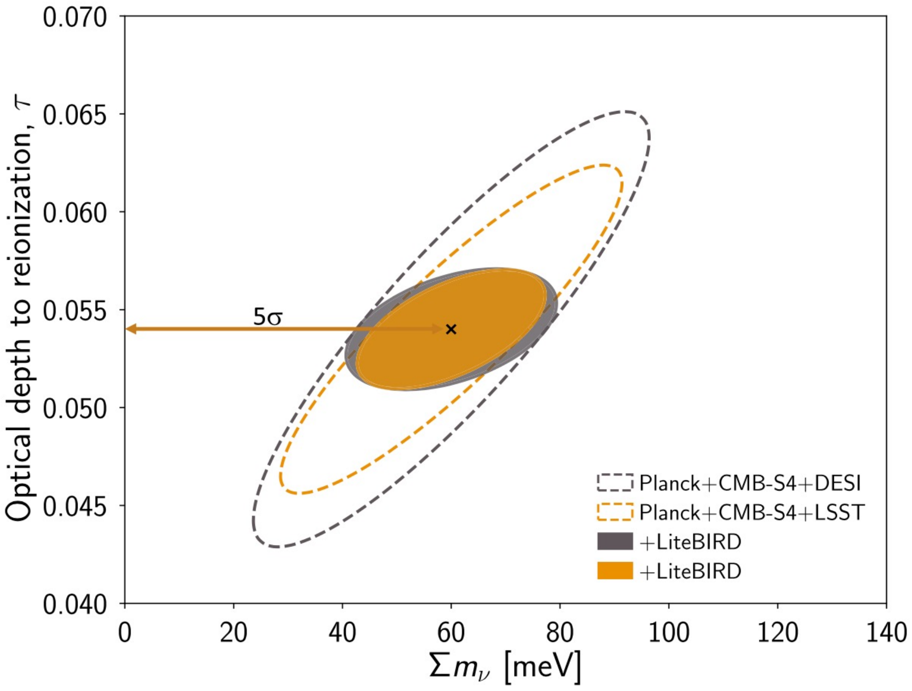
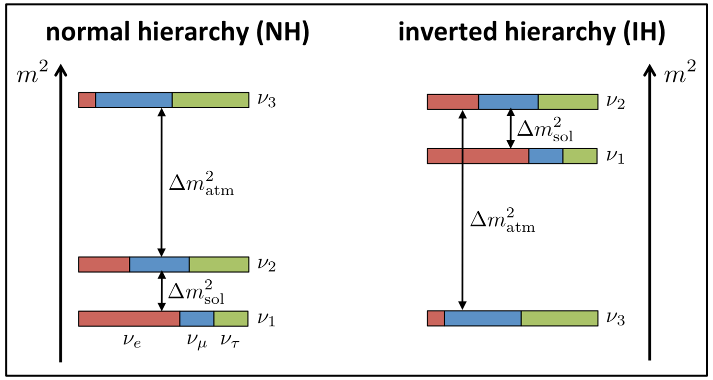
The LiteBIRD space mission







$\Sigma m_\nu > 0.06$ eV

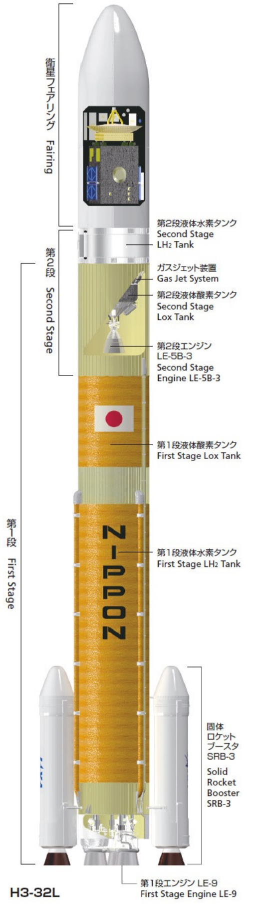
$\Sigma m_\nu > 0.10$ eV

(See M. Lattanzi's talk)

- CV-limited measurement of E-modes and optical depth to reionization τ
- 5σ detection of $\Sigma m_\nu = 0.06$ eV
- Resolving neutrino mass hierarchy

(See M. Gerbino's talk)

LiteBIRD Collaboration, PTEP 2023



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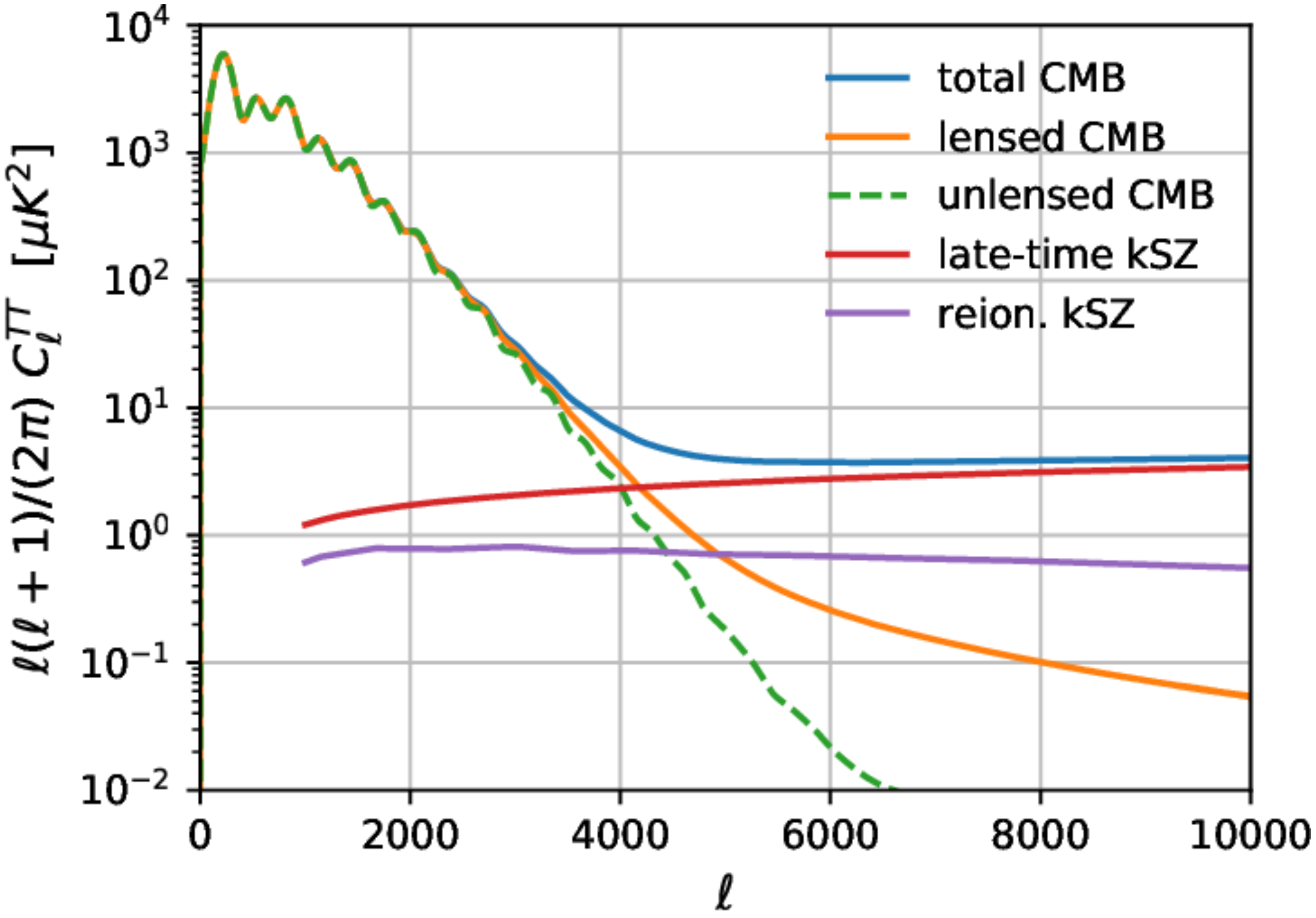
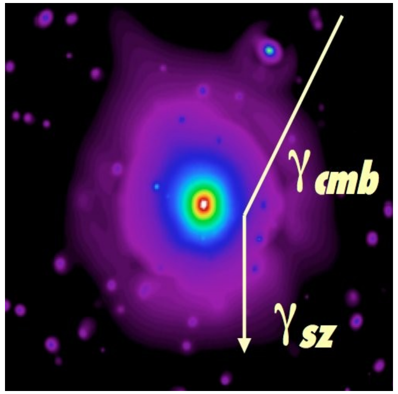
Secondary CMB anisotropies



