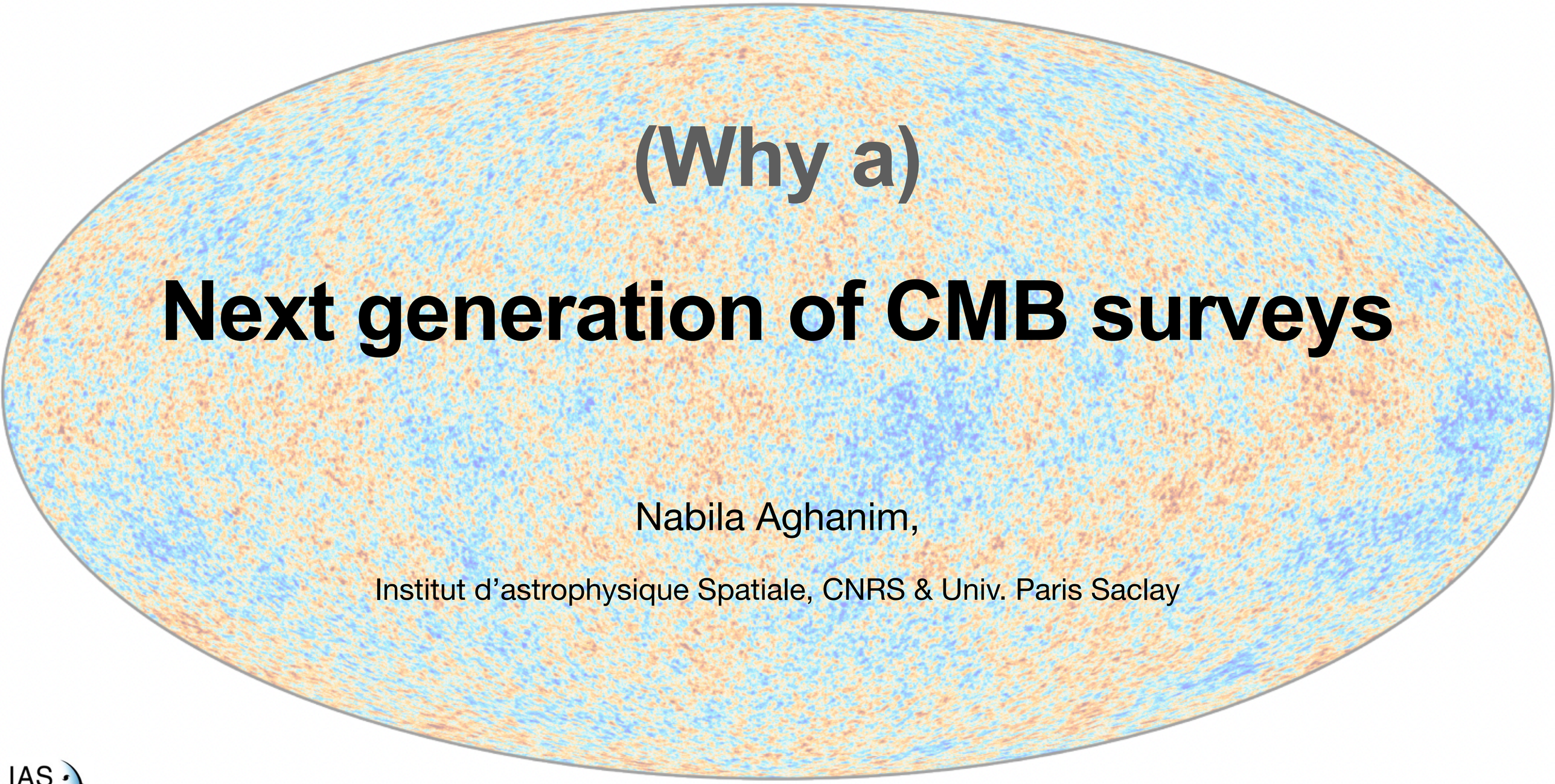


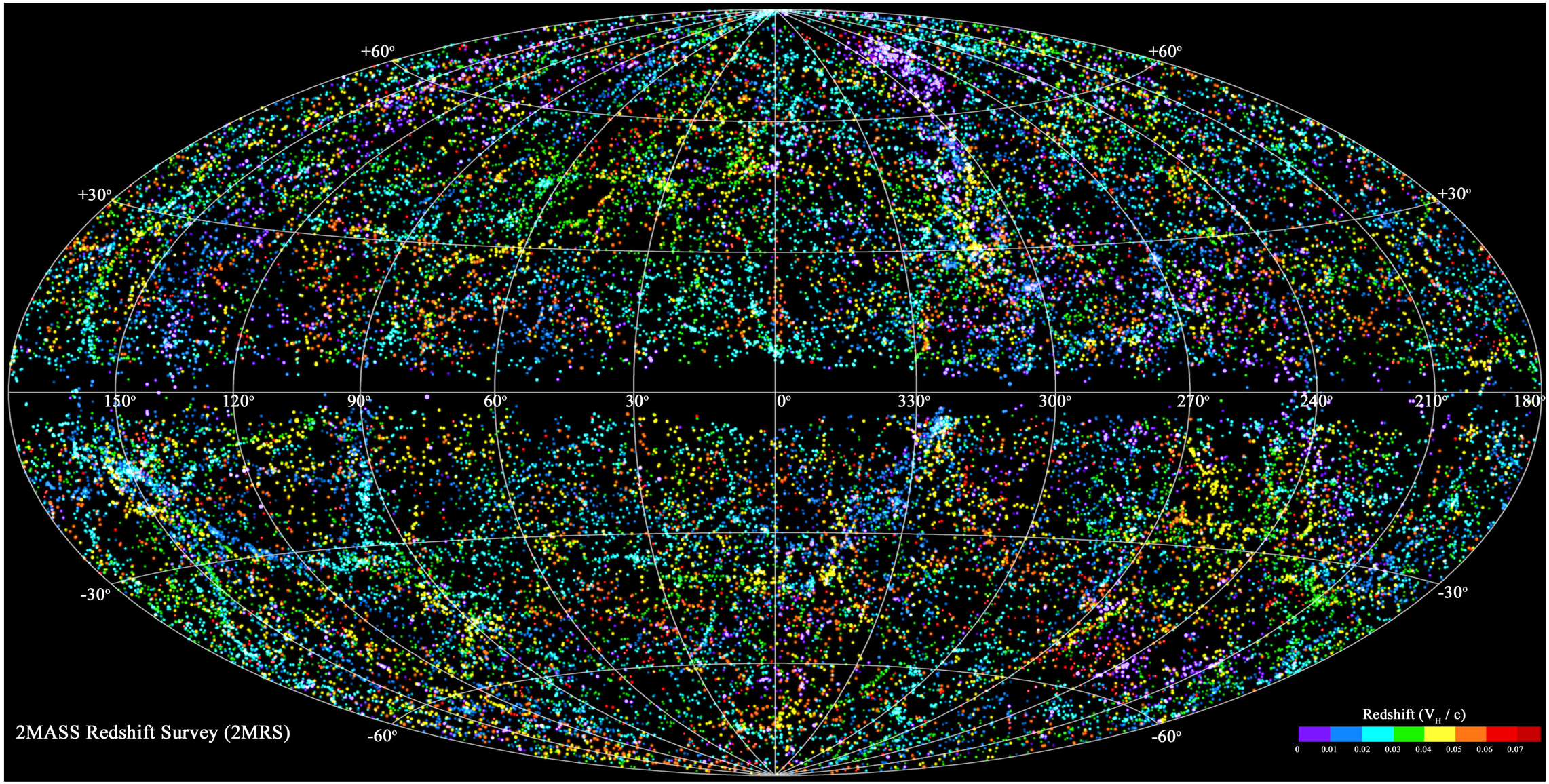
(Why a)

Next generation of CMB surveys

Nabila Aghanim,

Institut d’astrophysique Spatiale, CNRS & Univ. Paris Saclay

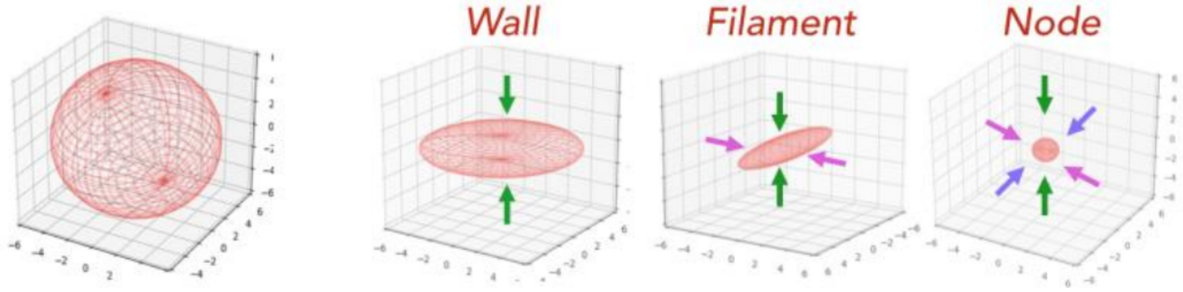
WHERE GALAXIES ORIGINATED FROM?



WHERE GALAXIES ORIGINATED FROM?

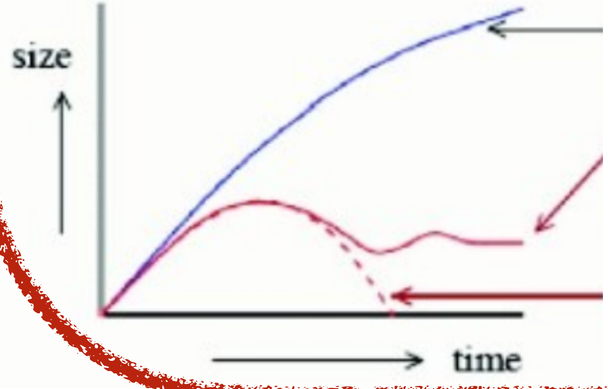
Emergence of the cosmic web from gravitational collapse of initial perturbations, Zel'dovich 1970's:

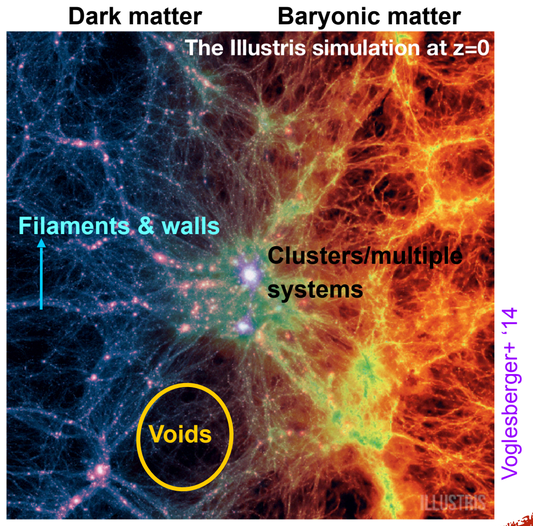
- collapse along one axis: **walls**
- contraction of second axis: **filaments**
- full collapse along 3 axes: **nodes**



Gravity vs expansion: spherical collapse → virialised objects

Cf. Lecture from Elisabeth Krause (Monday pm)





Initial density perturbations?

↓

Quantum fluctuations at inflation

Cf. Lectures from Guilherme Pimentel

CMB ANISOTROPIES FROM 90'S TO 2025

CMB spectrum & anisotropies ~10°

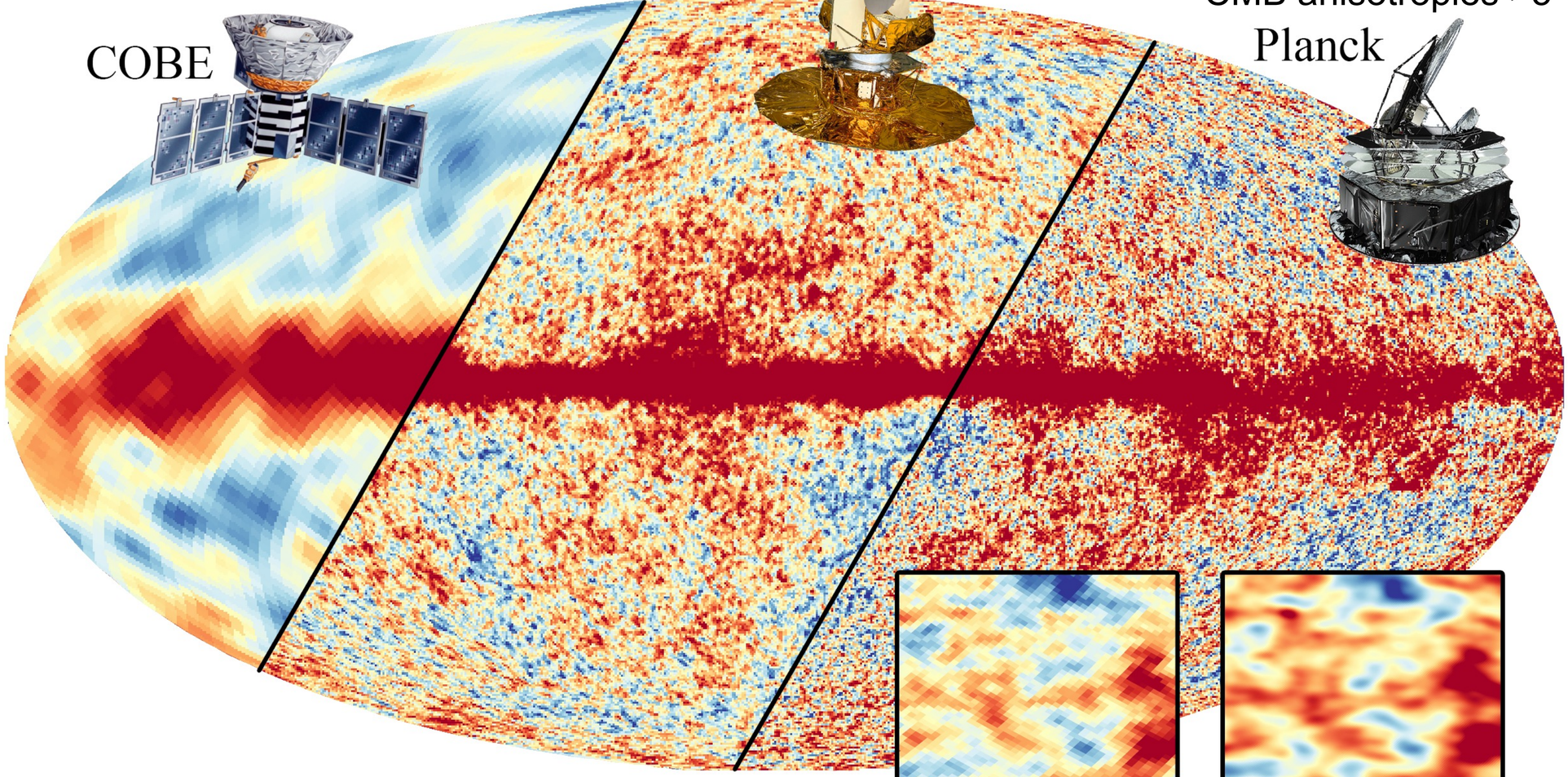
COBE

CMB anisotropies >12'

WMAP

CMB anisotropies >5'

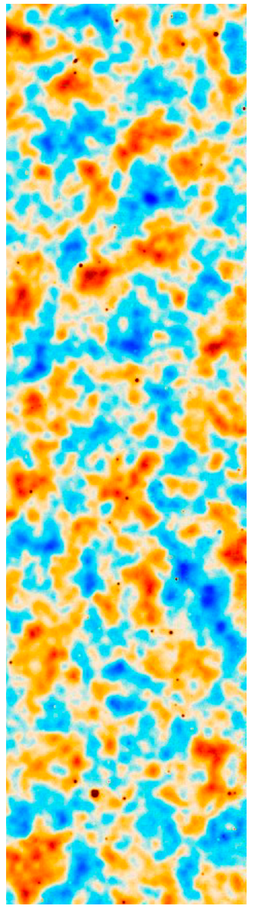
Planck



- 200 μK

200 μK

Anisotropies > 2'
ACT & Planck
Also SPT, SO…

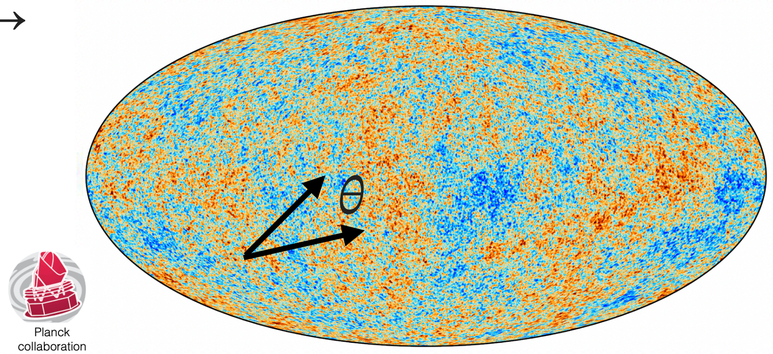


FROM MAPS TO COSMOLOGICAL ANALYSIS

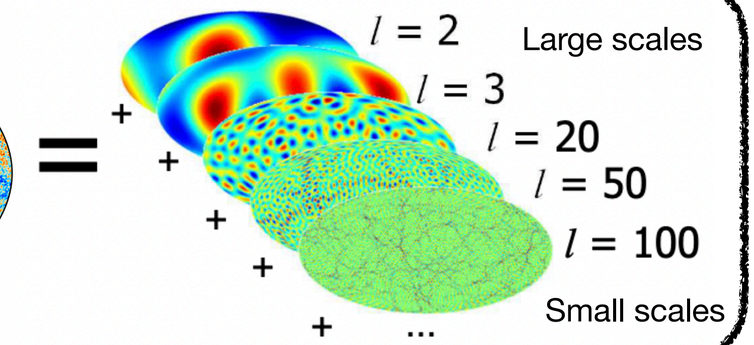
Spherical harmonic decomposition →
angular power spectrum
(summary statistics)

$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{T} Y_{\ell m}(\mathbf{n})$$