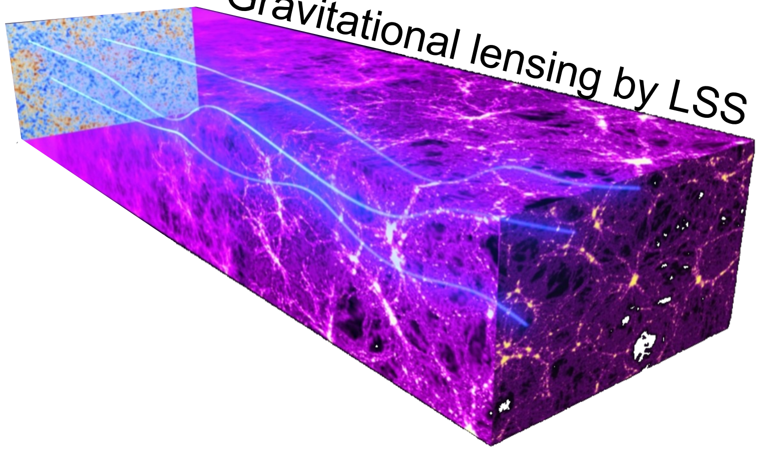
Smith et al 2018

Scattering by hot gas



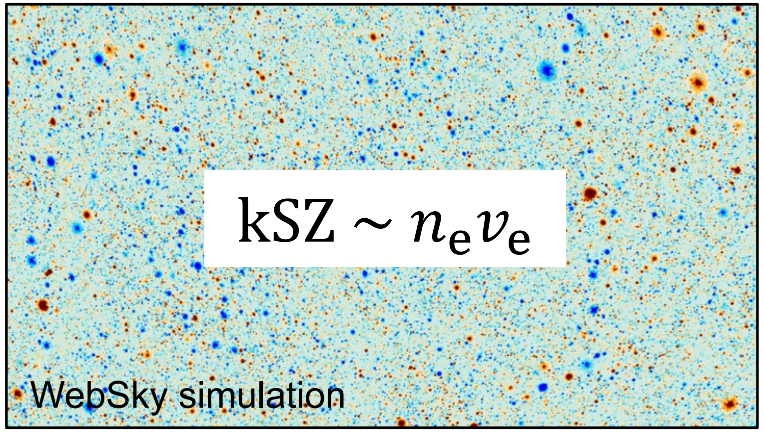
Sunyaev-Zeldovich (SZ) effect

Gravitational lensing by LSS

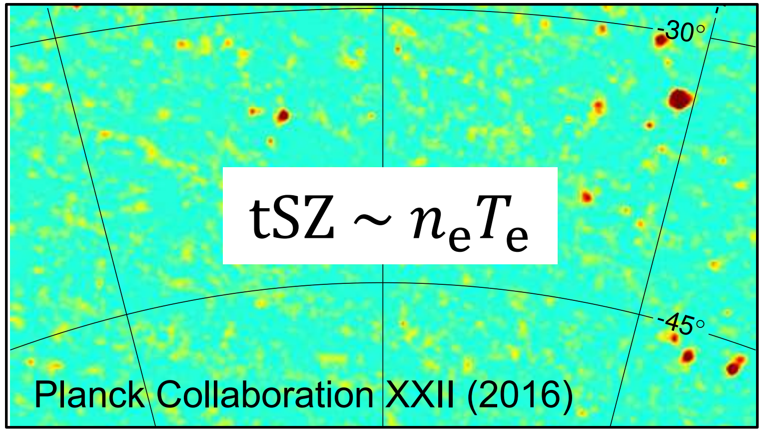


Baryon distribution with kinetic SZ effect

Kinetic SZ (kSZ)



Thermal SZ (tSZ)



- kSZ effect is a reliable tracker of the missing baryons extending beyond dark matter haloes
- tSZ biased towards measuring hot gas
- kSZ probes the full baryon density, irrespective of the gas temperature!

+ neutrino masses, dark energy

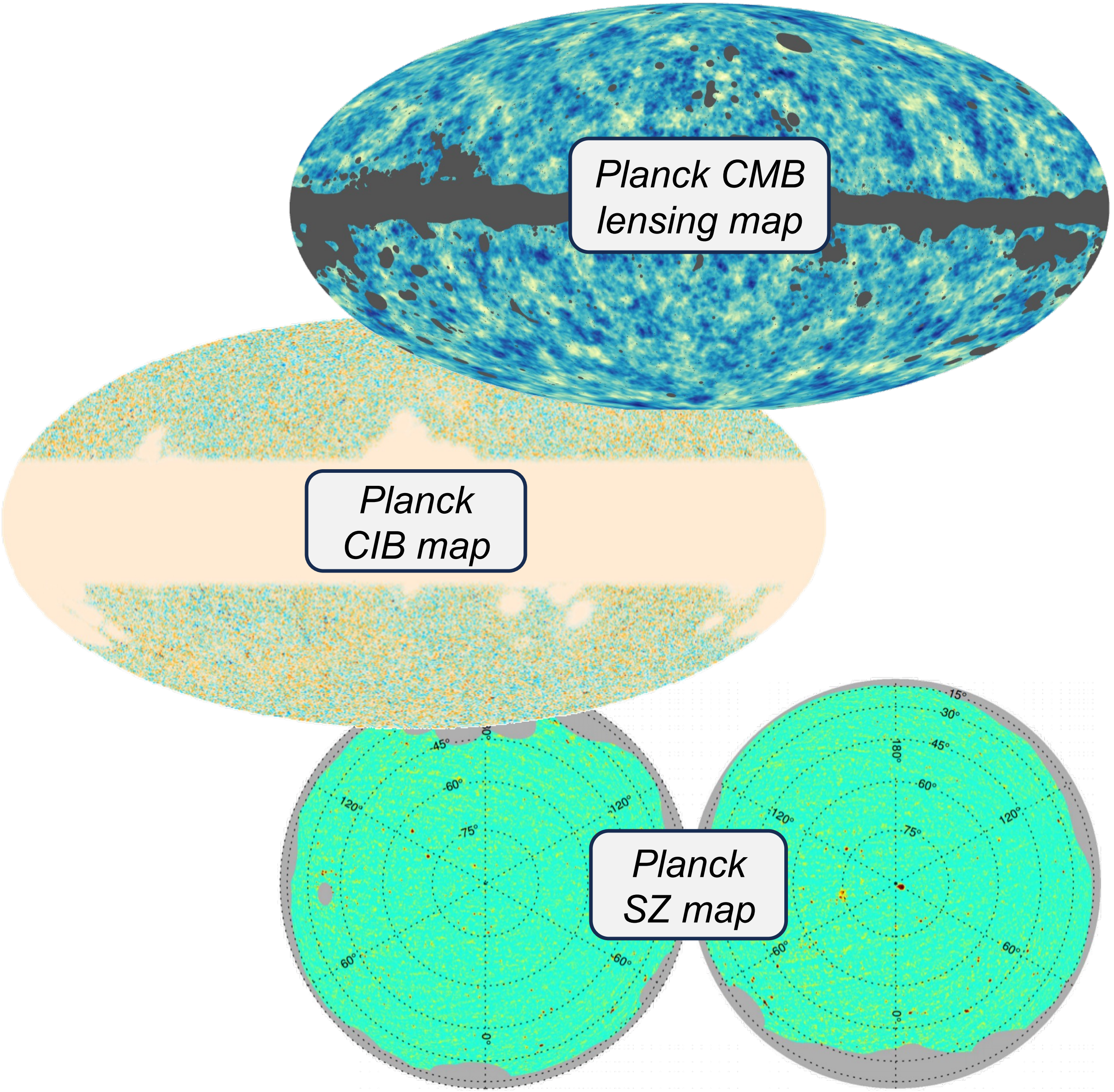
High-resolution CMB surveys ($\ell > 5000$) like SO and CMB-S4 are essential to overcome the kSZ-CMB spectral degeneracy

SIMONS OBSERVATORY

CMB-S4

Correlated tracers of matter distribution

(See G. Fabbian's talk)



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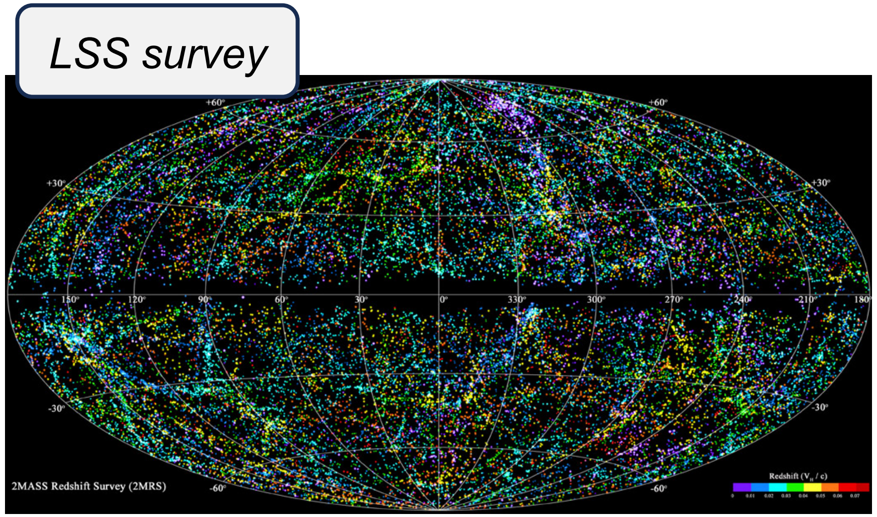

- Cross-correlations with LSS surveys
- Extract galaxy biases out of ratios between auto- and cross-spectra
- Get rid of instrumental systematics

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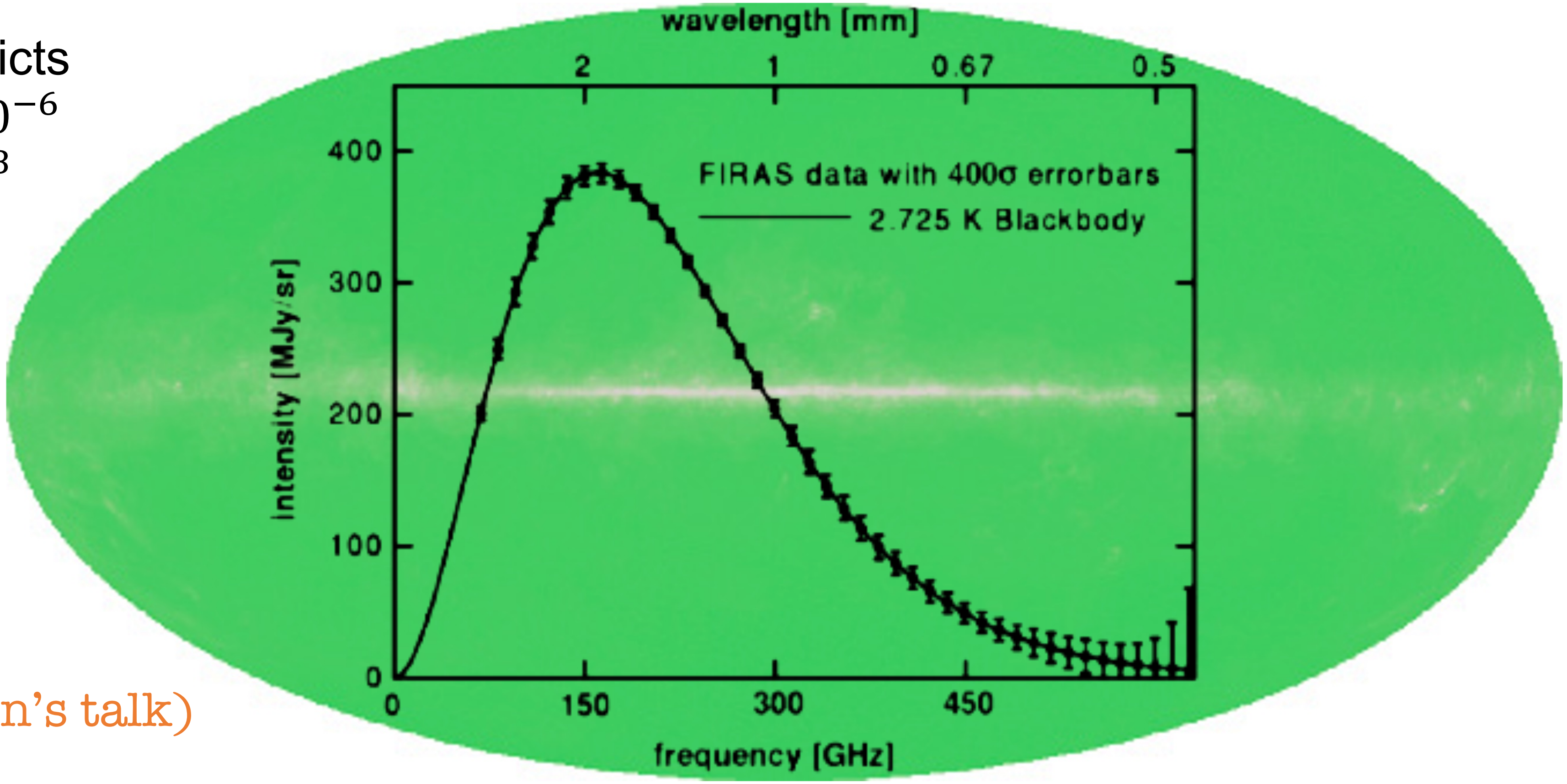
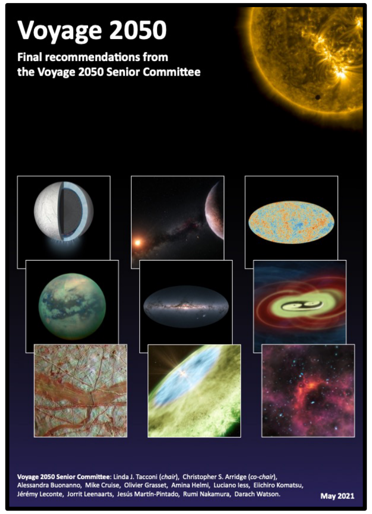
CMB Spectral Distortions

ΛCDM predicts
$y \sim \text{few} \times 10^{-6}$
$\mu \sim 2 \times 10^{-8}$



(See X. Coulon's talk)



Recognized by ESA Voyage 2050 as a potential probe for a future L-class mission

Small departures from a perfect blackbody?