$$C_\ell^{TT} = \langle a_{\ell m}^{T} \cdot a_{\ell m}^{T\star} \rangle$$

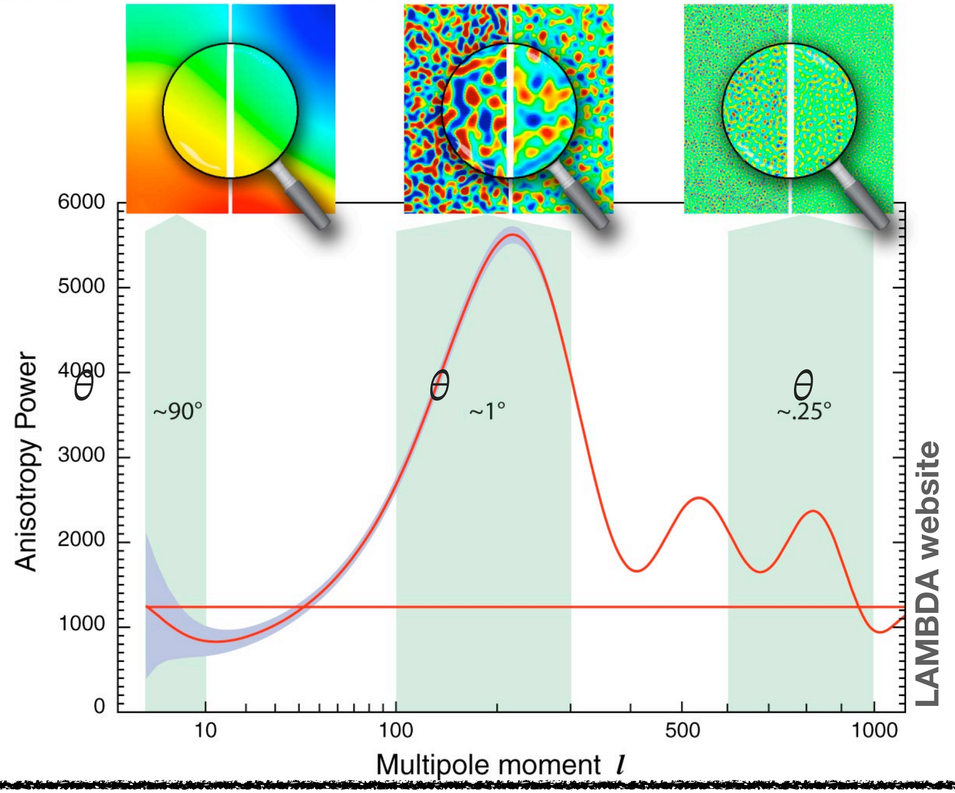


Planck collaboration



Cosmological information in the CMB angular power spectrum

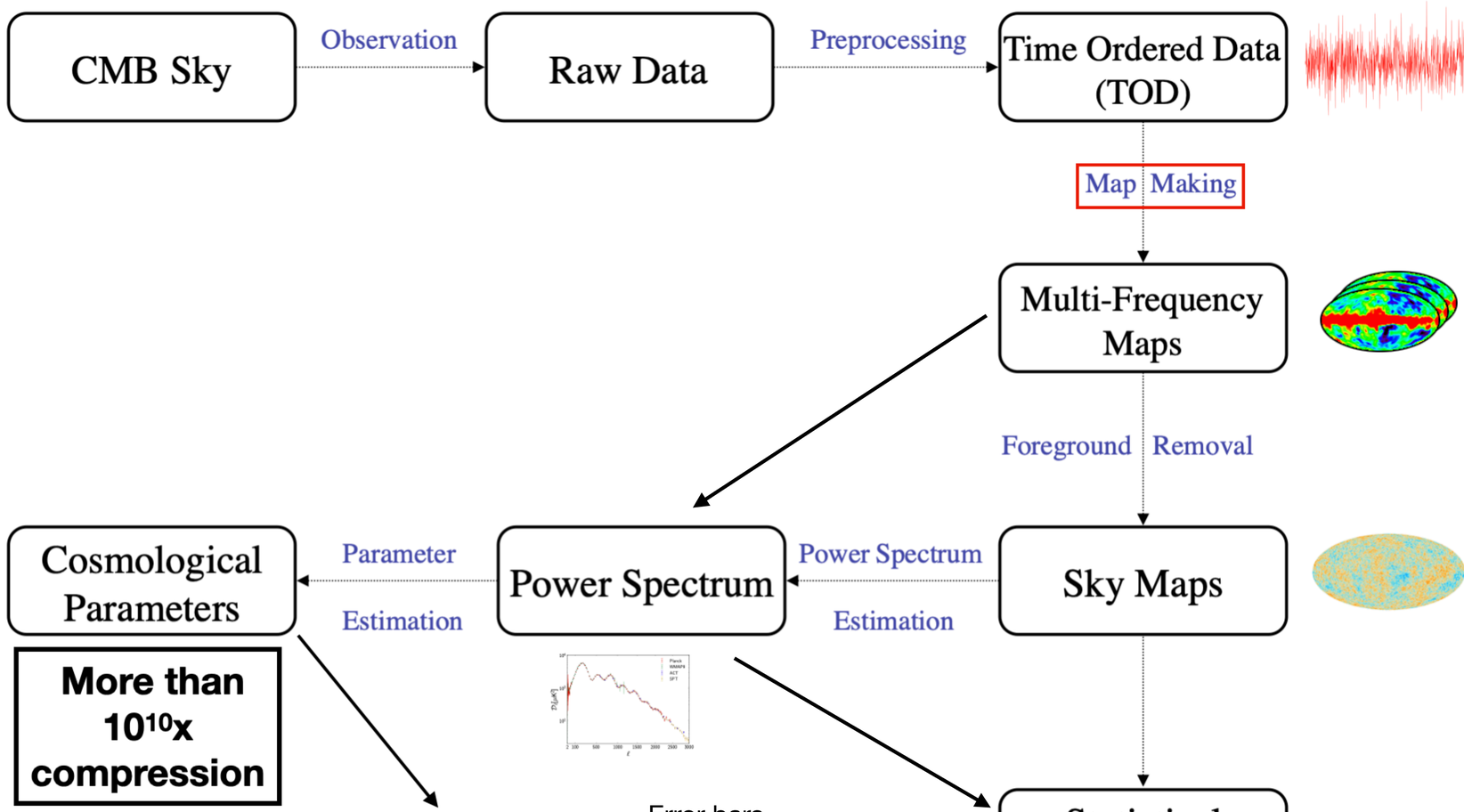
- **Large scales (>few degrees)**: Plateau → initial density perturbations
- **Intermediate scales (~degree)**: Acoustic oscillations → total energy content of the Universe
- **Small scales (<degree)**: Damping → cosmic ingredients, cosmological parameters



FROM MAPS TO COSMOLOGICAL ANALYSIS

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}[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

Planck Collab. '18



Ensemble of cosmological parameters derived using Bayesian inference

$$-\ln \mathcal{L}\left(\hat{\mathbf{C}}|\mathbf{C}(\theta)\right) = \frac{1}{2}\left(\hat{\mathbf{C}} - \mathbf{C}(\theta)\right)^T \boldsymbol{\Sigma}^{-1} \left(\hat{\mathbf{C}} - \mathbf{C}(\theta)\right) + c$$

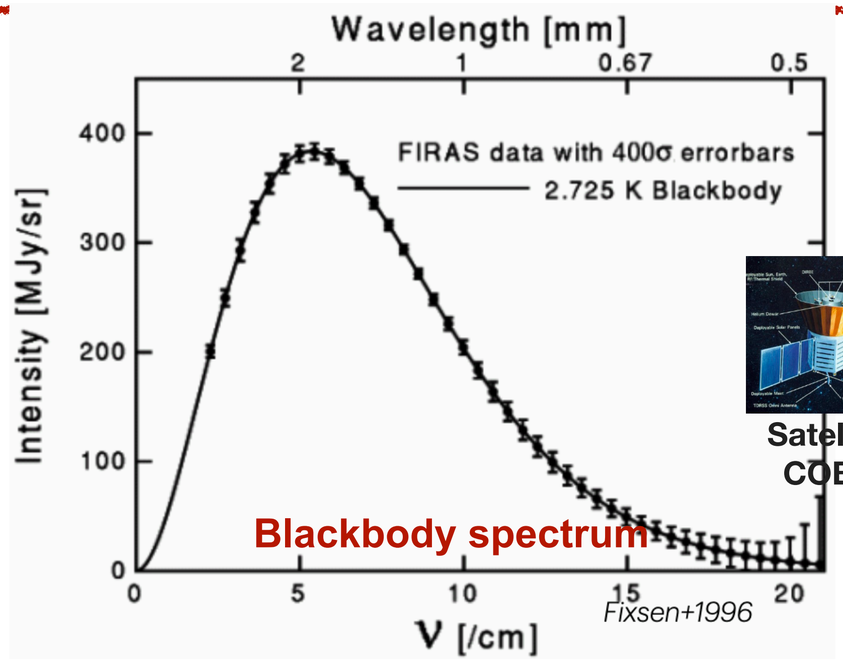
Error bars

Data

Theoretical Model

Adapted from G. Fabbian

COSMOLOGICAL SCENARIO



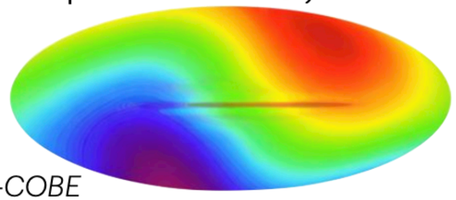
Satellite COBE

Blackbody spectrum

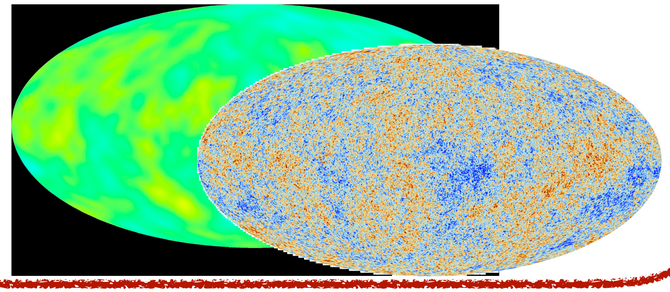
monopole $T \simeq 2.7$ K



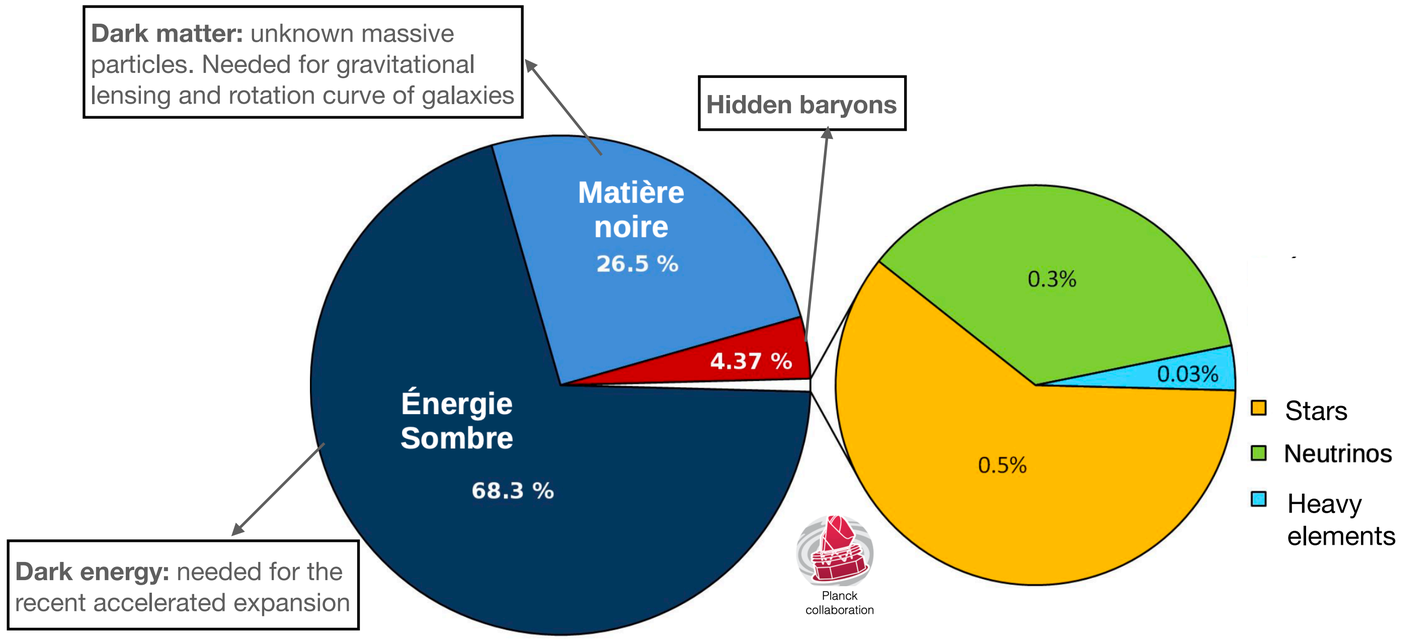
dipole $\Delta T \simeq 3{,}1$ mK



Crédits : NASA-COBE



Homogeneous & isotropic



- Hot **big-bang** scenario
- Existence of **initial density perturbations** seeding galaxies and the large scale structure (nodes, filaments, voids)
- Growth of perturbations into large-scale structure through **gravitational instability**
- Determined **geometry** & **composition** of the Universe

WHY DO NE NEED TO GO BEYOND?

- **How did the Universe begin?**
  - Initial density perturbations seeded by inflationary field → What powered inflation?
  - Scale invariant initial power spectrum → Could it explain primordial BHs? Seeds of Super-Massive BH? Are the perturbations non-Gaussian?

- **What is the Universe made of?**
  - Energy content of the Universe is made of 26.5% dark matter → What is its nature?
  - … and of 68.3% dark energy → What is it?

- **How did the Universe evolve?**
  - What is the thermal energy in the large-scale structure?
  - What is the energy injected by Super-Massive BH?
  - Cosmic start-formation history?

WHAT NEW CMB-RELATED OBSERVABLE ?

MAIN DIRECTIONS FOR CMB

CMB Polarisation

CMB Cross-correlations with LSS tracers

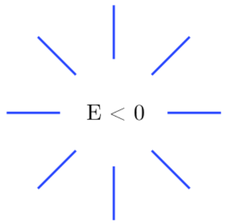
CMB Spectral distortions

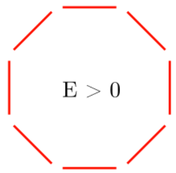
… A PERSONAL VIEW

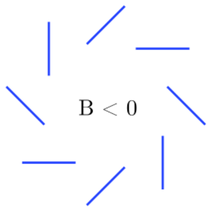
CMB POLARISATION

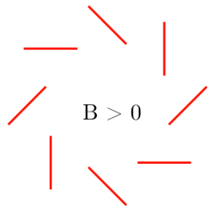
Result of Thomson scattering of CMB photons by free electrons in the presence of anisotropies

Radial or tangential configurations around hot/ cold spots.

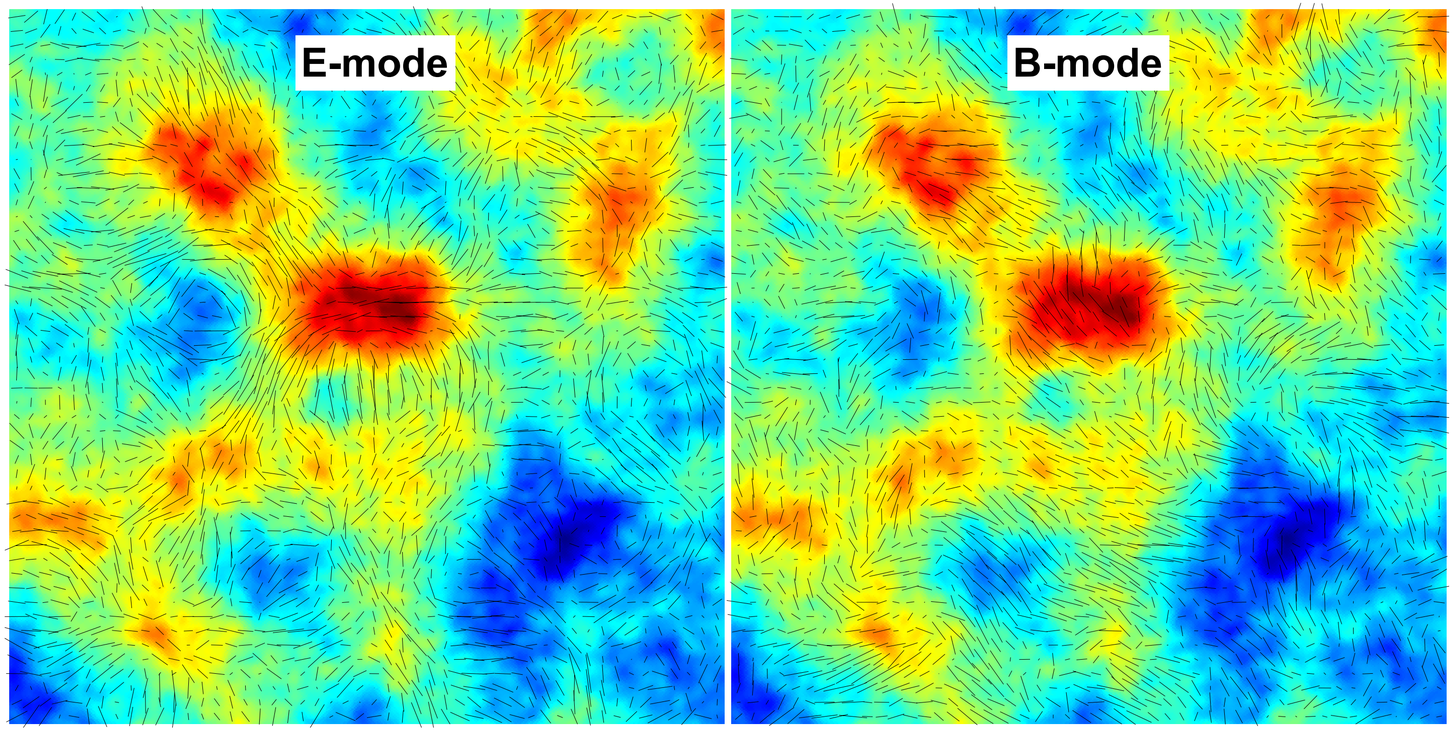






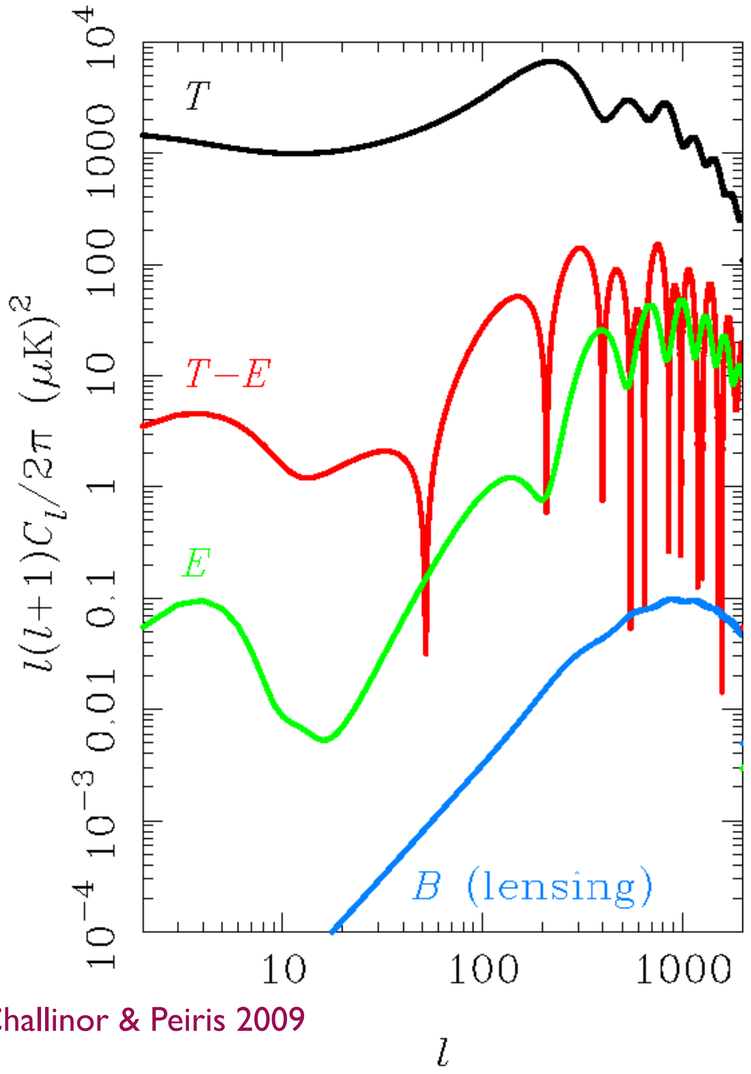


Spiral configurations exhibiting (clockwise or counter-clockwise) handedness



Simulation

CMB POLARISATION SCALAR PERTURBATIONS

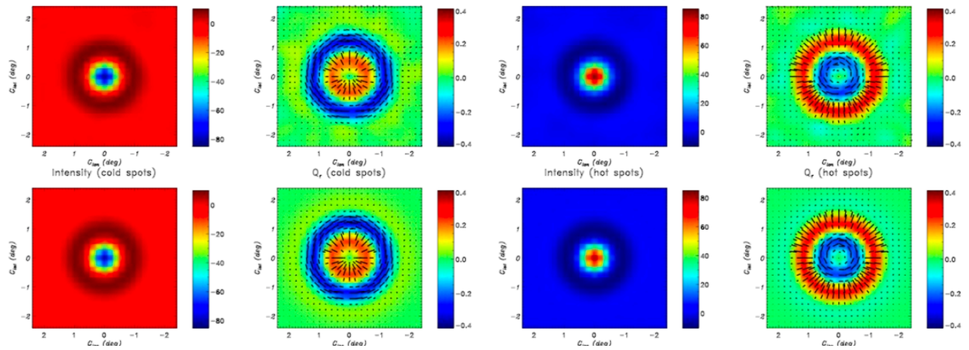


Challinor & Peiris 2009

Density (Scalar) Perturbations: pulling matter creates temperature differences (hot/cold spots) that source **E-mode polarisation**

- E-modes peak at minima of T (pressure and velocity are out of phase)
- Probe scalar nature of perturbations
- Probe baryon velocity at last scattering
- T and E-modes are spatially correlated