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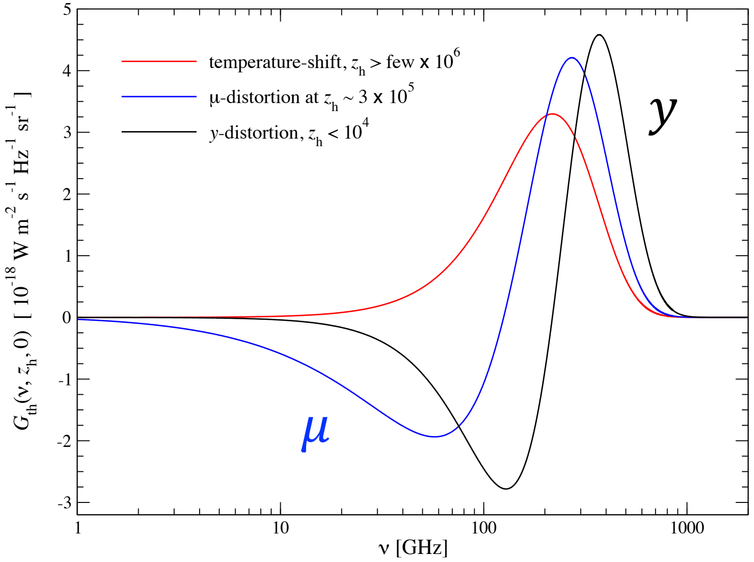
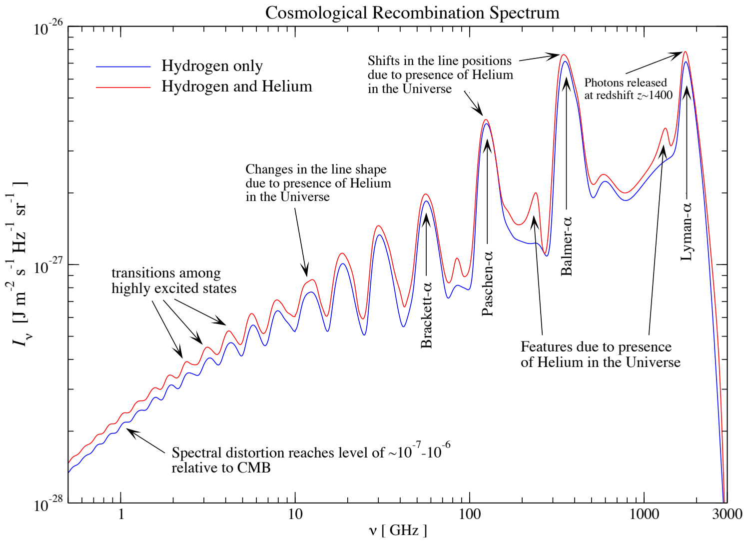
CMB Spectral Distortions

Chluba, 2014





- μ-distortion: signature of photon energy release by physical processes occurring at redshifts $z > 10^4$

- Distortions from H and He recombination lines

- Direct probe of first atoms & recombination physics

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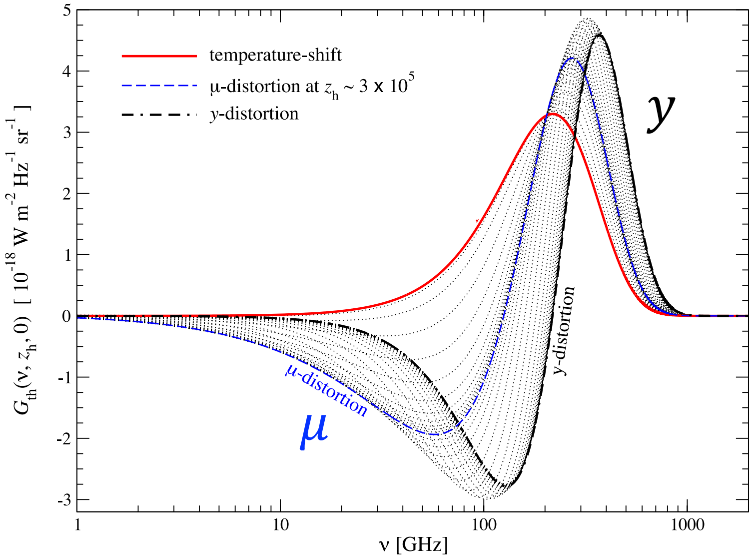
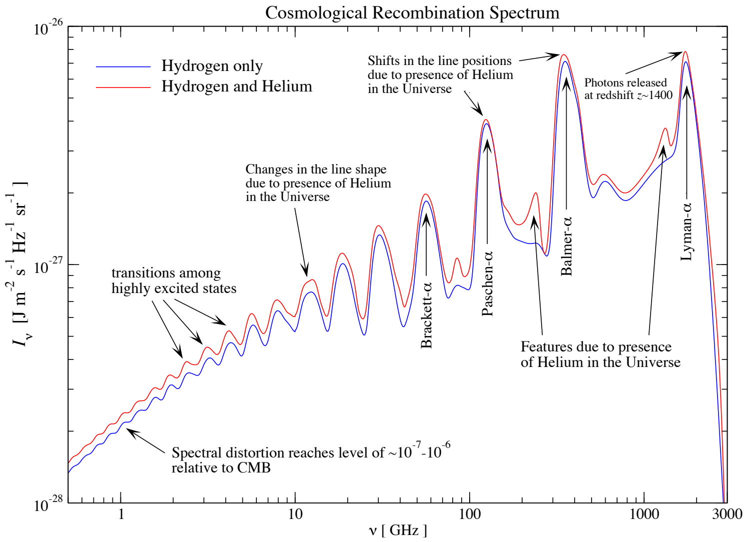
CMB Spectral Distortions





Chluba, 2014

- μ-distortion: signature of photon energy release by physical processes occurring at redshifts $z > 10^4$
- Intermediate-shape distortions can inform us on the lifetimes of decaying particles
- Distortions from H and He recombination lines
- Direct probe of first atoms & recombination physics