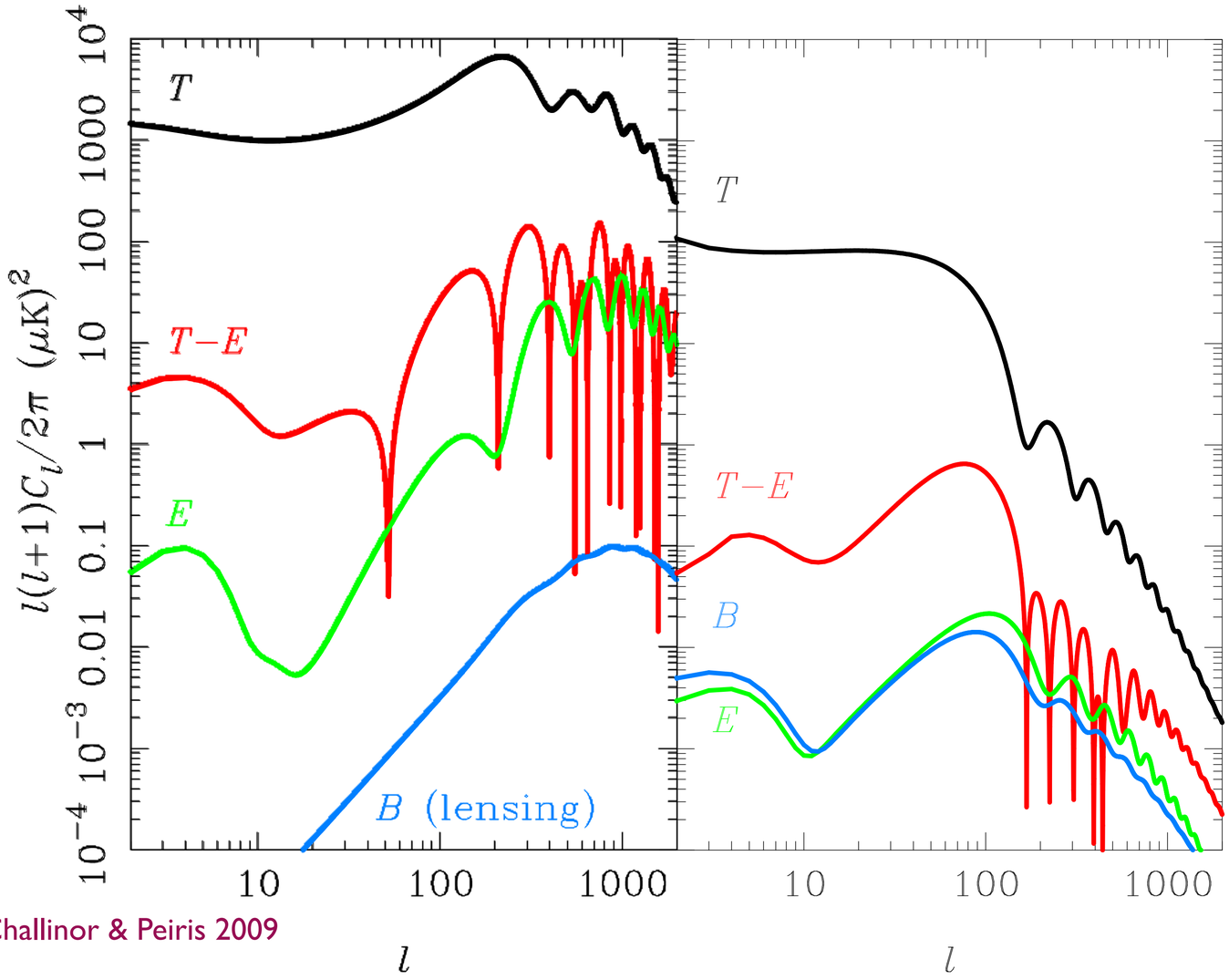
Stacking of Planck E-mode polarisation on tempreature peaks & throughs



Planck Collab.'13

Gravitational Lensing: distort E-mode photons into **secondary B-mode**

CMB POLARISATION TENSOR PERTURBATIONS



Challinor & Peiris 2009

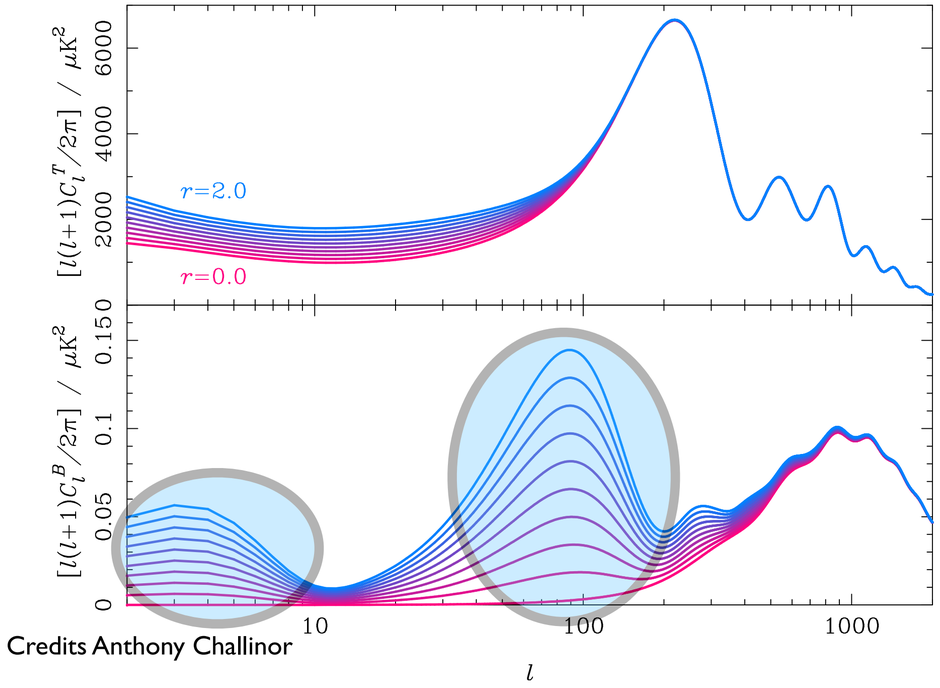
Gravitational Waves (Tensor) Perturbations: distort and shift radiation fields and generate **B-mode & E-mode**

Gravitational waves decay when the enter horizon → **B-modes dominate at large scales**

Cf. Lectures from Guilherme Pimentel

CMB POLARISATION: WHY FOR?

Testing inflation with B-modes



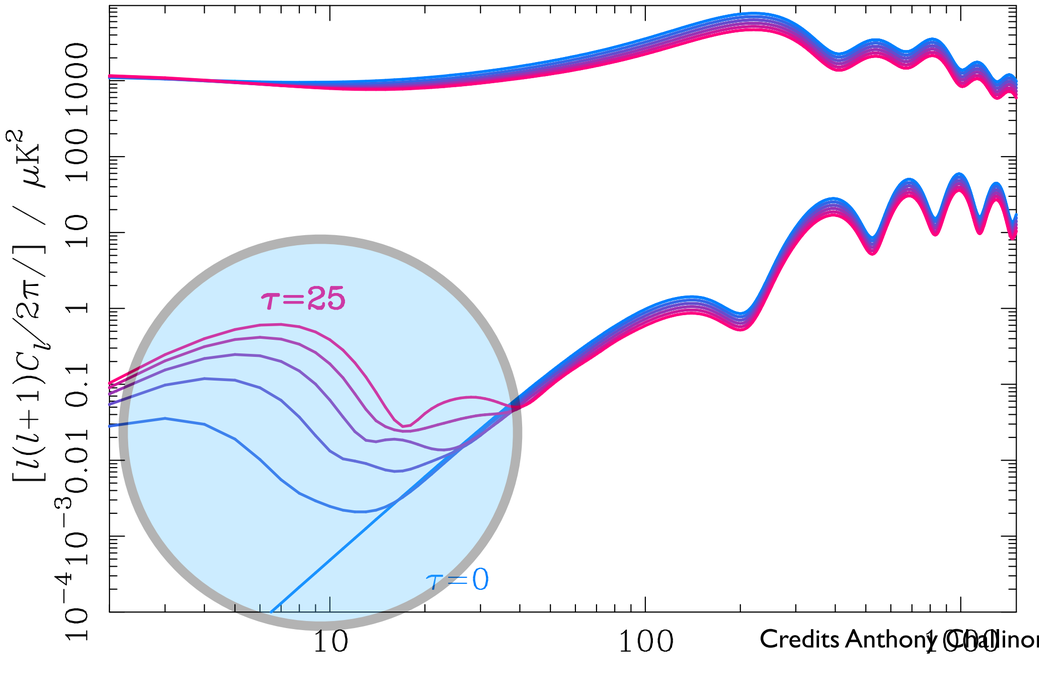
- B-modes : **smoking-gun evidence for gravitational waves in the early universe**

$$\Delta_s^2(k) \approx A_s k^{n_s - 1} \qquad \Delta_t^2(k) \equiv A_T k^{n_t} \longrightarrow r \equiv \frac{\Delta_t^2(k)}{\Delta_s^2(k)}$$

- Can constraints model and energy scale of inflation $V^{1/4} \approx \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\,\mathrm{GeV}$

Cf. Lectures from Guilherme Pimentel

Probing reionisation with E-modes

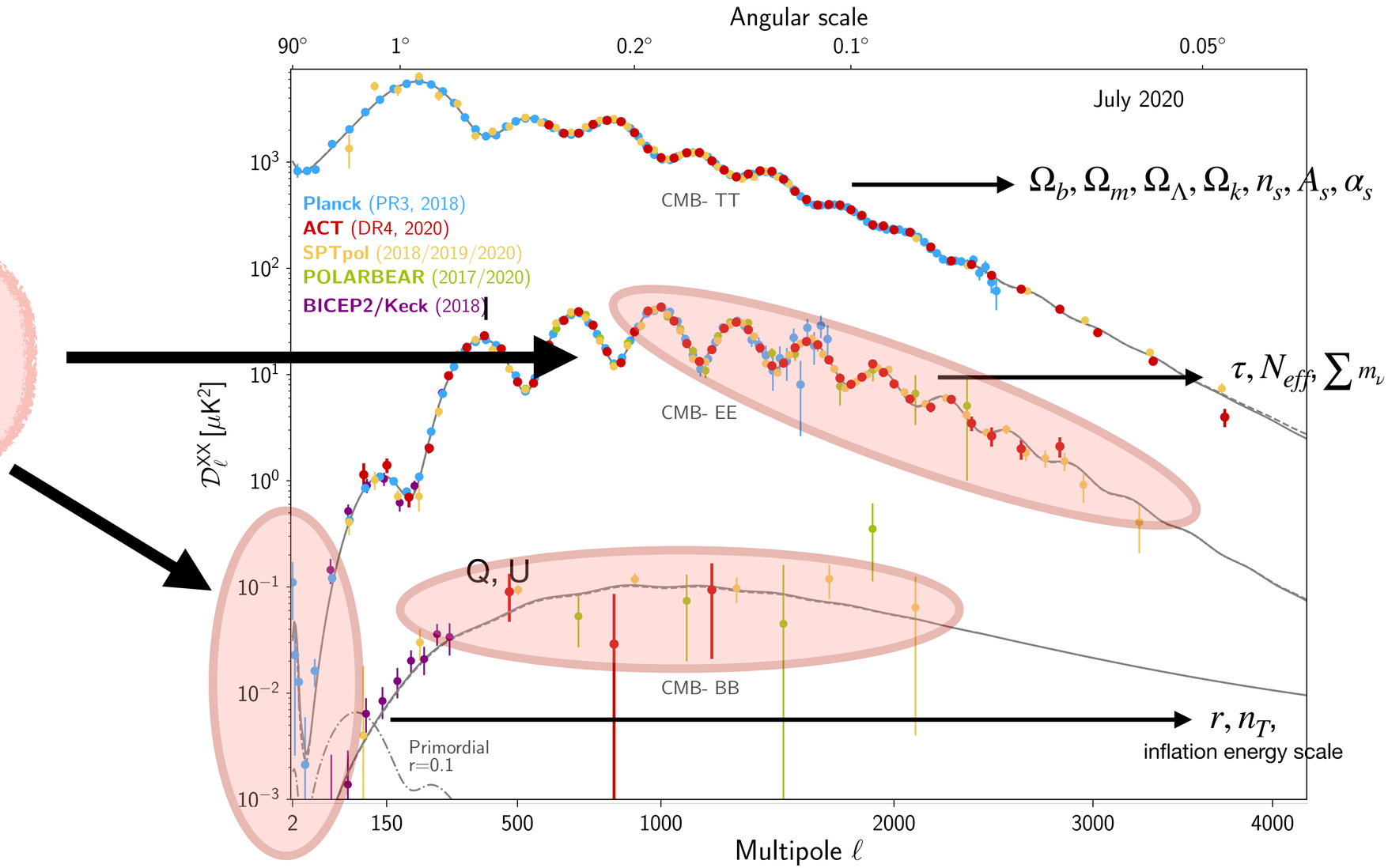


Rescattering erases CMB temp. anisotropies below the horizon scale and regenerates them on the horizon scale at that time

- Change in the normalisation for T and E at small scales
- Large scale E & B proportional to optical depth τ

CMB T & P ANISOTROPIES (~TODAY)

Targets of future surveys

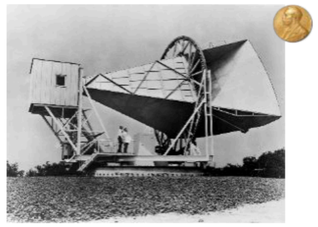


Aiola+2020

CMB IMAGING EXPERIMENTS

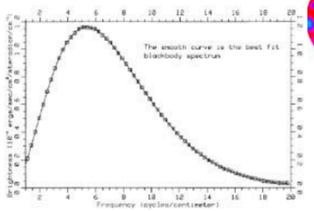
Context in CMB obs.

Discovery of the CMB (1964)

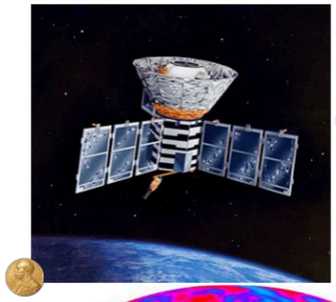


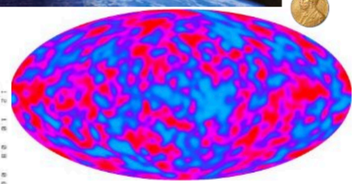
Observations by satellite

Ground and balloon Observation by telescope

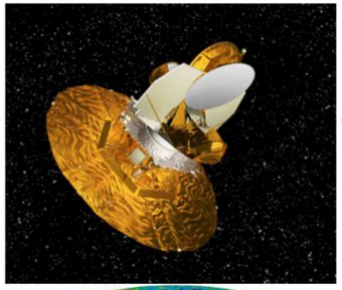


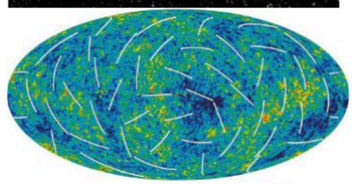
NASA COBE (1989)





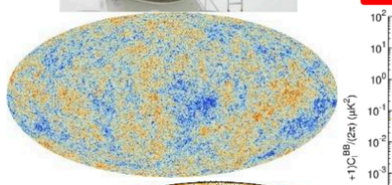
NASA WMAP (2001)



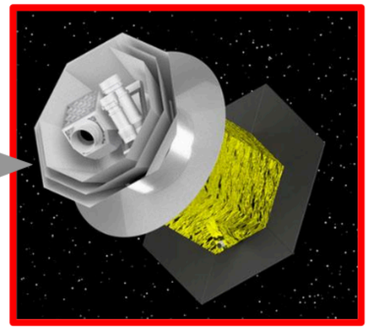


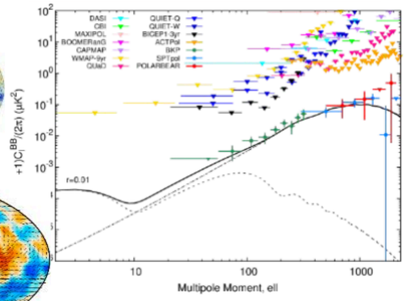
ESA Planck (2009)



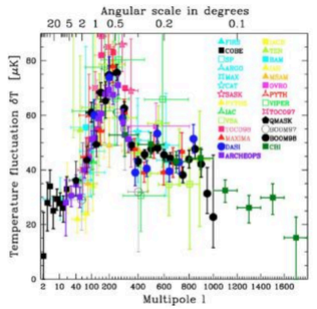


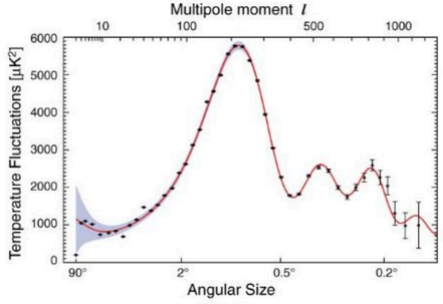
LiteBIRD





Large scales all sky







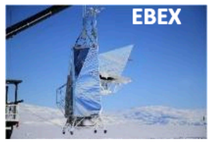










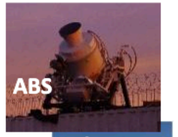




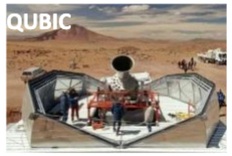






















Small scales fraction of sky

Credits Tomotake Matsumura

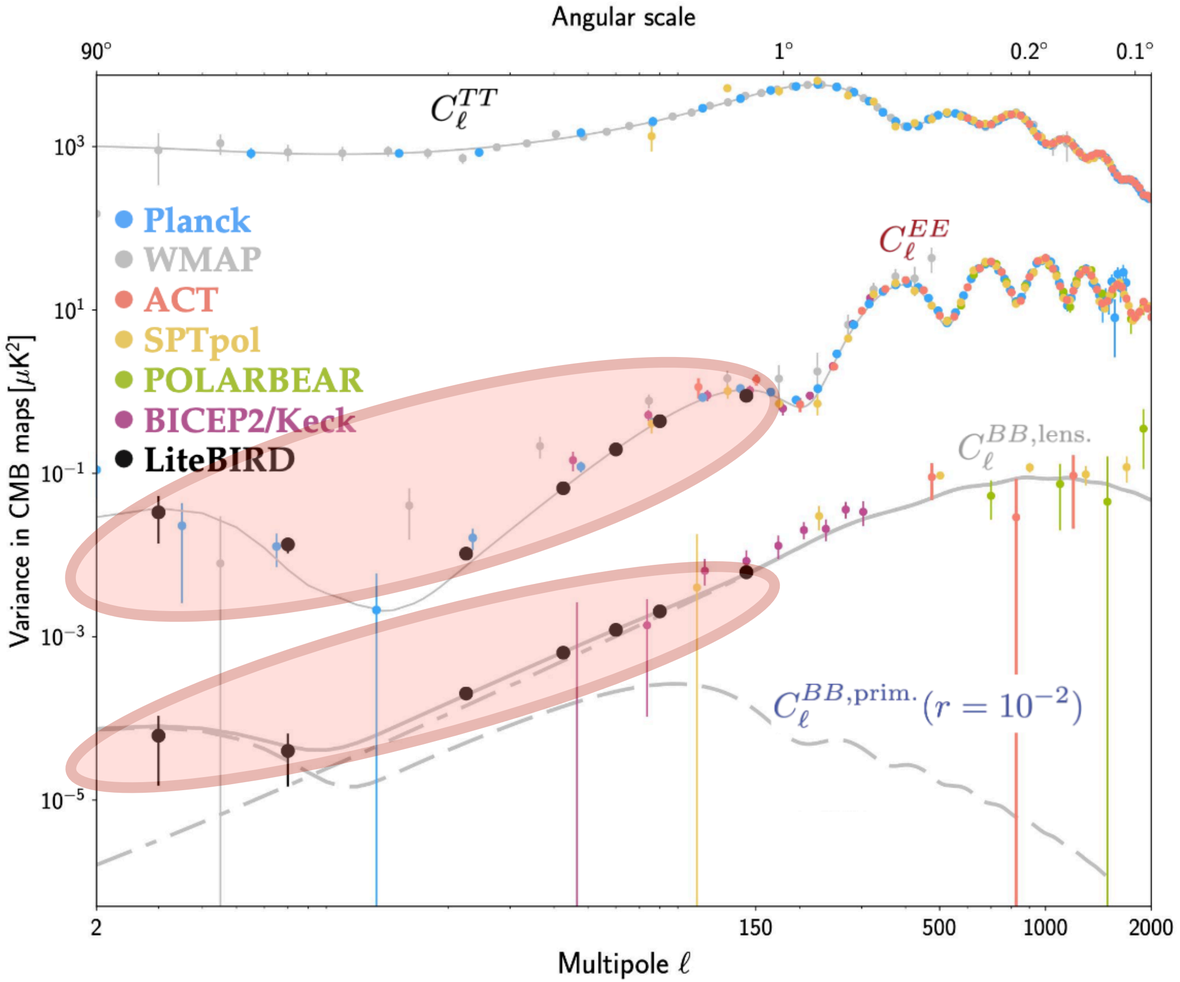
TOWARDS LARGE SCALE POLARISATION

LiteBIRD main scientific objectives

- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.032$ (95% C.L.)