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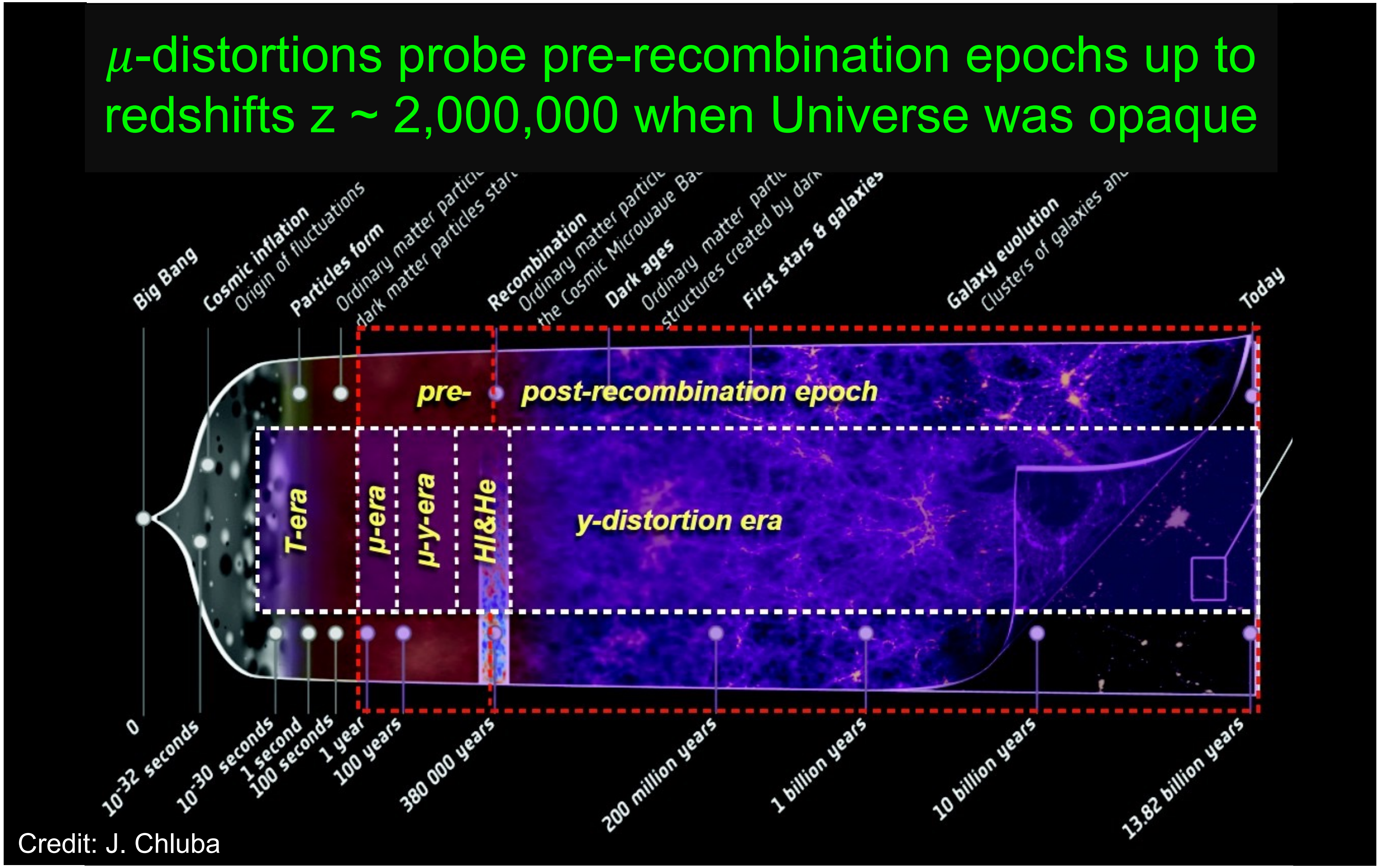
A peek behind the last-scattering surface



Some physics leading to spectral distortions:

Damping of primordial acoustic modes

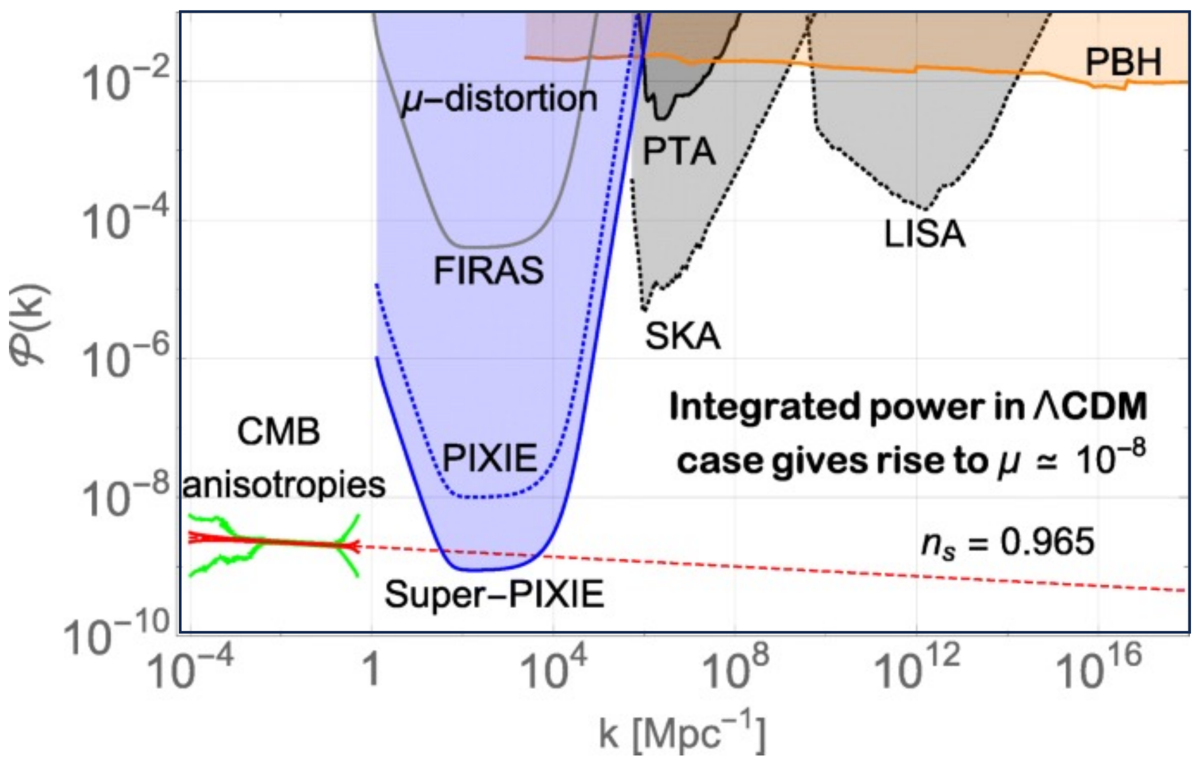
Decaying/Annihilating relic particles

Primordial black hole evaporation

Cosmological recombination lines

Probing inflation with spectral distortions

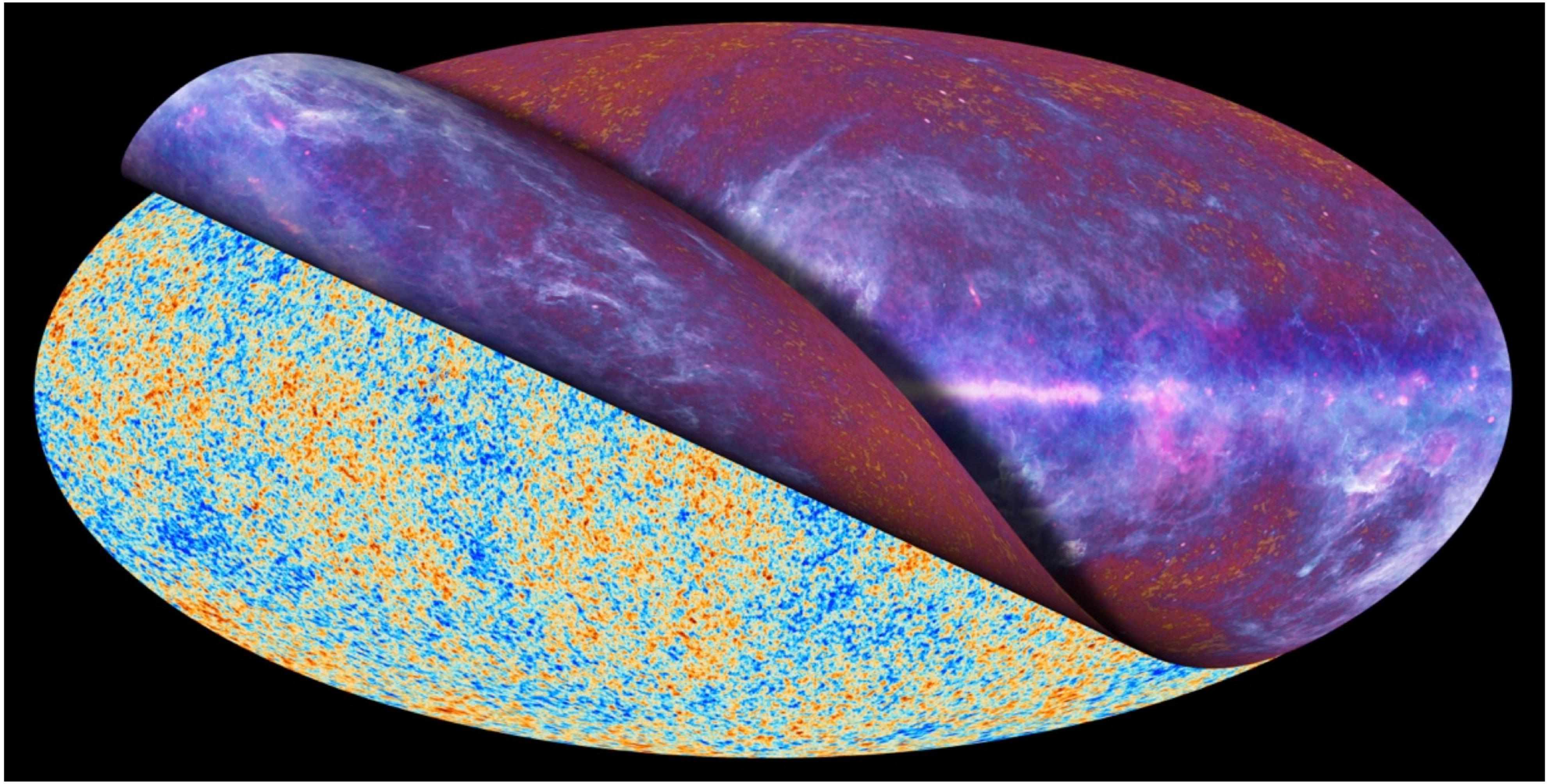
Primordial power spectrum mostly unknown at scales k > 3 Mpc⁻¹