(Tristram et al. 2022, combining BK18 and Planck PR4)

- *LiteBIRD* will significantly improve the current sensitivity on *r*
- The final goal is to achieve **a statistical uncertainty of $\sigma(r) \lesssim 0.001$ for $r = 0$**



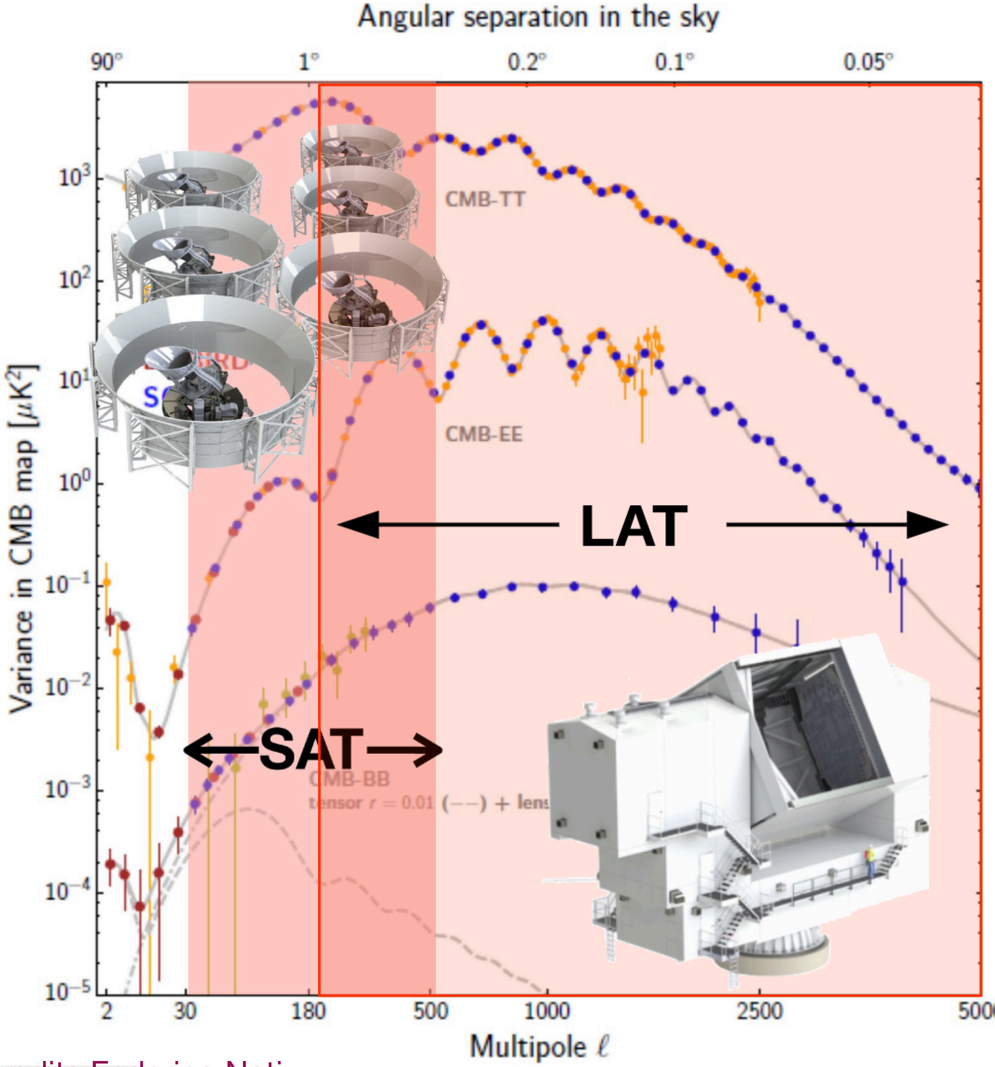
Credits Tomotake Matsumura

TOWARDS SMALL SCALE POLARISATION

Simons Observatory







Credits Federico Nati

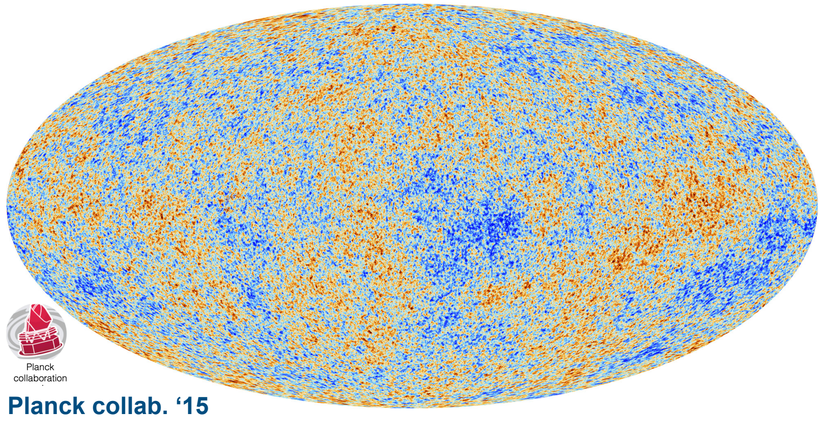
MAIN DIRECTIONS FOR CMB

CMB Polarisation
(and initial perturbations)

CMB Cross-correlations with LSS tracers

CMB Spectral distortions

CMB & Large Scale Structures

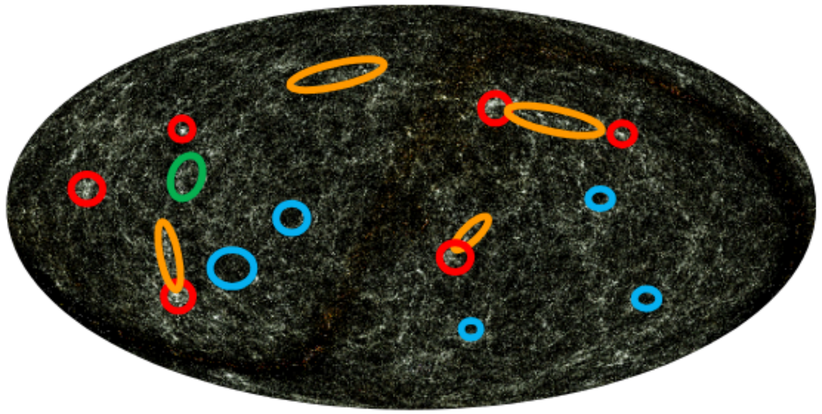


Planck collab. ‘15

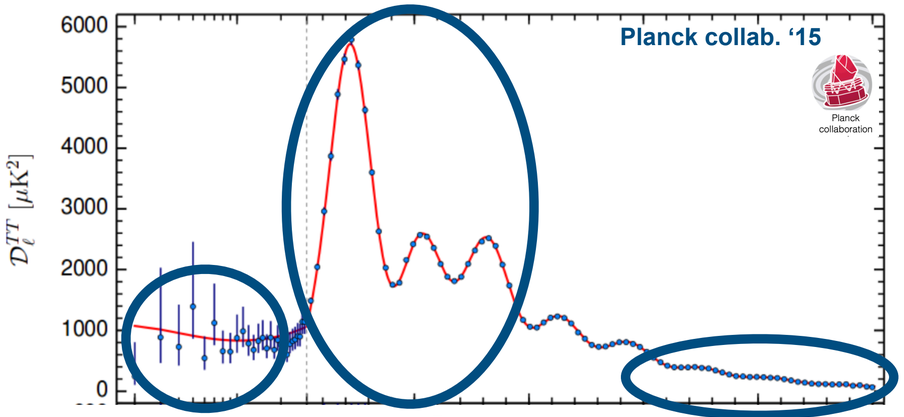
Early Universe
CMB temperature anisotropies

Gravity & baryonic physics

Time evolution



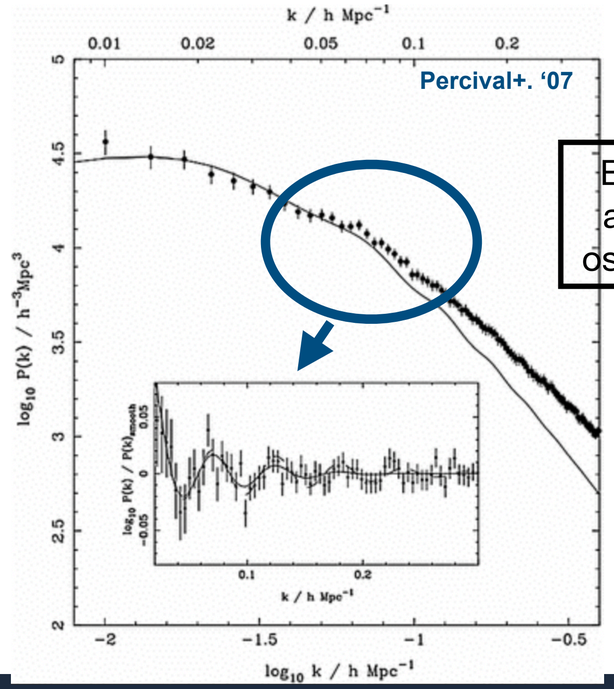
Late Universe=Cosmic web of nodes, walls, filaments, and voids



Sachs-Wolfe plateau
Initial conditions

Acoustic oscillations
Geometry & matter content & baryons

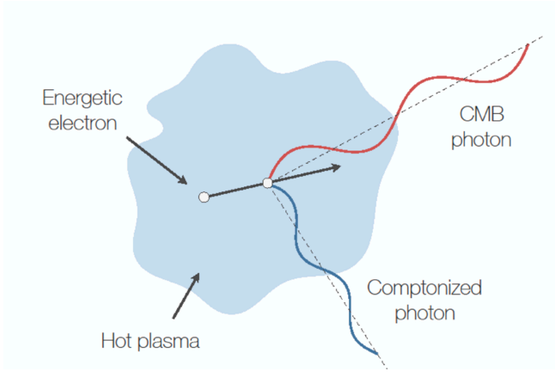
Silk damping
Initial conditions & reionisation & cosmo. param.

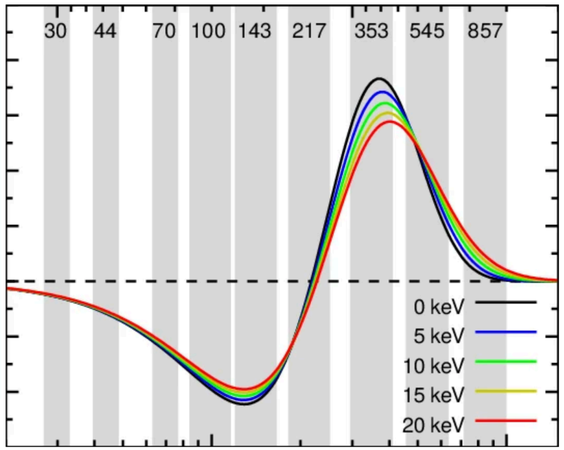


Baryonic acoustic oscillations

CMB PHOTONS' JOURNEY: SECONDARIES

Overall heating through inverse Compton du to presence of hot/warm gas in structures (clusters, groups…): thermal Sunyaev-Zeldovich (tSZ)

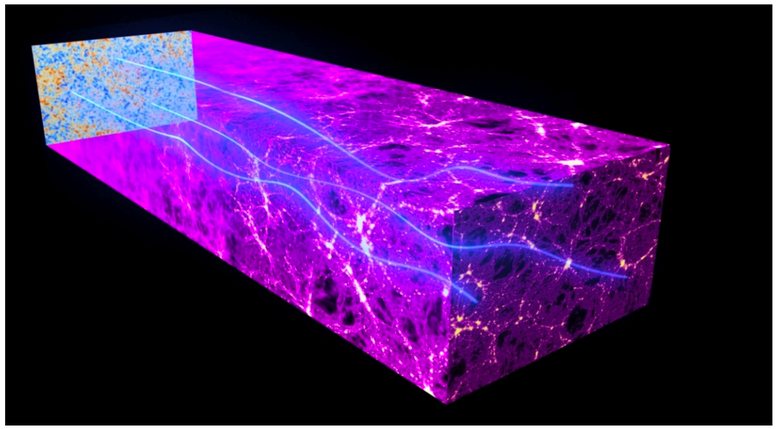




Specific spectral signature & amplitude y probing electron gas pressure

$$y(\hat{\mathbf{n}}) = \int n_{\mathrm{e}} \frac{k_{\mathrm{B}} T_{\mathrm{e}}}{m_{\mathrm{e}} c^2} \sigma_{\mathrm{T}} \, ds$$

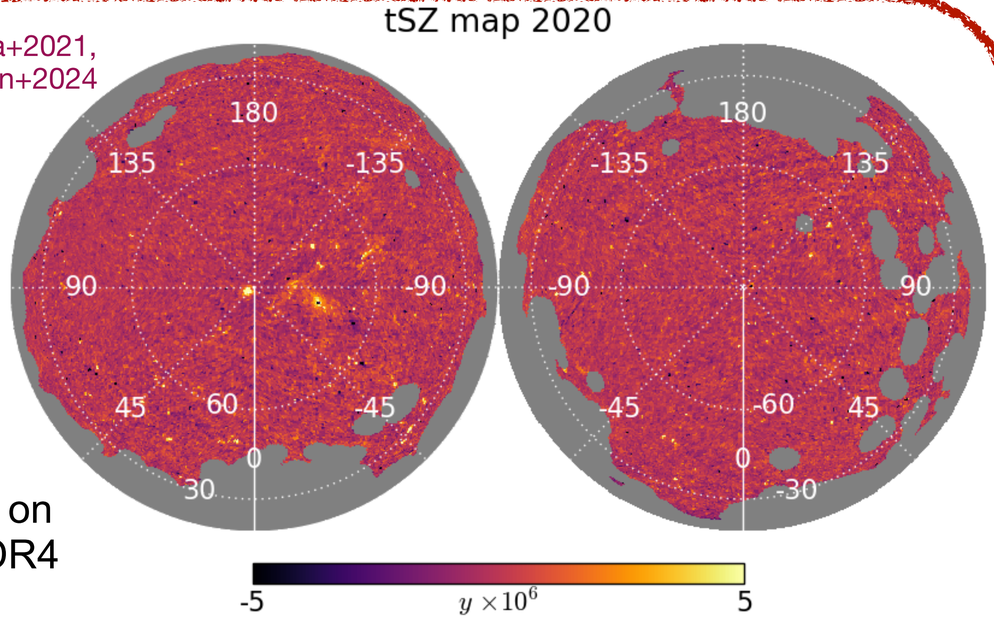
Deviations through gravitational effect due to presence of gravitational potential of structures : CMB lensing



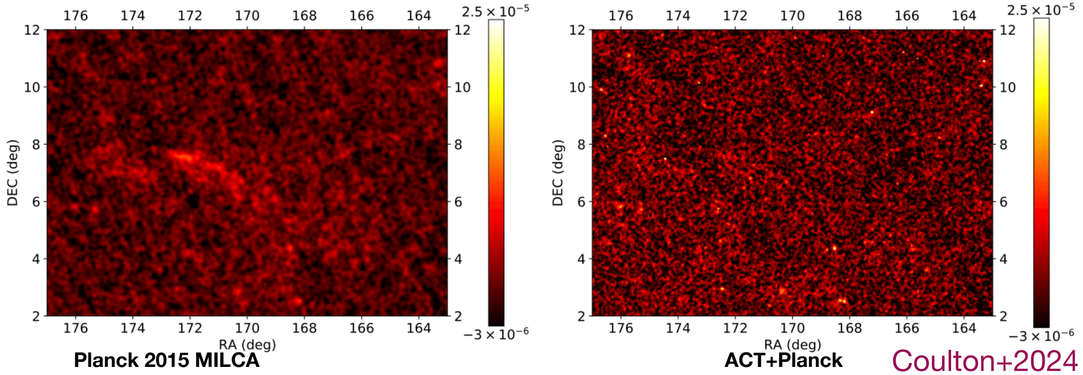
No spectral signature & amplitude probing the total matter distribution

CMB SECONDARIES: tSZ & LENSING

Tanimura+2021,
Chandran+2024



Analysis on
Planck DR4

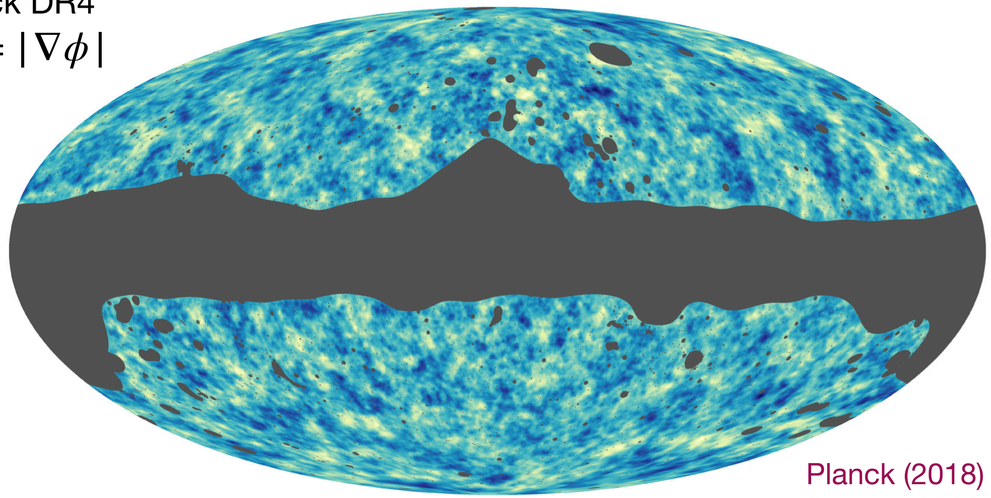


Coulton+2024

ACT DR6 higher-resolution map using Planck channel for cleaning

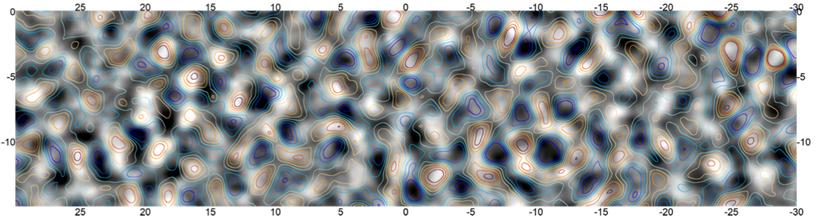
CMB lensing map

Planck DR4
$|\mathbf{d}| = |\nabla\phi|$



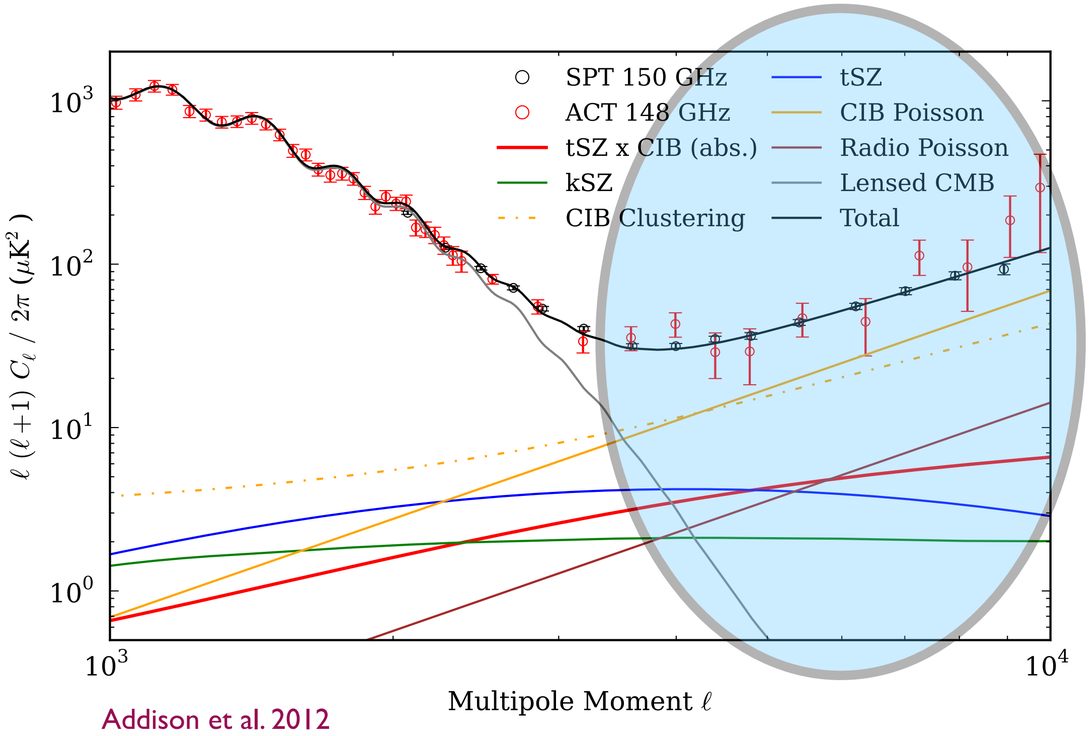
Planck (2018)
Carron+(2022)

ACT (~40% sky,
$\kappa \propto \nabla^2\phi$)

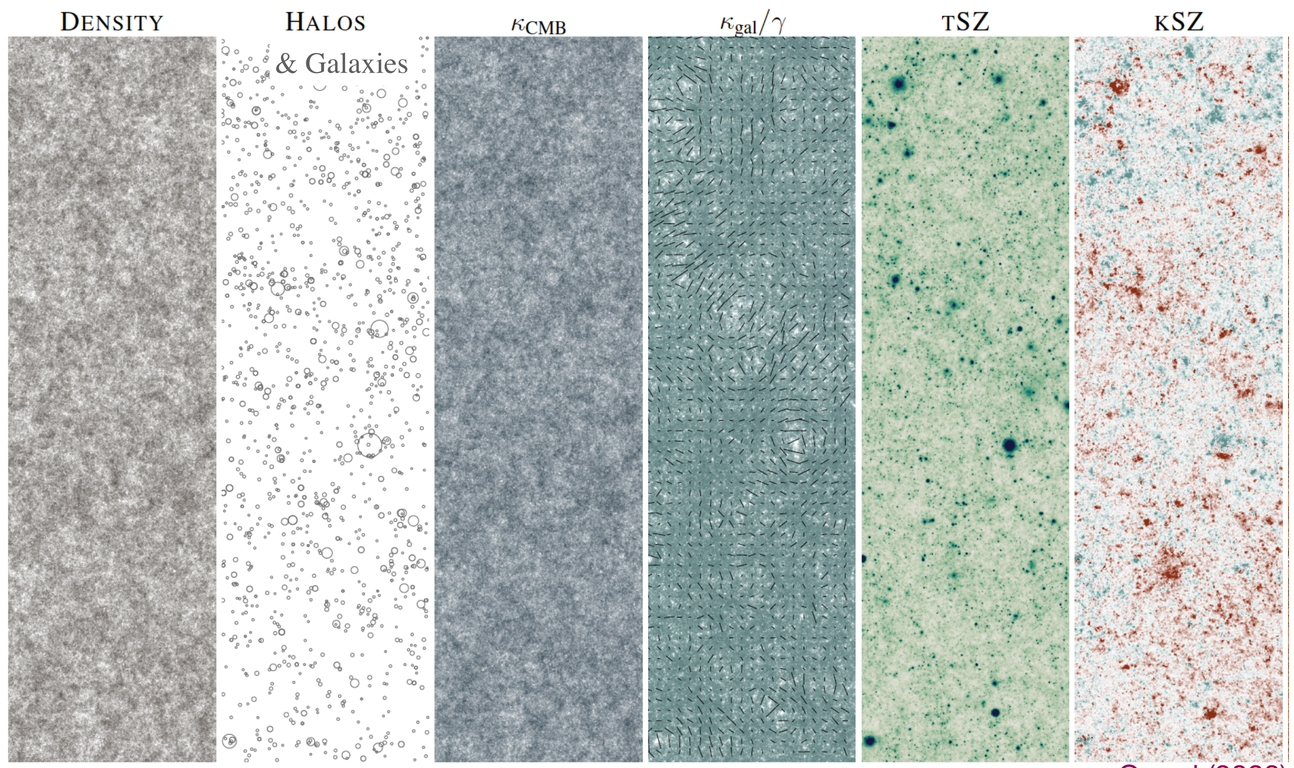


Madhavacheril+(2024), Qu+(2023).
See also Fe, Millea+(2024) for SPT on 1500deg2

CMB T @SMALL SCALES: SECONDARIES



Addison et al. 2012



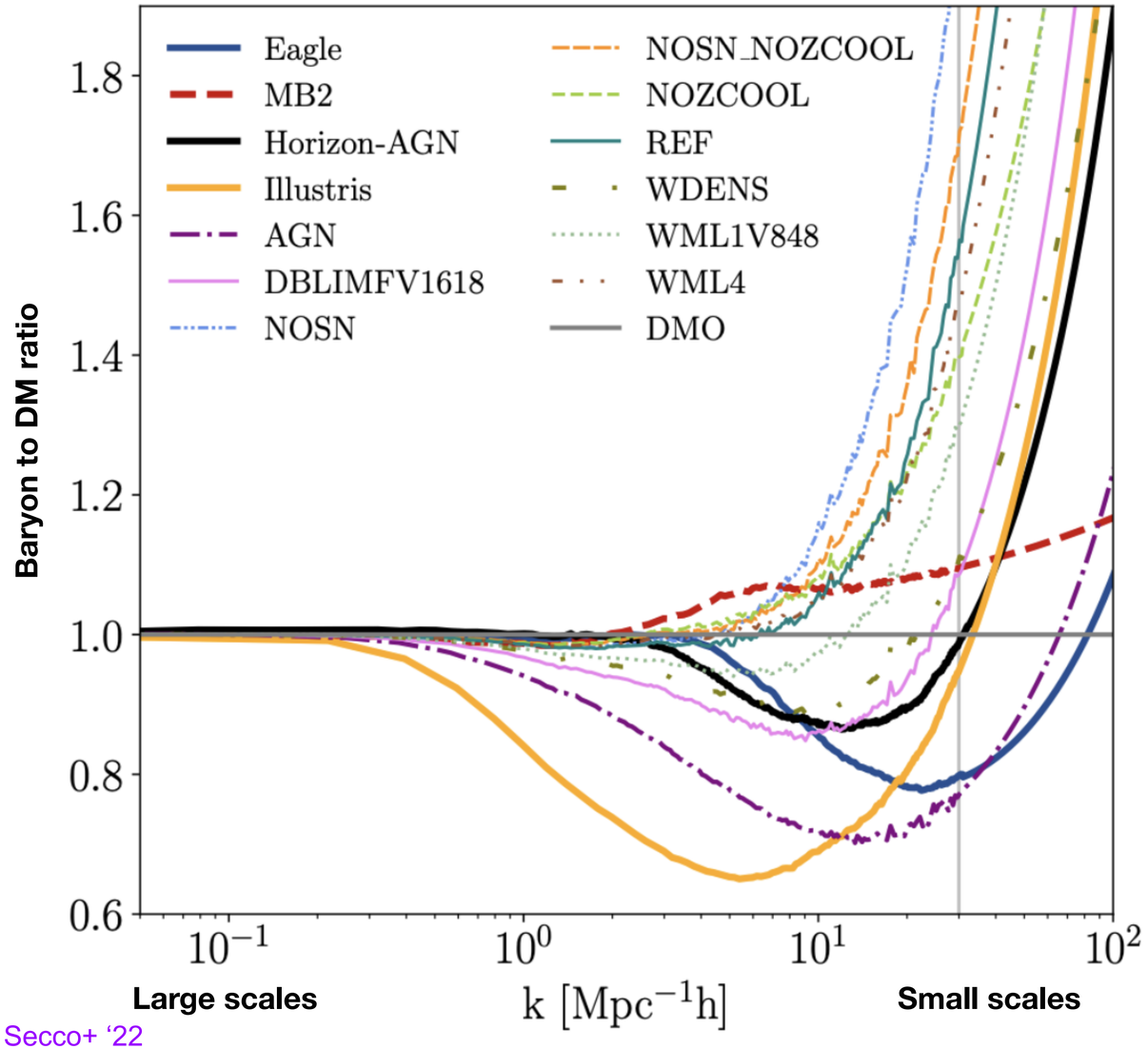
Omori (2023)

Imprints of **late time physics** (e.g. lensing, kinetic SZ) & **astrophysical emissions** (e.g. galaxies) all tracing the matter distribution

Synergies between CMB and other probes of matter (LSS) to understand physics/DM interplay

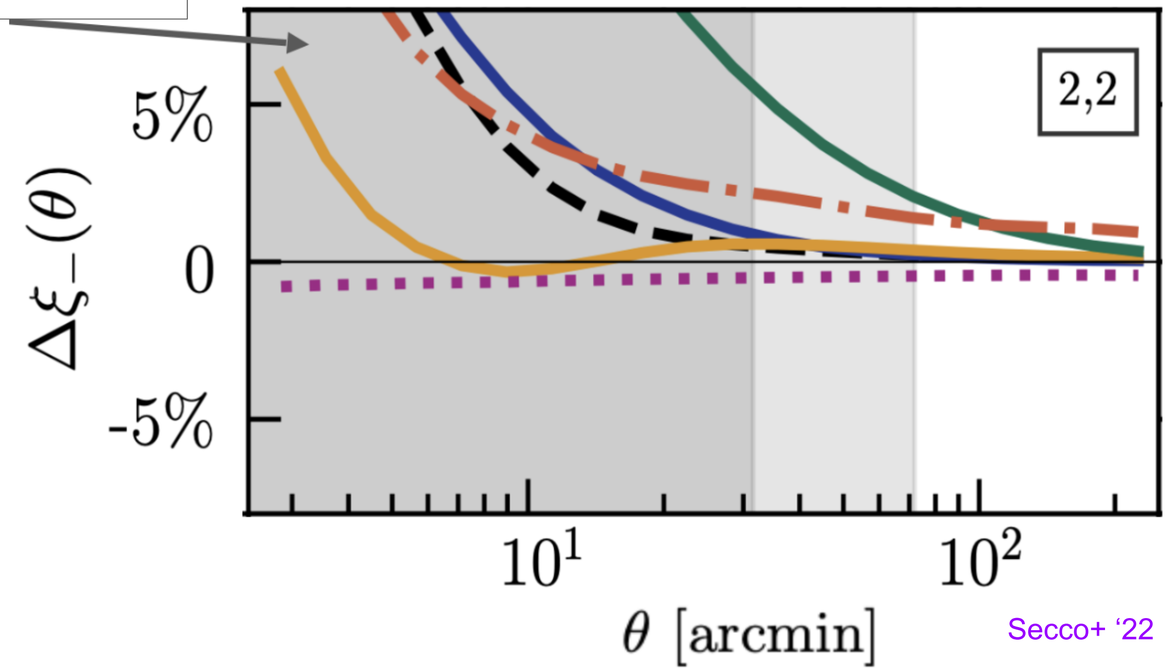
BARYONIC FEEDBACK AT SMALL SCALES

Cf. Lecture from Elisabeth Krause (Tuesday pm)



Secco+ '22

Excluded from DES y3 to avoid baryon bias



Secco+ '22

CMB CROSS-CORRELATIONS

CMB ⊗ LSS tracers (galaxies, shear…) =

(T_{prim}+**T_{lens}**+**$T_{(t+k)SZ}$**+**CIB**+Galaxy+$Noise_{CMB}$) ⊗ **LSS tracers**

$$C_L^{AB} \approx \int \frac{d\chi}{\chi^2} W_A(\chi) W_B(\chi) P_\delta \left(k = \frac{L+1/2}{\chi}, z(\chi) \right)$$

- **CMB lensing**
- **kSZ**
- **tSZ**
- **…**

$$W_g(\chi) = b_g(z) \frac{1}{n} \frac{dn}{dz} \frac{dz}{d\chi}$$

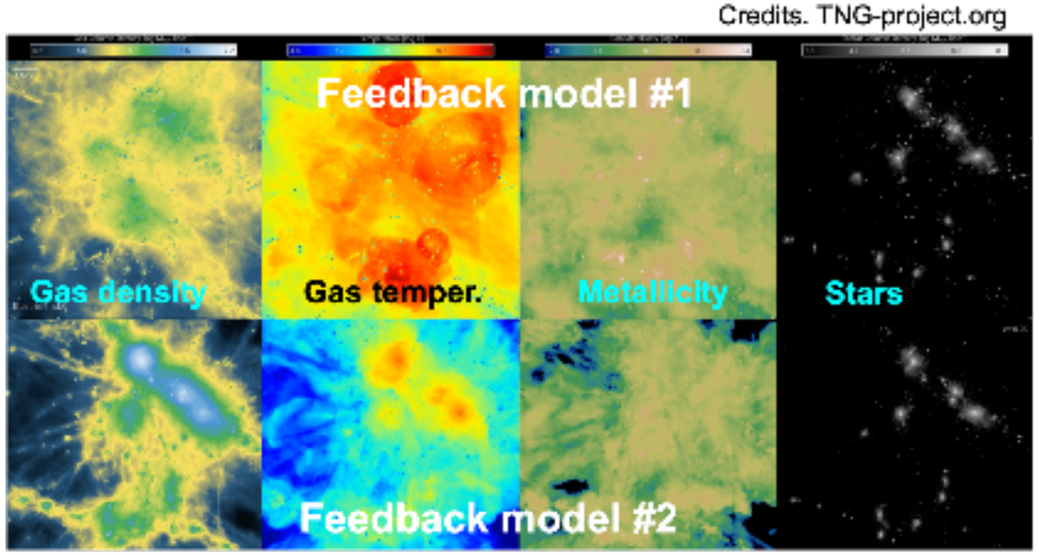
Galaxy distribution

$$W_\kappa(\chi, \chi_s) = \gamma(\chi) \chi^2 \left(\frac{1}{\chi} - \frac{1}{\chi_s} \right) \Theta(\chi_s - \chi)$$

Galaxy lensing

- Beats systematic effects
- Enhances low-amplitude signals
- Increases the constraining power of a given data set
- Mitigates astrophysics while constraining cosmological parameters

tSZ & GALAXY LENSING CORRELATION



- Probe the **pressure profile** in clusters and groups
- Probe the cluster mass scaling relation & Measure the hydrostatic mass bias
- Constrain the feedback processes

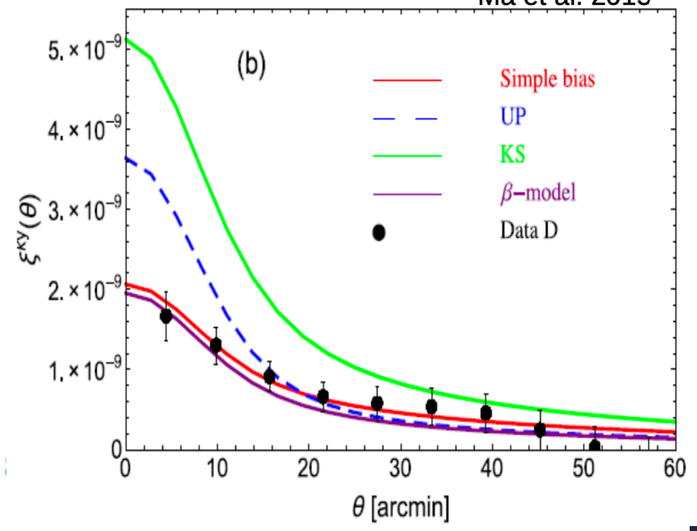
$$\tilde{u}_l^y(M,z) = \frac{4\pi r_{500c}}{l_{500c}^2} \int_{x_{min}}^{x_{max}} dx x^2 y_{3D}(x) \frac{\sin(lx/l_{500c})}{lx/l_{500c}}$$

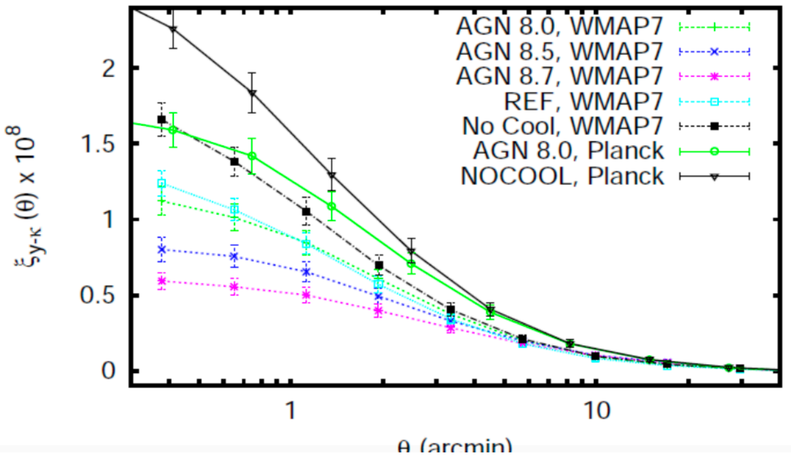
Pressure profile

$$P_e(x) = 1.65(h/0.7)^2 \text{ eV cm}^{-3} \times E^{8/3}(z) \left[\frac{M_{500c}}{3\times10^{14}(0.7/h)M_\odot}\right]^{2/3+\alpha_p} p(x)$$

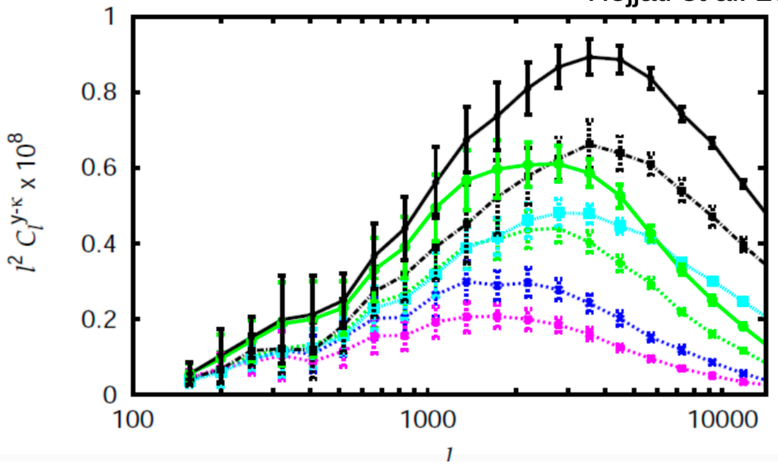
Some of the earliest works based on CFHT-LS galaxy lensing correlation with Planck tSZ map

Ma et al. 2015



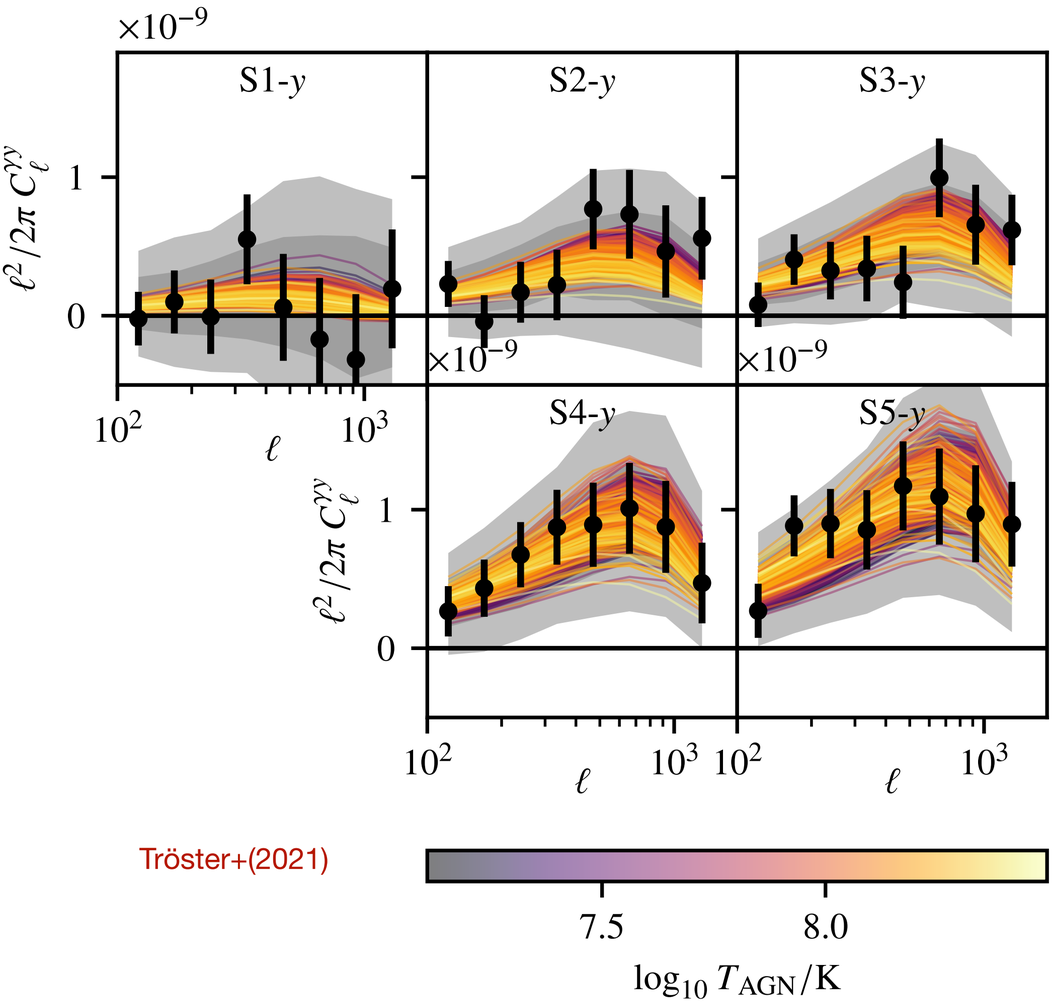


Hojjati et al. 2015



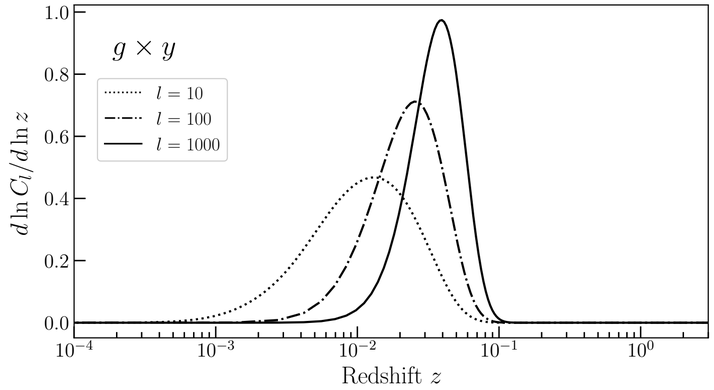
TSZ & GALAXIES CORRELATION

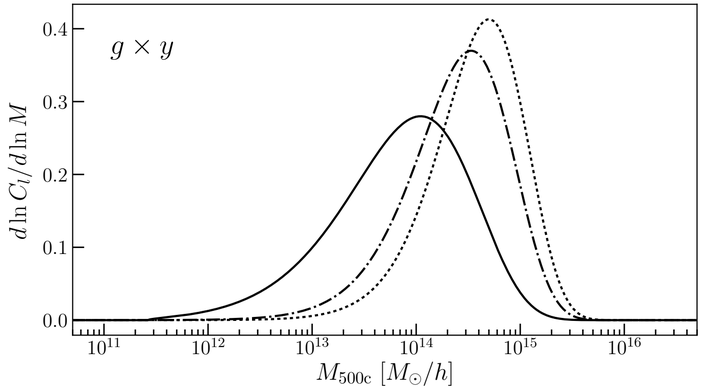
Probe the physics of the hot gas in baryons in redshift bins (tomographically)