Chluba et al, 2021

- ❑ CMB: k > 0.2 Mpc^{-1} erased by Silk damping
- ❑ LSS: k > 0.2 Mpc^{-1} enter non-linear regime
- ❑ Spectral distortions extend our lever arm up to k > 10^{4} Mpc^{-1} in the linear regime

CMB obscured by foreground emissions



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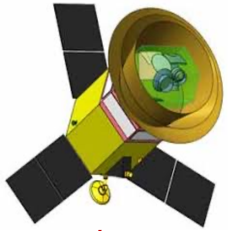
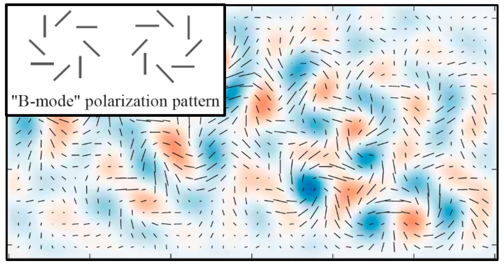
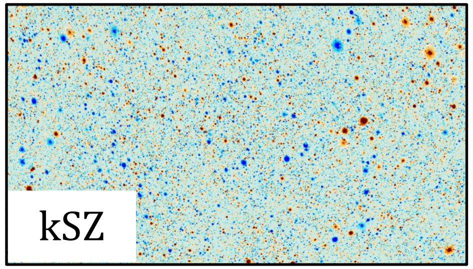
Weaker CMB signals, higher sensitivities





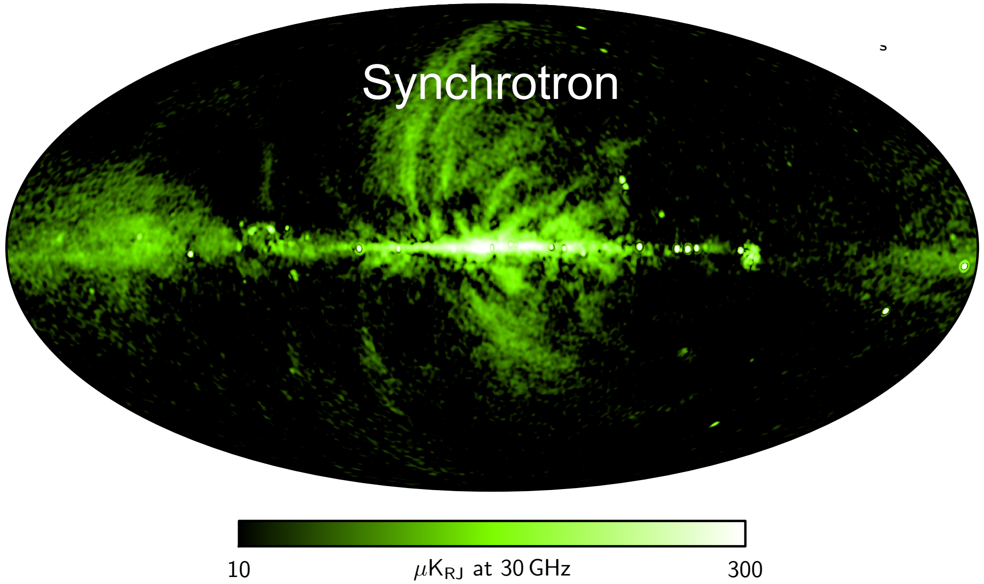


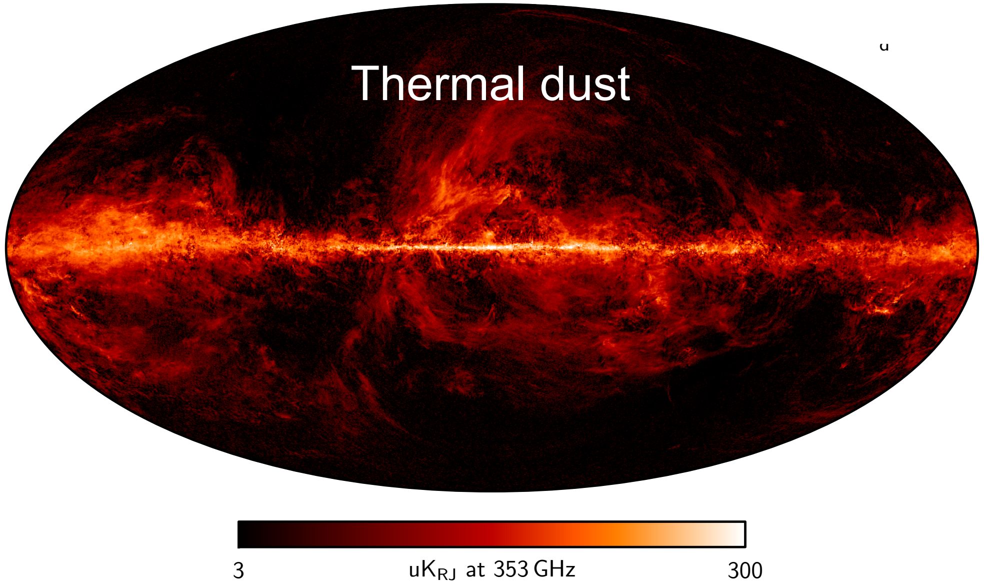
- ❑ B-modes
- ❑ Secondary anisotropies
- ❑ Spectral distortions

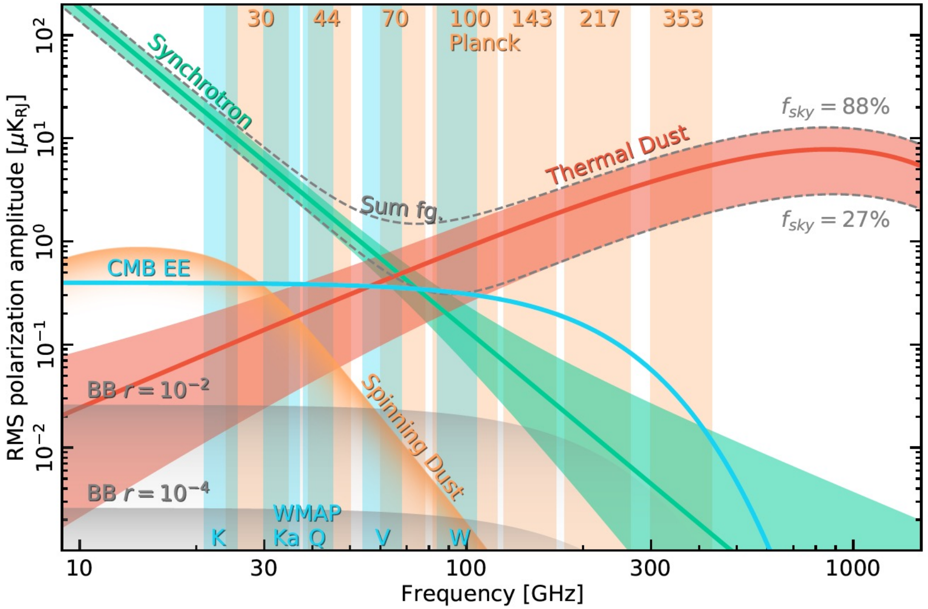
Much more sensitive to imperfect foreground modelling!