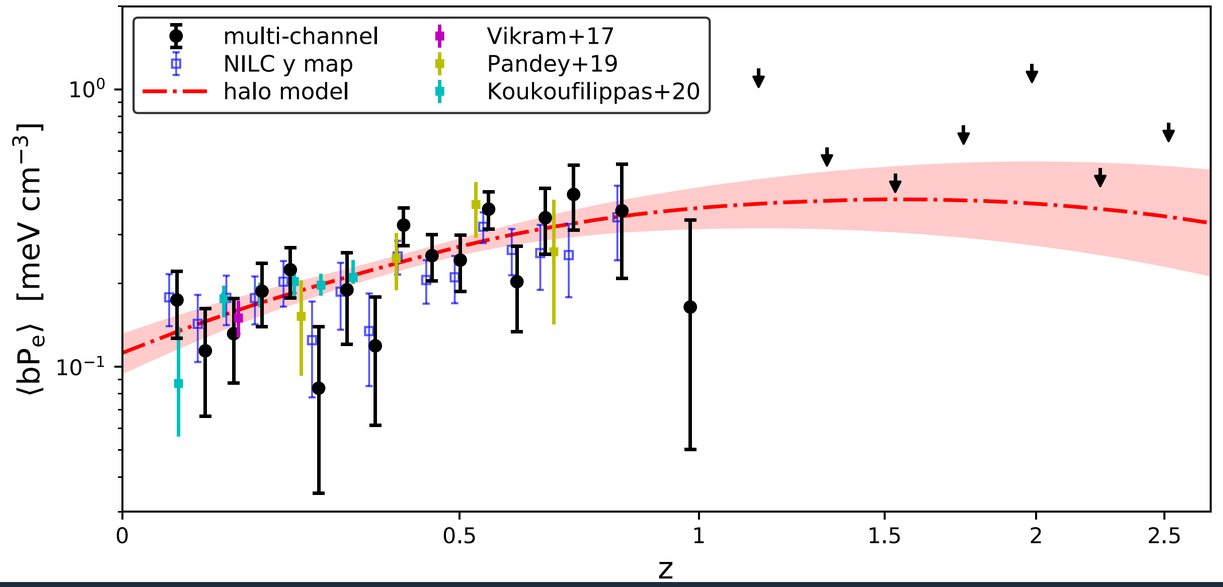
Tröster+(2021)

Makyia & Komatsu (2019)



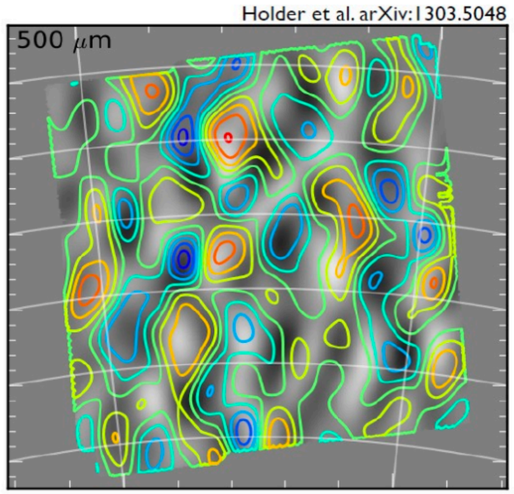


Chiang+(2020)

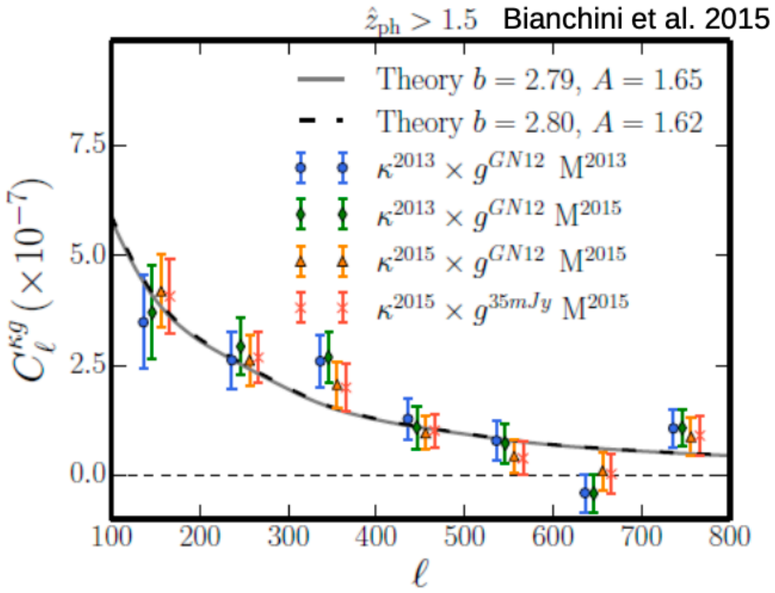


CMB-LENSING & GALAXIES CORRELATION

From the earliest 3σ detections and proof of concepts



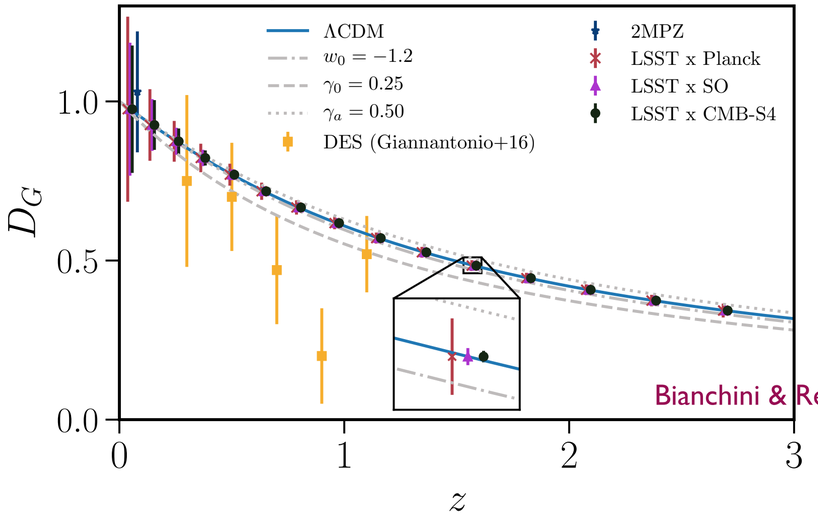
SPT lensing and distribution of high-z galaxies from Herschel



See also Hand+ '13, Hand+ '15, Kirk+ '15

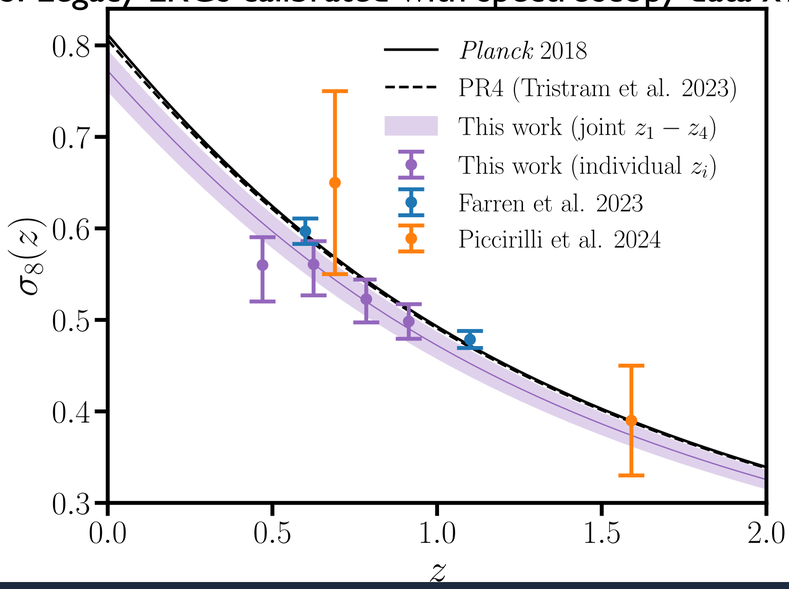
To constraints of the growth function and cosmological parameters

$$D_G \approx (C_\ell^{\kappa g})^2 / C_\ell^{gg} \approx \hat{\boldsymbol{\theta}} \in \{C_\ell^{\kappa g}, C_\ell^{gg}\}$$



Bianchini & Reichardt '18

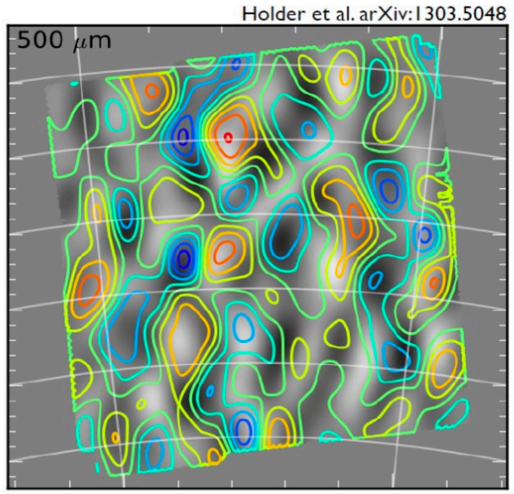
DESI Legacy LRGs calibrated with spectroscopy data x ACT DR6



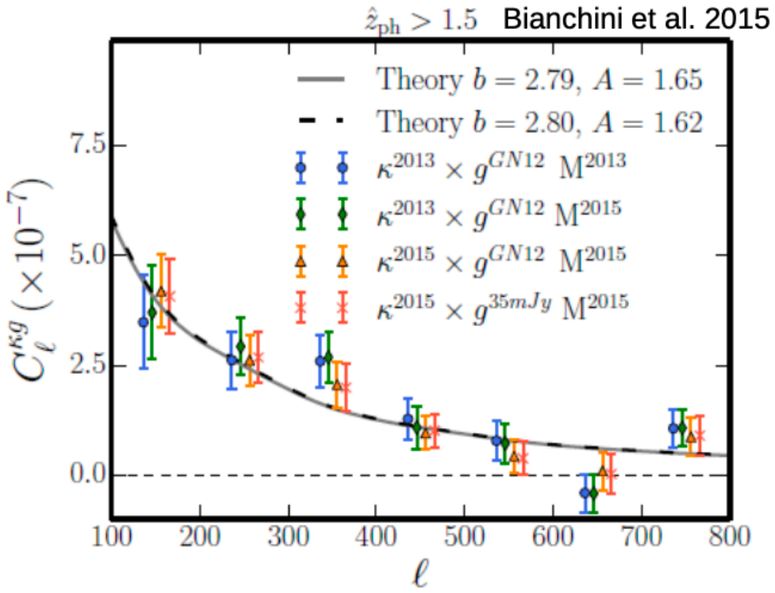
Sailer+ '24

CMB-LENSING & GALAXIES CORRELATION

From the earliest 3σ detections and proof of concepts

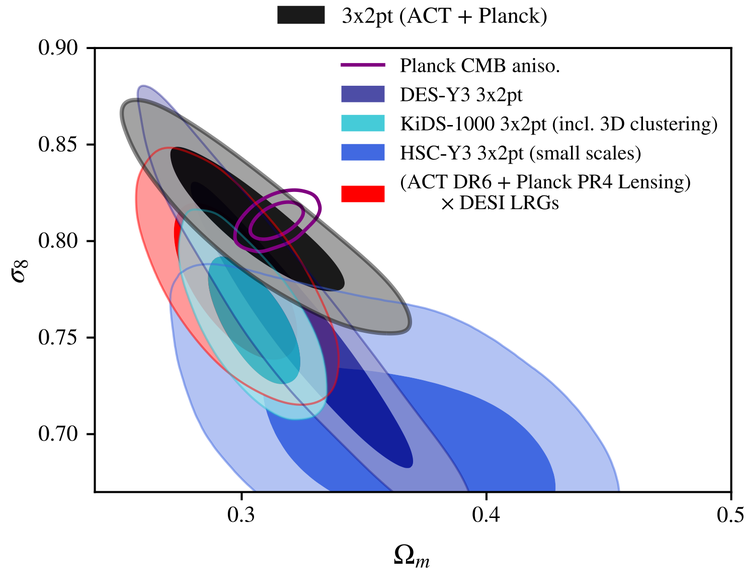


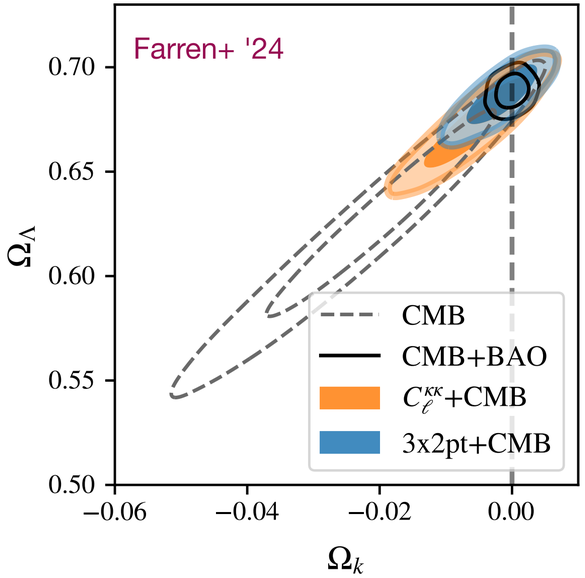
SPT lensing and distribution of high-z galaxies from Herschel



See also Hand+ '13, Hand+ '15, Kirk+ '15

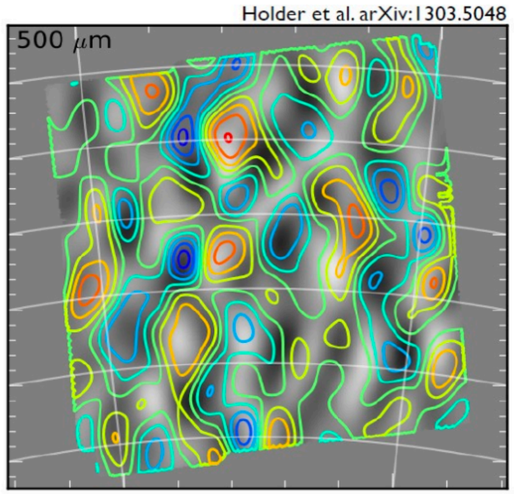
To constraints of the growth function and cosmological parameters



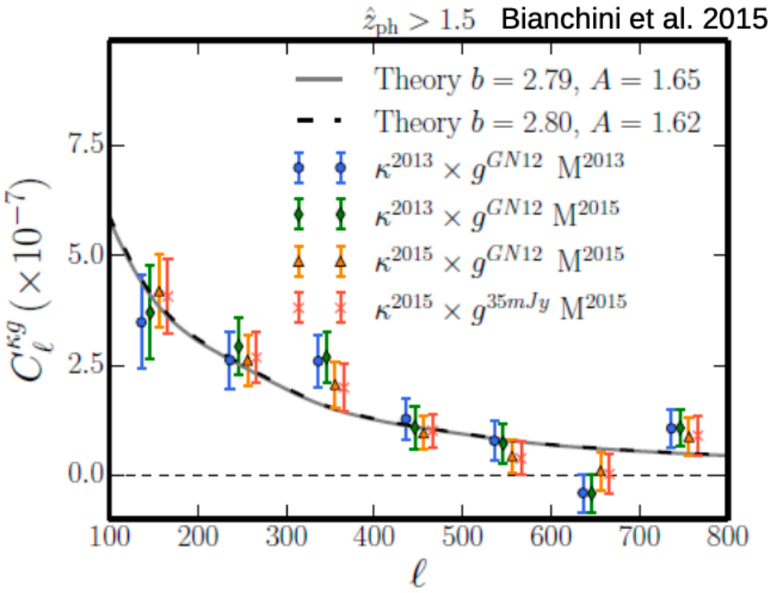


CMB-LENSING & GALAXIES CORRELATION

From the earliest 3σ detections and proof of concepts

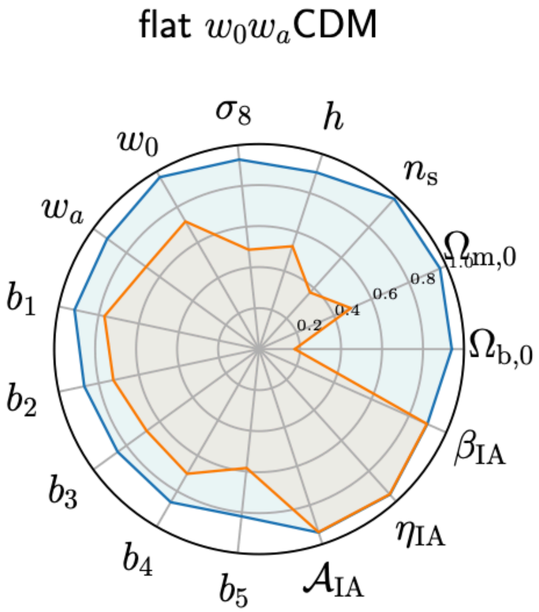


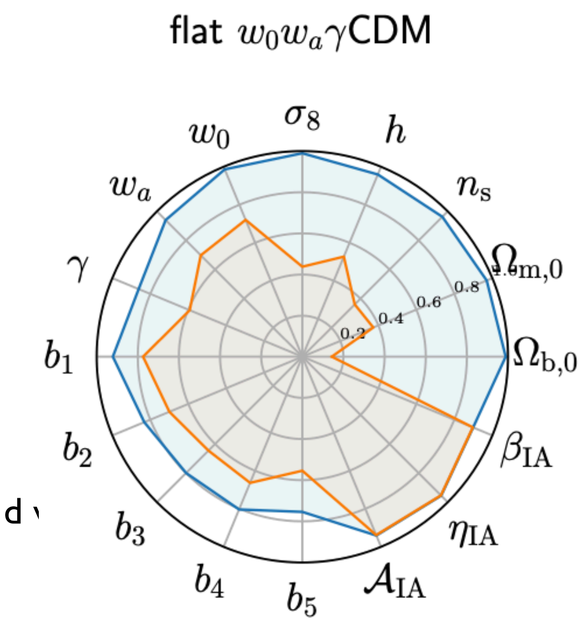
SPT lensing and distribution of high-z galaxies from Herschel



See also Hand+ '13, Hand+ '15, Kirk+ '15

To constraints of the growth function and cosmological parameters



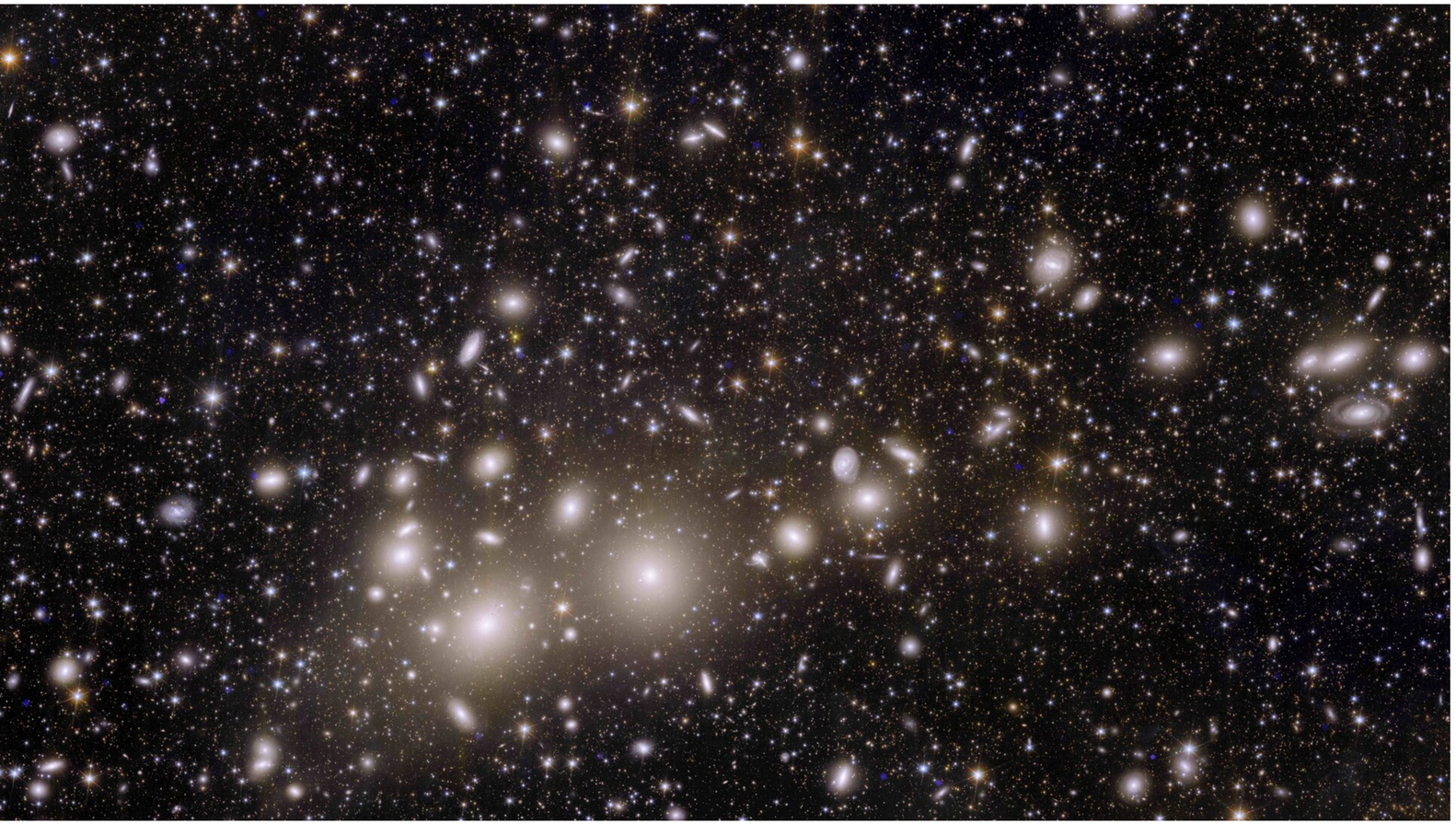


Euclid consortium: Ilic+ 2022)