M. Remazeilles

Galactic foregrounds vs CMB B-mode







Credit: BeyondPlanck

- For r < 0.01, both dust and synchrotron dominate over the primordial CMB B-mode signal across all frequencies, all angular scales, and all sky regions
- Huge amplitude discrepancies between the signal and the foregrounds
- Minor foreground uncertainties ⇒ large errors on r !

M. Remazeilles

New foreground challenges

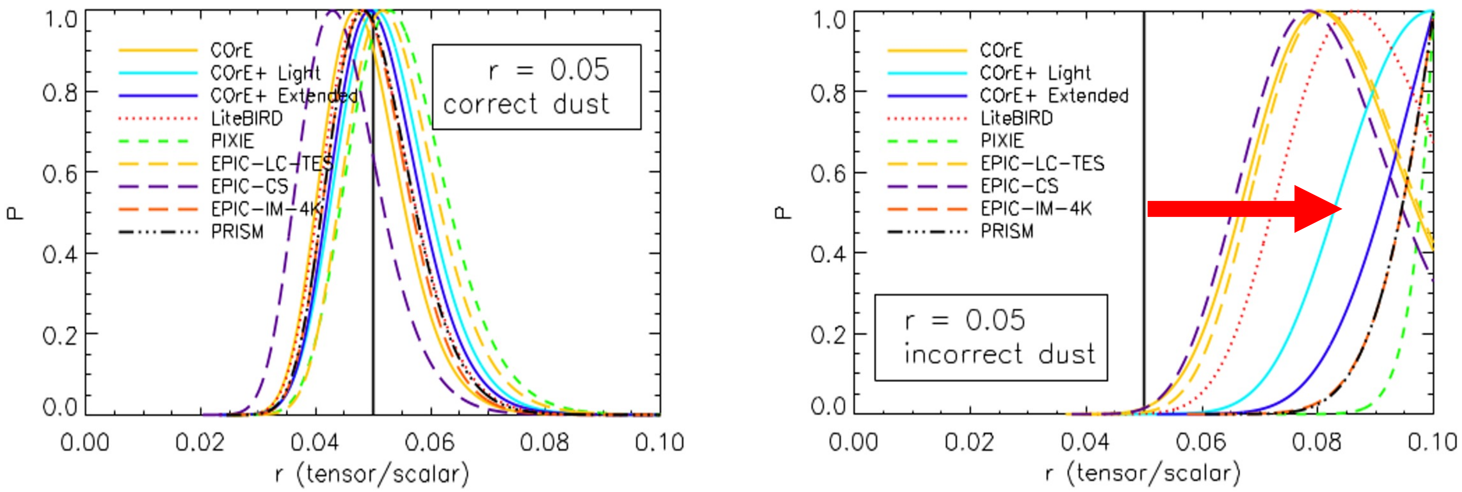
- **Spectral mismodelling of the foregrounds**
- **Spectral distortions of the foregrounds**
- **Spectral degeneracies**
- **Foregrounds correlated with the signal of interest**

Spectral mismodelling of the foregrounds

- Foregrounds poorly known at targeted signal sensitivity levels ($r \sim 10^{-3}$)
- Discrepancies between plausible dust models >> CMB B-mode ($r \sim 10^{-3}$)
- Unknown foregrounds: AME polarization? Magnetic dust?

(see talk by López-Caraballo)

Impact on r of mismodelling two dust modified blackbodies as a single one



Remazeilles et al 2016

Tiny modelling errors on foregrounds = Large error / bias on r !

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Spectral distortions of foregrounds

Line-of-sight averaging and beam averaging distort the expected SED of the foregrounds

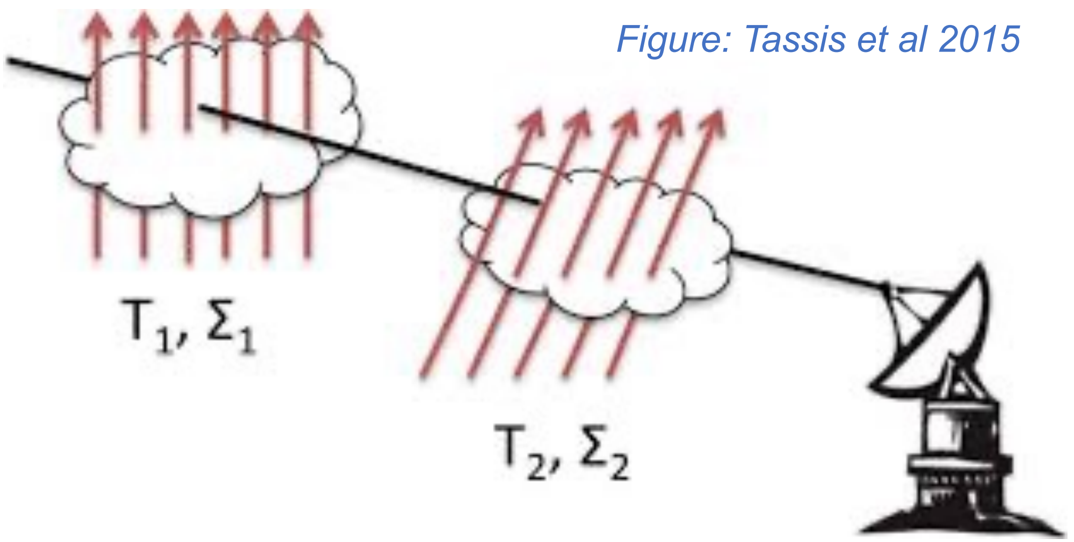


Figure: Tassis et al 2015

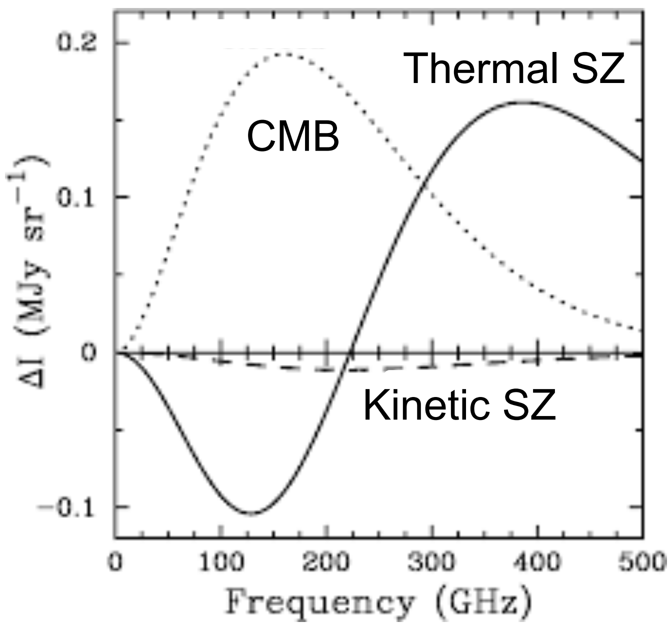
$$\nu^{\beta_1} B_\nu(T_1) + \nu^{\beta_2} B_\nu(T_2) \neq \nu^{\langle\beta\rangle} B_\nu(\langle T\rangle)$$