Euclid forecast → X-correlation improves ~3x on standard & extended model cosmological models + **Constrains the biais model, i.e. baryonic physics**

TOWARDS CMB SMALLEST SCALES

Euclid early release data



Rubin 1st wide image



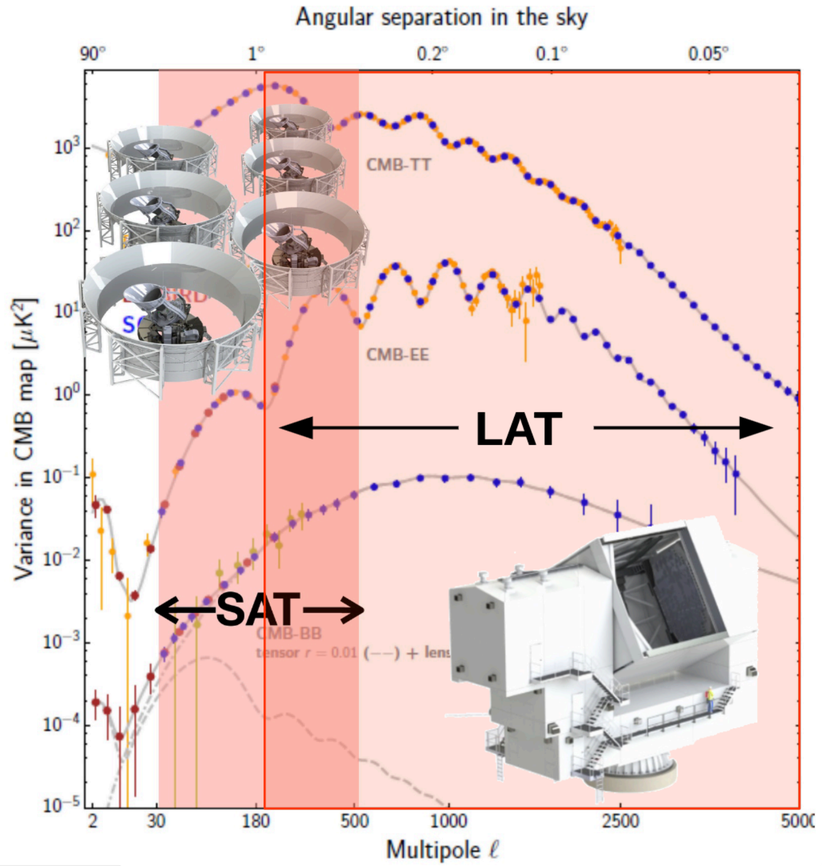
TOWARDS CMB SMALLEST SCALES

Simons Obs. / South Pole Obs. *observing now / SPO ~2029* arcmin · ~3 / ~0.5 μK-arcmin · half sky / 3.5%

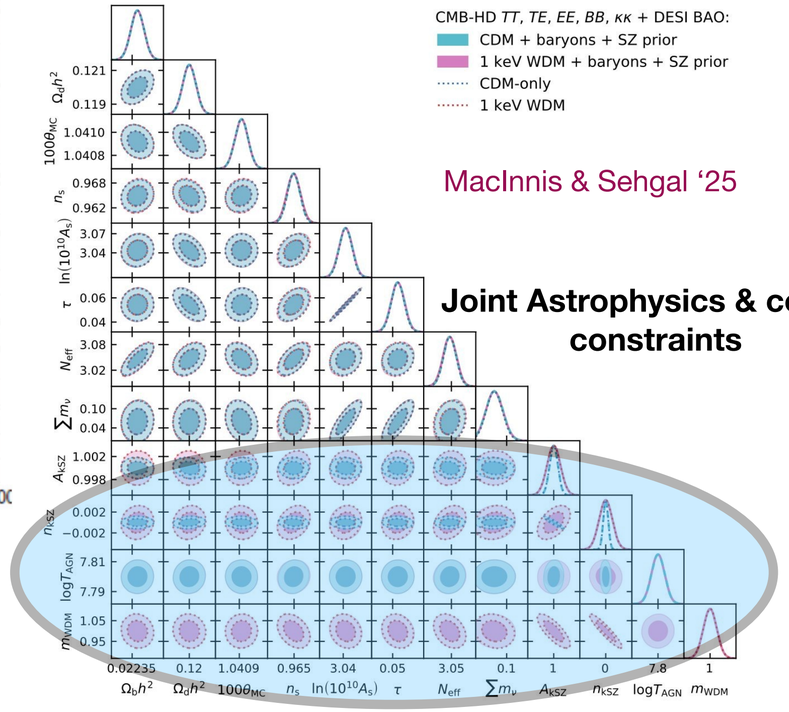
CMB-HD *proposed, 2030s* 15″ · 0.5 μK-arcmin · half sky

15″	0.5 μK-arcmin	2 × 30 m
angular resolution at 150 GHz	combined temperature noise	new telescopes in the Atacama
≈ 6× finer than Simons Observatory	*≈ 6× deeper than Simons Observatory*	*seven bands, ~30–350 GHz*

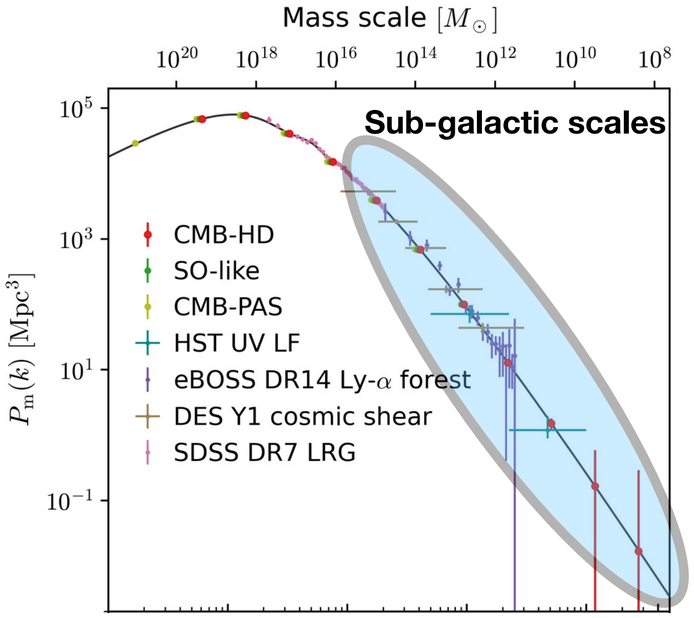
Credits N. Sehgal



Credits Federico Nati



MacInnis & Sehgal ‘25



Cheslog+ ’26, MacInnis & Sehgal ‘25

Main directions for CMB

CMB Polarisation
(and initial perturbations)

CMB Cross-correlations with LSS tracers
(and baryonic physics & feedback)

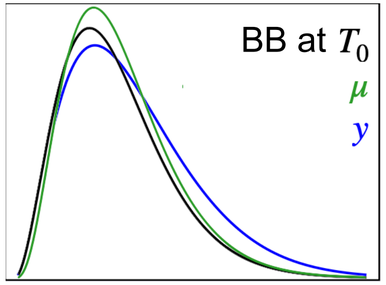
CMB Spectral distortions
(How black is the blackbody? What can we learn from it?)

CMB SPECTRAL DISTORTIONS

During cosmic evolution **energy or photon injection/extraction by physical process modifies the CMB BB spectrum,** if thermalisation via energy redistribution or photon creation/destruction is not possible

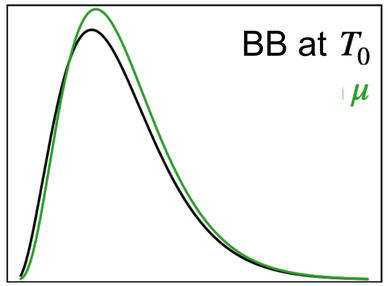
380,000 yrs — $z \lesssim 5 \times 10^4$
y-distortion = Inverse Compton

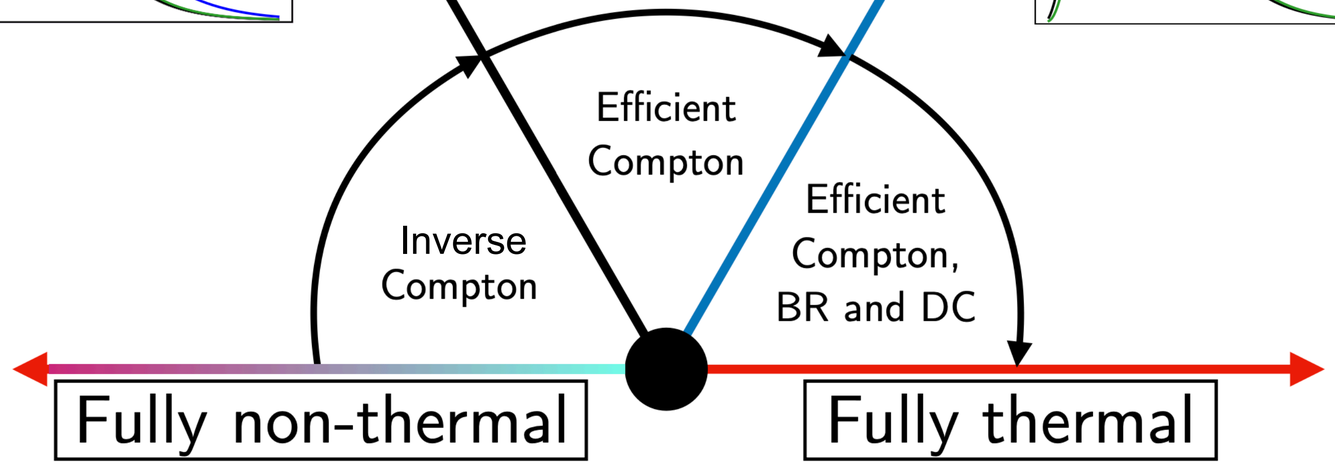
y-distortion



μ-distortion

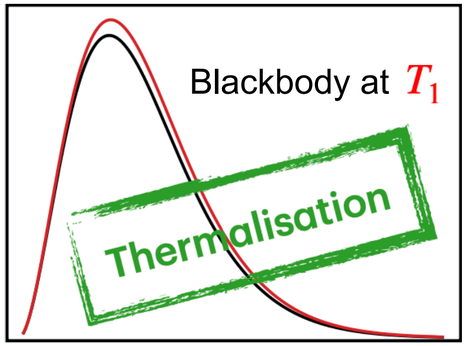
1yr to 100 yrs — $5 \times 10^4 \lesssim z \lesssim 10^6$
μ-distortion = chemical potential





Adapted from B. Cyr

<1yr — $z \gtrsim 10^6$
Temperature-shift

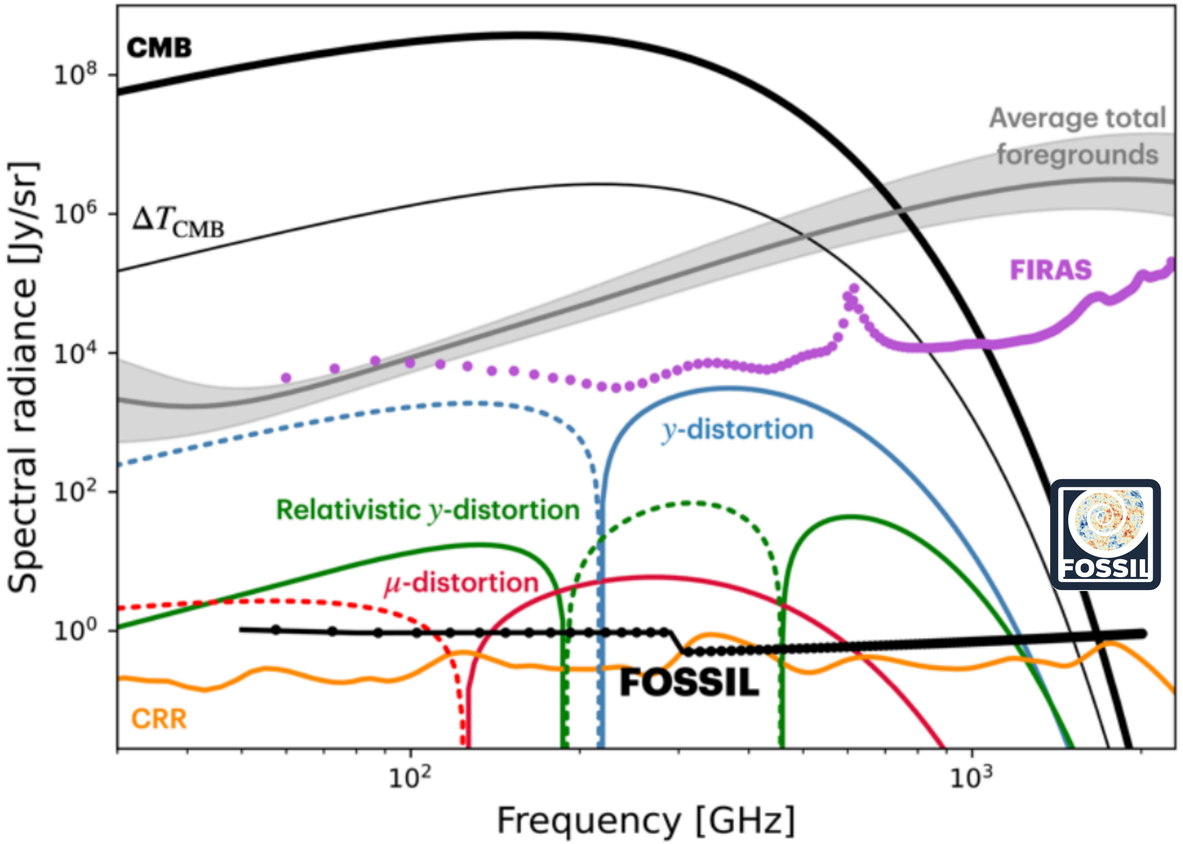


FUTURE FORESEEN CAPABILITIES: FOSSIL

Compared with COBE/FIRAS
- 10 times better in angular resolution
- ~1000 better in sensitivity

Modeling foregroungs & signals & instrument characteristics

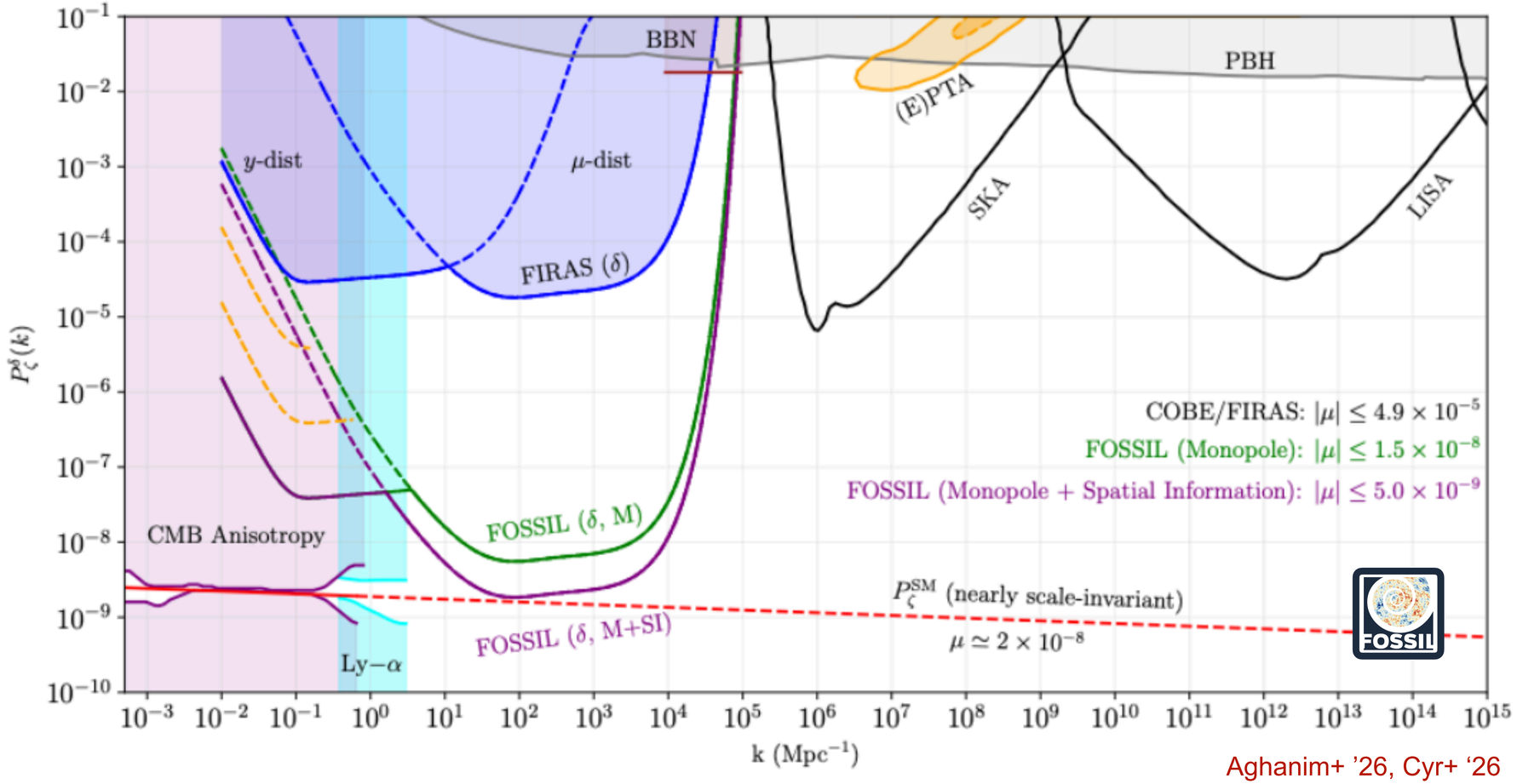
Three target measurements:
- Monopole **y distortion 3 orders magnitude better** than FIRAS → **σ(y) ~5 x 10^{-9}**
- First measure of average electron temperature down to **kT_{eSZ} ≃ 1.3 keV at tens σ**
- μ distortions **hundreds of times better** than FIRAS → **σ(μ) ~1.5 x 10^{-8}** to **~5 x 10^{-9}**



Credits Xavier Coulon PhD 2026, Aghanim+ ‘26

DISTORTIONS FROM EARLY UNIVERSE

- **Primordial power spectrum** at small scales → Open a unique window
- **Challenge the single-field slow-roll inflation** → departure from predicted μ?
- **Origin of super-massive BHs** → Test of primordial BHs as SMBH seeds



Dissipation of small-scale perturbations → **energy injection** → **distortion of CMB spectrum** for single-field inflation scale-invariant initial perturbations **μ ~ 2. 10^{-8}**

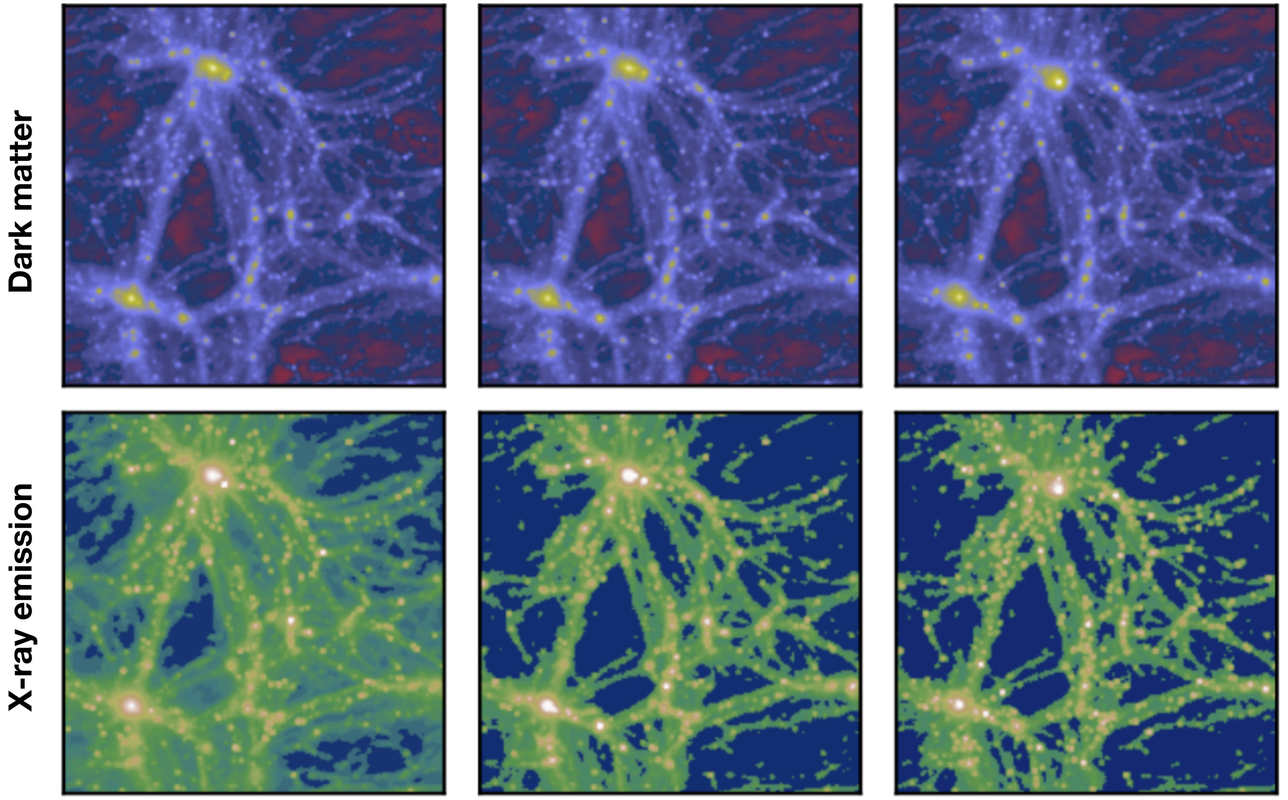
Aghanim+ ’26, Cyr+ ‘26

DISTORTIONS FROM BARYON PHYSICS

Probing thermodynamics of the Universe

- Collapse of baryons in the potential wells of cosmic web (clusters, filaments) → **Gravitational heating**
- Feedback from galaxies supernova (SN) and SMBH-powered AGN → **Energy injection**

After $z<10^3$, **Thermalisation is totally inefficient** → predicted **distortions the in CMB spectrum $y \sim 2. 10^{-6}$**

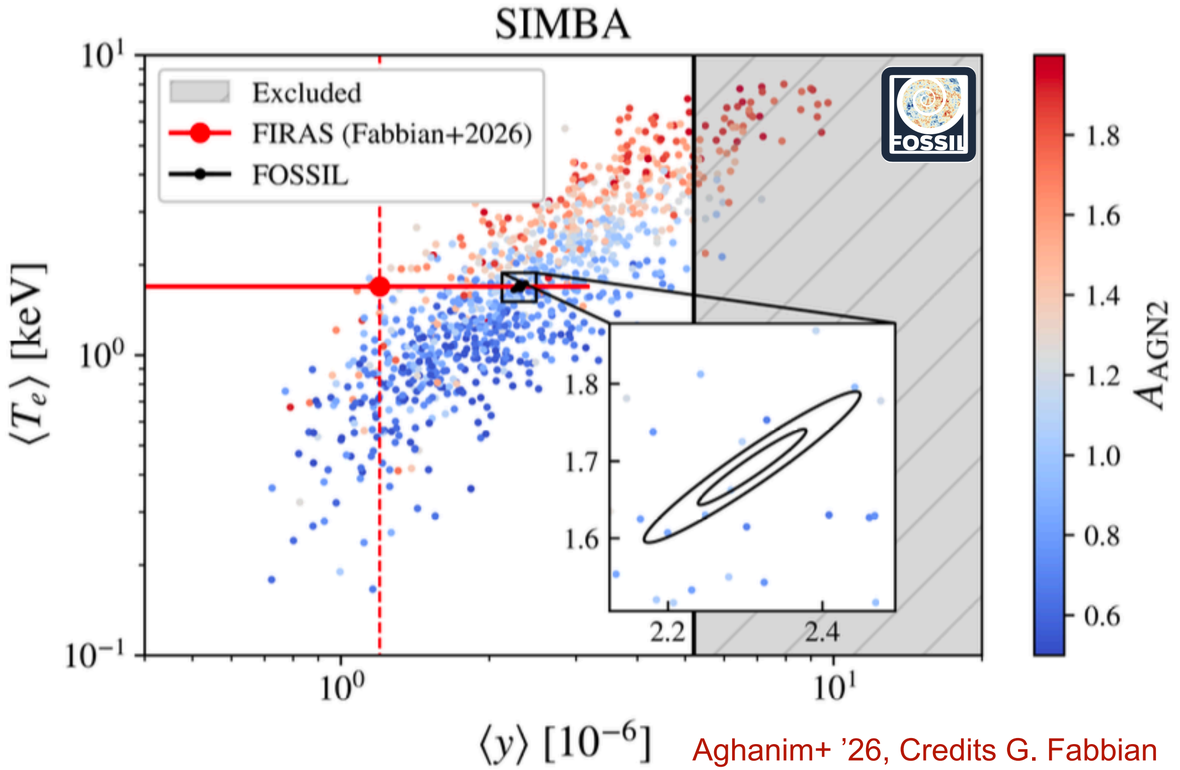


Villaescusa-Navarro+ '21

DISTORTIONS FROM BARYON PHYSICS

Probing thermodynamics of the Universe

- Non-relativistic *y* signal traces the **pressure** of ionised gas
  - Complete **census of hot baryons**
  - Probe of the **thermodynamic** state of ionised gas across cosmic time.
- Relativistic *y* signal traces the **electron temperature**
  - Measure temperature down to Te ≃1.3 keV
  - Put stringent **constraints on total energy injected** by SuperMassive BHs
  - **Isolate feedback models** among the range of possible models allowed by current observations



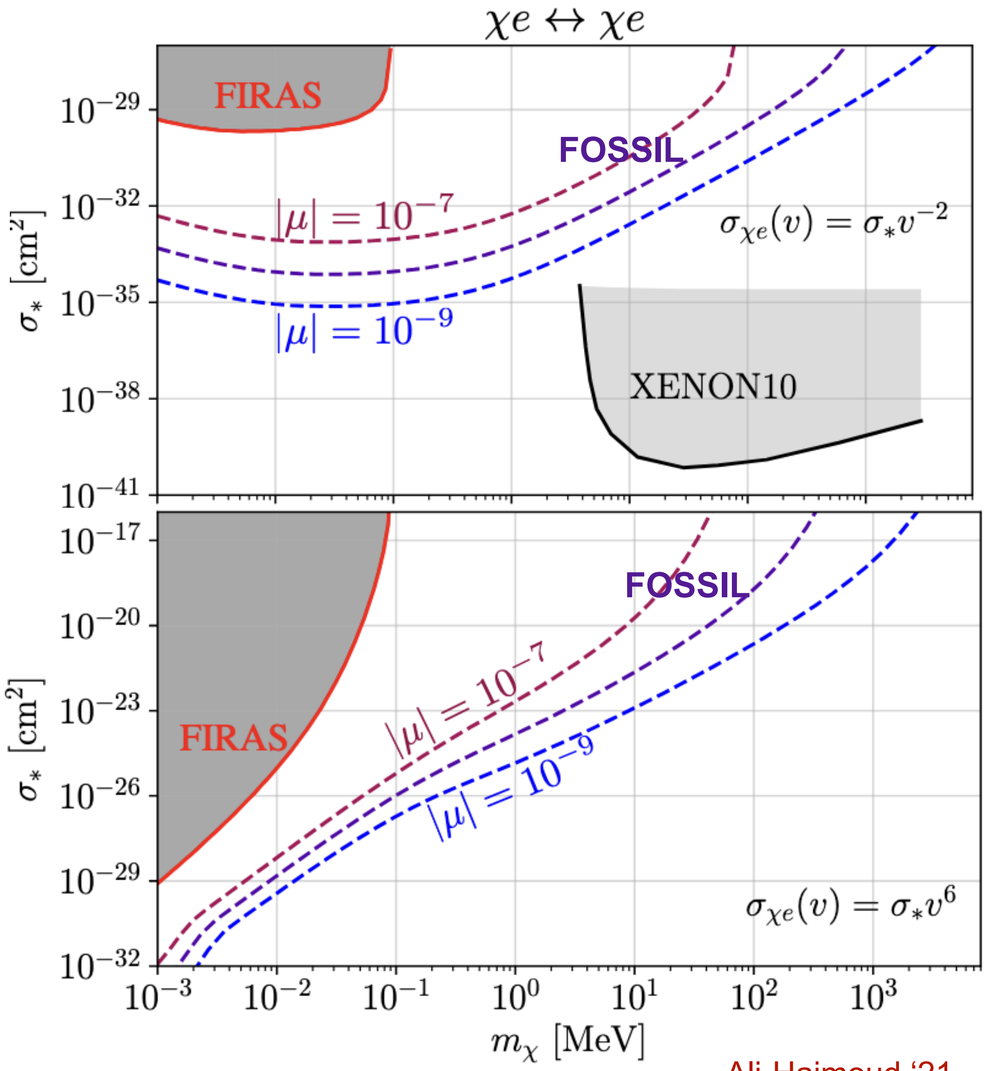
Aghanim+ ’26, Credits G. Fabbian

DISTORTIONS FROM DARK MATTER

Probing the nature of dark matter

Via imprints on the CMB spectrum of DM decay and annihilation or scattering with standard model (SM) particles

- **Scattering of DM** with photons, electrons, nuclei acts as a heat sink for the photon–baryon plasma → negative **μ distortion**
  - Probe DM masses up to ~ 1 GeV
  - Constrain models of the thermal decoupling of DM with the plasma
  - Discrimination among scattering models

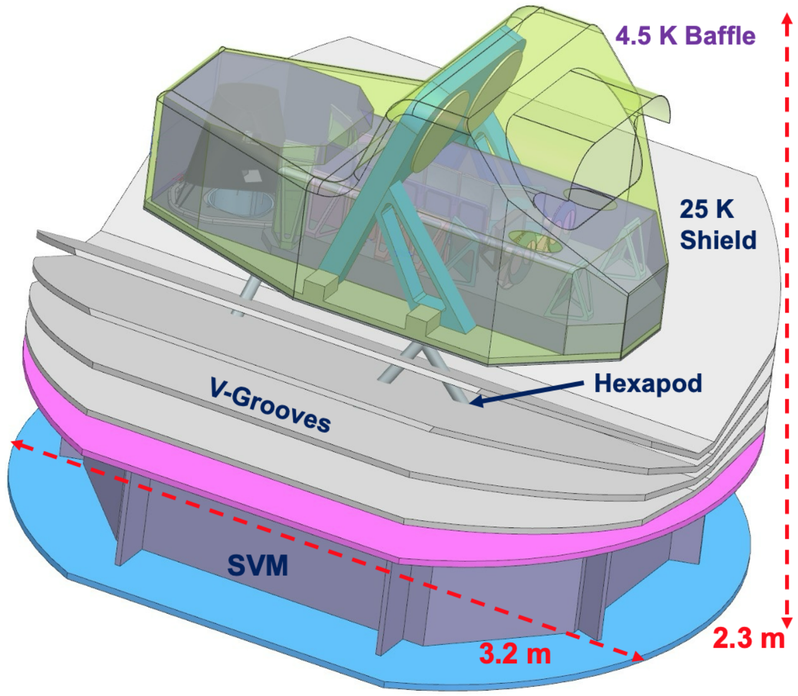


Ali-Haimoud '21

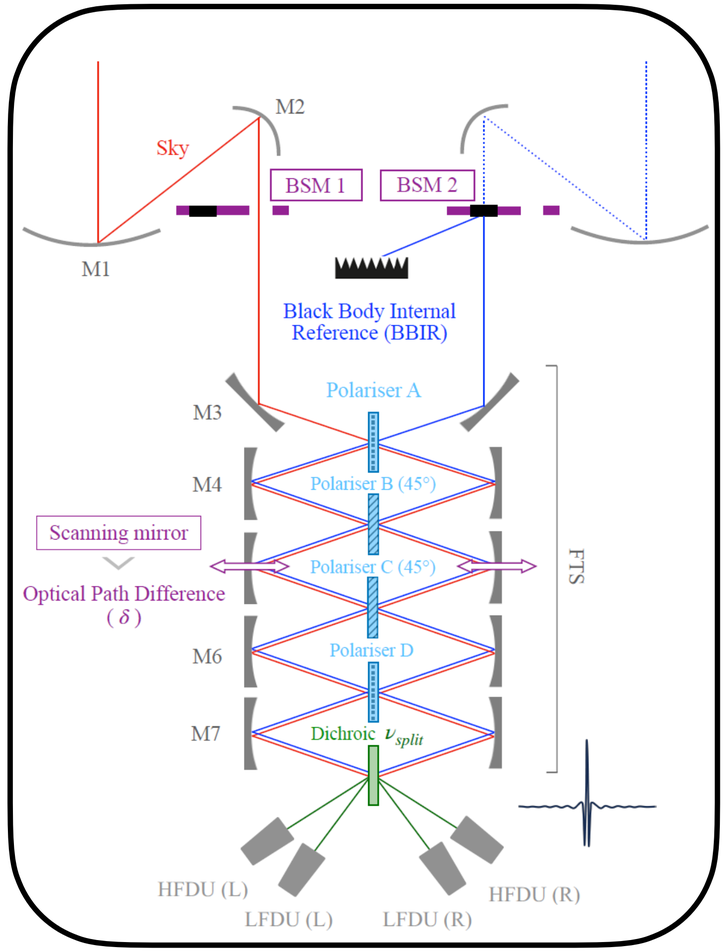
FOSSIL MISSION PROPOSED AS ESA M8

FTS f**O**r CMB **S**pectral di**S**tort**I**on exp**L**oration

PI. N. Aghanim



Aghanim+ ‘26



Credits Morgane Loquet Le Gall

- Full sky coverage from L2
- Duration 4 yrs
- **50 to 2000 GHz**
- $\Delta\nu$=15 GHz → 130 frequency bands
- Split @~300 GHz
  - 2 spectral bands
- 2 primary telescopes: ~40cm
- Spatial Resolution
  - **~1.6 deg** equivalent Gaussian beam

- **FTS with**
  - 2 inputs
  - 2 outputs → 4 focal plane units
- Instrument & telescopes cooled at ~4.5 K
- Focal planes cooled @50mK

MAIN DIRECTIONS FOR CMB

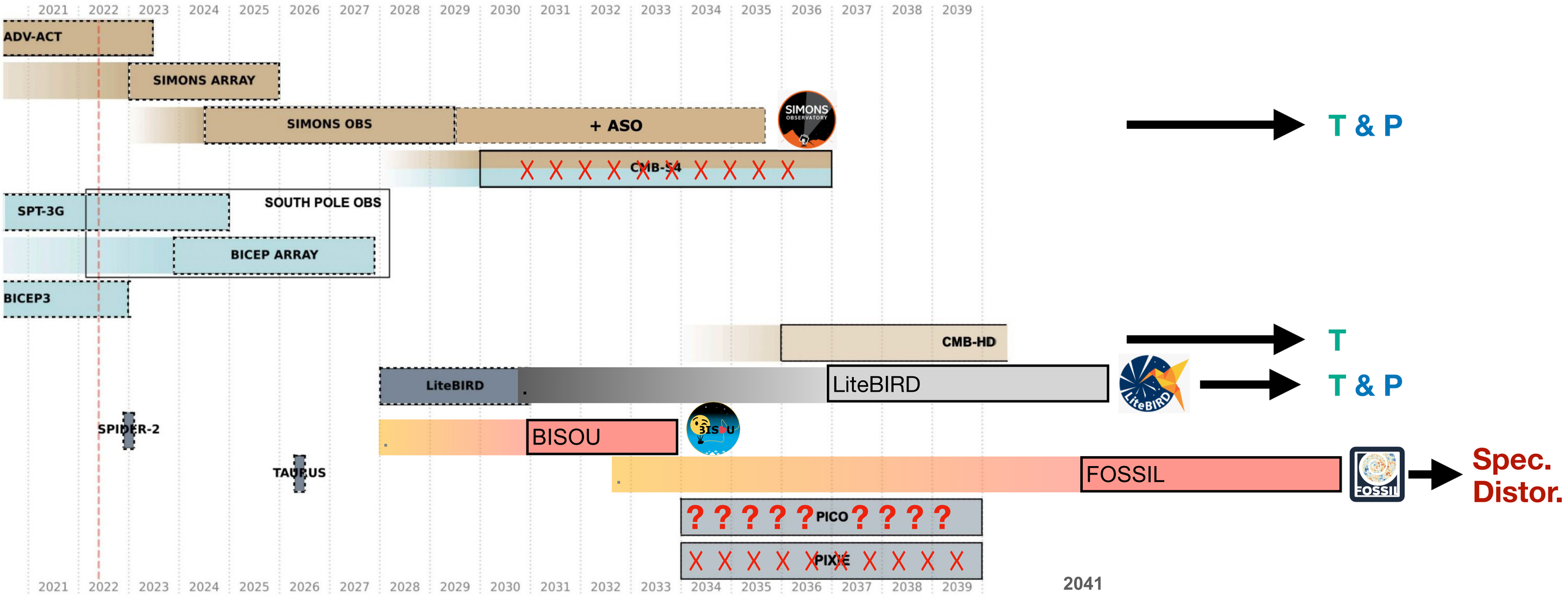
CMB Polarisation
(and initial perturbations)

CMB Cross-correlations with LSS tracers
(and baryonic physics & feedback)

CMB Spectral distortions
(Initial perturbations, baryonic physics, DM nature)

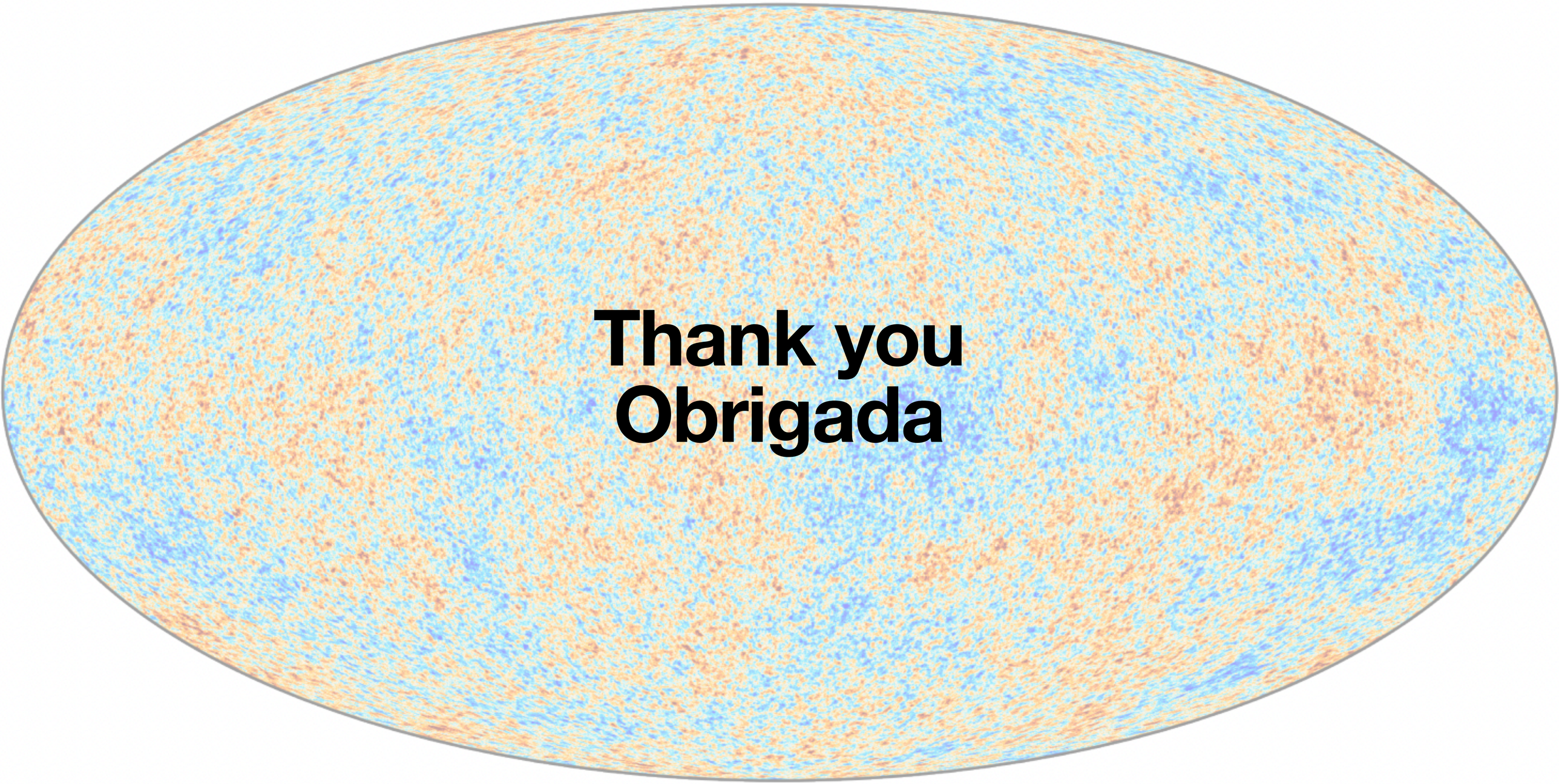
… A PERSONAL VIEW

CMB LANDSCAPE & POSSIBLE PROSPECTS



Timeline adapted from the Snowmass 2021 CF6 summary report (arXiv:2209.08654), with Advanced SO added.

Adapted from adaptation of N. Seghal


Thank you
Obrigada