Chluba et al 2017
Remazeilles et al 2021

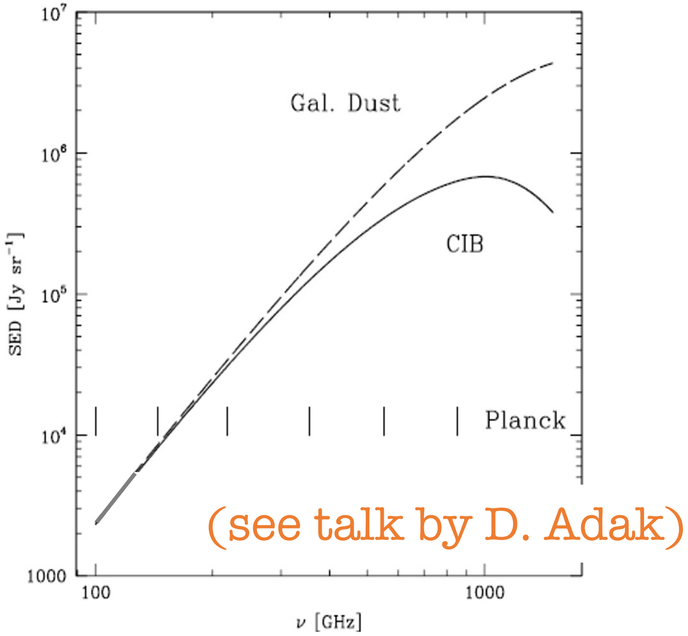
Tiny distortions to the foregrounds >> CMB B-mode & CMB spectral distortions

Spectral degeneracies

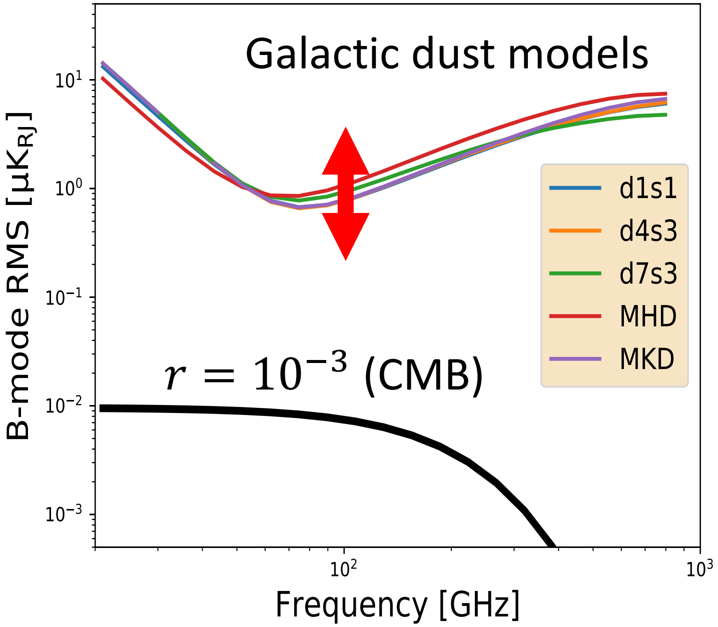
kSZ vs CMB



Dust vs CIB



Dust models over limited frequency ranges



Need to think beyond spectral modelling for component separation

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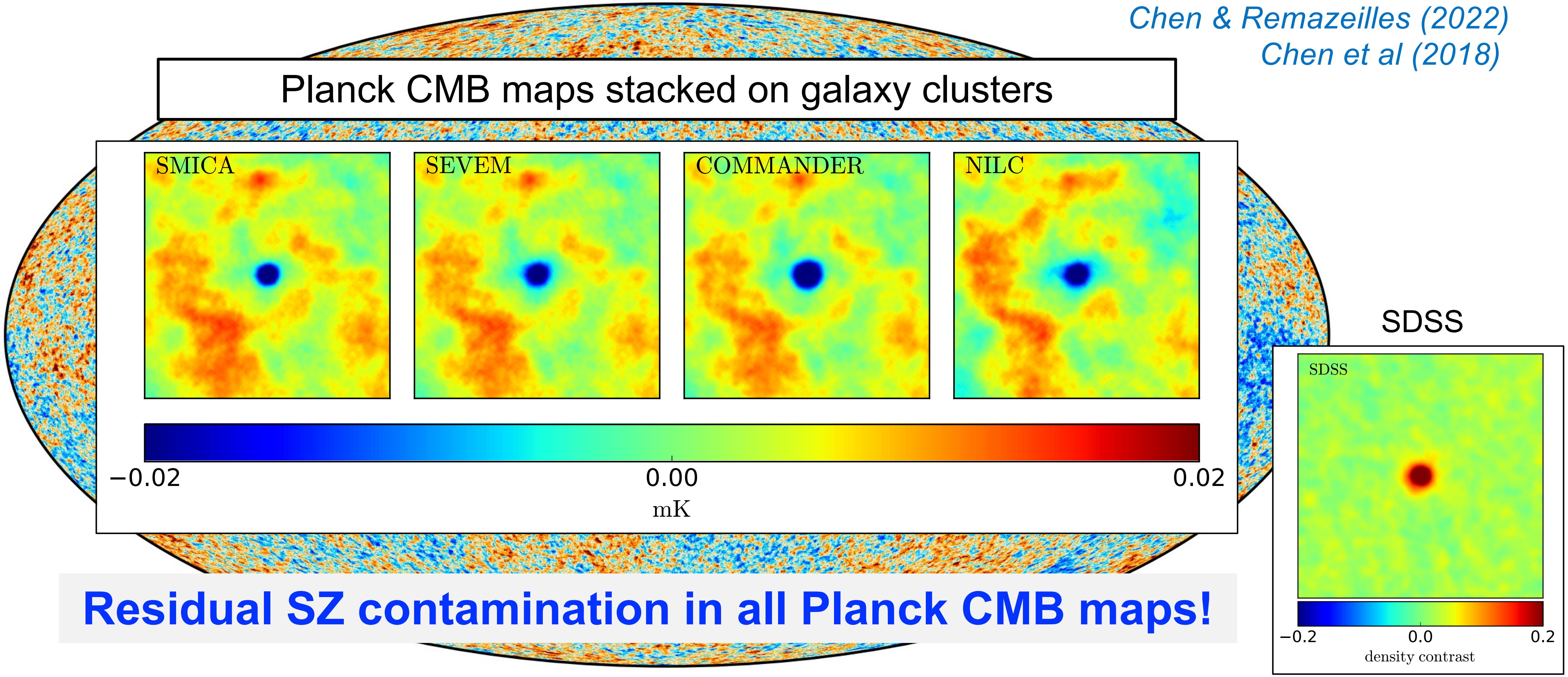
Extragalactic foregrounds to CMB x LSS

Chen & Remazeilles (2022)
Chen et al (2018)

Planck CMB maps stacked on galaxy clusters



Residual SZ contamination in all Planck CMB maps!

Extragalactic foregrounds (SZ, CIB) ⟶ Spurious correlations in CMB x LSS

Conclusions

- Standard ΛCDM model fits all available CMB data with sub-percent precision, but tensions on H_0 and σ_8 with low-redshift probes still need to be understood

- Evidence towards single-field inflation, but primordial gravitational waves still need to be discovered

- Bright future for CMB cosmology with upcoming sensitive CMB experiments from space and ground (LiteBIRD, Simons Observatory, CMB-Stage 4)

- Still a lot to learn from CMB polarization, CMB secondary anisotropies, and CMB spectral distortions

- Weaker signals and higher sensitivities imply new foreground challenges!